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Semi-numerical analysis of heat transfer performance of fractal based tube bundle in shell-and-tube heat exchanger

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ABSTRACT

A bundle of topologically arranged tubes based on fractal is proposed in this work to enhance the flow of shell-side fluid. The space for arranging tubes is separated into some periodic regions and the tubes are symmetrically arranged in these regions. The topological arrangement of tubes is in the radial direction starting from the shell center. Fractal treatment is applied to divide each periodic region into two smaller symmetric ones. With the alternately installed disc and doughnut baffles, the shell-side fluid converges to shell center or diverges away from the center, and the uniform shell-side flow is realized. According to the periodic characteristic of tube bundle, numerical heat transfer unit models are established and the characteristic temperatures in heat exchanger are obtained using the semi-numerical simulation algorithm. Comparing the results with the analytical solution to the outlet temperatures of shell-side and tube-side fluids based on the Bell-Delaware method, it is revealed that, even though the number density of tubes is reduced compared to the conventional version, the new structure has a higher heat transfer efficiency due to the full use of tubes. The fluid outflows from the tube near the shell center has a higher temperature, and the concurrent and countercurrent flows result in the different temperature increasing trends of tube-side fluid as well as the different temperature decreasing trend of shell-side fluid. The countercurrent results in a larger decrease of shell-side fluid temperature.

1. Introduction

Shell-and-tube heat exchanger is the most important equipment for efficient heat transfer between two fluids at different temperatures in process industry. Some distinct advantages include the large heat transfer area per unit volume, the wide range of operation conditions, as well as the versatile materials used in construction. As for the heat exchangers working under high pressure conditions, the structure composed of cylindrical shell and circular tubes is preferred undoubtedly. Many codes for the design of shell-and-tube heat exchangers are available for engineers, including TEMA and PPHX in America, GB 151-1999 in China, JIS B 8249 in Japan, BS 5500 in Britain and AD in Germany, etc. These references provide both economical and reliable structures for conventional designs of shell-and-tube heat exchangers.

To achieve a higher energy efficiency ratio, heat transfer enhancement techniques for both inside and outside tubes are constantly studied with emphasis on optimizing the design and operation of heat exchangers The conventional intensification techniques include tube-side enhancements with internal tube fins, twisted-tape inserts and coiled-wire inserts, and shell-side enhancements with external tube fins and helical baffles. Combining several enhancement techniques will achieve higher energy savings compared with implementing single technique [1].

Finned tubes and twisted oval tubes which can enhance turbulent flows of tube-side fluid are employed to substitute smooth circular tubes. The fins attached on tube walls can not only enlarge heat transfer area but also enhance turbulence near the wall. In the twisted oval tube heat exchanger, the overall shell-side heat transfer performance was found to be affected by both twisted pitch length and aspect ratio [2]. More attentions were paid on the technique to reinforce the turbulence intensity of shell-side fluid. The helical baffles have better capability in disturbing shell-side fluid flow while consume lower shell-side pressure drop. The experimental study on shell-side thermodynamic and hydraulics performance of helical baffles heat exchangers revealed that helical baffles structure is more suitable for fluid flow as the shell side pressure drop per unit fluid-flow distance is smaller [3,4]. The higher coil diameter, coil pitch and mass flow rate in shell and tube can enhance the heat transfer rate in these types of heat exchangers

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Nomenclature

A	heat transfer area, m^2
A_o	cross flow area for shell-side fluid, m^2
a_j	coefficient
b_j	coefficient
c_j	coefficient
$c_{p,s}$	the heat capacity of shell-side fluid
d_i	inner diameter of tube, mm
d_j	coefficient
d_o	outer diameter of tube, mm
d_s	spacing interval of tubes, mm
e	number of holes
L	tube length, mm
m	mass flow rate, kg s^{-1}
N	total number of holes
Pr	Prandtl number
R	fouling resistance, m^2 K W^{-1}
Re	Reynolds number
r_e	radius of non-tube region, mm
r_1	radius of the first auxiliary circle, mm
T	shell-side characteristic temperature, K
t	tube-side characteristic temperature, K
T_{in}	shell-side inlet temperature, K
T_{out}	shell-side outlet temperature, K
t_{in}	tube-side inlet temperature, K
t_{out}	tube-side outlet temperature, K
ΔT	shell-side temperature change, $\Delta T = T_{out} - T_{in}$, K
Δt	tube-side temperature change, $\Delta t = t_{out} - t_{in}$, K
ΔT_{lm}	is the log-mean temperature difference
x_i	x coordinate of hole n_i, mm
y_i	x coordinate of hole n_i, mm

