THE CONCEPT OF ENTRANSY AND ITS UTILIZATION IN THE ANALYSIS OF PROBLEMS IN THERMODYNAMICS AND HEAT TRANSFER

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Abstract. *The concept of entransy was recently proposed in terms of the analogy to the electric energy stored in a capacitor. The entransy of a system describes its heat transfer hability, as the exergy of a system quantifies its work production potential. Hence, the concept of entransy can be useful in problems where the heat transfer is the main objective, as for example, in systems collecting solar energy. This concept is very recent and there are only a few works related to this topic. It is expected, however, that this approach will soon become of extreme importance in the analysis of problems in thermodynamics and heat transfer. The objective of this work is to present a review of the concept of entransy in a systematic way, beginning with its definition, balance equations and a few examples of simple application. It is hoped that this concept of entransy be widely spread in the scientific community and efforts be directed in the sense of improving the thermal sciences.*

Keywords: *entransy, thermodynamics, heat transfer, entropy, exergy*

1. INTRODUCTION

Designers are always seeking new methods to improve heat transfer techniques in several fields of engineering. These methods can intensify the efficiency of energy utilization or to reduce the weight and dimensions of heat transfer equipments. For example, the utilization of high thermal conductivity materials can enhance the heat transfer rate by conduction, as well as an increase of the fluid velocity can enhance the heat transfer rate by convection.

There are several techniques to calculate the heat transfer rate, but there is not a concept to quantify the efficiency of these processes because in heat transfer problems the input data (for example, high thermal conductivity material or high fluid velocity) has different units than the output (augmentation in the heat transfer rate or reduction in the temperature difference). Therefore, a heat transfer process can be improved, but the question is how to optimize a heat transfer process.

Thus, there was a need to develop a concept to allow the analysis and optimization of heat transfer processes. This concept was recently proposed by Guo *et al.* (2007). The authors presented the concept of a new physical quantity, defined as “entransy”, that can be used to define efficiencies for a heat transfer process and to optimize heat transfer processes. The word “entransy” is derived from the expression “**en**ergy **trans**fer efficienc**y**”.

According to Guo *et al.* (2007) the entransy of a system describes its ability to transfer heat, in the same way that the electric energy in a capacitor describes its ability to store electrical charge. Dissipation of entransy occurs during heat transfer processes and is a measure of the irreversibilities due to heat transfer. The concepts of entransy and entransy dissipation were used to develop the principle of maximum entransy dissipation, used in the optimization of heat transfer processes.

Zhu and Guo (2007) and Guo and Chen (2007) used the concepts of entransy and entransy dissipation to optimize heat transfer processes. The entransy dissipation is a measure of the loss of the ability to transfer heat in the same way the entropy generation is proportional to the loss of the ability to produce work. The principle of maximum entransy dissipation was developed using the method of weighted residues. These concepts were used in the analysis and optimization of a problem of temperature distribution in materials of high thermal conductivity.

Chen et al. (2008) examined a problem of heat conduction which consists in determining the optimal distribution of a material of high thermal conductivity in a given volume such that the heat generated at each point is transferred more effectively to the boundaries of the volume. This analysis was done using the concept of entransy and the results were compared with those obtained by the constructal theory.

Wu and Liang (2008) applied the concepts of flow of entransy and entransy dissipation in the heat transfer by radiation. Entransy is partially dissipated during processes of heat transfer by radiation due to irreversibilities. The extreme principle of entransy dissipation was used to optimize a problem of heat transfer by radiation between three bodies.

Oliveira and Milanez (2009) used the concept of exergy and entransy to analyze an isothermal and other non-isothermal solar collector operating in steady state. The authors defined the number of entransy dissipation for a solar collector and showed that this parameter is the number of entropy dissipation. It is hoped that these results together with those obtained by minimizing the entropy generation will be useful in the design of cheaper and efficient collectors.

The objective of this work is to present the concept of entransy in a systematic way and to analyze two simple heat transfer problems to show the physical implementation of this concept. It is hoped that this concept will be of great importance in the development of thermal sciences.

2. ENTRANSY

2.1. Analogy between heat conduction and eletrical conduction

Experimental studies often use the analogy between electrical conduction and heat conduction to facilitate the analysis of steady state or transient heat conduction problems of complex systems. In order to exist electricity conduction there must be a difference of potential V and to exist heat conduction there must be a temperature difference T. A potential difference V originates a flow of electricity I'' and through a temperature difference there is a heat flux q''. The resistance to the electricity flux is the electrical resistance R_e and the resistance to the heat flow is the thermal resistance R_t. These variables can be viewed and compared in Tab. 1:

Table 1. Analogy between electrical and thermal parameters.

