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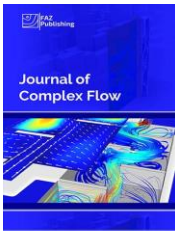

Thermoeconomic Analysis of Heat Exchanger by $P_1 – P_2$ and Effectiveness-NTU Method

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Abstract: Application of thermoeconomics principles to the heat exchanger design development will be one of the ways to reduce the energy demand. The process of heat exchange between two fluids that are at different temperatures and separated by a solid wall is widely used in many fields of technology. Therefore, heat transfer analysis and design heat exchanger become an important issue in energy conservation. Thermoeconomic study on two types of heat exchanger namely, counter flow heat exchanger and parallel flow heat exchanger had been performed. The P_1-P_2 method together with Effectiveness-NTU method had been followed. The main purpose of this study is to maximize cost saving on using these heat exchangers. The study showed counter flow heat exchanger outperformed than parallel type heat exchanger. The payback period of counter flow heat exchanger based on heat transfer surface area, is shorter compared to parallel flow heat exchanger.

Keywords: Heat exchanger, effectiveness-NTU, counter flow, parallel flow

1. Introduction

In daily life we need to step forward for a better lifestyle. Our world becomes smaller and natural resources become critical. Development of new technology and conservation of energy to harness the energy in the most economical way remains a challenge to us. Principles of thermoeconomics and its applications to engineering system can fulfil the human need. Thermoeconomic is a combination of thermal sciences (thermodynamics, heat transfer and fluid mechanics) and field of engineering economy. The thermoeconomic optimization analysis is to minimize the annualized total cost of owing an operating the system at the effective efficiency.

1.1 Thermoeconomic Analysis of Heat Exchanger

Discussion on future development in the art and techniques of exchanger design are was discussed long time ago by engineers in order to increase an efficiency and also the capability of the heat exchanger to reduce the cost in application. A principle of rating and design of shell-and-tube heat exchangers are described manual type methods to computerized applications [1]. Another researcher was described an optimization method, such as Fibonacci search method [2]. This is the most efficient of the single-variable search techniques that was first presented by Keifer, a thirteenth-century mathematician. There are some rules and steps to follow for any observation to be made.

In term of economic in heat exchanger, a method called P_1-P_2 method can be applied in developing economic evaluations of specific applications. The life cycle costs of insurance, maintenance and parasitic power, property taxes, and mortgage payments and life cycle fuel savings can be determined with the appropriate present worth factors. The P_1-P_2 method is quick, convenient, and extremely useful, not only for solar system but also the other thermal system [3, 4]. For optimum design of an energy system, there is a trade-off between exergy saving during operation and exergy use during construction of the energy system, exergy analysis and life cycle analysis should be combined [4].

The two methods are often used separately, but a limited number of studies have been carried out in which they are combined in some way. An exergetic optimization of a heat exchanger has been carried out on the basis of the life cycle analysis method in this paper. The optimization takes into account irreversibility due to frictional pressure drops and the temperature difference between the hot and cold stream and irreversibility due to the production of the materials and the construction of the heat exchanger [5]. As an example of this type of heat exchanger, a water to water heat exchanger in a city heating system has been selected. The influence of the configuration of the heating system, including the energy conversion, on the optimization of the heat exchangers has been shown [6]. The analysis of the heat exchanger in which exergy analysis and life cycle analysis are combined gives the design conditions of the heat exchangers which lead to the lowest life cycle irreversibility. With the combination of exergy analysis and life cycle analysis the optimal design of a heat exchanger can be obtained.

Two-phase heat exchangers used as condensers and evaporators also another interesting method introduced. By this method, the results are presented in terms of the optimum number of heat-transfer units (NTUs) as a function of the dimensionless unit-cost ratio and the exit-to-inlet absolute temperature ratio of the single-phase fluid [7]. The sensitivities of various unit-cost parameters (UCPs) are

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presented. It is demonstrated that the selection of UCPs play a significant role in sizing heat exchangers.

