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Full Length Article

Simulation of heat exchangers and heat exchanger networks with an economic aspect

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ABSTRACT

Relations between effectiveness (ε) and expense coefficients (ζ) were derived, and an economic simulation model was developed to simulate heat exchangers (HE) and HE networks (HEN) in all flow types for the first time. ε values of parallel flow, counter flow, cross flow and all HEs under the condition of $C_r = 0$ were derived in terms of ζ, *NTU* (Number of Transfer Unit) and minimum heat capacities (C_{min}). ε values obtained from economic calculations were used for developing economic simulation model of HEs. Vectors including outlet temperatures and inlet temperatures of flows were obtained from static simulation to utilize in economic simulation model. Then, case studies were performed with counter flow HE and ε values randomly determined in a sample HEN. Use (N), expense (P) and savings (E) of all HEs in a HEN were calculated easily by the way of linear equation systems without any complex processes, iterations, software and special hardware, in terms of both cold and hot flows properties by using economic simulation model.

1. Introduction

Energy is an essential parameter for all countries to maintain energy supply for industry, agriculture, transport and household requirements [1,2]. The increasing industrial facilities and fast technological improvements cause great energy requirements in contrary to diminishing energy sources [3,4]. In addition, increasing energy dependence emerges problems such as environmental pollution, global warming, increasing energy costs and inefficiency in energy usage [3,5]. So, several developing counties are in trouble with satisfying the energy gap between energy demand and supply [6].

Worldwide, 80% of total thermal energy production is performed by power plants using fossil fuels and 26% of this energy is not utilized and wasted by releasing into atmosphere [1,7,8]. In addition, 33% of primary energy usage was constituted by production industry [9]. Therefore, for industrial establishments operated with thermal energy, there is a significant energy source in waste energy in case of utilization of heat recovery devices [2,10,11]. HEs transfer heat between two or more fluids to recover waste heat in almost all power and chemical engineering facilities as a sub unit [12,13]. By this way a seconder energy resource is created for facilities. This seconder energy resource, ensures a significant decrease in consumption of primary energy source and primary energy cost. Furthermore, HEs directly enhance total efficiency of thermal system and reduces environmental impacts, provides a decrease in dimensions and number of equipment in thermal system [14,15].

HEs are used in distinguishing areas such as heating, refrigeration, air conditioning systems, petrochemical processes, reheating furnaces, sewage treatment and many others [10,14,16]. In this context HEN were subjected to extensive investigations since recent four decades to enhance total efficiency and minimize expenses [17]. For this purpose, several studies were done to carry out HEs cost and ε optimization. Sadeghzadeh et al.[18], used genetic and particle swarm algorithms in design of techno-economically optimum shell and tube heat exchangers. They defined a cost function including costs of HEs based on heat transfer surface area (A_R) and power consumption to overcome pressure drops. Manassaldi et al. [19], developed a mathematical model to reach optimum design of air cooled HEs by criteria of minimization of overall expenses including A_R and operating cost, by minimizing A_R and power consumed by fans. Asadi et al. [17], studied, a cuckoo search algorithm for optimization of a shell and tube HE. Total annual cost was selected as an objective function. Effectiveness of this approach was assessed by analyzing two cases. Case studies

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Nomenclature

A_R:	Required heat transfer area (m^2)	T^i:	Inlet temperature (°C)
C_r:	Heat capacities ratio (kJ/K)	T^I:	Inlet temperature vector (°C)
$\dot{C}_h$:	Heat capacity of hot flow (kW/K)	T^o:	Outlet temperature (°C)
$\dot{C}_c$:	Heat capacity of cold flow (kW/K)	Q_h:	Amount of heating (kWh)
C_{min}:	Minimum heat capacity (kW/K)	Q_c:	Amount of cooling (kWh)
C_{max}:	Maximum heat capacity (kW/K)	T_h^i:	Inlet temperature of hot flow (°C)
e:	Dimensionless saving coefficient	T_h^o:	Outlet temperature of hot flow (°C)
E:	Saving (€/a)	T_B:	Operating duration (h)
$\underline{E}$:	Unit matrix	T_c^i:	Inlet temp. of cold flow (°C)
I:	Input Matrix	T_c^o:	Outlet temp. of cold flow (°C)
K_0:	Total expense before HE (€/a)	U:	Overall heat transfer coeff. (W/m^2K)
K_B:	Cost of operating (€/a)	z:	Depreciation coefficient (1/a)
K_R:	Expense after heat recovery (€/a)	χ_h:	Energy production cost (€/kWh)
n:	Number of heat exchangers	χ_a:	Cost of unit area (€/kWh)
N:	Use (€/a)	χ_c:	Cooling cost (€/kWh)
O:	Output Matrix	κ:	Cost matrix
P:	Expense (€/a)	ξ:	Expense coefficient
S:	Structure matrix		