Electrical Potential	*Electrical Flux*	*Electrical Resistance*
V (V)	I'' (A/m^2)	(R_e) (V/A)
Thermal Potential	*Heat Flux*	*Thermal Resistance*
T (K)	q'' (W/m^2)	R_t (K/W)

Multiplying the electrical and heat flux by the respective areas the electricity transfer rate I and the conduction heat transfer rate q can be obtained. In the electrical conduction the electricity transfer rate is calculated through the Ohm's law. As for the heat conduction, the heat transfer rate is calculated using the Fourier's law. The electric charge stored in a capacitor is Q_e while as the heat stored in a body is U. These variables can be viewed and compared in Tab. 2:

Table 2. Analogy between electrical and thermal parameters.

Electricity Transfer Rate	*Ohm's Law*	*Electrical Charge Stored*
I (A)	$I=-k_e A\dfrac{dV}{dn}$ (A)	Q_e (C)
Heat Transfer Rate	*Fourier's Law*	*Heat Stored*
q (W)	$q=-kA\dfrac{dT}{dn}$ (W)	$U=mc_vT$ (J)

where k_e is the electrical conductivity, k is the thermal conductivity and n is the direction of the electric potential and of the heat potential. An additional analogy is the capacitance of a capacitor C_e and the thermal capacity of a body C. The electrical potential energy stored in a capacitor is E_e and there is no corresponding parameter in thermal systems, as shown in Tab. 3:

Table 3. Analogy between electrical and thermal parameters.

Capacitance	*Electrical potential energy stored in a capacitor*
$C_e=Q_e/V$ (F)	$E_e=\dfrac{Q_eV}{2}$ (J)
Thermal Capacity	*Thermal potential energy stored in a body*
$C=U/T$ (J/K)	?

In the analogy shown in Tab. 3 it may be noticed the absence of a parameter "thermal potential energy of a body" for thermal systems. This parameter corresponds to the electrical potential energy stored in a capacitor. In analogy to electrical systems, the following parameter can be defined:

$$E_n=\frac{UT}{2} \tag{1}$$

where $U = mc_v T$ is the thermal energy stored in a body and T represents the thermal potential. The physical meaning of that quantity was considered by Guo *et al.* (2007) in terms of an analysis of heat transfer to or from an object. In the same way an electrical capacitor stores electrical charge, resulting in electrical energy, a body can be seen as a thermal capacitor that stores heat (thermal load) resulting in "energy" of heat. The term energy was placed in quotes because its unit is the product of Joule and Kelvin, not only Joule. This concept was defined as the internal energy entransy because it has the nature of "potential energy" of a quantity of heat. The authors also interpreted that amount as a measure of the potential for heat transfer.

2.2. Entransy

The physical meaning of entransy can be understood by considering a reversible heating process of a body with temperature T and specific heat c_v, according to Fig. 1:

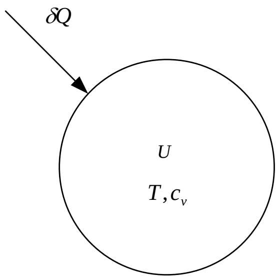

Figure 1. Thermal capacitor

In a reversible process of heating, the temperature difference between the body and the heat source, as well as the heat added, are infinitesimal. The continuous heating of the body implies an infinite number of heat sources that heat the body individually and in sequence. The temperature of these heat sources increases by an infinitesimal increment and each infinitesimal heat source provides an infinitesimal amount of heat to the body. The temperature represents the potential for heat transfer and this potential for heat transfer will change at different temperatures. Thus, the “potential energy” increases together with thermal energy (thermal charge) when heat is added. When an infinitesimal amount of heat is added to the system, the increase in the “potential energy” of the thermal energy can be written as the product of the thermal charge and the thermal potential (temperature) differential:

$$dE_n = UdT \tag{2}$$

If absolute zero is taken as the zero thermal potential, then the “potential energy” of the thermal energy of a body at a temperature T is:

$$E_n = \int_0^T UdT \tag{3}$$

The unit of the “potential of energy” of the thermal energy is the product between Joule and Kelvin (JK) and not Joule (J). Considering constant specific heat:

$$E_n = \int_0^T mc_v TdT = \frac{mc_v T^2}{2} \tag{4}$$

Thus, as an electrical capacitor stores electrical charge having energy stored as a result, a body can be seen as a thermal capacitor that stores thermal load having heat stored as a result. If the body is placed in contact with an infinite number of heat sinks with infinitesimal temperature lower than the body, the “potential energy” of the total energy that can be transferred from the body is $UT/2$.