For a systematic evaluation of two-phase heat exchangers, they have combined entropy generation due to irreversible heat transfer and pressure drops with unit-cost parameters [8]. They have determined optimum NTUs, single-phase fluid velocities, and optimal values for heat-transfer areas, lengths and diameters of tubes in case of shell-and-tube heat exchangers. The selection of optimum configurations for compact heat exchangers can also be accomplished similar to the shell-and-tube heat exchangers. It is expected that their approach should be useful in the design of optimal thermal systems at minimized cost.

M.S. Söylemez presented thermoeconomic optimization analysis yielding simple algebraic formulas for estimating the optimum heat exchanger area for energy recovery applications and for estimating the optimum heat pipe heat exchanger (HPHE) effectiveness for energy recovery applications [9]. The P_1 - P_2 method is used in the present study, together with the well-known Effectiveness-NTU method, for thermoeconomic analysis of three different unmixed type heat exchangers, i.e. counter-current flow, parallel flow and single fluid or phase change. The present results are obtained by using the parametric values of the sample problem. The effect of heat exchanger area on the effectiveness is presented. During the design, they found that the economy is vitally significant in applying energy recovery projects. The validity of the optimization formulation was confirmed and heat exchangers must be designed close to the optimum point presented.

For power plant cost based optimal design conditions, unit cost parameters of hot and cold end heat exchangers in distributing the heat transfer surface area of the power plant are considered for minimum total cost of the heat exchangers [10]. A closed form expression is given in terms of unit costs of the conductance of both heat exchangers, and the results are presented in terms of a unit cost ratio, G, and the hot and cold end heat exchangers costs. The results demonstrate a strong dependence cost ratio. It is also shown that for the case of equal unit costs of the hot and cold end heat exchangers, the total conductance is equally divided between the two heat exchangers.

With the increasing of the computer performance that can be used to help the analysis of the thermoeconomic of heat exchanger, there are a lot of computer program developed for the purpose [11, 12]. In a computer-based design, thousands of alternative exchanger configurations may be examined. Computer codes for design are organized to vary systematically the exchanger parameters such as, shell diameter, baffle spacing, number of tube-side pass to identify configurations that satisfy the specified heat transfer and pressure drops. A computer-based design model was made for preliminary design of shell-and-tube heat exchangers with single-phase fluid flow both on shell and tube side. The program covers segmental baffled U-tube, and fixed tube sheet heat exchangers one-pass and two-pass for tube-side flow. The program determines the overall dimensions of the shell, the tube bundle, and optimum heat transfer surface area required to meet the specified heat transfer duty by calculating minimum or allowable shell-side pressure drop.

The thermoeconomic analysis of heat exchanger is to present the optimum overall product cost which has been expressed in term the best application of thermal system and the most efficient condition of heat exchanger. The production of small size, inexpensive, safe, simple and convenient but effective heat exchanger to transfer more heat from the surfaces of heat exchanger is a very important subject in this project. In this study, P_1-P_2 method will be study for optimization hence the computer program will be built to solve the optimization problem.

Since there are a lot of parameter that will involve in actual cases of heat exchanger for thermoeconomic analysis, this study only focus on two type of heat exchanger for optimization which are parallel flow and counter flow. Besides that, all thermal properties are assumed constant and interest rate and energy rate is fixed.

2. Formulation of the Problem

Thermal and economic performance of heat exchanger is considered in the thermoeconomical optimization of three different heat exchanger types. There is countercurrent flow, parallel flow and single fluid or phase change. Variable parameters used in formulating the thermoeconomically optimum heat exchanger area are listed as: technical life of the heat exchanger, area dependent first cost of the heat exchanger, annual interest rate, present net price of the energy, annual energy price rate, heat capacity rate of flowing fluid which has the smaller heat capacity rate, overall heat transfer coefficient, maximum temperature differential, resale value and the ratio of annual maintenance and operation cost to the original cost.

