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

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-

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