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Research Paper

Heat exchanger network retrofit throughout overall heat transfer coefficient by using genetic algorithm

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HIGHLIGHTS

- An optimization model using GA is developed to retrofit the existing HEN.
- The retrofitting increased the amount of energy recovery by optimizing the value of overall heat transfer coefficient (U).
- Three types of optimization scenarios are conducted with different constraint of U.

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ABSTRACT

Heat integration through energy recovery is utilized to reduce energy consumption. Energy or heat recovery can be performed using heat exchanger (HE) in heat exchanger network (HEN). HEN is an arrangement of several interconnected HE, which is used to conduct heat recovery. This arrangement increases complexity of heat integration. In the existing HEN, some of the energy is wasted due to unproper HEN design. HEN retrofit can overcome this problem and increase the heat recovery in existing processes. In this research, HEN retrofit is performed by optimizing the maximum heat recovery (Q) without changing the area of heat transfer or adding new HE and the arrangement of HE in HEN. In order to fid out the maximum Q, genetic algorithm (GA) is used to search the best heat transfer coefficient (U) value. In this paper, three cases of optimization scenarios are performed by some constraints considered on the HEN model. In the first optimization scenario, U is optimized without the given the maximum and minimum limits. While in the second optimization scenario, U has limitation at the minimum value, which is the value of U on the initial design data. And on the third case optimization scenario, U has limits due to availability of existing technology, which is the increase in the maximum of U using internal fins, twisted tape insert, coiled wire insert, and helical baffle. Heat recovery obtained in the first case scenario optimization results was at 13.21%, whereas the second case scenario optimization was at 9.14%, and the third case scenario optimization was at 3.60% with an internal fin technology limitations, 2.77% by limitations of twisted tape inserts technology, 7.69% with coiled wire insert technology, and 4.61% with helical baffles technology.

1. Introduction

Heat recovery is a technique to take or reuse the heat from the product and or material that will be reused to reheat the raw materials. This process can be found in buildings, such as heater, ventilation, etc., or process equipment, such as oven, furnace, heat exchanger, etc. Heat recovery will be more effective for industrial applications that consume a large amount of energy.

Heat recovery can be achieved by doing heat integration. According to Smith [1], heat integration can be applied to heat exchanger network (HEN), reactor, distillation column, evaporator and dryer, etc., and according to Parsons et al. [2], by using heat integration, we can save the use of overall energy in the process by 70% with HEN. Thus almost all of the heat integration objective function is used to maximize the heat recovery for grassroots and retrofit.

Nowadays, heat exchanger network or HEN retrofit receives great attention from both the academic and industrial communities. From the research of Liu et al. [3], it is said that HEN retrofit is pivotal for plants with large energy consumption especially for energy saving and environmental impact, and has led to an increase in market competitiveness. HEN retrofit allows to increase heat recovery in existing processes. According to Pan et al. [4], such improvements can be achieved in various ways, namely by providing additional surface area or installing new heat exchangers (HE) and restructure the existing heat exchanger arrangement.

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There have been many studies conducted to improve the heat recovery of heat exchanger network (HEN). One is a research conducted by Wang et al. [5]. The research was conducted by using pinch technology and managing to save energy by 3.4%. Another way is to retrofit the heat exchanger network, which optimizes the overall heat transfer coefficient (U) to obtain the maximum heat recovery (Q), taking into account the operating conditions and technological limitations that exist in each heat exchanger design. There are so many researchers who already have researched technologies to improve the overall heat transfer coefficient in HE. Some of them were Huq et al. [6], Mokkapati and Lin [7], Martínez et al. [8], and Lei et al. [9]. They can increase the overall heat transfer coefficient by 52%, 35.5%, 300%, and 75%, respectively. The overall heat transfer coefficient is noteworthy because it will affect the performance of HE. By using this method, there is no need for an additional surface area or restructure of the existing HE. It means that this method has a big chance to be realized without additional cost for changing the surface area or the existing HE.

The heat recovery (Q) from HEN will increase linearly with the increase in the optimized U. The maximum heat recovery can be determined through the output temperature in each heat exchanger in the heat exchanger network (HEN). To determine the amount of heat generated from the output temperature, it is necessary to model the appropriate model of HEN. Almost all HEN modeling are performed using the mass and energy balances, both linear and non-linear model, such as the work of Ijaz et al. [10], as well as commercial software, such as GAMS, and self-programming software, such as MATLAB, like in the work of Biyanto et al. [11].

HEN appropriate model, objective function and optimization technique are required in optimization of U in each HE. Linear and non-linear equations are used to simulate HE in HEN, so it belongs to a class of non-linear programming problems (NLP). Solving the non-linear programming problems that have many local optimums requires optimization techniques to find the global optimum solution. Stochastic optimization algorithms based on adaptive random search methods, such as evolutionary algorithms, have the capability to find the global solution and have demonstrated to be a powerful tool for dealing with complex NLP problems. Genetic algorithm (GA) of Najafi et al. [12] and Ravagnani et al. [13] were proposed to solve the NLP problem.