2.1 Maximum Heat Tranfer Rate Analysis

The maximum possible heat transfer rate, q_{max}, for the heat exchanger could be achieved in a counter flow heat exchanger of infinite length. In such an exchanger, one of the fluids would experience the maximum possible temperature difference:

$$\Delta T = T_{h.i} - T_{c,i} \tag{1}$$

For heat exchanger analysis, we often deal with the heat capacity rate of fluid such as,

Hot : $C_h = \dot{m}_h C_{p,h}$

Cold : $C_c = \dot{m}_c C_{p,c}$

Consider the case, where $C_c < C_h$. The cold fluid would have the larger temperature change. Since $L \rightarrow \infty$ it would be heated to the inlet temperature of hot fluid. Therefore,

$$q_{\max} = C_c\left(T_{h,i} - T_{c,i}\right) \tag{2}$$

Similarly, if $C_c > C_h$, the hot fluid would have the larger temperature change. It would be cooled to the inlet temperature of cold fluid. Therefore,

$$q_{\max} = C_h\left(T_{h,i} - T_{c,i}\right) \tag{3}$$

The general equation of maximum heat rate,

$$q_{\max} = C_{\min}\left(T_{h,i} - T_{c,i}\right) \tag{4}$$

where, $C_{min} = C_h$ if $C_h < C_c$ and $C_{min} = C_h$ if $C_h < C_c$.

2.2 Optimum Heat Exchanger

It is obvious that area or size of the heat exchanger affects the effectiveness, which is an important indicator. On the other hand, the initial operational cost of the heat exchanger mainly depends on size of the heat exchanger itself. The method $\varepsilon - NTU$ is used together with the $P_1 - P_2$ method had been applied by M.S. Söylemez [13] for the optimization.

2.2.1 Counter Flow Heat Exchanger

The amount of annual total heat energy saved by the heat exchanger can be calculated by:

$$Q = \varepsilon\left(\dot{m}C_p\right)_{\min} \Delta T_{\max} \Delta t \tag{5}$$

The net amount of economic value of the energy savings corresponding to this heat recovery plan, S, can be formulated with the combined $\varepsilon - NTU$ and $P_1 - P_2$methods as,

$$S = P_1 C_E Q - P_2 C_A A \tag{6}$$

The parameter C_E is the present price of the energy, C_A is the area dependent first cost of the heat exchanger, A is the area of the heat exchanger, ΔT_{max} is the maximum temperature differential in the heat exchanger, ΔT is the annual operation time of the heat exchanger in seconds, P_1 is the ratio of total life cycle net savings of the heat recovery system to the first year's saving, and P_2 is the ratio of total life cycle cost of the heat recovery system to its initial cost.

The net savings function can be interpreted as in Eq. (6),

$$S = P_1 C_E \varepsilon \left(\dot{m} C_p\right)_{\min} \Delta T_{\max} \Delta t - P_2 C_A A \tag{7}$$

The optimum value of the net savings can be determined mathematically by equating to zero the derivative of the savings function with respect to area,

$$\frac{\partial S}{\partial A} = P_1 C_E \left(\dot{m} C_p\right)_{\min} \Delta T_{\max} \Delta t \frac{\partial \varepsilon}{\partial A} - P_2 C_A \tag{8}$$

so that,

$$\frac{\partial \varepsilon}{\partial A} = \frac{P_2 C_A}{P_1 C_E \left(\dot{m} C_p\right)_{\min} \Delta T_{\max} \Delta t} \tag{9}$$

The area derivative of is equated to the right-hand side of Eq. (9) to get the optimum areas. For the $C = 1$ case, the following optimum heat exchanger area formula is obtained,

$$A_{opt} = \frac{-\left(\dot{m} C_p\right)_{\min}}{U} \left[1 - \sqrt{\frac{P_1 C_E \Delta T_{\max} \Delta t U}{P_2 C_A}}\right] \tag{9}$$

The *P₁* and *P₂* values are defined by the following relation.

$$P_1 = \left[\frac{1}{i-d}\right]\left[1 - \left(\frac{1+d}{1+i}\right)^N\right] \quad \text{if } i \neq d$$

$$P_1 = \left[\frac{N}{1+d}\right] \quad \text{if } i = d$$

$$P_2 = 1 + P_1 M_s - R_v (1+i)^{-N}$$

The payback period, N_p, can be calculated by setting the net savings function to zero. For this condition, the following relation arises. For if $= d$,

$$N_p = \frac{(1+d) C_A A (1 + \mathrm{NTU})}{C_E \left(\dot{m} C_p\right)_{\min} \Delta T_{\max} \Delta t \mathrm{NTU}} \tag{10}$$

and if $i \neq d$,

$$N_p = \frac{\ln\left[1 - \dfrac{C_A A (i-d)(1+\mathrm{NTU})}{\mathrm{NTU} C_E \left(\dot{m} C_p\right)_{\min} \Delta T_{\max} \Delta t}\right]}{\ln\left(\dfrac{1+d}{1+i}\right)} \tag{11}$$