showed that annual operating cost can be reduced 77% and 48% compared to the result obtained by PSO (Particle Swarm Optimization) and GA (Genetic Algorithm). Teke et al. [7], studied a method to determine best HE, considering technical and economic parameters such as unit area cost ($\varkappa_a$), life time, lower heating value of fuel, overall heat transfer coefficient (U), operating time (T_B), heat capacities (C_p) of flows and many other parameters. The model provided maximum E and determined best HE with minimum A_R. Selbas et al. [20], developed a new design approach for shell and tube HEs by using genetic algorithms from economic point of view for optimal design. In their study, design variables were selected as outer tube diameter, tube layout, number of tube passages, baffle spacing, and baffle cut. Ponce-Ortega et al. [21], studied on a simple algorithm developed for design and economic optimization of multiple-pass 1–2 shell-and-tube HEs in series. They used F_T design method and inequality constraints that ensure feasible and practical HEs. Caputo et al. [22], proposed a procedure to provide an optimum design for shell and tube HE. They used genetic algorithm to minimize the total cost of equipment including capital investment and sum of discount annual energy expenditure related to pumping. Orozaliev et al. [23], proposed an automated method for design optimization with the aim of maximum efficiency due to the complex influences of parameters on HE efficiency. Configurations of HEs were assessed on investment and operating costs of entire system (heat exchanger, fan, pump, piping). Then specific approaches were developed to form the cost functions, particularly for HEs. However, none of them did not considered the economic contribution of HE and HENs on fuel consumption, heating and cooling costs. Furthermore, when considered many HEs existence in a facility, simulation of all HEs was not studied with an economic aspect.

In this study relations between ε and expense coefficients (ζ) were derived, and then an economic simulation model was developed to simulate overall E of all flow arrangements for the first time. Primarily, E values of parallel flow, counter flow, cross flow and all heat exchangers under C_r=0 conditions were derived in terms of ζ, *NTU* and minimum C_p. Secondly, relations were derived between thermal and economic calculations. Inlet and outlet temperatures required for economic simulation were obtained from static simulation model [24]. Lastly, a case study was performed to validate simulation model. Flow type was chosen counter flow in economic simulation followed by N, P and E of all HEs in network were calculated easily by the way of linear equation system without any complex processes, iterations software and special hardware, in terms of both cold and hot flows properties.

2. Material and method

Facilities using thermal energy, exerts waste energy via flue gas. To decrease energy production cost, increase facility efficiency and decrease cost of cooling flue gas, heat recovery is best method as a seconder energy resource. Firstly, overall saving in a facility was calculated by using energy production cost, cooling cost and operating cost for the conditions of with and without HE in a facility. After, relations were derived between saving coefficient (e) and ε followed by derivation of this relation for parallel, counter, cross flow and all heat exchangers (C_r=0). Expressions given and derived for economic and thermal calculations were reformed in forms of linear equation systems to develop an economic simulation model for a heat exchanger network consisted of many heat exchangers.