3. CASE STUDY

3.1. Physical situation 1

Consider a thermal system composed of 3 bodies, identified as 1, 2 and 3, according to Fig. 2a. The thermal capacitances of bodies 1, 2 and 3 are identified as C_1, C_2 and C_3, respectively, where $C_1, C_2 >> C_3$. The thermal conductivities of bodies 1, 2 and 3 are identified as k_1, k_2 and k_3, respectively, where $k_1, k_2 >> k_3$. The initial temperatures of bodies 1 and 2 are, respectively, T_{10} and T_{20}. It is assumed that $T_{10} > T_{20}$. The quantity of energy stored in bodies 1 and 2 in the beginning can be calculated as:

$$Q_{10} = C_1 T_{10} \tag{5}$$

$$Q_{20} = C_2 T_{20} \tag{6}$$

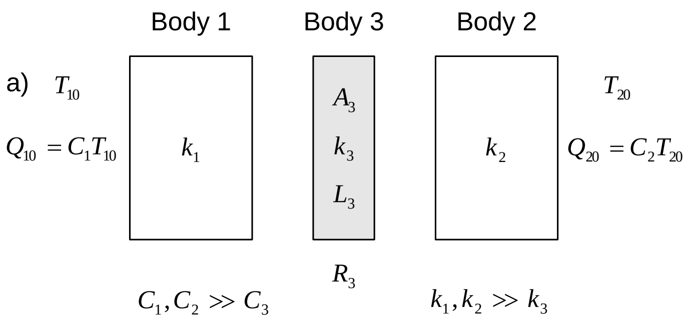

Figure 2a. Thermal system before contact

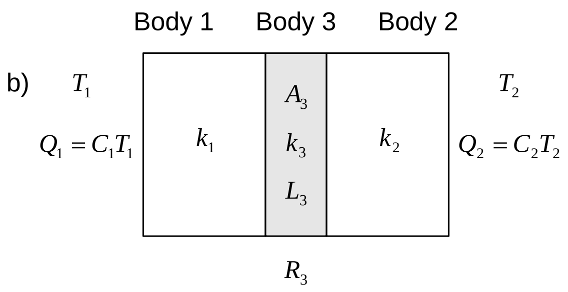

Figure 2b. Thermal system after contact

The 3 bodies are put in thermal contact and heat is transferred from body 1 to body 2 through body 3, according to Fig. 2b. The thermal conduction resistance in body 3 is:

$$R_3 = \frac{L_3}{k_3 A_3} \tag{7}$$

The situation described above consists in a transient heat transfer problem, where the temperature of body 1 decreases and the temperature of body 2 increases, being both functions of time. Besides, the energy stored in body 1 decreases and the energy stored in body 2 increases, also as function of time. The reason to use the thermal resistance in body 3 is due to its low thermal capacitance. A situation of steady state regime is rapidly established in body 3 and the concept of thermal resistance can be utilized when modeling body 3. The energy stored in bodies 1 and 2 at any instant can be calculated as:

$$Q_1 = C_1 T_1 \tag{8}$$

$$Q_2 = C_2 T_2 \tag{9}$$

The objective of this problem is to formulate a mathematical model to calculate the temperature and the energy stored in bodies 1 and 2 as function of time. This model is based in an energy and entransy balance for body 3. By doing this, the entransy dissipation rate for body 3, as well as the entransy variation rate for bodies 1 and 2 can be obtained. Neglecting kinetic and potential energy variations, and the work term, the energy balance in the rate form for body 3 gives:

$$\frac{dU_3}{dt} = \frac{\delta Q_3}{dt} \tag{10}$$

Utilizing the approximation $dU_3 = C_3 dT_3$ the net heat transfer rate can be rewritten as:

$$C_3 \frac{dT_3}{dt} = \frac{\delta Q_1}{dt} - \frac{\delta Q_2}{dt} \tag{11}$$

As it was assumed that the heat capacity of body 3 can be neglected, the term $C_3 \frac{dT_3}{dt}$ can also be neglected and Eq. (11) is expressed as:

$$\frac{\delta Q_1}{dt} = \frac{\delta Q_2}{dt} \tag{12}$$

Equation (12) indicates that the heat transfer rate from body 1 to body 3 must be equal to the heat transfer rate from body 3 to body 2. This heat transfer rate crosses body 3 by conduction. Denoting the conduction heat transfer rate in body 3 by $q = (\delta Q/dt)$, an energy balance at the boundary surface between bodies 1 and 3 and in the surface between bodies 3 and 2 gives:

$$\frac{\delta Q_1}{dt} = \frac{\delta Q_2}{dt} = \frac{\delta Q}{dt} = q \tag{13}$$