2.2.2 Parallel Flow Heat Exchanger

Similarly, the optimum heat exchanger area, A_{opt}, and the payback period, N_p can be determined by using the same procedure for the parallel flow heat exchanger as,

$$A_{opt} = \frac{-\left(\dot{m} C_p\right)_{\min}}{(1+C) U} \ln\left[\frac{P_2 C_A}{P_1 C_E \Delta T_{\max} \Delta t U}\right] \tag{12}$$

If $i = d$,

$$N_p = \frac{(1+d) C_A A (1+C)}{C_E \left(\dot{m} C_p\right)_{\min} \Delta T_{\max} \Delta t \left[1 - e^{-(1+C)\mathrm{NTU}}\right]} \tag{13}$$

and if $i \neq d$,

$$N_p = \frac{\ln\left[1 - \dfrac{P_2 C_A A (i-d)}{\varepsilon C_E \left(\dot{m} C_p\right)_{\min} \Delta T_{\max} \Delta t}\right]}{\ln\left(\dfrac{1+d}{1+i}\right)} \tag{14}$$

The optimum net life cycle energy savings can be calculated by inserting the optimum value of the heat exchanger is into the equations for all the two heat exchangers discussed.

3. Optimization Process

Optimization is the process of finding the conditions that give maximum or minimum values of a function. Optimization has always been an expected role of engineers, although sometimes on small projects the cost of engineering time may not justify an optimization effort. Often a design is difficult to optimize because of its complexity. In such cases, it may be possible to optimize subsystems and then choose the optimum combination of them [14].

3.1 Application of optimization

In designing a workable system, the process often consists of arbitrarily assuming certain parameters and selecting individual components around these assumptions. In contrast, when optimization is an integral part of the design, the parameters are free to float until the combination of parameters is reached which optimizes the design. Basic to any optimization process is the decision regarding which criterion is to be optimized. In an aircraft or space vehicle, minimum weight may be the criterion. In a heat exchanger, the size or area of a system may be the criterion.

On the other hand, the minimum owning and operating cost, even including such factors as those studied on economics, may not always be followed strictly. A manufacturer of domestic refrigerators, for example, does not try to design his system to provide minimum total cost to the consumer during the life of the equipment. The achievement of minimum first cost, which enhances sales, is more important than operating cost, although the operating cost cannot be completely out of bounds.

3.2 Levels of Optimization

Optimization were done by examining four alternate concepts, which probably means that the engineer has compared workable systems of four different concepts. The statement does emphasize the two levels of optimization, comparison of alternate concepts and optimization within a concept. The flow diagram and mathematical representation of the system must be available at the beginning, and the optimization process consists of a give and take of sizes of individual components. All this optimization is done within a given concept. There is nothing in the upcoming procedures that will jump from one model to a better one. No optimization procedure will automatically shift the system under consideration from a steam-electric generating plant to a fuel-cell concept [14]

A complete optimization procedure, then, consists of proposing all reasonable alternate concepts, optimizing the design of each concept, and then choosing the best of the optimized designs.

3.3 Selection Method of optimization

There are many optimization methods that can be used for certain purpose as mentioned. Although the frequently used methods in engineering practice, it is nowhere near exhaustive. In the optimization of systems, it is almost axiomatic that the objective function is dependent upon more than one variable. In fact, some thermal systems may have dozens or even hundreds of variables which demand sophisticated optimization techniques. While considerable effort may be required in the optimization process, developing mathematical relationships for the function to be optimized and the constraints may also require considerable effort.

In this project P_1-P_2 was selected to do life cycle savings analyses. This is a quick and convenient way of carrying out the optimization. The method is used in economic analyses of solar processes [15]. Similar with other simulation, the simulation of heat exchanger involves data input, calculations organizing and graph plotting. The simulation can be divided into four major sections and the optimization process are detailed as shown in Fig. 1.