Overall cost of a facility needs thermal energy such as in Fig. 1, consist of production cost of required energy for thermal processes ($\varkappa_h$), cooling cost of flue gas ($\varkappa_c$) to prevent thermal pollution and operating cost (K_B) of a facility. Overall cost of such a facility before heat recovery is calculated as in Eq. (1) [12].

$$K_0 = K_B + \chi_h T_B Q_h + \chi_c T_B Q_c \tag{1}$$

Where K_B is operating cost, $\varkappa_h$ is energy production cost, $\varkappa_c$ is cooling cost, T_B is yearly operating duration, Q_h is amount of heating, Q_c is amount of cooling. After application of heat recovery, overall cost decreases and there will be a saving depending on amount of investment and recovered heat. Overall cost K_R and saving E after a heat exchanger establishment were given in Eq. (2) and Eq. (3) [12].

$$K_R = K_B + \chi_h T_B (Q_h - Q_R) + \chi_c T_B (Q_c - Q_R) + \chi_a A_R z \tag{2}$$

$$E = T_B Q_R (\chi_h + \chi_c) - \chi_a A_R z \tag{3}$$

Where, $\varkappa_a$ is cost of unit heat transfer surface area, A_R is total heat transfer surface area of heat exchanger, z is depreciation coefficient.

The first part $T_B Q_R(\chi_h + \chi_c)$shows the total profit and second part $\chi_A A_R z$ shows total expense after a heat exchanger establish-

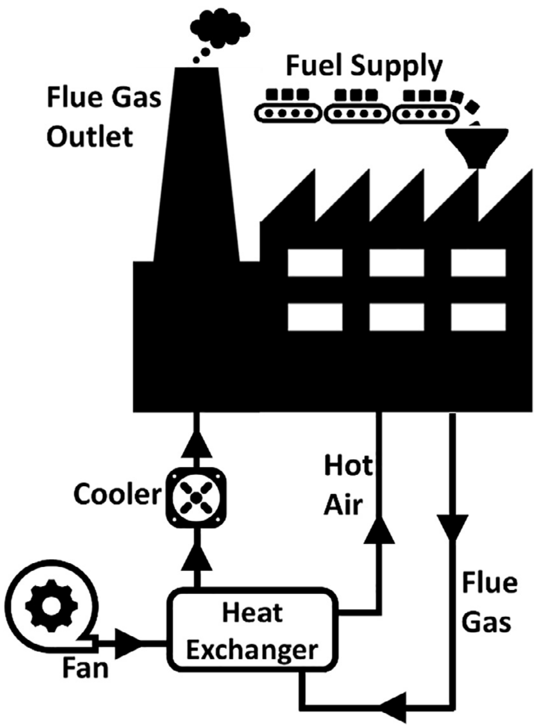

Fig. 1. Operating schema of a sample facility using thermal energy.

ment in Eq. (3). Another equation for heat recovery rate can be written as in Eq. (4) [25].

$$\dot{Q}_R = \varepsilon C_{min}(T_{h,i} - T_{c,i}) \tag{4}$$

Where ε is the effectiveness of heat exchanger, C_{min} is lower heat capacity of fluids, $T_{h,i}$ and $T_{c,i}$ are inlet temperatures of hot and cold flows respectively. Substituting the Eq. (4) in Eq. (3),

$$E = (\chi_h + \chi_c)T_B\varepsilon C_{min}(T_{h,i} - T_{c,i}) - \chi_A A_R z \tag{5}$$

was obtained. When the total saving was divided by the maximum possible saving, dimensionless saving coefficient e was obtained.

$$e = \frac{E}{(\chi_h + \chi_c)T_B C_{min}(T_{h,i} - T_{c,i})} \tag{6}$$

Substituting Eq. (3) in Eq. (6), multiplying the equations with overall heat transfer coefficient (U) Eqs. (7) and (8) were obtained.

$$e = (\varepsilon - \frac{\chi_a A_R z}{(\chi_h + \chi_c)T_B C_{min}(T_{h,i} - T_{c,i})})\frac{U}{U} \tag{7}$$

$$e = (\varepsilon\frac{U}{U} - \frac{\chi_a z}{(\chi_h + \chi_c)T_B U(T_{h,i} - T_{c,i})}\frac{A_R U}{C_{min}}) \tag{8}$$

In Eq. (8) the expressions

$$\frac{A_R U}{C_{min}} \tag{9}$$

and

$$\frac{\chi_A z}{(\chi_h + \chi_c)T_B U(T_{h,i} - T_{c,i})} \tag{10}$$

show NTU of heat exchangers and dimensionless expense coefficient (ζ) respectively [12]. Dimensionless saving coefficient was made simpler by substituting NTU and ζ in Eq. (10), as given in Eq. (11).