Greek symbols

α	heat transfer coefficients, W m^{-2} K^{-1}
θ	the first periodic angle, rad
λ	thermal conductivity, W m^{-1} K^{-1}

Subscripts

c	shell-side fluid flows toward shell center
d	shell-side fluid flows away from shell center
i	serial number of holes in tube sheet, i = 1,2,3...
j	serial number of heat transfer unit, j = 1,2,3...
k	serial number of symmetry line, k = 1,2,3...
s	shell-side
t	tube-side

[5]. The oil cooler with helical baffles was found to get lower shell-side pressure drop and higher heat transfer coefficient per unit pressure drop at a fixed volume flow rate than the oil cooler with segmental baffles [6,7]. The combination of rod and van type spoiler was designed to reduce flow pressure drop in shell-side [8].

Besides the improvement of structure, the modified heating and cooling medium are used to improve the performance of heat exchanger systems. Nanofluid is a new engineering fluid which can improve the performance of heat exchanger [9]. It was observed that the convective and overall heat transfer coefficient increased with the application of nanofluids compared to ethylene glycol or water based fluids [10]. Different parameters such as particle size, shape and volume concentration affect the performance of these systems [11]. Fitted porous media in heat exchanger can intensify the turbulent fluid flow and as a result, heat transfer performance is improved [12].

Since it is a large nonlinear system, the performance prediction of shell-and-tube heat exchanger depends on the algorithms which can establish the relationship among the construction and heat transfer capability. The artificial neural networks has been used to predict the outlet temperature differences in each side of shell-and-tube heat exchanger [13] and the heat transfer rates [14]. The optimization of shell-and-tube heat exchanger is a multi-objective duty comprising enlarging heat transfer area, reducing pumping power and lowering manufacturing cost, etc. [15,16]. The harmony search algorithm [17], particle swarm optimization technique [18] and genetic algorithm were applied to solve the associated optimization problems [19]. High efficient algorithms are required in optimization to evaluate the heat exchangers performances, among which the Bell-Delaware method is often preferred [20]. As a widely used analytical method, the Bell-Delaware method [21] was employed to predict the heat and mass transfer performances in a shell-and-tube heat exchanger. Furthermore, the imperialist competitive algorithm was successfully applied for optimal design of shell and tube heat exchangers with higher accuracy in less computational time [22]. Another efficient technique to increase energy saving is to retrofit heat exchanger networks. Such intensification has been widely studied in the process industry in recent years from the point of view of individual heat exchangers [1].

As a dangerous pressure vessel, the shell-and-tube heat exchanger operating at a high pressure experiences challenges such as hard design, manufacture, installation and inspection procedures. Due to process requirements, the size of some heat exchanger exceeds the range covered by the mandatory design code, hence additional heat transfer and stress analysis is indispensable. Since it is a complex fluid and structure coupled system comprising tube sheet, tube, head, shell, flange, baffle and fluid, it is very difficult to accurately calculate the temperature, deformation and stress of shell-and-tube heat exchanger, especially for huge heat exchanger with large number of tubes. The finite element method and finite volume method are widely used to aid the research on shell-and-tube heat exchanger. Some commercial software, such as ANSYS and FLUENT, are frequently used to perform the investigations into the stress, flow and temperature fields in heat exchangers. On the base of the advanced model building and numerical analysis techniques, the two- or three-dimensional thermal, fluid and thermal stress coupled analysis can be conveniently realized [23]. The baffle spacing, baffle cut and shell diameter dependencies of the heat transfer coefficient and the pressure drop can be measured by numerically modeling the heat exchanger [24]. Furthermore, the geometric optimization can also be performed based on numerical model [25]. Compared with numerical analysis, it is much difficult to obtain analytical results [26]. Though the numerical simulation is currently the most accurate method to carry out the analysis of shell-and-tube heat exchanger, there exists an unavoidable trouble, i.e. the huge number of grids in modeling. Even if the structure is symmetric or periodic, the simulation is still time-consuming and difficult to be performed.

As the main heat transfer component, steel tube bundle plays the most important role in shell-and-tube heat exchanger. The arrangement of tubes in shell-and-tube heat exchanger is usually in the form of regular triangle or square layout, and the tube spacing interval is a constant. A review of recent investigation on tube bundles shows that tube spacing plays an important role in determination of compactness of the heat exchanger [27]. When the