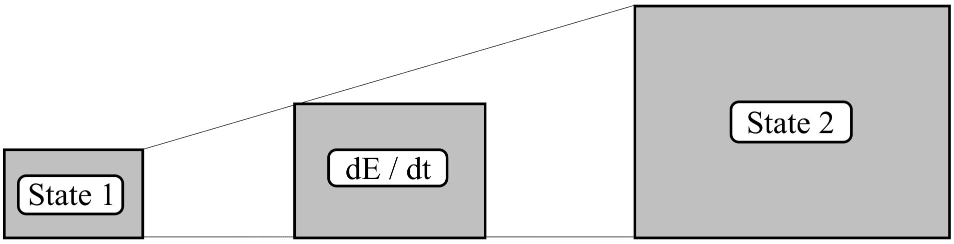
IV. THE FIRST PRINCIPLE

IV.1. CLOSED SYSTEM

The first law of classical thermodynamics deals with the equivalence of work transfer and heat transfer as forms of energy interactions. This principle encapsulates an experimental truth permanently ascertained in every energy transfer phenomenon. In Max Planck's words:

"*is nothing more than the principle of the conservation of energy applied to phenomena involving the production or absorption of heat*"

The first law and the second law of thermodynamics substantiated by the writings of William John MacQuorn Rankine, Rudolph Clausius and William Thomson (Lord Kelvin) in the early 1850s. They had to resolve together the conflict between Sadi Carnot' s theory that assumed the conservation of "caloric" and the real evidence that work through friction represents the end of the "caloric" concept. Let us consider a closed system respectively a control volume having a boundary impermeable to mass transfer with its environment, see Fig. IV.1.



time t_1 time t ($t_1 \le t \le t_2$) time t_2

Fig. IV.1 - *Statement of the First Law for closed systems*

This system experiences a change of its state from the initial state (1) to a final one (2) as a result of the interactions with its environment, such as work and heat transfer. The first law of thermodynamics requires:

Net energy transfer	=	Heat transfer	+	Work transfer	=	System energy change
(m = 1)	$\Rightarrow$	$(q_{1,2})$	+	$(-\overline{w}_{1,2})$	=	$(e_2 - e_1)$
$(m \neq 1)$	$\Rightarrow$	$(Q_{1,2})$	+	$(-\overline{W}_{1,2})$	=	$(E_2 - E_1)$
		energy transfers between the system and its environment (non-properties)				variation of the property called net system energy

According to the Equation (IV.1) the net energy transfer between the system and its environment (the left hand) is equal to the change in the thermodynamic property called the net energy of the system (the right hand). The first law of thermodynamics defines in this way the net energy of a system as a property, which measures by its variation the energy interactions of the system with the surroundings. The sign in the left-hand terms observe the "*heat engine sign convention*", i.e. the heat transfer toward the system and the work transfer from the system are considered positive. The following scheme presents the two sign conventions:

The "***heat engine sign convention***" accordingly is to the purpose of a heat engine as a closed thermodynamic system wich consumes heat to perform work on its environment. The net energy of the system as a property depends only on the state of the system and consequently its change is equal to the ($E_2 - E_1$) whereas the energy transfers as non-properties depend on the path (succesive states that link the ending states of the process).

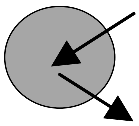
The net energy system contains two kinds of energy:

$$E = U + E_{exterior} = U + \left(E_{kinetic} + E_{gravity}\right) \qquad \text{(IV.2)}$$

where: U *is the internal energy which depends on the interior conditions,* $E_{exterior}$ *is the energy which depends on the exterior conditions*:

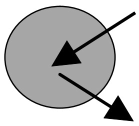
$$E_{exterior} = E_{kinetic} + E_{gravity} = m\frac{c^2}{2} + mgz \qquad \text{(IV.3)}$$

(the velocity *c* is related to an arbitrarily chosen geometrical system and the position *z* in the gravity field is depending on an arbitrary imposed zero)



$\left(Q_{1,2}\right)^{\text{heat engine}}_{\text{sign convention}}$ and $\left(Q_{1,2}\right)^{\text{physics}}_{\text{sign convention}}$ are positive (> 0)

$\left(Q_{1,2}\right)^{\text{heat engine}}_{\text{sign convention}}$ and $\left(Q_{1,2}\right)^{\text{physics}}_{\text{sign convention}}$ are negative (< 0)



$\left(-\overline{W}_{1,2}\right)^{\text{heat engine}}_{\text{sign convention}}$ and $\left(+\overline{W}_{1,2}\right)^{\text{physics}}_{\text{sign convention}}$ are positive (> 0)

$\left(-\overline{W}_{1,2}\right)^{\text{heat engine}}_{\text{sign convention}}$ and $\left(+\overline{W}_{1,2}\right)^{\text{physics}}_{\text{sign convention}}$ are negative (< 0)

Historically the principle of energy conservation was distinctly substantiated for mechanical phenomena and thermal phenomena.

For every pure mechanical phenomenon we may write the Equation:

$$W_{received} = W_{given} \qquad \text{(IV.4)}$$

For any pure thermal phenomenon we can equate:

$$Q_{received} = Q_{given} \qquad \text{(IV.5)}$$

In Equation (IV.1) the work transfer $\overline{W}_{1,2}$ includes two terms:

$$\overline{W}_{1,2} = W_{1,2}^{deformation} + W_{1,2}^{exterior} \qquad \text{(IV.6)}$$

where: $$\begin{cases} W_{1,2}^{deformation} = +\int_1^2 p \cdot dV \\ W_{1,2}^{exterior} = W_{1,2}^{\substack{\text{change of} \\ \text{kinetic energy}}} + W_{1,2}^{\substack{\text{change of position} \\ \text{in the gravity field}}} \end{cases} \qquad \text{(IV.7)}$$

The modification of the the kinetic energy and the change of the position in the gravity field are clearly mechanical phenomenona and consequently:

$$-W_{1\text{-}2}^{exterior} = \left(E_{kinetic,2} - E_{kinetic,1}\right) + \left(E_{gravity,2} - E_{gravity,1}\right) \qquad \text{(IV.8)}$$

Therefore for the closed thermodynamic systems, either moving or motionless, the Equation of the first principle becomes:

$$Q_{1,2} - W_{1,2} = \Delta U = U_2 - U_1 \qquad \text{(IV.9)}$$

where: $$W_{1,2} = +\int_1^2 p_{exterior} dV = +\int_1^2 pdV \qquad \text{(IV.10)}$$

is the work transfer that produces the deformation of the system, respectively modifies the sizes of the control volume. We considered that during the evolution of the system, shocks did not appear and thus we could permanently suppose that the exterior pressure $p_{exterior}$ is equal to the inner (internal) pressure p of the control volume. For the mass unit all previous relations must be divided by the mass and so we obtain the following relations:

$$\left.\begin{aligned} & e = \frac{E}{m}, q_{1,2} = \frac{Q_{1,2}}{m}, \overline{w}_{1,2} = \frac{\overline{W}_{1,2}}{m},\ u = \frac{U}{m}, w_{1,2} = \frac{W_{1,2}}{m} \\ & q_{1,2} - \overline{w}_{1,2} = e_2 - e_1 \text{ and } q_{1,2} - w_{1,2} = u_2 - u_1 \end{aligned}\right\} \qquad \text{(IV.11)}$$

IV.1.1. Infinitesimal Evolution

For an infinitesimal evolution of a closed thermodynamic system, the Equations of the first principle become:

$$\delta q - \delta w = du, \delta w = +p \cdot dv,\ \ \delta Q - \delta W = dU, \delta W = +p \cdot dV \qquad \text{(IV.12)}$$

where: $v = \dfrac{V}{m}$ *is the specific volume*

IV.1.2. Open Transformation of a Closed System

The first law of Thermodynamics allows us to show that the net energy transfer *NET* **=** (*Q* □ *W*) is a state function depending only on the final states although the terms of this algebraic sum are non-properties and so they depend on the path of the transformation. According to Figure IV.2, for any transformation between 1 and 2 states it yields:

$$E_2 - E_1 = Q_{1,a,2} - W_{1,a,2} = Q_{1,b,2} - W_{1,b,2} = \text{function}(1,2) \qquad \text{(IV.13)}$$

but: $$W_{1,a,2} = +\int_{1a2} p\,dV \neq W_{1,b,2} = +\int_{1b2} p\,dV \;\Rightarrow\; Q_{1,a,2} \neq Q_{1,b,2} \qquad \text{(IV.14)}$$

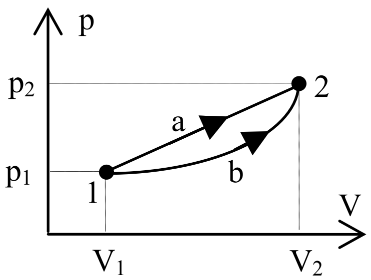


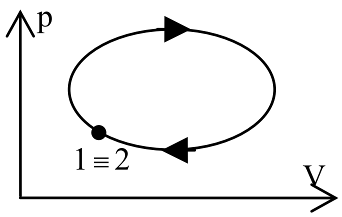
Fig. IV.2
Open transformations in p-V diagram

IV.1.3. *Closed transformation (cycle) of a closed system*

The Equation of the first principle permits to demonstrate that it is imposible to build a perpetuum mobile of the first kind. For this aim let us consider a closed system which experiences a closed transformation (cycle). - see Fig. IV.3. In this case, the energy conservation Equation is:

$$\left.\begin{array}{l} m = 1 \Rightarrow net \;\;= \oint \delta q - \oint \delta w \;= \oint du = u_2 - u_1 \;= 0 \\ m \neq 1 \Rightarrow NET = \oint \delta Q - \oint \delta W = \oint dU = U_2 - U_1 = 0 \end{array}\right\} \qquad \text{(IV.15)}$$

Fig. IV.3.
Closed transformation in p-V diagram



According to Equations (IV.15) it results that it is imposible to build a system, called perpetuum mobile of first kind, for which the net transfer energy *NET* (*net*) on a cycle can be non-zero.

A perpetuum mobile of first kind might either destroy or create the energy because *NET* (*net*) ≠ 0. In the same time the Equations (IV.15) and (IV.16) do not allow to affirm that it is impossible to build a perpetuum mobile of second kind. Correspondingly to these Equations it results:

$$\left.\begin{array}{l}\oint \delta q = \oint \delta w \Rightarrow q_{cyclic} = w_{cyclic} \\ \oint \delta Q = \oint \delta W \Rightarrow Q_{cyclic} = W_{cyclic}\end{array}\right\} \quad \text{(IV.16)}$$

Consequently we should be tempted to set up an engine of which the efficiency would be equal to 1:

$$\eta_{engine} = \frac{W_{useful}}{Q_{input}} = \frac{W_{cyclic}}{Q_{cyclic}} = 1 \quad \text{(IV.17)}$$

Supposing that Q_{cyclic} is the input heat with the purpose to produce useful work W_{cyclic} it is important to notice that such an engine must exchange the heat with a single external heat sink. Unfortunately the experimental truth at the macroscopic scale proves the impossibility to build such an engine. Every engine can cyclically work only by exchanging heat with at least two external heat sinks. This experimental truth susbstantiates the essence of the second principle of Thermodynamics.

IV.2 OPEN SYSTEM

An open system exchanges mass with its environment through its boundary walls. Such a system has a boundary with inlet and outlet ports for the mass transfer. Due to the mass transfer the energy conservation balance must be correlated with the mass conservation balance. This correlation allows us to know theoretically the evolution of the open system. In accordance with the two principles of conservation one can obtain the following axioms, see Fig. IV.4:

1. "***Through any inner closed surface within an open system, the balance of the energies which cross this surface in the unit time is equal to the variation in the same time of the energy of the content surrounded by the closed surface***."
2. "***Through any inner closed surface of the open system the balance of the mass which cross this surface in the unit time is equal to the variation in the same time of the mass of the content surrounded by the closed surface***."

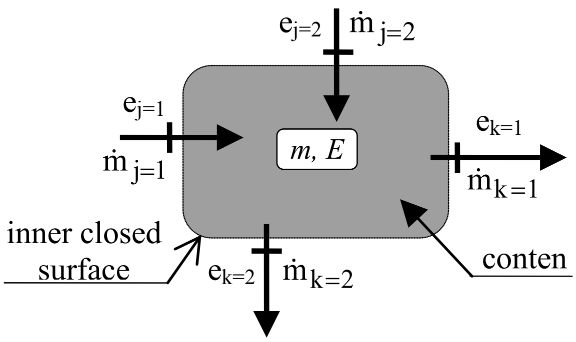


Fig.IV.4. *Inner closed surface within an open thermodynamic system*

Therefore at time it yields:

- ***the energy balance***:

$$\frac{\partial E}{\partial t} = \sum_j \dot{m}_j \cdot e_j - \sum_k \dot{m}_k \cdot e_k \tag{IV.18}$$

- ***the mass balance***:

$$\frac{\partial m}{\partial t} = \sum_j \dot{m}_j - \sum_k \dot{m}_k \tag{IV.19}$$

where:

- e_j - *the total specific energy that enters by inlet port* (j)
- e_k - *the total specific energy coming out by the outlet* (k)
- E - *the energy of the mass* m
- j - *number of the inlet port*
- k - *number of the outlet port*
- m - *the inner mass content*
- $\dot{m}_j$ - *the inlet mass flow rate*
- $\dot{m}_k$ - *the outlet mass flow rate*

The terms e_j and e_k correspond to the average values on the cross section area of j and k ports for the parameters: pressure *p*, specific volume *v*, temperature *T*, specific internal energy *u*, velocity *c* and height *z* in the gravity field.

The flow through the open thermodynamic system can be made in two different modes:

a) ***the steady-state flow*** when at any inner point all the parameters remain unchanged in time but vary from one point to the otherone,

a) ***the non steady-state flow*** when all the parameters depend both on the geometric variables and on time; this regime characterizes the beginning and the end of the processes within the open system.

For the case (a) the terms:

$$\frac{\partial E}{\partial t} = 0, \quad \frac{\partial m}{\partial t} = 0 \tag{IV.20}$$

and thus it yields:

- ***the energy balance***:

$$\sum_j \dot{m}_j \cdot e_j = \sum_k \dot{m}_k \cdot e_k \quad \text{(IV.21)}$$

- **the mass balance**:

$$\sum_j \dot{m}_j = \sum_k \dot{m}_k \quad \text{(IV.22)}$$

IV.2.1. ***<u>The Enthalpy as State Parameter</u>***

To understand the essence of enthalpy let us imagine the simplest open thermodynamic system, a segment of a duct. Its boundary includes the rigid, impermeable and insulated wall of the duct and the imaginary cross surfaces of the extremities of the segment. Through these imaginary surfaces the mass transfer is made. For the sake of simplicity we consider that there is a steady-state flow through the duct's segment. From the mass conservation Equation we obtain:

$$\dot{m}_{inlet} = \dot{m}_{outlet} \quad \text{(IV.23)}$$

From the energy conservation Equation it results:

$$e_{inlet} = e_{outlet} \quad \text{(IV.24)}$$

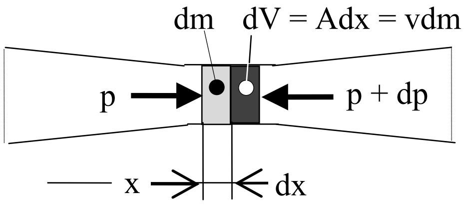
The total specific energy *e* of the mass unit which flows through the open system consists of four terms:

$$e = u + e_{kinetic} + e_{gravity} + w_d \quad \text{(IV.25)}$$

where:

- u *-the specific internal energy*
- $e_{kinetic}$ *-the specific kinetic energy*
- $e_{gravity}$ *-the specific gravity energy*
- w_d *-the specific flow work*

The specific flow work w_d is the necessary work either to introduce into the system or to pull out of the system the mass unit, see Fig. IV.5.



$$dW_d = F_p\,dx = pAdx = pdV = pvdm$$
$$dW_d = w_d\,dm$$

Fig. IV.5. *Scheme of the flow through a duct and the local flow work*

The specific flow work w_d is the necessary work either to introduce into the system or to pull out of the system the mass unit, see Fig. IV.5.

The specific flow work w_d is a product of two state parameters (*pv*) and consequently is a state function itself:

$$w_d = p \cdot v = \text{function of state} \qquad \text{(IV.26)}$$

Therefore for any cross section *A*, the total specific energy *e* is:

$$e = (u + p \cdot v) + \frac{c^2}{2} + g \cdot Z = \text{const.} \qquad \text{(IV.27)}$$

By definition the sum (*u* + *pv*) as a new state function was called specific enthalpy:

$$h = u + p\,v \qquad \text{(IV.28)}$$

and so:

$$e = h + \frac{c^2}{2} + g \cdot Z \qquad \text{(IV.29)}$$

The physical meaning of this new state parameter is obtained by comparison of the total specific energy of the mass unit for a closed moving system and the total specific energy of the same mass unit which flows through an open system:

$$e_{\text{closed system}} = u + \frac{c^2}{2} + g \cdot Z \qquad \text{(IV.30)}$$

$$e_{\text{open system}} = h + \frac{c^2}{2} + g \cdot Z \qquad \text{(IV.31)}$$

For a closed system the term *u* signifies the specific internal energy that reflects by its variation the interactions of the closed system by heat transfer (*q*) and deformation work transfer (*w*). For an open system the term *h* represents the specific enthalpy and has the meaning of the specific internal energy term which participates in the interactions of the open system by heat transfer (q) and engine work transfer (w_e). By engine work transfer we understand the work transfer by intermediary of a shaft and thus sometimes it is named shaft work. Since besides the enthalpy h also the terms $e_{kinetic}$ and $e_{gravity}$ participate in the engine work transfer the entity of local stagnation enthalpy was introduced as:

$$h^* = h + e_{kinetic} \qquad \text{(IV.32)}$$

In 1966 Kevin proposed an engineering generalization of the enthalpy concept under the label of methalpy:

$$h^0 = h + e_{kinetic} + e_{gravity} \qquad \text{(IV.33)}$$

which means "*beyond enthalpy*" or "*transcending enthalpy*" (the Greek word "*meta*" is the equivalent to the word "*beyond*").

IV.2.2. *The engine Work Transfer*

Figure IV.6 shows the scheme of an open thermodynamic system having:

- *one inlet port for mass flow*
- *one outlet port for mass flow*
- *a shaft for engine work transfer*

Between the inlet port and outlet ports, the mass, which flows through the open system simultaneously, exchanges heat (with the external heat sinks) and work (by the intermediary of the shaft).

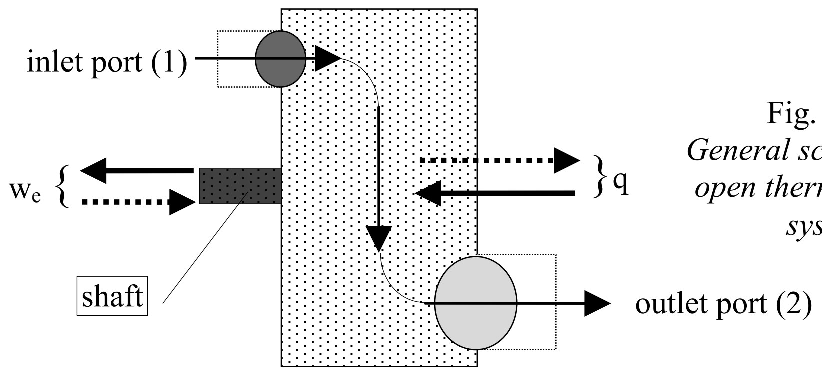


Fig. IV.6.
General scheme of the open thermodynamic system

For the open system shown in the previous Figure, let consider a steady-state flow. As a result, the local parameter values are constant in time. We additionally consider the flow through the open system as being reversible. In other words during the flow the friction does not appear as an irreversible cause. Consequently for the mass unit seen as a moving closed thermodynamic system crossing the open system, the heat exchanged with its environment is just the quantity (q) exchanged by the open system with the external heat sinks, for every mass unit which flows along the system. At the same time the quantity w_e is the engine work transfer corresponding to the same mass unit. For the mass unit, the energy conservation principle can be written in two different manners:

m = 1kg as moving closed system:

$$q_{1,2} = (u_2 - u_1) + \int_1^2 p dv \tag{IV.34}$$

m = 1kg flowing through the open thermodynamic system:

$$\begin{aligned} q_{1,2} - w_{e_{1,2}} &= (h_2 - h_1) + \frac{c_2^2 - c_1^2}{2} + g(z_2 - z_1) = \\ &= (u_2 - u_1) + \int_1^2 d(pv) + \frac{c_2^2 - c_1^2}{2} + g(z_2 - z_1) = \\ &= (u_2 - u_1) + \int_1^2 pdv + \int_1^2 vdp + \frac{c_2^2 - c_1^2}{2} + g(z_2 - z_1) \end{aligned} \tag{IV.35}$$

By replacing the reversible heat transfer (*q*) from Equation (IV.34) into Equation (IV.35) we obtain the relation of the steady-state specific engine work transfer for an open system through which a working fluid flows reversibly (without friction):

$$w_e = \int dw_e = -\int vdp - \int cdc - \int gdz \tag{IV.36}$$

The flow with friction can be known by experiment. Usually the real engine work transfer ($w_{e,real}$) is estimated by amplifying the reversible engine work transfer (w_e) by a correction factor obtained by experiences. For instance:

a) If the open system produces useful engine work:

$$\eta_i = \frac{w_{e,real}}{w_e} < 1 \Rightarrow w_{e,real} = \eta_i w_e \tag{IV.37}$$

b) If the open system consumes engine work:

$$\eta_i = \frac{w_e}{w_{e,real}} < 1 \Rightarrow w_{e,real} = \frac{1}{\eta_i} w_e \tag{IV.38}$$

The Equation of the reversible specific engine work can be used for any fluid, liquid or gas. For gases the term $\int g dZ$ can be neglected but not for liquids. If over the cross flow section area of the inlet and outlet ports the velocities are small and roughly equal then the term $\left(\int cdc\right)$ can be neglected. If we consider an engine as a closed thermodynamic system then the specific cyclic engine work transfer becomes:

$$w_{e,cyclic} = -\oint dw_e = -\oint vdp - \oint cdc - \oint gdZ = -\oint vdp \qquad \text{(IV.39)}$$

For the reversible flow (without friction) of gases with initial and final roughly equal speed values, the specific engine work transfer is:

$$w_e = -\int vdp \qquad \text{(IV.40)}$$

The engine power for the steady-state regime is a product of the specific engine work transfer and the mass flow:

$$P_e = \dot{m}w_e = -\dot{m}\left(\int vdp - \int cdc - \int gdz\right) = -\int \dot{V}dp - \dot{m}\int cdc - \dot{m}\int gdz \qquad \text{(IV.41)}$$

where $\dot{V}$[m^3/kg] is the volumetric flow rate.

V. THE IDEAL GAS

Before the second principle of Thermodynamics we shall introduce the concept of the ideal gas as an example to define some important thermodynamic ideas as the entropy and the average thermodynamic temperature of a non-adiabatic process. An ideal gas is an abstraction. Nevertheless it is a very useful one. For instance some real gases can be good enough described by the laws of the ideal gas when they flow through engines (Otto engine, Diesel engine, etc.).

The ideal gas has some important properties, which in fact are simplifying hypotheses regarding the microscopic structure of the real gases. The main properties are: *the molecules are material points (they have mass but no volume)*, *between molecules there are no interactions by forces such as attraction or repulsion; only perfect elastic collisions and momentum transfer makes the interactions between molecules*.

These two main properties involve the auxiliary properties: *due to the absence of the interactions by forces, the ideal gas is inviscid, the heat capacities of the ideal gas are constant*, *the internal energy of an ideal gas is a function only of the temperature*.

V.1. THE SIMPLE LAWS OF THE IDEAL GAS

The simple laws of the ideal gas have both a theoretical and an experimental statement. They reflect the main dependencies between the state parameters for simple open transformations. The old mathematical forms of the state equations for the simple open transformations were defined on the basis of the thermodynamic coefficient method that imposes a linear proportionality between the variable state parameters. The actual mathematical forms replace the thermodynamic coefficients of linear proportionality by the corespondent relations obtained on the basis of the fundamental state equation of the ideal gas.

V.1.1. Boyle - Mariotte law

This law describes the process at constant temperature - see Fig. V.1.

– ***the old state equations***: T = const. $\overset{m=const.}{\Rightarrow} V_2 = V_1\left[1-\chi\left(p_2 - p_1\right)\right]$ (V.1)

where: $\chi[Pa^{-1}]$ *is the thermodynamic coefficient of isothermal compression*: $\chi = -\frac{1}{V_1}\left(\frac{\partial V}{\partial p}\right)_T$

– ***the actual state equations***: $T = \text{const.} \overset{m=\text{const.}}{\Rightarrow} p \cdot V = \text{const.} \Rightarrow$

$$p \cdot \frac{V}{m} = p \cdot v = \frac{p}{\rho} = \text{const.} \qquad \text{(V.2)}$$

$$dT = 0 \overset{m=\text{const.}}{\Rightarrow} \frac{dp}{p} + \frac{dV}{V} = 0 \Rightarrow \frac{dp}{p} + \frac{dv}{v} = \frac{dp}{p} - \frac{d\rho}{\rho} = 0 \qquad \text{(V.3)}$$

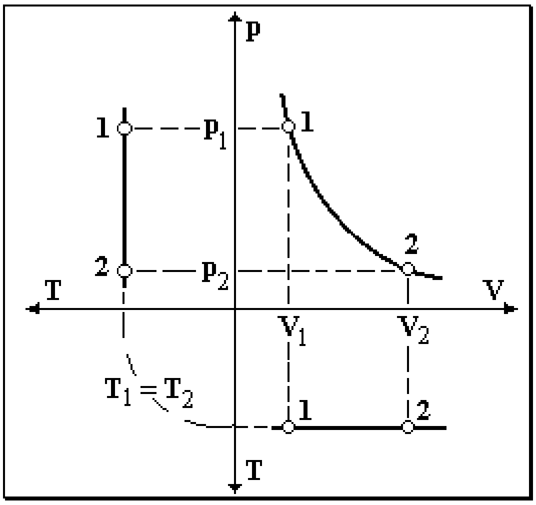


Fig. V.1.
The diagrams of the process at constant temperature

V.1.2. Gay - Lussac law

This law characterizes the process at constant pressure - see Fig.V.2.

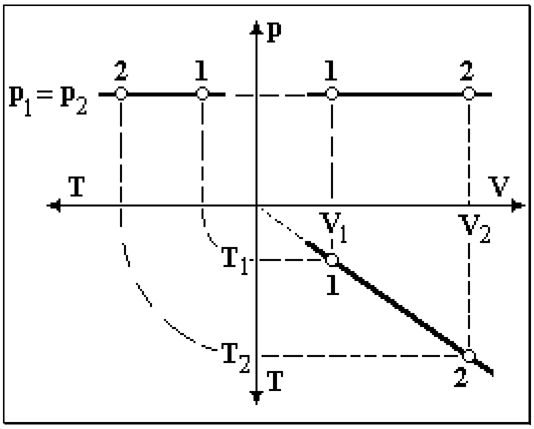


Fig. V.2.
The diagrams of the process at constant pressure

– ***the old state equations***: $p = \text{const.} \overset{m=\text{const.}}{\Rightarrow} V_2 = V_1[1 + \alpha(T_2 - T_1)]$ (V.4)

where

– $\alpha[K^{-1}]$ *is the thermodynamic coefficient of volumetric dilatation at constant pressure*: $\alpha = \frac{1}{V_1}\left(\frac{\partial V}{\partial T}\right)_p$

Supposing for any process at constant pressure that $T_1 = T_0 = 273.15$ K *then the coefficient of volumetric dilatation becomes*: $\alpha = \alpha_0 = \frac{1}{T_0} = \frac{1}{273.15} K^{-1} = const.$

(V.5)

– ***the actual state equations***: p = const. $\overset{m=const.}{\Rightarrow} \frac{V}{T} = const. \Rightarrow$

$\frac{V}{m}\frac{1}{T} = \frac{v}{T} = \frac{1}{\rho T} = const.$ (V.6)

dp = 0 $\overset{m=const.}{\Rightarrow} \frac{dV}{V} = \frac{dT}{T} \Rightarrow \frac{dv}{v} = -\frac{d\rho}{\rho} = \frac{dT}{T}$ (V.7)

V.1.3. Charles law

This law depicts the process at constant volume - see Fig.V.3.

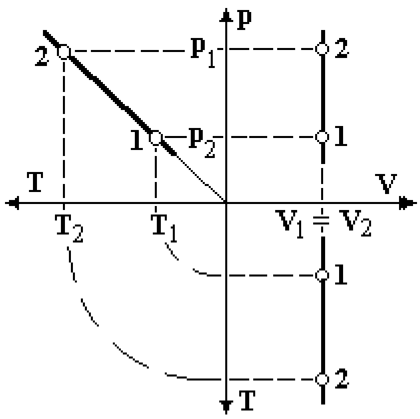


Fig.V.3. *The diagrams of the process at constant volume*

– ***the old state equations***: $V = \text{const.} \overset{m=\text{const.}}{\Rightarrow} p_2 = p_1\left[1+\beta\left(T_2 - T_1\right)\right]$

(V.8)

where: β [K *is the thermodynamic coefficient of thermal elasticity*: $\beta = \frac{1}{p}\left(\frac{\partial p}{\partial T}\right)_V$

Imposing for all processes at constant volume that $T_1 = T_0 = 273.15$ K *then the coefficient of thermal elasticity is*: $\beta = \beta_0 = \frac{1}{T_0} = \frac{1}{273.15} K^{-1} = \text{const.} = \alpha_0$

(V.9)

– ***the actual state equations***: V(v) = const. $\overset{m=\text{const.}}{\Rightarrow} \frac{p}{T} = \text{const.}$ (V.10)

$$dV(dv) = 0 \overset{m=\text{const.}}{\Rightarrow} \frac{dp}{p} = \frac{dT}{T} \quad \text{(V.11)}$$

The real gases comply with the simple laws of the ideal gas when the sum of the volumes of their own molecules is negligible by comparison with the whole volume and consequently due to the great distances between molecules the interaction by forces can be neglected. Nevertheless a real gas is always viscous, has non-constant heat capacities and its internal energy depends on the temperature and the volume. The real gases, which satisfy the simple laws of the ideal gas, are called to be in the *perfect state*.

V.1.4. Joule's law

"The internal energy of an ideal gas is only a function of the temperature"

This law has an experimental statement and it was the produce of the work of Gay - Lussac and Joule.

V.1.5. Avogadro's law

At the same pressure and the same temperature, the same volume of any ideal gas contains the same number of molecules."

The mass of the ideal gas contained in this volume is proportional to the molar mass, written as M [kg/kmol]. A kmol contain the same number of molecules for all ideal gases. This number of molecules is known as Avogadro's number:

$$N_A = 6.023 \cdot 10^{26} \text{ molecules / kmol}$$

V.1.6. <u>The reciprocal Avogadro's law</u>

"The volume of the mass quantity equal to the molar mass, at the same pressure and the same temperature is the same for all ideal gases"

This volume is named molar volume, written as V_M. For the normal physical conditions defined by:

$$p_0 = 1.013251 \text{ bar} = 101{,}325.1 \text{ Pa } [N/m^2],\ T_0 = 273.15 \text{ K } [0^0C]$$

the normal molar volume is: $V_{M0} = 22.414\ m_N^3 / \text{kmol}$ [normal cubic meter per kmol]

Some gauges use the normal cubic meter, [1 m_N^3], as the unit to measure the flow of gaseous fluid. Note that 1 m_N^3 in different conditions from the normal physical conditions is a mass unit because 1 m_N^3 corresponds to a mass quantity equal to the ratio between the molar mass and the normal molar volume: 1 $m_N^3 \Rightarrow m_{m_N^3} = M / V_{M0} = M / 22.414$ [kg / m_N^3]

V.2. <u>THE FUNDAMENTAL STATE EQUATION OF THE IDEAL GAS</u>

Let us consider a cubic control volume of size *a* (volume $V = a^3$). Let us suppose that the molecules of the ideal gas move permanently and chaotically within the control volume. Due to this motion and due to the very large number, *N*, of molecules we can admit that at any time ($N/3$) molecules move simultaneously along the each side. Every molecule of mass □ exchanges with the surface of area a^2 the following momentum transfer:

$$I = \mu c_j - (-\mu c_j) = 2\mu c_j \qquad \text{(V.12)}$$

Between two consecutive collisions, the elapsed time is:

$$t = 2a/c_j \qquad \text{(V.13)}$$

The frequency of the collisions will be:

$$f = 1/t = c_j/2a \qquad \text{(V.14)}$$

Every collision is supposed to be perfect, without shocks. The force, which appears at every collision j, is:

$$F_j = I \cdot f = \frac{2\mu}{a} \cdot \frac{c_j^2}{2} \qquad \text{(V.15)}$$

The total force that acts upon the surface a^2 is:

$$F = \sum_j F_j = \sum_j \frac{2\mu}{a} \cdot \frac{c_j^2}{2} = \frac{N}{3} \cdot \overline{F} = \frac{2}{3} \cdot \frac{N\mu}{a} \cdot \frac{\overline{c}^2}{2} \qquad \text{(V.16)}$$

where $\overline{F}$ *and* $\overline{c}$ *are the average values of* F_j *and* c_j.

The pressure, which appears due to the force, $\overline{F}$ will be:

$$p = \frac{\overline{F}}{a^2} = \frac{2}{3} \cdot \frac{N\mu}{a^3} \cdot \frac{\overline{c}^2}{2} \Rightarrow \frac{\rho = \frac{N\mu}{a^3}}{V = a^3} \Rightarrow \overline{c} = \sqrt{\frac{3p}{\rho}} \qquad \text{(V.16)}$$

The average kinetic energy of molecules is:

$$e_{kinetic} = \overline{c}^2 / 2 \qquad \text{(V.17)}$$

Therefore it yields:

$$p \cdot V = \frac{2}{3} \cdot N\mu \cdot e_{kinetic} = \frac{2}{3} \cdot m \cdot e_{kinetic} \qquad \text{(V.18)}$$

Equation (V.18) is in fact the fundamental state equation of the ideal gas. Unfortunately in this equation the term $e_{kinetic}$ cannot be known either theoretically or experimentally. For this reason it is necessary to introduce a new, subjective, parameter at the macroscopic scale that should be equivalent to the average kinetic energy of the molecules. This new state parameter is equal to zero when $e_{kinetic}$ is equal to zero. In this way we can define its absolute value. This new parameter is the absolute temperature or the thermodynamic temperature, written as T. For the real gases the essence of the absolute temperature is the same as for the ideal gas, respectively it "measures" the average energy of the molecules during their thermal motion. Supposing for the ideal gas that the dependence between $e_{kinetic}$ and T is linear, we can write:

$pV = mRT$ (Clapeyron's equation) (V.19)

$pV_M = MRT = R_MT$ (Mendeleev's equation) (V.20)

where:

$m = N\mu$ *is the mass of the ideal gas* [kg],

$R = R_M / M$ *is the characteristic constant of the ideal gas* [J/kg K],

T *is the absolute temperature* [K],

M *is the molar mass* [kg/kmol],

R_M *is the universal constant of the ideal gas* [J/kmol K].

The universal constant of the ideal gas was experimentally appreciated as being the ratio of the deformation work transfer to the temperature variation during the process at constant pressure. Adopting for the absolute temperature a measuring unit [1 Kelvin degree = 1 K] equal to that corresponding to the empirical scale of Celsius [1 K = 1^0C] then the universal constant of the ideal gas is:

$$\text{p=const.} \Rightarrow R_M = \frac{p\left(\frac{N}{m^2}\right) \cdot \Delta V_M \left(\frac{m^3}{kmol}\right)}{\Delta T\,(K)} \cong 8{,}314.5\left(\frac{J}{kmol \cdot K}\right) \quad \text{(V.21)}$$

In the absolute temperature scale [1 K = 1^0C] the zero point of the empirical scale of Celsius [0^0C] corresponds to the value of 273.15 K. This value was calculated on the basis of the ideal gas concept and of the standard state defined by:

p_0 = 1,01325.1 Pa (760 mm Hg) t_0 = 0^0C and V_{M0} = 22.414 m_N^3/kmol:

Therefore it yields:

$$T_0 = \frac{p_0 \cdot V_{M0}}{R_M} = \frac{1{,}01325.1\left(\frac{N}{m^2}\right) \cdot 22.414\left(\frac{m_N^3}{kmol}\right)}{8314.5\left(\frac{J}{kmol \cdot K}\right)} = 273.15\,(K) \quad \text{(V.22)}$$

The fundamental state equation can be obtained also on the basis of the simple laws of ideal gas. For this aim let us suppose, for a mass m, a certain process between the normal physical state (p_0 , V_0, T_0) and a different state (p, V, T), see Fig. V.4. This process can be replaced by any succession of two simple processes. Independently of the chosen path we obtain the so-called equation state of the general transformation:

$$\frac{pV}{T} = \frac{p_0 V_0}{T_0} = \text{const.} = \overline{R} \quad \text{(V.23)}$$

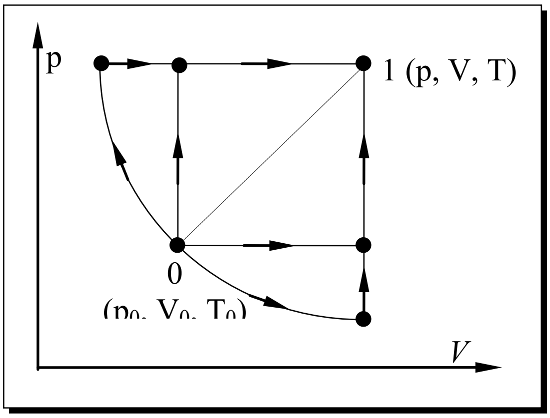


Fig.V.4.
The diagram p - V of a general process between the normal state and a current state

The constant $\overline{R}$ may be evaluated by imposing the standard mass. We can impose either the mass unit [1kg] or the quantity unit [1kmol]. Thus it yields:

$$m = 1\,kg \Rightarrow \overline{R} = R = \frac{1{,}01325.1\left(\frac{N}{m^2}\right)}{273.15\,(K)} v_0\left(\frac{m^3}{kg}\right) = 37.8 v_0\left(\frac{J}{kg\,K}\right)$$

$$m = M\,kg \Rightarrow \overline{R} = R_M = \frac{101{,}325.1\left(\frac{N}{m^2}\right)\cdot 22.414\left(\frac{m^3}{kmol}\right)}{273.15(K)} = 8{,}314.5\left(\frac{J}{kmol\cdot K}\right)$$

V.3. THE VARIATION OF INTERNAL ENERGY AND ENTHALPY

For an ideal gas the infinitesimal or finite variations of the specific internal energy and of the specific enthalpy are the same for any process which has the same ending states. The demonstration of this assertion is very simple. Let us suppose a certain transformation whose plot is shown in Fig. V.5. Independently of the path that links the states 1 and 2, the variations of *u* and *h* are the same:

$$\Delta h = \int_1^2 dh = h_2 - h_1 \ \text{ and } \ \Delta u = \int_1^2 du = u_2 - u_1 \qquad \text{(V.24)}$$

From the multitude of transformations, which pass through the states 1 and 2, we choose the simplest and most suitable path, which allows us to obtain the general relations of the variation of *u* and *h.*

Thus, for u we choose the way 1-b-2 consisting of processes 1-b at constant temperature and b-2 at constant volume. For h the convenient path is the succession of 1-a at constant temperature and a-2 at constant pressure. As a result it yields:

$$\Delta u = (u_2 - u_b)_v + (u_b - u_1)_T = (q_{b,2})_v + 0 = c_v(T_2 - T_1) \quad \text{(V.25)}$$

$$\Delta h = (h_2 - h_a)_p + (h_a - h_1)_T = (q_{a,2})_p + 0 = c_p(T_2 - T_1) \quad \text{(V.26)}$$

and so, for any infinitesimal transformation it yields:

$$du = c_v dT \text{ and } dh = c_p dT \quad \text{(V.27)}$$

where:

– c_v and c_p [J/kg K] are the heat capacities at constant volume and respectively at constant pressure.

V.4. ROBERT MAYER RELATION

According to the first principle of Thermodynamics and the fundamental state equation of the ideal gas it yields:

m = 1 kg $\quad du + pdv = dh - vdp = \delta q$

$$\Rightarrow (c_p - c_v)dT = d(pv) = RdT \quad \text{(V.27)}$$

m = *M* kg $\quad du_M + pdV_M = dh_M - V_M dp = \delta q_M$

$$\Rightarrow (C_{M,p} - C_{M,v})dT = d(pV_M) = R_M dT \quad \text{(V.28)}$$

and so, the Robert-Mayer relations are:

R = (c_p, c_v) [J/kg K] and R_M = ($C_{M,p}$, $C_{M,v}$) [J/kmol K] (V.29)

VI. THE SECOND PRINCIPLE

In essence, the second principle of Thermodynamics postulates the natural direction of the energy propagation. As a result, this principle deals with entities and criteria that reflect the quality during the energy transfers.

The specific thermodynamic entities related to second law are:

- **entropy,**
- **absolute temperature,**
- **exergy and anergy**.

The thermodynamic criteria of the second principle are:

- **lost exergy and second law efficiency,**
- **minimum rate of entropy generation,**
- **maximum output or minimum input power for a minimum time of life.**

Before to go thoroughly into the second principle of Thermodynamics let us turn to good account the knowledge related to the first principle and the concept of the ideal gas.

Every thermal machine operates on the basis of a closed transformation (cycle). The equation of the first principle is applied to define their coefficient of performance (COP) as a quantitative dimensionless parameter which measures the potency of the equivalence between the heat and the work transfer on the cyclic evolution. Thus for a reversible engine it reads:

$$\oint \delta Q = Q_{cyclic} = \oint \delta W = +\oint pdV = \oint \delta W_e = -\oint Vdp = W_{cyclic} \qquad (58)$$

In accord to the experimental reality the cyclic heat consists of two components, one component is positive respectively exhausted from the hot external heat reservoir and the other one is negative respectively rejected out of cycle to the cold external heat reservoir:

$$Q_{cyclic} = Q_{cyclic}^{input} - \left| Q_{cyclic}^{output} \right| = W_{cyclic} \qquad (59)$$

The first law efficiency (COP) becomes:

$$COP = \eta_e = \frac{\text{cyclic output work}}{\text{cyclic input heat}} = \frac{W_{cyclic}}{Q_{cyclic}^{input}} = 1 - \frac{\left|Q_{cyclic}^{output}\right|}{Q_{cyclic}^{input}} < 1 \qquad (60)$$

But the equations (58, 59, and 60) do not permit to know why it is impossible to set a perpetual mobile of second kind, respectively an engine with the coefficient of performance equal to the unit.

The cyclic work transfer can be graphically visualized in the diagram pressure - volume. Unfortunately this diagram cannot say us why the coefficient of performance of an engine is lower than the unit. This diagram does not answer at this question because it does not emphasize the heat transfer. For this reason we need a diagram in which we can visualize the heat transfer. Such a diagram can be defined on the basis of the first principle of Thermodynamics and the concept of the ideal gas.

Accordingly to the first principle, for the mass unit we have:

$$\delta q = du + pdv = dh - vdp \qquad (61)$$

For the ideal gas, this equation becomes:

$$\delta q = c_v dT + pdv = c_p dT - vdp \qquad (62)$$

because:

$du_{\text{ideal gas}} = c_v dT$ where c_v = const.

$dh_{\text{ideal gas}} = c_p dT$ where c_p = const.

Let us try to obtain for the infinitesimal heat transfer a similar equation as there is for the infinitesimal work transfer:

$\delta w = +pdv$ and $\delta w_e = -vdp$

For this aim it is necessarily to transform the inexact differential □q, depending on the path, into an exact differential by multiplication of equation (62) with an integrating factor that is in fact is a new state function.

Thus, it yields:

$$dN = f \cdot dq \qquad (63)$$

where:

- dN *is the exact differential of the new state function*;
- f *is the integrating factor, also a state function*.

Therefore it results:

$$dq = f\, dN \tag{64}$$

similarly as we have for □□ w_e and

The state functions **N** and **f** give us the possibility to set up the necessary diagram in which we can graphically visualize the reversible heat transfer by the intermediary of the equation:

$$q = \int f^{-1} dN \tag{65}$$

On the basis of the first law of Thermodynamics and the concept of the ideal gas we can rigorously define the integrating factor **f** and consequently the new state function **N**.

Therefore we write:

$$dN = f \cdot \delta q = f \cdot c_v \cdot dT + f \cdot p \cdot dv = f \cdot c_p \cdot dT - f \cdot v \cdot dp \tag{66}$$

The integrating factor **f** can be determined by using the mathematical properties of exact differentials such as the equality of the second mixed derivatives. As a state function, the new state parameter **N** is depending on the other two state parameters. Because the heat transfer firstly depends on the temperature, we prefer to adopt:

$$\text{either } N = N(T, v) \text{ or } N = N(T, p) \tag{67}$$

It yields:

$$\text{either } dN = \left(\frac{\partial N}{\partial T}\right)_v dT + \left(\frac{\partial N}{\partial v}\right)_T dv \text{ or } dN = \left(\frac{\partial N}{\partial T}\right)_p dT + \left(\frac{\partial N}{\partial p}\right)_T dp \tag{68}$$

By the comparison of the equations (66) and (68) it results:

$$\left(\frac{\partial N}{\partial v}\right)_T = fp; \left(\frac{\partial N}{\partial p}\right)_T = -fv; \left(\frac{\partial N}{\partial T}\right)_v = fc_v; \left(\frac{\partial N}{\partial T}\right)_p = fc_p \tag{69}$$

At its turn the state function **f** depends on the other two state parameters. For the sake of the simplicity we choose the separating variable method in order to obtain the following simplified equation:

$$f = f(T,N) = f_T(T) \cdot f_N(N) \tag{70}$$

where:

- $f_T(T)$ is a function depending only on temperature;
- $f_N(N)$ is a function depending only on the new state function **N**.

As a result it yields:

$$\frac{1}{f_N(N)}dN = f_T(T)\delta q = d[s(T,v)] = d[s(T,p)] = ds \qquad (71)$$

In this way we replace the function **N** with another new state function **s** without altering our aim. Thus it yields:

$$ds = f_T \cdot c_v \cdot dT + f_T \cdot p \cdot dv = f_T \cdot c_p \cdot dT - f_T \cdot v \cdot dp \qquad (72)$$

In the same way used for the state function **N**, we obtain:

$$\left(\frac{\partial s}{\partial v}\right)_T = f_T p;\ \left(\frac{\partial s}{\partial p}\right)_T = -f_T v;\ \left(\frac{\partial s}{\partial T}\right)_v = f_T c_v;\ \left(\frac{\partial s}{\partial T}\right)_p = f_T c_p \qquad (73)$$

The second mixed derivatives of the new function **s** will be:

$$s''_{T,v} = \left(\frac{\partial}{\partial T}\left(\frac{\partial s}{\partial v}\right)_T\right)_v = \left(\frac{\partial(f_T p)}{\partial T}\right)_v = p\frac{df_T}{dT} + f_T\left(\frac{\partial p}{\partial T}\right)_v \qquad (74)$$

$$s''_{v,T} = \left(\frac{\partial}{\partial v}\left(\frac{\partial s}{\partial T}\right)_v\right)_T = \left(\frac{\partial(f_T c_v)}{\partial v}\right)_T = 0 \qquad (75)$$

$$s''_{T,p} = \left(\frac{\partial}{\partial T}\left(\frac{\partial s}{\partial p}\right)_T\right)_p = -\left(\frac{\partial(f_T v)}{\partial T}\right)_p = -v\frac{df_T}{dT} - f_T\left(\frac{\partial v}{\partial T}\right)_p \qquad (76)$$

$$s''_{p,T} = \left(\frac{\partial}{\partial p}\left(\frac{\partial s}{\partial T}\right)_p\right)_T = \left(\frac{\partial(f_T c_p)}{\partial p}\right)_T = 0 \qquad (77)$$

$$s''_{T,v} = s''_{v,T} \quad \text{and} \quad s''_{T,p} = s''_{p,T} \qquad (78)$$

The partial derivatives of **p** and **v** may be known choosing once more the ideal gas as the theoretical standard substance:

$$p \cdot v = R \cdot T \Rightarrow \left(\frac{\partial p}{\partial T}\right)_v = \frac{R}{v} \text{ and } \left(\frac{\partial v}{\partial T}\right)_p = \frac{R}{p} \qquad (79)$$

We finally obtain:

$$d[\mathit{ln}(f_T)] + d[\mathit{ln}(T)] = 0 \qquad (80)$$

And thus:

$$ln\,(f_T \cdot T) = ln\,A \Rightarrow f_T = \frac{A}{T} \quad (81)$$

Since the value of constant A can be arbitrarily imposed, A = 1, it yields:

$$f_T = \frac{1}{T} \quad (82)$$

The sought diagram necessary to emphasize the heat transfer can be now construct with the help of the state parameters **T** and **s**. The new state function **s** is called the specific entropy and it is defined by the equation:

$$ds = \frac{\delta q}{T} \quad (83)$$

Since the heat transfer is an extensive non-parameter (depending on the mass) it results that the entropy at its turn is also an extensive state parameter respectively depends on the mass and thus:

$$dS = m \cdot ds = m\frac{\delta q}{T} = \frac{\delta Q}{T} \quad (84)$$

In the Fig.7 is shown the diagram **T - s** and the equivalent heat transfer for the reversible open and closed transformations.

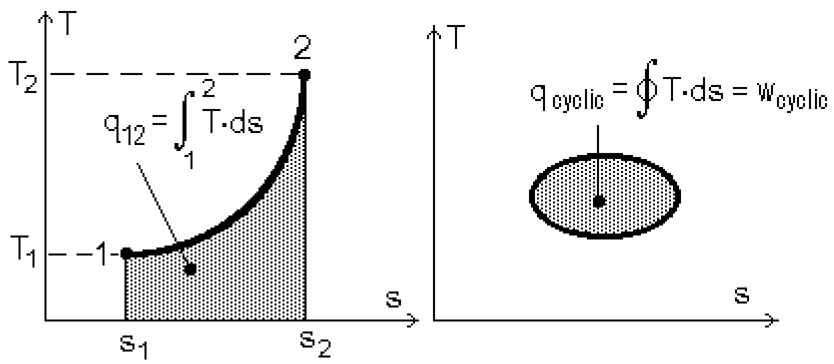


Fig. 7.

The graphical statement of the reversible heat transfer in the diagram temperature - entropy

The second principle of Thermodynamics emphasizes by different equivalent sentences, the natural direction of the real energetic transfers. This direction is unique because any energy transfer needs a finite potential difference depending as value on the energy's type. Sometimes this value may be neglected by comparison with the absolute value but never equal or tending to zero (i.e. infinitesimal). We subjectively defined the energy potential so that the energy transfer is made from the higher energetic potential to the lower energetic potential. In this way the uniqueness of the direction of the real energetic evolutions is caused by the uniqueness of the energetic potential differences that impose a unique direction to the energy transfer. The second principle of Thermodynamics may be defined by one of the following equivalent sentences:

R. Clausius:

- *" The heat cannot itself transfers from the lower temperature to the higher temperature"*

L. Sadi Carnot:

- *" It is impossible to set an engine that continuously supplies work exchanging heat only with a single external heat sink".*
- "*A thermal engine cannot continuously supplies work without exchanging heat with two heat external heat sinks at different temperatures*".

W. Thomson (Lord Kelvin):

- *"It is impossible by means of inanimate material agency to derive mechanical effect from any portion of matter by cooling it below the temperature of the coldest of the surrounding objects"*

with the following footnote:

- *"If this axiom be denied for all temperatures, it would have to be admitted that a self-acting machine might be set to work and produce mechanical effects by cooling the sea or earth, with no limit but the total loss of heat from the earth or sea, or, in reality, from the whole material world".*

M. Planck:

- *"It is impossible to construct an engine which will work in a complete cycle, and produce no effect except the raising of a weight and the cooling of a heat reservoir".*

C. Caratheodory:

- **axiom I:** *"The work is the same in all adiabatic processes that take a system from a given initial state to a given final state".*
- **axiom II:** *"In the immediate neighborhood of every state of a system, there are other states that cannot be reached from the first by any adiabatic process".*

Excepting the definition of R. Clausius, the all others postulate that it is impossible to set up a so-called perpetual mobile of second kind. We emphasize that every definition is equivalent to the others and allows to deduce the all consequences regarding the work of the thermal machines such as the fact that cyclic heat transfer (Q_{cyclic}) contains two components, one is positive (i.e. received) and the other is negative (i.e. rejected out).

The second principle of Thermodynamics allows us to study the quality of the energetic phenomena while the first principle of Thermodynamics reflects the quantity of the same phenomenon. The following aspects reflect the quality:

- *It is impossible to set a natural energy transfer from the lower energetic potential to the higher energetic potential. Consequently we can distinguish the real and non-real energetic phenomena;*

- *It is impossible to build a perpetual mobile of second kind, that is an engine that cyclically runs and exchanges heat with a single external heat sink. As a result we can define the ideal cycles with the maximum - maximorum coefficient of performance.*
- *It is impossible continuously to turn the all consumed heat into the work. This experimental reality compels us to classify the energies in two fundamental types, namely the ordered and disordered energies.*
- *It is possible to distinguish the mutual capacity of the energies to transform each other during the continuous work of the thermal machines. This mutual transformation potential is defined by the entities of exergy and anergy.*
- *It is possible to estimate the grade of irreversibility by means of the lost exergy and the second law efficiency.*

The diagram T - s for the ideal gas

The simplest transformations of the ideal gas can be plotted in this diagram on the basis of the following state equations:

- **The transformation at constant temperature:**

$$dT = 0 \Rightarrow T = \text{const.} \Rightarrow \text{ an horizontal line}$$

- *The transformation at constant pressure:*

$$dp = 0 \Rightarrow ds = c_p \cdot \frac{dT}{T} - \frac{v}{T} \cdot dp = c_p \cdot \frac{dT}{T} \text{ where } c_p = \text{const.}$$

$$\int_{T_0} \frac{dT}{T} = \int_{s_0} \frac{ds}{c_p} \Rightarrow T = T_0 \cdot exp\left(\frac{s - s_0}{c_p}\right) \text{ with the slope } \left(\frac{\partial T}{\partial s}\right)_p = \frac{T}{c_p}$$

- *The transformation at constant volume:*

$$dv = 0 \Rightarrow ds = c_v \cdot \frac{dT}{T} + \frac{p}{T} \cdot dv = c_v \cdot \frac{dT}{T} \text{ where } c_v = \text{const.}$$

$$\int_{T_0} \frac{dT}{T} = \int_{s_0} \frac{ds}{c_v} \Rightarrow T = T_0 \cdot exp\left(\frac{s - s_0}{c_v}\right) \text{with the slope} \left(\frac{\partial T}{\partial s}\right)_v = \frac{T}{c_v} > \left(\frac{\partial T}{\partial s}\right)_p$$

- *The adiabatic transformation:*

$$\delta q = 0 \Rightarrow ds = \frac{\delta q}{T} = 0 \Rightarrow s = \text{const.} \Rightarrow \text{a vertical line}$$

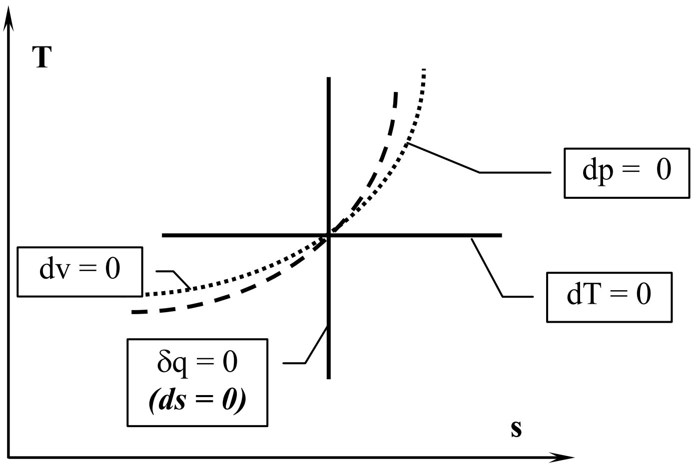


Fig.
The reversible transformations of ideal gas in the diagram T - s

The entropy variation of the ideal gas

For the reversible transformations it calculates:

$$ds = \frac{\delta q}{T} = \frac{du}{T} + \frac{p}{T} \cdot dv = \frac{dh}{T} - \frac{v}{T} \cdot dp$$

$$du = c_v \cdot dT;\ dh = c_p \cdot dT;\ p \cdot v = R \cdot T;\ c_v = \frac{R}{k-1};\ c_p = \frac{k \cdot R}{k-1}$$

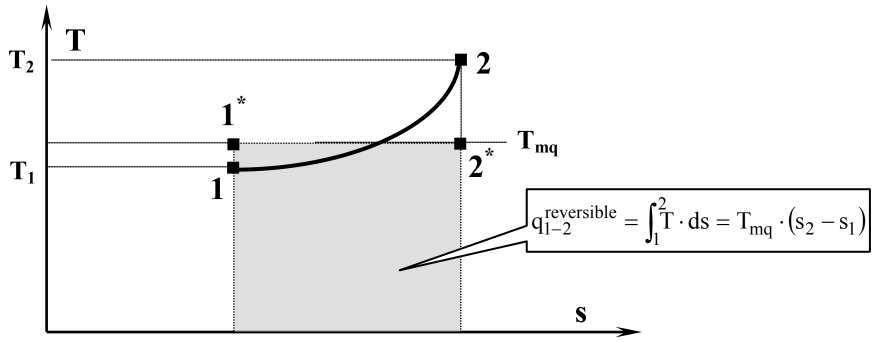
$$ds = c_v \cdot \frac{dT}{T} + R \cdot \frac{dv}{v} = c_p \cdot \frac{dT}{T} - R \cdot \frac{dp}{p} = c_v \cdot \frac{dp}{p} + c_p \cdot \frac{dv}{v}$$

$$\Delta s = c_v\, ln\frac{T_2}{T_1} + R\, ln\frac{v_2}{v_1} = c_p\, ln\frac{T_2}{T_1} - R\, ln\frac{p_2}{p_1} = c_v\, ln\frac{p_2}{p_1} + c_p\, ln\frac{v_2}{v_1}$$

The mean thermodynamic temperature of a non – adiabatic process

Let suppose a non-adiabatic process in the diagram T – s. By definition the mean thermodynamic temperature of the non-adiabatic process, 1-2, is:

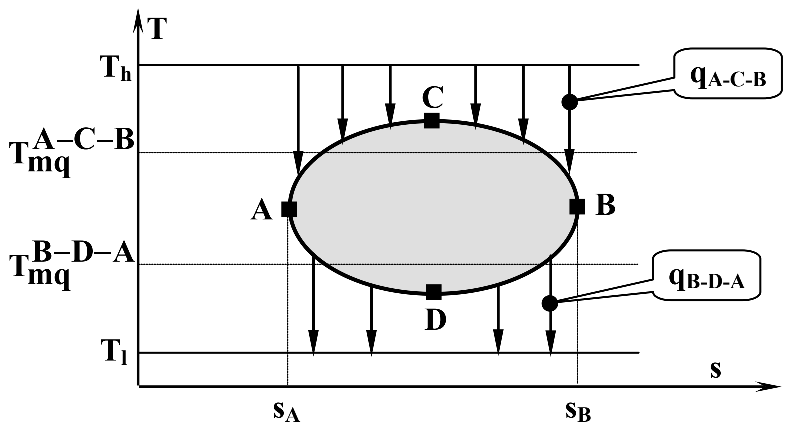
$$T_{mq} = \frac{1}{s_2 - s_1} \cdot \int_1^2 T \cdot ds = \frac{1}{\Delta s} \cdot \int_1^2 \delta q = \frac{q_{1\text{-}2}}{\Delta s}$$



From the physical point of view, the mean thermodynamic temperature is the temperature of the equivalent isothermal transformation, 1*-2*, during the heat transfer, $q_{1\text{-}2}$, and the entropy variation, $\Delta s = (s_2 - s_1)$, have the same values as during the non-adiabatic process, 1-2. In this way the heat transfer may be calculated as:

$$q_{1\text{-}2} = T_{mq} \cdot (s_2 - s_1)$$

In the Figure an engine cycle is plotted. As we know the heat transfer spontaneously is self-generated from the higher temperature to the lower temperature.