$$e = (\varepsilon - \xi NTU) \tag{11}$$

According to Eq. (11), if ε becomes maximum, saving of the facility will be maximum. When derivation of e is equal to zero, effectiveness will be maximum as in Eq. (10) and Eq. (11).

$$\frac{de}{dNTU} = (\frac{d\varepsilon}{dNTU} - \xi) = 0 \tag{12}$$

$$\frac{d\varepsilon}{dNTU} = \xi \tag{13}$$

In this way, relations between ε-NTU and e-ζ were derived as in Eq. (12) and Eq. (13). In accordance with Eq. (12) and Eq. (13), saving of a facility will be maximum when derivative of the ε versus NTU is equal to ζ.

3. Derivation of Effectiveness respect to the economic parameters

In this section, ε values of the parallel flow, counter flow and cross flow heat exchangers were derived in terms of ζ, NTU and C_{min}. Eq. (13) is general for all type heat exchangers.

3.1. Parallel flow heat exchangers

In order to derive the ε depending on economic parameters for parallel flow heat exchangers, we must substitute the ε obtained from thermal calculations of parallel flow heat exchangers in Eq. (11).

$$\varepsilon = \frac{1 - e^{[-NTU(1+C_r)]}}{1 + C_r} \tag{14}$$

Thus, Eq. (15) was obtained for parallel flow HEs.

$$e^{-NTU(1+C_r)} = \xi \tag{15}$$

We can see from the Eq. (15), $e^{-NTU(1+C_r)}$ is equal to $1 - \varepsilon(1 + C_r)$. Substituting $1 - \varepsilon(1 + C_r)$ in Eq. (15),

$$\varepsilon = \frac{1 - \xi}{1 + C_r} \tag{16}$$

Eq. (16) is derived. Thus, we obtained ε of parallel flow HE in terms of the economic parameters.

3.2. Counter flow heat exchangers

Effectiveness (ε) can be obtained in thermal calculations for counter flow HE with Eq. (17). Substituting Eq. (17) in Eq. (11),

$$\varepsilon = \frac{1 - e^{[-NTU(1-C_r)]}}{1 - C_r e^{[-NTU(1-C_r)]}} \tag{17}$$

$$\varepsilon = \frac{1 + C_r - \sqrt{(1 - C_r)^2 + 4C_r\xi}}{2C_r} \tag{18}$$

Eq. (18) was obtained. Thus, we obtained ε of counter flow HEs in terms of economic parameters.

3.3. Cross flow heat exchangers

Effectiveness (ε) can be obtained in thermal calculations for cross flow HE with Eq. (19), for the conditions of C_{min} unmixed and C_{max} mixed [25].

$$\varepsilon = \frac{1}{C_r}\left(1 - e^{-C_r(1-e^{-NTU})}\right) \tag{19}$$

Substituting Eq. (19) in Eq. (11), Eq. (20) is obtained.

$$\varepsilon = \frac{1}{C_r}\left(1 - \frac{\xi}{e^{-NTU}}\right) \tag{20}$$

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Effectiveness (ε) can be obtained in thermal calculations for cross flow HE with Eq. (21), for the conditions of C_{min} mixed and C_{max} unmixed [25],

$$\varepsilon = \left(1 - e^{-\frac{1}{C_r}\left(1-e^{-C_r NTU}\right)}\right) \quad (21)$$

Substituting Eq. (21) in Eq. (11), Eq. (22) is obtained.

$$\varepsilon = 1 - \frac{\xi}{e^{-C_r NTU}} \quad (22)$$

Thus, we obtained ε of cross flow HEs for the two conditions in terms of economic parameters.

3.4. All heat exchangers (Cr=0)

Effectiveness (ε) can be obtained in thermal calculations for all HEs (C_r=0) with Eq. (23) [25].

$$\varepsilon = 1 - e^{-NTU} \quad (23)$$

Eq. (24) was obtained by substituting Eq. (23) in Eq. (11).

$$\varepsilon = 1 - \xi \quad (24)$$

Thus, we obtained ε of all heat exchangers (C_r=0) in terms of economic parameters.