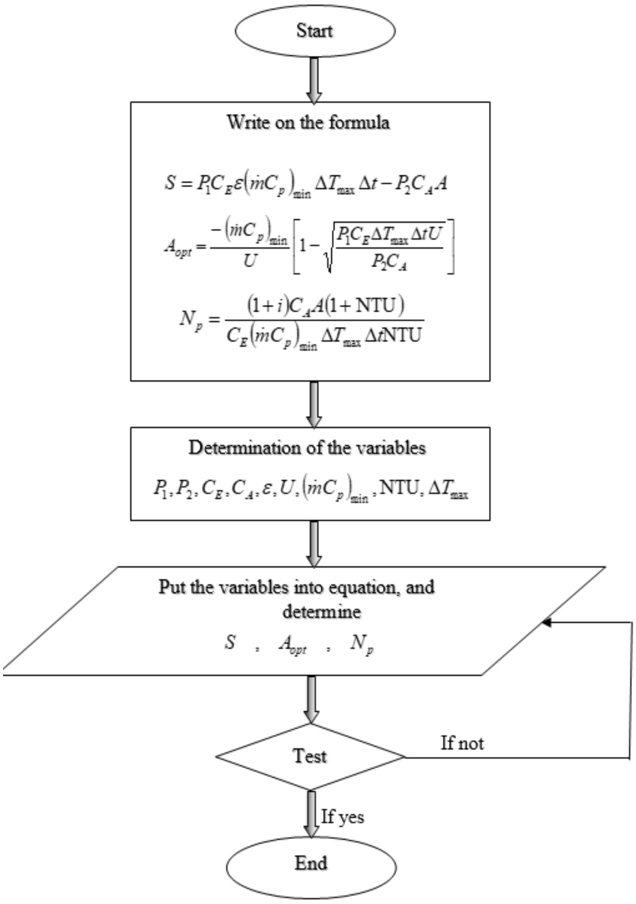

Fig. 1 – The flow chart of numerical simulation

4. Results and Discussion

Results for the simulation were discuss according to the effect of heat transfer area on effectiveness, net energy saving, payback period and effect of lifetime on energy saving. Details discussion were elaborated in the next subsection.

4.1 Effect of Heat Transfer Area on Effectiveness

Fig. 2 shows the effectiveness, ε of the heat exchanger is strongly influenced by the heat transfer area, A. However, the rate of change of ε to A i.e. $d\varepsilon/dA$ for counter flow is much greater for the parallel flow. This is exactly similar with theory that state for a given NTU and capacity ratio $C = C_{min}/C_{max} = 1$, the counter flow heat exchanger has the highest effectiveness, followed closely by the cross-flow heat exchangers with both fluids unmixed and the lowest effectiveness values are encountered in parallel flow heat exchangers.

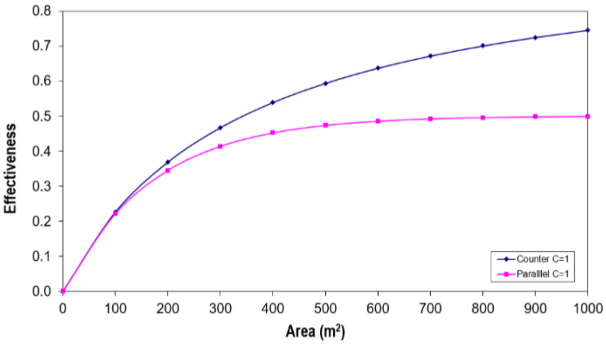

Fig. 2 - Effect of heat transfer area on effectiveness for C=1

The effectiveness of heat exchanger increases as the area of the exchanger increases. It is also seemed that for a parallel flow, as A reaches 400 m^2 the increases on ε is much slower. This is also shown in the counter flow exchanger. This is coinciding with the theory that the value of effectiveness range from 0 to 1 it increases rapidly with NTU for small values.

Fig. 3, when the $C < 1$, plot shows similar trend as Figure 2. However, the effectiveness give higher value than the effectiveness with the $C = 1$. Base on theory, for any heat exchanger maximum and minimum values are associated with $C = 0$ and $C = 1$ respectively. While for case $C > 1$, this does not satisfied the definition of ratio of heat capacity rates, C. Since C is always less than 1 unit.

