Application of Entransy Dissipation Number as Performance Parameter for Heat Exchanger

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Abstract: ***A new physical quantity, entransy has been identified as a basis for optimizing heat transfer processes in terms of the analogy between heat and electrical conduction. This quantity, which will be referred to as entransy, corresponds to the electric energy stored in a capacitor. The entransy is defined as one-half the product of heat capacity and temperature, the effect of entransy consumption rate on the irreversibility of heat transfer process, it can be found that entransy is a state variable, from which a new expression for the second law of thermodynamics is presented; Then by setting entransy consumption rate and power consumption rate as optimization objective and constraint condition for each other. In the heat exchanger, there mainly exist two kinds of irreversibility the first is heat conduction under finite temperature differences and the second is flow friction under finite pressure drops. Hence, rather working on any other aspect we can target to minimize the entransy dissipation number to increase the performance of a heat exchanger. This can be proved experimentally for water -water and oil-water heat exchangers.***

Keywords: Entransy, Heat Exchanger, Optimization Number, Heat Transfer, NTU, Irreversibility, Entransy Dissipation Number.

I. INTRODUCTION

Energy shortages are foreseen as a very large factor that could restrict economic development. Thus, improving the heat transfer efficiency is one of the effective ways to ameliorate the situation. Heat exchanger finds their application in petroleum refineries, food industries, power plants and pharmaceuticals. Therefore, reduction in unnecessary energy dissipation can help us a lot. For this one should improve the performance of heat exchange by optimising their design. The heat exchanger optimization can be done in two ways:

One is by deducting their cost with a loss in performance of heat exchanger and the second by reducing irreversibility with in the heat exchanger. A new physical quantity ENTRANSY has been defined, which act as a basis for optimization of the heat exchanger.

Thus, entransy can be defined by studying analogy between heat transfer and electrical conductance. To understand the concept of entransy we have to study the analogy between heat conduction and electrical conduction the entransy can be defined [1] as half of the product heat capacity and the temperature.

$$E = \frac{1}{2}mcT^2$$

Where, E=entransy, m=mass, C=sp heat, T=absolute temperature of the body. The entransy of a object is measure of its ability to transfer heat to another object, just The entransy of an object is a measure of its ability to transfer heat to another object, just as the electrical energy of a capacitor is a measure of its ability accompanied by entransy transfer .However, while thermal energy is conserved, entransy is not conserved due to dissipation [2]. The entransy dissipation concept can then be used to define efficiency for heat transfer processes and to optimize heat transfer processes. To qualify the dissipation of entransy a new dimension less entity can be introduced called as Entransy Dissipation Number (E.D.N.) [3].

The entransy is defined as one half the products of heat capacity and temperature

$$E=\frac{1}{2}mc_pT^2 \qquad (1)$$

Where T is the temperature, m is the mass and c_p is the specific heat at constant pressure.

Let us assume that the hot and cold fluids are incompressible. The inlet pressure and temperature of the hot and cold fluid are denoted as T_1, P_1, and T_2, P_2, respectively. Similarly outlet temperature and pressure are T_1', P_1', and T_2', P_2' respectively in heat exchanger their mainly exist two type of irreversibility; first the heat conduction under finite under finite temperature differences and second is the flow friction under finite pressure drops[4]. The entransy rate dissipation rate caused by heat conduction under finite temperature difference is written as

$$E_t = [\frac{1}{2}(\dot{m}c_p)\ T_1^2 + \frac{1}{2}(\dot{m}c_p)\ T_2^2] - [\frac{1}{2}(\dot{m}c_p)T_1'^2 + \frac{1}{2}(\dot{m}c_p)\ T_2'^2] \qquad (2)$$

The corresponding Entransy Dissipation Number due to spontaneous heat transfer is

$$(EDN)_T = \frac{E_t}{Q(T_1-T_2)} = \frac{E_t}{\varepsilon(\dot{m}c_p)(T_1-T_2)} \quad (3)$$