The equation obtained for cross flow HE in Eq. (20) is not only depended on dimensionless expense coefficient (ζ) and heat capacities ratio (C_r), but also depended on NTU. Therefore, in cross flow HEs (C_{min} unmixed and C_{max} mixed), when the outlet temperatures are known, namely the ε is calculated with respect thermal calculations, the solution is possible and otherwise solution is possible only with iterations for a restricted solution set. Equation obtained for cross flow HE in Eq. (22) is not only depended on dimensionless expense coefficient (ζ) and heat capacities ratio (C_r), but also depended on NTU. However, it has no solution numerically or iteratively in contrast with Eq. (22), because most of the results in solution consisted of imaginary numbers.

4. Economic simulation model

In a facility to calculate saving, each HE must be considered together, whether they connected to HEN or not. However, in case that economic calculations performed separately, it prevents the comparison of savings and monitoring all saving quantities of facility easily. Here by, to monitor all savings of facility in one step easily, an economic simulation model is required.

First part of economic use (N) for only one heat exchanger given in Eq. (3) can be written separately as in Eq. (25).

$$N = T_B Q_R(\chi_h + \chi_c) \quad (25)$$

When Eq. (25) was converted to a linear equation system to calculate N for a HEN or more than one HEs, Eq. (26) was derived.

$$N = \begin{bmatrix} \chi_{h1} + \chi_{c1} & 0 \\ 0 & \chi_{h2} + \chi_{c2} \end{bmatrix} \begin{bmatrix} T_{B1} & 0 \\ 0 & T_{B2} \end{bmatrix} \begin{bmatrix} Q_{R1} \\ Q_{R2} \end{bmatrix} \quad (26)$$

Recovered heat for only one heat exchanger was given in Eq. (4). When Eq. (4) was converted to linear equations system to calculate for a HEN or more than one HEs heat recovery, Eq. (28) was derived.

$$\dot{Q}_R = \begin{bmatrix} \varepsilon_1 & 0 \\ 0 & \varepsilon_2 \end{bmatrix} \begin{bmatrix} C_{min1} & 0 \\ 0 & C_{min2} \end{bmatrix} \begin{bmatrix} T_{h1,i} - T_{c1,i} \\ T_{h2,i} - T_{c2,i} \end{bmatrix} \quad (27)$$

The expense (P) for only one HE was given in second part of Eq. (3) as below.

$$P = \kappa A_R z \quad (28)$$

When Eq. (29) was converted to a linear equations system to calculate P for a HEN or more than one HEs, Eq. (30) was derived.

$$P = \begin{bmatrix} \chi_{a1} & 0 \\ 0 & \chi_{a2} \end{bmatrix} \begin{bmatrix} n_1 A_{R1} & 0 \\ 0 & n_2 A_{R2} \end{bmatrix} \begin{bmatrix} z_1 \\ z_2 \end{bmatrix} \quad (29)$$

Thus, to calculate and monitor the overall savings of all heat exchangers in facility, Eq.'s 26, 27 and 29 were substituted in Eq. (5), then economic model was obtained as given in Eq. (30).

$$E = \begin{bmatrix} \chi_{s1} & 0 \\ 0 & \chi_{s2} \end{bmatrix} \begin{bmatrix} T_{B1} & 0 \\ 0 & T_{B2} \end{bmatrix} \begin{bmatrix} \varepsilon_1 & 0 \\ 0 & \varepsilon_2 \end{bmatrix} \begin{bmatrix} C_{min1} & 0 \\ 0 & C_{min2} \end{bmatrix} \begin{bmatrix} \Delta T_1 \\ \Delta T_2 \end{bmatrix} - \begin{bmatrix} \chi_{a1} & 0 \\ 0 & \chi_{a2} \end{bmatrix} \begin{bmatrix} n_1 A_{R1} & 0 \\ 0 & n_2 A_{R2} \end{bmatrix} \begin{bmatrix} z_1 \\ z_2 \end{bmatrix} \quad (30)$$