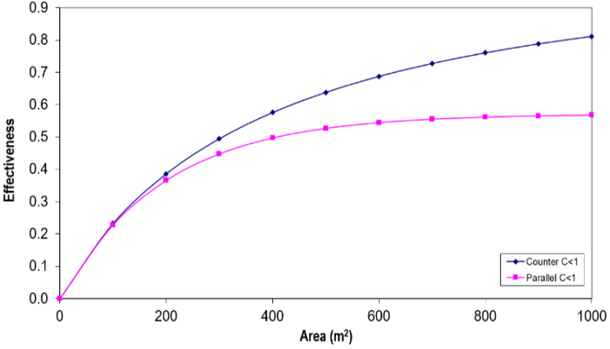

Fig. 3 - Effect of heat transfer area on effectiveness for C<1

4.2 Effect of Heat Transfer Area on Net Energy Savings

Fig. 4 shows the variation of net energy savings with the area of the two types of heat exchangers. As the area increases, the savings increases up to a local maximum point which determines the optimum heat exchanger area. Heat exchangers must be designed at maximum savings point, beyond which additional heat exchanger area is not cost effective.

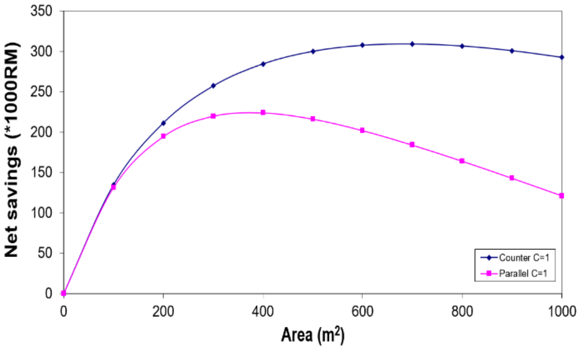

Fig. 4 - Effect on net energy savings for C=1

The plot shows, that for the parallel flow the maximum area *A* is reached earlier as compared to counter flow. For the counter flow heat exchanger the maximum occurs at about ± 700 m^2 where for the parallel flow heat exchanger the maximum occurs at about ± 350 m^2. Compared with Fig. 5 when $C < 1$, the plot shows for the counter flow heat exchanger the maximum occurs at about ± 800 m^2 where for the parallel flow heat exchanger the maximum occurs at about ± 420 m^2. It is gives the greater optimum value of heat exchanger area.

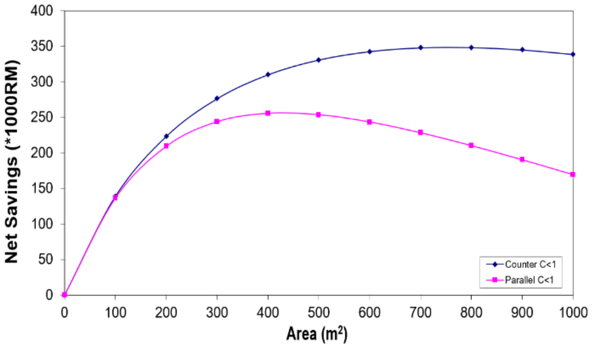

Fig. 5 - Effect on net energy savings for C<1

It is interesting to note that for a given *A* of the heat exchanger, counter flow heat exchanger saves more than a parallel flow. However, for $A < 100$ m^2, both type of heat exchangers saves equally.

4.3 Effect of Lifetime on Net Energy Savings

Fig. 6 indicates the net energy recovery savings with lifetime of the heat exchanger. The payback period, at which the net savings is zero, is seen in this figure. The longer the lifetime, the more is net energy savings. However, the counter flow heat exchanger seems to have energy saving as compared to parallel flow heat exchanger. As years goes by, counter flow heat exchanger have more energy savings than parallel flow. In fact, the longer the period, the better is the saving for counter flow heat exchanger.

