HEAT TRANSFER AND ENTROPY ANALYSIS AS TOPICS DELIVERED TO FUTURE MARINE ENGINEERS GRADUATING IN CMU

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ABSTRACT

Students enrolled in Constanta Maritime University (CMU) / Naval Electromechanics Faculty are dealing with heat transfer mechanisms combined with entropy analysis, during Undergraduate (Thermodynamics) and Master Studies Programs (Optimizing of Thermal and Refrigeration Plants).

Real processes, including thus the ones occurring on board the ship, are irreversible process, inside the thermal systems being produced entropy. This irreversible production of entropy inside the systems is accompanied by the loss of potential work. This is an important statement because it permits the determination of efficiency decrease in any particular case. Heat transfer is a typical irreversible process. Conduction heat transfer problems are encountered in many engineering applications on board the ship.

This paper deals with entropy generation during heat transfer through a plane wall, being presented cases exposed to students enrolled in Master Specialization called “Advanced Technologies of Electromechanic Engineering”. This knowledge will permit to future marine engineers to be able to deal with problems related to design optimization.

Keywords: *entropy generation, conduction, Master course.*

1. INTRODUCTION

Entropy generation and its minimization have been seen as an effective tool used to improve the performance of any heat transfer process. Skills specific to entropy generation investigation are gained by students enrolled in CMU, Naval Electromechanics Faculty, Master Specialization called “Advanced Technologies of Electromechanic Engineering”. One of the goals of this Master course is to supply information regarding solving problems related to entropy generation which should be minimised in order to arrive to optimum heat exchange design.

To be able to deal with this topic are needed concepts delivered during courses of Thermodynamics, as seen in Figure 1.

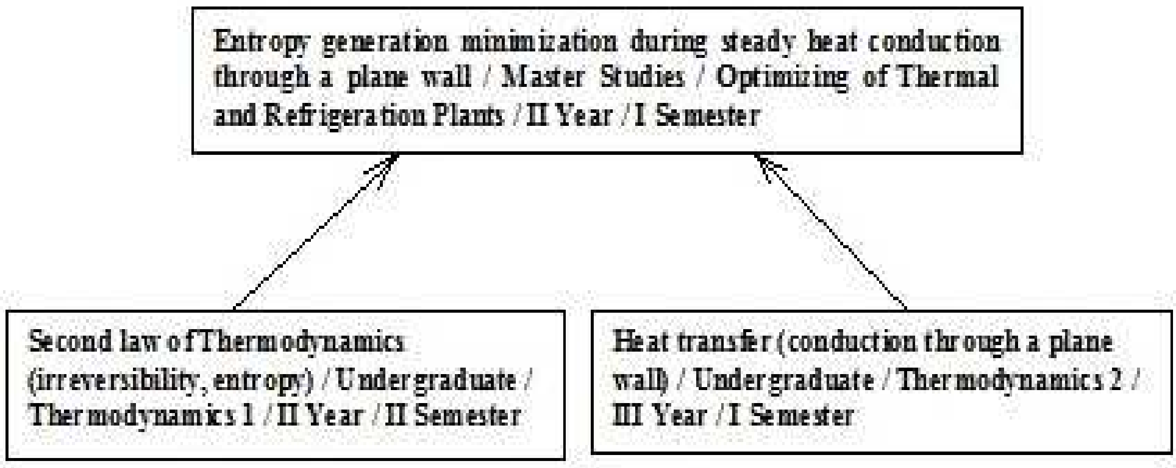

Figure 1 Background of entropy generation minimization

Future marine engineers are familiarised during “Thermodynamics 1” with the concept of entropy and with the fact that entropy change is a measure of how reversible a process is.

The most efficient processes possible for converting energy from one form to another are processes where the net entropy change of the system and the surroundings is null. Irreversibility is inherent in all processes, being impossible to make them reversible.

Heat transfer between systems having different temperatures is one typical irreversible process example. Heat transfer notions are delivered in CMU to future marine engineers during “Thermodynamics 2” course. Heat transfer by conduction will take place if there is a temperature gradient in a solid medium. Heat conduction is important for many engineering applications, being met on board the ships during conduction through walls (plane, cylinder).

Heat losses are seen as a loss of energy, specialists working on the minimisation of these. In all types of heat transfer processes, including conduction, irreversibility is associated with entropy generation, which leads to the destruction of available work.