An entransy balance in the rate form for body 3 gives:

$$\frac{dE_{n3}}{dt} = Q_1 \frac{dT_1}{dt} + Q_2 \frac{dT_2}{dt} + q^2 R_3 \tag{14}$$

As the heat capacity of body 3 is very low, its storage capacity is also very low. Thus, the steady state regime is rapidly reached in body 3 when the 3 bodies are in thermal contact. Therefore, the term dE_{n3}/dt can be ignored and Eq. (14) rewritten as:

$$Q_1 \frac{dT_1}{dt} + Q_2 \frac{dT_2}{dt} + q^2 R_3 = 0 \tag{15}$$

The solution of differential Eqs. (13) and (15) gives the variation in time of the amount of energy stored in bodies 1 and 2 as well as the variation in time of the temperature in bodies 1 and 2. The initial conditions to obtain the solution of these two differential equations are:

$$\begin{aligned} Q_1(t=0) &= Q_{10} \\ Q_2(t=0) &= Q_{20} \\ T_1(t=0) &= T_{10} \\ T_2(t=0) &= T_{20} \end{aligned} \tag{16}$$

Integrating Eq. (13) the result is $Q_1 = Q_2 + c$, where c is a constant of integration. Applying the initial condition for Q_1 and Q_2, $c = Q_{10} - Q_{20}$. Considering constant heat capacity for bodies 1 and 2, from Eqs. (8) and (9):

$$\frac{dT_1}{dt} = \frac{1}{C_1} \frac{\delta Q_1}{dt} \tag{17}$$

$$\frac{dT_2}{dt} = \frac{1}{C_2} \frac{\delta Q_2}{dt} = \frac{1}{C_2} \frac{\delta Q_1}{dt} \tag{18}$$

Substituting Eqs. (13), (17) and (18) into Eq. (15), with $Q_2 = Q_1 - c$ and rearranging:

$$\frac{\delta Q_1}{dt} + \frac{1}{R_3} \left(\frac{C_1 + C_2}{C_1 C_2} \right) Q_1 = \frac{Q_{10} - Q_{20}}{C_2} \tag{19}$$

Equation (19) is a first order differential equation that can be solved by the integration factor technique, resulting in an expression for Q_1. After that it is possible to obtain $Q_2 = Q_1 - C$ and expressions for T_1 and T_2 from Eqs. (8) and (9) respectively. After some algebraic manipulations and application of the initial conditions indicated by Eqs. (16):

$$Q_1 = A_1 + C(T_{10} - T_{20}) e^{-\frac{t}{R_3 C}} \tag{20}$$

$$Q_2 = A_2 - C(T_{10} - T_{20}) e^{-\frac{t}{R_3 C}} \tag{21}$$

$$T_1 = \frac{A_1}{C_1} + \frac{C}{C_1} (T_{10} - T_{20}) e^{-\frac{t}{R_3 C}} \tag{22}$$

$$T_2 = \frac{A_2}{C_2} - \frac{C}{C_2}\left(T_{10} - T_{20}\right)e^{-\frac{t}{R_3 C}} \tag{23}$$

where:

$$C = \frac{C_1 C_2}{C_1 + C_2}, \quad A_1 = \frac{C_1\left(Q_{10} + Q_{20}\right)}{C_1 + C_2} \quad \text{e} \quad A_2 = \frac{C_2\left(Q_{10} + Q_{20}\right)}{C_1 + C_2}$$

The entransy rate supplied by body 1 and the entransy rate received by body 2 are calculated as follows:

$$\dot{E}_{n1} = Q_1 \frac{dT_1}{dt} = \left(\frac{T_{10} - T_{20}}{R_3}\right) \times \left[\frac{A_1}{C_1} e^{-\frac{t}{R_3 C}} + \frac{C}{C_1}\left(T_{10} - T_{20}\right)e^{-\frac{2t}{R_3 C}}\right] \tag{24}$$

$$\dot{E}_{n2} = Q_2 \frac{dT_2}{dt} = \left(\frac{T_{10} - T_{20}}{R_3}\right) \times \left[\frac{A_2}{C_2} e^{-\frac{t}{R_3 C}} - \frac{C}{C_2}\left(T_{10} - T_{20}\right)e^{-\frac{2t}{R_3 C}}\right] \tag{25}$$