Where $\varkappa_s$ defines sum of heating and cooling cost ($\varkappa_h$+ $\varkappa_c$) and ΔT defines temperature difference between hot flow and cold flow inlets ($T_{h,i}$-$T_{c,i}$). Eq. (30) is practical for several heat exchangers in a facility, whether they connected to HEN or not. Effectiveness (ε) values, input temperatures of flows and other components of simulation must be written into equation manually. However, for HEN Eq. (30) must be modified. For this purpose, Eq. (4) was written as in Eq. (31) and Eq. (32),

$$\dot{Q}_R = \dot{C}_h(T_{h,i} - T_{h,o}) \quad (31)$$

$$\dot{Q}_R = \dot{C}_c(T_{c,o} - T_{c,i}) \quad (32)$$

In addition, to calculate outlet temperatures of a HEN, Eq. (33) can be used [24] and

$$T^o = (\underline{E} - \varepsilon \cdot S)^{-1} \cdot \underline{\varepsilon} \cdot I \cdot T^I \quad (33)$$

to calculate inlet temperatures of a HEN, Eq. (34) can be used [24],

$$T^i = S \cdot T^o + I \cdot T^I \quad (34)$$

where T^o is outlet temperatures vector, E is unit matrix, $\underline{\varepsilon}$ is effectiveness matrix, S is structure matrix defines the stream matches among hot and cold fluids of HENs, I input matrix defines the input coordinates of the inlet flows, T^I defines inlet temperatures vector of the system, T^i defines inlet temperatures vector of HEs in the network [24]. When establishing the economical simulation of HE and HENs, stream matches among hot and cold fluids were defined by structure matrix S, which is important for the integrity of the model. Here, S matrix constitutes of four sub matrixes stand for hot fluid path, cold fluid path and determine the matching points. In S matrix, path numbers also represent the fluids flow ratios, that's because numbers are possible to be used any values between 0 and 1 [24].

When T^o vector substituted into the economic model, a new economic simulation model for a HENs was obtained as given in Eq. (35) and Eq. (36).

$$E = \begin{bmatrix} \chi_{s1} & 0 \\ 0 & \chi_{s2} \end{bmatrix} \begin{bmatrix} T_{B1} & 0 \\ 0 & T_{B2} \end{bmatrix} \begin{bmatrix} C_h & 0 \\ 0 & C_c \end{bmatrix} \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix} \begin{bmatrix} \Delta T_1 \\ \Delta T_2 \end{bmatrix} - \begin{bmatrix} \chi_{a1} & 0 \\ 0 & \chi_{a2} \end{bmatrix} \begin{bmatrix} n_1 A_{R1} & 0 \\ 0 & n_2 A_{R2} \end{bmatrix} \begin{bmatrix} z_1 \\ z_2 \end{bmatrix} \quad (35)$$

$$E = \kappa T_B CF \Delta T -_a A_R z \quad (36)$$

Where κ is cost matrix defines sum of heating and cooling cost, T_B is duration matrix defines operating duration of the HEs, C is heat capacity matrix, F is correction matrix to obtain inlet and temperature difference of hot and cold flow respectively.

5. Case studies

Economic simulations of parallel, counter and cross flow heat exchangers with identic technical specifications performed and compared with each other.

5.1. Economic calculations of Parallel, Counter, cross flow and all heat exchangers

In economic calculations A_R, ζ, e, ε and NTU values for parallel flow HEs were calculated by using the equations in Eq.'s 9, 10, 11, 16, 26, substituting the specifications given in Table 1. Results of economic calculations were given in Table 2.

For these sample HEs, variation of ε and e with same technical specifications given in Table 1. were showed in Figs. 2 and 3.

5.2. Economic simulation of a sample heat exchanger network

In this section, economic simulation of a sample HEN was performed to monitor E of all HEs. If outlet temperatures of a network are known we can start with static simulation, that is because effectiveness' are known. After, economic simulation can be performed. If there is a maximum saving expectation, we should start with economic simulation to derive optimum ε, after continuing with static simulation. In this case study, first circumstance was considered.

First, to fill the Eq. (36), static simulation of sample network in Fig. 4, was performed to obtain the outlet and inlet temperatures of the HEs.