Every engine cycle contains two half-cycles, the one, A-C-B, receives the heat:

$$q_{A\text{-}C\text{-}B} = \int_{A\text{-}C\text{-}B} T \cdot ds = T_{mq}^{A\text{-}C\text{-}B} \cdot (s_2 - s_1) > 0$$

and the other one, B-D-A, rejects the heat:

$$q_{B\text{-}D\text{-}A} = \int_{B\text{-}D\text{-}A} T \cdot ds = T_{mq}^{B\text{-}D\text{-}A} \cdot (s_1 - s_2) < 0$$

During the half-cycle A-C-B the heat transfer, $q_{A\text{-}C\text{-}B}$, naturally could be made only from the higher temperature T_h to the mean thermodynamic temperature $T_{mq}^{A\text{-}C\text{-}B} < T_h$. On the half-cycle B-D-A the heat transfer, $q_{B\text{-}D\text{-}A}$ spontaneously might be generated itself only from the mean thermodynamic temperature, $T_{mq}^{B\text{-}D\text{-}A}$, to the lower temperature $T_l < T_{mq}^{B\text{-}D\text{-}A}$. Since $T_{mq}^{A\text{-}C\text{-}B} > T_{mq}^{B\text{-}D\text{-}A}$ it yields that it is impossible to set a perpetual mobile of second kind.

The ideal cycles

In Figures an engine and a refrigeration cycles are schetched

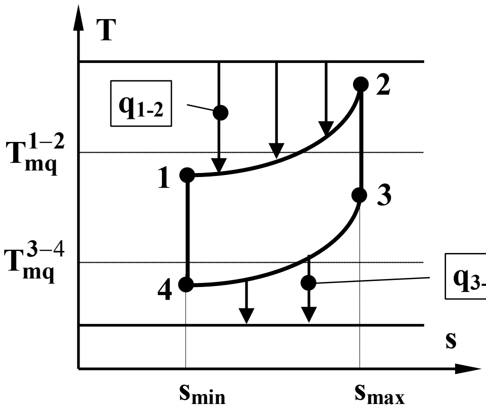


Fig.
Engine cycle in T – s

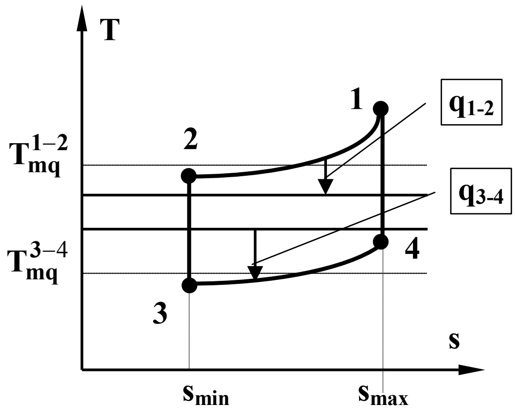


Fig.
Refrigeration cycle in T – s

For the engine cycle, 1-2-3-4-1, the coefficient of performance will be:

$$\eta_e = \frac{w_{cyclic}}{q_{cyclic}^{consumed}} = \frac{w_{cyclic}}{q_{1-2}} = 1 - \frac{|q_{3-4}|}{q_{1-2}}$$

In accordance with the first principle we write:

$$w_{cyclic} = \int_1^2 \delta q + \int_3^4 \delta q = T_{mq}^{1-2}(s_2 - s_1) + T_{mq}^{3-4}(s_4 - s_3) = (s_{max} - s_{min})(T_{mq}^{1-2} - T_{mq}^{3-4})$$

$$\eta_e = \frac{T_{mq}^{1-2} - T_{mq}^{3-4}}{T_{mq}^{1-2}} = 1 - \frac{T_{mq}^{3-4}}{T_{mq}^{1-2}} \text{ where } s_1 = s_4 = s_{min}; \quad s_2 = s_3 = s_{max}$$

Therefore as T_{mq}^{1-2} increases and T_{mq}^{3-4} decreases as the coefficient of performance increases. The ideal cycle is set when the two mean thermodynamic temperatures become infinitesimally different from the temperatures of the external heat sinks:

$$T_{mq}^{3-4} = T_l + dT_l \cong T_l \text{ and } T_{mq}^{1-2} = T_h - dT_h \cong T_h$$

Similarly, for the refrigeration cycle, 1-2-3-4-1, the coefficient of performance will be:

$$\varepsilon_r = \frac{\text{refrigeration}}{|w_{cyclic}|} = \frac{q_{3-4}}{|w_{cyclic}|} = \frac{q_{3-4}}{|q_{1-2}| - q_{3-4}}$$

In accordance with the first principle we write:

$$w_{cyclic} = \int_1^2 \delta q + \int_3^4 \delta q = T_{mq}^{1-2}(s_2 - s_1) + T_{mq}^{3-4}(s_4 - s_3) = (s_{min} - s_{max})(T_{mq}^{1-2} - T_{mq}^{3-4})$$

$$\varepsilon_r = \frac{T_{mq}^{3-4}}{T_{mq}^{1-2} - T_{mq}^{3-4}} \text{ where } s_1 = s_4 = s_{max}; \quad s_2 = s_3 = s_{min}$$

Therefore as T_{mq}^{1-2} decreases and T_{mq}^{3-4} increases as the coefficient of performance increases. The ideal cycle is set when the two mean thermodynamic temperatures become infinitesimally different from the temperatures of the external heat sinks:

$$T_{mq}^{3-4} = T_l - dT_l \cong T_l \text{ and } T_{mq}^{1-2} = T_h + dT_h \cong T_h$$

In both cases, the ideal cycles are consisting of two isothermal and two adiabatic processes (in fact these are the ideal **CARNOT** cycles).

Gouy – Stodola Theorem

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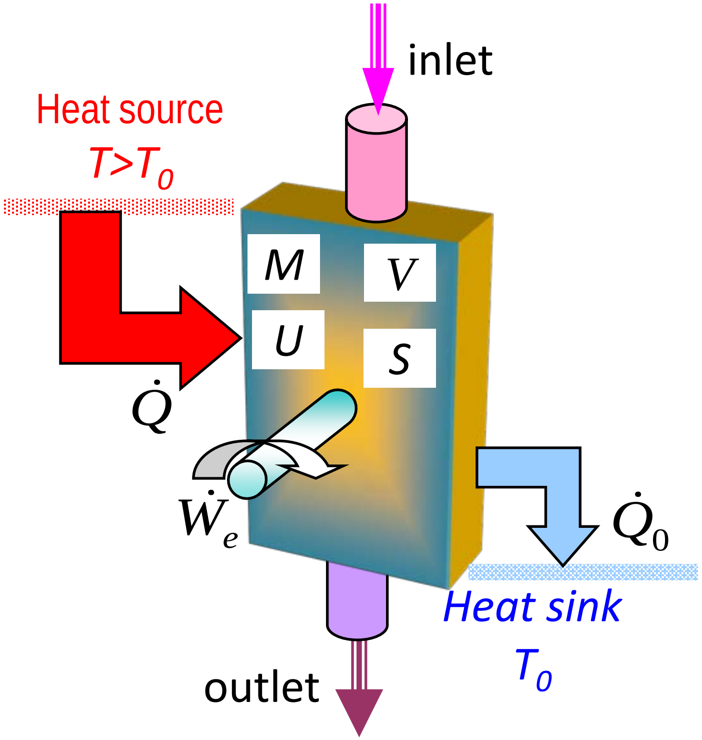
Assumptions

1. They will be analyzed non steady-state enlarged basic open thermodynamic systems, including both the thermal system and, the external heat reservoirs controlling the heat transfers and, the environment allowing the mass transfers;
2. The working fluid is a mixture of different chemical species, the inlet and outlet compositions might be different because of chemical reactions that can appear during the flow through the thermal system;
3. The inner boundary of the flow path through the thermal system is deformable under the environmental pressure;

Gouy – Stodola Theorem, Engines



First Law of Thermodynamics

$$\frac{\partial U}{\partial t} = \left(\dot{Q} - \left|\dot{Q}_0\right|\right) - \dot{W}_e - p_e \frac{\partial V}{\partial t} + \sum_{inlet} \dot{m} \left(h + \frac{\overline{V}^2}{2} + gZ \right) - \sum_{outlet} \dot{m} \left(h + \frac{\overline{V}^2}{2} + gZ \right)$$

Second Law of Thermodynamics

$$\dot{S}_{gen}^{irrev} = \frac{\partial S}{\partial t} - \left(\frac{\dot{Q}}{T} - \frac{\left|\dot{Q}_0\right|}{T_0} \right) - \sum_{inlet} \dot{m} \cdot s + \sum_{outlet} \dot{m} \cdot s \geq 0$$

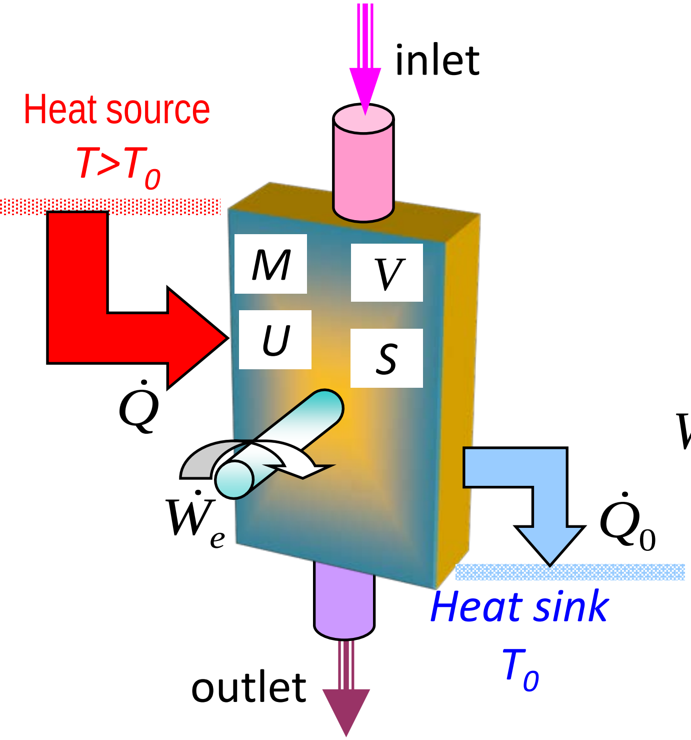
M: Mass of the working fluid surrounded by the operating engine inner walls at a certain operational time

V: Working fluid volume defined by the operating engine inner walls at a certain operational time

U: Inner operating engine working fluid energy at a certain operational time

S: Entropy of the working fluid surrounded by the operating engine inner walls at a certain operational time

Gouy – Stodola Theorem, Engines



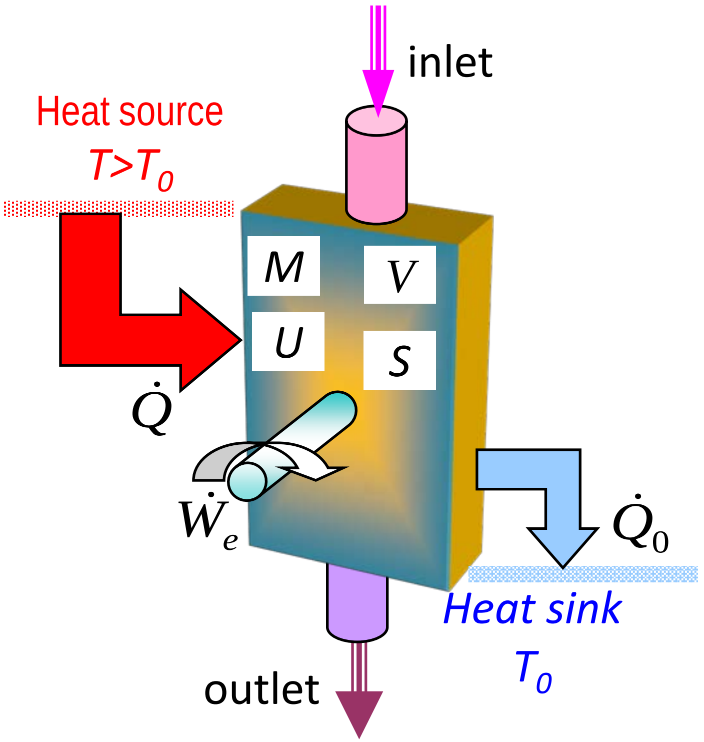
Combined First and Second Laws of Thermodynamics

$$\dot{W}_e = \dot{W}_e^{rev} + \dot{W}_{lost}^{irrev} = \dot{Q}\left(1 - \frac{T_0}{T}\right)$$

$$+ \sum_{inlet} \dot{m}\left((h - T_0 s) + \frac{\bar{V}^2}{2} + gZ \right) - \sum_{outlet} \dot{m}\left((h - T_0 s) + \frac{\bar{V}^2}{2} + gZ \right)$$

$$- \frac{\partial}{\partial t}\left(U + p_e V - T_0 S\right) - T_0 \dot{S}_{gen}^{irrev}$$

Gouy – Stodola Theorem, Engines



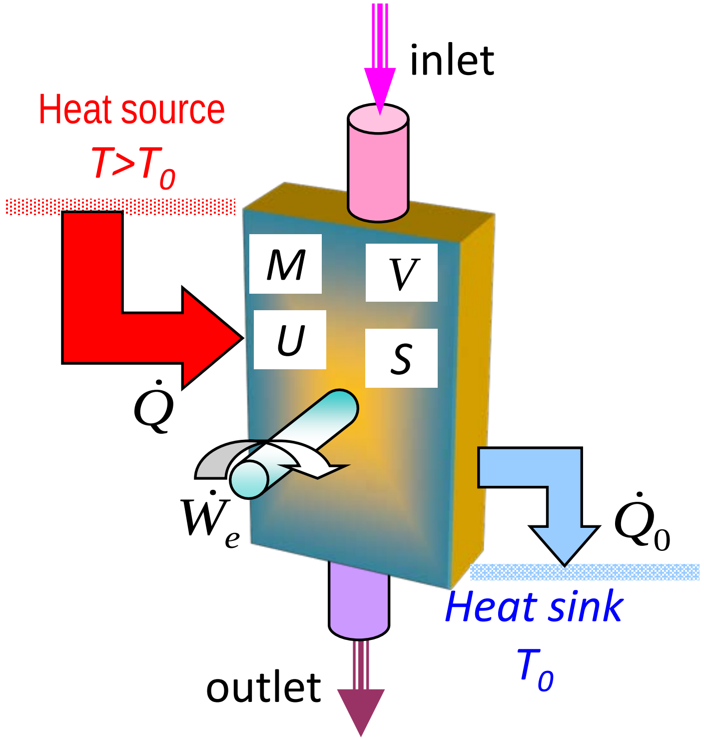
Reversible Engine Power

$$\dot{W}_e^{rev} = \dot{Q}\left(1 - \frac{T_0}{T}\right) + \sum_{inlet} \dot{m}\left(h^* - T_0 s\right) - \sum_{outlet} \dot{m}\left(h^* - T_0 s\right) - \frac{\partial}{\partial t}\left(U + p_e V - T_0 S\right) > 0$$

where

$$h^* = h + \frac{\overline{V}^2}{2} + gZ \quad \textit{is the methalpy}$$

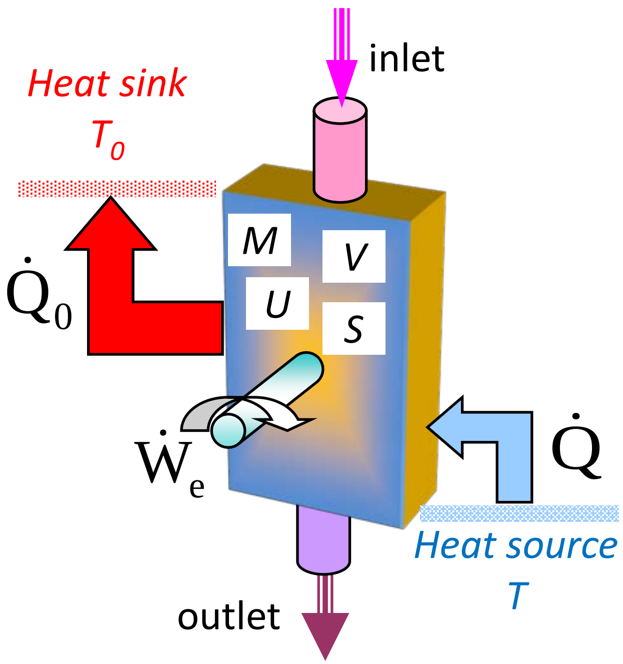
Gouy – Stodola Theorem, Engines



Irreversible Lost Power

$$\dot{W}_{lost}^{irrev} = -T_0 \cdot S_{gen}^{irrev}$$

Gouy – Stodola Theorem, Refrigeration Cycles



First Law of Thermodynamics

$$\frac{\partial U}{\partial t} = \left(\dot{Q} - \left|\dot{Q}_0\right|\right) - \dot{W}_e - p_e \frac{\partial V}{\partial t} + \sum_{inlet} \dot{m}\left(h + \frac{\overline{V}^2}{2} + gZ\right) - \sum_{outlet} \dot{m}\left(h + \frac{\overline{V}^2}{2} + gZ\right)$$

Second Law of Thermodynamics

$$\dot{S}_{gen}^{irrev} = \frac{\partial S}{\partial t} - \left(\frac{\dot{Q}}{T} - \frac{\left|\dot{Q}_0\right|}{T_0}\right) - \sum_{inlet} \dot{m} \cdot s + \sum_{outlet} \dot{m} \cdot s \geq 0$$

M: Mass of the working fluid surrounded by the operating engine inner walls at a certain operational time

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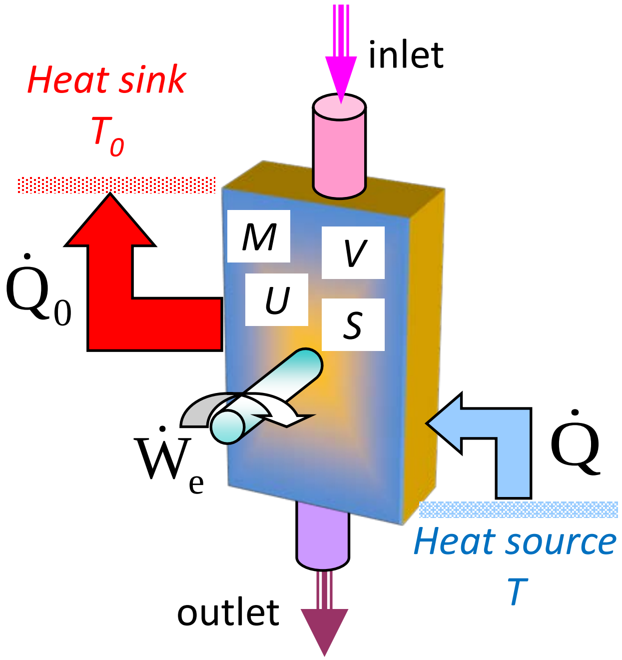
Gouy – Stodola Theorem, Refrigeration Cycles



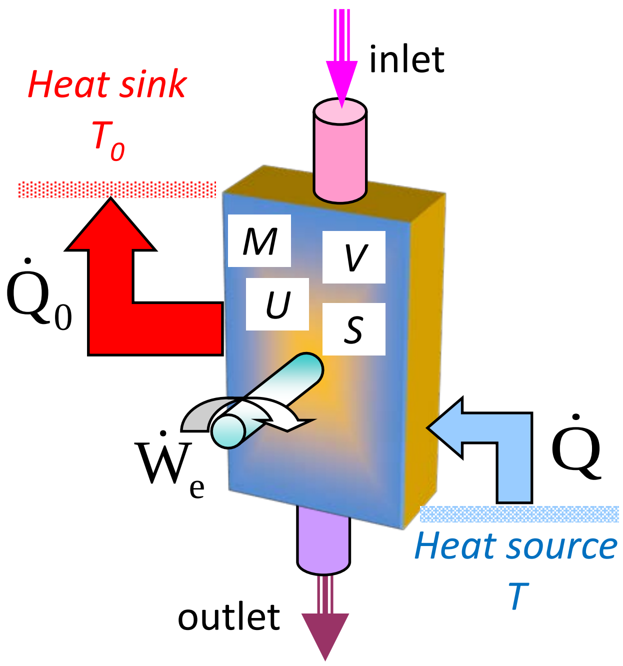
Combined First and Second Laws of Thermodynamics

$$\dot{W}_e = \dot{W}_e^{rev} + \dot{W}_{lost}^{irrev} = \dot{Q}\left(1 - \frac{T_0}{T}\right)$$

$$+ \sum_{inlet} \dot{m}\left((h - T_0 s) + \frac{\overline{V}^2}{2} + gZ\right) - \sum_{outlet} \dot{m}\left((h - T_0 s) + \frac{\overline{V}^2}{2} + gZ\right)$$

$$- \frac{\partial}{\partial t}\left(U + p_e V - T_0 S\right) - T_0 \dot{S}_{gen}^{irrev}$$

Gouy – Stodola Theorem, Refrigeration Cycles



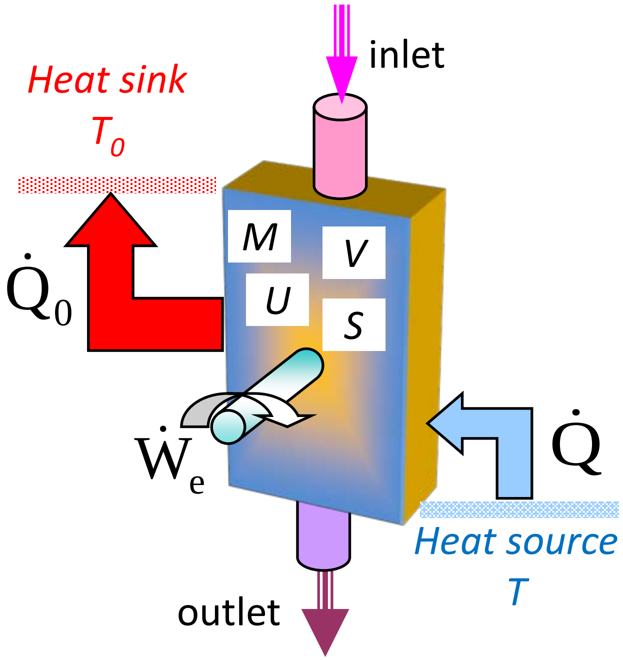
Reversible Consumed Power

$$\dot{W}_e^{rev} = \dot{Q}\left(1 - \frac{T_0}{T}\right) + \sum_{inlet} \dot{m}\left(h^* - T_0 s\right) - \sum_{outlet} \dot{m}\left(h^* - T_0 s\right) - \frac{\partial}{\partial t}\left(U + p_e V - T_0 S\right) < 0$$

where

$$h^* = h + \frac{\overline{V}^2}{2} + gZ \quad \text{is the methalpy}$$

Gouy – Stodola Theorem, Refrigeration Cycles



Irreversible Lost Power

$$\dot{W}_{lost}^{irrev} = -T_0 \cdot S_{gen}^{irrev}$$

Gouy – Stodola Theorem
Conclusions

$$\dot{S}_{gen}^{irrev} \to 0 \quad \dot{W}_{lost}^{irrev} = -T_0 \cdot S_{gen}^{irrev} \to 0$$

$$\dot{W}_e^{rev} = \dot{W}_{e,\dot{Q}}^{rev} + \dot{W}_{e,flow}^{rev} + \dot{W}_{e,storage}^{rev}$$

Gouy – Stodola Theorem
Conclusions

$$\dot{W}_e^{rev} = \dot{W}_{e,\dot{Q}}^{rev} + \dot{W}_{e,flow}^{rev} + \dot{W}_{e,storage}^{rev}$$

•Relationship Q – W, engines, (heat exergy)

$$\dot{W}_{e,\dot{Q}}^{rev} = \dot{Q}\left(1 - \frac{T_0}{T}\right) > 0$$

•Relationship Q – W, refrigeration cycles, (heat exergy)

$$\dot{W}_{e,\dot{Q}}^{rev} = -\dot{Q}\left(\frac{T_0}{T} - 1\right) = -\frac{\dot{Q}}{T/(T_0 - T)} < 0$$

Gouy – Stodola Theorem
Conclusions

$$\dot{W}_e^{rev} = \dot{W}_{e,\dot{Q}}^{rev} + \dot{W}_{e,\,flow}^{rev} + \dot{W}_{e,storage}^{rev}$$

Relationship flow– W, (flow exergy)

$$\dot{\mathrm{W}}_{\mathrm{e,flow}}^{\mathrm{rev}} = \sum_{inlet} \dot{\mathrm{m}}\left(\mathrm{h}^* - \mathrm{T}_0\mathrm{s}\right) - \sum_{\mathrm{outlet}} \dot{\mathrm{m}}\left(\mathrm{h}^* - \mathrm{T}_0\mathrm{s}\right)$$

Gouy – Stodola Theorem
Conclusions

$$\dot{W}_e^{rev} = \dot{W}_{e,\dot{Q}}^{rev} + \dot{W}_{e,\,flow}^{rev} + \dot{W}_{e,storage}^{rev}$$

Relationship “energy storage” – W, non steady-state system operation, (storage exergy)

$$\dot{\mathrm{W}}_{\mathrm{e,storage}}^{\mathrm{rev}} = -\frac{\partial}{\partial \mathrm{t}} \left(\mathrm{U} + \mathrm{p_e V} - \mathrm{T_0 S}\right)$$

Introduction to Irreversible Cycles

Assumptions

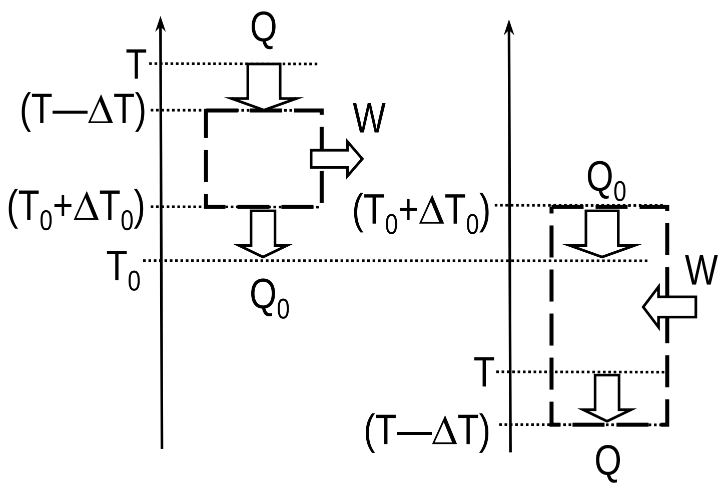
No mass transfer:

$$\sum_{inlet} \dot{m}\left(h + \frac{\overline{V}^2}{2} + gZ\right) - \sum_{\text{outlet}} \dot{m}\left(h + \frac{\overline{V}^2}{2} + gZ\right) = 0 \quad \text{and} \quad -\sum_{inlet} \dot{m} \cdot s + \sum_{\text{outlet}} \dot{m} \cdot s = 0$$

Non deformable boundary walls: $p_e \dfrac{\partial V}{\partial t} = 0$

Steady state operation: $\dfrac{\partial U}{\partial t} = 0$ and $\dfrac{\partial S}{\partial t} = 0$

Introduction to Irreversible Closed Cycles
Endo-reversible Carnot Cycle



Entropy Generation by Irreversibility

Enlarged System – including both the thermal system and the external heat reservoirs

Related to overall Irreversibility (external + internal)

$$\dot{S}_{gen}^{overall} = -\frac{\left|\dot{Q}\right|}{T} + \frac{\dot{Q}_0}{T_0} \geq 0$$

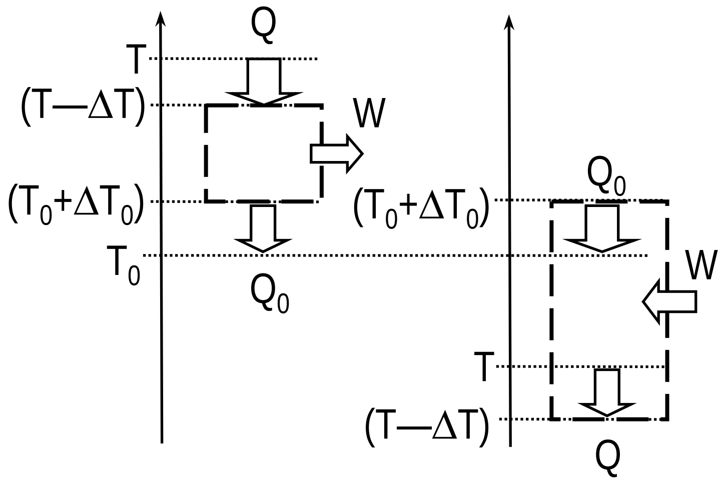
Entropy Generation by Irreversibility

Thermal System – excluding the external heat reservoirs

Related to internal irreversibility

$$\dot{S}_{gen}^{cycle} = -\frac{\left|\dot{Q}_0\right|}{T_0 + \Delta T_0} + \frac{\dot{Q}}{T - \Delta T} \geq 0$$

Introduction to Irreversible Closed Cycles
Endo-reversible Carnot cycle



Entropy Balance

Enlarged System – including both the thermal system and the external heat reservoirs

$$-\overline{\mathrm{Irr}}\frac{|\dot{Q}|}{T}+\frac{\dot{Q}_0}{T_0}=0$$

Entropy Balance

Thermal System – excluding the external heat reservoirs

Related to internal irreversibility

$$-\frac{|\dot{Q}_0|}{T_0+\Delta T_0}+N_{irrev}^{internal}\frac{\dot{Q}}{T-\Delta T}=-\frac{|\dot{Q}_0|}{T_0^*}+\mathrm{Irr}\frac{\dot{Q}}{T^*}=0$$

$\overline{\mathbf{Irr}}$ or N_{irrev} is the overall irreversibility function related to T and T_0,

$N_{irrev}^{internal}$ is the number of internal irreversibility related to (T - ΔT) and (T0 - ΔT_0),

Irr is the internal irreversibility function related to other reference temperatures on the cycle $\mathbf{T_0^*}$ and $\mathbf{T}^*$ different from (T - ΔT) and (T0 - ΔT_0)

Introduction to Irreversible non-Carnot Closed Cycles

Cyclic Heat Input

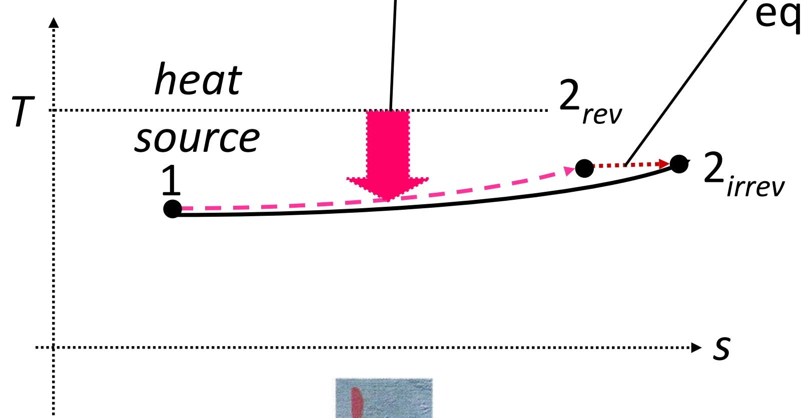
$$h_{2irrev} = h_{2rev} \Rightarrow T_{2irrev} \cong T_{2rev}$$

$$\dot{Q}_{\substack{heat\\input}} = \dot{Q}_{rev} = \dot{m} T_{mq} \Delta s_q$$

$$\dot{Q}_{12irrev} = \dot{Q}_{1-2rev} = \dot{m} T_{mq}^{1-2rev} \left(s_{2,rev} - s_1 \right)$$

$$\Delta s_{irrev} = \left(s_{2,irrev} - s_{2,rev} \right)$$

equivalent to a throtling



Introduction to Irreversible non-Carnot Closed Cycles

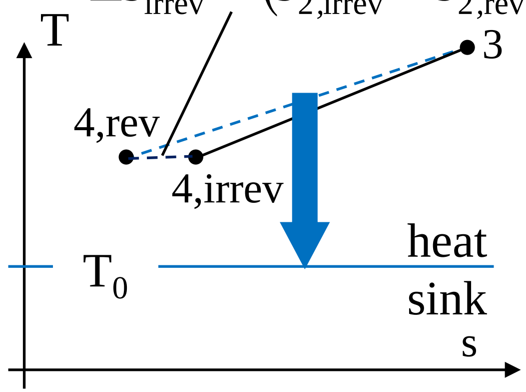
Cyclic Heat Output

$$h_{4irrev} = h_{4rev} \Rightarrow T_{4irrev} \cong T_{4rev}$$

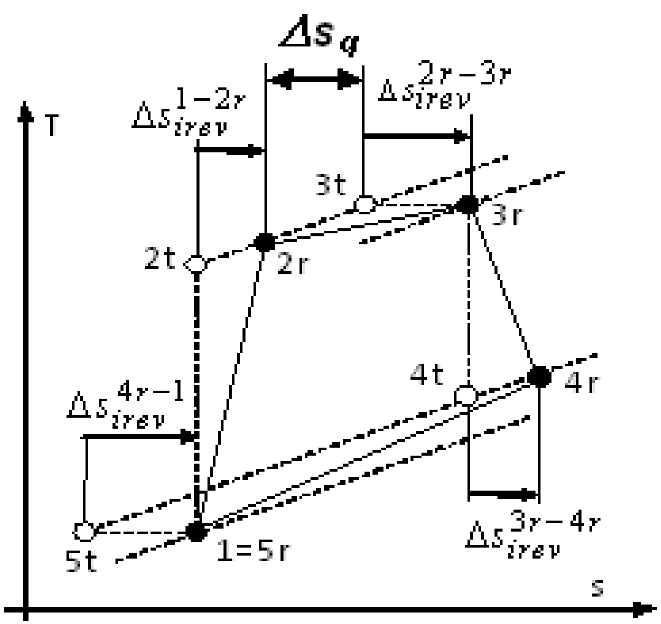
$$\dot{Q}_{\substack{heat\\input}} = \dot{Q}_{rev} = \dot{m} T_{mq} \Delta s_q$$

$$\dot{Q}_{34irrev} = \dot{Q}_{3-4rev} = \dot{m} T_{mq}^{3-4rev} \left(s_{4,rev} - s_3 \right)$$

$$\Delta s_{irrev} = \left(s_{2,irrev} - s_{2,rev} \right)$$ equivalent to a throttling



Introduction to Irreversible non Carnot Closed Cycles



Irreversible First Law Efficiency - Engines

$$FLE_{engines}^{irrev}=\eta_{irrev}=\frac{\dot{W}_e}{\dot{Q}}=\frac{\dot{W}_e^{rev}+\dot{W}_e^{irrev}}{\dot{Q}_{rev}}=\frac{\dot{W}_e^{rev}}{\dot{Q}_{rev}}-\frac{T_0\dot{S}_{gen}}{\dot{Q}_{rev}}$$

$$=1-\frac{T_0}{T}-\frac{T_0\dot{S}_{gen}}{\dot{m}T_{mq}^{2r-3t}\Delta s_q}=1-\frac{T_0}{T}\left(1+\frac{\dot{S}_{gen}}{\theta_{SLT}\dot{m}\Delta s_q}\right)$$

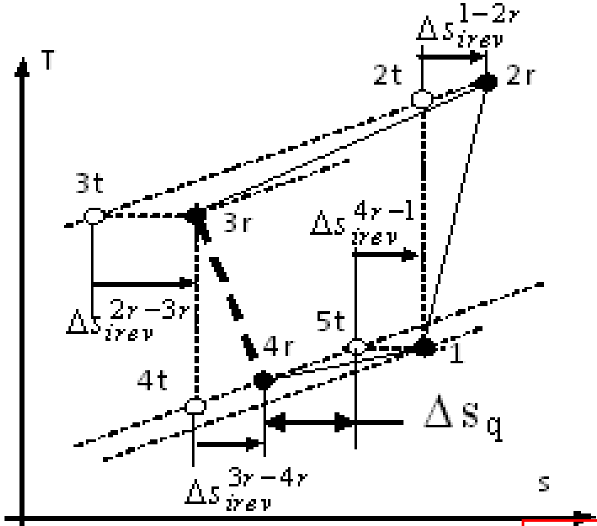
$$\eta_{irrev}=1-\frac{T_0}{T}N_{irrev}\overset{N_{irrev}>1}{<}1-\frac{T_0}{T}=\eta_{Carnot}\left(T_0,T\right)$$

Enlarged System Entropy Balance Equation

$$-\frac{\left|\dot{Q}\right|}{T}N_{irrev}+\frac{\dot{Q}_0}{T_0}=0$$

Where T is the temperature of the heat source and, $\theta_{SLT}=\frac{T}{T_{mq}^{2r-3t}}$ is a second law of thermodynamics correction function linking the heat transfer to the involved mean thermodynamic temperatures

Introduction to Irreversible non Carnot Closed Cycles



Irreversible First Law Efficiency - Refrigeration Cycles

$$FLE_{refrigeration}^{irrev} = COP_{irrev} = \frac{\dot{Q}}{\left|\dot{W}_e\right|} \overset{\dot{W}_e<0}{=} -\frac{\dot{Q}_{rev}}{\dot{W}_e} = -\frac{\dot{Q}_{rev}}{\dot{W}_e^{rev} + \dot{W}_{e,lost}^{irrev}}$$

$$= -\frac{1}{\frac{\dot{W}_e^{rev}}{\dot{Q}_{rev}} + \frac{\dot{W}_{e,lost}^{irrev}}{\dot{Q}_{rev}}} \overset{T<T_0}{=} -\frac{1}{1-\frac{T_0}{T}-\frac{T_0\dot{S}_{gen}}{\dot{Q}_{rev}}}$$

$$COP_{irrev} = -\frac{1}{1-\frac{T_0}{T}-\frac{T_0\dot{S}_{gen}}{\theta_{SLT}\dot{m}T_{mq}^{4r-5t}\Delta s_q}} = -\frac{1}{1-\frac{T_0}{T}\left(1+\frac{\dot{S}_{gen}}{\theta_{SLT}\dot{m}\Delta s_q}\right)}$$

$$COP_{irrev} = \frac{T}{T_0\left(1+\frac{\dot{S}_{gen}}{\theta_{SLT}\dot{m}\Delta s_q}\right)-T} = \frac{T}{T_0 N_{irrev} - T} \overset{N_{irrev}>1}{<} \frac{T}{T_0 - T} = COP_{Carnot}\left(T,T_0\right)$$

Enlarged System Entropy Balance Equation

$$-\frac{\left|\dot{Q}\right|}{T}N_{irrev} + \frac{\dot{Q}_0}{T_0} = 0$$

Where T is the temperature of the heat source and, $\theta_{SLT} = \frac{T}{T_{mq}^{4r-5t}}$ is a second law of thermodynamics correction function linking the heat transfer to the involved mean thermodynamic temperatures

Introduction to Irreversible non Carnot Closed Cycles

Conclusions

1. η_{irrev} and COPirrev includes explicitly the overall irreversibility (internal and external one)

2. $N_{irrev} = \left(1 + \frac{\dot{S}_{gen}}{\theta_{SLT}\dot{m}\Delta s_q}\right)$ has the meaning of the overall number of irreversibility, it evaluates both the external irreversibility due to the heat transfer at finite temperature differences, and the internal ones.

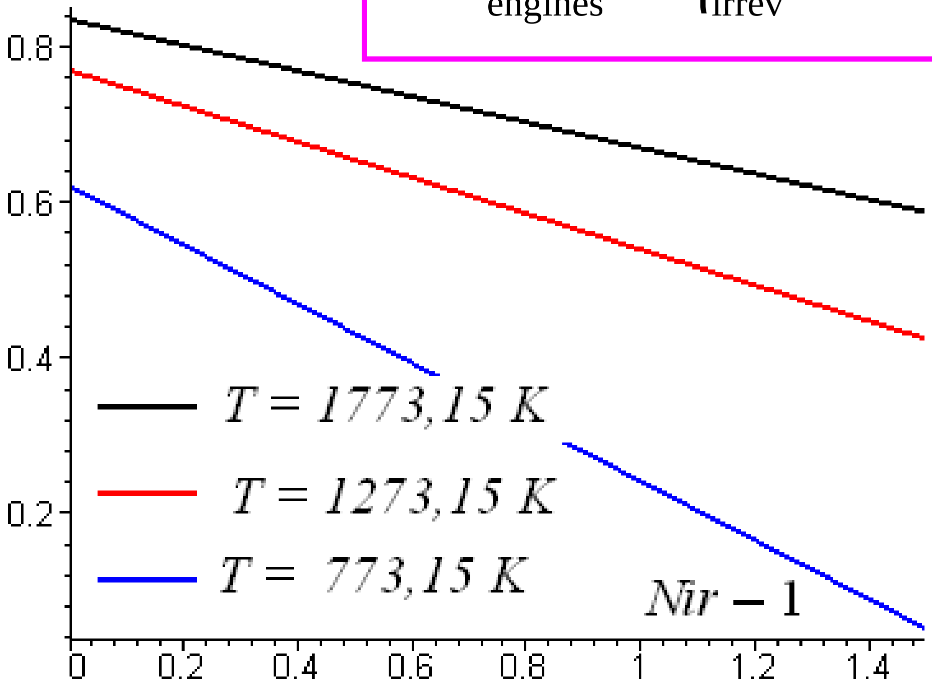
3. When $S_{gen} \rightarrow 0$ then $N_{irrev} \rightarrow 1$,

4. The correction function θ_{SLT} links the heat input at temperature T to the heat absorbed by the working fluid at temperature $T_{mq} < T$

Introduction to Irreversible non Carnot Closed Cycles

Conclusions – Engines

$$\mathrm{FLE}_{\mathrm{engines}}^{\mathrm{irrev}} = \eta_{\mathrm{irrev}} = 1 - \frac{T_0}{T} N_{\mathrm{irrev}} \overset{N_{\mathrm{irrev}}>1}{<} 1 - \frac{T_0}{T} = \eta_{\mathrm{Carnot}}\left(T_0, T\right)$$

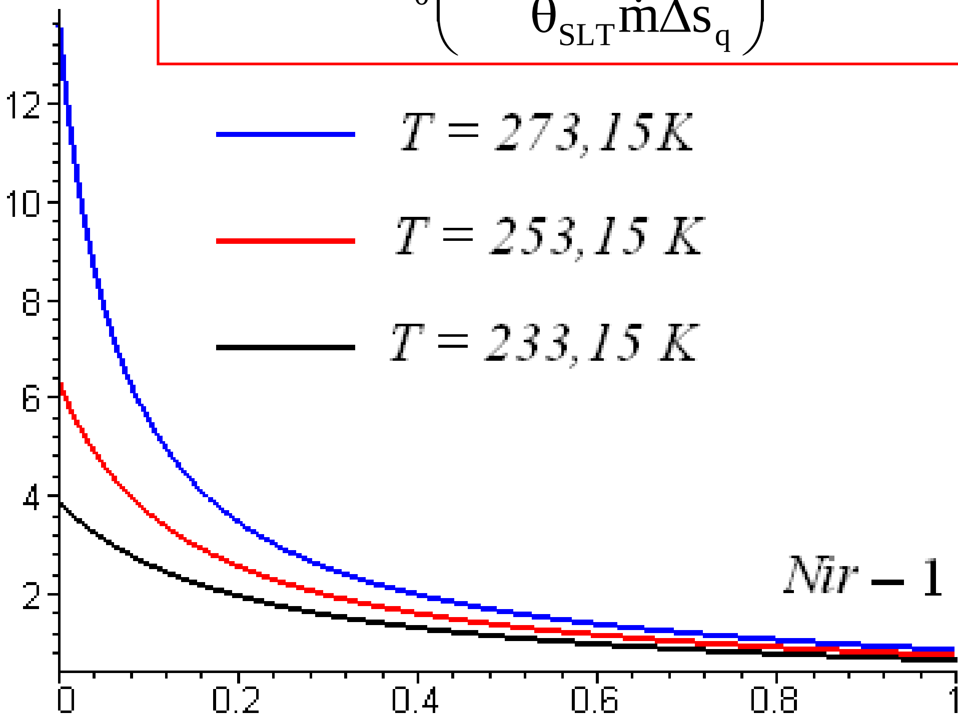


$T_0 = 273{,}15$ K

Introduction to Irreversible non Carnot Closed Cycles

Conclusions – Refrigeration cycles

$$COP_{irrev} = \frac{T}{T_0\left(1 + \frac{\dot{S}_{gen}}{\theta_{SLT}\dot{m}\Delta s_q}\right) - T} = \frac{T}{T_0 N_{irrev} - T} \overset{N_{irrev}>1}{<} \frac{T}{T_0 - T} = COP_{Carnot}\left(T, T_0\right)$$



T_0 + 293,15 K

THE WAY TO OPTIMIZE THE IRREVERSIBLE CYCLES

The optimization of cycles:

✓first and second law efficiencies (exergy analysis),

✓entropy generation minimization, and sometimes

✓Novikov–Curzon–Ahlborn maximum power issue.

The paper presents a concise method to evaluate directly the irreversibility, inside a unique criterion uniting first and second laws, called here ***the irreversible first law efficiency***.

Key words:

✓NTUS, second law effectiveness of external heat exchanges

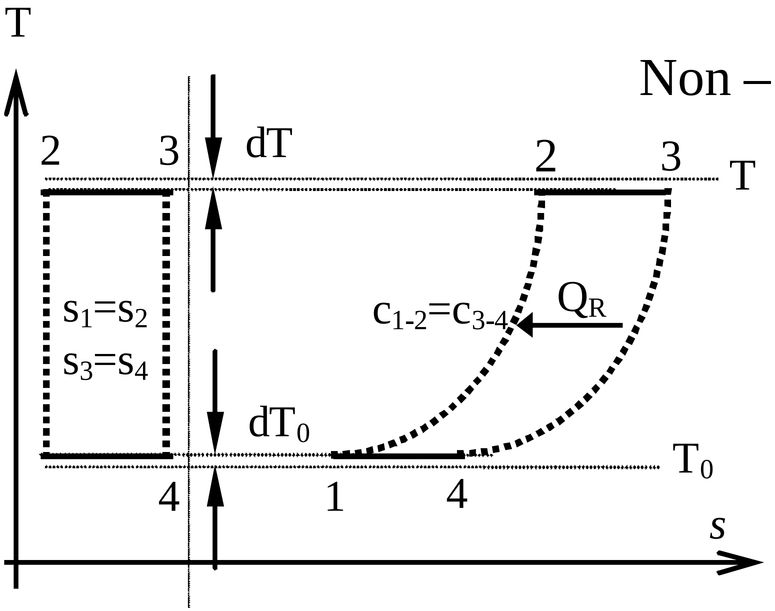
✓irreversible maximum power,

✓number of internal irreversibility, number of external irreversibility

✓irreversible first law efficiency

Engines Reversibility Principle
- engineering realm -

Any ideal cycle is characterized by no entropy generation $\dot{S}_{gen} = 0.$



The possible ideal engine cycles
in temperature – entropy diagram

Non – CARNOT complete Reversible Engine Cycles

$$s_2 - s_1 = s_3 - s_4 = c_n \ln\left(T/T_0\right)$$

All Complete Reversible Engine Cycles

$$\eta_{rev} = 1 - \frac{T_0}{T}$$

Introduction

"Optimization of Irreversible Cycles" , FTT or FST

The ideal cycles are characterized by no entropy generation, $\dot{S}_{gen} = 0.$

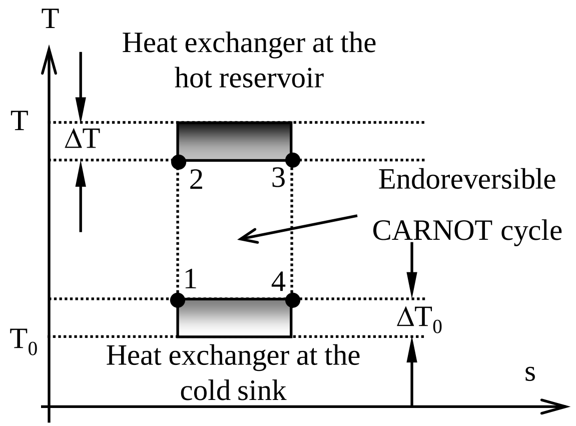
The ***Finite Time Thermodynamics (FTT),*** or ***Finite Speed Thermodynamics (FST)*** is a feature of the originator works of:

- CHAMBADAL (1957) and NOVIKOV (1958) – studies about nuclear cycles,
- CURZON et AHLBORN (1975) – the time-based thermodynamic analysis in view of the real heat transfer made at finite temperature difference,
- YAN et al. (1989), GROSU et al. (2004), CHEN et al. (1997, 1999) – analyzed the irreversible cycles with three external heat sinks

THE IDEAL REVERSIBLE CYCLES ARE CONSIDERED AS USELESS, THEY MIGHT SUPPLY THE MAXIMUM ENGINES WORK, BUT NO POWER. THE REQUIRED TIME BY THE REVERSIBLE HEAT TRANSFER AT INFINITESIMAL TEMPERATURE DIFFERENCE REQUIRES AN INFINITE PROCESS TIME (I.E. THE POWER, WHICH IS RATIO WORK PER TIME IS IN FACT ZERO).

The Irreversible First Law Efficiency
External Irreversibility
Endo-Reversible CARNOT Engine

The second law effectiveness of the heat exchange with the heat source



Number of Transfer Units per Reversible Entropy Variation due to reversible heat transfer

$$NTUS = \frac{UA}{\dot{m}\Delta s_q}$$

Basic Equations

$$\dot{Q} = UA\Delta T = \dot{m}(T - \Delta T)\Delta s_q = \dot{Q}_{rev}$$

$$\Delta T = T\frac{1}{NTUS+1} \Rightarrow \dot{Q} = \dot{m}(T-\Delta T)\Delta s_q = \dot{m}T\Delta s_q \frac{NTUS}{NTUS+1}$$

The second law effectiveness at the heat exchange at the hot reservoir

$$\varepsilon_{II} = \frac{\dot{Q}}{(\dot{Q})_{NTUS\to\infty}} = \frac{NTUS}{NTUS+1} < 1 \Rightarrow$$

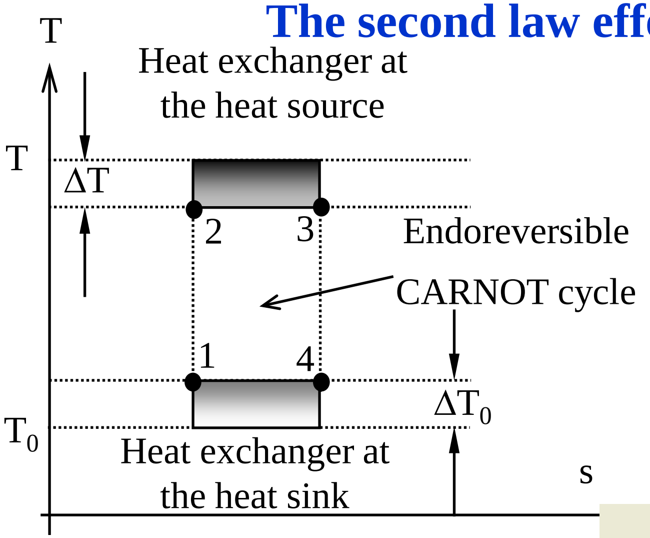
$$\dot{Q} = \varepsilon_{II}\dot{Q}_{NTUS\to\infty} = \varepsilon_{II}\dot{Q}^{rev}_{max} = \varepsilon_{II}\dot{m}T\Delta s_q \Rightarrow$$

$$\Delta s_q = (\Delta s_q)_{NTUS\to\infty},\ \Delta T \to 0$$

$$\dot{Q} < \dot{Q}^{rev}_{max}$$

The Irreversible First Law Efficiency
External Irreversibility
Endo-Reversible CARNOT Engine

The second law effectiveness of the heat exchange with the heat sink



Number of Transfer Units per Reversible Entropy Variation due to reversible heat transfer

$$NTUS_0 = \frac{U_0 A_0}{\dot{m}\left|\Delta s_{q,0}\right|}$$

Basic Equations

$$\left|\dot{Q}_0\right| = U_0 A_0 \Delta T_0 = \dot{m}\left(T_0 + \Delta T_0\right)\left|\Delta s_{q,0}\right|$$

$$\Delta T_0 = T_0 \frac{1}{NTUS_0 - 1} \Rightarrow \quad \left|\dot{Q}_0\right| = \dot{m}\left(T_0 - \Delta T_0\right)\left|\Delta s_{q,0}\right| = \dot{m} T_0 \left|\Delta s_{q,0}\right| \frac{NTUS_0}{NTUS_0 - 1}$$

The second law effectiveness of the heat exchange at the cold sink

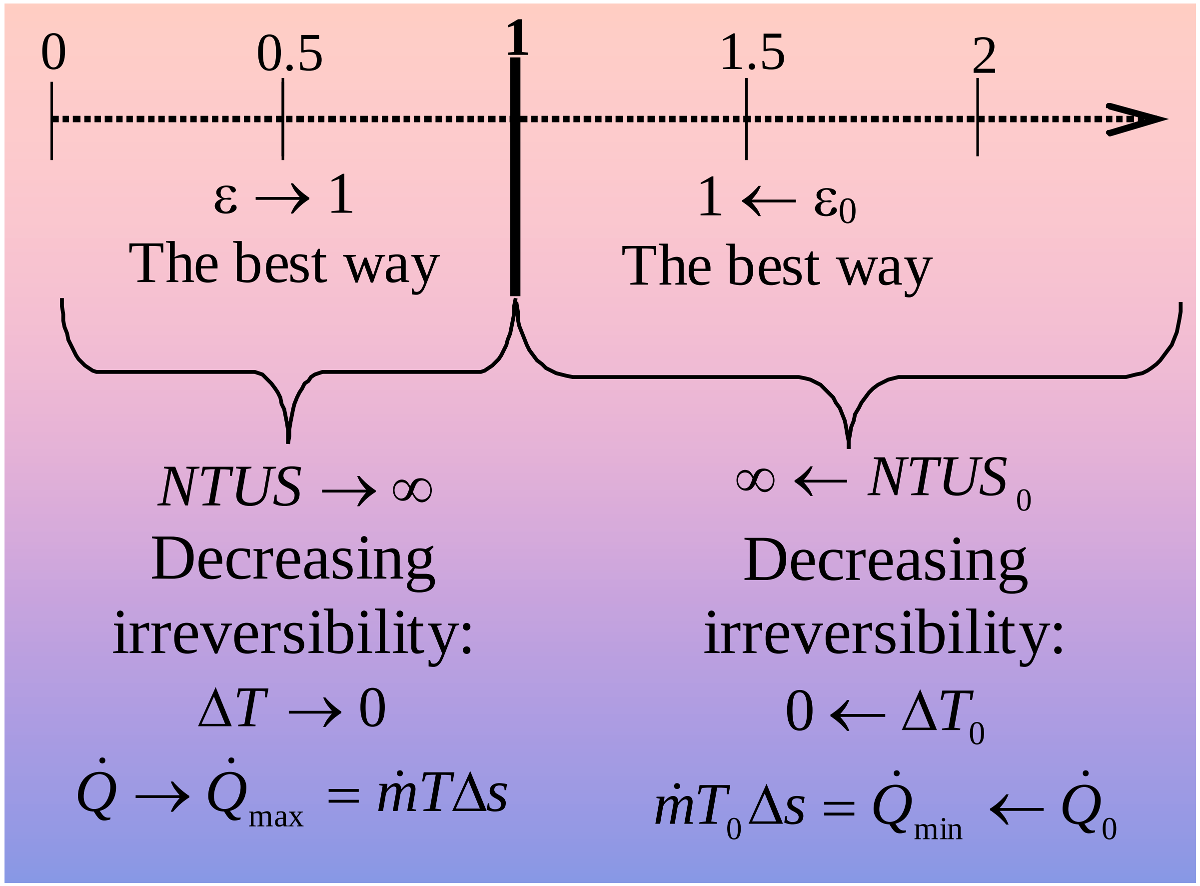
$$\varepsilon_{II,0} = \frac{\left|\dot{Q}_0\right|}{\left(\left|\dot{Q}_0\right|\right)_{NTUS_0 \to \infty}} = \frac{NTUS_0}{NTUS_0 - 1} > 1 \Rightarrow \left|\dot{Q}_0\right| = \varepsilon_0 \left(\left|\dot{Q}_0\right|\right)_{NTUS_0 \to \infty} = \varepsilon_{II,0}\left|\dot{Q}_{min}\right| = \varepsilon_{II,0} \dot{m} T_0 \left|\Delta s_{q,0}\right| \Rightarrow \left|\dot{Q}_0\right| > \left|\dot{Q}_{min}\right|$$

$$\left|\Delta s_{q,0}\right| = \left|\Delta s_{q,0}\right|_{NTUS_0 \to \infty}, \quad \Delta T_0 \to 0$$

The Irreversible First Law Efficiency

External Irreversibility

Endo-Reversible CARNOT Engine



***The dependence second law effectiveness – NTU*S**

The Irreversible First Law Efficiency

External Irreversibility

Endo-Reversible CARNOT Engine

The Power

$$P = \dot{Q} - \left|\dot{Q}_0\right| = \dot{Q}\left(1 - \frac{\left|\dot{Q}_0\right|}{\dot{Q}}\right) = Q_{max}\varepsilon_{II}\left(1 - \frac{\left|\dot{Q}_{min}\right|}{\dot{Q}_{max}}\frac{\varepsilon_{II,0}}{\varepsilon_{II}}\right) = \dot{m}T\Delta s_q \varepsilon_{II}\left(1 - \frac{1}{\tau}\frac{\varepsilon_{II,0}}{\varepsilon_{II}}\right)$$

The Irreversible First Law Efficiency

$$\eta_I = 1 - \frac{1}{\tau}\frac{\varepsilon_{II,0}}{\varepsilon_{II}} = 1 - \frac{1}{\tau}N_{irr,ext}$$

The Second Law Efficiency

$$\eta_{II} = \frac{1 - \frac{1}{\tau}N_{irr,ext}}{1 - \frac{1}{\tau}} \Rightarrow N_{irr,ext} \to 1 \Rightarrow \eta_{II} = 1$$

Considerations on the Real Power Cycles

The real power cycles are also internally irreversible, respectively:

- the heat transfer processes, 2–3 and 4–1, are non-isothermal;
- the adiabatic processes, 2–3 and 4–1, are non-isentropic;
- the external heat reservoirs have finite heat capacities, respectively are non-isothermal;
- the mean log temperature difference pertaining to the heat transfers has a value that it is not equalizing the difference of the mean thermodynamic temperatures.

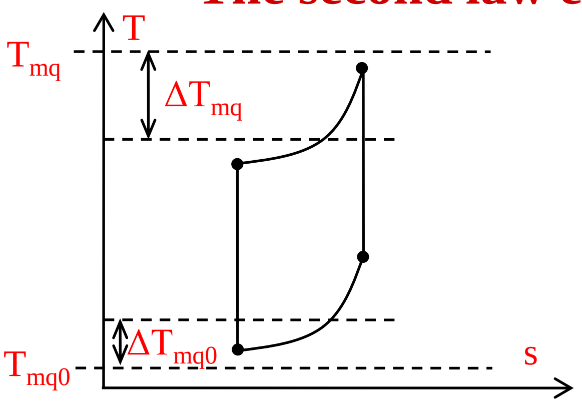
This dissimilarity can be solved step by step by introducing the necessary amendment coefficients in order to take into account also the internal irreversibility.