The entransy rate in body 3 is calculated as:

$$\dot{E}_{nd} = q^2 R_3 = \frac{\left(T_{10} - T_{20}\right)^2}{R_3} e^{-\frac{2t}{R_3 C}} \tag{26}$$

where q is the heat transfer rate across body 3, calculated as:

$$q = \frac{\delta Q_2}{dt} = \left(\frac{T_{10} - T_{20}}{R_3}\right)e^{-\frac{t}{R_3 C}} \tag{27}$$

As a certain quantity of the entransy is dissipated in body 3, an entransy transfer efficiency can be defined as the ratio between the entransy rate received by body 2 and the entransy rate supplied by body 1:

$$\eta = \frac{\left(\delta Q_2/dt\right)T_2}{\left(\delta Q_1/dt\right)T_1} = \frac{qT_2}{qT_1} = \frac{qT_1 - q^2 R_3}{qT_1} = 1 - \frac{qR_3}{T_1} \tag{28}$$

In order to visualize the behavior of the solutions obtained, numerical values were adopted for the thermal system of Fig. 2. These data are: $C_1 = C_2 = 10$ J/k, $T_{10} = 100$ °C, $T_{20} = 0$ °C, $L_3 = 0.01$ m, $k_3 = 0.001$ W/mK and $A_3 = 1$ m^2. In Fig. 3 the behavior of the energy stored in bodies 1 and 2 can be seen as a function of time. As expected, the energy of body 1 decreases exponentially and the energy of body 2 increases exponentially in function of time, according to Eqs. (20) and (21). Fig. 4 shows the temperature behavior of bodies 1 and 2 as a function of time. Also, as expected, the temperature of body 1 decreases exponentially and the temperature of body 2 increases exponentially in function of time, according to Eqs. (22) and (23).

Fig. 5 shows the heat transfer rate through body 3 as a function of time. According to Eq. (27) q exhibits an exponential drop with time. This heat transfer rate drop can be ser justified by the reduction of the temperature difference between bodies 1 and 2 as function of time. As the heat transfer rate is proportional to the temperature difference, a decrease in the temperature difference between bodies 1 and 2 in time leads to a decrease of the heat transfer rate through body 3 in function of time.

Fig. 6 shows the entransy rate released by body 1, the entransy rate received by body 2 and the entransy rate dissipated in body 3. At the initial instant it may be seen that body 1 delivers entransy while body 2 does not receive entransy. As the time increases, the entransy of body 1 decreases and the entransy of body 2 increases. However, these values are not equal because there is entransy dissipation in body 3. The entransy dissipation rate is proportional to the square of the heat transfer rate in body 3. As the heat transfer rate decreases in time according to Fig. 4, the bodies 1 and 2 also decreases with time. Thus, the entransy rate delivered by body 1 approximates the entransy rate received by body 2, according to Fig. 6. In particular, after 5 s, the entransy dissipation rate approaches zero and the delivered and received entransy rates are practically the same.

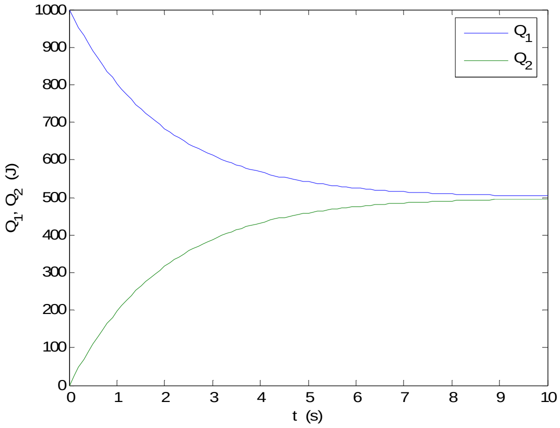

Figure 3. Energy stored in bodies 1 and 2 as a function of time.