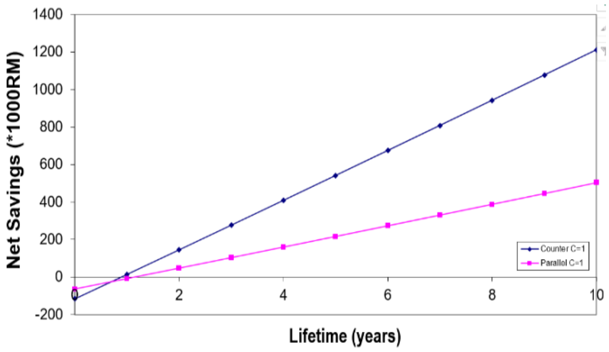

Fig. 6 - Effect of lifetime on net energy savings for C=1

Fig. 6 shows distinctively that the counter flow heat exchanger gives better net saving. In fact, the overall performance of this type heat exchanger, as shown in series of Fig. 2 and Fig. 4 is better than the parallel flow type.

4.4 Effect of Heat Transfer Area on Payback Period

Fig. 7 shows the larger heat transfer area the longer time to get payback period. The parallel flow heat exchanger needs longer time to get payback period than counter flow heat exchanger. As we know counter flow heat exchanger gives the higher effectiveness than parallel flow.

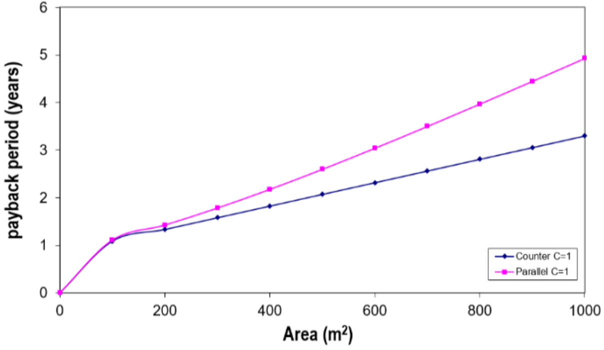

Fig. 7 - Effect of heat transfer area on payback period C=1

Compared to Fig. 8 it seems when $C < 1$ he plot get earlier payback period than case $C = 1$. From the series of Fig. 8, the plot show that parallel flow heat exchanger gives longer payback period. However, this type of heat exchanger is also net energy saving. This study shows counter flow heat exchanger outperformed parallel flow heat exchanger. However, for any heat exchanger saving even $A < 100$ m^2 they perform equally well.

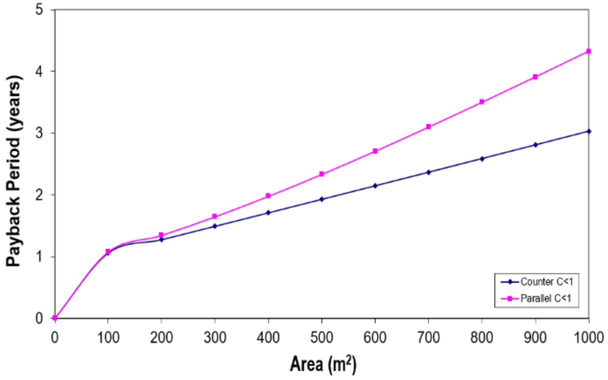

Fig. 8 - Effect of heat transfer area on payback period C<1

5. Conclusion

A thermoeconomic analysis of two common types unmixed flow heat exchangers have been analyzed. The $P_1 - P_2$ method is used in this study. The simulation study of this $P_1 - P_2$ method applied on the heat exchangers was accomplished by using in house code developed. From the results obtained, some interesting findings. Basically, the performances of heat exchangers are normally evaluated through the several factors. Thus heat exchangers need to be efficient, low cost or economical, safe and reliable. These factors are indirectly covered by the proposed $P_1 - P_2$ method in this study. In all the simulation runs that have been made, it seems that the counterflow type heat exchanger is outperformed the parallel flow type. In fact, the counter flow heat exchanger not only gives faster return of the investment, but the area needed to exchange the same amount of heat is also less. However, this finding is not conclusive. Further optimization study based on other aspects should be carried out. The $P_1 - P_2$ method itself, although effective, nevertheless have some parameters or constants coefficients that are hard to determine. The cost analysis carried out seems need to be reviewed.

The study showed counter flow heat exchanger outperformed than parallel type heat exchanger. The payback period of counter flow heat exchanger based on heat transfer surface area, is shorter compared to parallel flow heat exchanger. For a primarily study this analysis based on some assumed data, especially, on the cost factors is acceptable. However, more remunerative study, all constant factors that are used in this simulations have to be checked and verified.

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