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Optimization in plate-fin safety structure of heat exchanger using genetic and Monte Carlo algorithm

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ABSTRACT

A safety structure of plate-fin heat exchanger is designed for special applications to prevent fluid leakage from adjacent channel walls. A fractional volume of a cavity layer between two channels is filled with high thermal conductive column-shape metal. Genetic algorithm is used for optimization of column distributions to achieve the maximum heat transfer performance, and its output is better than the simple direct optimization. To optimize with uncertain fluid condition, a direct genetic algorithm method, two improved genetic algorithm methods and a specific type of Monte Carlo algorithm method are applied in searching suitable solution. The optimized structure can provide a new feasible and safety plate-fin heat exchanger, and its results obtained by using genetic algorithm and Monte Carlo algorithm can provide some guidelines for optimal designs of heat exchangers.

1. Introduction

Heat exchangers have been widely employed in many industrial applications [1], such as food, oil, and heat recovery, etc. Fluid leakage affects the production [2] seriously and fluid contamination may be dangerous in some applications [3,4]. Leakage is permissible within limits, but in some special applications fluid leakage is absolutely not allowed, so leakage detection is a key strategy. In these applications, some structures such as double-wall tubular exchanger, shell-and-tube exchanger [5] and double-plate exchanger [6] are used. Plate-fin heat exchanger has been widely used for its high heat transfer performance. However, leakage brings concerns in the applications of plate-fin heat exchanger. Therefore, a new structure of plate-fin heat exchanger is designed to solve this problem. This specific safety structure is shown in Fig. 1.

A cavity is added between flow channels. When leakage of one flow channel occurs at the surface, fluid will leak into the cavity, rather than directly leak into the adjacent channel, avoiding the mixture of two fluids. This cavity would be vacuumized. If one fluid leaks to the cavity, the pressure in cavity would grow rapidly, which makes easy leakage detection.

However, the cavity almost insulate heat transfer between flow channels, thus a series of columns with high thermal conductive are filled fractionally in volume of the cavity to enhance the thermal conductivity. The distribution of columns affects the heat transfer performance for a certain working condition.

Genetic algorithm has small dependence on the studied problems [7] and powerful searching ability [8,9]. Many researchers have implemented genetic algorithm in heat exchanger optimization design [10,11]. Ponce Ortega et al. [12] optimized shell-and-tube heat exchanger parameters with genetic algorithm, such as the number of tube-passes, the diameter and pitch of tube, and the baffle cut, etc. Xie [13] used it to optimize the structure size of plate-fin heat exchanger.

In addition, Monte Carlo method is a statistical technique to solve complex problem. It is applied in different fields such as space exploration, oil exploration, and economics etc [14]. In the heat exchanger design, Clarke et al. used it to study the sensitivity and uncertainty of heat exchanger designs for physical properties estimation [15]. Uma Maheswaran et al. used it to generate random possible combinations to evaluate performance of a compartmented cooling coil [16]. Abdelaziz et al. used it to estimate the heat exchanger performance distribution in modeling heat exchangers under consideration of uncertain flow distribution [17].

In this paper, genetic algorithm and Monte Carlo algorithm are used to search optimal distribution of columns for a better heat transfer performance. A simple direct optimization method is also

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Nomenclature

c_p	heat capacity, J/(kg K)
d_e	hydraulic diameter, m
h	convection coefficient, W/(m^2 K)
m	mass flow, kg/s
m_H	mass flow rate of hot fluid, kg/s
m_L	flow rate of cold fluid, kg/s
n	shift number of column in the direct optimization
n_c	condition number in CCGAM or MCGAM
n_i	individual number
n_g	generation number
n_r	discretized range number of condition for calculating the mean efficiency
N	numerical calculation number for temperature distribution
$P(t)$	generation in genetic algorithm method
Pr	Prandtl number
Q	total heat flux through heat exchanger, W
Re	Reynolds number
$S(t)$	sub-generation in genetic algorithm method
T_{H_in}	mean temperature of hot fluid inlet, °C
T_{L_in}	mean temperature of cold fluid inlet, °C
δ	thickness, m
η	heat transfer efficiency
θ	efficiency ratio compared with the reference efficiency
λ	heat conductivity coefficient, W/(m K)
φ	occurrence probability of condition

applied to compare with genetic algorithm with certain flow rate. Genetic algorithm is improved to solve the problem with uncertain conditions. Moreover, Monte Carlo algorithm is combined with genetic algorithm as another method for the case with uncertain working conditions.