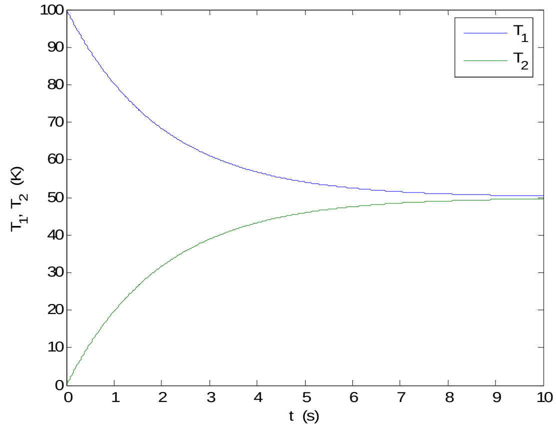

Figure 4. Temperature of bodies 1 and 2 as a function of time.

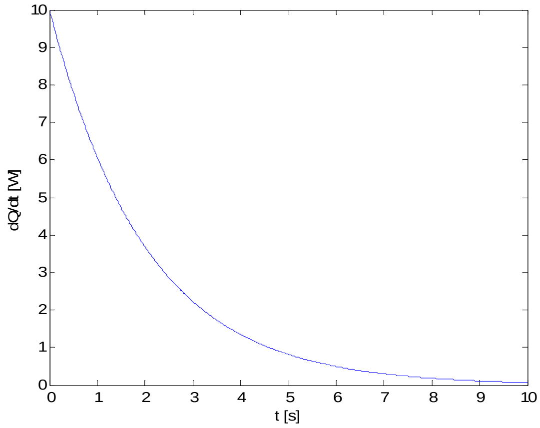

Figure 5. Heat transfer rate through body 3.

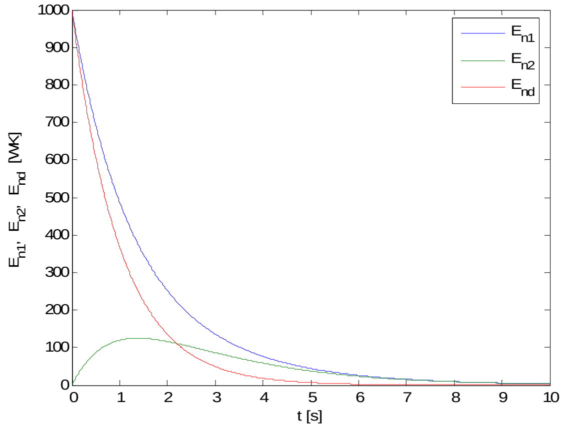

Figure 6. Entransy rate delivered by body 1, received by body 2 and dissipated in body 3.

Finally, in Fig. 7 it is possible to see the entransy transfer efficiency between bodies 1 and 2. It may be noticed that in the beginning this efficiency is very low due to the high entransy dissipation rate. However, as the entransy dissipation rate decreases together with the heat transfer rate through body 3, the entransy transfer efficiency from body 1 to body 2 increases, as can be seen in Fig. 7:

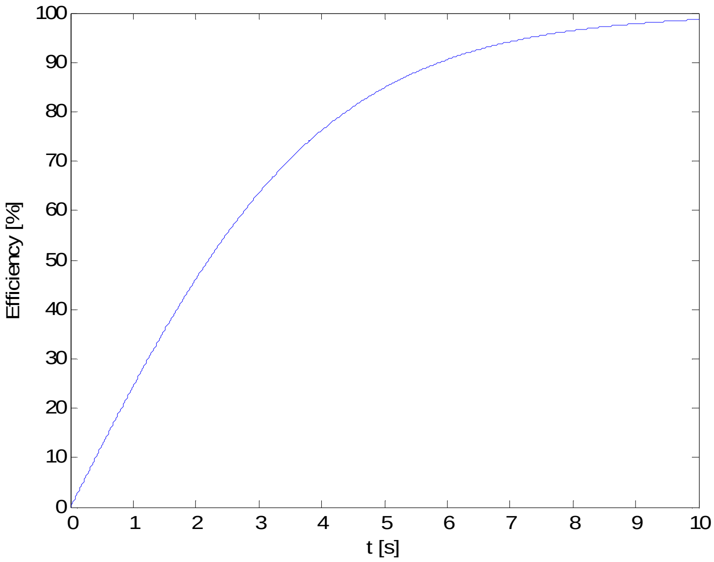

Figure 7. Entransy transfer efficiency from body 1 to body 2.