In a pure heat conduction process, the entropy generation occurs due to heat transfer through a finite temperature difference (Torabi, Aziz, 2012).

An entropy generation analysis related to steady heat conduction through a plane wall is presented below, as it is delivered to future marine engineers graduating from CMU.

2. EQUATIONS OF THE ANALYSIS

It is considered a plane wall for which will be studied the local entropy generation during steady heat conduction.

For the case regarding the uniform thermal conductivity and internal heat generation, the one-dimensional steady state heat conduction equation is:

$$\frac{d^2T}{dx^2} + \frac{q(x)}{k} = 0 \tag{1}$$

where: T – temperature, K,
x – coordinate axis, m,
q – internal heat generation rate, W/m^2,
k – thermal conductivity, W/(mK).

The internal heat generation is given by:

$$q(x) = -\frac{k}{T}\left(\frac{dT}{dx}\right)^2 \tag{2}$$

The local entropy generation in the wall is:

$$s''' = \frac{k}{T^2}\left(\frac{dT}{dx}\right)^2 + \frac{q(x)}{T} \tag{3}$$

or

$$s''' = \frac{k}{T^2}\left(\frac{dT}{dx}\right)^2 - \frac{k}{T^2}\left(\frac{dT}{dx}\right)^2 = 0 \tag{4}$$

It results that the entropy generation can be removed with the help of an internal heat generation expressed by Eq. (2).

The temperature variation is found as

$$T(x) = T_1\left(\frac{T_2}{T_1}\right)^{x/L} \tag{5}$$

where: L – thickness of the plane wall, m,
$T_1 = T\ (x = 0)$,
$T_2 = T\ (x = L)$.

Temperature variation T (x) as in Eq. (5) satisfies the heat conduction equation and yields null entropy generation rate. In order to maintain this temperature variation an internal heat generation is needed, which is obtained by introducing Eq. (5) in Eq. (2), resulting:

$$q(x) = -\frac{kT_1}{L^2} = \left[\ln\left(\frac{T_2}{T_1}\right)\right]^2 T_1\left(\frac{T_2}{T_1}\right)^{x/L} \tag{6}$$

By integrating the above equation along the thickness of the considered wall, results the total heat generation as:

$$Q = \int_0^L q(x)dx = -\frac{kT_1}{L}\ln\left(\frac{T_2}{T_1}\right)\left(\frac{T_2 - T_1}{T_1}\right) \tag{7}$$

If the plane wall separates two fluids of different temperatures, heat transfer occurs by convection from one fluid to the left surface of the wall – with a convective heat transfer coefficient "α_1", and also by convection from the other fluid to the right surface of the wall – with a convective heat transfer coefficient "α_2" (see Figure 2).

Corresponding boundary conditions according to the one dimensional steady state heat conduction equation through the considered wall are:

$$k\frac{dT}{dx}(x = 0) = \alpha_1[T(x = 0) - T_1] \tag{8}$$

$$k\frac{dT}{dx}(x = L) = -\alpha_2[T(x = L) - T_2] \tag{9}$$

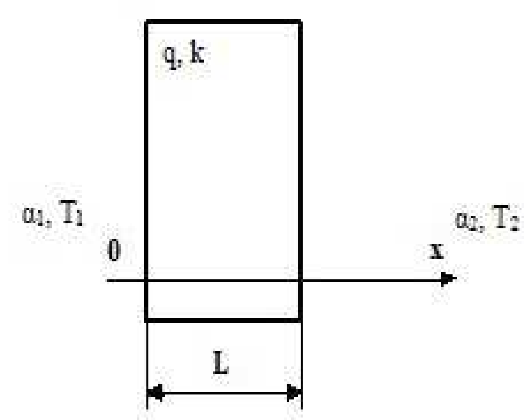

Figure 2 Heat transfer through a plane wall exposed to two fluids with different temperatures

The dimensionless parameters given below are introduced (El Haj Assad, 2011):

$$\theta = \frac{T - T_2}{T_1 - T_2},$$

$$X = \frac{x}{L},$$

$$M = m\,L,$$

$$Q = \frac{a\,L^2}{k(T_1 - T_2)},$$

$$Bi = \frac{\alpha L}{k},$$

where: m – internal heat generation constant, m^{-1},
a – internal heat generation at x = 0, [W m^{-3}],
Bi – Biot number

