International Communications in Heat and Mass Transfer 85 (2017) 62–69

Contents lists available at ScienceDirect

International Communications in Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ichmt

Configuration optimization of shell-and-tube heat exchangers with helical baffles using multi-objective genetic algorithm based on fluid-structure interaction

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ARTICLE INFO

Keywords:
Shell-and-tube heat exchangers with helical baffles
Fluid-structure interaction
Multi-objective genetic algorithm
Configuration optimization
Mechanical properties

ABSTRACT

The configuration parameters of helical angle and overlapped degree of shell-and-tube heat exchangers with helical baffles have been discussed for the thermal-structural comprehensive performance. Based on fluid-structure interaction theory, a method on configuration optimization of shell-and-tube heat exchangers with helical baffles is introduced using second-order polynomial regression response surface combined with Multi-objective Genetic Algorithm. The results show that the heat transfer coefficient per unit pressure drop of shell-and-tube heat exchangers with helical baffles increases firstly and then decreases with the increase of helical angle, and decreases with the increase of overlapped degree under certain shell-inlet velocity. And the performance of flow and heat transfer is more sensitive to helical angle compared with overlapped degree. The maximum shear stress increases with helical angle, but it is almost unaffected by overlapped degree for mechanical properties of helical baffles. The objectives of optimization are the heat transfer coefficient per unit pressure drop maximizing and maximum shear stress minimizing with scope of allowable stress, and three optimal structures are obtained. The optimal results indicate that the heat transfer coefficient per unit pressure drop increases averagely by 14.1%, the maximum shear stress decreases averagely by 4.1%, which provides theoretical guidance for industrial design of shell-and-tube heat exchangers with helical baffles.

1. Introduction

Shell-and-tube heat exchangers (STHXs) are robust construction, easy maintenance and reliable operation with a wide range of operation pressures and temperatures, which are widely used in oil refining, chemical industries, nuclear power plants and biopharmaceutical industries [1–3]. Baffles are important structural components in shell side, which have a significant influence on shell-side flow and heat transfer performance. The conventional shell-and-tube heat exchangers with segmental baffles (STHXsSB) are characterized by high pressure drop, flow dead zone, leakage flow in large quantities, easy fouling and flow induced vibration under high velocity [4–6]. In order to solve the problems above mentioned in STHXsSB, shell-and-tube heat exchangers with helical baffles (STHXsHB) were proposed by Lutcha and Nemcansky in 1990 [7] and realized industrialization by ABB in 1994. Four fan-shaped plain baffles form one helical pitch in shell side of STHXsHB to generate spiral flow, which decreases pressure drop and enhances heat transfer.

Many experimental or numerical investigations were performed to study the effects of baffle configuration on the performance in STHXsHB. Zhang et al. experimentally investigated four different helical angles of 20°, 30°, 40°and 50°when baffle overlapped degree was 0.5. The results showed the heat transfer coefficient per unit pressure drop of STHXsHB with helical angle of 40° was maximal [8]. Saeedan et al. used neural network to optimize helical angle and baffle pitch in order to improve the hydrothermal characteristics. The results indicated that the high baffle pitch and low helical angle were recommended when the importance of heat transfer and pressure drop was considered to be similar [9]. Bahiraei et al. optimized that not only helical angle and overlapped degree but also volume fraction of particles when nanofluid was applied to shell-and-tube heat exchangers with helical baffles [10–12]. Five heat exchangers with one helical angle of 40° and different baffle spaces were designed by numerical simulation, the results indicated that longer baffle spaces have higher heat transfer coefficient under the same working condition [13]. In order to optimize the configuration of helical baffles with the objective function in consideration both of transfer rate and total cost, an improved algorithm combing a kriging response surface and the

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http://dx.doi.org/10.1016/j.icheatmasstransfer.2017.04.016

Nomenclature

A	heat transfer area, m^2
b	regression coefficient
c_p	specific heat, J kg^{-1} K^{-1}
d	deformation, m
d_0	outer diameter of tubes, m
e	overlapped degree
$\{F\}$	load vector, N
h	heat transfer coefficient, W m^{-2} K^{-1}
$[K]$	stiffness matrix
k	turbulence pulsation kinetic-energy, m^2 s^{-2}
l_c	effective length of tubes, m
m	polynomial order
$\dot{m}$	mass flow rate, kg s^{-1}
$\mathbf{n}$	normal vector
P	pressure, Pa
q	heat flux, W m^{-2}
Q	heat transfer rate, W
T	temperature, K
T_m	logarithmic mean temperature difference, K
u_i	velocity in x, y, z direction, m s^{-1}
x	input variable
$\{x\}$	displacement, m
Δp	pressure drop in shell side, Pa
Y	output variable