3.2. Physical situation 2

In Fig. 8 the collector has a surface area A_C receiving solar radiation at a rate $\dot{Q}^*$. The solar radiation rate $\dot{Q}^*$ is proportional to the collector surface area A_C, and this proportionality is represented by $q^*\left(\dot{Q}^*/A_C\right)$ that varies with the geographic position of the Earth, with the orientation of the solar collector, with the local meteorological conditions and with the time of the day. In the present analysis, it is assumed that q^* is constant and the solar collector operate in steady state regime. Furthermore, variations of kinetic and potential energy are neglected.

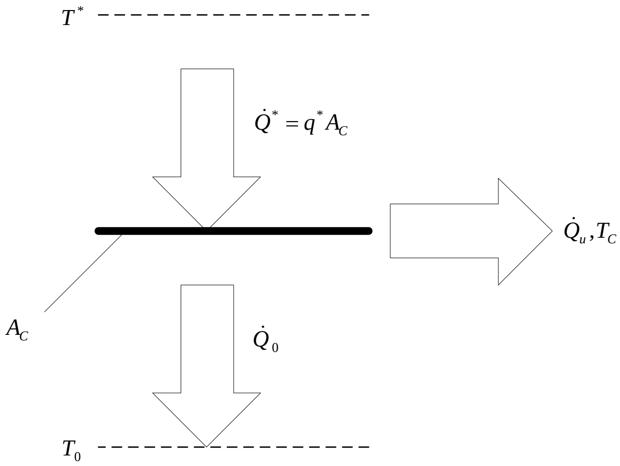

Figure 8. Schematic of an isothermal collector.

The incident solar radiation (irradiation) $\dot{Q}^*$ is partially utilized as useful energy $\dot{Q}_u$ and the remaining quantity $\dot{Q}_0$ represents the energy loss from the solar collector to the ambient. These quantities are related by the first law of thermodynamics, which is written for steady state as:

$$\dot{Q}^* = \dot{Q}_0 + \dot{Q}_u \tag{29}$$

The rate of heat loss to the ambient can be expressed by Newton's law of cooling replacing the convection heat transfer coefficient by an overall heat loss coefficient for the collector U_C, that is:

$$\dot{Q}_0 = U_C A_C \left(T_C - T_0\right) \tag{30}$$

where T_0 is the ambient temperature and U_C is assumed as a collector characteristic constant. Combining Eqs. (29) and (30) it may be noticed that the maximum collector temperature occurs when $\dot{Q}_u = 0$, that is, when all solar radiation rate $\dot{Q}^*$ is lost to the ambient. Thus, by assuming $\dot{Q}_u = 0$ in Eq. (29) and substituting the result in Eq. (30) it follows:

$$\dot{Q}^* = U_C A_C \left(T_{C,\max} - T_0\right) \tag{31}$$

where T_C is equal to $T_{C,\max}$. Hence, from Eq. (31) an expression can be written for the maximum collector temperature:

$$T_{C,\max} = T_0 + \frac{\dot{Q}^*}{U_C A_C} \tag{32}$$

Dividing Eq. (32) by the ambient temperature T_0 and defining $\theta_{\max} = T_{C,\max}/T_0$ an expression can be written for the dimensionless maximum collector temperature:

$$\theta_{\max} = 1 + \frac{\dot{Q}^*}{U_C A_C T_0} \tag{33}$$

where $T_{C,\max}$ is also called stagnation collector temperature. Applying the second law of thermodynamics for steady state regime, the entropy generation rate in the solar collector can be written as:

$$\dot{S}_{gen} = \frac{\dot{Q}_0}{T_0} + \frac{\dot{Q}_u}{T_C} - \frac{\dot{Q}^*}{T^*} = \frac{U_C A_C T_C}{T_0} + \frac{U_C A_C T_0}{T_0} + \frac{\dot{Q}^*}{T_C} - 2U_C A_C - \frac{\dot{Q}^*}{T^*} \tag{34}$$

Eq. (34) can be rearranged in the form:

$$N_S = \theta_C + \frac{\theta_{\max}}{\theta_C} - \frac{(\theta_{\max} - 1)}{\theta^*} - 2 \tag{35}$$

where $N_S = \dot{S}_{gen} / U_C A_C$ is the entropy generation number and $\theta^* = T^* / T_0$. The solar collector optimal temperature can be obtained by minimizing entropy generation rate, Eq. (35), that is, $d\dot{S}_{gen} / dT_C = 0,$ and the result is:

$$\left(\frac{T_{C,opt}}{T_0}\right)^2 = 1 + \frac{\dot{Q}^*}{U_C A_C T_0} \tag{36}$$

where T_C is equal to $T_{C,opt}$. Defining $\theta_{C,opt} = T_{C,opt} / T_0$ an expression can be obtained for the solar collector dimensionless optimal temperature:

$$\theta_{C,opt} = \left(1 + \frac{\dot{Q}^*}{U_C A_C T_0}\right)^{1/2} \tag{37}$$

