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Multi-objective shape optimization of double pipe heat exchanger with inner corrugated tube using RSM method

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ABSTRACT

Integrated a fully developing three-dimensional heat transfer and flow model, a multi-objective optimization aims to fulfill the geometric design for double-tube heat exchangers with inner corrugated tube is investigated in this work with RSM. Dimensionless corrugation pitch (p/D), dimensionless corrugation height (H/D), dimensionless corrugation radius (r/D) and Reynolds number (Re) are considered as four design parameters. Considering the process parameters, the characteristic numbers involving heat transfer characteristic, resistance characteristic and overall heat transfer performance calculated by CFD, and are served as objective functions to the RSM (Nu_c, f_c, Nu_c/Nu_s, f_c/f_s and η in this paper). The results of optimal designs are a set of multiple optimum solutions, called 'Pareto optimal solutions'. It reveals the identical tendency of Nu_c/Nu_s and f_c/f_s reflecting the conflict between them that means augmenting the heat transfer performance with various design parameters in the optimal situation inevitably sacrificed the increase of flow resistance. According to the Pareto optimal curves, the optimum designing parameters of double pipe heat exchanger with inner corrugated tube under the constrains of $Nu_c/Nu_s \geq 1.2$ are found to be $P/D = 0.82$, $H/D = 0.22$, $r/D = 0.23$, $Re = 26{,}263$, corresponding to the maximum value of $\eta = 1.12$.

1. Introduction

Heat transfer enhancement technology in heat exchanger has been developed and widely applied in the past decade. The purpose of augmenting heat transfer is to accommodate higher heat flux with limited space. Currently, reducing the size and costs of heat exchangers is significant mission. Therefore, compact heat exchangers characterized by a large heat transfer area per unit volume have been proposed and gradually paid attention. The key technology of compact tubular heat exchanger is the development of tube types. A corrugated tube as shown in Fig. 1 is a typical high efficiency heat transfer enhancement element that could be widely used in the waste heat recovery systems in many industries, such as industrial power generation plants, chemical, petrochemical, and petroleum industries. The corrugated heat exchanger is frequently used in waste heat recovery systems to enhance the heat transfer performance by regenerating the boundary layer inside and outside of tubes [1]. The mutual promotion between the wave and the straight tube increases the heat transfer coefficient drastically [2,3]. This type of the corrugated tube has various structural parameters, such as corrugation pitch, corrugation height, corrugation tough radius, etc. The changes in the structural parameters of the corrugated tube and flow conditions in it affect the thermal performance achieved. The effects of the sizes and orientations of these specific structural features are closely related to the performance of the transfer process.

Several heat transfer enhancement techniques previously researched has been introduced to improve the overall heat transfer performance of double pipe heat exchangers resulting in the reduction of both the heat exchanger size and the cost of operation. They are, for example, the double pipe with louvered strip inserts [4], the finned double pipe [5–7], conjugated with metal foam filled double pipe [8,9], the double pipe exchanger with helical wires [10]. All the heat transfer enhancement technology mentioned above possesses several structural parameters could affect the thermal performance. In order to understand the effect of various parameters on heat transfer performance, several numerical and analytical methods have been reported to design the optimal tube configuration, such as, coil finned-tube [11], finned-

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Nomenclature

c_p	constant pressure specific heat capacity (J kg^{-1} K^{-1})
d	diameter of inner tube
D	hydraulic diameter (m)
f	fanning friction factor (−)
H	corrugation height (m)
k	turbulence kinetic energy (m^2 s^{-2})
N	number of variables
Nu	Nusselt number (−)
P	pressure (Pa)
Pr	Prandtl number(−)
p	corrugation pitch (m)
q	heat flux (W m^{-2})
R	corrugation crest radius (m)
Re	Reynolds number (−)
r	corrugation tough radius (m)
T	temperature (K)
u	velocity (m s^{-1})

Greek letters

α	convective heat transfer coefficient (W K^{-1} m^{-2})
λ	thermal conductivity (W m^{-1} K^{-1})
μ	dynamic viscosity (Kg m^{-1} s^{-1})
ρ	density (Kg m^{-3})
η	overall heat transfer coefficient
Φ	scalar quantities
τ	stress tensor (Pa)
ε	turbulence dissipation rate (m^3 s^{-2})

Superscripts

$'$	fluctuating component

Subscripts

c	corrugated tube
f	flow region
in	inlet/inside
i, j, k	direction of coordinate
o	outlet/outside
t	turbulence
s	smooth tube
w	tube wall

Abbreviations

ANOVA	Analysis of Variance
CCD	Central Composite Design
CFD	Computational Fluid Dynamics
DOE	Design of Experiments
RANS	Reynolds-Averaged Navier–Stokes
RSM	Response Surface Methodology

tube [12–14], rib [15], coiled wire inserts tube [16], U-tube [17], calandria tube [18]. The optimal design for double-pipe heat exchangers also has been studied recently [19–21]. Combined with the heat transfer enhancement technology, this paper applies suitable optimal design method to optimize a double pipe heat exchanger with inner corrugated tube.

The response surface methodology (RSM), firstly induced by Box and Wilson [22], is a method for creating a relatively accurate prediction of engineered system input–output relationships and optimizing the system being designed. It has been widely used in numerous manufacturing fields for optimization [23–26]. The RSM is an empirical modeling approach for determining the relationship between various process parameters and responses with the various desired criteria and searching the significance of these process parameters on the coupled responses. One of the advantages of the RSM over the conventional experimental methods, in addition to reducing the experimental cost, is that it minimizes the variability around the target when bringing the performance value to the target value. Another advantage is that optimal working conditions, determined from the simulation or laboratory study, can be reproduced in real applications.

Fig. 1. Practical sample of outward convex corrugated tube.

In the current study, in order to identify the quantitative estimation of the various designing parameters affecting the thermal performance of double pipe heat exchanger with inner corrugated tube, a systematical optimal design based on RSM has been developed. The corrugated tube is adopted as a numerical specimen because it is adequately applied in the heat recovery system of nuclear plant. Furthermore, the practical application in our researching work is based on heating the thermal energy of steam generated from APWR (Advanced Pressurized Water Reactor) of generation 3. In addition, the present study will apply the quadratic model of RSM associated the Central composite design (CCD) with four factors and three levels in order to establish an effective optimal procedure for optimizing the design parameters of double pipe heat exchanger with inner corrugated tube. The corresponding mathematical models were developed by regressive analysis and then tested by analysis of variance (ANOVA) to examine the accuracy. To achieve the high-thermal performance under the given design constraint, the predictive model for thermal performance characteristics will be created using RSM combined with Pareto optimal solutions. Our working purpose is to provide efficient and reliable foundation for the development and application of heat transfer exchangers.

2. Simulation detail and method

2.1. Geometry of outward transverse corrugated tubes

A schematic view of the transverse configuration of the double tube exchanger with inner tube investigated currently is shown in