The Irreversible First Law Efficiency

External Irreversibility

Any Endo-Reversible Engine

The second law effectiveness of the heat exchange with the heat source



Number of Transfer Units per Entropy Variation

$$NTUS = \frac{UA}{\dot{m}\Delta s_q}$$

Basic Equations

$$\dot{Q} = UA\Delta T_{mq} C_{\Delta T} = \dot{m}\left(T_{mq} - \Delta T_{mq}\right)\Delta s_q$$

$$\Delta T_{mq} = T_{mq}\frac{1}{NTUS \cdot C_{\Delta T} + 1} \Rightarrow$$

$$\dot{Q} = \dot{m}\left(T_{mq} - \Delta T_{mq}\right)\Delta s = \dot{m}T_{mq}\Delta s_q \frac{NTUS \cdot C_{\Delta T}}{NTUS \cdot C_{\Delta T} + 1}$$

The second law effectiveness at the heat source

$$\varepsilon_{II} = \frac{\dot{Q}}{\left(\dot{Q}\right)_{\substack{NTUS\to\infty \\ A\to\infty}}} = C_{\Delta s_q}\frac{NTUS \cdot C_{\Delta T}}{NTUS \cdot C_{\Delta T} + 1} < 1 \Rightarrow$$

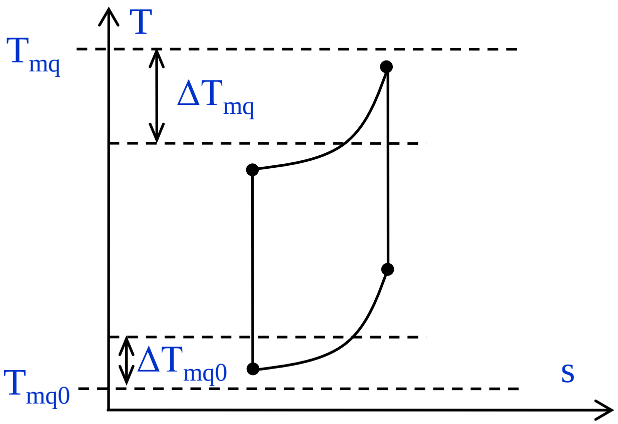
$$\dot{Q} = \varepsilon_{II}\dot{Q}_{max} = \varepsilon_{II}\dot{m}T_{mq}\left(\Delta s_q\right)_{\substack{NTUS\to\infty \\ A\to\infty}} \Rightarrow$$

$$C_{\Delta T} = \frac{\Delta T_{mean}^{\substack{heat \\ treansfer}}}{\Delta T_{mq}}, \quad C_{\Delta s_q} = \frac{\Delta s_q}{\left(\Delta s_q\right)_{\substack{NTUS\to\infty \\ A\to\infty}}}$$

$$\dot{Q} < \dot{Q}_{max}$$

The Irreversible First Law Efficiency
External Irreversibility
Any Endo-Reversible Engine

The second law effectiveness of the heat exchange with the heat sink



Number of Transfer Units per Entropy Variation

$$NTUS_0 = \frac{U_0 A_0}{\dot{m}\Delta s_{q0}}$$

Basic Equations

$$\left|\dot{Q}_0\right| = U_0 A_0 \Delta T_{mq0} C_{\Delta T0} = \dot{m}\left(T_{mq0} + \Delta T_{mq0}\right)\left|\Delta s_{q0}\right|$$

$$\Delta T_{mq0} = T_{mq0}\frac{1}{NTUS_0 \cdot C_{\Delta T0} - 1} \Rightarrow \left|\dot{Q}_0\right| = \dot{m}\left(T_{mq0} - \Delta T_{mq0}\right)\left|\Delta s_{q0}\right| = \dot{m}T_{mq0}\left|\Delta s_{q0}\right|\frac{NTUS_0 \cdot C_{\Delta T0}}{NTUS_0 \cdot C_{\Delta T0} - 1}$$

The second law effectiveness at the heat sink

$$\varepsilon_{II,0} = \frac{\left|\dot{Q}_0\right|}{\left(\left|\dot{Q}_0\right|\right)_{\substack{NTUS_0 \to \infty \\ A \to \infty}}} = C_{\Delta s_{q0}}\frac{NTUS_0 \cdot C_{\Delta T0}}{NTUS_0 \cdot C_{\Delta T0} - 1} > 1 \Rightarrow$$

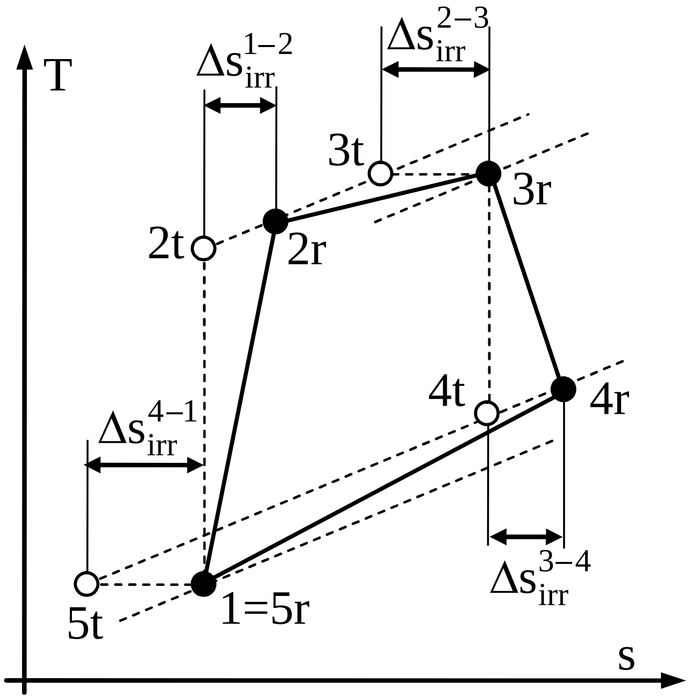
$$\left|\dot{Q}_0\right| = \varepsilon_{II,0}\left|\dot{Q}_{min}\right| = \varepsilon_{II,0}\dot{m}T_{mq0}\left|\Delta s_{q0}\right|_{\substack{NTUS \to \infty \\ A \to \infty}}$$

$$C_{\Delta T0} = \frac{\Delta T_{mean}^{\text{heat treansfer}}}{\Delta T_{mq}}, \quad C_{\Delta s_{q0}} = \frac{\Delta s_{q0}}{\left(\Delta s_{q0}\right)_{\substack{NTUS_0 \to \infty \\ A \to \infty}}}$$

$$\Rightarrow \left|\dot{Q}_0\right| > \left|\dot{Q}_{min}\right|$$

The Irreversible First Law Efficiency
Internal Irreversibility
Any Basic Irreversible Engine

1 – 2r irreversible adiabatic compression, 2r – 3r irreversible heating
3r – 4r irreversible adiabatic expansion, 4r – 1 irreversible cooling



$$\Delta s_q = s_{3t} - s_{2r}$$

$$\left|\Delta s_{q0}\right| = s_{4r} - s_{5t}$$

$$= s_q + \Delta s_{irr}^{1-2} + \Delta s_{irr}^{2-3} + \Delta s_{irr}^{3-4} + \Delta s_{irr}^{4-1} =$$

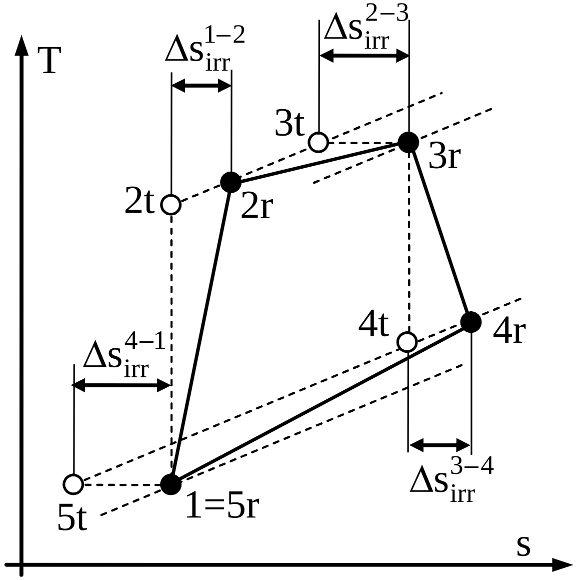
$$= \Delta s_q \cdot N_{irr,int}$$

$$N_{irr,int} = \left(1 + \frac{\left(\sum \Delta s_{irr}\right)_{int}}{\Delta s_q}\right) > 1$$

The Irreversible First Law Efficiency

Internal Irreversibility

Any Basic Irreversible Engine



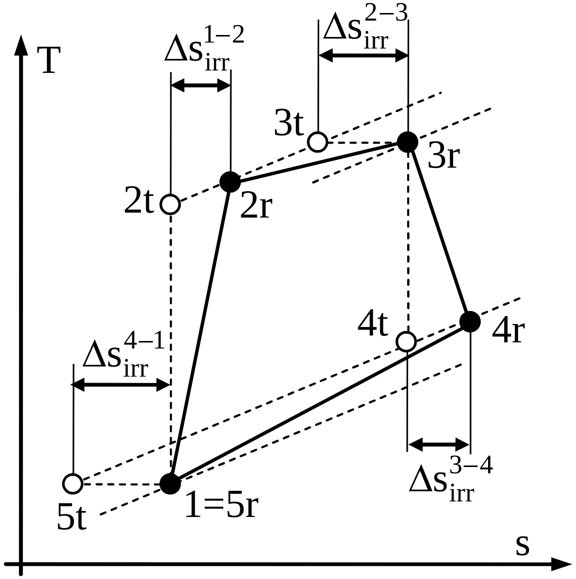
$$\eta_{engine} = \frac{P}{\dot{Q}^{2r-3t}} = 1 - \frac{\left|\dot{Q}_0^{4r-5t}\right|}{\dot{Q}^{2r-3t}} =$$

$$= 1 - \frac{\dot{m} \cdot T_{mq}^{4r-5t} \cdot \left|\Delta s_{q0}\right|}{\dot{m} \cdot T_{mq}^{2r-3t} \cdot \Delta s_q} = 1 - \frac{T_{mq}^{4r-5t}}{T_{mq}^{2r-3t}} N_{irr,int}^{engine}$$

The Irreversible First Law Efficiency

External and Internal Irreversibility

Any Basic Irreversible Engine



$$\varepsilon_{II} = \frac{\dot{Q}^{2r-3t}}{\dot{Q}_{max}^{2-3}} = \frac{\dot{m} T_{mq}^{2r-3t} \Delta s_q}{\dot{m} T_{mq} \Delta s_q} = C_{\Delta s_q} \frac{T_{mq}^{2r-3t}}{T_{mq}} < 1$$

$$\varepsilon_{II,0} = \frac{\dot{Q}^{4r-5t}}{\dot{Q}_{min}^{4-5}} = \frac{\dot{m} T_{mq}^{4r-5t} \Delta s_{q0}}{\dot{m} T_{mq0} \Delta s_{q0}} = C_{\Delta s_{q0}} \frac{T_{mq}^{4r-5t}}{T_{mq0}} > 1$$

$$N_{irr,ext} = \frac{\varepsilon_{II,0}}{\varepsilon_{II}} \frac{C_{\Delta s_q}}{C_{\Delta s_{q0}}} > 1$$

$$\eta_{engine} = 1 - \frac{T_{mq0}}{T_{mq}} \frac{\varepsilon_{II,0}}{\varepsilon_{II}} \frac{C_{\Delta s_q}}{C_{\Delta s_{q0}}} N_{irr,int} = 1 - \frac{1}{\tau} N_{irr,ext} \cdot N_{irr,int}$$

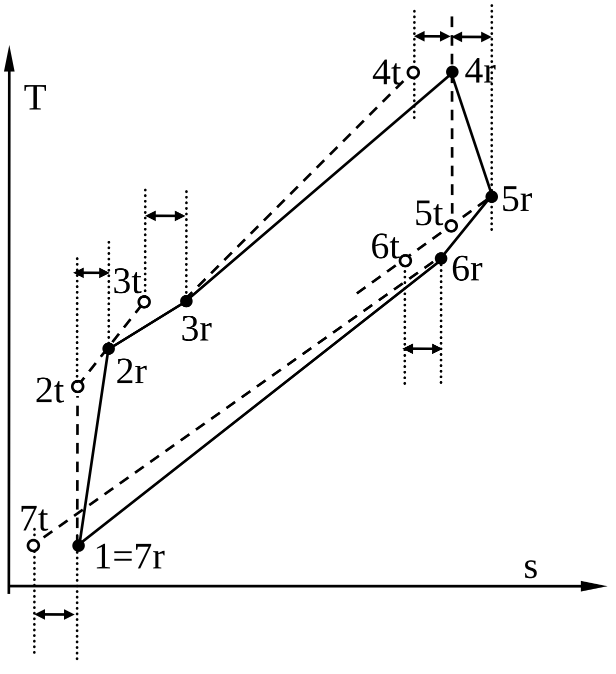
The Irreversible First Law Efficiency

Internal Irreversibility

Any Irreversible Engine with Internal Heat Transfer (Internal Regeneration of Heat)

1 – 2r irreversible adiabatic compression, 2r – 3r internal irreversible heating by heat regeneration, 3r – 4r irreversible heating, 4r – 5r irreversible adiabatic expansion, 5r – 6r internal irreversible cooling by heat regeneration,

6r – 1 irreversible cooling.



$$\Delta s_q = \Delta s_{3-4} = s_{4t} - s_{3r}$$

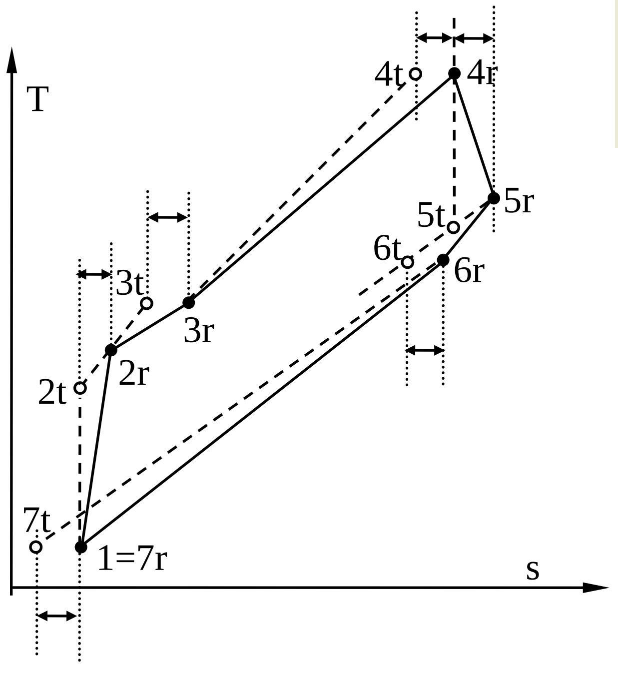
$$T_{mq}^{2r-3t}\left(s_{3t} - s_{2r}\right) = T_{mq}^{5r-6t}\left(s_{5t} - s_{6r}\right)$$

$$\left|\Delta s_{q0}\right| = s_{6r} - s_{7t} = \Delta s_q + \left(s_{3t} - s_{2r}\right)\left(1 - \frac{T_{mq}^{2r-3t}}{T_{mq}^{5r-6t}}\right) + \Delta s_{irr}^{1-2} + \Delta s_{irr}^{2-3} + \Delta s_{irr}^{3-4} + \Delta s_{irr}^{4-5} + \Delta s_{irr}^{5-6} + \Delta s_{irr}^{6-7}$$

The Irreversible First Law Efficiency

Internal Irreversibility

Any Irreversible Engine with Internal Heat Transfer (Internal Regeneration of Heat)



$$N_{irr,int} = \left(1 + \frac{\left(\sum \Delta s_{irr}\right)_{int}}{\Delta s_q} + \frac{\left(s_{3t} - s_{2r}\right)}{\Delta s_q}\left(1 - \frac{T_{mq}^{2r-3t}}{T_{mq}^{5r-6t}}\right)\right) > 1$$

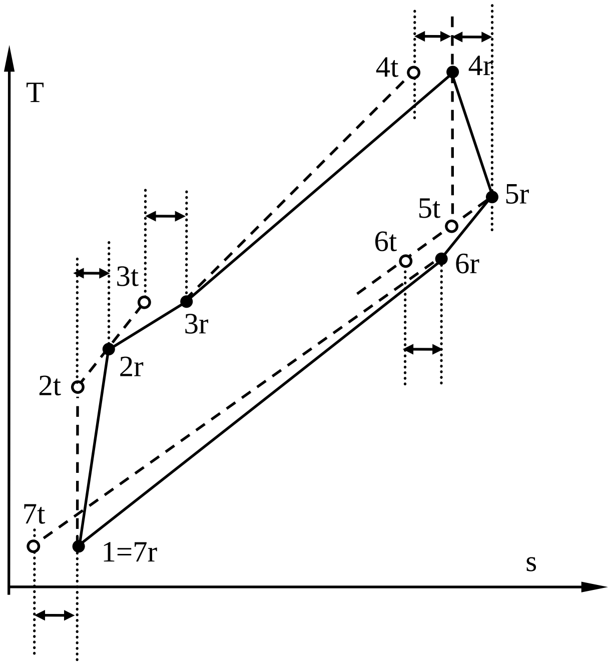
$$\eta_{engine} = \frac{\dot{W}}{\dot{Q}} = 1 - \frac{\left|\dot{Q}_0\right|}{\dot{Q}} = 1 - \frac{\dot{m} \cdot T_{mq}^{6r-7t} \cdot \left|\Delta s_{q0}\right|}{\dot{m} \cdot T_{mq}^{3r-4t} \cdot \Delta s_q} =$$

$$= 1 - \frac{T_{mq}^{6r-7t}}{T_{mq}^{3r-4t}} N_{irr,int}$$

The Irreversible First Law Efficiency

External and Internal Irreversibility

Any Irreversible Engine with Internal Heat Transfer (Internal Regeneration of Heat)



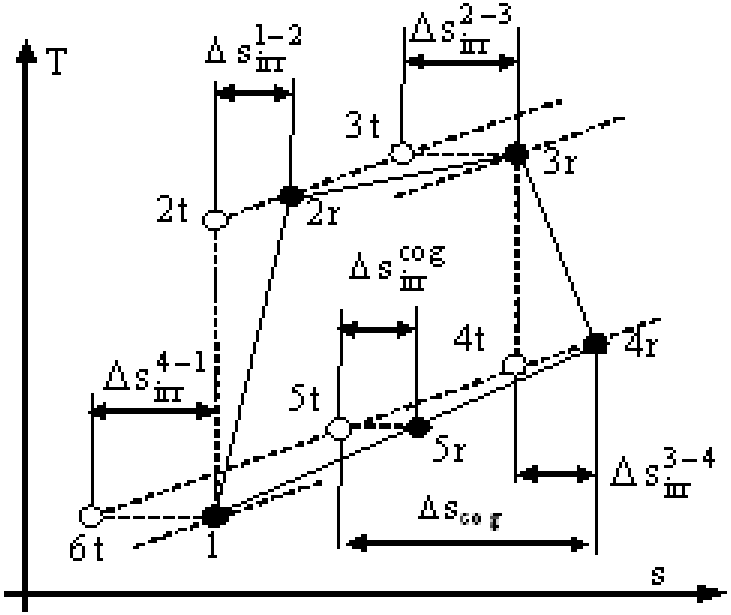
$$\eta_{engine} = 1 - \frac{T_{mq0}}{T_{mq}} \frac{\varepsilon_{II,0}}{\varepsilon_{II}} \frac{C_{\Delta s_q}}{C_{\Delta s_{q0}}} N_{irr,\text{int}} =$$

$$= 1 - \frac{1}{\tau} \cdot N_{irr,ext} \cdot N_{irr,\text{int}}$$

The Irreversible First Law Efficiency

Internal Irreversibility

Any Irreversible Co-generation Engine



$$\Delta s_q = \Delta s_{2-3} = s_{3t} - s_{2r}$$

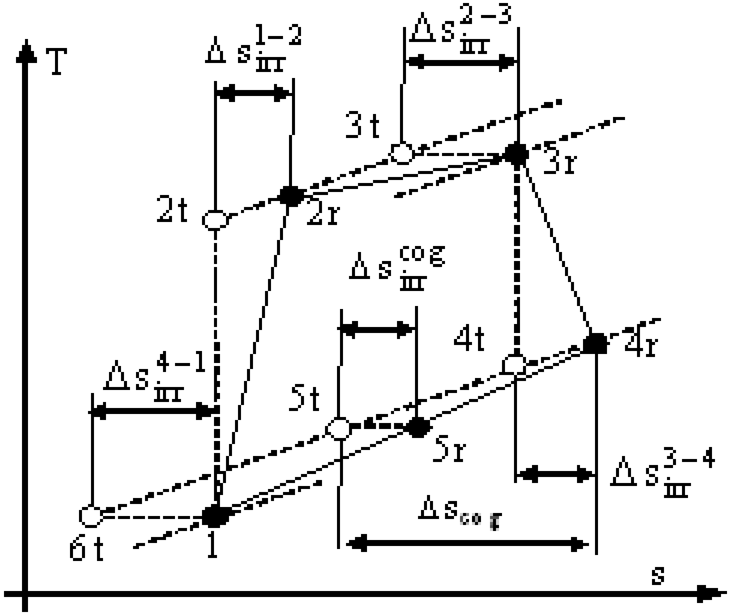
$$\left|\Delta s_{q0}\right| = \left|\Delta s_{4-1}\right| = s_{4r} - s_{6t} = \Delta s_q + \sum_{x=1,2,3,4}^{y=2,3,4,1} \Delta s_{irr}^{x-y} = \Delta s_q \left(1 + \frac{\left(\sum \Delta s_{irr}\right)_{int}^{engine}}{\Delta s_q} \right)$$

$$\left|\Delta s_{q,0}^{cog}\right| = \left|\Delta s_{5-1}\right| = s_{5t} - s_{6t} = \left|\Delta s_{4-1}\right| - \left|\Delta s_{cog}\right| = \Delta s_q \left(1 + \frac{\left(\sum \Delta s_{irr}\right)_{int}^{engine} - \left|\Delta s_{cog}\right|}{\Delta s_q} \right)$$

The Irreversible First Law Efficiency

Internal Irreversibility

Any Irreversible Co-generation Engine



$$\eta_{overall}=\frac{P+\left|\dot{Q}_{4-5}\right|}{\dot{Q}_{2-3}}=1-\frac{\left|\dot{Q}_{4-1}\right|-\left|\dot{Q}_{4-5}\right|}{\dot{Q}_{2-3}}=$$

$$1-\frac{\dot{m}\cdot\left(T_{mq}^{4r-6t}\cdot\left|\Delta s_{4-1}\right|-T_{mq}^{4r-5t}\cdot\left|\Delta s_{4-5}\right|\right)}{\dot{m}\cdot T_{mq}^{2r-3t}\cdot\Delta s_{2-3}}=$$

$$=1-\frac{T_{mq}^{4r-6t}}{T_{mq}^{2r-3t}}N_{irr,int}^{cog}$$

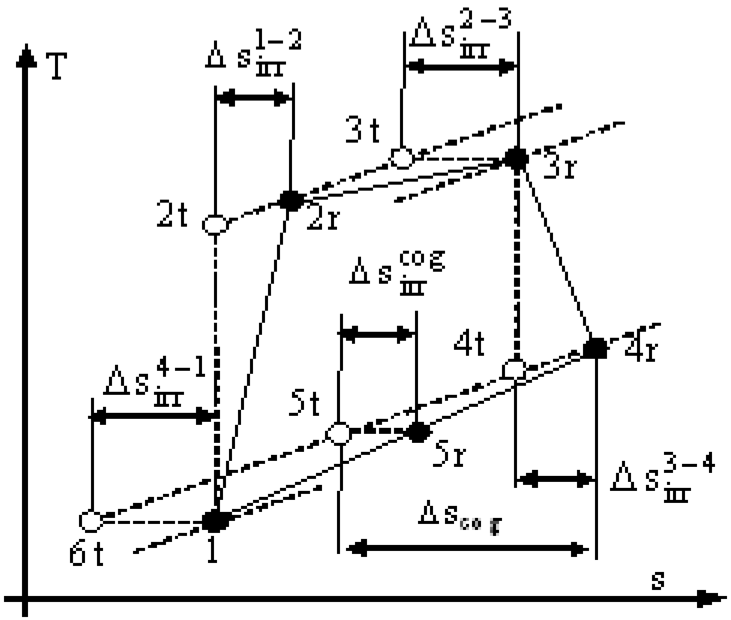
$$N_{irr,int}^{cog}=\left(1+\frac{\left(\sum\Delta s_{irr}\right)_{int}^{engine}}{\Delta s_{2-3}}-\frac{T_{mq}^{4r-5t}}{T_{mq}^{4r-6t}}\frac{\Delta s_{cog}}{\Delta s_{2-3}}\right)$$

For endo-reversibility $\quad N_{irr,int}^{cog}\rightarrow 0$

The Irreversible First Law Efficiency

External and Internal Irreversibility

Any Irreversible Co-generation Engine



$$\eta_{overall} = 1 - \frac{T_{mq0}}{T_{mq}} \frac{\varepsilon_{II,0}}{\varepsilon_{II}} \frac{C_{\Delta s_q}}{C_{\Delta s_{q0}}} N_{irr,int} =$$

$$= 1 - \frac{1}{\tau} N_{irr,ext} N_{irr,int}$$

For endo-reversibility $N_{irr,int}^{cog} \to 0$ and $\eta_{overall} \to 1$

Numerical Results

The computational procedure assumed the following restrictive conditions.

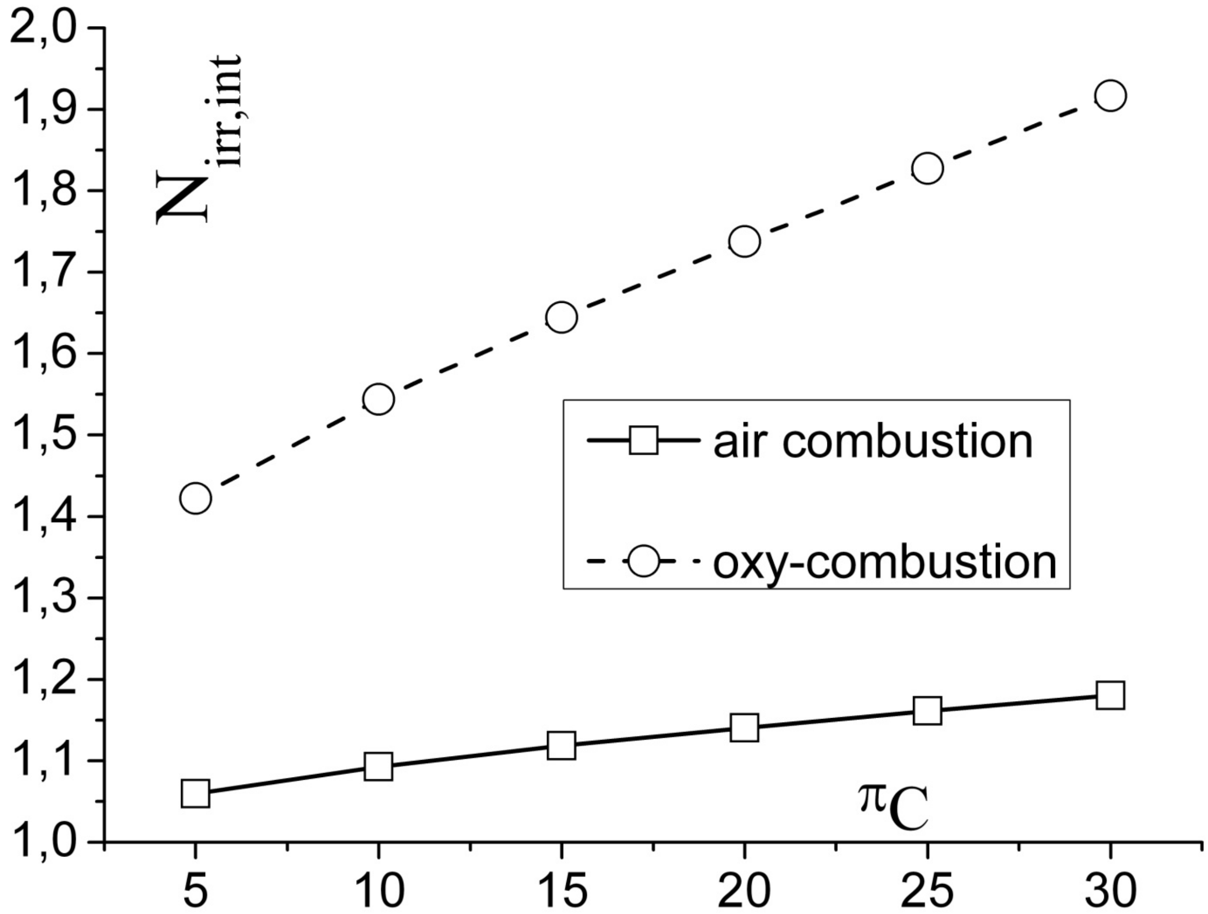
- *Variable heat capacities of gases, fourth degree temperature polynomials;*
- *Adiabatic exponents of the reversible processes computed as the ratio of enthalpy variation to internal energy variation.*
- *In the case of engine heated by combustion, they were considered negligible dissociation during combustion, and the mass and energy balance equations of combustion gave the flue gases composition, the excess air value, and the fuel mass flow rate.*

Numerical Results

First Figures compare the oxy-combustion with 90% mass fraction of O_2 in the oxygenated air, and the air combustion, for an open Joule – Brayton cogeneration cycle. The restrictive conditions were: maximum temperature on the cycle, 1200°C; isentropic efficiency of the compressor, 0.88; isentropic efficiency of the gas turbine, 0.94; pressure loss coefficient in the combustion chamber, 0.98; the fuel mass composition of 15% H_2 and 85% C; higher heating value of the fuel ~46,000 kJ/kg.

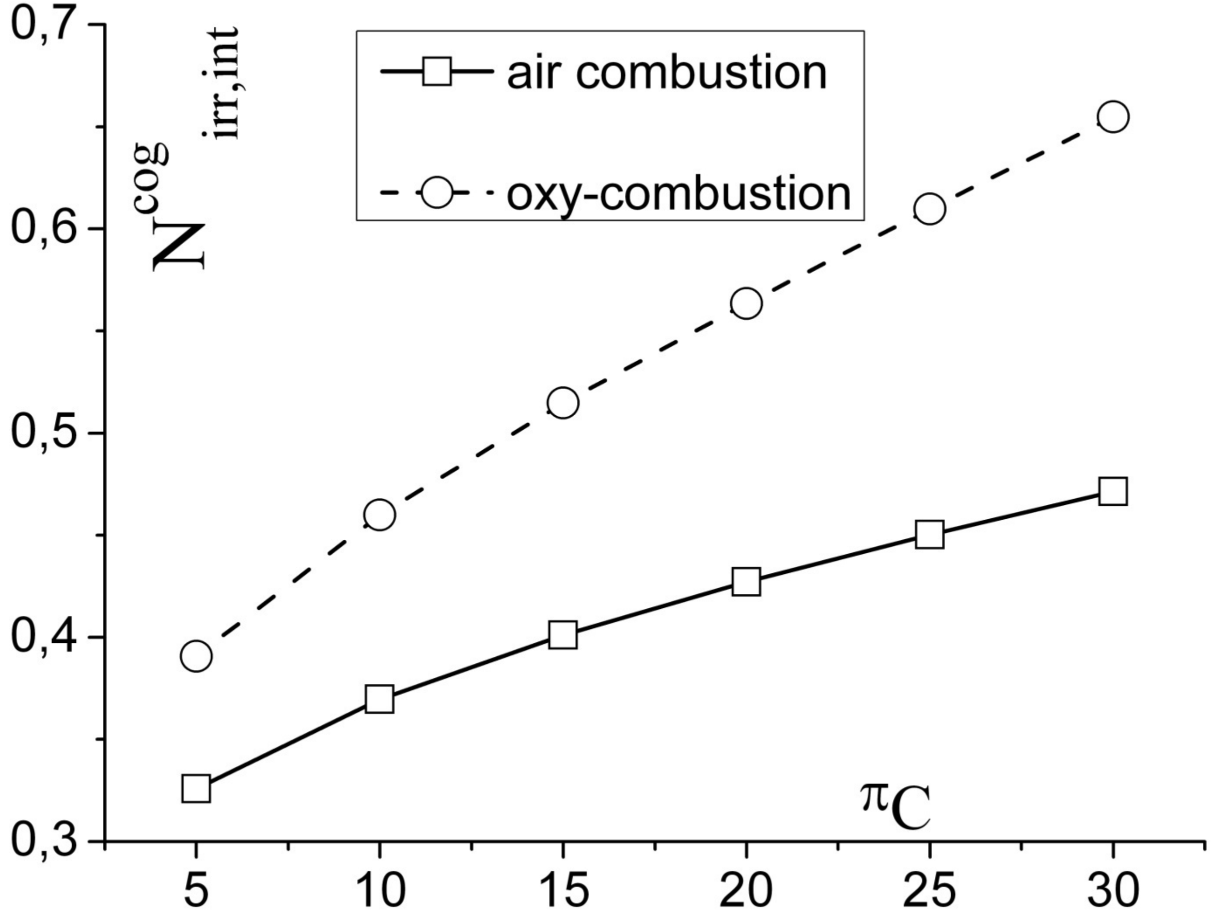
Next Figures compare six possible working fluids, air, O_2, N_2, CO_2, H_2 and He, in a closed Joule – Brayton engine cycle externally heated, e.g. by solar energy. The restrictive conditions were: maximum temperature on the cycle, 1000°C; the minimum temperature on the cycle, 20°C; isentropic efficiency of the compressor, 0.88; isentropic efficiency of the gas turbine, 0.94; pressure loss coefficient in the heat exchanger connecting the external hot source, 0.98; pressure loss coefficient in the heat exchanger connecting the external cold sink, 0.98; variable heat capacities; adiabatic exponent computed as the ratio of heat capacities at constant pressure and constant volume.

Numerical Results



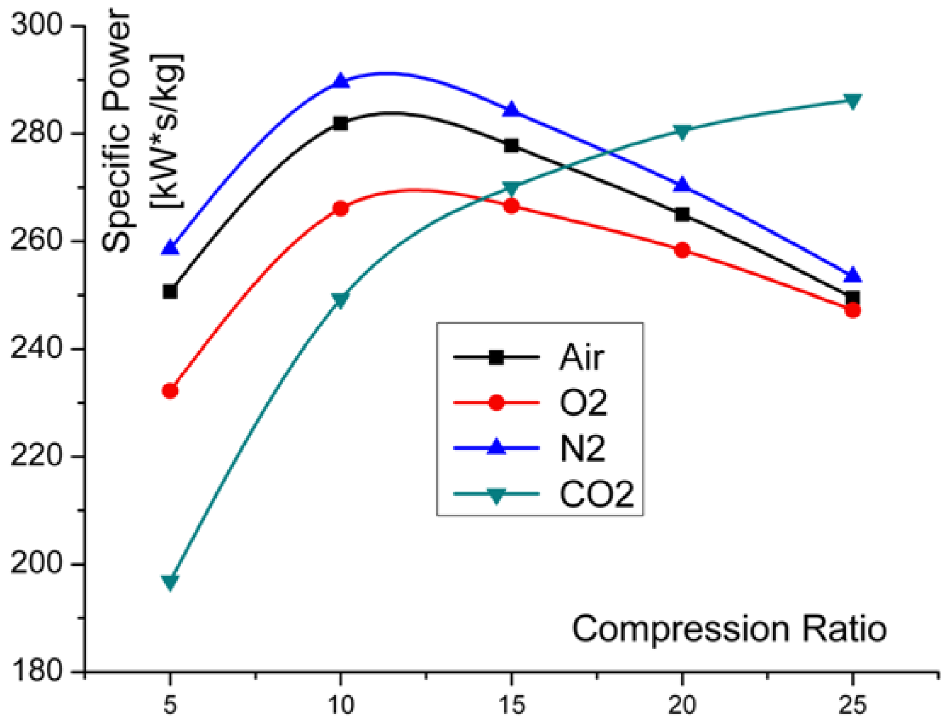
The dependence number of internal irreversibility – compression ratio for the basic engine cycle

Numerical Results



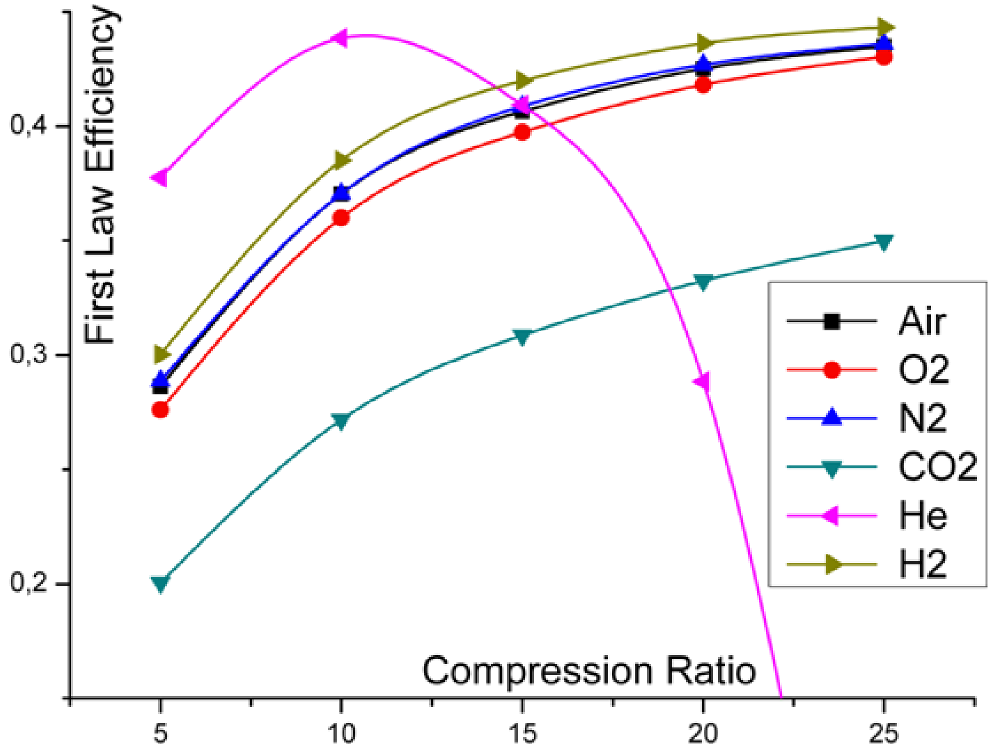
The dependence overall number of internal irreversibility – compression ratio for the cogeneration cycle

Numerical Results



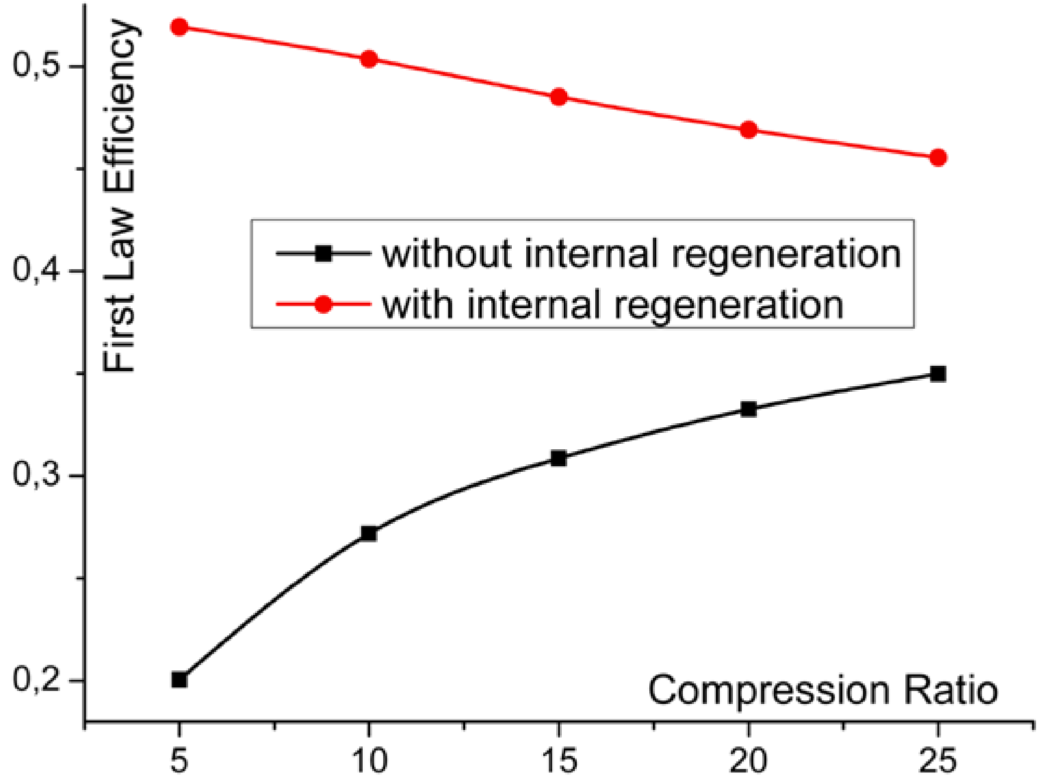
The dependence specific power output on compression ratio for the basic engine cycle

Numerical Results



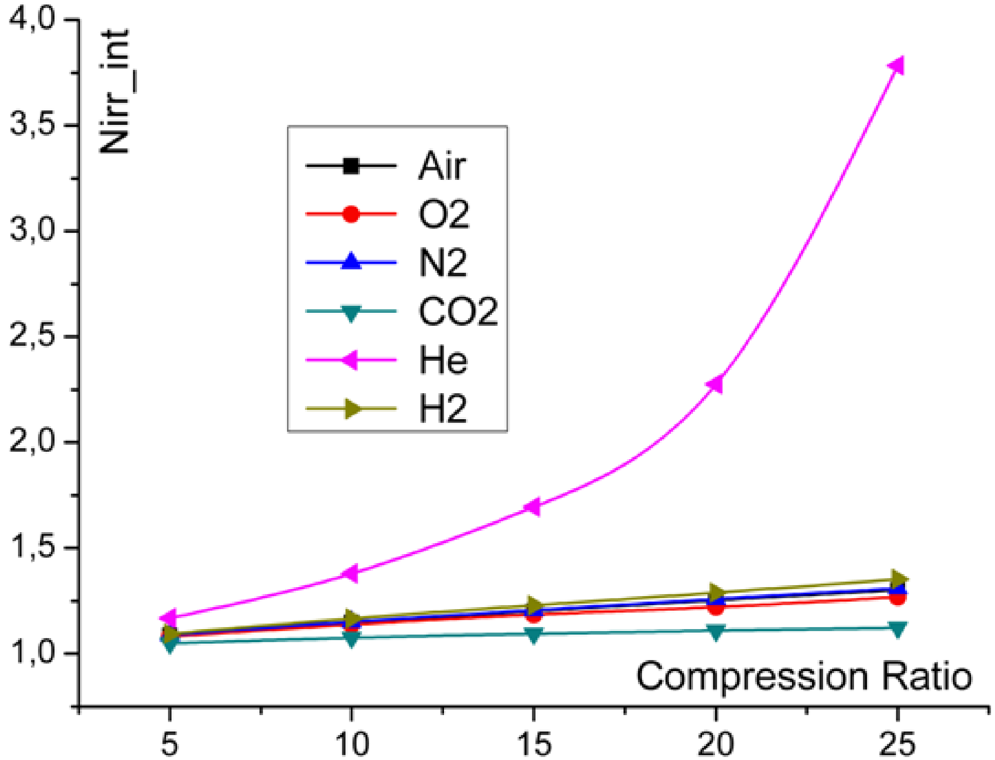
The dependence irreversible first law efficiency (thermodynamic efficiency) on compression ratio for the basic engine cycle

Numerical Results



Comparison of the dependence irreversible first law efficiency (thermodynamic efficiency) on compression ratio for both the basic engine cycle and the engine cycle with internal regeneration of heat, only for CO2 as working fluid

Numerical Results



The dependence number of internal irreversibility on compression ratio for the basic engine cycle

Conclusions

This paper deals with a new optimization criteria, the irreversible first law efficiency applied to the real cycles.

This new approach emphasizes the overall irreversibility by the means of the numbers of internal and external irreversibility, directly inside the first law efficiency.

It yields that the maximum power is not unique, as it was assumed untill now, respectively depends on the nature of the working fluid and on the restrictive conditions.

The irreversible first law efficiency conducts to the reversible limit, i.e. the reversible Carnot engine, respectively offers the simplest comparison.

Conclusions

For complex cycles, we have only to deal carefully with the entropy variations and thermal interactions during the heat transfer processes.

Important remark: *the second law effectiveness, defined in this paper, takes into account only the thermal interactions connecting the working fluids with external heat reservoirs, the internal heat exchanges of complex cycles, e.g. in the case of combined cycles, the heat transfer between the top cycle and the bottom one is included in the number of internal irreversibility; for instance, refer to the simple manner to manage the internal heat exchange of Power Cycles with Internal Heat Transfer.*

Conclusions

The direct method presented in this presentation is a concise one, equivalent to exergy analysis, since the lost exergy is proportional to the entropy irreversibly generated. The comparison of possible fluids used in a closed Joule – Brayton cycle, externally heated, shows that CO_2 offers a substantial potential for internal regeneration of heat, see the below table, that includes the difference of temperatures of the fluid leaving the turbine and the compressor.

Conclusions

Table 1. The difference between temperatures of the fluid leaving the turbine and the compressor, [℃]

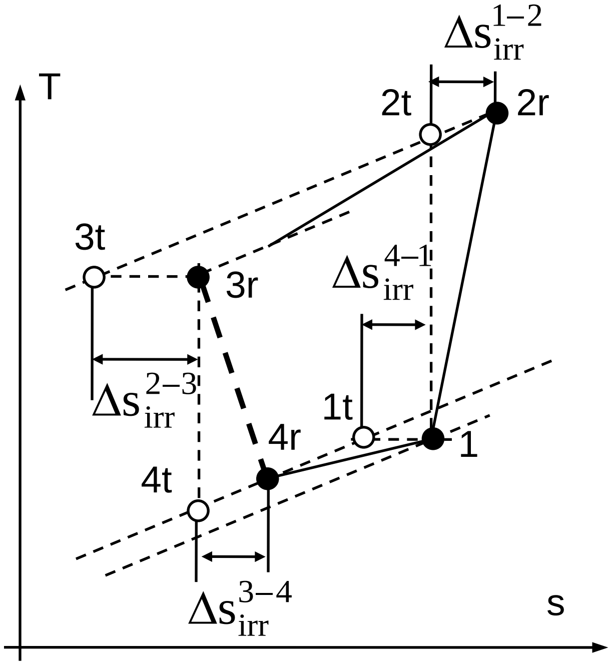
Compression Ratio	Air	O2	N2	CO2	He	H2
5,00	**401**	**423**	**397**	**593**	**123**	**367**
10,00	**158**	**191**	**152**	**431**	41	**115**
15,00	17	57	9	**337**		
20,00				**272**		
25,00				**221**		

Overview

1. ***Introduction***
2. ***Mathematical model***
3. ***Results and discussion***
4. ***Conclusions***

1. Introduction

First and Second Laws Relationship – CV-HP



- ***First Law – Energy Balance***

$$\dot{Q} = Q_e = \dot{Q}_{4r-1t} = \dot{m}T_{mq}^{4r-1t}\left(s_{1t} - s_{4r}\right) = \dot{m}T_{mq}^{4r-1t}\Delta s_q > 0$$

$$\dot{Q}_0 = \dot{Q}_c = \dot{Q}_{2r-3t} = \dot{m}T_{mq}^{2r-3t}\left(s_{3t} - s_{2r}\right) = \dot{m}T_{mq}^{2r-3t}\Delta s_{q0} < 0$$

$$\dot{W} = \dot{Q} + \dot{Q}_0 = \dot{Q} - \left|\dot{Q}_0\right| < 0$$

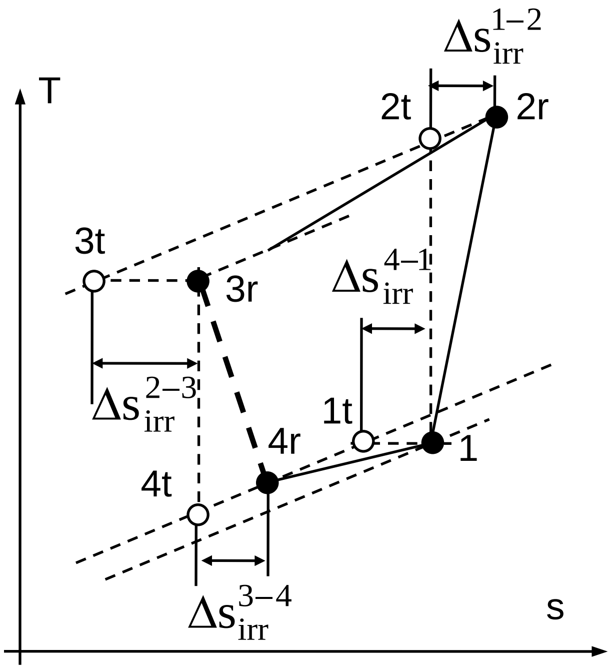
$$\Delta s_q = s_{1t} - s_{4r}$$

$$\Delta s_{q0} = s_{3t} - s_{2r} = \Delta s_q + \Delta s_{irrev}^{4-1} + \Delta s_{irrev}^{1-2} + \Delta s_{irrev}^{2-3} + \Delta s_{irrev}^{3-4}$$

$$= \Delta s_q + \left(\sum \Delta s_{irrev}\right)_{int}$$

1. Introduction

First and Second Laws Relationship – CV-HP



- ***First Law – Energy Balance***

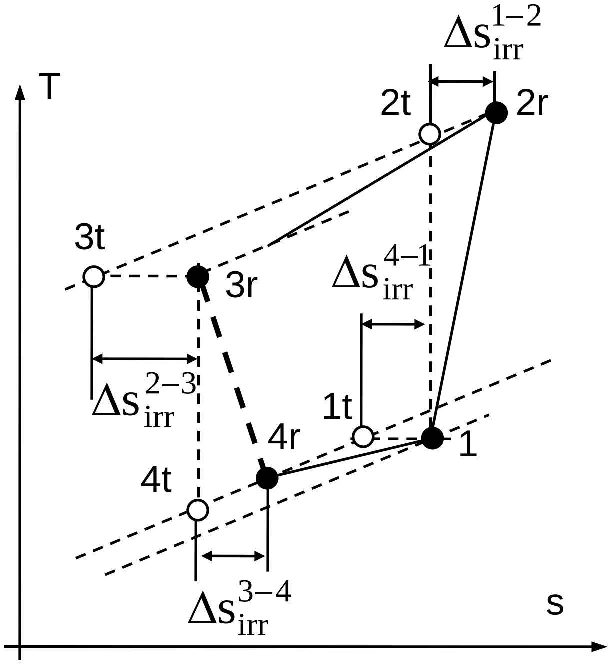
$$COP_{HP} = \frac{|\dot{Q}_0|}{|\dot{Q}_0| - \dot{Q}} = \frac{\dot{m} T_{mq}^{2r-3t} |\Delta s_{q0}|}{\dot{m}\left(T_{mq}^{2r-3t} |\Delta s_{q0}| - T_{mq}^{4r-1t} \Delta s_q\right)} =$$

$$= \frac{\dfrac{|\dot{Q}_0|}{\dot{Q}}}{\dfrac{|\dot{Q}_0|}{\dot{Q}} - 1} = \frac{\dfrac{T_{mq}^{2r-3t}}{T_{mq}^{4r-1t}} N_{irr,int}}{\dfrac{T_{mq}^{2r-3t}}{T_{mq}^{4r-1t}} N_{irr,int} - 1} \underset{HP}{\overset{e.g.}{=}} \frac{\dfrac{T_c}{T_e} Irr}{\dfrac{T_c}{T_e} Irr - 1}$$

$$N_{int,irr} = 1 + \frac{\left(\sum \Delta s_{irr}\right)_{int}}{\Delta s_q} > 1 \text{ or, } Irr = N_{int,irr} \frac{T_{mq}^{2r-3t}}{T_{ref}^{2-3}} \frac{T_e}{T_c}$$

1. Introduction

First and Second Laws Relationship – CV-HP



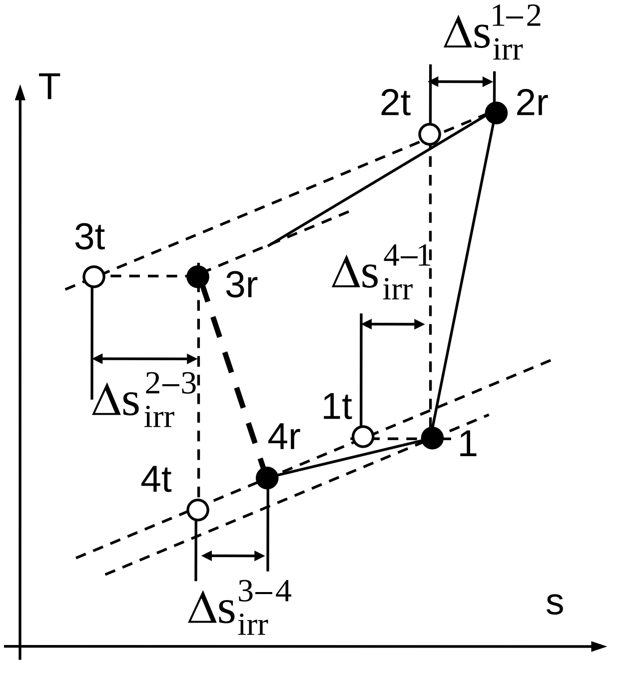
- ***Second Law – entropy balance***
  - ***Internal irreversibility***

$$\frac{\dot{Q}}{T_{mq}^{4r-1t}} N_{irr,int} - \frac{|\dot{Q}_0|}{T_{mq}^{2r-3t}} = 0 \text{ or } \frac{\dot{Q}}{T_{ref}^{4-1}} \mathrm{Irr} - \frac{|\dot{Q}_0|}{T_{ref}^{2-3}} = 0$$

$$\text{or e.g. (CV - HP) } \frac{\dot{Q}_e}{T_e} \mathrm{Irr} - \frac{|\dot{Q}_c|}{T_c} = 0$$

1. Introduction

First and Second Laws Relationship – CV-HP



- ***United First and Second Laws***

$$N_{irr,int} = COPR \frac{T_{mq}^{4r-1t}}{T_{mq}^{2r-3t}} \quad \text{or} \quad Irr = COPR \frac{T_{ref}^{4-1}}{T_{ref}^{2-3}}$$

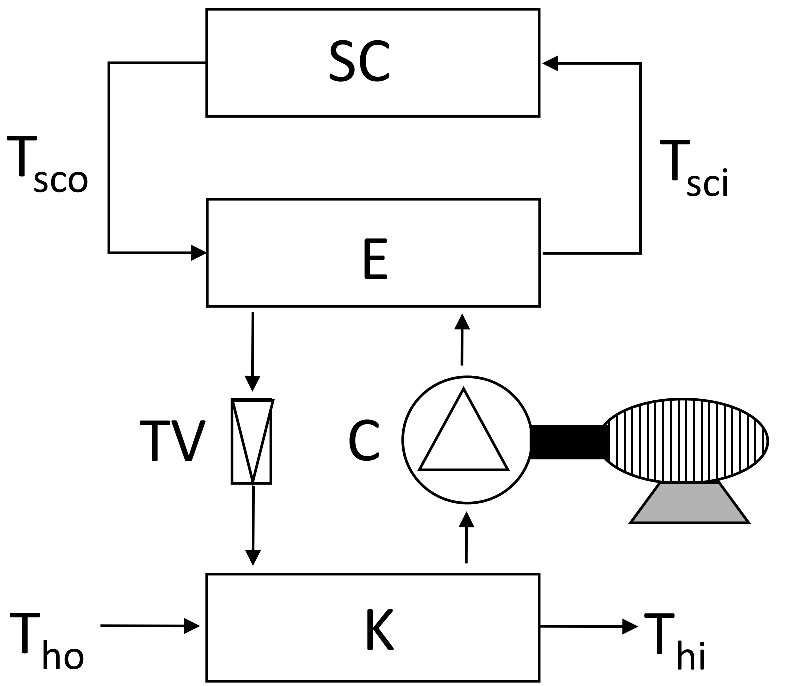
$$\text{or e.g. (CV - HP)} \; Irr = COPR \frac{T_e}{T_c}$$

$$\text{where } COPR = \frac{COP_{HP}}{COP_{HP} - 1}$$

2. Mathematical model

Thermal Relationships of a Solar Assisted Compression

Vapor Heat Pump (CV-HP)



2. Mathematical model

- ***Solar collector***
  - Collector temperature under non-flow conditions $$T_s = T_a + \frac{\eta_o I}{U_L}$$
  - Collector plate temperature $$T_{sc} = T_s - \frac{\eta_s I}{U_L}$$
  - Inlet temperature of the solar heat carrier $$T_{sci} = T_{sc} - \frac{\eta_s IA}{\varepsilon_{sc}\dot{C}_{sc}}$$
  - Outlet temperature of the solar heat carrier $$T_{sco} = T_{sci} + \frac{\eta_s IA}{\dot{C}_{sc}}$$

η_o is optical efficiency of solar collector, Ta is environmental temperature, U_L is solar collector heat-loss coefficient; ε_{sc} is solar collector effectiveness; *I is total solar radiation*.

2. Mathematical model

- ***Heating system***

Inlet/outlet temperatures of the useful heat carrier, were imposed by considering that the heating system asks:

✓ at $T_a = T_{aN}$ = 253.15K, $T_{hi} = T_{hiN}$ = 323.15K and, $T_{ho} = T_{hoN}$ = 333.15K;

✓ at $T_a = T_{aS}$ = 288.15K, $T_{hi} = T_{hiS}$ = 303.15K;

✓ for 253.15 K < T_a < 288.15 K: $T_{ho} \cong -0.5714286 \cdot T_a + 467.807143$

✓ $T_{room} = 295.15K$.

$$\frac{\dot{Q}_{heating}(T_a)}{\dot{Q}_{heating}(T_{aN})} = \frac{T_{hi} - T_{ho}}{T_{hiN} - T_{hoN}} \cong \frac{T_{room} - T_a}{T_{room} - T_{aN}} \Rightarrow T_{hi}(T_a)$$

2. Mathematical model

- ***Evaporator***

evaporator heat rate

$$\dot{Q}_e = \dot{C}_{sc}\left(T_{sco} - T_{sci}\right)$$

evaporator temperature

$$T_e = T_{sco} - \frac{\dot{Q}_e}{\varepsilon_e \dot{C}_{sc}}$$

Where ε_e is evaporator effectiveness.