Greek symbols

β	helical angle, °
δ	stress, MPa
ε	turbulent pulsating kinetic energy dissipation rate, kg $m^{-1}s^{-1}$
λ	thermal conductivity, W m^{-1} K^{-1}
μ	dynamic viscosity, Pa s
μ_{eff}	effective viscosity, Pa s
ρ	fluid density, kg m^{-3}
σ	principle stress, MPa
τ_{max}	maximum shear stress, MPa

Subscript

f, s	fluid, solid
1,2	inlet, outlet
0,i,j	polynomial power

multi-objective genetic algorithm (MOGA) was proposed [14]. Taguchi method was firstly used to quantitatively analyze the effect of the helical angle, the overlapped degree, tube diameter, tube layout and tube pitch on thermal-hydraulic characteristics [15]. Unfortunately, the configuration optimization of baffles is just confined to the shell-side flow and heat transfer and mechanical properties are ignored. However, in fact, due to the scour of high velocity and high temperature fluid, shell-and-tube heat exchangers are easily destructive, such as vibration damage and fatigue failure, especially for tube bundle.

Up to now, researchers have rarely studied the mechanical properties of shell-and-tube heat exchangers with helical baffles. In order to combine thermal-hydraulic performance and mechanical properties, fluid-structure interaction (FSI) theory is used, which usually solves the problem of interaction between fluid dynamics and solid mechanics. Fluid-structure intersection is mainly applied to, but not limited to, sedimentation, turbulence, aerodynamic, bio-fluid and bio-mechanics [16]. Stress distribution characteristics of pump impeller were analyzed under different flow rates and rotational speed using fluid-structure intersection, when pressure was transferred from CFD simulation to finite element method (FEM) [17]. Based on FSI, intersection between three-dimensional rods and cross flow was investigated to show flow induced vibration, and multiple cases with one rod and several rods were tested [18]. And heat transfer enhancement of elastic tube bundle heat exchangers by flow induced vibration was presented. The influence of tube-side flow velocity on natural frequency at different mode order was shown for conical spiral tube bundle [19]. The results of heat transfer coefficient, jf^{-1} factor, temperature and stress distribution were presented at different fin thicknesses and fin offsets for plate-fin heat exchangers by fluid-structure intersection and finite element method [20]. Many studies indicate that fluid-structure intersection can meet the demand of actual engineering design.

In this paper, the configuration optimum parameters (helical angle and overlapped degree) of shell-and-tube heat exchangers with helical baffles will be analyzed for thermal-hydraulic performance and mechanical properties based on fluid-structure interaction theory. And a method on configuration optimization of shell-and-tube heat exchangers with helical baffles will be introduced using second-order polynomial regression response surface combined with multi-objective genetic algorithm.

2. Calculation model and numerical method

2.1. Physical model and meshing

The shell-and-tube heat exchangers with helical baffles consist of the cylinder, the heat transfer tubes and baffles. The shell diameter of heat exchanger is 250 mm and is 2500 mm in length. There are 40 tubes with the diameter of 19 mm to form the tube bundle, which are arranged squarely with the tube pitch of 25 mm. Four fan-shaped plain baffles are spirally arranged as shown in Fig. 1, which have two main structural parameters, helical angle and overlapped degree. Hexahedral grids were used in tube side, while unstructured grids were used in shell side that was highly adaptable. To improve the accuracy of the calculation, grid independence was verified before the numerical simulation. Fig. 2 depicts the results of inspecting the grid independence test for the operating conditions (β = 27°, e = 0.5). It can be

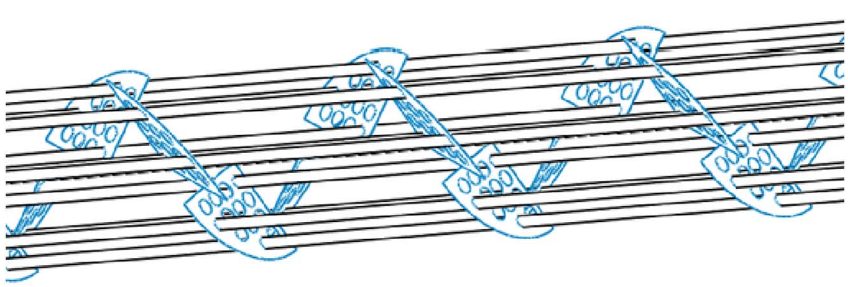

Fig. 1. Tube bundle of shell-and-tube heat exchangers with helical baffles.