Thus the heat conduction equation (1) becomes:

$$\frac{d^2\theta}{dX^2} + Qe^{-MX} = 0 \qquad (10)$$

Having the boundary conditions:

$$\frac{d\theta}{dX}(X=0) = Bi_1[\theta(X=0) - 1] \qquad (11)$$

$$\frac{d\theta}{dX}(X=1) = -Bi_2\theta(X=1) \qquad (12)$$

The solution of Eq. (10), considering the boundary conditions described by (11) and (12) is:

$$\theta(X) = -\frac{Q}{M^2}e^{-MX} + CX + D \qquad (13)$$

Above, C and D are given by:

$$C = \frac{Bi_1 Bi_2\left(Qe^{-M} - Q - M^2\right)}{M^2(Bi_1 + Bi_2 + Bi_1 Bi_2)} - \frac{Q\left(Bi_1 e^{-M} + Bi_2\right)}{M(Bi_1 + Bi_2 + Bi_1 Bi_2)} \qquad (14)$$

$$D = \frac{Bi_1 Bi_2\left(Q + M^2\right)}{M^2(Bi_1 + Bi_2 + Bi_1 Bi_2)} + \frac{Q\left(Bi_2 e^{-M} - Me^{-M} + Bi_2 M + Bi_1 + M\right) + M^2 Bi_1}{M^2(Bi_1 + Bi_2 + Bi_1 Bi_2)} \qquad (15)$$

The expression of the local entropy generation rate in the case of one-dimensional steady heat conduction through a plane wall (Bejan, 1995) is:

$$\dot{S}''' = \frac{k\left(\frac{dT}{dx}\right)^2}{T^2} \qquad (16)$$

The total entropy generation in the wall is obtained by integrating Eq. (16) over the thickness of the wall:

$$\dot{S} = \int_0^L \dot{S}''' A dx \qquad (17)$$

"A" above is the wall surface normal to the heat flow direction.

The dimensionless local volumetric rate of entropy generation is noted as "N_S", given by the formula:

$$N_S = \frac{\dot{S}''' L^2}{k} = \frac{1}{(\theta + t)^2}\left(\frac{d\theta}{dX}\right)^2 \qquad (18)$$

where: t – dimensionless temperature ratio,

$$t = \frac{T_2}{T_1 - T_2}$$

The dimensionless total entropy generation rate is noted as "N_T":

$$N_T = \frac{\dot{S} L}{kA} = \int_0^1 N_S \, dX \qquad (19)$$

3. RESULTS FOR A CASE STUDY

In the following are given results obtained for the case of the plane wall which is separating two fluids having different temperatures (T_1 and T_2).

In Table 1 it is given the dependence between the dimensionless parameters "N_T" and "Bi_1", for specified heat transfer parameters:

Q = 2
M = 0,5
t = 1

Observation of founded values for dimensionless "N_T" indicates that its values decrease together with the increase of dimensionless "Bi_1" values.

For a certain value of "Bi_1" (Bi_1 = 5), dimensionless "N_T" reaches its minimum value which is kept constant for Bi_1 > 5.

Also, dimensionless "N_T" presents higher values for the same value of "Bi_1" and higher values of "Bi_2".

Table 1. Variation (N_T – Bi_1), for two given values of Bi_2

Bi_2 = 2					
Bi_1	1	3	5	7	9
N_T	0,13	0,12	0,11	0,11	0,11
Bi_2 = 5					
Bi_1	1	3	5	7	9
N_T	0,32	0,30	0,29	0,29	0,29

4. CONCLUSIONS

Entropy generation is an indicator able to measure the loss of useful work caused by irreversibilities occuring in all real processes, including conduction.

That is why, in order to have an improved heat transfer by conduction, it is needed to approach conduction from the point of view of entropy generation minimisation.

Two cases specific of the conduction through a wall plane, taken from the entropy generation analysis delivered to Master students in CMU were given.

In the case of uniform thermal conductivity, entropy generation can be removed by introducing an internal heat source.

If the plane wall separates two fluids having different temperatures the expression of dimensionless total entropy generation rate „N_T” was found. For a particular case it resulted that dimensionless „N_T” is never null. But it is possible to get minimum values for „N_T” for high values of „Bi_1” and low values of „Bi_2”.

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