2. Mathematical model

- ***Heat pump irreversibility*** *(entropy and energy balance)*

$$\mathrm{Irr}\frac{\dot{Q}_e}{T_e} - \frac{\left|\dot{Q}_c\right|}{T_c} = 0 \quad \Rightarrow \; \dot{Q}_c$$

$$\mathrm{Irr} = \frac{\left(COP_{HP} + 1\right)}{COP_{HP}}\frac{T_e}{T_c} = COPR\,\frac{T_e}{T_c}$$

2. Mathematical model

- ***Condenser***

Condensing temperature

$$T_c = T_{ho} + \frac{\left|\dot{Q}_c\right|}{\varepsilon_c \dot{C}_h}$$

Where ε_c *is condenser effectiveness*

2. Mathematical model

By CoolPack, and for adopted restrictive conditions inside the heat pump, it was interpolated, by square roots, the irreversibility, for 303.15K < T_c < 338.15K, and, 258.15K < T_e < 288.15K:

- refrigerant R22, errors: +1.1%, – 3.1% $$COPR = -0.90971003 + 1.850627\frac{T_c}{T_e}$$
- refrigerant R717, errors: +1.1%, – 1.8% $$COPR = -0.60229 + 1.568338\frac{T_c}{T_e}$$
- refrigerant R410A, errors: +1.1%, – 6.6% $$COPR = -1.68326472 + 2.551254\frac{T_c}{T_e}$$
- refrigerant R407c, errors: +1.1%, – 4.9% $$COPR = -1.371045642 + 2.272844431\frac{T_c}{T_e}$$
- refrigerant R290, errors: +1.1%, – 3.7% $$COPR = -1.02348136 + 1.951886275\frac{T_c}{T_e}$$
- refrigerant R134a, errors: +1.1%, – 3.6% $$COPR = -0.9796944 + 1.9103469052\frac{T_c}{T_e}$$

2. Mathematical model

- ***Power balance***

$$\dot{W} = \dot{Q}_e + \dot{Q}_c = \dot{Q}_e - \left|\dot{Q}_c\right|$$

$$COP_{HP} = \frac{\left|\dot{Q}_c\right|}{\left|\dot{W}\right|}$$

3. Results and discussion

- The correlated compilation of previous equations allowed in MathLab to find out numerical results, depending only on ε_e and ε_c. Figures 2 to 5 show selected numerical results for:

$$T_a = 273.15K; I = 50\frac{W}{m^2}; \eta_o = 0.95; U_L = 2\frac{W}{m^2K};$$

$$\dot{C}_{sc} = 1000\frac{J}{KgK}; \dot{C}_h = 1000\frac{J}{KgK}; \eta_s = 0.75; \varepsilon_{sc} = 0.75$$

3. Results and discussion

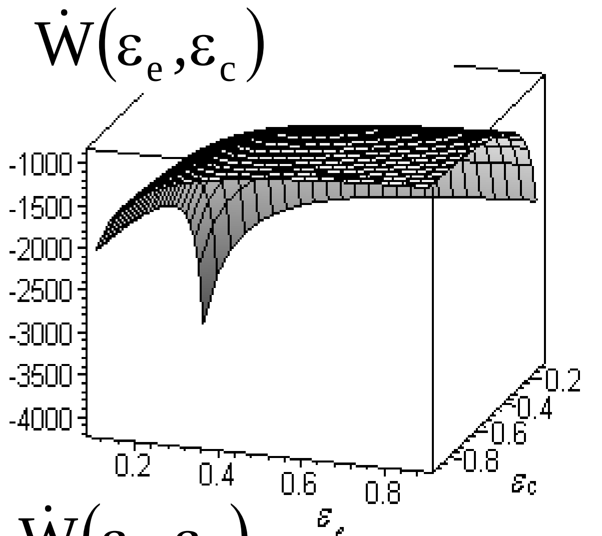


Fig.2. R22

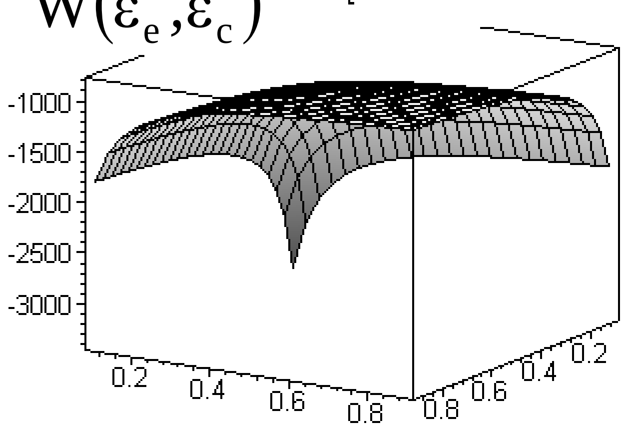


Fig.3. R717

3. Results and discussion

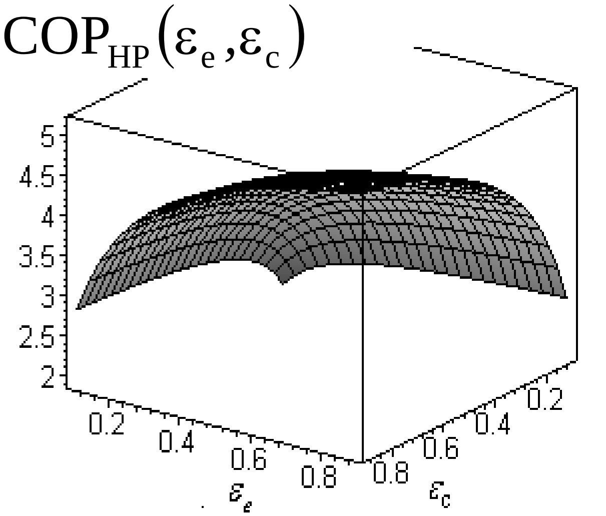


Fig.4. R22

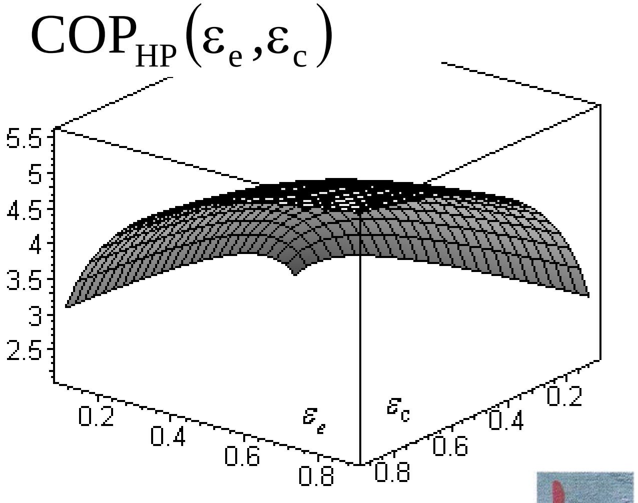


Fig.5. R717

3. Conclusions

The presentation presents a mathematical algorithm able in modeling the influences of evaporator and condenser effectiveness upon the all operational features of a heat pump: power, heat rates, and temperatures. The model start with the external heat sources imposed parameters and, combine these ones by the internal irreversibility of the heat pump (entropy balance).

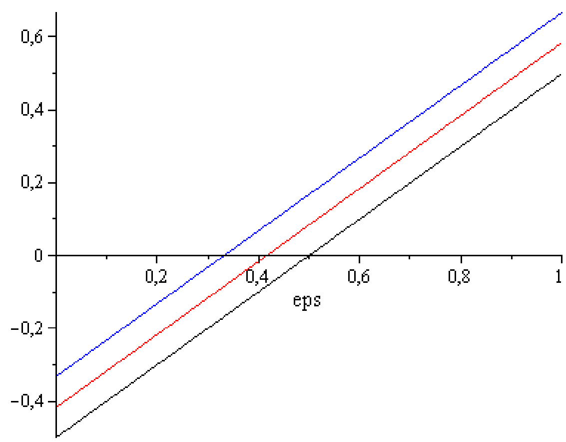
PROGRAM CICLU CARNOT ENDOREVERSIBIL

```
> restart;
> tau:=3;P1:=eps*(1-1/eps/tau);P2:=eps*(1-1.25/eps/tau);P3:=eps*(1-1.5/eps/tau);
```

$\tau := 3$

$P1 := eps\left(1 - \frac{1}{3}\,\frac{1}{eps}\right);\ P2 := eps\left(1 - \frac{0.4166666667}{eps}\right);\ P3 := eps\left(1 - \frac{0.5000000000}{eps}\right)$

```
> plot([P1(eps),P2(eps),P3(eps)], eps=0..1, color=[blue,red,black], style=[line,line,line]);
```

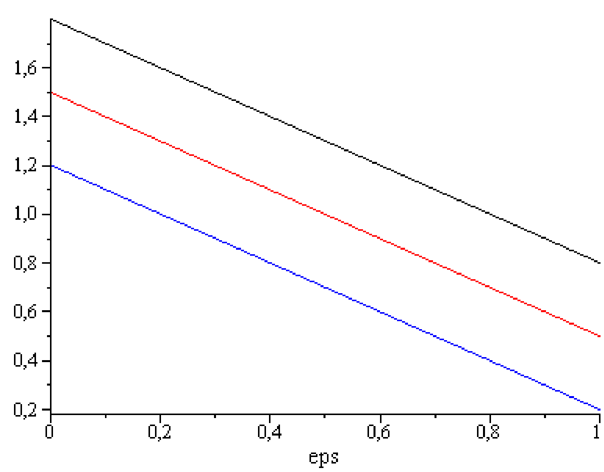



```
> restart;
> tau:=1.2;P1:=eps*(1*tau/eps-1);P2:=eps*(1.25*tau/eps-1);P3:=eps*(1.5*tau/eps-1);
```

$\tau := 1.2$

$P1 := eps\left(\frac{1.2 \cdot 1}{eps} - 1\right);\ P2 := eps\left(\frac{1.500 \cdot 1}{eps} - 1\right);\ P3 := eps\left(\frac{1.80 \cdot 1}{eps} - 1\right)$

```
> plot([P1(eps),P2(eps),P3(eps)], eps=0..1, color=[blue,red,black], style=[line,line,line]);
```



JOULE – BRAYTON AGENTI DE LUCRU

```
> restart;
> cpaer:=1.01027-1.73736E-4*T+6.08005E-7*T^(2)-3.80644E-10*T^(3)+7.49874E-14*T^(4);
cvaer:=0.72301-1.73889E-4*T+6.09496E-7*T^(2)-3.81877E-10*T^(3)+7.52717E-14*T^(4);
cpO2:=0.82397+3.05587E-4*T+5.32089E-8*T^2-1.30137E-10*T^3+3.58225E-14*T^4;
cvO2:=0.56574+2.96923E-4*T+6.54515E-8*T^2-1.36918E-10*T^3+3.71407E-14*T^4;
cpH2O:=1.84336-2.31223E-4*T+1.1966E-6*T^2-6.15263E-10*T^3+1.0015E-13*T^4;
cvH2O:=1.38161-2.29361E-4*T+1.19327E-6*T^2-6.13657E-10*T^3+9.99765E-14*T^4;
cpN2:=1.07623-3.25964E-4*T+7.92186E-7*T^2-4.66137E-10*T^3+8.87148E-14*T^4;
cvN2:=0.77884-3.22759E-4*T+7.86981E-7*T^2-4.62795E-10*T^3+8.79811E-14*T^4;
cpCO2:=0.46236+0.0016*T-1.2402E-6*T^2+4.78609E-10*T^3-7.32796E-14*T^4;
cvCO2:=0.27337+0.0016*T-1.24189E-6*T^2+4.79536E-10*T^3-7.34111E-14*T^4;
cpHe:=5.19; cvHe:=3.12;
cpH2:=13.63327+0.00349*T-5.57821E-6*T^2+4.56786E-9*T^3-1.12853E-12*T^4;
cvH2:=9.44039+0.00386*T-6.19336E-6*T^2+4.94382E-9*T^3-1.2046E-12*T^4;
Raer:=(.2868355533+0.28726)/2;
RO2:=(.2599467914+0.25823)/2;
RN2:=(.2967773441+0.29739)/2;
RCO2:=(.190161689+0.18899)/2;
RHe:=2.07;
RH2:=(4.14292647+4.19288)/2;
```

$$cpaer := 1.01027 - 0.000173736T + 6.08005\,10^{-7}\,T^2 - 3.80644\,10^{-10}\,T^3 + 7.49874\,10^{-14}\,T^4$$

$$cvaer := 0.72301 - 0.000173889T + 6.09496\,10^{-7}\,T^2 - 3.81877\,10^{-10}\,T^3 + 7.52717\,10^{-14}\,T^4$$

$$cpO2 := 0.82397 + 0.000305587T + 5.32089\,10^{-8}\,T^2 - 1.30137\,10^{-10}\,T^3 + 3.58225\,10^{-14}\,T^4$$

$$cvO2 := 0.56574 + 0.000296923\,T + 6.54515\,10^{-8}\,T^2 - 1.36918\,10^{-10}\,T^3 + 3.71407\,10^{-14}\,T^4$$

$$cpH2O := 1.84336 - 0.000231223\,T + 0.0000011966\,T^2 - 6.15263\,10^{-10}\,T^3 + 1.0015\,10^{-13}\,T^4$$

$$cvH2O := 1.38161 - 0.000229361\,T + 0.00000119327\,T^2 - 6.13657\,10^{-10}\,T^3 + 9.99765\,10^{-14}\,T^4$$

$$cpN2 := 1.07623 - 0.000325964\,T + 7.92186\,10^{-7}\,T^2 - 4.66137\,10^{-10}\,T^3 + 8.87148\,10^{-14}\,T^4$$

$$cvN2 := 0.77884 - 0.000322759\,T + 7.86981\,10^{-7}\,T^2 - 4.62795\,10^{-10}\,T^3 + 8.79811\,10^{-14}\,T^4$$

$$cpCO2 := 0.46236 + 0.0016\,T - 0.0000012402\,T^2 + 4.78609\,10^{-10}\,T^3 - 7.32796\,10^{-14}\,T^4$$

$$cvCO2 := 0.27337 + 0.0016\,T - 0.00000124189\,T^2 + 4.79536\,10^{-10}\,T^3 - 7.34111\,10^{-14}\,T^4$$

$$cpHe := 5.19$$

$$cvHe := 3.12$$

$$cpH2 := 13.63327 + 0.00349\,T - 0.00000557821\,T^2 + 4.56786\,10^{-9}\,T^3 - 1.12853\,10^{-12}\,T^4$$

$$cvH2 := 9.44039 + 0.00386\,T - 0.00000619336\,T^2 + 4.94382\,10^{-9}\,T^3 - 1.2046\,10^{-12}\,T^4$$

$$Raer := 0.28704777$$

$$RO2 := 0.25908839$$

$$RN2 := 0.29708367$$

$$RCO2 := 0.18957584$$

$$RHe := 2.07$$

$$RH2 := 4.1679032$$

```
> T0:=273;etaC:=0.88;etaT:=0.94;etam:=0.99;dpsursa_calda:=0.98;dpsursa_rece:=0.98;
T0 := 273
etaC := 0.88
etaT := 0.94
etam := 0.99
dpsursa_calda := 0.98
dpsursa_rece := 0.98
> DOMENIUpic;piC:=25;DomeniuT3;T3:=1273.15;
DOMENIUpic
piC := 25
DomeniuT3
T3 := 1273.15
> p1:=1;T1:=293.13;p2:=p1*piC;
p1 := 1
T1 := 293.13
p2 := 25
> COMPRIMARE;
dh12aer:=int(cpaer,T=T1..T2);
dh12O2:=int(cpO2,T=T1..T2);
dh12N2:=int(cpN2,T=T1..T2);
dh12CO2:=int(cpCO2,T=T1..T2);
dh12He:=int(cpHe,T=T1..T2);
dh12H2:=int(cpH2,T=T1..T2);
du12aer:=int(cvaer,T=T1..T2);
du12O2:=int(cvO2,T=T1..T2);
du12N2:=int(cvN2,T=T1..T2);
du12CO2:=int(cvCO2,T=T1..T2);
du12He:=int(cvHe,T=T1..T2);
du12H2:=int(cvH2,T=T1..T2);
k12aer:=dh12aer/du12aer;
k12O2:=dh12O2/du12O2;
```

k12N2:=dh12N2/du12N2;

k12CO2:=dh12CO2/du12CO2;

k12He:=dh12He/du12He;

k12H2:=dh12H2/du12H2;

COMPRIMARE

$$dh12aer := 1.010270000\,T2 - 293.1108246 - 0.00008686800000\,T2^2 + 2.026683333\,10^{-7}\,T2^3 - 9.516100000\,10^{-11}\,T2^4 + 1.499748000\,10^{-14}\,T2^5$$

$$dh12O2 := 0.8239700000\,T2 - 254.8811671 + 0.0001527935000\,T2^2 + 1.773630000\,10^{-8}\,T2^3 - 3.253425000\,10^{-11}\,T2^4 + 7.164500000\,10^{-15}\,T2^5$$

$$dh12N2 := 1.076230000\,T2 - 307.3000470 - 0.0001629820000\,T2^2 + 2.640620000\,10^{-7}\,T2^3 - 1.165342500\,10^{-10}\,T2^4 + 1.774296000\,10^{-14}\,T2^5$$

$$dh12CO2 := 0.4623600000\,T2 - 194.7110245 + 0.0008000000000\,T2^2 - 4.134000000\,10^{-7}\,T2^3 + 1.196522500\,10^{-10}\,T2^4 - 1.465592000\,10^{-14}\,T2^5$$

$$dh12He := 5.190000000\,T2 - 1521.34470$$

$$dh12H2 := 13.63327000\,T2 - 4107.369452 + 0.001745000000\,T2^2 - 0.000001859403333\,T2^3 + 1.141965000\,10^{-9}\,T2^4 - 2.257060000\,10^{-13}\,T2^5$$

$$du12aer := 0.7230100000\,T2 - 208.9100927 - 0.00008694450000\,T2^2 + 2.031653333\,10^{-7}\,T2^3 - 9.546925000\,10^{-11}\,T2^4 + 1.505434000\,10^{-14}\,T2^5$$

$$du12O2 := 0.5657400000\,T2 - 178.9048192 + 0.0001484615000\,T2^2 + 2.181716667\,10^{-8}\,T2^3 - 3.422950000\,10^{-11}\,T2^4 + 7.428140000\,10^{-15}\,T2^5$$

$$du12N2 := 0.7788400000\,T2 - 220.2259625 - 0.0001613795000\,T2^2 + 2.623270000\,10^{-7}\,T2^3 - 1.156987500\,10^{-10}\,T2^4 + 1.759622000\,10^{-14}\,T2^5$$

$$du12CO2 := 0.2733700000\,T2 - 139.2998512 + 0.0008000000000\,T2^2 - 4.139633333\,10^{-7}\,T2^3 + 1.198840000\,10^{-10}\,T2^4 - 1.468222000\,10^{-14}\,T2^5$$

$$du12He := 3.120000000\,T2 - 914.565600$$

$$du12H2 := 9.440390000\,T2 - 2889.703067 + 0.001930000000\,T2^2 - 0.000002064453333\,T2^3 + 1.235955000\,10^{-9}\,T2^4 - 2.409200000\,10^{-13}\,T2^5$$

$$k12aer := \left(1.010270000\,T2 - 293.1108246 - 0.00008686800000\,T2^2 + 2.026683333\,10^{-7}\,T2^3 - 9.516100000\,10^{-11}\,T2^4 + 1.499748000\,10^{-14}\,T2^5\right) \Big/ \left(0.7230100000\,T2 - 208.9100927 - 0.00008694450000\,T2^2 + 2.031653333\,10^{-7}\,T2^3 - 9.546925000\,10^{-11}\,T2^4 + 1.505434000\,10^{-14}\,T2^5\right)$$

$$k12O2 := \left(0.8239700000\,T2 - 254.8811671 + 0.0001527935000\,T2^2 + 1.773630000\,10^{-8}\,T2^3 - 3.253425000\,10^{-11}\,T2^4 + 7.164500000\,10^{-15}\,T2^5\right) \Big/ \left(0.5657400000\,T2 - 178.9048192 + 0.0001484615000\,T2^2 + 2.181716667\,10^{-8}\,T2^3 - 3.422950000\,10^{-11}\,T2^4 + 7.428140000\,10^{-15}\,T2^5\right)$$

$$k12N2 := \left(1.076230000\,T2 - 307.3000470 - 0.0001629820000\,T2^2 + 2.640620000\,10^{-7}\,T2^3 - 1.165342500\,10^{-10}\,T2^4 + 1.774296000\,10^{-14}\,T2^5\right) \Big/ \left(0.7788400000\,T2 - 220.2259625 - 0.0001613795000\,T2^2 + 2.623270000\,10^{-7}\,T2^3 - 1.156987500\,10^{-10}\,T2^4 + 1.759622000\,10^{-14}\,T2^5\right)$$

$$k12CO2 := (0.4623600000 T2 - 194.7110245 + 0.0008000000000 T2^2 - 4.134000000 10^{-7} T2^3 + 1.196522500 10^{-10} T2^4 - 1.465592000 10^{-14} T2^5) / (0.2733700000 T2 - 139.2998512 + 0.0008000000000 T2^2 - 4.139633333 10^{-7} T2^3 + 1.198840000 10^{-10} T2^4 - 1.468222000 10^{-14} T2^5)$$

$$k12He := \frac{5.190000000 T2 - 1521.344700}{3.120000000 T2 - 914.5656000}$$

$$k12H2 := (13.63327000 T2 - 4107.369452 + 0.001745000000 T2^2 - 0.000001859403333 T2^3 + 1.141965000 10^{-9} T2^4 - 2.257060000 10^{-13} T2^5) / (9.440390000 T2 - 2889.703067 + 0.001930000000 T2^2 - 0.000002064453333 T2^3 + 1.235955000 10^{-9} T2^4 - 2.409200000 10^{-13} T2^5)$$

```
> eq12taer:=T2-T1*piC^((k12aer-1)/k12aer);
eq12tO2:=T2-T1*piC^((k12O2-1)/k12O2);
eq12tN2:=T2-T1*piC^((k12N2-1)/k12N2);
eq12tCO2:=T2-T1*piC^((k12CO2-1)/k12CO2);
eq12tHe:=T2-T1*piC^((k12He-1)/k12He);
eq12tH2:=T2-T1*piC^((k12H2-1)/k12H2);T2taer:=fsolve(eq12taer,T2);
T2tO2:=fsolve(eq12tO2,T2);
T2tN2:=fsolve(eq12tN2,T2);
T2tCO2:=fsolve(eq12tCO2,T2);
T2tHe:=fsolve(eq12tHe,T2);
T2tH2:=fsolve(eq12tH2,T2);
```

$$eq12tN2 := T2$$

$$- 293.13$$

$$(((1.076230000\,T2 - 307.3000470 - 0.0001629820000\,T2^2$$

$$25$$

$$+ 2.640620000\,10^{-7}\,T2^3 - 1.165342500\,10^{-10}\,T2^4 + 1.774296000\,10^{-14}\,T2^5) \Big/$$

$$(0.7788400000\,T2 - 220.2259625 - 0.0001613795000\,T2^2$$

$$+ 2.623270000\,10^{-7}\,T2^3 - 1.156987500\,10^{-10}\,T2^4 + 1.759622000\,10^{-14}\,T2^5)$$

$$- 1)\,(0.7788400000\,T2 - 220.2259625 - 0.0001613795000\,T2^2$$

$$+ 2.623270000\,10^{-7}\,T2^3 - 1.156987500\,10^{-10}\,T2^4 + 1.759622000\,10^{-14}\,T2^5))$$

$$\Big/ (1.076230000\,T2 - 307.3000470 - 0.0001629820000\,T2^2$$

$$+ 2.640620000\,10^{-7}\,T2^3 - 1.165342500\,10^{-10}\,T2^4 + 1.774296000\,10^{-14}\,T2^5)$$

$$eq12tCO2 := T2$$

$$- 293.13$$

$$(((0.4623600000\,T2 - 194.7110245 + 0.0008000000000\,T2^2$$

$$25$$

$$- 4.134000000\,10^{-7}\,T2^3 + 1.196522500\,10^{-10}\,T2^4 - 1.465592000\,10^{-14}\,T2^5) \Big/$$

$$(0.2733700000\,T2 - 139.2998512 + 0.0008000000000\,T2^2$$

$$- 4.139633333\,10^{-7}\,T2^3 + 1.198840000\,10^{-10}\,T2^4 - 1.468222000\,10^{-14}\,T2^5)$$

$$- 1)\,(0.2733700000\,T2 - 139.2998512 + 0.0008000000000\,T2^2$$

$$- 4.139633333\,10^{-7}\,T2^3 + 1.198840000\,10^{-10}\,T2^4 - 1.468222000\,10^{-14}\,T2^5))$$

$$\Big/ (0.4623600000\,T2 - 194.7110245 + 0.0008000000000\,T2^2$$

$$- 4.134000000\,10^{-7}\,T2^3 + 1.196522500\,10^{-10}\,T2^4 - 1.465592000\,10^{-14}\,T2^5)$$

$$eq12tHe := T2 - 293.13\, 25^{\frac{\left(\frac{5.190000000\, T2 - 1521.344700}{3.120000000\, T2 - 914.5656000} - 1\right)(3.120000000\, T2 - 914.5656000)}{5.190000000\, T2 - 1521.344700}}$$

$$eq12tH2 := T2 - 293.13\, 25^{\left(\left(\left(13.63327000\, T2 - 4107.369452 + 0.001745000000\, T2^2 - 0.000001859403333\, T2^3 + 1.141965000\, 10^{-9}\, T2^4 - 2.257060000\, 10^{-13}\, T2^5\right) \middle/ \left(9.440390000\, T2 - 2889.703067 + 0.001930000000\, T2^2 - 0.000002064453333\, T2^3 + 1.235955000\, 10^{-9}\, T2^4 - 2.409200000\, 10^{-13}\, T2^5\right) - 1\right)\left(9.440390000\, T2 - 2889.703067 + 0.001930000000\, T2^2 - 0.000002064453333\, T2^3 + 1.235955000\, 10^{-9}\, T2^4 - 2.409200000\, 10^{-13}\, T2^5\right)\right) \middle/ \left(13.63327000\, T2 - 4107.369452 + 0.001745000000\, T2^2 - 0.000001859403333\, T2^3 + 1.141965000\, 10^{-9}\, T2^4 - 2.257060000\, 10^{-13}\, T2^5\right)}$$

$T2taer := 715.540678$

$T2tO2 := 693.282320$

$T2tN2 := 719.926594$

$T2tCO2 := 557.074029$

$T2tHe := 1058.32768$

$T2tH2 := 732.468008$

```
> dh12taer:=int(cpaer,T=T1..T2taer);
dh12tO2:=int(cpO2,T=T1..T2tO2);
dh12tN2:=int(cpN2,T=T1..T2tN2);
dh12tCO2:=int(cpCO2,T=T1..T2tCO2);
dh12tHe:=int(cpHe,T=T1..T2tHe);
dh12tH2:=int(cpH2,T=T1..T2tH2);
```

```
dh12raer:=dh12taer/etaC;
dh12rO2:=dh12tO2/etaC;
dh12rN2:=dh12tN2/etaC;
dh12rCO2:=dh12tCO2/etaC;
dh12rHe:=dh12tHe/etaC;
dh12rH2:=dh12tH2/etaC;
```

$dh12taer := 437.418274$

$dh12tO2 := 389.343024$

$dh12tN2 := 453.691271$

$dh12tCO2 := 250.392205$

$dh12tHe := 3971.37597$

$dh12tH2 := 6365.19180$

$dh12raer := 497.066220$

$dh12rO2 := 442.435254$

$dh12rN2 := 515.558262$

$dh12rCO2 := 284.536596$

$dh12rHe := 4512.92723$

$dh12rH2 := 7233.17250$

```
> eq12raer:=dh12raer-int(cpaer,T=T1..T2riaer);
eq12rO2:=dh12rO2-int(cpO2,T=T1..T2riO2);
eq12rN2:=dh12rN2-int(cpN2,T=T1..T2riN2);
eq12rCO2:=dh12rCO2-int(cpCO2,T=T1..T2riCO2);
eq12rHe:=dh12rHe-int(cpHe,T=T1..T2riHe);
eq12rH2:=dh12rH2-int(cpH2,T=T1..T2riH2);
T2raer:=fsolve(eq12raer,T2riaer);
T2rO2:=fsolve(eq12rO2,T2riO2);
T2rN2:=fsolve(eq12rN2,T2riN2);
T2rCO2:=fsolve(eq12rCO2,T2riCO2);
T2rHe:=fsolve(eq12rHe,T2riHe);
T2rH2:=fsolve(eq12rH2,T2riH2);
```

$eq12raer := 790.1770455 - 1.010270000 T2riaer + 0.0000868680000 T2riaer^2 - 2.026683333 10^{-7} T2riaer^3 + 9.516100000 10^{-11} T2riaer^4 - 1.499748000 10^{-14} T2riaer^5$

$eq12rO2 := 697.3164218 - 0.8239700000 T2riO2 - 0.0001527935000 T2riO2^2 - 1.773630000 10^{-8} T2riO2^3 + 3.253425000 10^{-11} T2riO2^4 - 7.164500000 10^{-15} T2riO2^5$

$eq12rN2 := 822.8583097 - 1.076230000 T2riN2 + 0.0001629820000 T2riN2^2 - 2.640620000 10^{-7} T2riN2^3 + 1.165342500 10^{-10} T2riN2^4 - 1.774296000 10^{-14} T2riN2^5$

$eq12rCO2 := 479.2476212 - 0.4623600000 T2riCO2 - 0.0008000000000 T2riCO2^2 + 4.134000000 10^{-7} T2riCO2^3 - 1.196522500 10^{-10} T2riCO2^4 + 1.465592000 10^{-14} T2riCO2^5$

$eq12rHe := 6034.271939 - 5.190000000 T2riHe$

$eq12rH2 := 11340.54196 - 13.63327000 T2riH2 - 0.001745000000 T2riH2^2 + 0.000001859403333 T2riH2^3 - 1.141965000 10^{-9} T2riH2^4 + 2.257060000 10^{-13} T2riH2^5$

$T2raer := 770.588174$

$T2rO2 := 744.709858$

$T2rN2 := 775.747907$

$T2rCO2 := -836.3372280, 589.4623521, 4891.31270$

$T2rHe := 1162.67282$

$T2rH2 := -1860.068448, 791.5362518, 4191.59390$

>

SURSA_CALDA;T2aer:=770.5881744;T2O2:=744.7098586;T2N2:=775.7479070;T2CO2:=589.4623521;T2He:=1162.672821;T2H2:=791.5362518;dh23aer:=int(cpaer,T=T2aer..T3);dh23O2:=int(cpO2,T=T2O2..T3);dh23N2:=int(cpN2,T=T2N2..T3);dh23CO2:=int(cpCO2,T=T2CO2..T3);dh23He:=int(cpHe,T=T2He..T3);dh23H2:=int(cpH2,T=T2H2..T3);p3:=p2*dpsursa_calda;

SURSA_CALDA

$T2aer := 770.588174$

$T2O2 := 744.709858$

$T2N2 := 775.747907$

$T2CO2 := 589.462352$

$T2He := 1162.67282$

$T2H2 := 791.536251$

$dh23aer := 573.627311$

$dh23O2 := 574.473793$

$dh23N2 := 581.273441$

$dh23CO2 := 818.360928$

$dh23He := 573.376559$

$dh23H2 := 7253.31858$

$p3 := 24.50$

```
> DESTINDERE;p4:=p1/dpsursa_rece;dh34aer:=int(cpaer,T=T3..T4);dh34O2:=int(cpO2,T=T3..T4);dh34N2:=int(cpN2,T=T3..T4);dh34CO2:=int(cpCO2,T=T3..T4);dh34He:=int(cpHe,T=T3..T4);dh34H2:=int(cpH2,T=T3..T4);du34aer:=int(cvaer,T=T3..T4);du34O2:=int(cvO2,T=T3..T4);du34N2:=int(cvN2,T=T3..T4);du34CO2:=int(cvCO2,T=T3..T4);du34He:=int(cvHe,T=T3..T4);du34H2:=int(cvH2,T=T3..T4);k34aer:=dh34aer/du34aer;k34O2:=dh34O2/du34O2;k34N2:=dh34N2/du34N2;k34CO2:=dh34CO2/du34CO2;k34He:=dh34He/du34He;k34H2:=dh34H2/du34H2;
```

DESTINDERE

$p4 := 1.02040816$

$$dh34aer := 1.010270000 T4 - 1363.804357 - 0.00008686800000 T4^2 + 2.026683333 10^{-7}\, T4^3 - 9.516100000 10^{-11}\, T4^4 + 1.499748000 10^{-14}\, T4^5$$

$$dh34O2 := 0.8239700000 T4 - 1271.790215 + 0.0001527935000 T4^2 + 1.773630000 10^{-8}\, T4^3 - 3.253425000 10^{-11}\, T4^4 + 7.164500000 10^{-15}\, T4^5$$

$$dh34N2 := 1.076230000 T4 - 1404.131751 - 0.0001629820000 T4^2 + 2.640620000 10^{-7}\, T4^3 - 1.165342500 10^{-10}\, T4^4 + 1.774296000 10^{-14}\, T4^5$$

$$dh34CO2 := 0.4623600000 T4 - 1297.608550 + 0.0008000000000 T4^2 - 4.134000000\,10^{-7}\,T4^3 + 1.196522500\,10^{-10}\,T4^4 - 1.465592000\,10^{-14}\,T4^5$$

$$dh34He := 5.190000000 T4 - 6607.64850$$

$$dh34H2 := 13.63327000 T4 - 18593.86055 + 0.001745000000 T4^2 - 0.000001859403333 T4^3 + 1.141965000\,10^{-9}\,T4^4 - 2.257060000\,10^{-13}\,T4^5$$

$$du34aer := 0.7230100000 T4 - 998.3612444 - 0.00008694450000 T4^2 + 2.031653333\,10^{-7}\,T4^3 - 9.546925000\,10^{-11}\,T4^4 + 1.505434000\,10^{-14}\,T4^5$$

$$du34O2 := 0.5657400000 T4 - 940.8522976 + 0.0001484615000 T4^2 + 2.181716667\,10^{-8}\,T4^3 - 3.422950000\,10^{-11}\,T4^4 + 7.428140000\,10^{-15}\,T4^5$$

$$du34N2 := 0.7788400000 T4 - 1026.231034 - 0.0001613795000 T4^2 + 2.623270000\,10^{-7}\,T4^3 - 1.156987500\,10^{-10}\,T4^4 + 1.759622000\,10^{-14}\,T4^5$$

$$du34CO2 := 0.2733700000 T4 - 1056.354316 + 0.0008000000000 T4^2 - 4.139633333\,10^{-7}\,T4^3 + 1.198840000\,10^{-10}\,T4^4 - 1.468222000\,10^{-14}\,T4^5$$

$$du34He := 3.120000000 T4 - 3972.22800$$

$$du34H2 := 9.440390000 T4 - 13328.46365 + 0.001930000000 T4^2 - 0.000002064453333 T4^3 + 1.235955000\,10^{-9}\,T4^4 - 2.409200000\,10^{-13}\,T4^5$$

$$k34aer := \big(1.010270000 T4 - 1363.804357 - 0.0000868680000 T4^2 + 2.026683333\,10^{-7}\,T4^3 - 9.516100000\,10^{-11}\,T4^4 + 1.499748000\,10^{-14}\,T4^5\big) \big/ \big(0.7230100000 T4 - 998.3612444 - 0.0000869445000 T4^2 + 2.031653333\,10^{-7}\,T4^3 - 9.546925000\,10^{-11}\,T4^4 + 1.505434000\,10^{-14}\,T4^5\big)$$

$$k34O2 := \big(0.8239700000 T4 - 1271.790215 + 0.0001527935000 T4^2 + 1.773630000\,10^{-8}\,T4^3 - 3.253425000\,10^{-11}\,T4^4 + 7.164500000\,10^{-15}\,T4^5\big) \big/ \big(0.5657400000 T4 - 940.8522976 + 0.0001484615000 T4^2 + 2.181716667\,10^{-8}\,T4^3 - 3.422950000\,10^{-11}\,T4^4 + 7.428140000\,10^{-15}\,T4^5\big)$$

$$k34N2 := \big(1.076230000 T4 - 1404.131751 - 0.0001629820000 T4^2 + 2.640620000\,10^{-7}\,T4^3 - 1.165342500\,10^{-10}\,T4^4 + 1.774296000\,10^{-14}\,T4^5\big) \big/ \big(0.7788400000 T4 - 1026.231034 - 0.0001613795000 T4^2 + 2.623270000\,10^{-7}\,T4^3 - 1.156987500\,10^{-10}\,T4^4 + 1.759622000\,10^{-14}\,T4^5\big)$$

$$k34CO2 := \big(0.4623600000 T4 - 1297.608550 + 0.0008000000000 T4^2 - 4.134000000\,10^{-7}\,T4^3 + 1.196522500\,10^{-10}\,T4^4 - 1.465592000\,10^{-14}\,T4^5\big) \big/ \big(0.2733700000 T4 - 1056.354316 + 0.0008000000000 T4^2 - 4.139633333\,10^{-7}\,T4^3 + 1.198840000\,10^{-10}\,T4^4 - 1.468222000\,10^{-14}\,T4^5\big)$$

$$k34He := \frac{5.190000000 T4 - 6607.648500}{3.120000000 T4 - 3972.228000}$$

$$k34H2 := \big(13.63327000 T4 - 18593.86055 + 0.001745000000 T4^2 - 0.000001859403333 T4^3 + 1.141965000\,10^{-9}\,T4^4 - 2.257060000\,10^{-13}\,T4^5\big) \big/ \big(9.440390000 T4 - 13328.46365 + 0.001930000000 T4^2 - 0.000002064453333 T4^3 + 1.235955000\,10^{-9}\,T4^4 - 2.409200000\,10^{-13}\,T4^5\big)$$

```
> piT:=p4/p3;eq34taer:=T4-T3*piT^((k34aer-1)/k34aer);eq34tO2:=T4-T3*piT^((k34O2-1)/k34O2);eq34tN2:=T4-T3*piT^((k34N2-1)/k34N2);eq34tCO2:=T4-T3*piT^((k34CO2-1)/k34CO2);eq34tHe:=T4-T3*piT^((k34He-1)/k34He);eq34tH2:=T4-T3*piT^((k34H2-
```

1)/k34H2);T4taer:=fsolve(eq34taer,T4);T4tO2:=fsolve(eq34tO2,T4);T4tN2:=fsolve(eq34tN2,T4);T4tCO2:=fsolve(eq34tCO2,T4);T4tHe:=fsolve(eq34tHe,T4);T4tH2:=fsolve(eq34tH2,T4);

$piT := 0.0416493127$

$$eq34taer := T4 - 1273.15\, 0.04164931278^{\left(\left(\left(1.010270000\, T4 - 1363.804357 - 0.00008686800000\, T4^2 + 2.026683333\, 10^{-7}\, T4^3 - 9.516100000\, 10^{-11}\, T4^4 + 1.499748000\, 10^{-14}\, T4^5\right) / \left(0.7230100000\, T4 - 998.3612444 - 0.00008694450000\, T4^2 + 2.031653333\, 10^{-7}\, T4^3 - 9.546925000\, 10^{-11}\, T4^4 + 1.505434000\, 10^{-14}\, T4^5\right) - 1\right) \left(0.7230100000\, T4 - 998.3612444 - 0.00008694450000\, T4^2 + 2.031653333\, 10^{-7}\, T4^3 - 9.546925000\, 10^{-11}\, T4^4 + 1.505434000\, 10^{-14}\, T4^5\right)\right) \Big/ \left(1.010270000\, T4 - 1363.804357 - 0.00008686800000\, T4^2 + 2.026683333\, 10^{-7}\, T4^3 - 9.516100000\, 10^{-11}\, T4^4 + 1.499748000\, 10^{-14}\, T4^5\right)}$$

$$
\mathit{eq34tO2} := T4 - 1273.15 \cdot 0.04164931278^{\left(\left(\left(0.8239700000\, T4 - 1271.790215 + 0.0001527935000\, T4^{2} + 1.773630000\, 10^{-8}\, T4^{3} - 3.253425000\, 10^{-11}\, T4^{4} + 7.164500000\, 10^{-15}\, T4^{5}\right) \middle/ \left(0.5657400000\, T4 - 940.8522976 + 0.0001484615000\, T4^{2} + 2.181716667\, 10^{-8}\, T4^{3} - 3.422950000\, 10^{-11}\, T4^{4} + 7.428140000\, 10^{-15}\, T4^{5}\right) - 1\right) \left(0.5657400000\, T4 - 940.8522976 + 0.0001484615000\, T4^{2} + 2.181716667\, 10^{-8}\, T4^{3} - 3.422950000\, 10^{-11}\, T4^{4} + 7.428140000\, 10^{-15}\, T4^{5}\right)\right) \middle/ \left(0.8239700000\, T4 - 1271.790215 + 0.0001527935000\, T4^{2} + 1.773630000\, 10^{-8}\, T4^{3} - 3.253425000\, 10^{-11}\, T4^{4} + 7.164500000\, 10^{-15}\, T4^{5}\right)}
$$

$$
\begin{aligned}
\mathit{eq34tN2} := {} & T4 \\
& - 1273.15 \\
& 0.04164931278^{\left(\left(\left(1.076230000\, T4 - 1404.131751 - 0.0001629820000\, T4^{2} + 2.640620000\ 10^{-7}\, T4^{3} - 1.165342500\ 10^{-10}\, T4^{4} + 1.774296000\ 10^{-14}\, T4^{5}\right) \middle/ \left(0.7788400000\, T4 - 1026.231034 - 0.0001613795000\, T4^{2} + 2.623270000\ 10^{-7}\, T4^{3} - 1.156987500\ 10^{-10}\, T4^{4} + 1.759622000\ 10^{-14}\, T4^{5}\right) - 1\right) \left(0.7788400000\, T4 - 1026.231034 - 0.0001613795000\, T4^{2} + 2.623270000\ 10^{-7}\, T4^{3} - 1.156987500\ 10^{-10}\, T4^{4} + 1.759622000\ 10^{-14}\, T4^{5}\right)\right) \middle/ \left(1.076230000\, T4 - 1404.131751 - 0.0001629820000\, T4^{2} + 2.640620000\ 10^{-7}\, T4^{3} - 1.165342500\ 10^{-10}\, T4^{4} + 1.774296000\ 10^{-14}\, T4^{5}\right)}
\end{aligned}
$$

$$
eq34tCO2 := T4 - 1273.15\, 0.04164931278^{\left(\left(\left(0.4623600000\, T4 - 1297.608550 + 0.0008000000000\, T4^{2} - 4.134000000\, 10^{-7}\, T4^{3} + 1.196522500\, 10^{-10}\, T4^{4} - 1.465592000\, 10^{-14}\, T4^{5}\right) / \left(0.2733700000\, T4 - 1056.354316 + 0.0008000000000\, T4^{2} - 4.139633333\, 10^{-7}\, T4^{3} + 1.198840000\, 10^{-10}\, T4^{4} - 1.468222000\, 10^{-14}\, T4^{5}\right) - 1\right) \left(0.2733700000\, T4 - 1056.354316 + 0.0008000000000\, T4^{2} - 4.139633333\, 10^{-7}\, T4^{3} + 1.198840000\, 10^{-10}\, T4^{4} - 1.468222000\, 10^{-14}\, T4^{5}\right)\right) \Big/ \left(0.4623600000\, T4 - 1297.608550 + 0.0008000000000\, T4^{2} - 4.134000000\, 10^{-7}\, T4^{3} + 1.196522500\, 10^{-10}\, T4^{4} - 1.465592000\, 10^{-14}\, T4^{5}\right)}
$$

$$
eq34tHe := T4 - 1273.15\, 0.04164931278^{\frac{1}{5.190000000\, T4 - 6607.648500} \left(\left(1 / \left(3.120000000\, T4 - 3972.228000\right) \left(5.190000000\, T4 - 6607.648500\right) - 1\right) \left(3.120000000\, T4 - 3972.228000\right)\right)}
$$

$$eq34tH2 := T4 - 1273.15\,\Big(0.04164931278 \Big(\Big(\big(13.63327000\,T4 - 18593.86055 + 0.001745000000\,T4^2 - 0.000001859403333\,T4^3 + 1.141965000\;10^{-9}\,T4^4 - 2.257060000\;10^{-13}\,T4^5\big) \big/ \big(9.440390000\,T4 - 13328.46365 + 0.001930000000\,T4^2 - 0.000002064453333\,T4^3 + 1.235955000\;10^{-9}\,T4^4 - 2.409200000\;10^{-13}\,T4^5\big) - 1\Big) \big(9.440390000\,T4 - 13328.46365 + 0.001930000000\,T4^2 - 0.000002064453333\,T4^3 + 1.235955000\;10^{-9}\,T4^4 - 2.409200000\;10^{-13}\,T4^5\big)\Big)\Big) \Big/ \big(13.63327000\,T4 - 18593.86055 + 0.001745000000\,T4^2 - 0.000001859403333\,T4^3 + 1.141965000\;10^{-9}\,T4^4 - 2.257060000\;10^{-13}\,T4^5\big)$$

$T4taer := 563.8582880$

$T4tO2 := 588.5638418$

$T4tN2 := 558.6141847$

$T4tCO2 := 779.2203937$

$T4tHe := 358.3591844$

$T4tH2 := 527.2298360$

```
> dh34taer:=int(cpaer,T=T3..T4taer);dh34tO2:=int(cpO2,T=T3..T4tO2);dh34tN2:=int(cpN2,T=T3..T4tN2);dh34tCO2:=int(cpCO2,T=T3..T4tCO2);dh34tHe:=int(cpHe,T=T3..T4tHe);dh34tH2:=int(cpH2,T=T3..T4tH2);dh34raer:=dh34taer*etaT;dh34rO2:=dh34tO2*etaT;dh34rN2:=dh34tN2*etaT;dh34rCO2:=dh34tCO2*etaT;dh34rHe:=dh34tHe*etaT;dh34rH2:=dh34tH2*etaT;
```

$dh34taer := -794.205571$

$dh34tO2 := -733.684384$

$dh34tN2 := -818.145225$

$dh34tCO2 := -607.270583$

$dh34tHe := -4747.76433$

$dh34tH2 := -11114.3957$

$dh34raer := -746.553236$

$dh34rO2 := -689.663321$

$dh34rN2 := -769.056511$

$dh34rCO2 := -570.834348$

$dh34rHe := -4462.89847$

$dh34rH2 := -10447.5320$

```
> eq34raer:=dh34raer-int(cpaer,T=T3..T4riaer);eq34rO2:=dh34rO2-int(cpO2,T=T3..T4riO2);eq34rN2:=dh34rN2-int(cpN2,T=T3..T4riN2);eq34rCO2:=dh34rCO2-int(cpCO2,T=T3..T4riCO2);eq34rHe:=dh34rHe-int(cpHe,T=T3..T4riHe);eq34rH2:=dh34rH2-int(cpH2,T=T3..T4riH2);T4raer:=fsolve(eq34raer,T4riaer);T4rO2:=fsolve(eq34rO2,T4riO2);T4rN2:=fsolve(eq34rN2,T4riN2);T4rCO2:=fsolve(eq34rCO2,T4riCO2);T4rHe:=fsolve(eq34rHe,T4riHe);T4rH2:=fsolve(eq34rH2,T4riH2);
```

$$eq34raer := 617.2511202 - 1.010270000\,T4riaer + 0.00008686800000\,T4riaer^2 - 2.026683333\,10^{-7}\,T4riaer^3 + 9.516100000\,10^{-11}\,T4riaer^4 - 1.499748000\,10^{-14}\,T4riaer^5$$

$$eq34rO2 := 582.1268939 - 0.8239700000\,T4riO2 - 0.0001527935000\,T4riO2^2 - 1.773630000\,10^{-8}\,T4riO2^3 + 3.253425000\,10^{-11}\,T4riO2^4 - 7.164500000\,10^{-15}\,T4riO2^5$$

$$eq34rN2 := 635.0752395 - 1.076230000\,T4riN2 + 0.0001629820000\,T4riN2^2 - 2.640620000\,10^{-7}\,T4riN2^3 + 1.165342500\,10^{-10}\,T4riN2^4 - 1.774296000\,10^{-14}\,T4riN2^5$$

$$eq34rCO2 := 726.7742013 - 0.4623600000\,T4riCO2 - 0.0008000000000\,T4riCO2^2 + 4.134000000\,10^{-7}\,T4riCO2^3 - 1.196522500\,10^{-10}\,T4riCO2^4 + 1.465592000\,10^{-14}\,T4riCO2^5$$

$$eq34rHe := 2144.750027 - 5.190000000\,T4riHe$$

$eq34rH2 := 8146.32855 - 13.63327000 T4riH2$
$- 0.001745000000 T4riH2^2 + 0.000001859403333 T4riH2^3$
$- 1.141965000 10^{-9} T4riH2^4 + 2.257060000 10^{-13} T4riH2^5$

$T4raer := 609.257707$

$T4rO2 := 632.335514$

$T4rN2 := 604.360402$

$T4rCO2 := -942.683089, 810.585948, 4856.64497$

$T4rHe := 413.246633$

$T4rH2 := -1798.689934, 573.150139, 4229.48545$

>

SURSA_RECE;T4aer:=609.2577079;T4O2:=632.3355147;T4N2:=604.3604020;T4CO2:=810.5859486;T4He:=413.2466333;T4H2:=573.1501398;dh41aer:=int(cpaer,T=T4aer..T1);dh41O2:=int(cpO2,T=T4O2..T1);dh41N2:=int(cpN2,T=T4N2..T1);dh41CO2:=int(cpCO2,T=T4CO2..T1);dh41He:=int(cpHe,T=T4He..T1);dh41H2:=int(cpH2,T=T4H2..T1);

SURSA_RECE

$T4aer := 609.257707$

$T4O2 := 632.335514$

$T4N2 := 604.360402$

$T4CO2 := 810.585948$

$T4He := 413.246633$

$T4H2 := 573.150139$

$dh41aer := -324.140295$

$dh41O2 := -327.245726$

$dh41N2 := -327.775192$

$dh41CO2 := -532.063176$

$dh41He := -623.405326$

$dh41H2 := -4038.959099$

>

RANDAMENT;Eaer:=1+dh41aer/dh23aer;EO2:=1+dh41O2/dh23O2;EN2:=1+dh41N2/dh23N2;ECO2:=1+dh41CO2/dh23CO2;EHe:=1+dh41He/dh23He;EH2:=1+dh41H2/dh23H2;

RANDAMENT

Eaer := 0.434928760

EO2 := 0.430355691

EN2 := 0.436108431

ECO2 := 0.349842889

EHe := −0.08725290

EH2 := 0.443157080

```
>
PUTERI;Paer:=dh41aer+dh23aer;PO2:=dh41O2+dh23O2;PN2:=dh41N2+dh23N2;PCO2:=dh41CO2+dh23CO2;P
He:=dh41He+dh23He;PH2:=dh41H2+dh23H2;
```

PUTERI

Paer := 249.487015

PO2 := 247.228066

PN2 := 253.498249

PCO2 := 286.297751

PHe := −50.028767

PH2 := 3214.35948

```
> GENERARE_ENTROPIE;ds12aer:=int(cpaer/T,T=T2taer..T2aer);ds23aer:=int(-
Raer/p,p=p2..p3);ds34aer:=int(cpaer/T,T=T4taer..T4aer);ds41aer:=int(-
Raer/p,p=p4..p1);dsqaer:=int(cpaer/T,T=T2aer..T3);Nirraer_int:=1+(ds12aer+ds23aer+ds34aer+ds41aer)/dsqae
r;
```

GENERARE_ENTROPIE

ds12aer := 0.0803040545

ds23aer := 0.00579914221

ds34aer := 0.0812765143

ds41aer := 0.00579914214

dsqaer := 0.571043608

Nirraer_int := 1.30326730

```
> ds12O2:=int(cpO2/T,T=T2tO2..T2O2);ds23O2:=int(-
RO2/p,p=p2..p3);ds34O2:=int(cpO2/T,T=T4tO2..T4O2);ds41O2:=int(-
RO2/p,p=p4..p1);dsqO2:=int(cpO2/T,T=T2O2..T3);NirrO2_int:=1+(ds12O2+ds23O2+ds34O2+ds41O2)/dsqO2;
```

ds12O2 := 0.0738685503

$ds23O2 := 0.00523428702$

$ds34O2 := 0.0721386018$

$ds41O2 := 0.00523428696$

$dsqO2 := 0.580882494$

$NirrO2\_int := 1.26937586$

```
> ds12N2:=int(cpN2/T,T=T2tN2..T2N2);ds23N2:=int(-RN2/p,p=p2..p3);ds34N2:=int(cpN2/T,T=T4tN2..T4N2);ds41N2:=int(-RN2/p,p=p4..p1);dsqN2:=int(cpN2/T,T=T2N2..T3);NirrN2_int:=1+(ds12N2+ds23N2+ds34N2+ds41N2)/dsqN2;
```

$ds12N2 := 0.0827604852$

$ds23N2 := 0.00600189447$

$ds34N2 := 0.0844582794$

$ds41N2 := 0.00600189439$

$dsqN2 := 0.576846956$

$NirrN2\_int := 1.31069341$

```
> ds12CO2:=int(cpCO2/T,T=T2tCO2..T2CO2);ds23CO2:=int(-RCO2/p,p=p2..p3);ds34CO2:=int(cpCO2/T,T=T4tCO2..T4CO2);ds41CO2:=int(-RCO2/p,p=p4..p1);dsqCO2:=int(cpCO2/T,T=T2CO2..T3);NirrCO2_int:=1+(ds12CO2+ds23CO2+ds34CO2+ds41CO2)/dsqCO2;
```

$ds12CO2 := 0.0595716623$

$ds23CO2 := 0.00382994530$

$ds34CO2 := 0.0458416931$

$ds41CO2 := 0.00382994525$

$dsqCO2 := 0.910904234$

$NirrCO2\_int := 1.12413296$

```
> ds12He:=int(cpHe/T,T=T2tHe..T2He);ds23He:=int(-RHe/p,p=p2..p3);ds34He:=int(cpHe/T,T=T4tHe..T4He);ds41He:=int(-RHe/p,p=p4..p1);dsqHe:=int(cpHe/T,T=T2He..T3);NirrHe_int:=1+(ds12He+ds23He+ds34He+ds41He)/dsqHe;
```

$ds12He := 0.488023520$

$ds23He := 0.0418196041$

$ds34He := 0.739620661$

$ds41He := 0.0418196036$

$dsqHe := 0.471109969$

$NirrHe\_int := 3.78339129$

> ds12H2:=int(cpH2/T,T=T2tH2..T2H2);ds23H2:=int(-RH2/p,p=p2..p3);ds34H2:=int(cpH2/T,T=T4tH2..T4H2);ds41H2:=int(-RH2/p,p=p4..p1);dsqH2:=int(cpH2/T,T=T2H2..T3);NirrH2_int:=1+(ds12H2+ds23H2+ds34H2+ds41H2)/dsqH2;

$ds12H2 := 1.13962191$

$ds23H2 := 0.084202929$

$ds34H2 := 1.21274522$

$ds41H2 := 0.084202928$

$dsqH2 := 7.14349516$

$NirrH2\_int := 1.35287669$

> save piC,piT,T1,T3,T2aer,T4aer,T2O2,T4O2,T2N2,T4N2,T2CO2,T4CO2,T2He,T4He,T2H2,T4H2,Paer,PO2,PN2,PCO2,PHe,PH2,Eaer,EO2,EN2,ECO2,EHe,EH2,Nirraer_int,NirrO2_int,NirrN2_int,NirrCO2_int,NirrHe_int,NirrH2_int,"date brayton agenti de lucru";read "date brayton agenti de lucru";

$piC := 25$

$piT := 0.041649312$

$T1 := 293.1$

$T3 := 1273.1$

$T2aer := 770.588174$

$T4aer := 609.257707$

$T2O2 := 744.709858$

$T4O2 := 632.335514$

$T2N2 := 775.747907$

$T4N2 := 604.360402$

$T2CO2 := 589.462352$

$T4CO2 := 810.585948$

$T2He := 1162.67282$

$T4He := 413.246633$

$T2H2 := 791.536251$

$T4H2 := 573.150139$

Paer := 249.4870158

PO2 := 247.2280663

PN2 := 253.4982490

PCO2 := 286.2977510

PHe := −50.0287678

PH2 := 3214.359480

Eaer := 0.4349287609

EO2 := 0.4303556911

EN2 := 0.4361084317

ECO2 := 0.3498428892

EHe := −0.0872529000

EH2 := 0.4431570802

Nirraer_int := 1.303267300

NirrO2_int := 1.269375868

NirrN2_int := 1.310693419

NirrCO2_int := 1.124132968

NirrHe_int := 3.783391297

NirrH2_int := 1.352876699

>

PROGRAM ARDERE CU RECIRCULARE GAZE DE ARDERE

```
> restart;
> p1:=0.94;T0:=273;T1:=293;T2:=1473;p0:=1;pv0s:=610.8/100000;
```

p1 := 0.94

T0 := 273

T1 := 293

T2 := 1473

p0 := 1

pv0s := 0.006108000000

```
> mair:=4;l0:=2500;u0:=l0-610.8*206.3/1000;
```

mair := 4

l0 := 2500

$u0 := 2373.99196($

```
>
Molar_mass_in_kg_per_kmole;MCH4:=16;MC2H6:=30;MC3H8:=44;MC4H10:=58;MCO2
:=44;MN2:=28;MC:=12;MH2:=2;MO2:=32;MH2O:=18;
```

Molar_mass_in_kg_per_kmole

$MCH4 := 16$

$MC2H6 := 30$

$MC3H8 := 44$

$MC4H10 := 58$

$MCO2 := 44$

$MN2 := 28$

$MC := 12$

$MH2 := 2$

$MO2 := 32$

$MH2O := 18$

```
> Natural_gas_mole_composition_in_kmole_per_kmole_fuel;
rCH4f:=0.865;rC2H6f:=0.079;rC3H8f:=0.022;rC4H10f:=0.003;rCO2f:=0.005;rN
2f:=0.026;sumrif:=rCH4f+rC2H6f+rC3H8f+rC4H10f+rCO2f+rN2f;Mf:=rCH4f*MCH4
+rC2H6f*MC2H6+rC3H8f*MC3H8+rC4H10f*MC4H10+rCO2f*MCO2+rN2f*MN2;
```

Natural_gas_mole_composition_in_kmole_per_kmole_fuel

$rCH4f := 0.865$

$rC2H6f := 0.079$

$rC3H8f := 0.022$

$rC4H10f := 0.003$

$rCO2f := 0.005$

$rN2f := 0.026$

$sumrif := 1.000$

$Mf := 18.300$

```
>
Natural_gas_mass_composition_in_kg_per_kg_fuel;gCH4f:=rCH4f*MCH4/Mf;gC2
H6f:=rC2H6f*MC2H6/Mf;gC3H8f:=rC3H8f*MC3H8/Mf;gC4H10f:=rC4H10f*MC4H10/Mf
```

```
;gCO2f:=rCO2f*MCO2/Mf;gN2f:=rN2f*MN2/Mf;sumgif:=gCH4f+gC2H6f+gC3H8f+gC4
H10f+gCO2f+gN2f;gCf:=MC*(rCH4f+2*rC2H6f+3*rC3H8f+4*rC4H10f)/Mf;gH2f:=MH
2*(2*rCH4f+3*rC2H6f+4*rC3H8f+5*rC4H10f)/Mf;sumgif_C_H2:=gCf+gH2f+gCO2f+
gN2f;
```

Natural_gas_mass_composition_in_kg_per_kg_fuel

gCH4f := 0.756284153

gC2H6f := 0.129508196

gC3H8f := 0.052896174

gC4H10f := 0.00950819672

gCO2f := 0.012021857

gN2f := 0.039781420

sumgif := 1.00000000

gCf := 0.721967213

gH2f := 0.226229508

sumgif_C_H2 := 1.00000000

```
>
Dried_Air_Mole_composition_in_kmole_per_kmole_dair;rO2dair:=0.2059;rN2d
air:=0.7809;rCO2dair:=0.0132;Mdair:=rO2dair*MO2+rN2dair*MN2+rCO2dair*MC
O2;
```

Dried_Air_Mole_composition_in_kmole_per_kmole_dair

rO2dair := 0.2059

rN2dair := 0.7809

rCO2dair := 0.0132

Mdair := 29.034

```
>
Dried_Air_Mass_composition_in_kg_per_kg_dair;gO2dair:=rO2dair*MO2/Mdair
;gN2dair:=rN2dair*MN2/Mdair;gCO2dair:=rCO2dair*MCO2/Mdair;sumgdair:=gO2
dair+gN2dair+gCO2dair;
```

Dried_Air_Mass_composition_in_kg_per_kg_dair

gO2dair := 0.226927686

gN2dair := 0.753068731

gCO2dair := 0.0200035819

sumgdair := 1.00000000(

```
> Humid_Air_Mass_composition_in_kg_per_kg_dair;phi1:=0.5;t1:=T1-273.15;pvsH2O1:=-.4164460979e-18*t1^10+.2004215749e-15*t1^9+.6588432820e-3*t1-.4117823023e-13*t1^8-.4560213564e-4*t1^2+.4719547427e-11*t1^7+.6985705427e-5*t1^3-.3308562609e-9*t1^6-.4022805689e-6*t1^4+.1465463358e-7*t1^5+.6108e-2;x1:=MH2O*phi1*pvsH2O1/(p1-phi1*pvsH2O1)/Mdair;
```

Humid_Air_Mass_composition_in_kg_per_kg_dair

$\phi 1$:= 0.5

t1 := 19.85

pvsH2O1 := 0.0231529699:

x1 := 0.00773008459:

```
>
Humid_Air_Mass_composition_in_kg_per_kg_air;R:=8.3145;gO2air:=gO2dair/(1+x1);gN2air:=gN2dair/(1+x1);gCO2air:=gCO2dair/(1+x1);gH2Oair:=x1/(1+x1);sumgair:=gO2air+gN2air+gCO2air+gH2Oair;Rair:=R*(gO2air/MO2+gN2air/MN2+gCO2air/MCO2+gH2Oair/MH2O);
```

Humid_Air_Mass_composition_in_kg_per_kg_air

R := 8.3145

gO2air := 0.225186972‹

gN2air := 0.747292099‹

gCO2air := 0.0198501386.

gH2Oair := 0.00767078874

sumgair := 0.999999999:

Rair := 0.287709893(

```
>
Humid_Air_Mass_flow_rates_in_kg_per_sec;mO2air:=mair*gO2air;mN2air:=mair*gN2air;mCO2air:=mair*gCO2air;mH2Oair:=mair*gH2Oair;summair:=mO2air+mN2air+mCO2air+mH2Oair;
```

Humid_Air_Mass_flow_rates_in_kg_per_sec

$mO2air := 0.900747889$

$mN2air := 2.98916839$

$mCO2air := 0.079400554$

$mH2Oair := 0.030683154$

$summair := 3.99999999$

```
>
Stoechiometric_relations_in_kg_per_kg_fuel;mO2min:=MO2*(gCf/MC+gH2f/MH2/2);mairmin:=mO2min/gO2air;
```

Stoechiometric_relations_in_kg_per_kg_fuel

$mO2min := 3.73508196$

$mairmin := 16.5865810$

```
> First_Flue_gases_mass_flow_rates_in_kg_per_sec;mO2fg1:=mair*gO2air-mf1*mO2min;mN2fg1:=mair*gN2air+mf1*gN2f;mCO2fg1:=mair*gCO2air+mf1*(MCO2*gCf/MC+gCO2f);mH2Ofg1:=mair*gH2Oair+mf1*(MH2O*gH2f/MH2);mfg1:=mCO2fg1+mO2fg1+mN2fg1+mH2Ofg1;mfg_verif1:=mair+mf1*(gN2f+MCO2*gCf/MC+gCO2f+MH2O*gH2f/MH2-mO2min);
```

First_Flue_gases_mass_flow_rates_in_kg_per_sec

$mO2fg1 := 0.9007478896 - 3.735081968\, mf1$

$mN2fg1 := 2.989168399 + 0.03978142077\, mf1$

$mCO2fg1 := 0.07940055460 + 2.659234973\, mf1$

$mH2Ofg1 := 0.03068315497 + 2.036065574\, mf1$

$mfg1 := 3.999999998 + 1.000000000\, mf1$

$mfg\_verif1 := 4 + 1.000000000\, mf1$

```
>
First_Flue_gases_mass_compozition_in_kg_per_kg;gO2fg1:=mO2fg1/mfg1;gN2fg1:=mN2fg1/mfg1;gCO2fg1:=mCO2fg1/mfg1;gH2Ofg1:=mH2Ofg1/mfg1;
```

First_Flue_gases_mass_compozition_in_kg_per_kg

$$gO2fg1 := \frac{0.9007478896 - 3.735081968\, mf1}{3.999999998 + 1.000000000\, mf1}$$

$$gN2fg1 := \frac{2.989168399 + 0.03978142077\, mf1}{3.999999998 + 1.000000000\, mf1}$$

$$gCO2fg1 := \frac{0.07940055460 + 2.659234973\, mf1}{3.999999998 + 1.000000000\, mf1}$$

$$gH2Ofg1 := \frac{0.03068315497 + 2.036065574\,mf1}{3.999999998 + 1.000000000\,mf1}$$

```
> First_Dried_flue_gases_mass_composition_in_kg_per_kg;gO2fgd1:=mO2fg1/(mfg1-mH2Ofg1);gN2fgd1:=mN2fg1/(mfg1-mH2Ofg1);gCO2fgd1:=mCO2fg1/(mfg1-mH2Ofg1);
```

First_Dried_flue_gases_mass_composition_in_kg_per_kg

$$gO2fgd1 := \frac{0.9007478896 - 3.735081968\,mf1}{3.969316843 - 1.036065574\,mf1}$$

$$gN2fgd1 := \frac{2.989168399 + 0.03978142077\,mf1}{3.969316843 - 1.036065574\,mf1}$$

$$gCO2fgd1 := \frac{0.07940055460 + 2.659234973\,mf1}{3.969316843 - 1.036065574\,mf1}$$

```
> Heating_values_of_fuel_in_kJ_per_kg_fuel;HHV_CH4:=evalf(4.185*212790/MCH4);HHV_C2H6:=evalf(4.185*372810/MC2H6);HHV_C3H8:=evalf(4.185*530570/MC3H8);HHV_C4H10:=evalf(4.185*686310/MC4H10);HHV:=gCH4f*HHV_CH4+gC2H6f*HHV_C2H6+gC3H8f*HHV_C3H8+gC4H10f*HHV_C4H10;
```

Heating_values_of_fuel_in_kJ_per_kg_fuel

HHV_CH4 := 55657.8843

HHV_C2H6 := 52006.9950

HHV_C3H8 := 50464.4420

HHV_C4H10 := 49520.8163

HHV := 51968.7377

```
> cpO2:=0.82397+3.05587E-4*T+5.32089E-8*T^2-1.30137E-10*T^3+3.58225E-14*T^4;cvO2:=0.56574+2.96923E-4*T+6.54515E-8*T^2-1.36918E-10*T^3+3.71407E-14*T^4;cpH2O:=1.84336-2.31223E-4*T+1.1966E-6*T^2-6.15263E-10*T^3+1.0015E-13*T^4;cvH2O:=1.38161-2.29361E-4*T+1.19327E-6*T^2-6.13657E-10*T^3+9.99765E-14*T^4;cpN2:=1.07623-3.25964E-4*T+7.92186E-7*T^2-4.66137E-10*T^3+8.87148E-14*T^4;cvN2:=0.77884-3.22759E-4*T+7.86981E-7*T^2-4.62795E-10*T^3+8.79811E-14*T^4;cpCO2:=0.46236+0.0016*T-1.2402E-6*T^2+4.78609E-10*T^3-7.32796E-14*T^4;cvCO2:=0.27337+0.0016*T-1.24189E-6*T^2+4.79536E-10*T^3-7.34111E-
```

```
14*T^4;cpCH4:=0.18537+0.00191*T-3.13681E-6*T^2+2.2951E-
9*T^3;cpair:=gO2air*cpO2+gN2air*cpN2+gCO2air*cpCO2+gH2Oair*cpH2O;cvair:
=gO2air*cvO2+gN2air*cvN2+gCO2air*cvCO2+gH2Oair*cvH2O;cpC2H6:=4.185*(1.6
2+42.1E-3*T-13.9E-6*T^2)/MC2H6;cpC3H8:=4.185*(0.12+64.47E-3*T-22.76E-
6*T^2)/MC3H8;cpC4H10:=1.25*4.185*(0.12+64.47E-3*T-22.76E-6*T^2)/MC4H10;
```

$$cpO2 := 0.82397 + 0.000305587 T + 5.32089\,10^{-8}\, T^2 - 1.30137\,10^{-10}\, T^3 + 3.58225\,10^{-14}\, T^4$$

$$cvO2 := 0.56574 + 0.000296923 T + 6.54515\,10^{-8}\, T^2 - 1.36918\,10^{-10}\, T^3 + 3.71407\,10^{-14}\, T^4$$

$$cpH2O := 1.84336 - 0.000231223 T + 0.0000011966 T^2 - 6.15263\,10^{-10}\, T^3 + 1.0015\,10^{-13}\, T^4$$

$$cvH2O := 1.38161 - 0.0002293361 T + 0.00000119327 T^2 - 6.13657\,10^{-10}\, T^3 + 9.99765\,10^{-14}\, T^4$$

$$cpN2 := 1.07623 - 0.000325964 T + 7.92186\,10^{-7}\, T^2 - 4.66137\,10^{-10}\, T^3 + 8.87148\,10^{-14}\, T^4$$

$$cvN2 := 0.77884 - 0.000322759 T + 7.86981\,10^{-7}\, T^2 - 4.62795\,10^{-10}\, T^3 + 8.79811\,10^{-14}\, T^4$$

$$cpCO2 := 0.46236 + 0.0016\, T - 0.0000012402 T^2 + 4.78609\,10^{-10}\, T^3 - 7.32796\,10^{-14}\, T^4$$

$$cvCO2 := 0.27337 + 0.0016\, T - 0.00000124189 T^2 + 4.79536\,10^{-10}\, T^3 - 7.34111\,10^{-14}\, T^4$$

$$cpCH4 := 0.18537 + 0.00191\, T - 0.00000313681 T^2 + 2.2951\,10^{-9}\, T^3$$

$$cpair := 1.013123421 - 0.0001447895516 T + 5.885370144\,10^{-7}\, T^2 - 3.728647520\,10^{-10}\, T^3 + 7.367624877\,10^{-14}\, T^4$$

$$cvair := 0.7254427276 - 0.0001443312173\,T + 5.87345142510^{-7}\,T^2 - 3.71863574310^{-10}\,T^3 + 7.34208608410^{-14}\,T^4$$

$$cpC2H6 := 0.2259900000 + 0.005872949999\,T - 0.000001939050000\,T^2$$

$$cpC3H8 := 0.01141363636 + 0.006131976138\,T - 0.000002164786364\,T^2$$

$$cpC4H10 := 0.01082327586 + 0.005814804956\,T - 0.000002052814655\,T^2$$

```
> cplw:=4.185;mlw1:=0;eqca1:=0.95*mf1*HHV+mf1*(gCH4f*int(cpCH4,T=T0..T1)+gC2H6f*int(cpC2H6,T=T0..T1)+gC3H8f*int(cpC3H8,T=T0..T1)+gC4H10f*int(cpC4H10,T=T0..T1))+mO2air*int(cpO2,T=T0..T1)+mN2air*int(cpN2,T=T0..T1)+mCO2air*int(cpCO2,T=T0..T1)+mH2Oair*(int(cpH2O,T=T0..T1)+l0)+mlw1*int(cplw,T=T0..T1)-mN2fg1*int(cpN2,T=T0..T2)-mCO2fg1*int(cpCO2,T=T0..T2)-(mH2Ofg1+mlw1)*(int(cpH2O,T=T0..T2)+l0)-mO2fg1*int(cpO2,T=T0..T2)=0;mfv1:=solve(eqca1,mf1);Qfuel1:=mfv1*HHV;
```

$cplw := 4.185$

$mlw1 := 0$

$eqca1 := 39886.26112\,mf1 - 5322.718235 = 0$

$mfv1 := 0.133447409$

$Qfuel1 := 6935.09343$

```
> First_Flue_gases_mass_flow_rates_values_in_kg_per_sec;mO2fgv1:=mair*gO2air-mfv1*mO2min;mN2fgv1:=mair*gN2air+mfv1*gN2f;mCO2fgv1:=mair*gCO2air+mfv1*(MCO2*gCf/MC+gCO2f);mH2Ofgv1:=mair*gH2Oair+mfv1*(MH2O*gH2f/MH2)+mlw1;mfgv1:=mCO2fgv1+mO2fgv1+mN2fgv1+mH2Ofgv1;mfg_verifv:=mair+mlw1+mfv1*(gN2f+MCO2*gCf/MC+gCO2f+MH2O*gH2f/MH2-mO2min);coef_stoechiometric1:=mfgv1/mairmin;
```

First_Flue_gases_mass_flow_rates_values_in_kg_per_sec

mO2fgv1 := 0.402310875

mN2fgv1 := 2.99447712

mCO2fgv1 := 0.434268573

mH2Ofgv1 := 0.302390832

mfgv1 := 4.13344740

mfg_verifv := 4.13344741

coef_stoechiometric1 := 0.249204305

\>

First_Flue_gases_mass_compozition_values_in_kg_per_kg;gO2fgv1:=mO2fgv1/mfgv1;gN2fgv1:=mN2fgv1/mfgv1;gCO2fgv1:=mCO2fgv1/mfgv1;gH2Ofgv1:=mH2Ofgv1/mfgv1;sumgfgv1:=gO2fgv1+gN2fgv1+gCO2fgv1+gH2Ofgv1;

First_Flue_gases_mass_compozition_values_in_kg_per_kg

gO2fgv1 := 0.0973305901

gN2fgv1 := 0.724450278

gCO2fgv1 := 0.105062078

gH2Ofgv1 := 0.0731570532

sumgfgv1 := 1.00000000

\>

First_Flue_gases_mole_compozition_values_in_kmole_per_kmole;rO2fgv1:=gO2fgv1/MO2/(gO2fgv1/MO2+gN2fgv1/MN2+gCO2fgv1/MCO2+gH2Ofgv1/MH2O);rN2fgv1:=gN2fgv1/MN2/(gO2fgv1/MO2+gN2fgv1/MN2+gCO2fgv1/MCO2+gH2Ofgv1/MH2O);rCO2fgv1:=gCO2fgv1/MCO2/(gO2fgv1/MO2+gN2fgv1/MN2+gCO2fgv1/MCO2+gH2Ofgv1/MH2O);rH2Ofgv1:=gH2Ofgv1/MH2O/(gO2fgv1/MO2+gN2fgv1/MN2+gCO2fgv1/MCO2+gH2Ofgv1/MH2O);sumrfgv1:=rO2fgv1+rN2fgv1+rCO2fgv1+rH2Ofgv1;

First_Flue_gases_mole_compozition_values_in_kmole_per_kmole

rO2fgv1 := 0.0860008750

rN2fgv1 := 0.731566894

rCO2fgv1 := 0.0675144605

rH2Ofgv1 := 0.114917770

sumrfgv1 := 1.00000000

```
> First_Dried_Flue_gases_mass_compozition_values_in_kg_per_kg;gO2dfgv1:=mO2fgv1/(mO2fgv1+mN2fgv1+mCO2fgv1);gN2dfgv1:=mN2fgv1/(mO2fgv1+mN2fgv1+mCO2fgv1);gCO2dfgv1:=mCO2fgv1/(mO2fgv1+mN2fgv1+mCO2fgv1);sumgdfgv1:=gO2dfgv1+gN2dfgv1+gCO2dfgv1;
```

First_Dried_Flue_gases_mass_compozition_values_in_kg_per_kg

gO2dfgv1 := 0.105013034

gN2dfgv1 := 0.781632186

gCO2dfgv1 := 0.113354779

sumgdfgv1 := 0.999999999

```
> Rair:=int((cpair-cvair),T=T1..T2)/(T2-T1);RO2:=int((cpO2-cvO2),T=T1..T2)/(T2-T1);RN2:=int((cpN2-cvN2),T=T1..T2)/(T2-T1);RCO2:=int((cpCO2-cvCO2),T=T1..T2)/(T2-T1);RH2O:=int((cpH2O-cvH2O),T=T1..T2)/(T2-T1);
```

Rair := 0.287646633

RO2 := 0.260118272

RN2 := 0.296756205

RCO2 := 0.189735137

RH2O := 0.461693151

```
> Rfgv1:=gO2fgv1*RO2+gN2fgv1*RN2+gCO2fgv1*RCO2+gH2Ofgv1*RH2O;Rdfgv1:=gO2dfgv1*RO2+gN2dfgv1*RN2+gCO2dfgv1*RCO2;
```

Rfgv1 := 0.294012658

Rdfgv1 := 0.280777395

```
> Second_Flue_gases_mass_flow_rates_in_kg_per_sec;mO2fg2:=mO2fgv1-mf2*mO2min;mN2fg2:=mN2fgv1+mf2*gN2f;mCO2fg2:=mCO2fgv1+mf2*(MCO2*gCf/MC+gCO2f);mH2Ofg2:=mH2Ofgv1+mf2*(MH2O*gH2f/MH2);mfg2:=mCO2fg2+mO2fg2+mN2fg2+mH2Ofg2;mfg_verif2:=mfgv1+mf2*(gN2f+MCO2*gCf/MC+gCO2f+MH2O*gH2f/MH2-mO2min);
```

Second_Flue_gases_mass_flow_rates_in_kg_per_sec

mO2fg2 := 1.005721359 − 3.735081968 *mf2*

$mN2fg2 := 3.435336272 + 0.03978142077 mf2$

$mCO2fg2 := 0.1121605930 + 2.659234973 mf2$

$mH2Ofg2 := 0.05464753373 + 2.036065574 mf2$

$mfg2 := 4.607865758 + 1.000000000 mf2$

$mfg\_verif2 := 4.607865758 + 1.000000000 mf2$

```
> mlw2:=0;eqca2:=0.95*mf2*HHV+mf2*(gCH4f*int(cpCH4,T=T0..T1)+gC2H6f*int(cpC2H6,T=T0..T1)+gC3H8f*int(cpC3H8,T=T0..T1)+gC4H10f*int(cpC4H10,T=T0..T1))+mN2fgv1*int(cpN2,T=T0..T9r)+mCO2fgv1*int(cpCO2,T=T0..T9r)+mlw2*int(cplw,T=T0..T1)+mH2Ofgv1*(int(cpH2O,T=T0..T9r)+l0)+mO2fgv1*int(cpO2,T=T0..T9r)-mN2fg2*int(cpN2,T=T0..T10r)-mCO2fg2*int(cpCO2,T=T0..T10r)-(mH2Ofg2+mlw2)*(int(cpH2O,T=T0..T10r)+l0)-mO2fg2*int(cpO2,T=T0..T10r)=0;mfv2:=solve(eqca2,mf2);Qfuel2:=mfv2*HHV;
```

$mlw2 := 0$

$eqca2 := 41349.22464 mf2 - 354.7447349 = 0$

$mfv2 := 0.00857923547$

$Qfuel2 := 445.852038$

```
> Second_Flue_gases_mass_flow_rates_values_in_kg_per_sec;mO2fgv2:=mO2fgv1-mfv2*mO2min;mN2fgv2:=mN2fgv1+mfv2*gN2f;mCO2fgv2:=mCO2fgv1+mfv2*(MCO2*gCf/MC+gCO2f);mH2Ofgv2:=mH2Ofgv1+mfv2*(MH2O*gH2f/MH2)+mlw2;mfgv2:=mCO2fgv2+mO2fgv2+mN2fgv2+mH2Ofgv2;mfg_verifv2:=mfgv1+mlw2+mfv2*(gN2f+MCO2*gCf/MC+gCO2f+MH2O*gH2f/MH2-mO2min);coef_stoechiometric1:=mfgv2/mairmin;
```

Second_Flue_gases_mass_flow_rates_values_in_kg_per_sec

$mO2fgv2 := 0.973677211$

$mN2fgv2 := 3.43567756$

$mCO2fgv2 := 0.134974796$

$mH2Ofgv2 := 0.0721154197$

$mfgv2 := 4.61644499$

$mfg\_verifv2 := 4.61644499$

coef_stoechiometric1 := 0.278120026:

>

```
Second_Flue_gases_mass_compozition_values_in_kg_per_kg;gO2fgv2:=mO2fgv2/mfgv2;gN2fgv2:=mN2fgv2/mfgv2;gCO2fgv2:=mCO2fgv2/mfgv2;gH2Ofgv2:=mH2Ofgv2/mfgv2;
```

Second_Flue_gases_mass_compozition_values_in_kg_per_kg

gO2fgv2 := 0.210914938

gN2fgv2 := 0.744225821

gCO2fgv2 := 0.0292378217

gH2Ofgv2 := 0.0156214186

>

```
Second_Flue_gases_mole_compozition_values_in_kmole_per_kmole;rO2fgv2:=gO2fgv2/MO2/(gO2fgv2/MO2+gN2fgv2/MN2+gCO2fgv2/MCO2+gH2Ofgv2/MH2O);rN2fgv2:=gN2fgv2/MN2/(gO2fgv2/MO2+gN2fgv2/MN2+gCO2fgv2/MCO2+gH2Ofgv2/MH2O);rCO2fgv2:=gCO2fgv2/MCO2/(gO2fgv2/MO2+gN2fgv2/MN2+gCO2fgv2/MCO2+gH2Ofgv2/MH2O);rH2Ofgv2:=gH2Ofgv2/MH2O/(gO2fgv2/MO2+gN2fgv2/MN2+gCO2fgv2/MCO2+gH2Ofgv2/MH2O);sumrfgv2:=rO2fgv2+rN2fgv2+rCO2fgv2+rH2Ofgv2;
```

Second_Flue_gases_mole_compozition_values_in_kmole_per_kmole

rO2fgv2 := 0.189928928:

rN2fgv2 := 0.765914794:

rCO2fgv2 := 0.0191481179

rH2Ofgv2 := 0.0250081589

sumrfgv2 := 1.000000000

>

```
Second_Dried_Flue_gases_mass_compozition_values_in_kg_per_kg;gO2dfgv2:=mO2fgv2/(mO2fgv2+mN2fgv2+mCO2fgv2);gN2dfgv2:=mN2fgv2/(mO2fgv2+mN2fgv2+mCO2fgv2);gCO2dfgv2:=mCO2fgv2/(mO2fgv2+mN2fgv2+mCO2fgv2);sumgdfgv2:=gO2dfgv2+gN2dfgv2+gCO2dfgv2;
```

Second_Dried_Flue_gases_mass_compozition_values_in_kg_per_kg

gO2dfgv2 := 0.214262015

$gN2dfgv2 := 0.756036178$

$gCO2dfgv2 := 0.0297018061$

$sumgdfgv2 := 1.00000000$

```
> 
Rfgv2:=gO2fgv2*RO2+gN2fgv2*RN2+gCO2fgv2*RCO2+gH2Ofgv2*RH2O;Rdfgv2:=gO2dfgv2*RO2+gN2dfgv2*RN2+gCO2dfgv2*RCO2;
```

$Rfgv2 := 0.288480830$

$Rdfgv2 := 0.285733467$

```
> 
dh78t:=mCO2fgv1*int(cpCO2,T=T7r..T8)+mN2fgv1*int(cpN2,T=T7r..T8)+mH2Ofgv1*(int(cpH2O,T=T7r..T8)+l0)+mO2fgv1*int(cpO2,T=T7r..T8);du78t:=mCO2fgv1*int(cvCO2,T=T7r..T8)+mN2fgv1*int(cvN2,T=T7r..T8)+mH2Ofgv1*(int(cvH2O,T=T7r..T8)+u0)+mO2fgv1*int(cpO2,T=T7r..T8);k78t:=dh78t/du78t;eq78t:=T8-T7r*(p8/p7)^((k78t-1)/k78t)=0;T8t:=fsolve(eq78t,T8);
```

$$dh78t := 4.678489834\,T8 - 5480.984425 - 0.0003228196987\,T8^2 + 9.004094329\,10^{-7}\,T8^3 - 4.280401102\,10^{-10}\,T8^4 + 6.760929816\,10^{-14}\,T8^5$$

$$du78t := 3.610424451\,T8 - 4279.734220 - 0.0003172636955\,T8^2 + 8.943252819\,10^{-7}\,T8^3 - 4.251219525\,10^{-10}\,T8^4 + 6.710035083\,10^{-14}\,T8^5$$

$$k78t := \left(4.678489834\,T8 - 5480.984425 - 0.0003228196987\,T8^2 + 9.004094329\,10^{-7}\,T8^3 - 4.280401102\,10^{-10}\,T8^4 + 6.760929816\,10^{-14}\,T8^5\right) \Big/ \left(3.610424451\,T8 - 4279.734220 - 0.0003172636955\,T8^2 + 8.943252819\,10^{-7}\,T8^3 - 4.251219525\,10^{-10}\,T8^4 + 6.710035083\,10^{-14}\,T8^5\right)$$

$$eq78t := T8 - 1133.15 \; 0.3397513034 \Big(\Big(\Big(\big(4.678489834\, T8 - 5480.984425 - 0.0003228196987\, T8^2 + 9.004094329\, 10^{-7}\, T8^3 - 4.280401102\, 10^{-10}\, T8^4 + 6.760929816\, 10^{-14}\, T8^5\big) \Big/ \big(3.610424451\, T8 - 4279.734220 - 0.0003172636955\, T8^2 + 8.943252819\, 10^{-7}\, T8^3 - 4.251219525\, 10^{-10}\, T8^4 + 6.710035083\, 10^{-14}\, T8^5\big) - 1\Big) \big(3.610424451\, T8 - 4279.734220 - 0.0003172636955\, T8^2 + 8.943252819\, 10^{-7}\, T8^3 - 4.251219525\, 10^{-10}\, T8^4 + 6.710035083\, 10^{-14}\, T8^5\big)\Big) \Big/ \big(4.678489834\, T8 - 5480.984425 - 0.0003228196987\, T8^2 + 9.004094329\, 10^{-7}\, T8^3 - 4.280401102\, 10^{-10}\, T8^4 + 6.760929816\, 10^{-14}\, T8^5\big) = 0$$

$T8t := 897.172380$

```
> dh78t:=mCO2fgv1*int(cpCO2,T=T7r..T8t)+mN2fgv1*int(cpN2,T=T7r..T8t)+mH2Ofgv1*(int(cpH2O,T=T7r..T8t)+l0)+mO2fgv1*int(cpO2,T=T7r..T8t);dh78r:=mCO2fgv1*int(cpCO2,T=T7r..T8)+mN2fgv1*int(cpN2,T=T7r..T8)+mH2Ofgv1*(int(cpH2O,T=T7r..T8)+l0)+mO2fgv1*int(cpO2,T=T7r..T8);;eq78r:=dh78r/dh78t-etat1=0;T8r:=fsolve(eq78r,T8);t8r:=T8r-273.15;
```

$dh78t := -1131.20994$

$$dh78r := 4.678489834\, T8 - 5480.984425 - 0.0003228196987\, T8^2 + 9.004094329\, 10^{-7}\, T8^3 - 4.280401102\, 10^{-10}\, T8^4 + 6.760929816\, 10^{-14}\, T8^5$$

$eq78r := -0.004135828073 T8 + 3.895240677 + 2.853755848 10^{-7}\, T8^2 - 7.959702258 10^{-10}\, T8^3 + 3.783913970 10^{-13}\, T8^4 - 5.976724183 10^{-17}\, T8^5 = 0$

$T8r := 907.921882$

$t8r := 634.771882$

```
> cpfgv1:=gN2fgv1*cpN2+gO2fgv1*cpO2+gCO2fgv1*cpCO2+gH2Ofgv1*cpH2O;Pt1:=-etam*mfgv1*int(cpfgv1,T=T7r..T8r);Pc12:=-mair*(int(cpair,T=T1..T2r)+int(cpair,T=T3r..T4r));
```

$cpfgv1 := 1.015326852 - 0.0001401167985 T + 5.862211360 10^{-7}\, T^2 - 3.715734205 10^{-10}\, T^3 + 7.336292083 10^{-14}\, T^4$

$Pt1 := 1199.15559$

$Pc12 := -1199.02223$

```
> dh1011t:=mCO2fgv2*int(cpCO2,T=T10r..T11)+mN2fgv2*int(cpN2,T=T10r..T11)+mH2Ofgv2*(int(cpH2O,T=T10r..T11)+l0)+mO2fgv2*int(cpO2,T=T10r..T11);du1011t:=mCO2fgv2*int(cvCO2,T=T10r..T11)+mN2fgv2*int(cvN2,T=T10r..T11)+mH2Ofgv2*(int(cvH2O,T=T10r..T11)+u0)+mO2fgv2*int(cpO2,T=T10r..T11);k1011t:=dh1011t/du1011t;eq1011t:=T11-T10r*(p11/p10)^((k1011t-1)/k1011t)=0;T11t:=fsolve(eq1011t,T11);
```

$dh1011t := 4.695201706 T11 - 5495.385028 - 0.0003115395871 T11^2 + 8.974671769 10^{-7}\, T11^3 - 4.269944156 10^{-10}\, T11^4 + 6.740129206 10^{-14}\, T11^5$

$du1011t := 3.614657373 T11 - 4276.794476 - 0.0003059667744 T11^2 + 8.913501925 10^{-7}\, T11^3 - 4.240636722 10^{-10}\, T11^4 + 6.689108848 10^{-14}\, T11^5$

$$k1011t := \left(4.695201706\,T11 - 5495.385028 - 0.0003115395871\,T11^2 + 8.974671769\,10^{-7}\,T11^3 - 4.269944156\,10^{-10}\,T11^4 + 6.740129206\,10^{-14}\,T11^5\right) \Big/ \left(3.614657373\,T11 - 4276.794476 - 0.0003059667744\,T11^2 + 8.913501925\,10^{-7}\,T11^3 - 4.240636722\,10^{-10}\,T11^4 + 6.689108848\,10^{-14}\,T11^5\right)$$

$$eq1011t := T11 - 1138.15\; 0.3522723927^{\left(\left(\left(4.695201706\,T11 - 5495.385028 - 0.0003115395871\,T11^2 + 8.974671769\,10^{-7}\,T11^3 - 4.269944156\,10^{-10}\,T11^4 + 6.740129206\,10^{-14}\,T11^5\right) / \left(3.614657373\,T11 - 4276.794476 - 0.0003059667744\,T11^2 + 8.913501925\,10^{-7}\,T11^3 - 4.240636722\,10^{-10}\,T11^4 + 6.689108848\,10^{-14}\,T11^5\right) - 1\right) \left(3.614657373\,T11 - 4276.794476 - 0.0003059667744\,T11^2 + 8.913501925\,10^{-7}\,T11^3 - 4.240636722\,10^{-10}\,T11^4 + 6.689108848\,10^{-14}\,T11^5\right)\right) \Big/ \left(4.695201706\,T11 - 5495.385028 - 0.0003115395871\,T11^2 + 8.974671769\,10^{-7}\,T11^3 - 4.269944156\,10^{-10}\,T11^4 + 6.740129206\,10^{-14}\,T11^5\right)} = 0$$

$T11t := 901.220433$

```
> 
dh1011t:=mCO2fgv2*int(cpCO2,T=T10r..T11t)+mN2fgv2*int(cpN2,T=T10r..T11t)+mH2Ofgv2*(int(cpH2O,T=T10r..T11t)+l0)+mO2fgv2*int(cpO2,T=T10r..T11t);dh1011r:=mCO2fgv2*int(cpCO2,T=T10r..T11)+mN2fgv2*int(cpN2,T=T10r..T11)+mH2Ofgv2*(int(cpH2O,T=T10r..T11)+l0)+mO2fgv2*int(cpO2,T=T10r..T11);eq1011r:=dh1011r/dh1011t-etat2=0;T11r:=fsolve(eq1011r,T11);t11r:=T11r-273.15;
```

$dh1011t := -1101.68980$

$dh1011r := 4.695201706 T11 - 5495.385028 - 0.0003115395871 T11^2 + 8.974671769\,10^{-7}\, T11^3 - 4.269944156\,10^{-10}\, T11^4 + 6.740129206\,10^{-14}\, T11^5$

$eq1011r := -0.004261818225 T11 + 4.038141837 + 2.827833974\,10^{-7}\, T11^2 - 8.146278286\,10^{-10}\, T11^3 + 3.875813429\,10^{-13}\, T11^4 - 6.117991790\,10^{-17}\, T11^5 = 0$

$T11r := 911.617594$

$t11r := 638.467594$

```
> cpfgv2:=gN2fgv2*cpN2+gO2fgv2*cpO2+gCO2fgv2*cpCO2+gH2Ofgv2*cpH2O;Pel:=-etam*etael*mfgv2*int(cpfgv2,T=T10r..T11r);DP:=100*(Pel-1200)/1200;
```

$cpfgv2 := 1.017060035 - 0.0001349694787 T + 5.832196712\,10^{-7}\, T^2 - 3.699768251\,10^{-10}\, T^3 + 7.300129444\,10^{-14}\, T^4$

$Pel := 1202.47868$

$DP := 0.206557$

```
> eqrec:=mfgv2*int(cpfgv2,T=T12r..T11r)-mair*int(cpair,T=T4r..T5)=0;T5r:=fsolve(eqrec,T5);t5r:=T5r-273.15;
```

$eqrec := 4094.222169 - 4.663167775 T5 + 0.0003331617204 T5^2 - 9.031070014\,10^{-7}\, T5^3 + 4.289988414\,10^{-10}\, T5^4 - 6.780000582\,10^{-14}\, T5^5 = 0$

$T5r := 852.022832$

$t5r := 578.872832$

```
> t1:=T1-273.15;t13:=90;T13:=t13+273.15;T13r:=T13;saturation_pressure_of_water_vapor;p_in_bar;t_in_degrees_Celsius; pvsH2O1:=-.4164460979e-18*t1^10+.2004215749e-15*t1^9+.6588432820e-3*t1-.4117823023e-13*t1^8-.4560213564e-4*t1^2+.4719547427e-11*t1^7+.6985705427e-5*t1^3-.3308562609e-9*t1^6-.4022805689e-6*t1^4+.1465463358e-7*t1^5+.6108e-2;xsfgv21:=Rdfgv2*pvsH2O1/(p1-pvsH2O1)/RH2O;pvsH2O13:=-.4164460979e-
```

```
18*t13^10+.2004215749e-15*t13^9+.6588432820e-3*t13-.4117823023e-13*t13^8-.4560213564e-4*t13^2+.4719547427e-11*t13^7+.6985705427e-5*t13^3-.3308562609e-9*t13^6-.4022805689e-6*t13^4+.1465463358e-7*t13^5+.6108e-2;xsfgv213:=Rdfgv2*pvsH2O13/(p12-pvsH2O13)/RH2O;
```

$t1 := 25.00$

$t13 := 90$

$T13 := 363.15$

$T13r := 363.15$

saturation_pressure_of_water_vapor

p_in_bar

t_in_degrees_Celsius

$pvsH2O1 := 0.031672113$

$xsfgv21 := 0.0215836565$

$pvsH2O13 := 0.70110010$

$xsfgv213 := 1.78135895$

```
> LHV:=HHV-mH2Ofgv2*10/(mfv1+mfv2);
```

$LHV := 41005.6114$

```
> xfgv2:=mH2Ofgv2/(mO2fgv2+mCO2fgv2+mN2fgv2);dxfgv2:=xfgv2-xsfgv21;
```

$xfgv2 := 0.0158693199$

$dxfgv2 := -0.0057143366$

```
> mH2Ofgv2_cond:=(mN2fgv2+mCO2fgv2+mO2fgv2)*(xfgv2-xsfgv21);
```

$mH2Ofgv2\_cond := -0.0259678291$

```
>
Qfuel:=Qfuel1+Qfuel2;Q:=Qfuel+mair*int(cpair,T=T5r..T6r)+mfgv1*int(cpfgv1,T=T8r..T9r);Q0:=mN2fgv2*int(cpN2,T=T12r..T1)+mO2fgv2*int(cpO2,T=T12r..T1)+mCO2fgv2*int(cpCO2,T=T12r..T1)+mH2Ofgv2*(int(cpH2O,T=T12r..T1))+mair*int(cpair,T=T2r..T3r);Q0rec:=mfgv2*int(cpfgv2,T=T12r..T1)+mair*int(cpair,T=T2r..T3r);P:=mfgv2*int(cpfgv2,T=T11r..T10r);eft:=P/Q;efel:=Pel/Q;
```

$Qfuel := 854.625601$

$Q := 2908.60214$

$Q0 := -1542.24136$

$Q0rec := -1542.24136$

$P := 1226.89387$

$eft := 0.421815638$

$efel := 0.413421507$

```
> h1:=int(cpair,T=T0..T1);h2t:=int(cpair,T=T0..T2t);h2r:=int(cpair,T=T0..T2r);h3r:=int(cpair,T=T0..T3r);h4t:=int(cpair,T=T0..T4t);h4r:=int(cpair,T=T0..T4r);h5r:=int(cpair,T=T0..T5r);h6r:=int(cpair,T=T0..T6r);h7r:=int(cpfgv1,T=T0..T7r);h8t:=int(cpfgv1,T=T0..T8t);h8r:=int(cpfgv1,T=T0..T8r);h9r:=int(cpfgv1,T=T0..T9r);h10r:=int(cpfgv2,T=T0..T10r);h11t:=int(cpfgv2,T=T0..T11t);h11r:=int(cpfgv2,T=T0..T11r);h12r:=int(cpfgv2,T=T0..T12r);
```

$h1 := 25.3056305$

$h2t := 139.064322$

$h2r := 159.139385$

$h3r := 26.3192842$

$h4t := 132.850815$

$h4r := 153.142536$

$h5r := 615.046771$

$h6r := 869.402192$

$h7r := 943.536454$

$h8t := 668.391985$

$h8r := 680.666756$

$h9r := 872.499951$

$h10r := 953.202657$

$h11t := 675.504480$

$h11r := 687.436710$

$h12r := 227.177899$

```
> Final_1_Flue_gases_mass_compozition_values_in_kg_per_kg;gO2fgv1:=mO2fgv
```

```
/(mfgv-mH2Ofgv+mH2Ofg_rest1);gN2fgv1:=mN2fgv/(mfgv-
mH2Ofgv+mH2Ofg_rest1);gCO2fgv1:=mCO2fgv/(mfgv-
mH2Ofgv+mH2Ofg_rest1);gH2Ofgv1:=mH2Ofg_rest1/(mfgv-
mH2Ofgv+mH2Ofg_rest1);sumfg1:=gO2fgv1+gN2fgv1+gCO2fgv1+gH2Ofgv1;
```

Final_1_Flue_gases_mass_compozition_values_in_kg_per_kg

$$gO2fgv1 := \frac{mO2fgv}{mfgv - mH2Ofgv + mH2Ofg\_rest1}$$

$$gN2fgv1 := \frac{mN2fgv}{mfgv - mH2Ofgv + mH2Ofg\_rest1}$$

$$gCO2fgv1 := \frac{mCO2fgv}{mfgv - mH2Ofgv + mH2Ofg\_rest1}$$

$$gH2Ofgv1 := \frac{mH2Ofg\_rest1}{mfgv - mH2Ofgv + mH2Ofg\_rest1}$$

$$sumfg1 := \frac{mO2fgv}{mfgv - mH2Ofgv + mH2Ofg\_rest1} + \frac{mN2fgv}{mfgv - mH2Ofgv + mH2Ofg\_rest1} + \frac{mCO2fgv}{mfgv - mH2Ofgv + mH2Ofg\_rest1} + \frac{mH2Ofg\_rest1}{mfgv - mH2Ofgv + mH2Ofg\_rest1}$$

```
>
Final_1_Flue_gases_mole_compozition_values_in_kmole_per_kmole;rO2fgv1:=
gO2fgv1/MO2/(gO2fgv1/MO2+gN2fgv1/MN2+gCO2fgv1/MCO2+gH2Ofgv1/MH2O);rN2fg
v1:=gN2fgv1/MN2/(gO2fgv1/MO2+gN2fgv1/MN2+gCO2fgv1/MCO2+gH2Ofgv1/MH2O);r
CO2fgv1:=gCO2fgv1/MCO2/(gO2fgv1/MO2+gN2fgv1/MN2+gCO2fgv1/MCO2+gH2Ofgv1/
MH2O);rH2Ofgv1:=gH2Ofgv1/MH2O/(gO2fgv1/MO2+gN2fgv1/MN2+gCO2fgv1/MCO2+gH
2Ofgv1/MH2O);sumrfg1:=rO2fgv1+rN2fgv1+rCO2fgv1+rH2Ofgv1;
```

Final_1_Flue_gases_mole_compozition_values_in_kmol
e

$$rO2fgv1 := \frac{1}{32}\, mO2fgv \Bigg/ \Bigg((mfgv - mH2Ofgv + mH2Ofg\_rest1) \bigg(\frac{1}{32} \frac{mO2fgv}{mfgv - mH2Ofgv + mH2Ofg\_rest1} + \frac{1}{28} \frac{mN2fgv}{mfgv - mH2Ofgv + mH2Ofg\_rest1} + \frac{1}{44} \frac{mCO2fgv}{mfgv - mH2Ofgv + mH2Ofg\_rest1} + \frac{1}{18} \frac{mH2Ofg\_rest1}{mfgv - mH2Ofgv + mH2Ofg\_rest1} \bigg) \Bigg)$$

$$rN2fgv1 := \frac{1}{28}\, mN2fgv \Bigg/ \Bigg((mfgv - mH2Ofgv + mH2Ofg\_rest1) \bigg(\frac{1}{32} \frac{mO2fgv}{mfgv - mH2Ofgv + mH2Ofg\_rest1} + \frac{1}{28} \frac{mN2fgv}{mfgv - mH2Ofgv + mH2Ofg\_rest1} + \frac{1}{44} \frac{mCO2fgv}{mfgv - mH2Ofgv + mH2Ofg\_rest1} + \frac{1}{18} \frac{mH2Ofg\_rest1}{mfgv - mH2Ofgv + mH2Ofg\_rest1} \bigg) \Bigg)$$

$$rCO2fgv1 := \frac{1}{44}\, mCO2fgv \Bigg/ \Bigg((mfgv - mH2Ofgv + mH2Ofg\_rest1) \bigg(\frac{1}{32} \frac{mO2fgv}{mfgv - mH2Ofgv + mH2Ofg\_rest1} + \frac{1}{28} \frac{mN2fgv}{mfgv - mH2Ofgv + mH2Ofg\_rest1} + \frac{1}{44} \frac{mCO2fgv}{mfgv - mH2Ofgv + mH2Ofg\_rest1} + \frac{1}{18} \frac{mH2Ofg\_rest1}{mfgv - mH2Ofgv + mH2Ofg\_rest1} \bigg) \Bigg)$$

$$rH2Ofgv1 := \frac{1}{18}\, mH2Ofg\_rest1 \Bigg/ \Bigg((mfgv - mH2Ofgv + mH2Ofg\_rest1) \bigg(\frac{1}{32} \frac{mO2fgv}{mfgv - mH2Ofgv + mH2Ofg\_rest1} + \frac{1}{28} \frac{mN2fgv}{mfgv - mH2Ofgv + mH2Ofg\_rest1} + \frac{1}{44} \frac{mCO2fgv}{mfgv - mH2Ofgv + mH2Ofg\_rest1} + \frac{1}{18} \frac{mH2Ofg\_rest1}{mfgv - mH2Ofgv + mH2Ofg\_rest1} \bigg) \Bigg)$$

$$
\begin{aligned}
sumrfg1 := {} & \frac{1}{32}\, mO2fgv \Bigg/ \Bigg((mfgv - mH2Ofgv \\
& + mH2Ofg\_rest1) \left(\frac{1}{32}\, \frac{mO2fgv}{mfgv - mH2Ofgv + mH2Ofg\_rest1} \right. \\
& + \frac{1}{28}\, \frac{mN2fgv}{mfgv - mH2Ofgv + mH2Ofg\_rest1} \\
& + \frac{1}{44}\, \frac{mCO2fgv}{mfgv - mH2Ofgv + mH2Ofg\_rest1} \\
& \left. + \frac{1}{18}\, \frac{mH2Ofg\_rest1}{mfgv - mH2Ofgv + mH2Ofg\_rest1} \right) \Bigg) \\
& + \frac{1}{28}\, mN2fgv \Bigg/ \Bigg((mfgv - mH2Ofgv \\
& + mH2Ofg\_rest1) \left(\frac{1}{32}\, \frac{mO2fgv}{mfgv - mH2Ofgv + mH2Ofg\_rest1} \right. \\
& + \frac{1}{28}\, \frac{mN2fgv}{mfgv - mH2Ofgv + mH2Ofg\_rest1} \\
& + \frac{1}{44}\, \frac{mCO2fgv}{mfgv - mH2Ofgv + mH2Ofg\_rest1} \\
& \left. + \frac{1}{18}\, \frac{mH2Ofg\_rest1}{mfgv - mH2Ofgv + mH2Ofg\_rest1} \right) \Bigg) \\
& + \frac{1}{44}\, mCO2fgv \Bigg/ \Bigg((mfgv - mH2Ofgv \\
& + mH2Ofg\_rest1) \left(\frac{1}{32}\, \frac{mO2fgv}{mfgv - mH2Ofgv + mH2Ofg\_rest1} \right. \\
& + \frac{1}{28}\, \frac{mN2fgv}{mfgv - mH2Ofgv + mH2Ofg\_rest1} \\
& + \frac{1}{44}\, \frac{mCO2fgv}{mfgv - mH2Ofgv + mH2Ofg\_rest1} \\
& \left. + \frac{1}{18}\, \frac{mH2Ofg\_rest1}{mfgv - mH2Ofgv + mH2Ofg\_rest1} \right) \Bigg) \\
& + \frac{1}{18}\, mH2Ofg\_rest1 \Bigg/ \Bigg((mfgv - mH2Ofgv \\
& + mH2Ofg\_rest1) \left(\frac{1}{32}\, \frac{mO2fgv}{mfgv - mH2Ofgv + mH2Ofg\_rest1} \right. \\
& + \frac{1}{28}\, \frac{mN2fgv}{mfgv - mH2Ofgv + mH2Ofg\_rest1} \\
& + \frac{1}{44}\, \frac{mCO2fgv}{mfgv - mH2Ofgv + mH2Ofg\_rest1} \\
& \left. + \frac{1}{18}\, \frac{mH2Ofg\_rest1}{mfgv - mH2Ofgv + mH2Ofg\_rest1} \right) \Bigg)
\end{aligned}
$$

```
> p0N2:=rN2air*p0;p0O2:=rO2air*p0;p0CO2:=rCO2air*p0;p0H2O:=pv0;p4tN2:=rN2fgv*p4t;p4tO2:=rO2fgv*p4t;p4tCO2:=rCO2fgv*p4t;p4tH2O:=rH2Ofgv*p4t;sump4t:=p4tN2+p4tO2+p4tCO2+p4tH2O=p3r;p4rN2:=rN2fgv*p4r;p4rO2:=rO2fgv*p4r;p4rCO2:=rCO2fgv*p4r;p4rH2O:=rH2Ofgv*p4r;sump4r:=p4rN2+p4rO2+p4rCO2+p4rH2O=p4r;p5tN2:=rN2fgv*p5t;p5tO2:=rO2fgv*p5t;p5tCO2:=rCO2fgv*p5t;p5tH2O:=rH2Ofgv*p5t;sump5t:=p5tN2+p5tO2+p5tCO2+p5tH2O=p5t;p5rN2:=rN2fgv*p5r;p5rO2:=rO2fgv*p5r;p5rCO2:=rCO2fgv*p5r;p5rH2O:=rH2Ofgv*p5r;sump5r:=p5rN2+p5rO2+p5rCO2+p5rH2O=p5r;p6tN2:=rN2fgv*p6t;p6tO2:=rO2fgv*p6t;p6tCO2:=rCO2fgv*p6t;p6tH2O:=rH2Ofgv*p6t;sump6t:=p6tN2+p6tO2+p6tCO2+p6tH2O=p6t;p6rN2:=rN2fgv*p6r;p6rO2:=rO2fgv*p6r;p6rCO2:=rCO2fgv*p6r;p6rH2O:=rH2Ofgv*p6r;sump6r:=p6rN2+p6rO2+p6rCO2+p6rH2O=p6r;p7tN2:=rN2fgv*p7t;p7tO2:=rO2fgv*p7t;p7tCO2:=rCO2fgv*p7t;p7tH2O:=rH2Ofgv*p7t;sump7t:=p7tN2+p7tO2+p7tCO2+p7tH2O=p7t;p7rN2:=rN2fgv*p7r;p7rO2:=rO2fgv*p7r;p7rCO2:=rCO2fgv*p7r;p7rH2O:=rH2Ofgv*p7r;sump7r:=p7rN2+p7rO2+p7rCO2+p7rH2O=p7r;p1N2:=rN2fgv1*p1;p1O2:=rO2fgv1*p1;p1CO2:=rCO2fgv1*p1;p1H2O:=rH2Ofgv1*p1;sump1fg:=p1N2+p1O2+p1CO2+p1H2O=p1;
```

$p0N2 := 0.780$

$p0O2 := 0.205$

$p0CO2 := 0.013$

$p0H2O := 0.00610800000$

$p4tN2 := 3.39350615$

$p4tO2 := 0.761208722$

$p4tCO2 := 0.126268502$

$p4tH2O := 0.129016617$

$sump4t := 4.410000000 = 4.410$

$p4rN2 := 3.35957109$

$p4rO2 := 0.753596635$

$p4rCO2 := 0.125005817$

$p4rH2O := 0.127726451$

$sump4r := 4.365900000 = 4.3659$

$p5tN2 := 0.830682279$

$p5tO2 := 0.186333122$

$p5tCO2 := 0.0309087423$

$p5tH2O := 0.0315814420$

$sump5t := 1.079505586 = 1.07950558$

$p5rN2 := 0.830682279$

$p5rO2 := 0.186333122$

$p5rCO2 := 0.0309087423$

$p5rH2O := 0.0315814420$

$sump5r := 1.079505586 = 1.07950558$

$p6tN2 := 0.830682279$

$p6tO2 := 0.186333122$

$p6tCO2 := 0.0309087423$

$p6tH2O := 0.0315814420$

$sump6t := 1.079505586 = 1.07950558$

$p6rN2 := 0.805761811$

$p6rO2 := 0.180743128$

$p6rCO2 := 0.0299814801$

$p6rH2O := 0.0306339987$

$sump6r := 1.047120419 = 1.04712041$

$p7tN2 := 0.805761811$

$p7tO2 := 0.180743128$

$p7tCO2 := 0.0299814801$

$p7tH2O := 0.0306339987$

$sump7t := 1.047120419 = 1.04712041$

$p7rN2 := 0.769502530$

$p7rO2 := 0.172609687$

$p7rCO2 := 0.0286323135$

$p7rH2O := 0.0292554688$

$sump7r := 0.9999999999 = 1$

$p1N2 := 0.774159948$

$p1O2 := 0.173654408$

$p1CO2 := 0.0288056107$

$p1H2O := 0.0233800317$

$sump1fg := 1.000000000 = 1$

```
> T7t:=T7r;s1:=int(cpair/T,T=T0..T1)-
Rair*int(1/p,p=p0..p1)/1000;s2t:=int(cpair/T,T=T0..T2t)-
Rair*int(1/p,p=p0..p2t)/1000;s2r:=int(cpair/T,T=T0..T2r)-
Rair*int(1/p,p=p0..p2r)/1000;Ds12t_in_proc:=100*(s2t-
s1)/s1;s3t:=int(cpair/T,T=T0..T3t)-
Rair*int(1/p,p=p0..p3t)/1000;s3r:=int(cpair/T,T=T0..T3r)-
Rair*int(1/p,p=p0..p3r)/1000;s4t:=gN2fgv*(int(cpN2/T,T=T0..T4t)-
RN2*int(1/p,p=p0N2..p4tN2)/1000)+gO2fgv*(int(cpO2/T,T=T0..T4t)-
RO2*int(1/p,p=p0O2..p4tO2)/1000)+gCO2fgv*(int(cpCO2/T,T=T0..T4t)-
RCO2*int(1/p,p=p0CO2..p4tCO2)/1000)+gH2Ofgv*(l0/T0+int(cpH2O/T,T=T0..T4
t)-
RH2O*int(1/p,p=p0H2O..p4tH2O)/1000);s4r:=gN2fgv*(int(cpN2/T,T=T0..T4r)-
RN2*int(1/p,p=p0N2..p4rN2)/1000)+gO2fgv*(int(cpO2/T,T=T0..T4r)-
RO2*int(1/p,p=p0O2..p4rO2)/1000)+gCO2fgv*(int(cpCO2/T,T=T0..T4r)-
RCO2*int(1/p,p=p0CO2..p4rCO2)/1000)+gH2Ofgv*(l0/T0+int(cpH2O/T,T=T0..T4
r)-
RH2O*int(1/p,p=p0H2O..p4rH2O)/1000);s5t:=gN2fgv*(int(cpN2/T,T=T0..T5t)-
RN2*int(1/p,p=p0N2..p5tN2)/1000)+gO2fgv*(int(cpO2/T,T=T0..T5t)-
RO2*int(1/p,p=p0O2..p5tO2)/1000)+gCO2fgv*(int(cpCO2/T,T=T0..T5t)-
RCO2*int(1/p,p=p0CO2..p5tCO2)/1000)+gH2Ofgv*(l0/T0+int(cpH2O/T,T=T0..T5
t)-RH2O*int(1/p,p=p0H2O..p5tH2O)/1000);Ds45t_in_proc:=100*(s5t-
s4r)/s5t;s5r:=gN2fgv*(int(cpN2/T,T=T0..T5r)-
RN2*int(1/p,p=p0N2..p5rN2)/1000)+gO2fgv*(int(cpO2/T,T=T0..T5r)-
RO2*int(1/p,p=p0O2..p5rO2)/1000)+gCO2fgv*(int(cpCO2/T,T=T0..T5r)-
RCO2*int(1/p,p=p0CO2..p5rCO2)/1000)+gH2Ofgv*(l0/T0+int(cpH2O/T,T=T0..T5
r)-
RH2O*int(1/p,p=p0H2O..p5rH2O)/1000);s6t:=gN2fgv*(int(cpN2/T,T=T0..T6t)-
RN2*int(1/p,p=p0N2..p6tN2)/1000)+gO2fgv*(int(cpO2/T,T=T0..T6t)-
```

```
RO2*int(1/p,p=p0O2..p6tO2)/1000)+gCO2fgv*(int(cpCO2/T,T=T0..T6t)-
RCO2*int(1/p,p=p0CO2..p6tCO2)/1000)+gH2Ofgv*(l0/T0+int(cpH2O/T,T=T0..T6
t)-
RH2O*int(1/p,p=p0H2O..p6tH2O)/1000);s6r:=gN2fgv*(int(cpN2/T,T=T0..T6r)-
RN2*int(1/p,p=p0N2..p6rN2)/1000)+gO2fgv*(int(cpO2/T,T=T0..T6r)-
RO2*int(1/p,p=p0O2..p6rO2)/1000)+gCO2fgv*(int(cpCO2/T,T=T0..T6r)-
RCO2*int(1/p,p=p0CO2..p6rCO2)/1000)+gH2Ofgv*(l0/T0+int(cpH2O/T,T=T0..T6
r)-
RH2O*int(1/p,p=p0H2O..p6rH2O)/1000);s7t:=gN2fgv*(int(cpN2/T,T=T0..T7t)-
RN2*int(1/p,p=p0N2..p7tN2)/1000)+gO2fgv*(int(cpO2/T,T=T0..T7t)-
RO2*int(1/p,p=p0O2..p7tO2)/1000)+gCO2fgv*(int(cpCO2/T,T=T0..T7t)-
RCO2*int(1/p,p=p0CO2..p7tCO2)/1000)+gH2Ofgv*(l0/T0+int(cpH2O/T,T=T0..T7
t)-
RH2O*int(1/p,p=p0H2O..p7tH2O)/1000);s7r:=gN2fgv*(int(cpN2/T,T=T0..T7r)-
RN2*int(1/p,p=p0N2..p7rN2)/1000)+gO2fgv*(int(cpO2/T,T=T0..T7r)-
RO2*int(1/p,p=p0O2..p7rO2)/1000)+gCO2fgv*(int(cpCO2/T,T=T0..T7r)-
RCO2*int(1/p,p=p0CO2..p7rCO2)/1000)+gH2Ofgv*(l0/T0+int(cpH2O/T,T=T0..T7
r)-
RH2O*int(1/p,p=p0H2O..p7rH2O)/1000);s1fg:=gN2fgv1*(int(cpN2/T,T=T0..T1)
-RN2*int(1/p,p=p0N2..p1N2)/1000)+gO2fgv1*(int(cpO2/T,T=T0..T1)-
RO2*int(1/p,p=p0O2..p1O2)/1000)+gCO2fgv1*(int(cpCO2/T,T=T0..T1)-
RCO2*int(1/p,p=p0CO2..p1CO2)/1000)+gH2Ofgv1*(l0/T0+int(cpH2O/T,T=T0..T1
)-RH2O*int(1/p,p=p0H2O..p1H2O)/1000);
```

$T7t := 363.15$

$s1 := 0.0709992849$

$s2t := 0.0706206250$

$s2r := 0.1599450117$

$Ds12t\_in\_proc := -0.5333292583$

$s3t := 0.8230767264$

$s3r := 0.8288609463$

$s4t := 1.3661320400$

$s4r := 1.369027367$

s5t := 1.36970293'

Ds45t_in_proc := 0.0493223736

s5r := 1.46624681:

s6t := 0.856963817:

s6r := 0.865738582:

s7t := 0.437752773:

s7r := 0.451017226'

s1fg := 0.199918188:

```
> Tmq2r3t:=(T3t-T2r)/ln(T3t/T2r);Tmq2r3ts:=(h3t-h2r)/(s3t-
s2r);Tmq5r6t:=(T5r-T6t)/ln(T5r/T6t);Tmq5r6ts:=(h5r-h6t)/(s5r-
s6t);Tmq6r7r:=(T6r-T7t)/ln(T6r/T7t);Tmq6r7rs:=(h6r-h7r)/(s6r-s7t);
```

Tmq2r3t := 674.812909'

Tmq2r3ts := 677.782884

Tmq5r6t := 728.219340:

Tmq5r6ts := 731.073804(

Tmq6r7r := 448.629194:

Tmq6r7rs := 449.158641(

```
> DTairmax_fgin:=T5r-T3r;eps_rec:=(T3r-T2r)/(T5r-T2r);
```

DTairmax_fgin := 42.493730:

eps_rec := 0.907217659

```
> etaelref:=0.35;etaQref:=0.95;HP:=-Qcog/P;HPel:=-
Qcog/Pel;Exfuel:=Qfuel*0.9875;ExQcog:=-Qcog*(1-
T0/Tmq6r7rs);etaexcog:=(P+ExQcog)/Exfuel;etaexelcog:=(Pel+ExQcog)/Exfue
l;Qfuelref:=Pel/etaelref-Qcog/etaQref;FESR:=1-Qfuel/Qfuelref;
```

etaelref := 0.35

etaQref := 0.95

HP := 1.45406872:

HPel := 1.49873090'

Exfuel := 371.305203

ExQcog := 60.8083838:

etaexcog := 0.451186810'

etaexelcog := 0.442621768

Qfuelref := 459.1717229

FESR := 0.181122768

```
> save DTairmax_fgin,p1,p2r,p3r,p4r,p5r,p6r,p7r,T1,T2r,T3r,T4r,T5r,T6r,T7r,eps_rec,P,Pel,Qfuel,Qcog,HP,HPel,etaHHV,etaelHHV,etacogHHV,etaelcogHHV,etaexcog,etaexelcog,FESR,"date brayton Michel";read "date brayton Michel";
```

DTairmax_fgin := 42.4937303

p1 := 1

p2r := 4.5

p3r := 4.410

p4r := 4.36590

p5r := 1.079505586

p6r := 1.047120419

p7r := 1

T1 := 293.15

T2r := 488.2489243

T3r := 903.7489243

T4r := 1223.15

T5r := 946.2426546

T6r := 546.5724449

T7r := 363.15

eps_rec := 0.9072176594

P := 106.7196268

Pel := 103.5393820

Qfuel := 376.0052693

Qcog := −155.1776713

HP := 1.454068721

HPel := 1.498730901

etaHHV := 0.283824817

etaelHHV := 0.2753668377

etacogHHV := 0.696525606

etaelcogHHV := 0.688067626

etaexcog := 0.451186810

etaexelcog := 0.442621768

FESR := 0.181122768

TURBOMOTORUL DUBLUFLUX – GAZ PERFECT

cpaer =1.01027-1.73736E-4*T+6.08005E-7*T^2-3.80644E-10*T^3+7.49874E-14*T^4 [kJ/kgK];

cvaer =0.72301-1.73889E-4*T+6.09496E-7*T^2-3.81877E-10*T^3+7.52717E-14*T^4 [kJ/kgK];

cpO2 =0.82397+3.05587E-4*T+5.32089E-8*T^2-1.30137E-10*T^3+3.58225E-14*T^4 [kJ/kgK];

cvO2 =0.56574+2.96923E-4*T+6.54515E-8*T^2-1.36918E-10*T^3+3.71407E-14*T^4 [kJ/kgK];

cpH2O =1.84336-2.31223E-4*T+1.1966E-6*T^2-6.15263E-10*T^3+1.0015E-13*T^4 [kJ/kgK];

cvH2O =1.38161-2.29361E-4*T+1.19327E-6*T^2-6.13657E-10*T^3+9.99765E-14*T^4 [kJ/kgK];

cpN2 =1.07623-3.25964E-4*T+7.92186E-7*T^2-4.66137E-10*T^3+8.87148E-14*T^4 [kJ/kgK];

cvN2 =0.77884-3.22759E-4*T+7.86981E-7*T^2-4.62795E-10*T^3+8.79811E-14*T^4 [kJ/kgK];

cpCO2 =0.46236+0.0016*T-1.2402E-6*T^2+4.78609E-10*T^3-7.32796E-14*T^4 [kJ/kgK];

cvCO2 =0.27337+0.0016*T-1.24189E-6*T^2+4.79536E-10*T^3-7.34111E-14*T^4 [kJ/kgK];

```
>
>
nC:=0.85/12;nH2:=0.15/2;Maer:=0.21*32+0.79*28;Hs:=(nC*94030+nH2*57800)*
4.185;
```

nC := 0.0708333333

nH2 := 0.0750000000

Maer := 28.84

Hs := 46015.9931

```
>
> restart;
> nC:=0.85/12;nH2:=0.15/2;Maer:=0.21*32+0.79*28;Hs:=46000;
```

nC := 0.0708333333

nH2 := 0.0750000000

$Maer := 28.84$

$Hs := 4600$

```
> gO2:=0.21*32/Maer;gN2:=0.79*28/Maer;nO2:=gO2/32;nN2:=gN2/28;
```