Where $(EDN)_T$ is the entransy dissipation number due to spontaneous heat transfer, Q is heat transfer rate; ε is the effectiveness of the heat exchanger which is defined as the ratio of the actual heat transfer rate to the maximum possible heat transfer rate [5]. The entransy dissipation due to flow friction under a finite pressure drop is expressed as

$$(EDN)_p = \frac{\dot{m}_1 \Delta P_1}{\rho_1}\frac{T_1'-T_1}{\ln T_1' - \ln T_1} + \frac{\dot{m}_2 \Delta P_2}{\rho_2}\frac{T_2'-T_2}{\ln T_2' - \ln T_2} \quad (4)$$

Where ΔP_1 and ΔP_2, refer to the pressure drops in the hot and cold water, respectively; ρ_1 and ρ_2 are their corresponding densities. Thus, the Entransy Dissipation Number due to pressure

$$(EDN)_P = \frac{-\Delta P_1}{(\rho C_P)_1(T_1-T_2)} \frac{1}{\ln\frac{T_1}{T_2}\left[1-(1-\varepsilon)\frac{T_2-T_1}{T_2}\right]} + \frac{\Delta P_2}{(\rho C_P)_2(T_1-T_2)} \frac{1}{\ln\frac{T_1}{T_2}\left[1-(1-\varepsilon)\frac{T_2-T_1}{T_1}\right]} \quad (5)$$

This is called Entransy Dissipation Number due to flow friction $(EDN)_P$ [2]. Assuming heat exchanger behaves as nearly ideal exchanger, then (1-ε) considerably small usual operating conditions, the inlet temperature difference between hot and cold water ,$\Delta T = T_1 - T_2$,is less than 100k.hence $\Delta T/T$,<100/273≅ 0.36.Therefore eq (5) can be simplified to

$$(EDN)_P = \frac{\Delta P_1}{(\rho C_P)_1(T_1-T_2)} \frac{1}{\ln\frac{T_1}{T_2}} + \frac{\Delta P_2}{(\rho C_P)_2(T_1-T_2)} \frac{1}{\ln\frac{T_1}{T_2}} \quad (6)$$

Accordingly, the overall Entransy Dissipation Number (E.D.N.) [6] becomes,

$$EDN^* = (EDN)_T + (EDN)_P \quad (7)$$

$$EDN^* = (1-\varepsilon) + \frac{\Delta P_1}{(\rho C_P)_1(T_1-T_2)} \frac{1}{\ln\frac{T_1}{T_2}} + \frac{\Delta P_2}{(\rho C_P)_2(T_1-T_2)} \frac{1}{\ln\frac{T_1}{T_2}} \quad (8)$$

II.ANALYTICAL ANALYSIS:

Now, to solve equation (8) further, the value of the ε for counter flow heat exchanger is substituted and then multiplying numerator and denominator by p_1 and p_2 Therefore,

$$EDN^* = (1-\varepsilon) + \frac{\Delta P_1}{(\rho C_P)_1(T_1-T_2)} \frac{1}{\ln\frac{T_1}{T_2}} + \frac{\Delta P_2}{(\rho C_P)_2(T_1-T_2)} \frac{1}{\ln\frac{T_1}{T_2}}$$

[Since, $\varepsilon = \frac{1-e^{-NTU(1-C)}}{1-Ce^{-NTU(1-C)}}$][7]

$$EDN^* = \left(1 - \left[\frac{1-e^{-NTU(1-C)}}{1-Ce^{-NTU(1-C)}}\right]\right) + \frac{P_1}{(\rho C_P)_1(T_1-T_2)} \frac{1}{\ln\frac{T_1}{T_2}} \frac{\Delta P_1}{P_1} + \frac{P_2}{(\rho C_P)_2(T_1-T_2)} \frac{1}{\ln\frac{T_1}{T_2}} \frac{\Delta P_2}{P_2}$$