Initial data was taken from Table 3. The network given in Fig. 4 is consisting of three hot flows and two cold flows. Temperature values of hot flows were assumed as 120 °C, 200 °C and 150 °C and temperature values of cold flows were assumed 20 °C and 30 °C for hot flow 1, hot flow 2, hot flow 3, cold flow 1, cold flow 2, respectively. A_R of all HEs are calculated by considering counter flow in this case study.

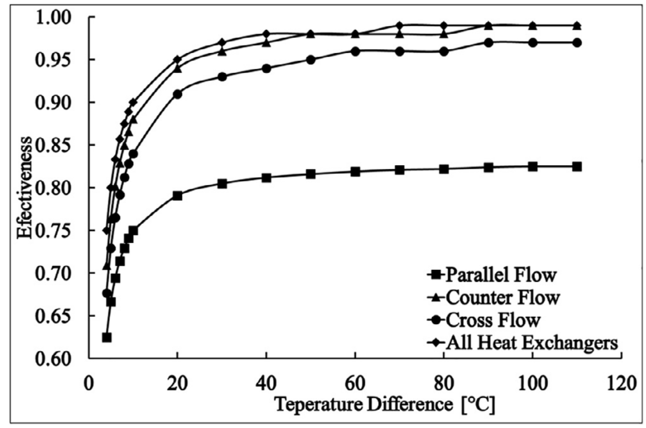

Fig. 2. Effectiveness change for sample HEs.

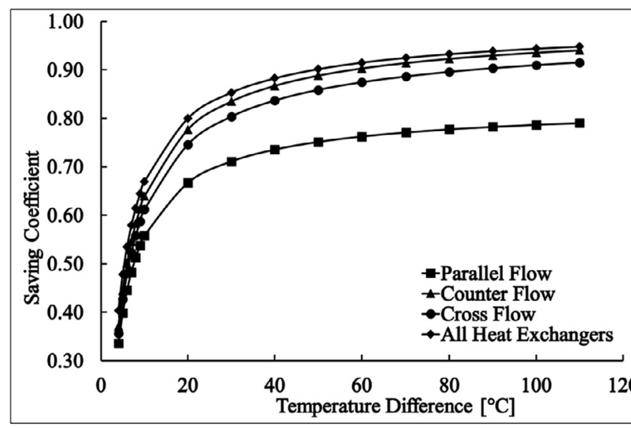

Fig. 3. Saving coefficient change for sample HEs.

To simulate the HENs, we should substitute this vectors into Eq. (36) solve the equations by utilizing a simple mathematic software. The summary table he of the economic simulation was given in Table 4.

Table 1
Technical identic specifications of sample HEs.

C_{min} [kW/K]	C_{max} [kW/K]	χ_h [€/kWh]	χ_c [€/kWh]	χ_a [€/m^2]	z [1/h]	T_h^i [°C]	T_c^i [°C]	T_B [h]	U [kW/m^{2}K]
2	10	0.04	0.01	400	0.1	120	10	4000	0.2

Table 2
Result of economic calculations.

Flow Type	A_R [m^2]	ξ	e	ε	NTU	T_h^o [°C]	T_c^o [°C]	Q_R [kW]	Saving [€/a]
Parallel	39.17	0.00909	0.79	0.825	3.917	29.1	28.1	181.6	34 766
Counter	53.25	0.00909	0.94	0.99	5.32	11.2	31.8	217.5	41 371
Cross	60.1	0.00909	0.92	0.97	6.01	13.3	31.3	213.3	40 263
All	47	0.00909	0.95	0.99	4.70	11	32	218	41 719