$gO2 := 0.233009708$

$gN2 := 0.766990291$

$nO2 := 0.00728155339$

$nN2 := 0.0273925104$

```
> cp:=1.01027-1.73736E-4*T+6.08005E-7*T^(2)-3.80644E-10*T^(3)+7.49874E-14*T^(4);cv:=0.72301-1.73889E-4*T+6.09496E-7*T^(2)-3.81877E-10*T^(3)+7.52717E-14*T^(4);cpO2:=0.82397+3.05587E-4*T+5.32089E-8*T^2-1.30137E-10*T^3+3.58225E-14*T^4;cvO2:=0.56574+2.96923E-4*T+6.54515E-8*T^2-1.36918E-10*T^3+3.71407E-14*T^4;cpH2O:=1.84336-2.31223E-4*T+1.1966E-6*T^2-6.15263E-10*T^3+1.0015E-13*T^4;cvH2O:=1.38161-2.29361E-4*T+1.19327E-6*T^2-6.13657E-10*T^3+9.99765E-14*T^4;cpN2:=1.07623-3.25964E-4*T+7.92186E-7*T^2-4.66137E-10*T^3+8.87148E-14*T^4;cvN2:=0.77884-3.22759E-4*T+7.86981E-7*T^2-4.62795E-10*T^3+8.79811E-14*T^4;cpCO2:=0.46236+0.0016*T-1.2402E-6*T^2+4.78609E-10*T^3-7.32796E-14*T^4;cvCO2:=0.27337+0.0016*T-1.24189E-6*T^2+4.79536E-10*T^3-7.34111E-14*T^4;
```

$$cp := 1.01027 - 0.000173736T + 6.08005\,10^{-7}\,T^2 - 3.80644\,10^{-10}\,T^3 + 7.49874\,10^{-14}\,T^4$$

$$cv := 0.72301 - 0.000173889T + 6.09496\,10^{-7}\,T^2 - 3.81877\,10^{-10}\,T^3 + 7.52717\,10^{-14}\,T^4$$

$$cpO2 := 0.82397 + 0.000305587T + 5.32089\,10^{-8}\,T^2 - 1.30137\,10^{-10}\,T^3 + 3.58225\,10^{-14}\,T^4$$

$$cvO2 := 0.56574 + 0.000296923T + 6.54515\,10^{-8}\,T^2 - 1.36918\,10^{-10}\,T^3 + 3.71407\,10^{-14}\,T^4$$

$cpH2O := 1.84336 - 0.000231223 T + 0.0000011966 T^2$
$- 6.15263 10^{-10} T^3 + 1.0015 10^{-13} T^4$

$cvH2O := 1.38161 - 0.000229361 T + 0.00000119327 T^2$
$- 6.13657 10^{-10} T^3 + 9.99765 10^{-14} T^4$

$cpN2 := 1.07623 - 0.000325964 T + 7.92186 10^{-7} T^2$
$- 4.66137 10^{-10} T^3 + 8.87148 10^{-14} T^4$

$cvN2 := 0.77884 - 0.000322759 T + 7.86981 10^{-7} T^2$
$- 4.62795 10^{-10} T^3 + 8.79811 10^{-14} T^4$

$cpCO2 := 0.46236 + 0.0016 T - 0.0000012402 T^2 + 4.78609 10^{-10} T^3$
$- 7.32796 10^{-14} T^4$

$cvCO2 := 0.27337 + 0.0016 T - 0.00000124189 T^2 + 4.79536 10^{-10} T^3$
$- 7.34111 10^{-14} T^4$

```
>
p1:=1;p7:=1;T0:=273;T1:=293;h1:=int(cp,T=T0..T1);T5:=1573;efv1:=0.9;efv
2:=0.9;piv1:=1.1;piv2:=1;pic:=35/piv1/piv2;efc:=0.8;eft:=0.85;dpca:=0.9
8;mv1:=350;mv2:=mv1/2;mc:=evalf(mv1/5);
```

$p1 := 1$

$p7 := 1$

$T0 := 273$

$T1 := 293$

$h1 := 20.0332308$

$T5 := 1573$

$efv1 := 0.9$

$efv2 := 0.9$

$piv1 := 1.1$

$piv2 := 1$

$pic := 31.8181818$

$efc := 0.8$

$eft := 0.85$

$dpca := 0.98$

$mv1 := 350$

$mv2 := 175$

$mc := 70.$

```
> p2:=p1*piv1;T2t:=T1*piv1^((1.401282041-1)/1.401282041);dh12t:=int( cp, T=T1..T2t);du12t:=int( cv, T=T1..T2t);km12t:=dh12t/du12t;dh12:=dh12t/efv1;h2t:=int( cp, T=T0..T2t);
```

$p2 := 1.1$

$T2t := 301.107208($

$dh12t := 8.13088108$

$du12t := 5.80245863$

$km12t := 1.40128204$

$dh12 := 9.03431231($

$h2t := 28.1641119($

```
> eq12:=dh12-int(cp, T=T1..T2)=0;
```

$$eq12 := 302.0148059 - 1.010270000 T2 + 0.000086868000000 T2^2 - 2.026683333 10^{-7} T2^3 + 9.516100000 10^{-11} T2^4 - 1.499748000 10^{-14} T2^5 = 0$$

```
> T2eq:=evalf(solve(eq12,T2));
```

$$T2eq := -685.3537193 - 1788.099286 I, -685.3537193 + 1788.099286 I, 302.0076223, 3706.916233 - 2107.695718 I, 3706.916233 + 2107.695718 I$$

```
> T2:=302.0076223;ev1:=(T2t-T1)/(T2-T1);h2:=int( cp,T=T0..T2);c12:=(h2-h1)/(T2-T1);du12:=int(cv,T=T1..T2); km12:=dh12/du12;
```

$T2 := 302.007622$

$ev1 := 0.900038626$

$h2 := 29.0675430$

$c12 := 1.00296304$

$du12 := 6.44728901($

$km12 := 1.40125753$

```
> p3:=p2*piv2;T3t:=T2*piv2^((1.397001058-1)/1.397001058);dh23t:=int(
cp, T=T2..T3t);du23t:=int( cv,
T=T2..T3t);km23t:=dh23t/du23t;dh23:=dh23t/efv2;
```

$p3 := 1.1$

$T3t := 302.007622$

$dh23t := 0.$

$du23t := 0.$

$km23t := Float(undefined)$

$dh23 := 0.$

```
> eq23:=dh23-simplify(int(cp, T=T2..T3))=0;
```

$$eq23 := 302.0148059 - 1.010270000 T3 + 0.0000868680000 T3^2 - 2.026683333 10^{-7} T3^3 + 9.516100000 10^{-11} T3^4 - 1.499748000 10^{-14} T3^5 = 0$$

```
> T3eq:=evalf(solve(eq23,T3));
```

$$T3eq := -685.3537193 - 1788.099286 I, -685.3537193 + 1788.099286 I, 302.0076223, 3706.916233 - 2107.695718 I, 3706.916233 + 2107.695718 I$$

```
> T3:=302.0076223;ev2:=(T3t-T2)/(T3-T2);h3:=int( cp,T=T0..T3);c23:=(h3-
h2)/(T3-T2);du23:=int(cv,T=T2..T3); km23:=dh23/du23;
```

$T3 := 302.007622$

$ev2 := Float(undefined)$

$h3 := 29.0675430$

$c23 := Float(undefined)$

$du23 := 0.$

$km23 := Float(undefined)$

```
> p4:=p3*pic;T4t:=T3*pic^((1.379753301-1)/1.379753301);dh34t:=int( cp,
T=T3..T4t);du34t:=int( cv,
T=T3..T4t);km34t:=dh34t/du34t;dh34:=dh34t/efc;h4t:=int( cp, T=T0..T4t);
```

$p4 := 35.0000000$

$T4t := 782.714504$

$dh34t := 501.392583$

$du34t := 363.392897$

$km34t := 1.37975339$

$dh34 := 626.740729$

$h4t := 530.460126$

```
> eq34:=dh34-simplify(int(cp, T=T3..T4))=0;
```

$$eq34 := 928.7555350 - 1.010270000 T4 + 0.0000868680000 T4^2 - 2.026683333 10^{-7} T4^3 + 9.516100000 10^{-11} T4^4 - 1.499748000 10^{-14} T4^5 = 0$$

```
> T4eq:=evalf(solve(eq34,T4));
```

$$T4eq := -881.7301576 - 1789.018572 I, -881.7301576 + 1789.018572 I, 896.1614303, 3606.215767 - 2089.579802 I, 3606.215767 + 2089.579802 I$$

```
> T4:=896.1614303;ec:=(T4t-T3)/(T4-T3);h4:=int( cp, T=T0..T4);c34:=(h4-h3)/(T4-T3);du34:=int(cv,T=T3..T4); km34:=dh34/du34;
```

$T4 := 896.161430$

$ec := 0.809061350$

$h4 := 655.808272$

$c34 := 1.05484593$

$du34 := 456.190125$

$km34 := 1.37385860$

```
>
> eqca:=mcb*Hs+mc*int(cp,T=T0..T4)-mc*nN2*28*int(cpN2,T=T0..T5)-mcb*nC*44*int(cpCO2,T=T0..T5)-mcb*nH2*18*int(cpH2O,T=T0..T5)-(mc*nO2-mcb*nC-mcb*nH2/2)*32*int(cpO2,T=T0..T5)=0;
```

$eqca := 42126.69337 mcb - 56455.88487 = 0$

```
> mcb:=solve(eqca,mcb);
```

$mcb := 1.34014517$

```
> mga:=mc+mcb;mga:=mc*nN2*28+mcb*nC*44+mcb*nH2*18+(mc*nO2-mcb*nC-mcb*nH2/2)*32;
```

$mga := 71.3401451$

$mga := 71.3401451$

```
>
h5:=(mc*nN2*28*int(cpN2,T=T0..T5)+mcb*nC*44*int(cpCO2,T=T0..T5)+mcb*nH2*18*int(cpH2O,T=T0..T5)+(mc*nO2-mcb*nC-mcb*nH2/2)*32*int(cpO2,T=T0..T5))/mga;
```

$h5 := 1507.61197$

```
>
> p5:=p4*dpca;c45:=(h5-h4)/(T5-T4);
```

$p5 := 34.3000000$

$c45 := 1.25850348$

```
>
dh56ti:=(mc*nN2*28*int(cpN2,T=T5..T6t)+mcb*nC*44*int(cpCO2,T=T5..T6t)+mcb*nH2*18*int(cpH2O,T=T5..T6t)+(mc*nO2-mcb*nC-mcb*nH2/2)*32*int(cpO2,T=T5..T6t))/mga;dh56i:=dh56ti*eft;
```

$$dh56ti := 1.018496892 T6t - 1784.992168 - 0.00005376798496 T6t^2 + 1.875402014 10^{-7} T6t^3 - 8.991673071 10^{-11} T6t^4 + 1.417440051 10^{-14} T6t^5$$

$$dh56i := 0.8657223582 T6t - 1517.243343 - 0.00004570278722 T6t^2 + 1.594091712 10^{-7} T6t^3 - 7.642922110 10^{-11} T6t^4 + 1.204824043 10^{-14} T6t^5$$

```
> eqI:=mv1*dh12+mv2*dh23+mc*dh34+mga*dh56i=0;
```

$$eqI := -61206.49995 + 61.76075871 T6t - 0.003260443475 T6t^2 + 0.00001137227341 T6t^3 - 5.452471729 10^{-9} T6t^4 + 8.595232213 10^{-13} T6t^5 = 0$$

```
> T6teqI:=evalf(solve(eqI,T6t));
```

$$T6teqI := -960.3467968 - 1808.727417 I, -960.3467968 + 1808.727417 I, 942.9968412, 3660.648506 - 2146.163286 I, 3660.648506 + 2146.163286 I$$

```
>
T6t:=942.9968412;dh56t:=(mc*nN2*28*int(cpN2,T=T5..T6t)+mcb*nC*44*int(cp
```

```
CO2,T=T5..T6t)+mcb*nH2*18*int(cpH2O,T=T5..T6t)+(mc*nO2-mcb*nC-
mcb*nH2/2)*32*int(cpO2,T=T5..T6t))/mga;dh56:=dh56t*eft;du56t:=(mc*nN2*2
8*int(cvN2,T=T5..T6t)+mcb*nC*44*int(cvCO2,T=T5..T6t)+mcb*nH2*18*int(cvH
2O,T=T5..T6t)+(mc*nO2-mcb*nC-
mcb*nH2/2)*32*int(cvO2,T=T5..T6t))/mga;h6t:=(mc*nN2*28*int(cpN2,T=T0..T
6t)+mcb*nC*44*int(cpCO2,T=T0..T6t)+mcb*nH2*18*int(cpH2O,T=T0..T6t)+(mc*
nO2-mcb*nC-
mcb*nH2/2)*32*int(cpO2,T=T0..T6t))/mga;dh56:=dh56t*eft;km56t:=dh56t/du5
6t;
```

$T6t := 942.996841$

$dh56t := -775.635559$

$dh56 := -659.290225$

$du56t := -593.756753$

$h6t := 731.976415$

$dh56 := -659.290225$

$km56t := 1.30631871$

```
> eqIverificare:=mv1*dh12+mv2*dh23+mc*dh34+mga*dh56=0;
```

$eqIverificare := -0.00002 = 0$

```
> eq56:=dh56-
simplify((mc*nN2*28*int(cpN2,T=T5..T6)+mcb*nC*44*int(cpCO2,T=T5..T6)+mc
b*nH2*18*int(cpH2O,T=T5..T6)+(mc*nO2-mcb*nC-
mcb*nH2/2)*32*int(cpO2,T=T5..T6))/mga)=0;
```

$$eq56 := 1125.701943 - 1.018496892\, T6 + 0.00005376798496\, T6^2 - 1.875402014\,10^{-7}\, T6^3 + 8.991673071\,10^{-11}\, T6^4 - 1.417440051\,10^{-14}\, T6^5 = 0$$

```
> T6eq:=evalf(solve(eq56,T6));
```

$$T6eq := -989.8076466 - 1814.419979 I, -989.8076466 + 1814.419979 I, 1041.347056, 3640.934247 - 2143.940324 I, 3640.934247 + 2143.940324 I$$

```
> T6:=1041.347056;p6:=p5*(T6t/T5)^((dh56t/du56t)/((dh56t/du56t)-
1));et:=(T5-T6)/(T5-
```

```
T6t);h6:=(mc*nN2*28*int(cpN2,T=T0..T6)+mcb*nC*44*int(cpCO2,T=T0..T6)+mcb*nH2*18*int(cpH2O,T=T0..T6)+(mc*nO2-mcb*nC-mcb*nH2/2)*32*int(cpO2,T=T0..T6))/(mc*nN2*28+mcb*nC*44+mcb*nH2*18+(mc*nO2-mcb*nC-mcb*nH2/2)*32);c56:=(h6-h5)/(T6-T5);du56:=(mc*nN2*28*int(cvN2,T=T5..T6)+mcb*nC*44*int(cvCO2,T=T5..T6)+mcb*nH2*18*int(cvH2O,T=T5..T6)+(mc*nO2-mcb*nC-mcb*nH2/2)*32*int(cvO2,T=T5..T6))/(mc*nN2*28+mcb*nC*44+mcb*nH2*18+(mc*nO2-mcb*nC-mcb*nH2/2)*32);km56:=dh56/du56;
```

$T6 := 1041.34705$

$p6 := 3.86925212$

$et := 0.843889330$

$h6 := 848.321749$

$c56 := 1.24007631$

$du56 := -505.806259$

$km56 := 1.30344418$

```
> T7t:=T6*(p7/p6)^((1.331543213-1)/1.331543213);dh67t:=(mc*nN2*28*int(cpN2,T=T6..T7t)+mcb*nC*44*int(cpCO2,T=T6..T7t)+mcb*nH2*18*int(cpH2O,T=T6..T7t)+(mc*nO2-mcb*nC-mcb*nH2/2)*32*int(cpO2,T=T6..T7t))/mga;du67t:=(mc*nN2*28*int(cvN2,T=T6..T7t)+mcb*nC*44*int(cvCO2,T=T6..T7t)+mcb*nH2*18*int(cvH2O,T=T6..T7t)+(mc*nO2-mcb*nC-mcb*nH2/2)*32*int(cvO2,T=T6..T7t))/mga;km67t:=dh67t/du67t;h7t:=(mc*nN2*28*int(cpN2,T=T0..T7t)+mcb*nC*44*int(cpCO2,T=T0..T7t)+mcb*nH2*18*int(cpH2O,T=T0..T7t)+(mc*nO2-mcb*nC-mcb*nH2/2)*32*int(cpO2,T=T0..T7t))/mga;
```

$T7t := 743.500454$

$dh67t := -345.348592$

$du67t := -259.359703$

$km67t := 1.33154298$

$h7t := 502.973157$

```
> dh67:=dh67t*0.98;
```

$dh67 := -338.441620$

```
> eq67:=dh67-
```

```
simplify((mc*nN2*28*int(cpN2,T=T6..T7)+mcb*nC*44*int(cpCO2,T=T6..T7)+mcb*nH2*18*int(cpH2O,T=T6..T7)+(mc*nO2-mcb*nC-mcb*nH2/2)*32*int(cpO2,T=T6..T7))/mga)=0;
```

$$eq67 := 787.2603228 - 1.018496892\,T7 + 0.00005376798488\,T7^2 - 1.875402016\,10^{-7}\,T7^3 + 8.991673070\,10^{-11}\,T7^4 - 1.417440049\,10^{-14}\,T7^5 = 0$$

```
> T7eq:=evalf(solve(eq67,T7));
```

$$T7eq := -899.8723869 - 1800.029561 I,\ -899.8723869 + 1800.029561 I,\ 749.6445992,\ 3696.850220 - 2151.191691 I,\ 3696.850220 + 2151.191691 I$$

```
> T7:=749.6445992;eaj:=(T7-T6)/(T7t-T6);h7:=(mc*nN2*28*int(cpN2,T=T0..T7)+mcb*nC*44*int(cpCO2,T=T0..T7)+mcb*nH2*18*int(cpH2O,T=T0..T7)+(mc*nO2-mcb*nC-mcb*nH2/2)*32*int(cpO2,T=T0..T7))/mga;c67:=(h7-h6)/(T7-T6);du67:=(mc*nN2*28*int(cvN2,T=T6..T7)+mcb*nC*44*int(cvCO2,T=T6..T7)+mcb*nH2*18*int(cvH2O,T=T6..T7)+(mc*nO2-mcb*nC-mcb*nH2/2)*32*int(cvO2,T=T6..T7))/mga;km67:=dh67/du67;
```

$T7 := 749.644599$

$eaj := 0.979371446$

$h7 := 509.880129$

$c67 := 1.16022889$

$du67 := -254.226445$

$km67 := 1.33126048$

```
>
> w7:=sqrt(-2000*dh67);Ft7:=mga*w7/1000/9.81;
```

$w7 := 804.121376$

$Ft7 := 5.84771993$

```
> w7v2:=sqrt(2000*0.98*(dh12+dh23));Ft7v2:=(mv2-mc)*w7v2/1000/9.81;
```

$w7v2 := 133.068599$

$Ft7v2 := 1.42428164$

```
> w7v1:=sqrt(2000*0.98*dh12);Ft7v1:=(mv1-mv2-mc)*w7v1/1000/9.81;
```

$w7v1 := 133.068599$

$Ft7v1 := 1.42428164$

```
> Ft:=Ft7+Ft7v2+Ft7v1;
```

$Ft := 8.69628322$

```
> > restart;
> cpN2:=evalf(1.742661-22878.11/T^(3/2)+478584.8/T^2-3.660212*10^7/T^3);cpO2:=evalf(1.670028+8.968502*T^(3/2)/10^7-7966.8957/T^(3/2)+105683.9/T^2);cpH2O:=evalf(6.382172-2.5894729*T^0.25+0.3691933*T^0.5-1.6502632*T/10^3);cpCO2:=evalf(-0.1666681+0.136205*T^0.5-1.8307308*T/10^3+1.079593*T^2/10^7);
```

$$cpN2 := 1.742661 - \frac{22878.11}{T^{3/2}} + \frac{4.78584810^{5}}{T^{2}} - \frac{3.66021200010^{7}}{T^{3}}$$

$$cpO2 := 1.670028 + 8.96850200010^{-7}\, T^{3/2} - \frac{7966.8957}{T^{3/2}} + \frac{1.05683910^{5}}{T^{2}}$$

$$cpH2O := 6.382172 - 2.5894729 T^{0.25} + 0.3691933 T^{0.5} - 0.001650263200 T$$

$$cpCO2 := -0.1666681 + 0.136205 T^{0.5} - 0.001830730800 T + 1.07959300010^{-7}\, T^{2}$$

```
> cpaer:=0.21*cpO2+0.79*cpN2;
```

$$cpaer := 1.72740807 + 1.88338542010^{-7}\, T^{3/2} - \frac{19746.75500}{T^{3/2}} + \frac{4.0027561110^{5}}{T^{2}} - \frac{2.89156748010^{7}}{T^{3}}$$

```
> haer:=cpaer*(T-T0);evalf(int( haer, T = T0..T1 ));
```

$$haer := \left(1.72740807 + 1.88338542010^{-7}\, T^{3/2} - \frac{19746.75500}{T^{3/2}} + \frac{4.0027561110^{5}}{T^{2}} - \frac{2.89156748010^{7}}{T^{3}}\right)(T - 273)$$

$$\frac{1}{T1^{5/2}}\left(2.930402930\,10^{-18}\left(1.836300784\,10^{10}\,T1^{6} - 7.018341598\,10^{12}\,T1^{5} - 1.347716029\,10^{22}\,T1^{3} - 3.679264758\,10^{24}\,T1^{2} + 2.947390019\,10^{17}\,T1^{9/2} - 1.609274951\,10^{20}\,T1^{7/2} - 1.346910204\,10^{27}\sqrt{T1} + 4.715765029\,10^{25}\,T1^{3/2} + 1.365940523\,10^{23}\ln(T1)\,T1^{5/2} - 4.535592942\,10^{23}\,T1^{5/2}\right)\right)$$

```
> DUBLUFLUX OPTIMIZARE;
```

DUBLUFLUX

```
>
> restart;
>
m:=355;mga:=1.02*m/rm;k12:=1.4;k23:=1.37;k45:=1.305;c12:=1.005;c23:=1.0
55;c45:=1.24;efv:=0.9;efc:=0.8;eft:=0.85;T1:=293;T4:=1573;;pic:=35/piv;
```

$m := 355$

$mga := \frac{362.10\cdot 1}{rm}$

$k12 := 1.4$

$k23 := 1.37$

$k45 := 1.305$

$c12 := 1.005$

$c23 := 1.055$

$c45 := 1.24$

$efv := 0.9$

$efc := 0.8$

$eft := 0.85$

$T1 := 293$

$T4 := 1573$

$pic := \frac{35\cdot 1}{piv}$

```
> T2t:=T1*(piv)^((k12-1)/k12);T2:=T1+(T2t-T1)/efv;
```

$T2t := 293\, piv^{0.2857142857}$

$T2 := -32.5555555 + 325.5555555 piv^{0.2857142857}$

```
> T3t:=T2*(pic)^((k23-1)/k23);
```

$$T3t := 2.612227984\left(-32.5555555 + 325.5555555 piv^{0.2857142857}\right)\left(\frac{1}{piv}\right)^{0.2700729927}$$

```
> T3:=T2+(T3t-T2)/efc;
```

$$T3 := 8.13888888 - 81.3888889 piv^{0.2857142857} + 3.265284980\left(-32.5555555 + 325.5555555 piv^{0.2857142857}\right)\left(\frac{1}{piv}\right)^{0.2700729927}$$

```
> p4:=p3*dpca;
```

$p4 := p3\ dpca$

```
> p5:=p4*pit;T5t:=T4*pit^((k45-1)/k45);
```

$p5 := p3\ dpca\ pit$

$T5t := 1573\, pit^{0.2337164751}$

```
>
> T5:=T4-(T4-T5t)*eft;
```

$T5 := 235.95 + 1337.05 pit^{0.2337164751}$

```
> p6:=1;
```

$p6 := 1$

```
>
> T6t:=T5*(p6/p5)^((k56-1)/k56);
```

$$T6t := \left(235.95 + 1337.05 pit^{0.2337164751}\right)\left(\frac{1}{p3\ dpca\ pit}\right)^{\frac{k56-1}{k56}}$$

```
>
> T6:=T5-(T5-T6t)*efaj;
```

$$T6 := 235.95 + 1337.05 pit^{0.2337164751} - \left(235.95 + 1337.05 pit^{0.2337164751} - \left(235.95 + 1337.05 pit^{0.2337164751}\right) \left(\frac{1}{p3\ dpca\ pit}\right)^{\frac{k56-1}{k56}}\right) efaj$$

```
>
> eqI:=evalf((mga*c45*(T4-T5)-m*c12*(T2-T1)+m*c23*(T3-T4)/rm))=0;
```

$$eqI := \frac{449.0040 \left(1337.05 - 1337.05 pit^{0.2337164751}\right)}{rm} - 1.16150083310^{5}\ piv^{0.2857142857} + 1.16150083310^{5} + \frac{1}{rm}\left(374.525\left(-1564.861111 - 81.3888889 piv^{0.2857142857} + 3.265284980\left(-32.5555555 + 325.5555555 piv^{0.2857142857}\right)\left(\frac{1}{piv}\right)^{0.2700729927}\right)\right) = 0$$

```
>
>
>
> 449.0040*(1337.05-1337.05*pit^.2337164751)/rm=116150.0833*piv^.2857142857-116150.0833-374.525*(-1564.861111-81.3888889*piv^.2857142857+3.265284980*(-32.5555555+325.5555555*piv^.2857142857)*(1/piv)^.2700729927)/rm;
```

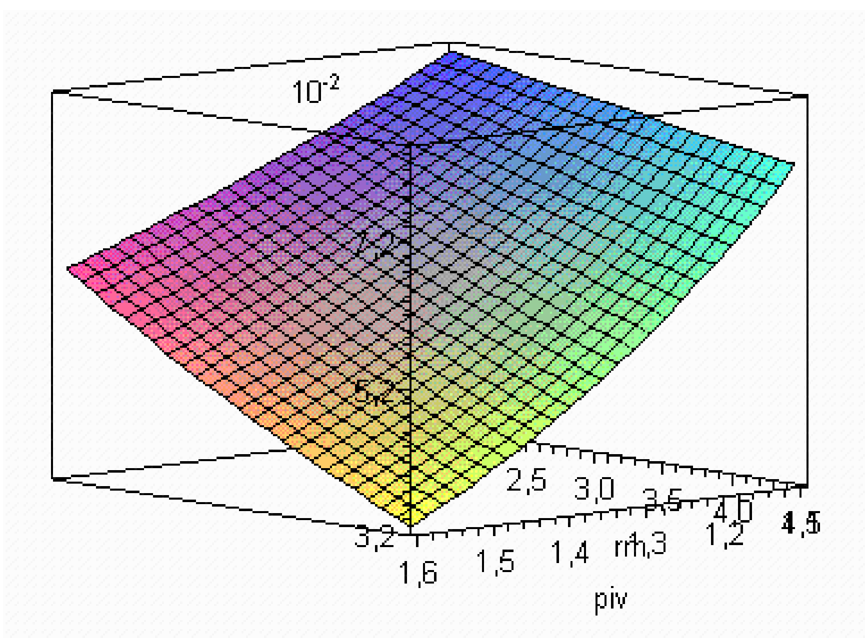
$$\frac{449.0040 \left(1337.05 - 1337.05 pit^{0.2337164751}\right)}{rm} = 1.16150083310^{5}\ piv^{0.2857142857} - 1.16150083310^{5} - \frac{1}{rm}\left(374.525\left(-1564.861111 - 81.3888889 piv^{0.2857142857} + 3.265284980\left(-32.5555555 + 325.5555555 piv^{0.2857142857}\right)\left(\frac{1}{piv}\right)^{0.2700729927}\right)\right)$$

\>

```
> pit:=(-(rm*(116150.0833*piv^.2857142857-116150.0833-374.525*(-1564.861111-81.3888889*piv^.2857142857+3.265284980*(-32.5555555+325.5555555*piv^.2857142857)*(1/piv)^.2700729927)/rm)/449.0040/1337.05-1))^(1/.2337164751);
```

$$pit := \left(-0.000001665720542\, rm \left(1.16150083310^{5}\, piv^{0.2857142857} - 1.16150083310^{5} - \frac{1}{rm}\left(374.525\left(-1564.861111 - 81.3888889 piv^{0.2857142857} + 3.265284980\left(-32.5555555 + 325.5555555 piv^{0.2857142857}\right)\left(\frac{1}{piv}\right)^{0.2700729927}\right)\right)\right) + 1\right)^{4.278688525}$$

```
> plot3d( pit,piv=1.1..1.6,rm=2..4.5);
```



\>

\>

\>

```
> restart;
> dh12:=wv^2/2;dh56:=wt^2/2;
```

$$dh12 := \frac{1}{2}\,wv^2$$

$$dh56 := \frac{1}{2}\,wt^2$$

```
> m:=1;mga:=1.02*m/rm;
```

$$m := 1$$

$$mga := \frac{1.02\cdot 1}{rm}$$

```
>
> eqI:=m*dh12+m*dh23/rm-mga*dh45=0;
```

$$eqI := \frac{1}{2}\,wv^2 + \frac{dh23}{rm} - \frac{1.02\,dh45}{rm} = 0$$

```
> eqT:=fT-mga*wt-m*wv/rm=0;
```

$$eqT := fT - \frac{1.02\,wt}{rm} - \frac{wv}{rm} = 0$$

POMPA DE CALDURA CU APORT SOLAR

```
A:=aperture;Asc:=absorber_area;Is:=solar_insolation;FO:=optical_efficiency;etasc:=solar_colector_efficiency;epssc:=solar_colector_effectiveness;UL:=solar_colector_heat_loss_coefficient;Tsai:=-.6666666666*Ta+491.9166666;Tsao:=-.9047619047*Ta+562.1904761;Ca:=1000;Csc:=1000;
```

$A := aperture$

$Asc := absorber\_area$

$Is := solar\_insolation$

$FO := optical\_efficiency$

$etasc := solar\_colector\_efficiency$

$epssc := solar\_colector\_effectiveness$

$UL := solar\_colector\_heat\_loss\_coefficient$

$Tsai := -0.6666666666 Ta + 491.916666$

$Tsao := -0.9047619047 Ta + 562.190476$

$Ca := 1000$

$Csc := 1000$

```
> Ntsai_50_30;DNtsai_tsao_10;with(CurveFitting):
Tsai:=PolynomialInterpolation([[253.15,323.15],[288.15,303.15]], Ta);
```

Ntsai_50_30

DNtsai_tsao_10

$Tsai := -0.5714285714 Ta + 467.807142$

```
> with(CurveFitting):
Tsao:=PolynomialInterpolation([[253.15,333.15],[288.15,304.4]], Ta);
```

$Tsao := -0.8214285714 Ta + 541.094642$

```
> restart;
>
Refrigerent_R134a;Ta:=253.15;Is:=50;FO:=0.95;UL:=2;Ca:=1000;Csc:=1000;e
tasc:=0.75;epssc:=0.75;
```

Refrigerent_R134a

$Ta := 253.15$

$Is := 50$

$FO := 0.95$

$UL := 2$

$Ca := 1000$

$Csc := 1000$

$etasc := 0.75$

$epssc := 0.75$

```
> Tsai:=-.5714285714*Ta+467.8071428;Tsao:=-.8214285714*Ta+541.0946428;
```

$Tsai := 323.150000$

$Tsao := 333.150000$

```
> Condenser;Tc:=Tsai+Qc/Ca/epsc;
```

Condenser

$$Tc := 323.1500000 + \frac{1}{1000} \frac{Qc}{epsc}$$

```
> Solar_colector;Asc:=100;A:=Asc;Tsc:=Ta+Is*(FO-
```

```
etasc)/UL;Ts:=Ta+Is*FO/UL;Tsco:=Ta+Is*(FO-etasc)/UL-
etasc*Is*Asc/epssc/Csc;Tsci := Ta+etasc*Is*Asc*(1-1/epssc)/Csc+Is*(FO-
etasc)/UL;
```

Solar_colector

$Asc := 100$

$A := 100$

$Tsc := 258.1500000$

$Ts := 276.9000000$

$Tsco := 253.1500000$

$Tsci := 256.9000000$

```
> Evaporator;Te:=Ta+etasc*Is*Asc*(1-1/epssc)/Csc+Is*(FO-etasc)/UL-
etasc*Is*Asc/epse/Csc;Qe:=epse*Csc*(Tsci-Te);
```

Evaporator

$$Te := 256.9000000 - \frac{3.750000000}{epse}$$

$Qe := 3750.000000$

```
> Irreversibility;RT:=Tc/Te;COP_r:=-
.9796943861+1.91034690519667039*RT;;Irr:=COP_r/RT;
```

Irreversibility

$$RT := \frac{323.1500000 + \frac{1}{1000}\frac{Qc}{epsc}}{256.9000000 - \frac{3.750000000}{epse}}$$

$$COP\_r := -0.9796943861 + \frac{1.91034690519667039\left(323.1500000 + \frac{1}{1000}\frac{Qc}{epsc}\right)}{256.9000000 - \frac{3.750000000}{epse}}$$

$$Irr := \frac{1}{323.1500000 + \frac{1}{1000}\,\frac{Qc}{epsc}}\left(\left(-0.9796943861 + \frac{1.91034690519667039\left(323.1500000 + \frac{1}{1000}\,\frac{Qc}{epsc}\right)}{256.9000000 - \frac{3.750000000}{epse}}\right)\left(256.9000000 - \frac{3.750000000}{epse}\right)\right)$$

```
> Qc:=solve((Qc-Qe*RT*Irr),Qc);Tsao:=Tsai+Qc/Ca;
```

$$Qc := \left(150.\, epsc\, \left(4.57056393210^{12}\, epse + 4.59231743510^{10}\right)\right) / \left(1.28450000010^{11}\, epsc\, epse - 1.87500000010^{9}\, epsc - 3.58190044710^{9}\, epse\right)$$

$$Tsao := 323.1500000 + \left(0.1500000000\, epsc\, \left(4.57056393210^{12}\, epse + 4.59231743510^{10}\right)\right) / \left(1.28450000010^{11}\, epsc\, epse - 1.87500000010^{9}\, epsc - 3.58190044710^{9}\, epse\right)$$

```
> W:=Qe-Qc;COP:=-Qc/W;
```

$$W := 3750.000000 - \left(150.\, epsc\, \left(4.57056393210^{12}\, epse + 4.59231743510^{10}\right)\right) / \left(1.28450000010^{11}\, epsc\, epse - 1.87500000010^{9}\, epsc - 3.58190044710^{9}\, epse\right)$$

$$COP := -\left(150.\, epsc\, \left(4.57056393210^{12}\, epse + 4.59231743510^{10}\right)\right) \Big/ \Big(\left(1.28450000010^{11}\, epsc\, epse - 1.87500000010^{9}\, epsc - 3.58190044710^{9}\, epse\right) \Big(3750.000000 - \left(150.\, epsc\, \left(4.57056393210^{12}\, epse + 4.59231743510^{10}\right)\right) / \left(1.28450000010^{11}\, epsc\, epse - 1.87500000010^{9}\, epsc - 3.58190044710^{9}\, epse\right)\Big)\Big)$$

```
> COP_Carnot:=Tc/(Tc-Te);R_COP:=COP/COP_Carnot;
```

$$COP\_Carnot := \Big(323.1500000 + \big(0.1500000000\big(4.57056393210^{12}\ eps$$

$$+\ 4.59231743510^{10}\big)\big) \big/ \big(1.28450000010^{11}\ epsc\ epse$$

$$-\ 1.87500000010^{9}\ epsc - 3.58190044710^{9}\ epse\big)\Big) \Big/$$

$$\Big(66.2500000 + \big(0.1500000000\big(4.57056393210^{12}\ epse$$

$$+\ 4.59231743510^{10}\big)\big) \big/ \big(1.28450000010^{11}\ epsc\ epse$$

$$-\ 1.87500000010^{9}\ epsc - 3.58190044710^{9}\ epse\big)$$

$$+\ \frac{3.750000000}{epse}\Big)$$

$$R\_COP := -\Big(150.\ epsc\ \big(4.57056393210^{12}\ epse$$

$$+\ 4.59231743510^{10}\big)\ \Big(66.2500000$$

$$+\ \big(0.1500000000\big(4.57056393210^{12}\ epse + 4.59231743510^{10}\big)\big) /$$

$$\big(1.28450000010^{11}\ epsc\ epse - 1.87500000010^{9}\ epsc$$

$$-\ 3.58190044710^{9}\ epse\big) + \frac{3.750000000}{epse}\Big)\Big) \Big/$$

$$\Big(\big(1.28450000010^{11}\ epsc\ epse - 1.87500000010^{9}\ epsc$$

$$-\ 3.58190044710^{9}\ epse\big)\ \Big(3750.000000$$

$$-\ \big(150.\ epsc\ \big(4.57056393210^{12}\ epse + 4.59231743510^{10}\big)\big) \big/$$

$$\big(1.28450000010^{11}\ epsc\ epse - 1.87500000010^{9}\ epsc$$

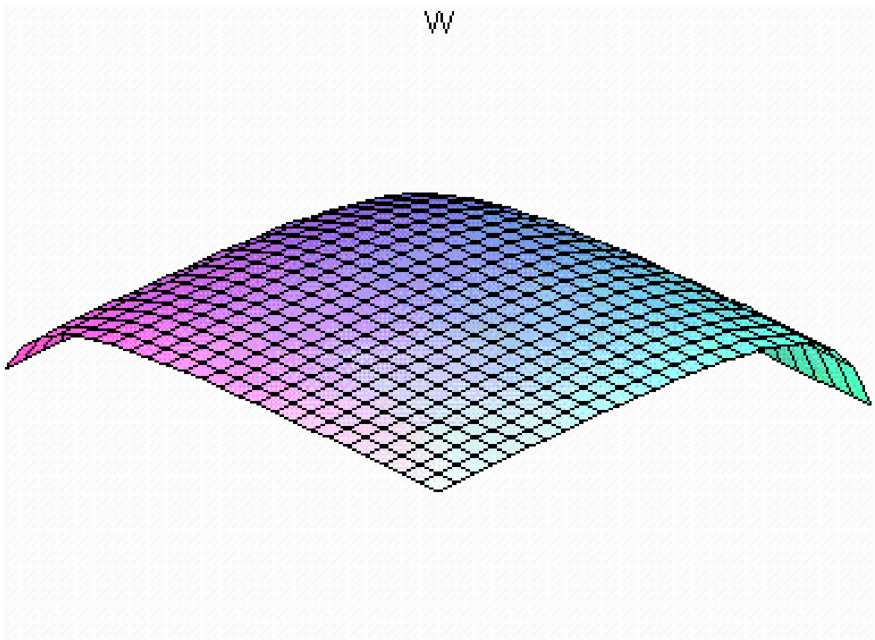
$$-\ 3.58190044710^{9}\ epse\big)\big)\ \Big(323.1500000$$

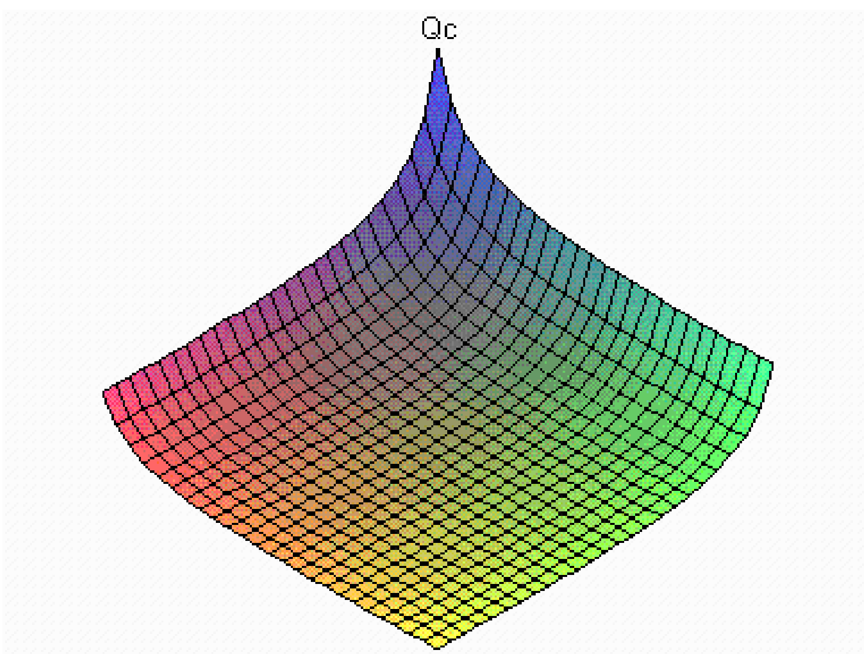
$$+\ \big(0.1500000000\big(4.57056393210^{12}\ epse + 4.59231743510^{10}\big)\big) /$$

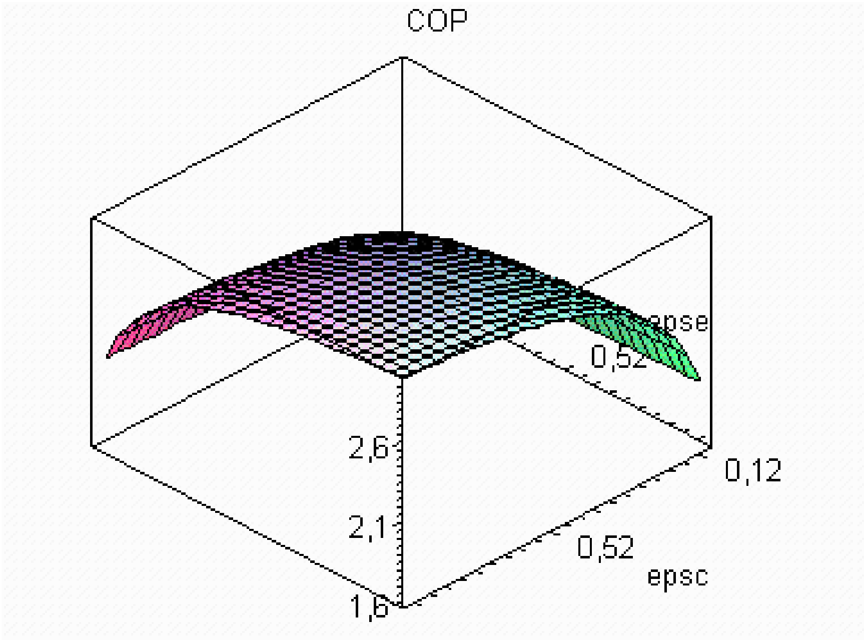
$$\big(1.28450000010^{11}\ epsc\ epse - 1.87500000010^{9}\ epsc$$

$$-\ 3.58190044710^{9}\ epse\big)\Big)\Big)$$

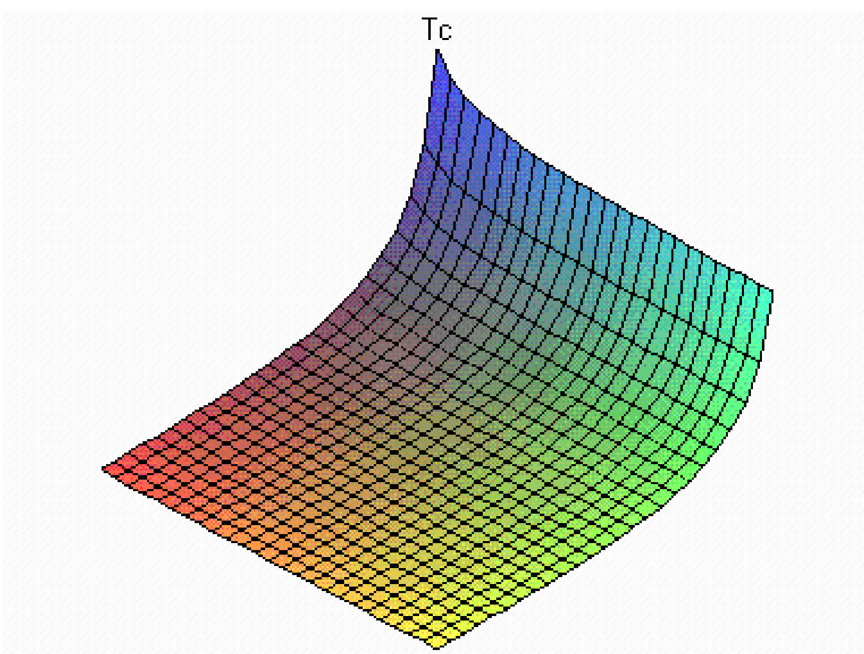
```
>
plot3d(W,epsc=0.1..0.9,epse=0.1..0.9,title="W");plot3d(Qc,epsc=0.1..0.9
,epse=0.1..0.9,title="Qc");plot3d(COP,epsc=0.1..0.9,epse=0.1..0.9,title
="COP");
```

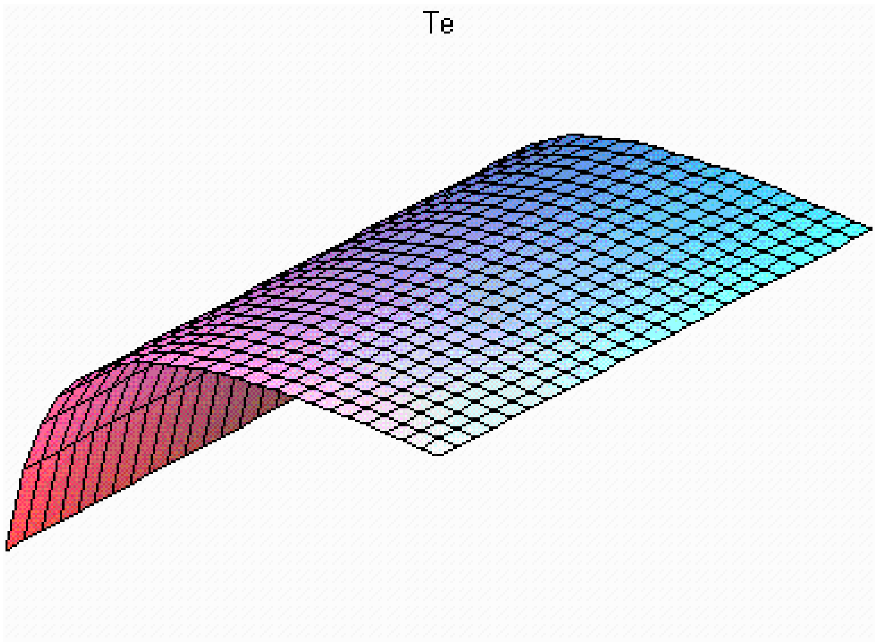




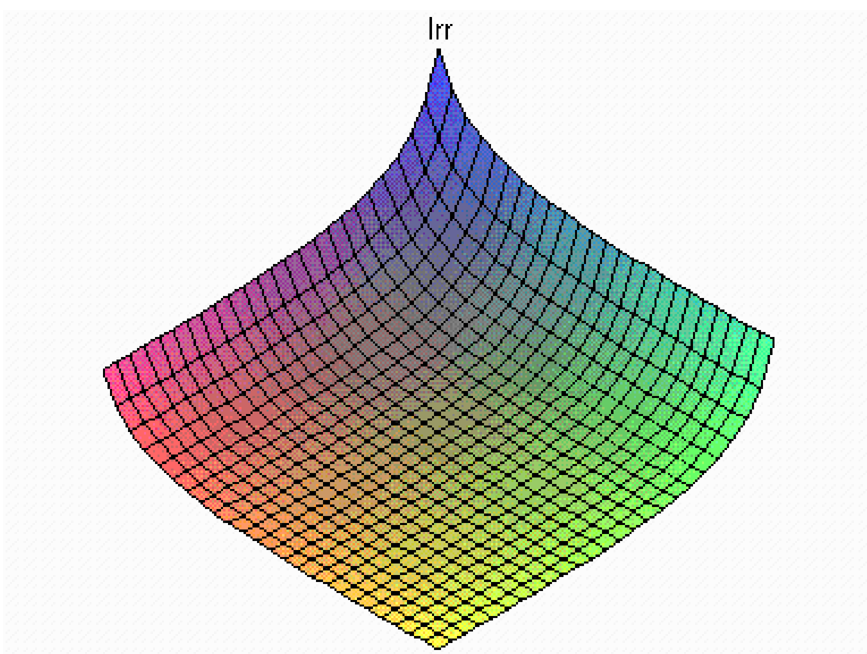


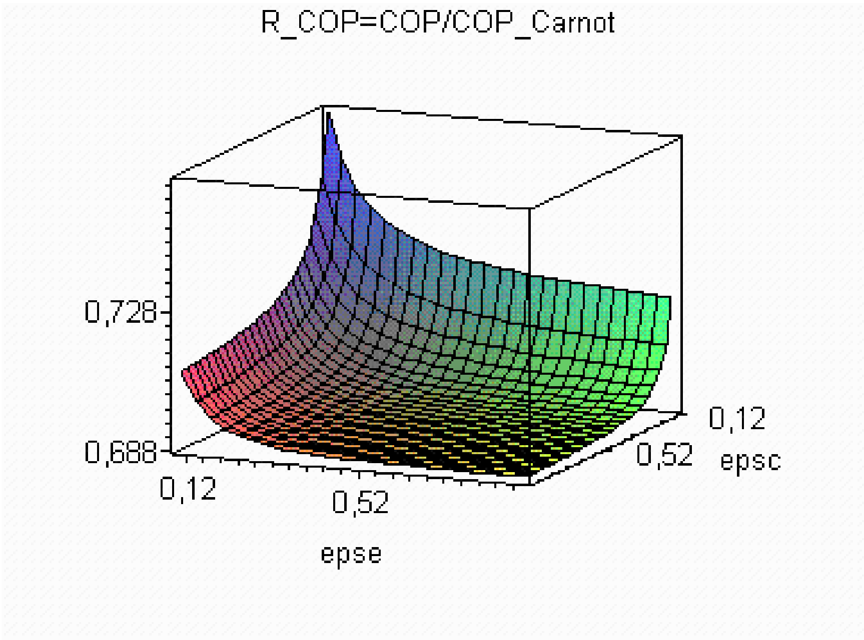

```
> 
plot3d(Tc,epsc=0.1..0.9,epse=0.1..0.9,title="Tc");plot3d(Te,epsc=0.1..0
.9,epse=0.1..0.9,title="Te");
```

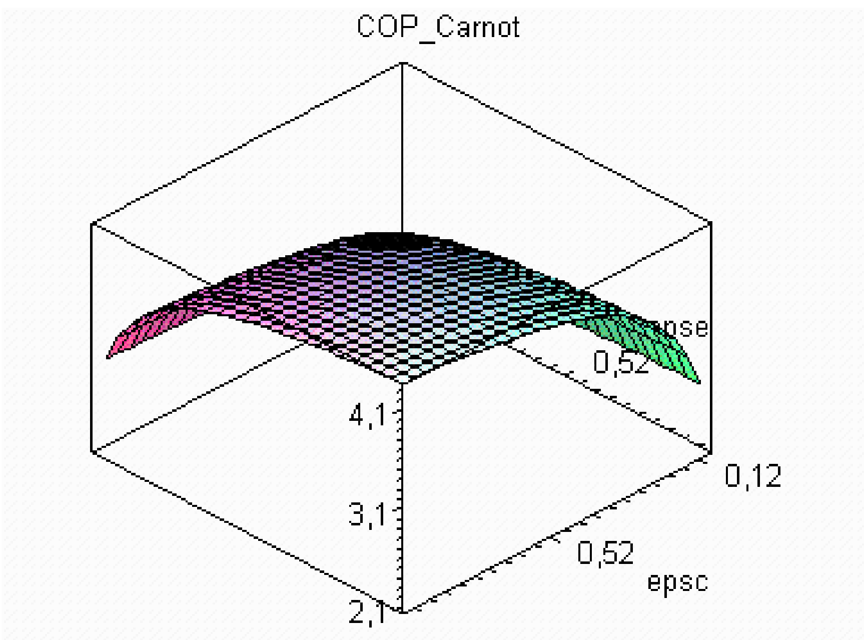





```
>
plot3d(Irr,epsc=0.1..0.9,epse=0.1..0.9,title="Irr");plot3d(R_COP,epsc=0
.1..0.9,epse=0.1..0.9,title="R_COP=COP/COP_Carnot");plot3d(COP_Carnot,e
psc=0.1..0.9,epse=0.1..0.9,title="COP_Carnot");
```







>

COMPRESOR CENTRIFUGAL

```
> restart;
```

1-Debitul masic: m [kg/s]

```
> m:=1.2;
```

$m := 1.2$

2-Umiditatea relativa a aerului aspirat de compresor: fiN

```
> fiN:=0.7;
```

$fiN := 0.7$

3-Presiunea totala a aerului aspirat de compresor: p_tot_N, [n/m2]

```
> p_tot_N:=101325;
```

$p\_tot\_N := 101325$

4-Temperatura aerului aspirat de compresor: T_tot_N, [K]

```
> T_tot_N:=288;
```

$T\_tot\_N := 288$

5-Constanetele de gaz perfect pentru aerul aspirat de compresor si vaporii de apa: R_a_us si R_v, [J/kg K]

```
> R_a_us:=287;R_v:=462;
```

$R\_a\_us := 287$

$R\_v := 462$

6-Exponentul adiabatic al aerului: k

```
> k:=1.395;
```

$k := 1.395$

7-Presiunea de saturatie a vaporilor din aerul umed: p_sat, [N/m2]

```
> p_sat:=1704.1;
```

$p\_sat := 1704.1$

8-Presiunea partiala a vaporilor din aerul umed aspirat: p_v, [N/m2]

```
> p_v:=fiN*p_sat;
```

$p\_v := 1192.87$

9-Continutul de umiditate al aerului umed aspirat de compresor: x, [kg/kg]

```
> x:=0.622*p_v/(p_tot_N-p_v);
```

$x := 0.00740986075$

10-Constanta de gaz perfect a aerului umed, R_a_um, [J/kg K]

```
> R_a_um:=(R_a_us+x*R_v)/(1+x);
```

$R\_a\_um := 288.287187$

11-Caldura specifica izobara a aerului umed aspirat de compresor: cp, [J/kg K]

```
> cp:=k*R_a_um/(k-1);
```

$cp := 1018.12816$

12-Viteza absoluta a aerului aspirat de compresor: c1, [m/s]

```
> cN:=30;
```

$cN := 30$

Viteza absoluta a aerului la intrarea in rotor: c1, [m/s]

```
> c1:=60;
```

$c1 := 60$

13-Unghiul vitezei absolute la intrarea in rotor, pozitiv in sensul de rotatie al rotorului, considerat constant pe raza (se alege intre 0 si 30 grade): psi, [rad]

```
> psi:=(30*evalf(Pi)/180);psi_gr:=psi*180/evalf(Pi);
```

$\psi := 0.523598775$

$psi\_gr := 30.0000000$

Temperatura statica a aerului aspirat de compresor: TN, [K]

```
> TN:=T_tot_N-cN^2*(k-1)/2/k/R_a_um;
```

$TN := 287.558012$

14-Presiunea statica a aerului aspirat de compresor: pN, [N/m2]

```
> pN:=p_tot_N*(TN/T_tot_N)^(k/(k-1));
```

$pN := 1.007768903 10^5$

15-Raportul vitezelor in racordul de aspiratie, c1_cN

```
> c1_cN:=c1/cN;
```

$c1\_cN := 2$

16-Temperatura teoretica statica a aerului la intrarea in rotor, T1s, [K]

```
> T1s:=T_tot_N-c1^2*(k-1)/2/k/R_a_um;
```

$T1s := 286.232049$

17-Coeficientul de pierderi in racordul de aspiratie, (se alege in domeniul 0,5....1,5): zRI

```
> zRI:=1;
```

$zRI := 1$

18-Pierderi in racordul de aspiratie: l_N_1, [J/kg]; L_N_1, [W]

```
> l_N_1:=zRI*c1^2/2;L_N_1:=l_N_1*m;
```

$l\_N\_1 := 1800$

$L\_N\_1 := 2160.0$

19-Cifra politropica in racordul de aspiratie, (este de fapt n/(n-1)): sRI

```
> sRI:=k*(1-l_N_1*(k-1)/k/R_a_um/(T1s-TN))/(k-1);
```

$sRI := 8.24050641$

20-Exponentul politropic in racordul de aspiratie: n

```
> n:=sRI/(sRI-1);
```

$n := 1.13811188$

21-Temperatura statica a aerului la intrarea in rotor, T1, [K]

```
> T1:=T_tot_N-(c1^2-cN^2)/2/cp-l_N_1/cp;
```

$T1 := 284.906087$

22-Presiunea statica la intrarea in rotor: p1, [N/m2]

```
> p1:=pN*(T1/TN)^(n/(n-1));
```

$p1 := 93369.1178$

23-Presiunea totala la intrarea in rotor: p1_tot, [N/m2]

```
> p1_tot:=p1*(T_tot_N/T1)^(k/(k-1));
```

$p1\_tot := 96999.4687$

Coeficientul de restabilire a presiunii totale: DRI

```
> DRI:=p1_tot/p_tot_N;
```

$DRI := 0.957310325$

24-Presiunea totala a aerului comprimat: p_tot_K, [N/m2]

```
> p_tot_K:= 920000;
```

$p\_tot\_K := 920000$

25-Raportul de comprimare al compresorului, in parametri de franare: piC

```
> piC_tot:=evalf(p_tot_K/p_tot_N);
```

$piC\_tot := 9.07969405$

26-Randamentul izentropic global, se impune initial in domeniul 0,75....0,85 si se verifica ulterior: etas

```
> etas_tot:=.7166739258;
```

$etas\_tot := 0.716673925$

27-Consumurile energetice teoretice globale: ladC_tot, [J/kg] si LadC_tot, [W]

```
> ladC_tot:=k*R_a_um*T_tot_N*(piC_tot^((k-1)/k)-1)/(k-
1);LadC_tot:=m*ladC_tot;
```

$ladC\_tot := 2.54395876710^{5}$

LadC_tot := $3.052750520\,10^5$

28-Consumuri energetice reale globale: l_real_C, [J/kg] si L_real_C, [W]

```
> l_real_C_tot:=ladC_tot/etas_tot;L_real_C_tot:=m*l_real_C_tot;
```

l_real_C_tot := $3.549673953\,10^5$

L_real_C_tot := $4.259608744\,10^5$

29-Cifra de debit (aleasa intre 0,25....0,35, probabil este raportul c2r/u2): fi2

```
> fi2:=0.25;
```

fi2 := 0.25

30-Numarul de palete pe rotor (intre 15 ....35): z2

```
> z2:=18;
```

z2 := 18

31-Unghiul geometric de iesire din paletele mobile: beta2 [rad]

```
> beta2:=evalf(Pi/2);
```

$\beta 2$:= 1.57079632'

32-Raportul dintre diametrul minim al paletei la intrare (curgerea axiala) si diametrul maxim al rotorului (uzual intre 0,15 ....0,35): db_rap

```
> db_rap:=0.015;
```

db_rap := 0.015

33-Raportul dintre diametrul maxim al paletei la intrare (curgerea axiala) si diametrul maxim al rotorului (intre 0,45 ....0,65): db_rap

```
> dext_rap:=0.545;
```

dext_rap := 0.545

34-Raportul dintre diametrul mediu al paletei la intrare (curgerea axiala) si diametrul maxim al rotorului: d1_pe_d2

```
> d1_pe_d2:=sqrt((dext_rap^2+db_rap^2)/2);
```

d1_pe_d2 := 0.385519130:

35-Coeficientul de circulatie: miu

```
> miu:=1/(1+2*evalf(Pi)/3/z2/(1-d1_pe_d2^2));
```

miu := 0.879764759·

36-Coeficientul cinematic de sarcina (probabil c2u/u2): fiu2

```
> fiu2:=miu*(1-fi2*cot(beta2));
```

fiu2 := 0.879764759

37-Coeficient de pierderi prin frecare (intre 0,03....0,1): alfa

```
> alfa:=0.075;
```

alfa := 0.075

38-Unghiul vitezei absolute la intrarea in rotor: alfa1 [rad], alfa1_gr [grade]

```
> alfa1:=evalf(Pi/2)-psi;alfa1_gr:=alfa1*180/evalf(Pi);
```

alfa1 := 1.04719755

alfa1_gr := 59.9999999

39-Viteza tangentiala la intrarea in rotor (considerata constanta pe raza, zona de curgere axiala): c1u [m/s]

```
> c1u:=c1*cos(alfa1);
```

c1u := 30.0000000

Viteza axiala la intrarea in rotor (considerata constanta pe raza, zona de curgere axiala): c1a [m/s]

```
> c1a:=c1*sin(alfa1);
```

c1a := 51.9615242

40-Viteza tangentiala la iesirea din rotor: u2 [m/s]

```
>
u2:=c1u*d1_pe_d2/2/(fiu2+alfa)+sqrt((c1u*d1_pe_d2/2/(fiu2+alfa))^2+l_re
al_C_tot/(fiu2+alfa));
```

u2 := 615.828749

41-Densitatea aerului la intrarea in rotor: ro1 [kg/m3]

```
> ro1:=p1/R_a_um/T1;
```

ro1 := 1.13677937

42-Pierderi raportate prin scapari, intre roata si carcasa (intre 0,02....0,04): betapr

```
> betapr:=0.03;
```

betapr := 0.03

43-Diametrul exterior al rotorului: d2 [m]

```
> d2:=sqrt(4*m*(1+betapr)/evalf(Pi)/ro1/c1a/(dext_rap^2-db_rap^2));
```

d2 := 0.299607935

44-Diametrul butucului la intrare (la baza paletei, curgere axiala): d1b [m]

```
> d1b:=d2*db_rap;
```

d1b := 0.00449411903

45-Diametrul maxim al rotorului la intrare (la varful paletei, curgere axiala): d1ext [m]

```
> d1ext:=d2*dext_rap;
```

$d1ext := 0.163286325$

46-Diametrul mediu al rotorului la intrare (curgere axiala): d1 [m]

```
> d1:=d2*d1_pe_d2;
```

$d1 := 0.115504590$

47-Turatia rotorului: turatia [rot/min]

```
> turatia:=60*u2/evalf(Pi)/d2;
```

$turatia := 39256.1790$

Viteza unghiulara a rotorului: omega [rad/s]

```
> omega:=evalf(Pi)*turatia/30;
```

$\omega := 4110.89745$

48-Viteza tangentiala intrarea in rotor, la diametrul mediu: u1 [m/s]

```
> u1:=u2*d1_pe_d2;
```

$u1 := 237.413764$

49-Viteza tangentiala la varful paletei, la intrarea in rotor: u1ext [m/s]

```
> u1ext:=u2*dext_rap;
```

$u1ext := 335.626668$

50-Viteza tangentiala la baza paletei, la intrarea in rotor: u1b [m/s]

```
> u1b:=u2*db_rap;
```

$u1b := 9.23743124$

51-Componenta tangentiala a vitezei relative a aerului la d1ext (negativa pentru ca este in sens contrar lui u): w1ext [m/s]

```
> w1uext:=c1u-u1ext;
```

$w1uext := -305.626668$

52-Componenta tangentiala a vitezei relative aerului la d1b (negativa pentru ca este in sens contrar lui u): w1b [m/s]

```
> w1ub:=c1u-u1b;
```

$w1ub := 20.7625687$

53-Unghiul vitezei relative la d1ext (masurat de la axa +u): beta1ext [rad], beta1ext_gr [grade]

```
> beta1ext:=evalf(Pi)-arctan(c1a/(u1ext-
```

```
c1u));beta1ext_gr:=beta1ext*180/evalf(Pi);
```

beta1ext := 2.97318662

beta1ext_gr := 170.351045

54-Unghiul vitezei relative la d1b (masurat de la axa +u): beta1b [rad], beta1b_gr [grade]

```
> beta1b:=evalf(Pi)-arctan(c1a/(u1b-
c1u));beta1b_gr:=beta1b*180/evalf(Pi);
```

beta1b := 4.33224832

beta1b_gr := 248.219545

55-Unghiul vitezei relative la d1 (masurat de la axa +u): beta1 [rad], beta1_gr [grade]

```
> beta1:=evalf(Pi)-arctan(c1a/(u1-c1u));beta1_gr:=beta1*180/evalf(Pi);
```

$\beta 1$:= 2.89612360

beta1_gr := 165.935659

56-Viteza relativa la d1ext: w1ext [m/s]

```
> w1ext:=sqrt(c1a^2+w1uext^2);
```

w1ext := 310.012355

57-Viteza sunetului la intrarea in rotor: a1 [m/s]

```
> a1:=sqrt(k*T1*R_a_um);
```

a1 := 338.493737

58-Numarul Mach la d1ext: Mw1ext [m/s]

```
> Mw1ext:=w1ext/a1;
```

Mw1ext := 0.915858466

59-Viteza relativa la intrarea in rotor, la diametrul mediu: w1 [m/s]

```
> w1:=c1a/sin(beta1);
```

w1 := 213.823454

60-Unghiul vitezei absolute la iesirea din rotor: alfa2 [rad], alfa2_gr [grade]

```
> alfa2:=arctan(fi2/fiu2);alfa2_gr:=alfa2*180/evalf(Pi);
```

alfa2 := 0.276868447

alfa2_gr := 15.8633935

61-Viteza absoluta la iesirea din rotor: c2 [m/s]

```
> c2:=u2*sqrt(fi2^2+fiu2^2);
```

c2 := 563.234574

Temperatura franata a aerului la iesirea din rotor: T2_tot [K]

```
> T2_tot:=TN+l_real_C_tot*(k-1)/k/R_a_um;
```

$T2\_tot := 636.205074$

62-Temperatura franata a aerului la iesirea din rotor: T2_tot [K]

```
> T2:=T2_tot-c2^2*(k-1)/2/k/R_a_um;
```

$T2 := 480.412711$

63-Coeficientii de rezistenta ai rotii de lucru, la intrare csi1 (intre 0,1...0,3) si la rasucirea curentului in roata de lucru csi2 (intre 0,1...0,2)

```
> csi1:=0.15;csi2:=0.15;
```

$csi1 := 0.15$

$csi2 := 0.15$

64-Pierderi in rotor: suma_lr [J/kg], suma_Lr [W]

```
> suma_lr:=csi1*w1^2/2+csi2*fi2^2*u2^2/2;suma_Lr:=m*suma_lr;
```

$suma\_lr := 5206.74640$

$suma\_Lr := 6248.09569$

65-Pierderi prin frecare i rotor: lf [J/kg], Lf [W]

```
> lf:=alfa*u2^2;Lf:=m*lf;
```

$lf := 28443.3786$

$Lf := 34132.0544$

66-Cifra politropica in roata de lucru: sr1

```
> sr1:=k*(1-(k-1)*(lf+suma_lr)/k/R_a_um/(T2-T1))/(k-1);
```

$sr1 := 2.93461047$

67-Exponentul politropic in roata de lucru: n_r1

```
> n_r1:=sr1/(sr1-1);
```

$n\_r1 := 1.51689992$

68-Presiunea statica la iesirea din rotor: p2 [N/m2]

```
> p2:=p1*(T2/T1)^sr1;
```

$p2 := 4.326172420 10^5$

69-Densitatea aerului la iesirea din rotor: ro2 [kg/m3]

```
> ro2:=p2/T2/R_a_um;
```

$ro2 := 3.12366169$

70-Latimea raportata a rotii de lucru la iesire:b2_pe_d2 (uzual intre 0,03....0,08)

```
> b2_pe_d2:=m/evalf(Pi)/d2^2/fi2/ro2/u2;
```

$b2\_pe\_d2 := 0.00884831933$

71-Latimea rotii de lucru la iesire:b2 [m]

```
> b2:=d2*b2_pe_d2;
```

$b2 := 0.00265102668$

72-Viteza sunetului la iesirea din rotor: a2 [m/s]

```
> a2:=sqrt(k*R_a_um*T2);
```

$a2 := 439.548720$

73-Numarul Mach la iesirea din rotor, pentru viteza absoluta: Mc2

```
> Mc2:=c2/a2;
```

$Mc2 := 1.28139282$

74-Consumuri energetice politropice in roata de lucru: lpol12 [J/kg], Lpol12 [W]

```
> lpol12:=n_r1*R_a_um*T1*((p2/p1)^((n_r1-1)/n_r1)-1)/(n_r1-
1);Lpol12:=m*lpol12;
```

$lpol12 := 1.654006770 10^5$

$Lpol12 := 1.984808124 10^5$

75-Randamentul interior al rotii de lucru: etai12

```
> etai12:=(lpol12+0.5*(c2^2-c1^2))/l_real_C_tot;
```

$etai12 := 0.907737652$

76-Dimensiunea radiala raportata a difuzorului nepaletat (intre 1,03....1,15): d3_pe_d2

```
> d3_pe_d2:=1.2;
```

$d3\_pe\_d2 := 1.2$

77-Latimea difuzorului nepaletat la iesire (normal = b2+(0,0005....0,001): b3 [m]

```
> b3:=b2+0.001;
```

$b3 := 0.00365102668$

78-Raportul intre densitatea ro2 si ro3, (se alege prealabil 0,75...0,98 si se verifica ulterior): ro3 [kg/m3]

```
> ro2_pe_ro3:=.9100861254;
```

$ro2\_pe\_ro3 := 0.910086125$

79-Unghiul de orientare a gazului la iesirea din difuzorul nepaletat: alfa3 [rad], alfa_gr [grade]

```
>
```

```
alfa3:=arctan(b2*ro2_pe_ro3*tan(alfa2)/b3);alfa3_gr:=180*alfa3/evalf(Pi
);
```

alfa3 := 0.185620806

alfa3_gr := 10.6352888

80-Diametrul la iesire din difuzorul nepaletat: d3 [m]

```
> d3:=d2*d3_pe_d2;
```

d3 := 0.359529522

81-Viteza gazului la iesirea din difuzorul nepaletat: c3 [m/s]

```
> c3:=m*ro2_pe_ro3/evalf(Pi)/ro2/d3/b3/sin(alfa3);
```

c3 := 459.378288

81-Temperatura statica la iesirea din difuzorul nepaletat: T3 [K]

```
> T3:=T2_tot-(k-1)*c3^2/2/k/R_a_um;
```

T3 := 532.569590

82-Coeficientul de rezistenta al difuzorului nepaletat (intre 0,03...0,25; valori mai mici pentru d3/d2 mai mici): csidn

```
> csidn:=0.15;
```

csidn := 0.15

83-Pierderi pe difuzorul nepaletat: lp_dn [J/kg], Lp_dn [W]

```
> lp_dn:=csidn*c2^2/2;Lp_dn:=m*lp_dn;
```

lp_dn := 23792.4889

Lp_dn := 28550.9867

84-Cifra politropica pentru comprimarea din difuzorul nepaletat: sdn

```
> sdn:=k*(1-lp_dn*(k-1)/k/R_a_um/(T3-T2))/(k-1);
```

sdn := 1.94929414

85-Exponentul politropic pentru comprimarea din difuzorul nepaletat: n_dn

```
> n_dn:=sdn/(sdn-1);
```

n_dn := 2.05341427

86-Recalcularea raportului ro2_pe_ro3

```
> ro2_pe_ro3_f:=(T2/T3)^(1/(n_dn-1));errro:=ro2_pe_ro3/ro2_pe_ro3_f;
```

ro2_pe_ro3_f := 0.906792282

errro := 1.00363241

87-Presiunea statica la iesirea din difuzorul nepaletat: p3 [N/m2]

```
> p3:=p2*(T3/T2)^(sdn);
```

$p3 := 5.28880900210^{5}$

88-Viteza sunetului la iesirea din difuzorul nepaletat: a3 [m/s]

```
> a3:=sqrt(k*R_a_um*T3);
```

$a3 := 462.794252$

89-Numarul Mach la iesirea din difuzorul nepaletat: Mc3

```
> Mc3:=c3/a3;
```

$Mc3 := 0.992618827$

90-Viteza gazului la iesirea din difuzorul paletat (intre 60...120): c4 [m/s]

```
> c4:=70;
```

$c4 := 70$

91-Latimea difuzorului paletat la iesire - nu are indicatie de alegere: b4 [m]

```
> b4:=b3;
```

$b4 := 0.00365102668$

92-Unghiul geometric al paletelor la intrarea in difuzorul paletat (alfa3 + pana la 2 grade): alfa3p [rad] alfa3p_gr [grade]

```
> alfa3p:=alfa3+1.42*evalf(Pi)/180; alfa3p_gr:=alfa3_gr+1.42;
```

$alfa3p := 0.210404482$

$alfa3p\_gr := 12.0552888$

93-Unghiul geometric al paletelor la iesirea din difuzorul paletat (alfa3p + (10..15) grade): alfa4p [rad] alfa4p_gr [grade]

```
> alfa4p:=alfa3p+14*evalf(Pi)/180;alfa4p_gr:=alfa3p_gr+14;
```

$alfa4p := 0.454750577$

$alfa4p\_gr := 26.0552888$

94-Unghiul de ramanere in urma a curentului la iesirea din difuzorul paletat (1..3 grade): dalfa4 [rad] dalfa4_gr [grade]

```
> dalfa4:=2*evalf(Pi)/180;dalfa4_gr:=dalfa4*180/evalf(Pi);
```

$dalfa4 := 0.0349065850$

$dalfa4\_gr := 2.00000000$

95-Unghiul vitezei absolute la iesirea din difuzorul paletat: alfa4 [rad], alfa_gr [grade]

```
> alfa4:=alfa4p-dalfa4;alfa4_gr:=alfa4p_gr-dalfa4_gr;
```

$alfa4 := 0.419843992$

$alfa4\_gr := 24.0552888$

96-Coefientul de rezistenta al difuzorului paletat (intre 0,1....0,25): csidp

```
> csidp:=0.12;
```

$csidp := 0.12$

97-Pierderi in difuzorul paletat: lp_dp [J/kg], Lp_dp [W]

```
> lp_dp:=csidp*c3^2/2;Lp_dp:=m*lp_dp;
```

$lp\_dp := 12661.7047$

$Lp\_dp := 15194.0456$

98-Temperatura statica la iesirea din difuzorul paletat: T4 [K]

```
> T4:=T2_tot-c4^2*(k-1)/2/k/R_a_um;
```

$T4 := 633.798697$

99-Cifra politropica in difuzorul paletat: sdp

```
> sdp:=k*(1-lp_dp*(k-1)/k/R_a_um/(T4-T3))/(k-1);
```

$sdp := 3.09777376$

100-Exponentul politropic in difuzorul paletat: n_dp

```
> n_dp:=sdp/(sdp-1);
```

$n\_dp := 1.47669582$

101-Presiunea statica la iesirea din difuzorul paletat: p4 [N/m2]

```
> p4:=p3*(T4/T3)^sdp;
```

$p4 := 9.067176448\,10^{5}$

102-Raportul dimetrelor in difuzorul paletat (recomandabil intre 1,25...1,35): d4_pe_d3 [m]

```
> d4_pe_d3:=c3*(T3/T4)^(1/(n_dp-1))*b3*sin(alfa3)/c4/b4/sin(alfa4);
```

$d4\_pe\_d3 := 2.06257481$

103-Diametrul de iesire din difuzorul paletat: d4 [m]

```
> d4:=d3*d4_pe_d3;
```

$d4 := 0.741556537$

104-Unghiul mediu de deschidere echivalent al unui difuzor plan (se alege intre 6....8 grade): tetam [rad], tetam_gr [grade]

```
> tetam_gr:=7;tetam:=tetam_gr*evalf(Pi)/180;
```

$tetam\_gr := 7$

$tetam := 0.122173047$

105-Numarul de palete din difuzor (se rotunjeste, e de dorit ca z2 si z3 sa fie numere prime intre ele): z3

```
>
z3:=round(2*evalf(Pi)*sin((alfa3p)^2)*((d4*sin(alfa4p)/d3/sin(alfa3p))^
2-1)/((d4/d3)^2-1)/tetam);
```

$z3 := 12$

106-Sectiunile de curgere normale la vitezele de intrare si iesire din difuzorul paletat: S3, S4 [m2]

```
> S3:=evalf(Pi)*d3*b3*sin(alfa3);S4:=evalf(Pi)*d4*b4*sin(alfa4);
```

$S3 := 0.000761078199$

$S4 := 0.00346706913$

107-Raportul ariiloe S4/S3, mai mic de 4: S4_pe_S3

```
> S4_pe_S3:=S4/S3;
```

$S4\_pe\_S3 := 4.55547029$

108-Viteza la iesirea din camera spirala, (intre 40...80, dar mai mica decat c4): c5 [m/s]

```
> c5:=50;
```

$c5 := 50$

109-Coeficient de rezistenta in camera spirala (intre 0,15...0,3): csics

```
> csics:=0.258;
```

$csics := 0.258$

110-Pierderi in camera spirala: lp_cs [J/kg], Lp_cs [W]

```
> lp_cs:=csics*c4^2/2;Lp_cs:=m*lp_cs;
```

$lp\_cs := 632.100000$

$Lp\_cs := 758.520000$

111-Temperatura statica la iesirea din camera spirala: T5 [K]

```
> T5:=T2_tot-c5^2*(k-1)/2/k/R_a_um;
```

$T5 := 634.977331$

112-Cifra politropica din camera spirala: scs

```
> scs:=k*(1-(k-1)*lp_cs/k/R_a_um/(T5-T4))/(k-1);
```

$scs := 1.67135121$

113-Exponentul politropic in camera spirala: n_cs

```
> n_cs:=scs/(scs-1);
```

$n\_cs := 2.48953331$

114-Presiunea statica la iesirea din camera spirala: p5 [N/m2]

```
> p5:=p4*(T5/T4)^scs;
```

$p5 := 9.095375739\,10^{5}$

115-Presiunea totala la iesirea din camera spirala: p5_tot [N/m2]

```
> p5_tot:=p5*(T2_tot/T5)^(k/(k-1));
```

$p5\_tot := 9.157635832\,10^{5}$

116-Raportul de crestere a presiunii totale: piC_tot_f

```
> piC_tot_f:=p5_tot/p_tot_N;errpiC:=piC_tot/piC_tot_f;
```

$piC\_tot\_f := 9.03788387$

$errpiC := 1.00462610$

117-Randamentul izentropic calculat in parametrii de franare: etas_tot_f

```
> etas_tot_f:=T_tot_N*(piC_tot_f^((k-1)/k)-1)/(T2_tot-
T_tot_N);erretas:=etas_tot/etas_tot_f;
```

$etas\_tot\_f := 0.715566227$

$erretas := 1.00154800$

118-Randamentul mecanic al compresorului (intre 0,95...0,99): etamec

```
> etamec:=0.975;
```

$etamec := 0.975$

119-Puterea totala reala a compresorului: Pm [J/kg], P [W]

```
> Pm:=l_real_C_tot/etamec;P:=m*Pm;
```

$Pm := 3.640691234\,10^{5}$

$P := 4.368829481\,10^{5}$

```
>
>
>
>
> save
m,psi_gr,piC_tot_f,P,turatia,etas_tot_f,etai12,TN,T1,T2,T3,T4,T5,pN,p1,
p2,p3,p4,p5,p5_tot,d1b,d1ext,d1,d2,d3,d4,b2,b3,b4,beta1b_gr,beta1ext_gr
```

```
,beta1_gr,Mw1ext,alfa2_gr,c2,Mc2,c3,Mc3,c4,c5,alfa3p_gr,alfa4p_gr,alfa4
_gr,z2,z3, "date COMCIP";
> read "date COMCIP";
```

$m := 1.2$

$psi\_gr := 30.0000000$

$piC\_tot\_f := 9.03788387$

$P := 4.368829481\,10^5$

$turatia := 39256.1790$

$etas\_tot\_f := 0.715566227$

$etai12 := 0.907737652$

$TN := 287.558012$

$T1 := 284.906087$

$T2 := 480.412711$

$T3 := 532.569590$

$T4 := 633.798697$

$T5 := 634.977331$

$pN := 1.007768903\,10^5$

$p1 := 93369.1178$

$p2 := 4.326172420\,10^5$

$p3 := 5.288809002\,10^5$

$p4 := 9.067176448\,10^5$

$p5 := 9.095375739\,10^5$

$p5\_tot := 9.157635832\,10^5$

$d1b := 0.00449411903$

$d1ext := 0.163286325$

$d1 := 0.115504590$

$d2 := 0.299607935$

$d3 := 0.359529522$

$d4 := 0.741556537$

$b2 := 0.00265102668$

$b3 := 0.00365102668$

$b4 := 0.00365102668$

$beta1b\_gr := 248.2195450$

$beta1ext\_gr := 170.3510454$

$beta1\_gr := 165.9356593$

$Mw1ext := 0.9158584664$

$alfa2\_gr := 15.8633935$

$c2 := 563.2345749$

$Mc2 := 1.28139282$

$c3 := 459.378288$

$Mc3 := 0.992618827$

$c4 := 70$

$c5 := 50$

$alfa3p\_gr := 12.0552888$

$alfa4p\_gr := 26.0552888$

$alfa4\_gr := 24.0552888$

$z2 := 18$

$z3 := 12$

>

IREVERSIBILITATE - VARIATII CONSTANTE DE ENTROPIE

> $restart;$

> $eqdT := U \cdot A \cdot \Delta T - (T - \Delta T) \cdot \Delta S = 0;\ \Delta T := solve(eqdT, \Delta T);$

$$eqdT := U\,A\,\Delta T - (T - \Delta T)\,\Delta S = 0$$

$$\Delta T := \frac{T\,\Delta S}{U\,A + \Delta S}$$

> $eqdT0 := U0 \cdot A0 \cdot \Delta T0 - (T0 + \Delta T0) \cdot \Delta S;\ \Delta T0 := solve(eqdT0, \Delta T0);$

$$eqdT0 := U0\,A0\,\Delta T0 - (T0 + \Delta T0)\,\Delta S$$

$$\Delta T0 := \frac{T0\,\Delta S}{U0\,A0 - \Delta S}$$

> $Q := U \cdot A \cdot \Delta T;$

$$Q := \frac{U\,A\,T\,\Delta S}{U\,A + \Delta S}$$

> $Q0 := U0 \cdot A0 \cdot \Delta T0;$

$$Q0 := \frac{U0\,A0\,T0\,\Delta S}{U0\,A0 - \Delta S}$$

> $P := Q - Q0;$

$$P := \frac{U\,A\,T\,\Delta S}{U\,A + \Delta S} - \frac{U0\,A0\,T0\,\Delta S}{U0\,A0 - \Delta S}$$

> $\eta := 1 - \frac{Q0}{Q};$

$$\eta := 1 - \frac{U0\,A0\,T0\,(U\,A + \Delta S)}{(U0\,A0 - \Delta S)\,U\,A\,T}$$

>

> $restart;$

> $\Delta S := 25; A := 1; A0 := 1; T := 900; T0 := 450;$

$$\Delta S := 25$$

$$A := 1$$

$$A0 := 1$$

$$T := 900$$

$$T0 := 450$$

> $\Delta T := \frac{T\,\Delta S}{U\,A + \Delta S}; \Delta T0 := \frac{T0\,\Delta S}{U0\,A0 - \Delta S};$

$$\Delta T := \frac{22500}{U + 25}$$

$$\Delta T0 := \frac{11250}{U0 - 25}$$

> $Q := \frac{U\,A\,T\,\Delta S}{U\,A + \Delta S}; Q0 := \frac{U0\,A0\,T0\,\Delta S}{U0\,A0 - \Delta S}; P := \frac{U\,A\,T\,\Delta S}{U\,A + \Delta S} - \frac{U0\,A0\,T0\,\Delta S}{U0\,A0 - \Delta S}; \eta := 1 - \frac{U0\,A0\,T0\,(U\,A + \Delta S)}{(U0\,A0 - \Delta S)\,U\,A\,T};$

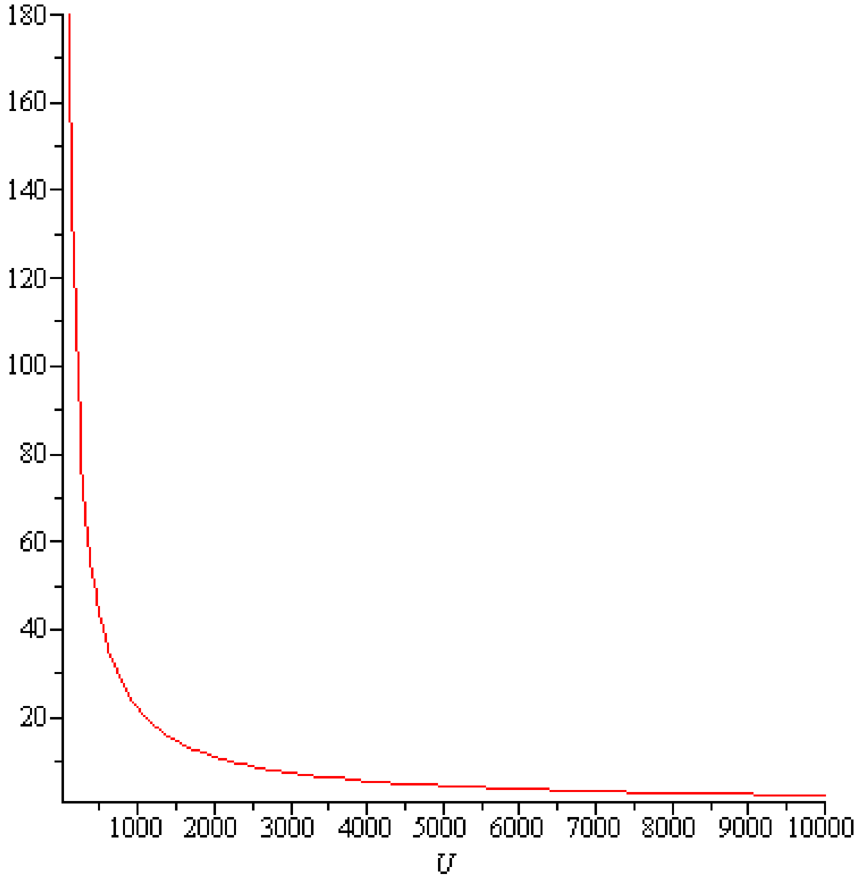
$$Q := \frac{22500\,U}{U + 25}$$

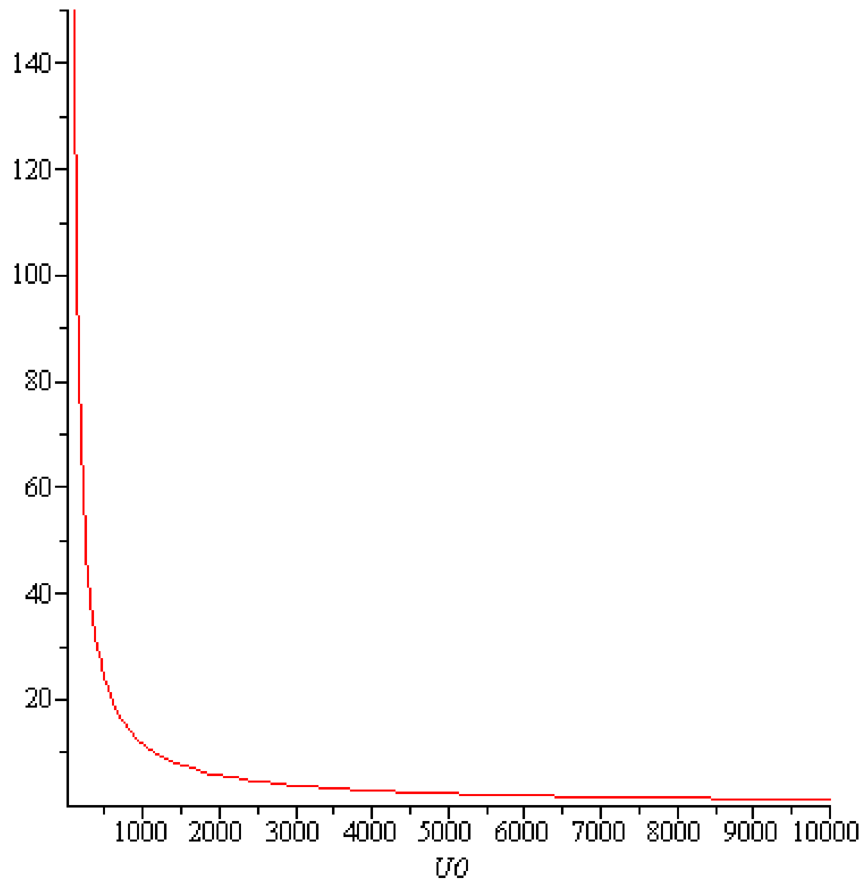
$$Q0 := \frac{11250\,U0}{U0 - 25}$$

$$P := \frac{22500\,U}{U + 25} - \frac{11250\,U0}{U0 - 25}$$

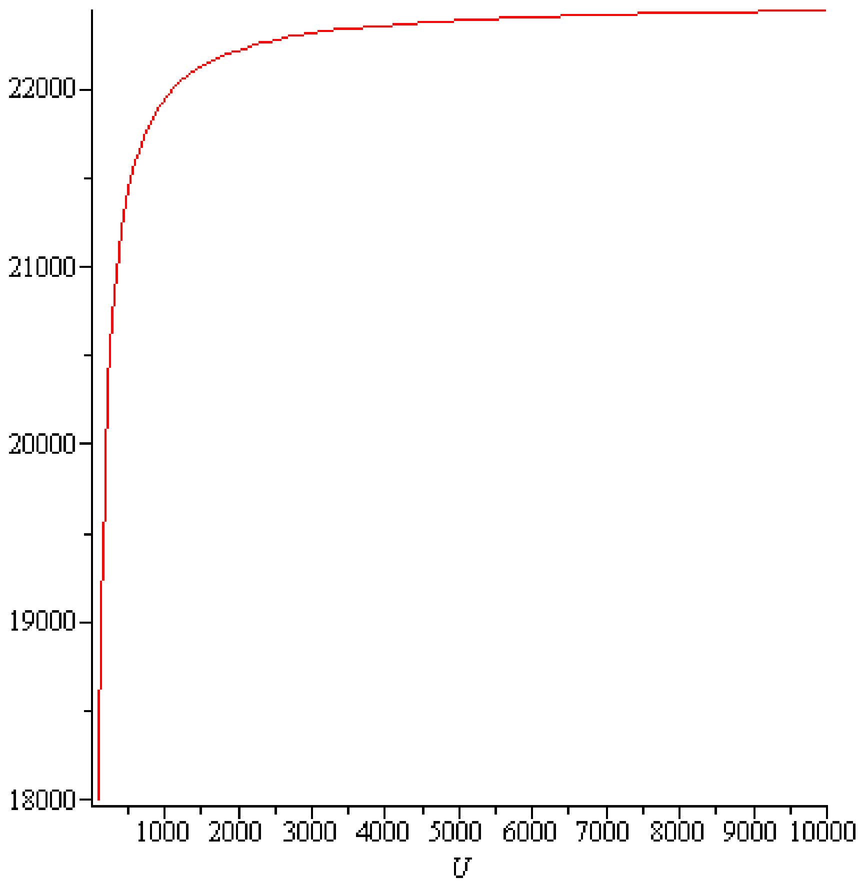
$$\eta := 1 - \frac{1}{2}\,\frac{U0\,(U+25)}{(U0-25)\,U}$$

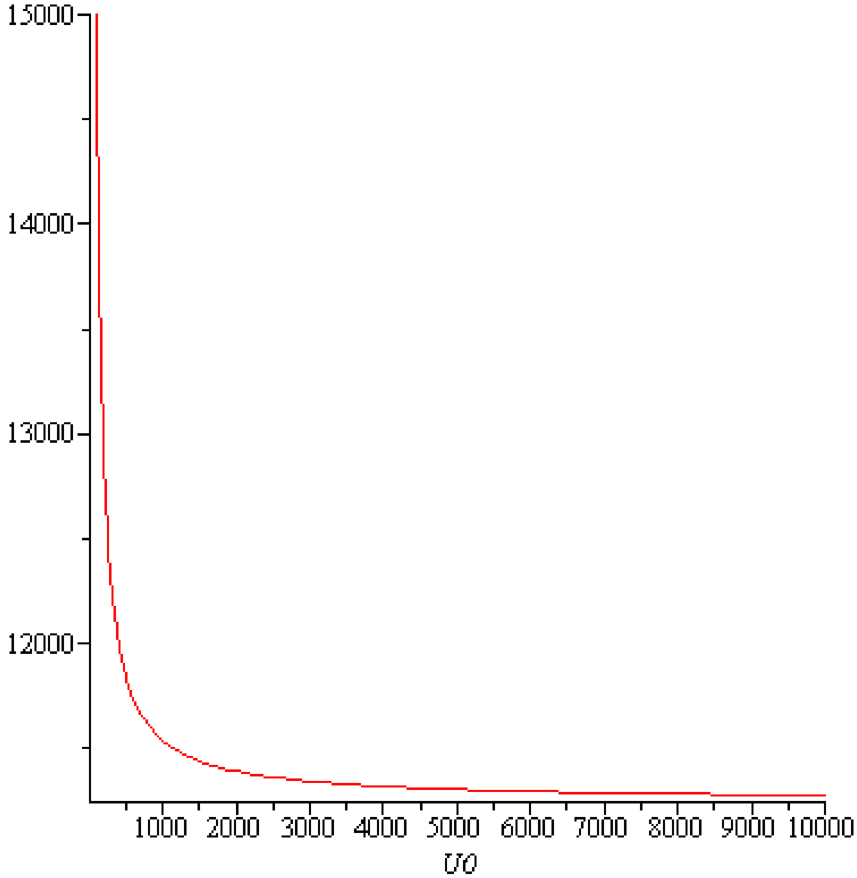
> $plot(\Delta T, U = 100..10000);\ plot(\Delta T0, U0 = 100..10000);$



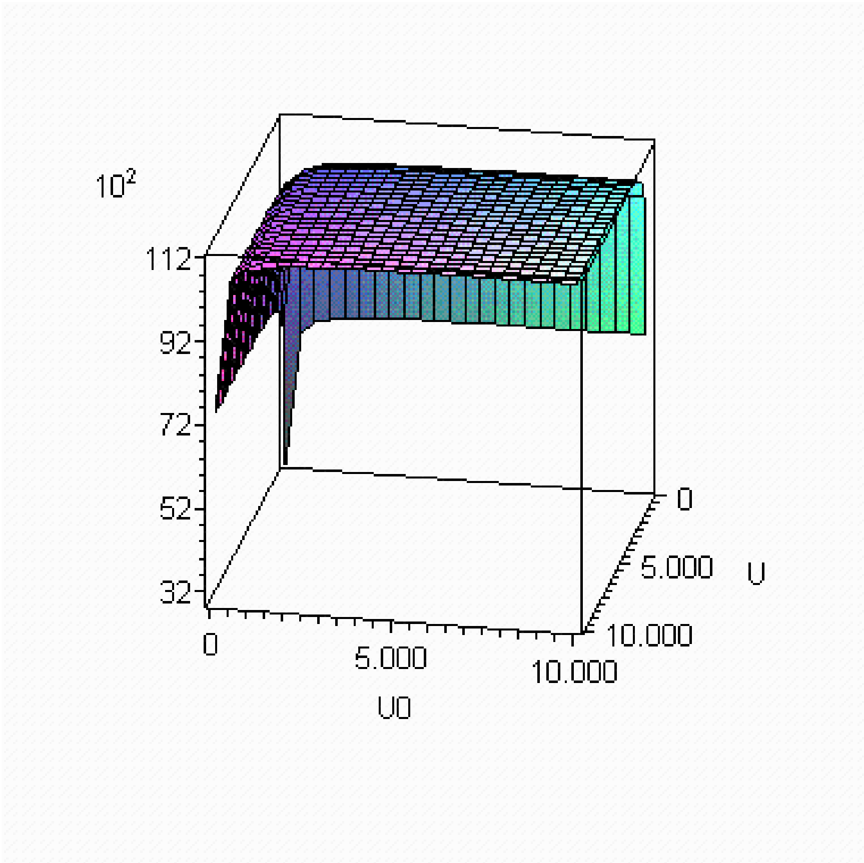


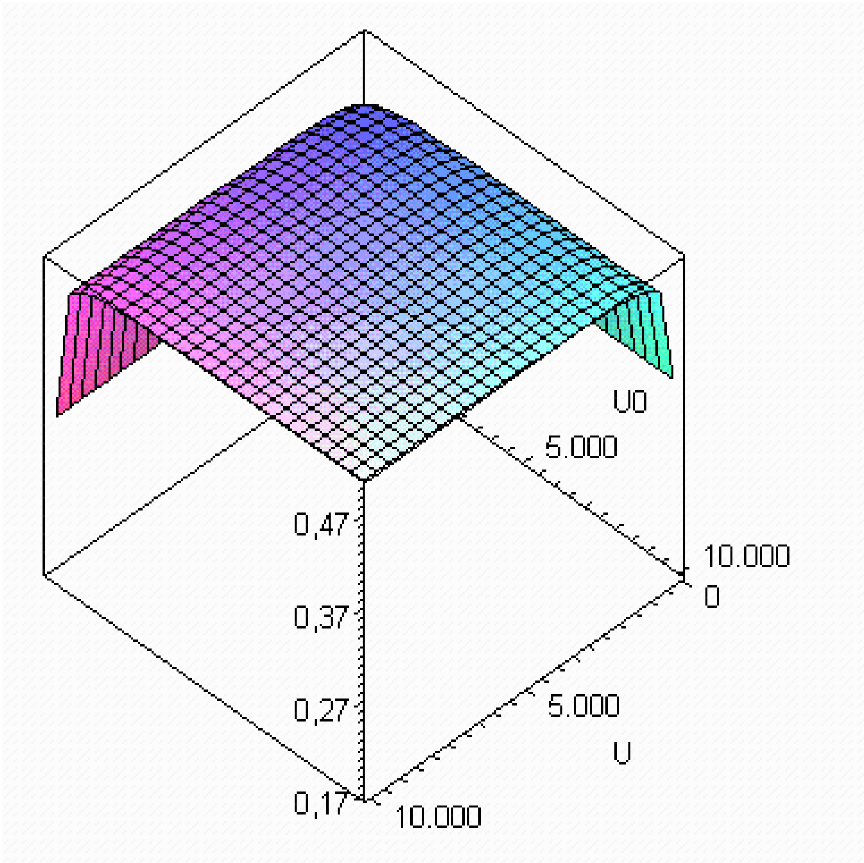
> $plot(Q, U = 100..10000); plot(Q0, U0 = 100..10000);$


22000
21000
20000
19000
18000
1000 2000 3000 4000 5000 6000 7000 8000 9000 10000
U



> *plot3d*(P, U = 100..10000, U0 = 100..10000); *plot3d*(η, U = 100..10000, U0 = 100..10000);


10^2
112
92
72
52
32
0
5.000
10.000
U0
0
5.000
10.000
U



>

>

IREVERSIBILITATE - VARIATII CONSTANTE DE ENTROPIE

> $restart;$

> $eqdT := U \cdot A \cdot \Delta T - (T - \Delta T) \cdot \Delta S = 0; \Delta T := solve(eqdT, \Delta T);$

$$eqdT := U\,A\,\Delta T - (T - \Delta T)\,\Delta S = 0$$

$$\Delta T := \frac{T\,\Delta S}{U\,A + \Delta S}$$

> $eqdT0 := U0 \cdot A0 \cdot \Delta T0 - (T0 + \Delta T0) \cdot \Delta S; \Delta T0 := solve(eqdT0, \Delta T0);$

$$eqdT0 := U0\,A0\,\Delta T0 - (T0 + \Delta T0)\,\Delta S$$

$$\Delta T0 := \frac{T0\,\Delta S}{U0\,A0 - \Delta S}$$

> $Q := U \cdot A \cdot \Delta T;$

$$Q := \frac{U\,A\,T\,\Delta S}{U\,A + \Delta S}$$

> $Q0 := U0 \cdot A0 \cdot \Delta T0;$

$$Q0 := \frac{U0\,A0\,T0\,\Delta S}{U0\,A0 - \Delta S}$$

> $P := Q - Q0;$

$$P := \frac{U\,A\,T\,\Delta S}{U\,A + \Delta S} - \frac{U0\,A0\,T0\,\Delta S}{U0\,A0 - \Delta S}$$

> $\eta := 1 - \frac{Q0}{Q};$

$$\eta := 1 - \frac{U0\,A0\,T0\,(U\,A + \Delta S)}{(U0\,A0 - \Delta S)\,U\,A\,T}$$

>

> $restart;$

> $\Delta S := 25;\ A := 1;\ A0 := 1;\ T := 900;\ T0 := 450;$

$\Delta S := 25$

$A := 1$

$A0 := 1$

$T := 900$

$T0 := 450$

> $\Delta T := \frac{T\,\Delta S}{U\,A + \Delta S};\ \Delta T0 := \frac{T0\,\Delta S}{U0\,A0 - \Delta S};$

$$\Delta T := \frac{22500}{U + 25}$$

$$\Delta T0 := \frac{11250}{U0 - 25}$$

> $Q := \frac{U\,A\,T\,\Delta S}{U\,A + \Delta S};\ Q0 := \frac{U0\,A0\,T0\,\Delta S}{U0\,A0 - \Delta S};\ P := \frac{U\,A\,T\,\Delta S}{U\,A + \Delta S} - \frac{U0\,A0\,T0\,\Delta S}{U0\,A0 - \Delta S};\ \eta := 1 - \frac{U0\,A0\,T0\,(U\,A + \Delta S)}{(U0\,A0 - \Delta S)\,U\,A\,T};$

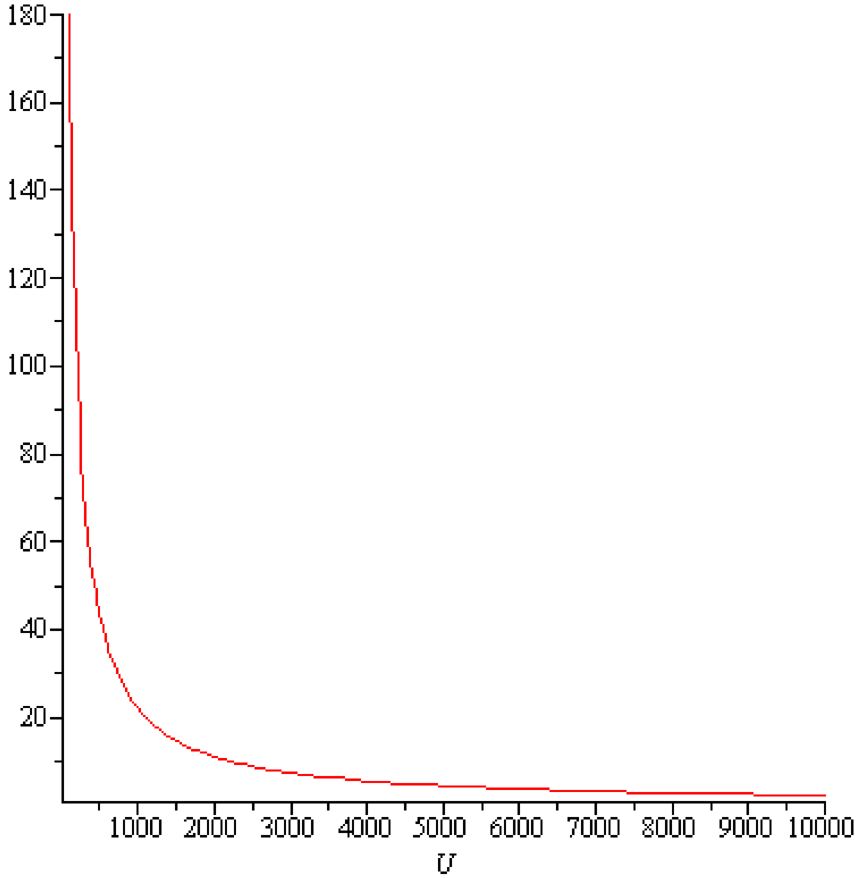
$$Q := \frac{22500\,U}{U + 25}$$

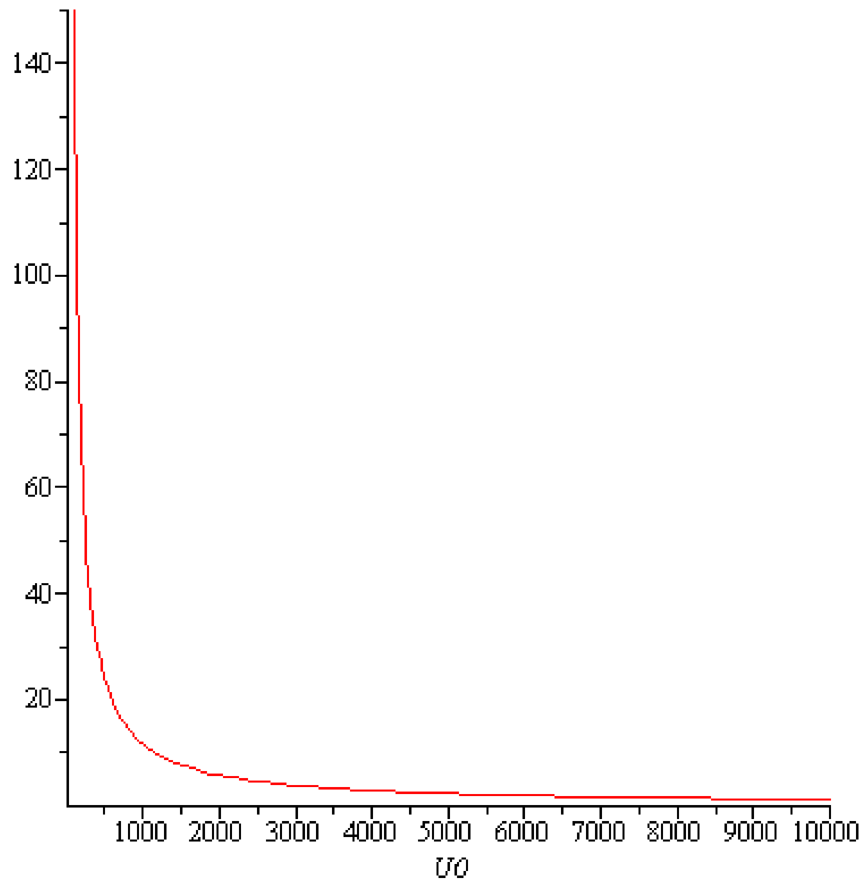
$$Q0 := \frac{11250\,U0}{U0 - 25}$$

$$P := \frac{22500\,U}{U + 25} - \frac{11250\,U0}{U0 - 25}$$

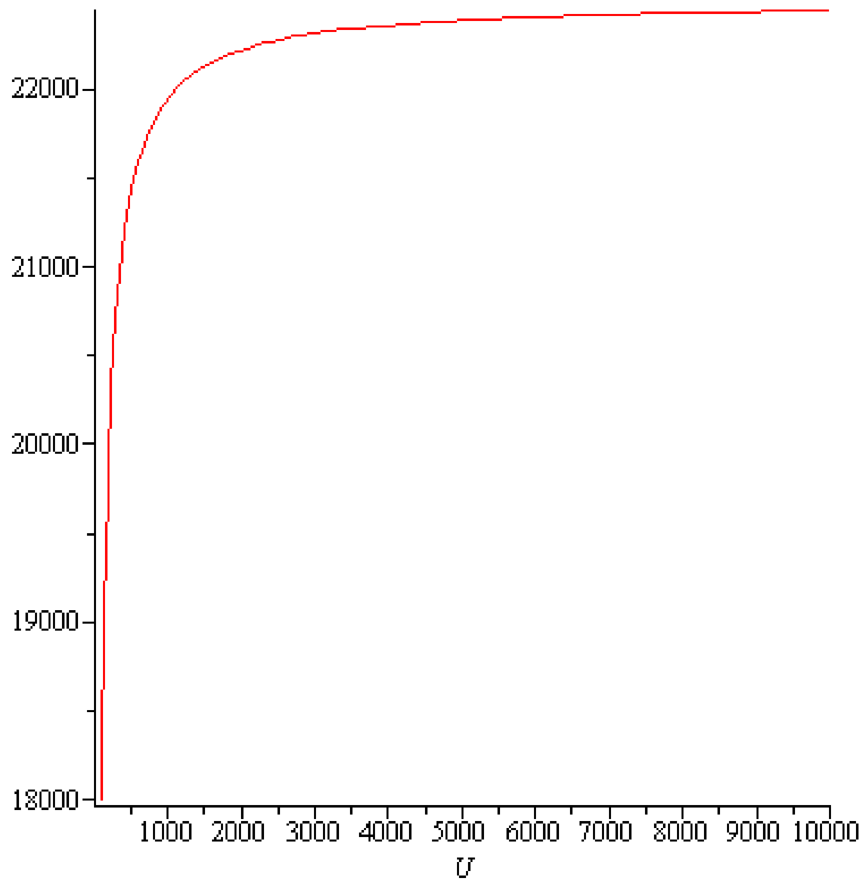
$$\eta := 1 - \frac{1}{2}\,\frac{U0\,(U+25)}{(U0-25)\,U}$$

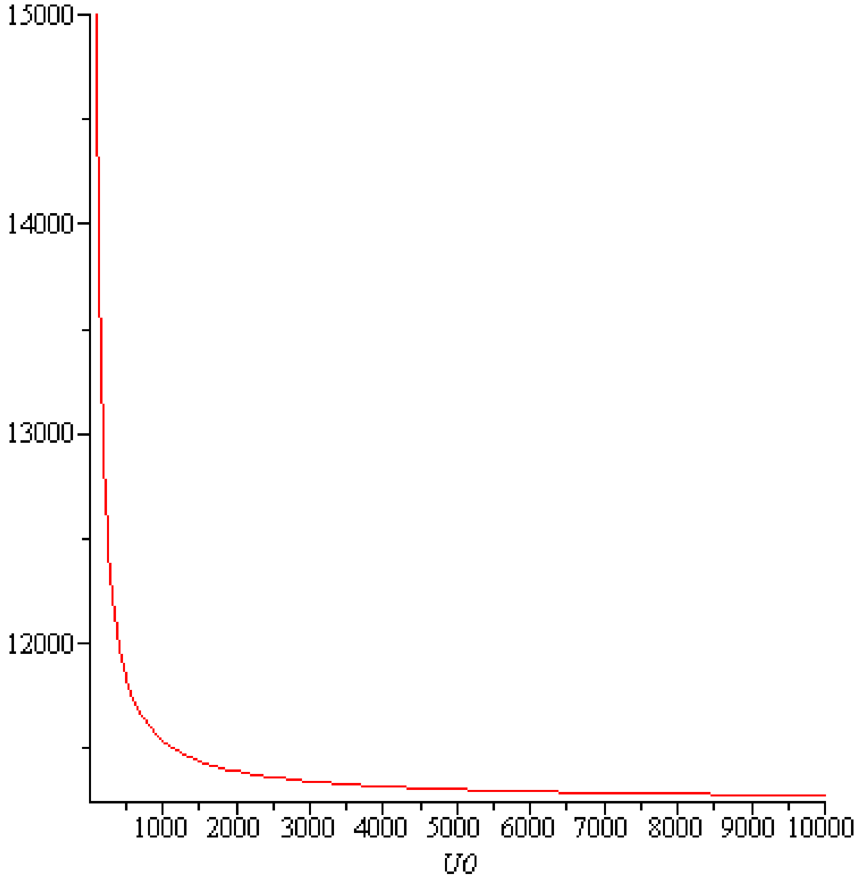
> $plot(\Delta T, U = 100..10000);\ plot(\Delta T0, U0 = 100..10000);$



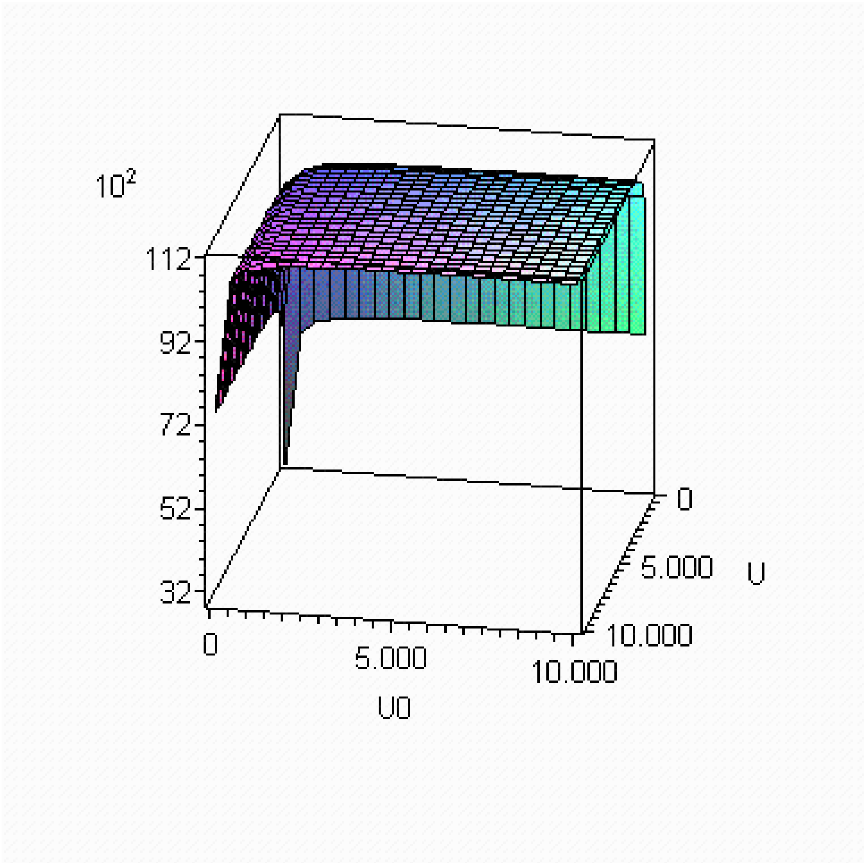


> $plot(Q, U = 100..10000);\ plot(Q0, U0 = 100..10000);$

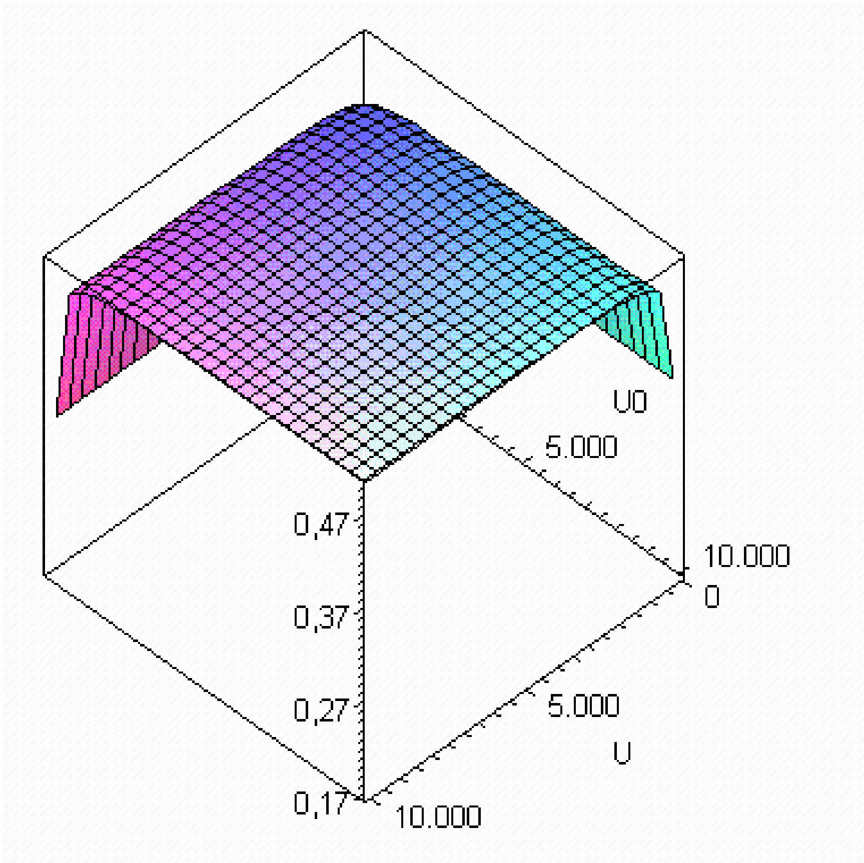

22000
21000
20000
19000
18000
1000 2000 3000 4000 5000 6000 7000 8000 9000 10000
U



> *plot3d*(P, U = 100..10000, U0 = 100..10000); *plot3d*(η, U = 100..10000, U0 = 100..10000);



10^2
112
92
72
52
32
0
5.000
10.000
U0
0
5.000
10.000
U



>

> **IREVERSIBILITATE - Q CONSTANT**

> *restart*;

> $T := 900;\ T0 := 300;\ UA0perdS := \frac{(T0 + dT0)}{dT0};\ UAperdS := \frac{(T - dT)}{dT};$

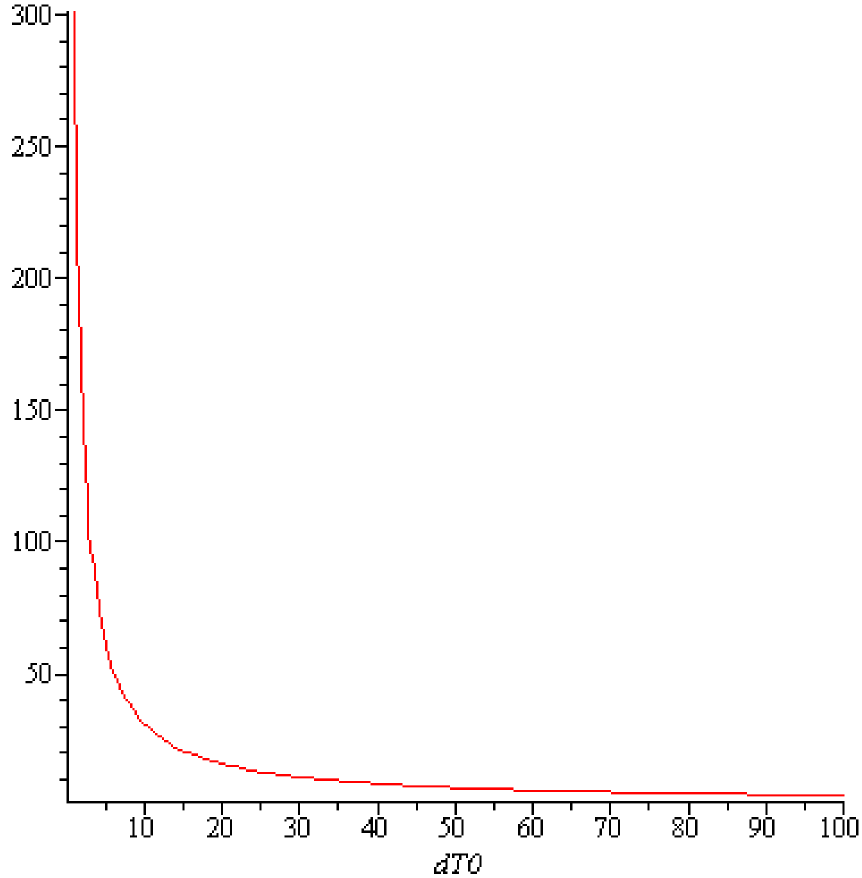
$T := 900$

$T0 := 300$

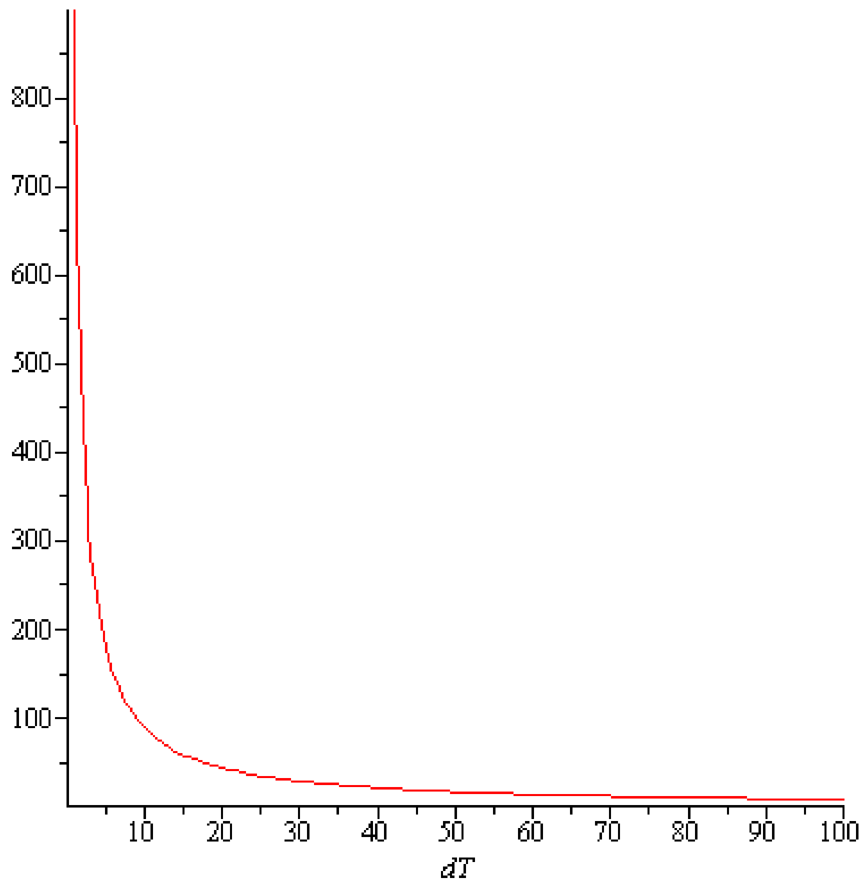
$UA0perdS := \frac{300 + dT0}{dT0}$

$UAperdS := \frac{900 - dT}{dT}$

> $plot(UA0perdS, dT0 = 1..100);\ plot(UAperdS, dT = 1..100);$



300
250
200
150
100
50
10
20
30
40
50
60
70
80
90
100
dT0



> *restart*;