Substituting Eq. (33) into Eq. (37) results:

$$\theta_{C,opt} = (\theta_{\max})^{1/2} \tag{38}$$

Finally, the minimum entropy generation rate consists in the substitution of the result obtained from Eq. (38) into Eq. (35), that is:

$$N_{S,\min} = 2\left[(\theta_{\max})^{1/2} - 1\right] - \frac{(\theta_{\max} - 1)}{\theta^*} \tag{39}$$

The entransy dissipation rate can be obtained from the equation $\dot{E}_{dissip} = T_0^2 S_{gen}$ suggested by Guo and Chen (2007) and from Eq. (34):

$$\frac{\dot{E}_{dissip}}{U_C A_C T_0^2} = \frac{T_C}{T_0} + \frac{T_0}{T_C} + \frac{\dot{Q}^*}{U_C A_C T_C} - 2 - \frac{\dot{Q}^*}{U_C A_C T^*} \tag{40}$$

The left hand side of Eq. (40), $\dot{E}_{dissip} / U_C A_C T_0^2$, is a dimensionless parameter that can be defined as an “entransy dissipation number” for an isothermal collector, that is:

$$N_E = \frac{\dot{E}_{dissip}}{U_C A_C T_0^2} \tag{41}$$

Eq. (41) can be rearranged in the form:

$$N_E = \theta_C + \frac{\theta_{\max}}{\theta_C} - \frac{(\theta_{\max} - 1)}{\theta^*} - 2 \tag{42}$$

It is interesting to note that the expression for the entropy generation number, Eq. (35) is similar to the expression for the entransy dissipation number, Eq. (42). In this way, the minimum entransy dissipation can be obtained substituting $N_{S,\min}$ for $N_{E,\min}$ in Eq. (42):

$$N_{E,\min} = 2\left[(\theta_{\max})^{1/2} - 1\right] - \frac{(\theta_{\max} - 1)}{\theta^*} \tag{43}$$

In Fig. 9 the entransy dissipation number, Eq. (42), can be visualized in function of the collector temperature $(\theta_{\max} = 10)$. It may be noticed that the entransy dissipation number reaches a minimum value $N_{E,\min}$ close to temperature $\theta_C = 3$. From Eq. (38) this temperature is the optimum temperature $\theta_{C,opt} = 3.16$ and the corresponding minimum entransy dissipation number according to Eq. (43) is $N_{E,\min} = 4.29$.

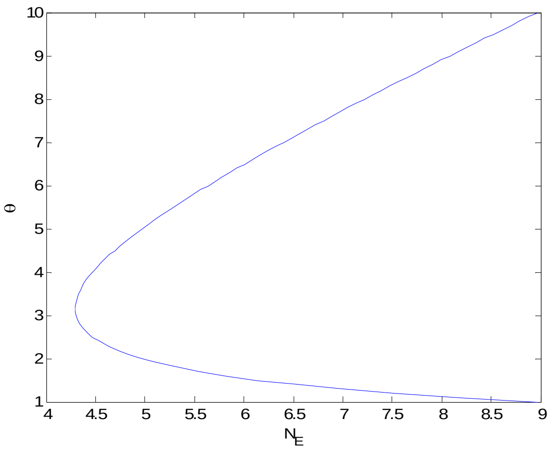

Figure 9. Entransy dissipation number for an isothermal collector.

4. CONCLUSIONS

According to the physical situations presented here the following statements can be made:

- Entransy is not conserved, and heat transfer rate is always accompanied by entransy transfer rate.
- Entransy can be stored in a body. A heat transfer rate to a body increases the entransy stored in this body. Similarly, a heat transfer rate from a body decreases the entransy stored in this body.
- The entransy describes the ability of a body to transfer heat just as the electrical energy describes the ability of a capacitor to transfer electrical charge.
- Ideally a reversible heat transfer process (infinitesimal temperature difference) has zero entransy dissipation. For this special idealized case the entransy is conserved. For real heat transfer processes, the temperature difference is finite and the entransy is not conserved. For this case an entransy dissipation takes place.

5. REFERENCES

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6. RESPONSIBILITY NOTICE

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