2. Optimization methods and implementation

2.1. Effects of different distributions

The cavity is divided into uniform grids, with each column in the center of a grid. When the quantity of columns is smaller than the quantity of grids, the heat transfer performance is depending on the distribution of columns.

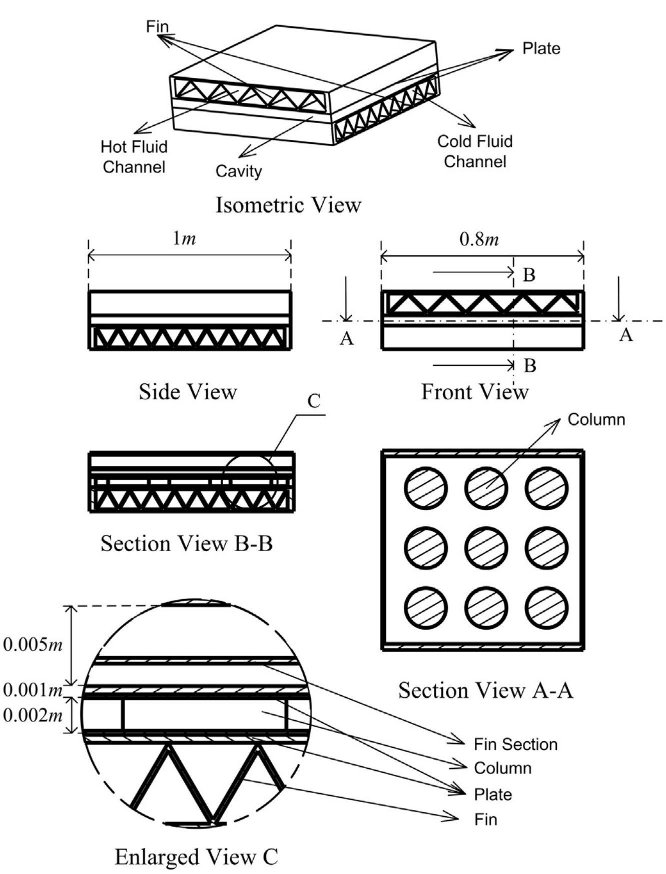

Fig. 1. The new structure of plate-fin heat exchanger.

A basic heat transfer unit model is shown as Fig. 2. The heat flux through a column is depending on the difference between inlets temperature. Define T_{L_in} as the mean temperature of cold fluid inlet, T_{H_in} as the mean temperature of hot fluid inlet. With the increase of the difference between T_{L_in} and T_{H_in}, the heat flux through a column becomes larger. It means that putting the finite columns into grids with large inlet temperature difference will make high heat flux.

In the current study, we define air as the hot fluid, and fuel as the cold fluid, and suppose some physical parameters are constant. The mass flow of hot fluid is 0.03 kg/s and the cold fluid is 0.06 kg/s, some constant physical parameters are shown in Table 1. The length and width of heat exchanger are 1 m and 0.8 m, the volume of columns is 30% of the total volume of cavity, and other parameters for calculation are shown in Table 2.

The heat transfer coefficient could be calculated as Eq. (1).

$$h = 0.023\frac{\lambda}{d_e}Re^{0.8}Pr^{x} \tag{1}$$

where d_e is the hydraulic diameter, Re is Reynolds number, Pr is Prandtl number, x is 0.3 for hot fluid, 0.4 for cold fluid.

For example, define the grid quantity as 4 and the column quantity as 3. The quantity of rows and lines as two, and there are four distributions. These distributions are named as Distribution A/B/C/D and shown in Fig. 3.

Define heat transfer efficiency

$$\eta = \frac{Q}{(mc_p)_{min}(T_{H\_in} - T_{L\_in})} \tag{2}$$

where Q is the heat flux through heat exchanger, $(mc_p)_{min}$ is the lower product of mass flow and heat capacity.

The heat flux through distribution A to D could be estimated by Eqs. (3)–(6).

$$Q_A = (mc_p)_{min}\eta_{core}\Delta T\left[3 - \eta_{core}\left(1 + \frac{(mc_p)_{min}}{(mc_p)_{max}}\right)\right] \tag{3}$$

$$Q_B = (mc_p)_{min}\eta_{core}\Delta T\left[3 - \eta_{core}\left(1 + (1 - \eta_{core})\frac{(mc_p)_{min}}{(mc_p)_{max}}\right)\right] \tag{4}$$