> $dSlim := \frac{Q}{T}$;

$$dSlim := \frac{Q}{T}$$

> $dT := \frac{Q}{U \cdot A}$; $dS := \frac{Q}{T - \frac{Q}{U \cdot A}}$;

$$dT := \frac{10000}{U}$$

$$dS := \frac{10000}{900 - \frac{10000}{U}}$$

> $Q0 := (T0 + dT0) \cdot dS$; $P := Q - Q0$;

$$Q0 := \frac{(T0 + dT0)\ Q}{T - \frac{Q}{U\ A}}$$

$$P := Q - \frac{(T0 + dT0)\,Q}{T - \frac{Q}{U\,A}}$$

> $eqdT0 := Q0 - U0 \cdot A0 \cdot dT0 = 0;\ dT0 := solve(eqdT0, dT0);$

$$eqdT0 := \frac{(T0 + dT0)\,Q}{T - \frac{Q}{U\,A}} - U0\,A0\,dT0 = 0$$

$$dT0 := \frac{T0\,Q\,U\,A}{-Q\,U\,A + U0\,A0\,T\,U\,A - U0\,A0\,Q}$$

> $restart;$

> $\%Q := 10000;\ \%A := 1;\ \%A0 := 1;\ \%T := 900;\ \%T0 := 400;$

$\%Q := 10000$

$\%A := 1$

$\%A0 := 1$

$\%T := 900$

$\%T0 := 400$

> $dT := \frac{Q}{U \cdot A};\ dT0 := \frac{T0}{\frac{U0\,A0}{Q}\,T - \frac{U0\,A0}{U \cdot A} - 1};\ dS := \frac{Q}{T - \frac{Q}{U \cdot A}};$

$$dT := \frac{Q}{U\,A}$$

$$dT0 := \frac{T0}{\frac{U0\,A0\,T}{Q} - \frac{U0\,A0}{U\,A} - 1}$$

$$dS := \frac{Q}{T - \frac{Q}{U\,A}}$$

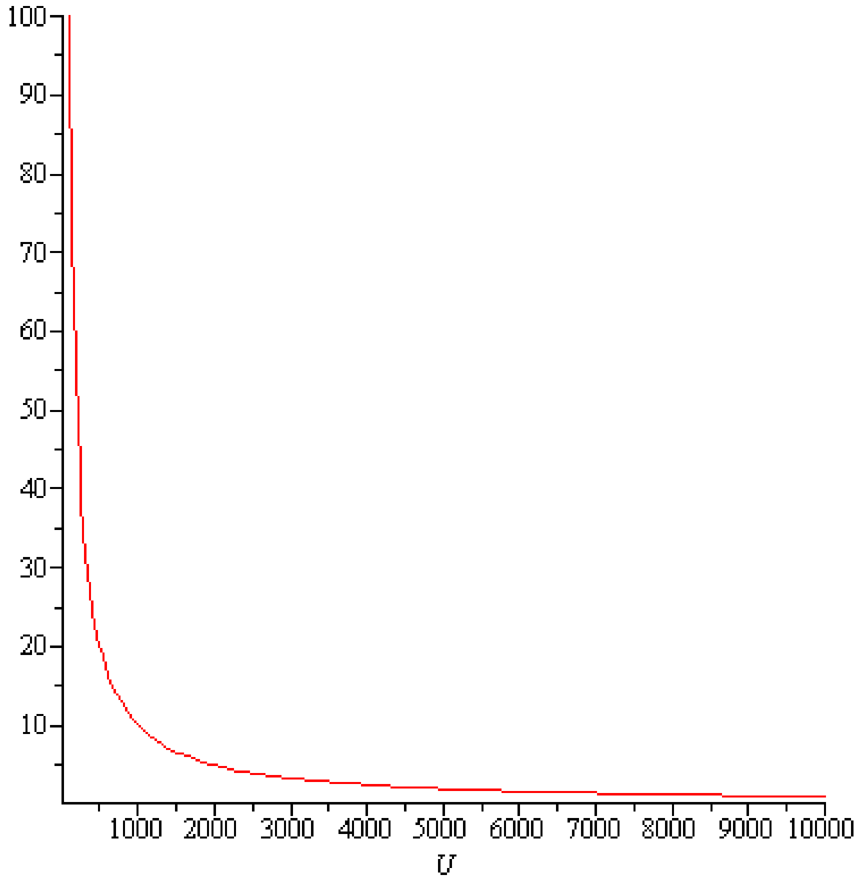
> $Q0 := (T0 + dT0) \cdot dS;\ P := Q - Q0;\ \eta := \frac{P}{Q};$

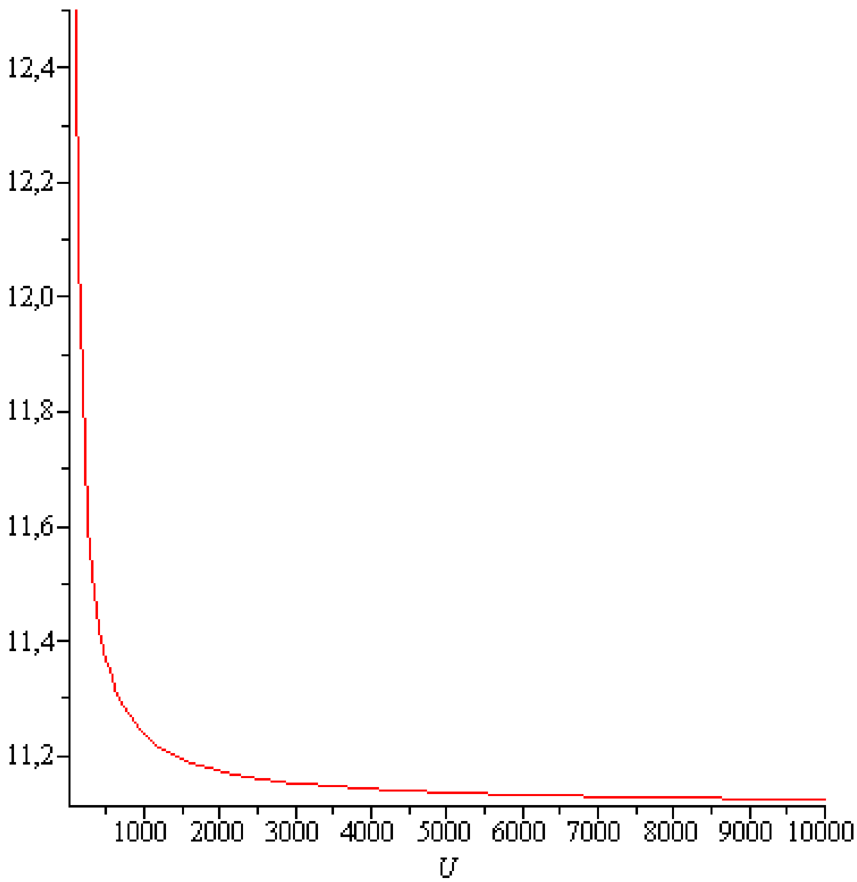
$$Q0 := \frac{\left(T0 + \frac{T0}{\frac{U0\,A0\,T}{Q} - \frac{U0\,A0}{U\,A} - 1}\right) Q}{T - \frac{Q}{U\,A}}$$

$$P := Q - \frac{\left(T0 + \frac{T0}{\frac{U0\,A0\,T}{Q} - \frac{U0\,A0}{U\,A} - 1}\right) Q}{T - \frac{Q}{U\,A}}$$

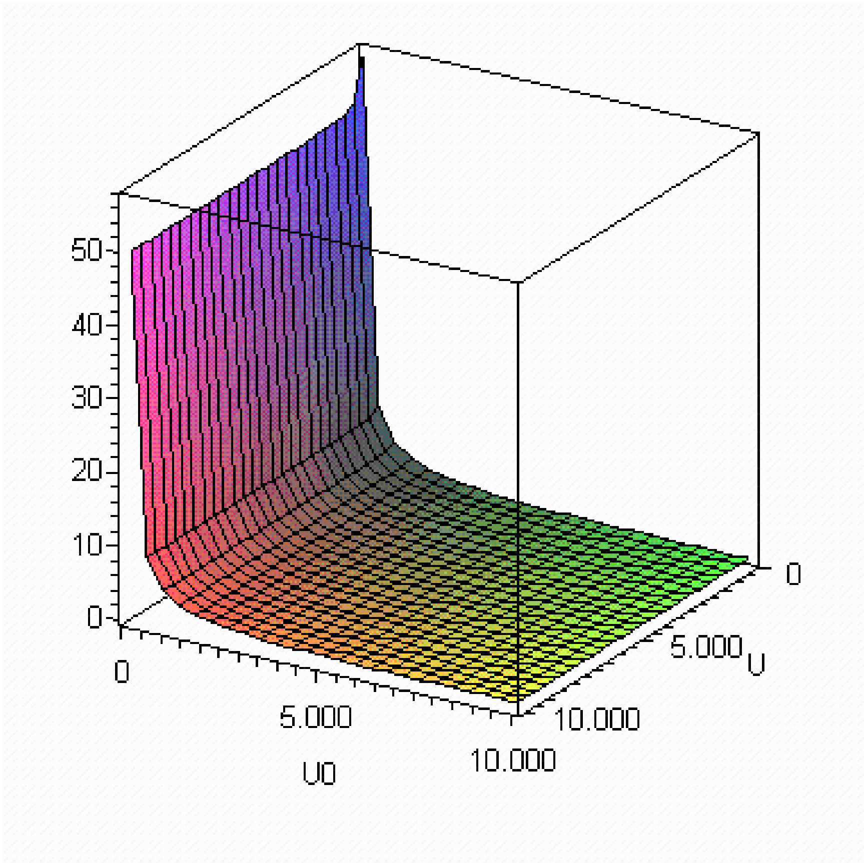
$$\eta := \frac{Q - \dfrac{\left(T0 + \dfrac{T0}{\dfrac{U0\ A0\ T}{Q} - \dfrac{U0\ A0}{U\ A} - 1}\right) Q}{T - \dfrac{Q}{U\ A}}}{Q}$$

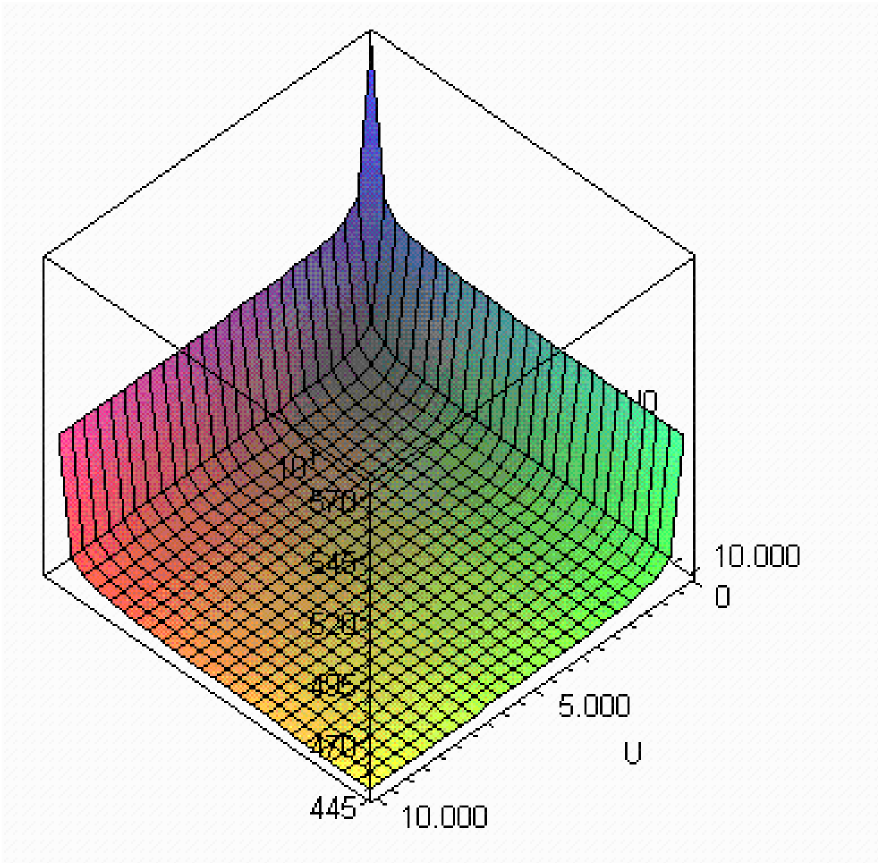
> *plot*(*dT*, *U* = 100..10000); *plot*(*dS*, *U* = 100..10000);



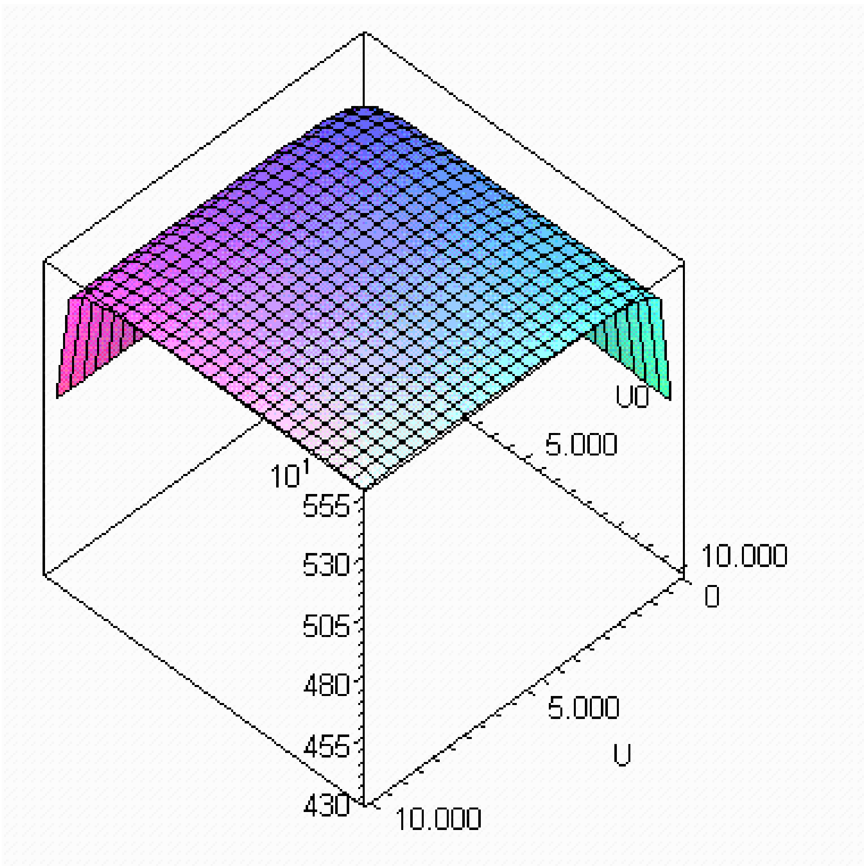


> *plot3d*(dT0, U = 100..10000, U0 = 100..10000); *plot3d*(Q0, U = 100..10000, U0 = 100..10000); *plot3d*(P, U = 100..10000, U0 = 100..10000); *plot3d*(η, U = 100..10000, U0 = 100..10000);

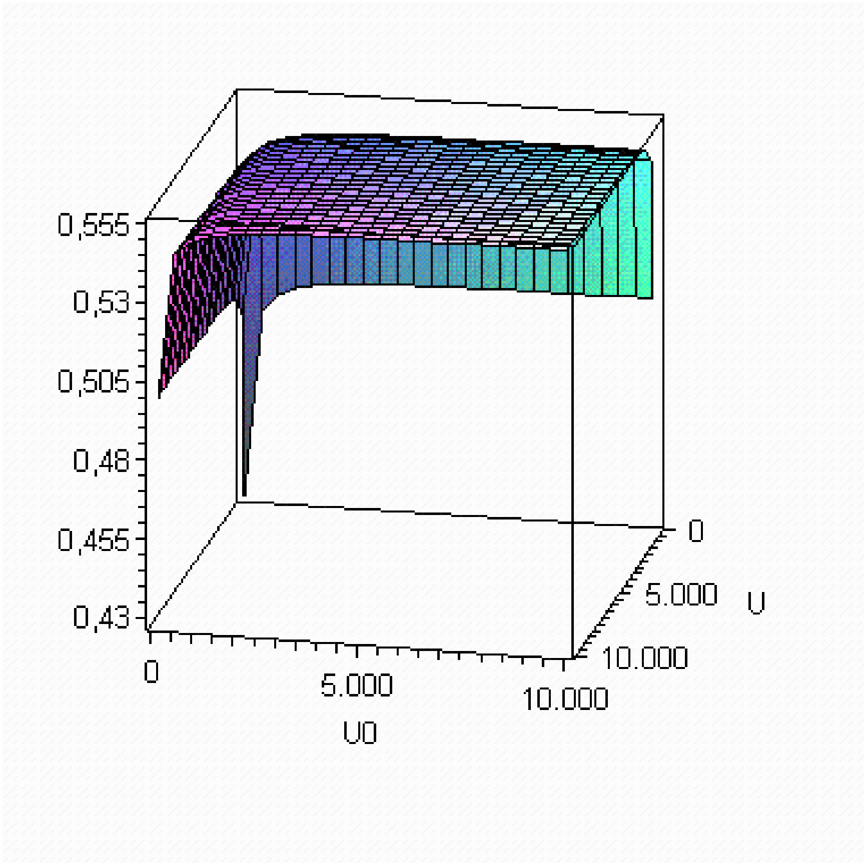

50
40
30
20
10
0
0
5.000
U0
10.000
10.000
5.000
U
0



570
545
520
495
470
445
10.000
0
5.000
U
10.000



U0
5.000
10¹
555
530
505
480
455
430
10.000
0
5.000
U
10.000



> **TURBOMOTORUL TRIPLUFLUX**

```
> restart;
> G2:=solve((RF-G1/G2),G2);G1:=solve((R-((G1+G2)/(G-G1-G2))),G1);
```

$$G2 := \frac{G1}{RF}$$

$$G1 := \frac{R\,G\,RF}{R\,RF + R + RF + 1}$$

```
> restart;
>
G:=359;R:=10.869;RF:=3;G1:=evalf(G*R*RF/(R+RF+1+R*RF));G2:=evalf(G1/RF)
;G3:=G-G1-G2;sumG:=G1+G2+G3;
```

$G := 359$

$R := 10.869$

$RF := 3$

$G1 := 246.564853$

$G2 := 82.1882846($

$G3 := 30.2468616($

$sumG := 359.000000($

```
>
piF:=1.745;piF1:=1.288;piF2:=piF/piF1;piC:=32.7/piF;es12:=0.92;es23:=0.92;es34:=0.88;es56:=0.94;em:=0.99;fi2a:=0.99;fi3b:=0.99;fi6c:=0.99;
```

$piF := 1.745$

$piF1 := 1.288$

$piF2 := 1.35481366$

$piC := 18.7392550$

$es12 := 0.92$

$es23 := 0.92$

$es34 := 0.88$

$es56 := 0.94$

$em := 0.99$

$fi2a := 0.99$

$fi3b := 0.99$

$fi6c := 0.99$

```
> Ta:=273.15;p0:=1.01325;T0:=288;
```

$Ta := 273.15$

$p0 := 1.01325$

$T0 := 288$

```
>
aer_uscat;rausO2:=0.2059;rausN2:=0.7809;rausCO2:=0.0132;MO2:=32;MN2:=28.016;MCO2:=44.01;MH2O:=18.0156;Maus:=rausO2*MO2+rausN2*MN2+rausCO2*MCO2;gausO2:=rausO2*MO2/Maus;gausN2:=rausN2*MN2/Maus;gausCO2:=rausCO2*MCO2/Maus;sumgaus:=gausO2+gausN2+gausCO2;
```

aer_uscat

$rausO2 := 0.2059$

$rausN2 := 0.7809$

$rausCO2 := 0.0132$

$MO2 := 32$

$MN2 := 28.016$

$MCO2 := 44.01$

$MH2O := 18.0156$

$Maus := 29.0474264$

$gausO2 := 0.2268290452$

$gausN2 := 0.7531715237$

$gausCO2 := 0.0199994310$

$sumgaus := 1.000000000$

```
> aer_umed;l0:=2500;u0:=l0-610.8*206.3/1000;phi0:=0.4;t0:=T0-
273.15;pvsH2O0:=-.4164460979e-18*t0^10+.2004215749e-
15*t0^9+.6588432820e-3*t0-.4117823023e-13*t0^8-.4560213564e-
4*t0^2+.4719547427e-11*t0^7+.6985705427e-5*t0^3-.3308562609e-9*t0^6-
.4022805689e-6*t0^4+.1465463358e-7*t0^5+.6108e-
2;x0:=MH2O*phi0*pvsH2O0/(p0-
phi0*pvsH2O0)/Maus;gaumO2:=gausO2/(1+x0);gaumN2:=gausN2/(1+x0);gaumCO2:
=gausCO2/(1+x0);gaumH2O:=x0/(1+x0);sumgaum:=gaumO2+gaumN2+gaumCO2+gaumH
2O;
```

aer_umed

$l0 := 2500$

$u0 := 2373.991960$

$\phi 0 := 0.4$

$t0 := 14.85$

$pvsH2O0 := 0.0168449354$

$x0 := 0.00415194359$

$gaumO2 := 0.2258911579$

$gaumN2 := 0.7500573277$

$gaumCO2 := 0.0199167378$

$gaumH2O := 0.004134776240$

$sumgaum := 0.9999999999$

```
> cpO2:=0.82397+3.05587E-4*T+5.32089E-8*T^2-1.30137E-10*T^3+3.58225E-
```

```
14*T^4;cvO2:=0.56574+2.96923E-4*T+6.54515E-8*T^2-1.36918E-
10*T^3+3.71407E-14*T^4;cpH2O:=1.84336-2.31223E-4*T+1.1966E-6*T^2-
6.15263E-10*T^3+1.0015E-13*T^4;cvH2O:=1.38161-2.29361E-4*T+1.19327E-
6*T^2-6.13657E-10*T^3+9.99765E-14*T^4;cpN2:=1.07623-3.25964E-
4*T+7.92186E-7*T^2-4.66137E-10*T^3+8.87148E-14*T^4;cvN2:=0.77884-
3.22759E-4*T+7.86981E-7*T^2-4.62795E-10*T^3+8.79811E-
14*T^4;cpCO2:=0.47158+0.00155*T-1.15247E-6*T^2+4.2015E-10*T^3-6.01131E-
14*T^4;cvCO2:=0.28209+0.00156*T-1.15879E-6*T^2+4.24136E-10*T^3-
6.09268E-
14*T^4;cpaum:=gaumO2*cpO2+gaumN2*cpN2+gaumCO2*cpCO2+gaumH2O*cpH2O;cvaum
:=gaumO2*cvO2+gaumN2*cvN2+gaumCO2*cvCO2+gaumH2O*cvH2O;Raum:=cpaum-
cvaum;RO2:=cpO2-cvO2;RH2O:=cpH2O-cvH2O;RN2:=cpN2-cvN2;RCO2:=cpCO2-
cvCO2;
```

$$cpO2 := 0.82397 + 0.000305587 T + 5.32089\,10^{-8}\, T^2 - 1.30137\,10^{-10}\, T^3 + 3.58225\,10^{-14}\, T^4$$

$$cvO2 := 0.56574 + 0.000296923 T + 6.54515\,10^{-8}\, T^2 - 1.36918\,10^{-10}\, T^3 + 3.71407\,10^{-14}\, T^4$$

$$cpH2O := 1.84336 - 0.000231223 T + 0.0000011966 T^2 - 6.15263\,10^{-10}\, T^3 + 1.0015\,10^{-13}\, T^4$$

$$cvH2O := 1.38161 - 0.000229361 T + 0.00000119327 T^2 - 6.13657\,10^{-10}\, T^3 + 9.99765\,10^{-14}\, T^4$$

$$cpN2 := 1.07623 - 0.000325964 T + 7.92186\,10^{-7}\, T^2 - 4.66137\,10^{-10}\, T^3 + 8.87148\,10^{-14}\, T^4$$

$$cvN2 := 0.77884 - 0.000322759 T + 7.86981\,10^{-7}\, T^2 - 4.62795\,10^{-10}\, T^3 + 8.79811\,10^{-14}\, T^4$$

$$cpCO2 := 0.47158 + 0.00155\, T - 0.00000115247 T^2 + 4.2015\,10^{-10}\, T^3 - 6.01131\,10^{-14}\, T^4$$

$cvCO2 := 0.28209 + 0.00156\,T - 0.00000115879\,T^2$
$+ 4.24136\,10^{-10}\,T^3 - 6.09268\,10^{-14}\,T^4$

$cpaum := 1.010375951 - 0.0001455473973\,T + 5.881985646\,10^{-7}\,T^2$
$- 3.732022277\,10^{-10}\,T^3 + 7.385001281\,10^{-14}\,T^4$

$cvaum := 0.7233012736 - 0.0001448937181\,T + 5.869203687\,10^{-7}\,T^2$
$- 3.721412754\,10^{-10}\,T^3 + 7.358054183\,10^{-14}\,T^4$

$Raum := 0.2870746774 - 6.536792\,10^{-7}\,T + 1.2781959\,10^{-9}\,T^2$
$- 1.0609523\,10^{-12}\,T^3 + 2.6947098\,10^{-16}\,T^4$

$RO2 := 0.25823 + 0.000008664\,T - 1.22426\,10^{-8}\,T^2 + 6.781\,10^{-12}\,T^3$
$- 1.3182\,10^{-15}\,T^4$

$RH2O := 0.46175 - 0.000001862\,T + 3.33\,10^{-9}\,T^2 - 1.606\,10^{-12}\,T^3$
$+ 1.735\,10^{-16}\,T^4$

$RN2 := 0.29739 - 0.000003205\,T + 5.205\,10^{-9}\,T^2 - 3.342\,10^{-12}\,T^3$
$+ 7.337\,10^{-16}\,T^4$

$RCO2 := 0.18949 - 0.00001\,T + 6.32\,10^{-9}\,T^2 - 3.986\,10^{-12}\,T^3$
$+ 8.137\,10^{-16}\,T^4$

```
> w1r:=160;w1t:=w1r/0.99;h0:=int(cpaum,T=Ta..T0);h1r:=h0-
w1r^2/2/1000;h1t:=h0-w1t^2/2/1000;es01:=(h0-h1r)/(h0-h1t);
```

$w1r := 160$

$w1t := 161.616161$

$h0 := 14.9697442$

$h1r := 2.1697442$

$h1t := 1.9098523$

$es01 := 0.980100000$

```
> eq01t:=h1t-
int(cpaum,T=Ta..T1ti)=0;T1t:=fsolve(eq01t,T1ti);eq01r:=h1r-
```

```
int(cpaum,T=Ta..T1ri)=0;T1r:=fsolve(eq01r,T1ri);k01:=int(cpaum,T=T0..T1
t)/int(cvaum,T=T0..T1t);
```

$$eq01t := 275.9632285 - 1.010375951 T1ti + 0.00007277369865 T1ti^2 - 1.960661882\,10^{-7}\, T1ti^3 + 9.330055692\,10^{-11}\, T1ti^4 - 1.477000256\,10^{-14}\, T1ti^5 = 0$$

$T1t := 275.045814$

$$eq01r := 276.2231203 - 1.010375951 T1ri + 0.00007277369865 T1ri^2 - 1.960661882\,10^{-7}\, T1ri^3 + 9.330055692\,10^{-11}\, T1ri^4 - 1.477000256\,10^{-14}\, T1ri^5 = 0$$

$T1r := 275.303769$

$k01 := 1.39791173$

```
> combustibil;gC:=0.85;gH2:=0.15;Hs:=46000;
```

combustibil

$gC := 0.85$

$gH2 := 0.15$

$Hs := 46000$

```
> p1:=(T1t/T0)^(k01/(k01-1));
```

$p1 := 0.850710312$

```
>
compression_F1;h1f:=h1r+w1r^2/2/1000;T1f:=fsolve((int(cpaum,T=Ta..T1fi)
-
h1f),T1fi);k11f:=int(cpaum,T=T1r..T1f)/int(cvaum,T=T1r..T1f);p1f:=p1*(T
1f/T1r)^(k11f/(k11f-
1));k1f2:=int(cpaum,T=T1f..T2ti)/int(cvaum,T=T1f..T2ti);eq12:=T1f*piF1^
((k1f2-1)/k1f2)-
T2ti=0;T2t:=fsolve(eq12,T2ti);h2t:=int(cpaum,T=Ta..T2t);h2r:=h1f+(h2t-
h1f)/es12;T2r:=fsolve((int(cpaum,T=Ta..T2ri)-h2r),T2ri);es02:=(h2t-
h0)/(h2r-h0);PF1:=G*(h2r-h1f);
```

compression_F1

$h1f := 14.969744$

$T1f := 287.999999$

$k11f := 1.39790441$

$p1f := 0.996714225$

$$k1f2 := \big(1.010375951\,T2ti - 289.0231202 - 0.00007277369865\,T2ti^2 + 1.960661882\,10^{-7}\,T2ti^3 - 9.330055692\,10^{-11}\,T2ti^4 + 1.477000256\,10^{-14}\,T2ti^5\big) \big/ \big(0.7233012736\,T2ti - 206.3642627 - 0.00007244685905\,T2ti^2 + 1.956401229\,10^{-7}\,T2ti^3 - 9.303531885\,10^{-11}\,T2ti^4 + 1.471610837\,10^{-14}\,T2ti^5\big)$$

$eq12 :=$

$$287.9999999 \; 1.288^{\Big(\big(\big(1.010375951\,T2ti - 289.0231202 - 0.00007277369865\,T2ti^2 + 1.960661882\,10^{-7}\,T2ti^3 - 9.330055692\,10^{-11}\,T2ti^4 + 1.477000256\,10^{-14}\,T2ti^5\big) \big/ \big(0.7233012736\,T2ti - 206.3642627 - 0.00007244685905\,T2ti^2 + 1.956401229\,10^{-7}\,T2ti^3 - 9.303531885\,10^{-11}\,T2ti^4 + 1.471610837\,10^{-14}\,T2ti^5\big) - 1\big) \big(0.7233012736\,T2ti - 206.3642627 - 0.00007244685905\,T2ti^2 + 1.956401229\,10^{-7}\,T2ti^3 - 9.303531885\,10^{-11}\,T2ti^4 + 1.471610837\,10^{-14}\,T2ti^5\big)\Big) \Big/ \big(1.010375951\,T2ti - 289.0231202 - 0.00007277369865\,T2ti^2 + 1.960661882\,10^{-7}\,T2ti^3 - 9.330055692\,10^{-11}\,T2ti^4 + 1.477000256\,10^{-14}\,T2ti^5\big)} - T2ti = 0$$

$T2t := 309.471934$

$h2t := 36.6572189$

$h2r := 38.5430863$

$T2r := 311.336554$

$es02 := 0.919999999$

$PF1 := 8462.82981$

```
> speed_of_first_jet;p2:=p1f*piF1;k2a:=int(cpaum,T=T2r..Ttai)/int(cvaum,T=T2r..Ttai);Tta:=fsolve((T2r*(p0/p2)^((k2a-1)/k2a)-Ttai),Ttai);wat:=sqrt(2000*int(cpaum,T=Tta..T2r));war:=wat*fi2a;Th1:=G1*war;Tra:=T2r-(T2r-Tta)*fi2a^2;Rgpa:=int(Raum,T=Tta..Tra)/(Tra-Tta);ka:=int(cpaum,T=Tra..Tta)/int(cvaum,T=Tra..Tta);Machar:=war/sqrt(1000*Rgpa*ka*Tra);
```

$speed\_of\_first\_jet$

$p2 := 1.28376792$

$$k2a := (1.010375951 Ttai - 312.5964624 - 0.00007277369865 Ttai^2 + 1.960661882 10^{-7} Ttai^3 - 9.330055692 10^{-11} Ttai^4 + 1.477000256 10^{-14} Ttai^5) / (0.7233012736 Ttai - 223.2407787 - 0.00007244685905 Ttai^2 + 1.956401229 10^{-7} Ttai^3 - 9.303531885 10^{-11} Ttai^4 + 1.471610837 10^{-14} Ttai^5)$$

$Tta := 291.098403$

$wat := 202.222815$

$war := 200.200587$

$Th1 := 49362.4284$

$Tra := 291.501142$

$Rgpa := 0.286968438$

$ka := 1.39733757$

$Machar := 0.585568196$

```
> compression_F2;k23:=int(cpaum,T=T2r..T3ti)/int(cvaum,T=T2r..T3ti);eq23:=T2r*piF2^((k23-1)/k23)-T3ti=0;T3t:=fsolve(eq23,T3ti);h3t:=int(cpaum,T=Ta..T3t);h3r:=h2r+(h3t-h2r)/es23;T3r:=fsolve((int(cpaum,T=Ta..T3ri)-h3r),T3ri);p3:=p2*piF2;PF2:=(G-G1)*(h3r-h2r);
```

$compression\_F2$

$$k23 := \left(1.010375951\,T3ti - 312.5964624 - 0.00007277369865\,T3ti^2 + 1.960661882\,10^{-7}\,T3ti^3 - 9.330055692\,10^{-11}\,T3ti^4 + 1.477000256\,10^{-14}\,T3ti^5\right) \Big/ \left(0.7233012736\,T3ti - 223.2407787 - 0.00007244685905\,T3ti^2 + 1.956401229\,10^{-7}\,T3ti^3 - 9.303531885\,10^{-11}\,T3ti^4 + 1.471610837\,10^{-14}\,T3ti^5\right)$$

$$eq23 := 311.3365548\; 1.354813665^{\left(\left(\left(1.010375951\,T3ti - 312.5964624 - 0.00007277369865\,T3ti^2 + 1.960661882\,10^{-7}\,T3ti^3 - 9.330055692\,10^{-11}\,T3ti^4 + 1.477000256\,10^{-14}\,T3ti^5\right) / \left(0.7233012736\,T3ti - 223.2407787 - 0.00007244685905\,T3ti^2 + 1.956401229\,10^{-7}\,T3ti^3 - 9.303531885\,10^{-11}\,T3ti^4 + 1.471610837\,10^{-14}\,T3ti^5\right) - 1\right) \left(0.7233012736\,T3ti - 223.2407787 - 0.00007244685905\,T3ti^2 + 1.956401229\,10^{-7}\,T3ti^3 - 9.303531885\,10^{-11}\,T3ti^4 + 1.471610837\,10^{-14}\,T3ti^5\right)\right) \Big/ \left(1.010375951\,T3ti - 312.5964624 - 0.00007277369865\,T3ti^2 + 1.960661882\,10^{-7}\,T3ti^3 - 9.330055692\,10^{-11}\,T3ti^4 + 1.477000256\,10^{-14}\,T3ti^5\right)} - T3ti = 0$$

$T3t := 339.296254$

$h3t := 66.8738811$

$h3r := 69.3374285$

$T3r := 341.722740$

$p3 := 1.73926632$

$PF2 := 3462.36636$

>

```
speed_of_second_jet;p3:=p2*piF2;k3b:=int(cpaum,T=T3r..Ttbi)/int(cvaum,T=T3r..Ttbi);Ttb:=fsolve((T3r*(p0/p3)^((k3b-1)/k3b)-Ttbi),Ttbi);wbt:=sqrt(2000*int(cpaum,T=Ttb..T3r));wbr:=wbt*fi3b;Th2:=G2*wbr;Trb:=T3r-(T3r-Ttb)*fi3b^2;Rgpb:=int(Raum,T=Ttb..Trb)/(Trb-Ttb);kb:=int(cpaum,T=Trb..Ttb)/int(cvaum,T=Trb..Ttb);Machbr:=wbr/sqrt(1000*Rgpb*kb*Trb);
```

speed_of_second_jet

$p3 := 1.73926632$

$$k3b := \left(1.010375951 Ttbi - 343.3908045 - 0.00007277369865 Ttbi^2 + 1.960661882 10^{-7} Ttbi^3 - 9.330055692 10^{-11} Ttbi^4 + 1.477000256 10^{-14} Ttbi^5\right) \Big/ \left(0.7233012736 Ttbi - 245.3153895 - 0.00007244685905 Ttbi^2 + 1.956401229 10^{-7} Ttbi^3 - 9.303531885 10^{-11} Ttbi^4 + 1.471610837 10^{-14} Ttbi^5\right)$$

$Ttb := 293.195167$

$wbt := 313.448985$

$wbr := 310.314495$

$Th2 := 25504.2160$

$Trb := 294.160866$

$Rgpb := 0.286968078$

$kb := 1.39719280$

$Machbr := 0.903575924$

```
>
compression_34;k34:=int(cpaum,T=T3r..T4ti)/int(cvaum,T=T3r..T4ti);eq34:=T4ti-T3r*piC^((k34-1)/k34);T4t:=fsolve(eq34,T4ti);h4t:=int(cpaum,T=Ta..T4t);h4r:=h3r+(h4t-h3r)/es34;T4r:=fsolve((int(cpaum,T=Ta..T4ri)-h4r),T4ri);p4:=p3*piC;PC:=G3*(h4r-h3r);
```

compression_34

$$k34 := \big(1.010375951\,T4ti - 343.3908045 - 0.00007277369865\,T4ti^2 + 1.960661882\,10^{-7}\,T4ti^3 - 9.330055692\,10^{-11}\,T4ti^4 + 1.477000256\,10^{-14}\,T4ti^5\big) \Big/ \big(0.7233012736\,T4ti - 245.3153895 - 0.00007244685905\,T4ti^2 + 1.956401229\,10^{-7}\,T4ti^3 - 9.303531885\,10^{-11}\,T4ti^4 + 1.471610837\,10^{-14}\,T4ti^5\big)$$

$$eq34 := T4ti$$

$$- 341.7227402$$

$$\big(\big(\big(1.010375951\,T4ti - 343.3908045$$

$$18.73925502$$

$$- 0.00007277369865\,T4ti^2 + 1.960661882\,10^{-7}\,T4ti^3$$

$$- 9.330055692\,10^{-11}\,T4ti^4 + 1.477000256\,10^{-14}\,T4ti^5\big) \big/ \big(0.7233012736\,T4ti$$

$$- 245.3153895 - 0.00007244685905\,T4ti^2 + 1.956401229\,10^{-7}\,T4ti^3$$

$$- 9.303531885\,10^{-11}\,T4ti^4 + 1.471610837\,10^{-14}\,T4ti^5\big) - 1\big)$$

$$\big(0.7233012736\,T4ti - 245.3153895 - 0.00007244685905\,T4ti^2$$

$$+ 1.956401229\,10^{-7}\,T4ti^3 - 9.303531885\,10^{-11}\,T4ti^4$$

$$+ 1.471610837\,10^{-14}\,T4ti^5\big)\big) \Big/ \big(1.010375951\,T4ti - 343.3908045$$

$$- 0.00007277369865\,T4ti^2 + 1.960661882\,10^{-7}\,T4ti^3$$

$$- 9.330055692\,10^{-11}\,T4ti^4 + 1.477000256\,10^{-14}\,T4ti^5\big)$$

$$T4t := 758.590791$$

$$h4t := 508.934142$$

$$h4r := 568.879148$$

$$T4r := 812.778401$$

$$p4 := 32.5925551$$

$$PC := 15109.5692$$

>

```
combustion;T5:=1540;p5:=p4*0.97;eca:=0.98;GO2:=gaumO2*G3;GN2:=gaumN2*G3
;GCO2:=gaumCO2*G3;GH2O:=gaumH2O*G3;h5N2:=int(cpN2,T=T0..T5);h5CO2:=int(
cpCO2,T=T0..T5);h5O2:=int(cpO2,T=T0..T5);h5H2O:=l0+int(cpH2O,T=T0..T5);
u5N2:=int(cvN2,T=T0..T5);u5CO2:=int(cvCO2,T=T0..T5);u5O2:=int(cvO2,T=T0
..T5);u5H2O:=u0+int(cvH2O,T=T0..T5);
```

combustion

$T5 := 1540$

$p5 := 31.6147785$

$eca := 0.98$

$GO2 := 6.83249859$

$GN2 := 22.6868801$

$GCO2 := 0.602418812$

$GH2O := 0.125064004$

$h5N2 := 1431.55209$

$h5CO2 := 1456.20844$

$h5O2 := 1324.93416$

$h5H2O := 5299.90799$

$u5N2 := 1060.01493$

$u5CO2 := 1226.95512$

$u5O2 := 999.282467$

$u5H2O := 4595.84717$

```
> eq45:=eca*mcb*Hs+G3*(h4r+gaumH2O*l0)-GN2*h5N2-
(GCO2+44*mcb*gC/12)*h5CO2-(GH2O+18*mcb*gH2/2)*h5H2O-(GO2-
32*mcb*(gC/12+gH2/4))*h5O2=0;mcb:=fsolve(eq45,mcb);
```

$eq45 := 37979.71298\, mcb - 25550.66774 = 0$

$mcb := 0.672745150$

```
>
GO2consumat:=32*mcb*(gC/12+gH2/4);alfaO2:=GO2/GO2consumat;Gga:=G3+mcb;
```

$GO2consumat := 2.33218318$

$alfaO2 := 2.92965776$

$Gga := 30.9196067$

```
> h5:=(GN2*h5N2+(GCO2+44*mcb*gC/12)*h5CO2+(GH2O+18*mcb*gH2/2)*h5H2O+(GO2-32*mcb*(gC/12+gH2/4))*h5O2)/Gga;u5:=(GN2*u5N2+(GCO2+44*mcb*gC/12)*u5CO2+(GH2O+18*mcb*gH2/2)*u5H2O+(GO2-32*mcb*(gC/12+gH2/4))*u5O2)/Gga;
```

$h5 := 1547.45888$

$u5 := 1183.90878$

```
> eqpr1:=Gga*(h5-h6)-(PF1+PF2+PC)/em=0;
```

$eqpr1 := 20538.97638 - 30.91960675 h6 = 0$

```
> h6r:=fsolve(eqpr1,h6);h6t:=h5-(h5-h6r)/es56;
```

$h6r := 664.270297$

$h6t := 607.896557$

```
> h6N2:=int(cpN2,T=T0..T6);h6CO2:=int(cpCO2,T=T0..T6);h6O2:=int(cpO2,T=T0..T6);h6H2O:=l0+int(cpH2O,T=T0..T6);
```

$$h6N2 := 1.076230000 T6 - 301.9771738 - 0.0001629820000 T6^2 + 2.640620000\,10^{-7}\, T6^3 - 1.165342500\,10^{-10}\, T6^4 + 1.774296000\,10^{-14}\, T6^5$$

$$h6CO2 := 0.4715800000 T6 - 191.6187609 + 0.0007750000000 T6^2 - 3.841566667\,10^{-7}\, T6^3 + 1.050375000\,10^{-10}\, T6^4 - 1.202262000\,10^{-14}\, T6^5$$

$$h6O2 := 0.8239700000 T6 - 250.1907158 + 0.0001527935000 T6^2 + 1.773630000\,10^{-8}\, T6^3 - 3.253425000\,10^{-11}\, T6^4 + 7.164500000\,10^{-15}\, T6^5$$

$$h6H2O := 1970.192045 + 1.843360000 T6 - 0.0001156115000 T6^2 + 3.988666667\,10^{-7}\, T6^3 - 1.538157500\,10^{-10}\, T6^4 + 2.003000000\,10^{-14}\, T6^5$$

```
> eq6r:=h6r-(GN2*h6N2+(GCO2+44*mcb*gC/12)*h6CO2+(GH2O+18*mcb*gH2/2)*h6H2O+(GO2-32*mcb*(gC/12+gH2/4))*h6O2)/Gga=0;eq6t:=h6t-
```

```
(GN2*h6N2+(GCO2+44*mcb*gC/12)*h6CO2+(GH2O+18*mcb*gH2/2)*h6H2O+(GO2-
32*mcb*(gC/12+gH2/4))*h6O2)/Gga=0;
```

$$eq6r := 873.1449765 - 1.012366545\, T6 + 0.00003355662422\, T6^2 - 1.761279113\, 10^{-7}\, T6^3 + 8.621180480\, 10^{-11}\, T6^4 - 1.368130484\, 10^{-14}\, T6^5 = 0$$

$$eq6t := 816.7712367 - 1.012366545\, T6 + 0.00003355662422\, T6^2 - 1.761279113\, 10^{-7}\, T6^3 + 8.621180480\, 10^{-11}\, T6^4 - 1.368130484\, 10^{-14}\, T6^5 = 0$$

```
> T6r:=fsolve(eq6r,T6);T6t:=fsolve(eq6t,T6);
```

$T6r := 822.047914$

$T6t := 772.926796$

```
>
u6N2t:=int(cvN2,T=T0..T6t);u6CO2t:=int(cvCO2,T=T0..T6t);u6O2t:=int(cvO2
,T=T0..T6t);u6H2Ot:=u0+int(cvH2O,T=T0..T6t);u6N2r:=int(cvN2,T=T0..T6r);
u6CO2r:=int(cvCO2,T=T0..T6r);u6O2r:=int(cvO2,T=T0..T6r);u6H2Or:=u0+int(
cvH2O,T=T0..T6r);u6t:=(GN2*u6N2t+(GCO2+44*mcb*gC/12)*u6CO2t+(GH2O+18*mc
b*gH2/2)*u6H2Ot+(GO2-
32*mcb*(gC/12+gH2/4))*u6O2t)/Gga;u6r:=(GN2*u6N2r+(GCO2+44*mcb*gC/12)*u6
CO2r+(GH2O+18*mcb*gH2/2)*u6H2Or+(GO2-
32*mcb*(gC/12+gH2/4))*u6O2r)/Gga;PT:=Gga*(h5-h6r);DP:=PT-
(PC+PF2+PF1)/em;
```

$u6N2t := 373.842217$

$u6CO2t := 402.724901$

$u6O2t := 350.328056$

$u6H2Ot := 3110.91518$

$u6N2r := 414.259904$

$u6CO2r := 450.843682$

$u6O2r := 389.119662$

$u6H2Or := 3193.77362$

$u6t := 464.408458$

$u6r := 506.6800250$

$PT := 27307.84390$

$DP := 0.$

```
> k56:=(h5-h6t)/(u5-u6t);p6:=p5*(T6t/T5)^(k56/(k56-1));
```

$k56 := 1.30585393$

$p6 := 1.66596871$

```
>
p7:=p0;h7N2:=int(cpN2,T=T0..T7);h7CO2:=int(cpCO2,T=T0..T7);h7O2:=int(cp
O2,T=T0..T7);h7H2O:=l0+int(cpH2O,T=T0..T7);u7N2:=int(cvN2,T=T0..T7);u7C
O2:=int(cvCO2,T=T0..T7);u7O2:=int(cvO2,T=T0..T7);u7H2O:=u0+int(cvH2O,T=
T0..T7);h7t:=(GN2*h7N2+(GCO2+44*mcb*gC/12)*h7CO2+(GH2O+18*mcb*gH2/2)*h7
H2O+(GO2-
32*mcb*(gC/12+gH2/4))*h7O2)/Gga;u7t:=(GN2*u7N2+(GCO2+44*mcb*gC/12)*u7CO
2+(GH2O+18*mcb*gH2/2)*u7H2O+(GO2-
32*mcb*(gC/12+gH2/4))*u7O2)/Gga;k67:=(h6r-h7t)/(u6r-u7t);
```

$p7 := 1.01325$

$$h7N2 := 1.076230000 T7 - 301.9771738 - 0.0001629820000 T7^2 + 2.640620000 10^{-7}\, T7^3 - 1.165342500 10^{-10}\, T7^4 + 1.774296000 10^{-14}\, T7^5$$

$$h7CO2 := 0.4715800000 T7 - 191.6187609 + 0.0007750000000 T7^2 - 3.841566667 10^{-7}\, T7^3 + 1.050375000 10^{-10}\, T7^4 - 1.202262000 10^{-14}\, T7^5$$

$$h7O2 := 0.8239700000 T7 - 250.1907158 + 0.0001527935000 T7^2 + 1.773630000 10^{-8}\, T7^3 - 3.253425000 10^{-11}\, T7^4 + 7.164500000 10^{-15}\, T7^5$$

$$h7H2O := 1970.192045 + 1.843360000 T7 - 0.0001156115000 T7^2 + 3.988666667 10^{-7}\, T7^3 - 1.538157500 10^{-10}\, T7^4 + 2.003000000 10^{-14}\, T7^5$$

$$u7N2 := 0.7788400000\,T7 - 216.4257834 - 0.0001613795000\,T7^2 + 2.623270000\,10^{-7}\,T7^3 - 1.156987500\,10^{-10}\,T7^4 + 1.759622000\,10^{-14}\,T7^5$$

$$u7CO2 := 0.2820900000\,T7 - 137.4165703 + 0.0007800000000\,T7^2 - 3.862633333\,10^{-7}\,T7^3 + 1.060340000\,10^{-10}\,T7^4 - 1.218536000\,10^{-14}\,T7^5$$

$$u7O2 := 0.5657400000\,T7 - 175.5475052 + 0.0001484615000\,T7^2 + 2.181716667\,10^{-8}\,T7^3 - 3.422950000\,10^{-11}\,T7^4 + 7.428140000\,10^{-15}\,T7^5$$

$$u7H2O := 1977.114606 + 1.381610000\,T7 - 0.0001146805000\,T7^2 + 3.977566667\,10^{-7}\,T7^3 - 1.534142500\,10^{-10}\,T7^4 + 1.999530000\,10^{-14}\,T7^5$$

$$h7t := 1.012366545\,T7 - 208.8746788 - 0.00003355662422\,T7^2 + 1.761279113\,10^{-7}\,T7^3 - 8.621180480\,10^{-11}\,T7^4 + 1.368130484\,10^{-14}\,T7^5$$

$$u7t := 0.7246028460\,T7 - 130.2752195 - 0.00003254373812\,T7^2 + 1.752278458\,10^{-7}\,T7^3 - 8.574510158\,10^{-11}\,T7^4 + 1.359664263\,10^{-14}\,T7^5$$

$$k67 := \left(873.1449765 - 1.012366545\,T7 + 0.00003355662422\,T7^2 - 1.761279113\,10^{-7}\,T7^3 + 8.621180480\,10^{-11}\,T7^4 - 1.368130484\,10^{-14}\,T7^5\right) \Big/ \left(636.9552445 - 0.7246028460\,T7 + 0.00003254373812\,T7^2 - 1.752278458\,10^{-7}\,T7^3 + 8.574510158\,10^{-11}\,T7^4 - 1.359664263\,10^{-14}\,T7^5\right)$$

```
> eq67:=T7-T6r*(p7/p6)^((k67-1)/k67)=0;
```

$$eq67 := T7 - 822.0479146 \; 0.6082047000 \Big(\Big(\big((873.1449765 - 1.012366545\, T7 + 0.00003355662422\, T7^2 - 1.761279113\, 10^{-7}\, T7^3 + 8.621180480\, 10^{-11}\, T7^4 - 1.368130484\, 10^{-14}\, T7^5) \big/ (636.9552445 - 0.7246028460\, T7 + 0.00003254373812\, T7^2 - 1.752278458\, 10^{-7}\, T7^3 + 8.574510158\, 10^{-11}\, T7^4 - 1.359664263\, 10^{-14}\, T7^5) - 1 \big) (636.9552445 - 0.7246028460\, T7 + 0.00003254373812\, T7^2 - 1.752278458\, 10^{-7}\, T7^3 + 8.574510158\, 10^{-11}\, T7^4 - 1.359664263\, 10^{-14}\, T7^5) \Big) \Big/ (873.1449765 - 1.012366545\, T7 + 0.00003355662422\, T7^2 - 1.761279113\, 10^{-7}\, T7^3 + 8.621180480\, 10^{-11}\, T7^4 - 1.368130484\, 10^{-14}\, T7^5) \Big) = 0$$

```
> T7t:=fsolve(eq67,T7);
```

$T7t := 725.411406$

```
>
h7N2t:=int(cpN2,T=T0..T7t);h7CO2t:=int(cpCO2,T=T0..T7t);h7O2t:=int(cpO2,T=T0..T7t);h7H2Ot:=l0+int(cpH2O,T=T0..T7t);u7N2t:=int(cvN2,T=T0..T7t);u7CO2t:=int(cvCO2,T=T0..T7t);u7O2t:=int(cvO2,T=T0..T7t);u7H2Ot:=u0+int(cvH2O,T=T0..T7t);h7t:=(GN2*h7N2t+(GCO2+44*mcb*gC/12)*h7CO2t+(GH2O+18*mcb*gH2/2)*h7H2Ot+(GO2-32*mcb*(gC/12+gH2/4))*h7O2t)/Gga;u7t:=(GN2*u7N2t+(GCO2+44*mcb*gC/12)*u7CO2t+(GH2O+18*mcb*gH2/2)*u7H2Ot+(GO2-32*mcb*(gC/12+gH2/4))*u7O2t)/Gga;k67:=(h6r-h7t)/(u6r-u7t);
```

$h7N2t := 465.062001$

$h7CO2t := 438.320351$

$h7O2t := 427.130325$

$h7H2Ot := 3360.23788$

$u7N2t := 335.266149$

$u7CO2t := 357.134521$

$u7O2t := 313.312262$

$u7H2Ot := 3032.37213$

$h7t := 553.957513$

$u7t := 424.111554$

$k67 := 1.33601584$

```
> speed_of_third_jet;wcr:=fi6c*sqrt(2000*(h6r-h7t));Rfg:=(GN2*RN2+(GCO2+44*mcb*gC/12)*RCO2+(GH2O+18*mcb*gH2/2)*RH2O+(GO2-32*mcb*(gC/12+gH2/4))*RH2O)/Gga;h7r:=h6r-fi6c^2*(h6r-h7t);
```

speed_of_third_jet

$wcr := 465.010881$

$$Rfg := 0.3173858154 - 0.000003557820116\,T + 4.966771545\,10^{-9}\,T^2 - 3.087531779\,10^{-12}\,T^3 + 6.404263934\,10^{-16}\,T^4$$

$h7r := 556.152737$

```
>
h7N2r:=int(cpN2,T=T0..T7ri);h7CO2r:=int(cpCO2,T=T0..T7ri);h7O2r:=int(cpO2,T=T0..T7ri);h7H2Or:=l0+int(cpH2O,T=T0..T7ri);T7r:=fsolve(h7r-(GN2*h7N2r+(GCO2+44*mcb*gC/12)*h7CO2r+(GH2O+18*mcb*gH2/2)*h7H2Or+(GO2-32*mcb*(gC/12+gH2/4))*h7O2r)/Gga,T7ri);u7N2r:=int(cvN2,T=T0..T7r);u7CO2r:=int(cvCO2,T=T0..T7r);u7O2r:=int(cvO2,T=T0..T7r);u7H2Or:=u0+int(cvH2O,T=T0..T7r);u7r:=(GN2*u7N2r+(GCO2+44*mcb*gC/12)*u7CO2r+(GH2O+18*mcb*gH2/2)*u7H2Or+(GO2-32*mcb*(gC/12+gH2/4))*u7O2r)/Gga;k7:=(h7r-h7t)/(u7r-u7t);Rfgc:=int(Rfg,T=T7t..T7r)/(T7r-T7t);Machc:=wcr/sqrt(1000*Rfgc*k7*T7r);
```

$$h7N2r := 1.076230000\,T7ri - 301.9771738 - 0.0001629820000\,T7ri^2 + 2.640620000\,10^{-7}\,T7ri^3 - 1.165342500\,10^{-10}\,T7ri^4 + 1.774296000\,10^{-14}\,T7ri^5$$

$h7CO2r := 0.4715800000 T7ri - 191.6187609$
$+ 0.0007750000000 T7ri^2 - 3.841566667 10^{-7} T7ri^3$
$+ 1.050375000 10^{-10} T7ri^4 - 1.202262000 10^{-14} T7ri^5$

$h7O2r := 0.8239700000 T7ri - 250.1907158 + 0.0001527935000 T7ri^2$
$+ 1.773630000 10^{-8} T7ri^3 - 3.253425000 10^{-11} T7ri^4$
$+ 7.164500000 10^{-15} T7ri^5$

$h7H2Or := 1970.192045 + 1.843360000 T7ri - 0.0001156115000 T7ri^2$
$+ 3.988666667 10^{-7} T7ri^3 - 1.538157500 10^{-10} T7ri^4$
$+ 2.003000000 10^{-14} T7ri^5$

$T7r := 727.355311($

$u7N2r := 336.834396'$

$u7CO2r := 358.98011 5($

$u7O2r := 314.81649 1($

$u7H2Or := 3035.55479($

$u7r := 425.748645'$

$k7 := 1.34092973($

$Rfgc := 0.31641705 9($

$Machc := 0.83706050 9($

```
>
Thfg:=Gga*wcr;Th:=Th1+Th2+Thfg;mcbspecific:=36000*mcb/Th;difmcbspecific
:=100*(0.383-mcbspecific)/0.383;
```

$Thfg := 14377.9536($

$Th := 89244.5981($

$mcbspecific := 0.271375813($

$difmcbspecific := 29.1446961($

```
> X:=(PF1+PF2+PC)/(PT+Gga*(h6r-
h7r));XT:=(es12*PF1+es23*PF2+es34*PC)/(PT/es56+Gga*(h6t-h7t));
```

$X := 0.88202489 6($

$XT := 0.78999514 0($

```
> save R,RF, X,piF1, piF2, piF,piC,war, wbr, wcr, Th1, Th2, Thfg, Th,
```

```
mcb,mcbspecific,difmcbspecific, G1,G2,G3,Gga, "date tripluflux";
> read "date tripluflux";
```

$R := 10.869$

$RF := 3$

$X := 0.88202489 6$

$piF1 := 1.288$

$piF2 := 1.35481366$

$piF := 1.745$

$piC := 18.7392550$

$war := 200.200587$

$wbr := 310.314495$

$wcr := 465.010881$

$Th1 := 49362.4284$

$Th2 := 25504.2160$

$Thfg := 14377.9536$

$Th := 89244.5981$

$mcb := 0.672745150$

$mcbspecific := 0.271375813$

$difmcbspecific := 29.1446961$

$G1 := 246.564853$

$G2 := 82.1882846$

$G3 := 30.2468616$

$Gga := 30.9196067$

```
>
>
>
```