This research focuses on increasing heat recovery by optimizing the overall heat transfer coefficient (U) using GA. Optimization is performed by considering the limitations of the operating condition and the design capacity of heat exchangers, as well as the availability of existing technologies to increase the U. The technologies used in this research are internal fins, twisted-tape inserts, coiled wire inserts, and helical baffles.

2. Steady state heat exchanger equation

Steady state heat exchanger equations (Eq. 1–7) are described in detail in Kuppan [14]. Basically, when analyzing the performance of the heat exchanger, the principle of mass balance and energy can be applied. Hot and cold fluids have the same amount of energy, that is

$$Q_h = Q_c \tag{1}$$

While the equation of heat generated is

$$Q = mc_p(T_i - T_o) \tag{2}$$

The process of heat transfer that occurs in the heat exchanger is that hot fluid will provide the necessary heat and cold fluid will receive the heat, so we get the equations for mass and energy balances contained in the heat exchanger, which is

$$Q = m_h c_{p,h}(T_{h,i} - T_{h,o}) = m_c c_{p,c}(T_{c,o} - T_{c,i}) \tag{3}$$

Heat transfer rate equation, which takes place between the heat exchanger tube and shell sides, is

$$Q = UA\Delta T_{lm} \tag{4}$$

LMTD is the average temperature difference between hot fluid (product) and cold fluid (crude). The equation of the LMTD is

$$\Delta T_{lm} = LMTD = \frac{\Delta t_1 - \Delta t_2}{\ln(\Delta t_1/\Delta t_2)} \tag{5}$$

where,

$$\Delta t_1 = T_{h,i} - T_{c,i} \tag{6}$$

$$\Delta t_2 = T_{h,o} - T_{c,o} \tag{7}$$

The maximum LMTD is obtained when two fluid streams are in pure countercurrent flow. However, most shell-and-tube heat exchangers have multiple shell-and-tube-passes to enhance the heat transfer. In multi-pass shell-and-tube exchangers, the flow pattern varies between counter-current, co-current and cross flow. Hence, a correction factor, *F*, is introduced to account for the deviations in the LMTD values due to the variations in flow patterns in the heat exchanger. The factor, *F*, is defined as the ratio of the true mean temperature difference (MTD) to the logarithmic mean temperature difference (LMTD). The correction factor depends on the terminal temperatures and the flow pattern and can be determined from algebraic equation proposed by Fakheri [15].

Fakheri proposed a single equation for the determination of the LMTD correction factor applicable to shell and tube heat exchangers with 2M number of tube and N shell passes [15]. Therefore, for a shell and tube heat exchanger, with N = 1,2,3,… shell passes and 2M = 2,4,6,8… tube passes per shell, the LMTD correction factor is given by

$$F_{N,2N,M} = \frac{\dfrac{\sqrt{R^2+1}}{R^2-1}\ln\left[\dfrac{1-PR}{1-P}\right]^{1/N}}{\ln\dfrac{1+\left[\dfrac{1-PR}{1-P}\right]^{1/N} - \dfrac{\sqrt{R^2+1}}{R-1} + \dfrac{\sqrt{R^2+1}}{R-1}\left[\dfrac{1-PR}{1-P}\right]^{1/N}}{1+\left[\dfrac{1-PR}{1-P}\right]^{1/N} - \dfrac{\sqrt{R^2+1}}{R-1} + \dfrac{\sqrt{R^2+1}}{R+1}\left[\dfrac{1-PR}{1-P}\right]^{1/N}}} \tag{8}$$

$$P = \frac{T_{c,o} - T_{c,i}}{T_{h,i} - T_{c,i}} \tag{9}$$

$$R = \frac{T_{h,i} - T_{h,o}}{T_{c,o} - T_{c,i}} \tag{10}$$

The equations of steady state heat exchanger are used to simulate the heat exchanger. Heat will be transferred from hot fluid to the cold fluid equivalent to the change of enthalpy of hot fluid. According to the work of Biyanto et al. [11], the equation of the heat exchanger output temperature becomes

$$T_{c,o} = \left[\frac{k_1(\exp(-k_2F(k_1-1))-1)}{\exp(-k_2F(k_1-1))-k_1}\right]T_{h,i} + \left[\frac{(1-k_1)(\exp(-k_2F(k_1-1)))}{\exp(-k_2F(k_1-1))-k_1}\right]T_{c,i} \tag{11}$$

$$T_{h,o} = \left[\frac{\exp(-k_2F(k_1-1))-1}{\exp(-k_2F(k_1-1))-k_1}\right]T_{c,i} + \left[\frac{(k_1-1)}{\exp(-k_2F(k_1-1))-k_1}\right]T_{h,i} \tag{12}$$