Solving further,

$$EDN^* = \left(\frac{-Ce^{-NTU(1-C)}+e^{-NTU(1-C)}}{1-Ce^{-NTU(1-C)}}\right) + \frac{P_1}{(\rho C_P)_1(T_1-T_2)} \frac{1}{\ln\frac{T_1}{T_2}} \frac{\Delta P_1}{P_1} + \frac{P_2}{(\rho C_P)_2(T_1-T_2)} \frac{1}{\ln\frac{T_1}{T_2}} \frac{\Delta P_2}{P_2}$$

$$EDN^* = \left(\frac{1-C}{e^{NTU(1-C)}-C}\right) + \frac{P_1}{(\rho C_P)_1(T_1-T_2)} \frac{1}{\ln\frac{T_1}{T_2}} \frac{\Delta P_1}{P_1} + \frac{P_2}{(\rho C_P)_2(T_1-T_2)} \frac{1}{\ln\frac{T_1}{T_2}} \frac{\Delta P_2}{P_2} \quad (9)$$

Recalling the definition of Stanton number St [$(Re)_D$, Pr]And the friction factor f [$(Re)_D$]:

$$NTU = \frac{4L}{D} St$$

And $\left(\frac{\Delta P_i}{P_i}\right) = f \frac{4L}{D} \frac{G^2}{2\rho_i p_i} \quad (i = 1, 2)$

Where $G = \dot{m}/A$ is the mass velocity, L is the path flow length and D is the hydraulic diameter. Introducing the dimensionless mass velocity, $G^* = G/\sqrt{2\rho_i P_i}$ $(i = 1, 2)$

Putting the value in the equation (9), it reduces to

$$EDN^* = \frac{1-C}{e^{\left(\frac{4L}{D}\right)St}-C} + \left(\tau_1^2 f \left(\frac{4L}{D}\right) G_1^{*2}\right) + \left(\tau_2^2 f \left(\frac{4L}{D}\right) G_2^{*2}\right)$$

Let $Z = \left[\left(\tau_1^2 f G_1^{*2}\right) + \left(\tau_2^2 f G_2^{*2}\right)\right]$

$$EDN^* = \frac{1-C}{e^{\frac{4L}{D}St}-C} + \left(\frac{4L}{D}\right)[Z] \quad (10)$$

To get the minimum value of Entransy Dissipation Number with the respect to $\left(\frac{4L}{D}\right)$ we first differentiate the equation then put it equal to zero.

$$\frac{d(EDN^*)}{d\left(\frac{4L}{D}\right)} = \frac{d\left[\frac{1-C}{e^{\frac{4L}{D}St}-C} + \left(\frac{4L}{D}\right)(Z)\right]}{d\left(\frac{4L}{D}\right)} - \frac{[(1-C)St]\, e^{\left(\frac{4L}{D}\right)St}}{\left[e^{\left(\frac{4L}{D}\right)St}-C\right]^2} + z = 0$$

$$\frac{[(1-C)St]\, e^{\left(\frac{4L}{D}\right)St}}{\left[e^{\left(\frac{4L}{D}\right)St}-C\right]^2} = z$$

$$\left(\frac{(1-C)St}{z}\right) e^{\left(\frac{4L}{D}\right)St} = \left[e^{\left(\frac{4L}{D}\right)St}-C\right]^2$$

$$\pm\sqrt{\left(\frac{(1-C)St}{z}\right)}\, e^{\frac{\left(\frac{4L}{D}\right)St}{2}} = e^{\left(\frac{4L}{D}\right)St} - C$$

$$e^{\left(\frac{4L}{D}\right)St} \mp \sqrt{\left(\frac{1-C}{z}\right)}\, e^{\frac{\left(\frac{4L}{D}\right)St}{2}} - C = 0$$