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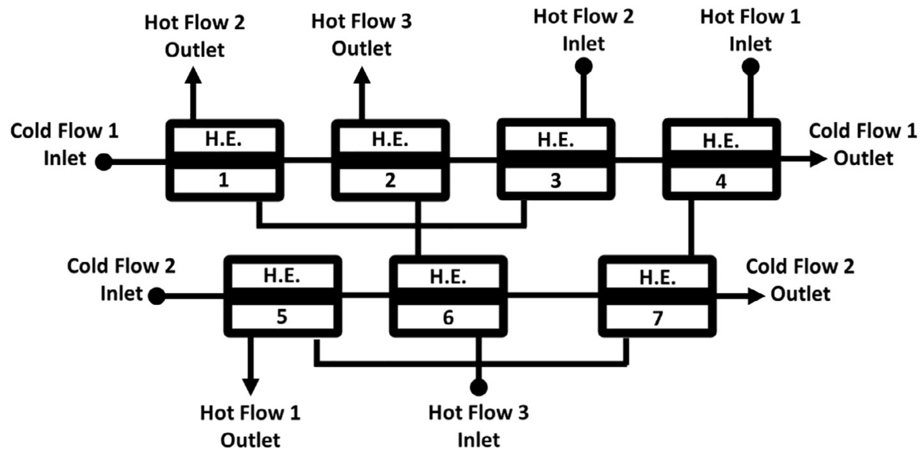

Fig. 4. Sample HEN.

Table 3
Initial input data of HEs.

Nr.	C_h [kW/K]	C_c [kW/K]	χ_h [€/kWh]	χ_c [€/kWh]	χ_a [€/m^2]	z [1/h]	T_B [h]	U [kW/m^{2}K]	ε	A_R [m^2]
HE 1	2	10	0.04	0.01	400	0.1	4000	0.1	0.75	30.6
HE 2	2	10	0.04	0.01	400	0.1	4000	0.1	0.60	19.7
HE 3	2	10	0.04	0.01	400	0.1	4000	0.1	0.65	22.7
HE 4	2	10	0.04	0.01	400	0.1	4000	0.1	0.70	26.3
HE 5	2	10	0.04	0.01	400	0.1	4000	0.1	0.50	14.6
HE 6	2	10	0.04	0.01	400	0.1	4000	0.1	0.35	8.9
HE 7	2	10	0.04	0.01	400	0.1	4000	0.1	0.40	10.6

Table 4
Summary table of economic simulation.

Nr.	Hot Flow Inlet [°C]	Hot Flow Outlet [°C]	Cold Flow Inlet [°C]	Cold Flow Outlet [°C]	Use [€/a]	Expense [€/a]	Saving [€/a]
HE 1	96.5	39.1	20	31	22 957	1 224	21 733
HE 2	109.2	62.5	31.4	40.8	18 650	788	17 862
HE 3	200	96.5	40.8	61.5	41 391	908	40 483
HE 4	120	79	61.5	69.7	16 380	1 052	15 328
HE 5	64	47	30	33.4	6 811	584	6 227
HE 6	150	109.2	33.4	41.5	16 324	356	15 968
HE 7	79	64	41.5	44.5	5 997	424	5 573

Considering the Fig. 4 and Table 4 together, the economic contributions of each HE in the sample network can be observed clearly in only one table.

6. Conclusion

Relations between effectiveness and expense coefficients were derived, and then an economic simulation model was prepared to simulate the HEs in all flow types and monitor the savings in a facility. E value of parallel flow, counter flow, cross flow and all heat exchangers in the condition of C_r=0 were derived in terms of ζ, NTU and C_{min}. Variation of e and ε versus temperature difference were given in way of curves in Figs. 2 and 3. ε obtained from economic calculations were used in economic simulations of sample HEs. In cross flow heat exchangers, when the outlet temperature of the HE is known, namely the ε is calculated respect to the thermal calculations, solution is possible, otherwise solution is possible only with iterations. Considering the results in Figs. 2 and 3, difference of e versus temperature difference was almost identical with difference of ε versus temperature. In addition, e is always in an increase with increase of ε because of the decrease in required A_R. Thus, a common heat exchanger economic simulation model was developed after the derivation of all relations of all flow types as given in Eq. (35) and Eq. (36) for the first time. For the three flow types, economic simulation model was run, and results were summarized in Table 4.

For the economic simulation, outlet temperatures and inlet temperatures vectors, obtained from another static simulation model. Flow type was chosen as counter flow and ε of heat exchangers were randomly determined for HEs in sample network. Consequently, use, expense and savings of the all heat exchangers in the facility are calculated easily by the way of linear equation system without any complex processes.

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