Solving the quadratic equation we get,

$$e^{\frac{\left(\frac{4L}{D}\right)St}{2}} = \mp\frac{\sqrt{\frac{(1-C)St}{z}} + \sqrt{\frac{(1-C)St}{z}+4C}}{2}$$

$$e^{\frac{\left(\frac{4L}{D}\right)St}{2}} = \frac{1}{2\sqrt{z}}\left(\mp\sqrt{(1-C)St} + \sqrt{(1-C)St+4z}\right)$$

Taking log on both sides we get,

$\frac{\left(\frac{4L}{D}\right)st}{2} = \ln\left(\frac{\left(\mp\sqrt{(1-C)St}+\sqrt{(1-C)St+4z}\right)}{2\sqrt{z}}\right)$ One value of 4L/D stands for maximum and one for minimum EDN. Thus considering the value of $\frac{4L}{D}$ which yields minimum EDN.

Therefore,

$$\frac{4L}{D} = \frac{2}{St}\ln\left(\frac{\left(-\sqrt{(1-C)St}+\sqrt{(1-C)St+4z}\right)}{2\sqrt{z}}\right) \qquad (11)$$

Thus, to get the minimum value of Entransy Dissipation Number one should put the value of $\frac{4L}{D}$ in equation (10)

III.EXPERIMENTAL ANALYSIS:

On the basis of the data obtained from the heat exchanger a few required quantities are as follows

Table1: Parameter and specification of shell and tube type heat exchanger

Process parameters	Units	Tube side	Shell side
Fluid	-	Cooling water	Hot effluent
Flow rate	Kg/hr	185000	80000
Temperature inlet	Kelvin	303	333
Temperature outlet	Kelvin	308	317
Operating pressure	Kg/cm^2	5	5
Actual pressure drop	Kg/cm^2	0.5	1.0
Heat load	Kcal/hr	924000	924000
Density	Kg/m^3	991	1296
Specific heat	Kcal/kg℃	1.0	0.77
Thermal conductivity	Kcal/hr m ℃	0.51	0.58

After the collection of data for shell and tube type counter flow heat exchanger, following quantities are calculated.

$St = 0.01675$ $C=0.332$

$\tau_1^2 = 41.73$ $\tau_2^2 = 41.448$

$f_1=0.000562$ $f_2=0.00672$

$G_1^* = 0.0383$ $G_2^* = 0.011719$

To optimize the performance of heat exchanger the variation of the Entransy Dissipation Number and effectiveness with the variable i.e. 4L/D is shown below.

Table2: Observation table showing the value of optimum ratio where the entransy dissipation number is minimised and the effectiveness achieved is maximised.

(4L/D)	(EDN) *10^2	ε	T_1' (°C)	T_2'(°C)	ΔS_{UNIV} (kJ/K)
200	38.73	0.632	41.046	36.311	0.239
225	31.97	0.697	39.084	36.965	0.2459
250	28.43	0.734	37.971	37.33	0.2431
275	26.82	0.753	37.416	37.52	0.2468
300	26.28	0.759	37.218	37.592	0.25076
305.05	26.20	0.760	37.194	37.594	0.2465
325	26.55	0.758	37.257	37.573	0.246
375	28.56	0.742	37.746	37.343	0.200
400	29.92	0.723	38.11	37.28	0.240

From the equation giving the optimum value of EDN we can compute that for the given data 4L/D=305.05 yields minimum value of EDN & the same can be verified

IV.CONCLUSIVE REMARK

It is evident by the analytical analysis of the latest information available about entransy and its relation with the heat exchanger that keeping other parameter fixed the effectiveness [the most commonly used performance parameter for heat exchanger] can be enhanced by focussing over efforts for minimization of EDN. The analytical relations derived are verified by further experiments done on heat exchanger and cogent results are obtained. The results obtained in this study can be of great use & might change the basic heat exchanger design which is generally made by targeting the higher value of area of contact or NTU. The new heat exchanger design based on minimized EDN definitely yield higher performance & will lead to great savings in terms of energy and protection of environment. The present work will be of great use for further research in the same direction.

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