Energy Conversion and Management 175 (2018) 86–98

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Experimental investigation on thermal performance and economic analysis of cosine wave tube structure in a shell and tube heat exchanger

Kamel Milani Shirvan, Mojtaba Mamourian*, Javad Abolfazli Esfahani

Department of Mechanical Engineering, Ferdowsi University of Mashhad, P.O.B. 91775–1111, Mashhad, Iran

A R T I C L E I N F O

Keywords:
Wavy tubes
Thermal performance factor
Shell and tube heat exchanger
Economic analysis

A B S T R A C T

A novel design of tube structure with cosine wave is proposed in this study to investigate effects of wavy surface characteristics on enhancement of heat transfer in a shell and tube heat exchanger, experimentally. All experiments have been designed and carried out on water/water loops. Response Surface Methodology is used to investigate the optimization procedure. Four effective parameters of wavy starting length ($0\,mm \le b \le 120\,mm$), hot water flow rates ($11\,l/min \le Q_c \le 19\,l/min$), cold water flow rates ($7\,l/min \le Q_h \le 11\,l/min$) and wavy wavelength ($0\,mm \le \lambda \le 80\,mm$) in five levels was selected to obtain the maximum thermal performance factor. The results showed that the thermal performance factor reduces by increasing of the hot water flow rate. The thermal performance factor of wave tubes is found to be larger than that of smooth tubs. Optimizing of the procedure indicated that to maximize the thermal performance factor, the lower values of wave starting length and hot water flow rate, and higher values of cold water flow rate and a wavelength of 33.13 mm, must be selected. Also results show that the corrugating process is useful from economic analysis point of view.

1. Introduction

Shell and tube heat exchangers are the most popular types of heat exchangers in industries, especially in petrochemical industry, oil and gas refinery, food industries and etc. [1,2]. This type of heat exchangers is usable for high temperature and high pressure conditions. The structure of the shell and tube heat exchangers is consisting of a number of tubes that are placed inside a cylinder; and the two fluids of cold and hot, exchange their heat through metal wall of the pipes without interacting directly. In other words, one of the two fluids flows inside the tubes, and the other enters around them within a shell. One of the characteristics of these types of heat exchangers is that the two fluids can be moved in two phases and in counter flow directions. The shell and tube heat exchangers have vast of advantages, such as high contact levels in low volume, good mechanical design and uniform distribution of pressure and easy cleaning procedure for tubes [3].

In recent years, a significant attention to the shell and tube heat exchangers has been observed and according to their importance and application in industries, many studies have been addressed by the scientific communities and academic researchers in this field. One of the most popular issues, which researchers in the field of heat exchangers are interested in is baffle. They presented numerical and experimental studies on baffle type and changed its structure or the space between baffles or shell to investigate their effects on heat transfer and flow characteristics, such as: Yang and liu [4] have designed and performed a numerical and experimental research on a novel shell-and-tube heat exchanger with new plate baffles. Their results showed that the novel design in plate baffle have higher performance than those with rod baffles. Maakoul et al. [5] have carried out a 3-D numerical simulation on low shell side flow rates conditions to evaluate effects of novel trefoil-hole, helical baffles and the conventional segmental baffles on the shell-side flow behavior, heat transfer characteristics and the pressure drop. The results showed that using of helical baffles and trefoil-hole baffles may be more effective than segmental baffles. The shell-side thermo-hydraulic characteristics have been studied in a shell and tube heat exchanger with trefoil-hole baffles experimentally by You et al. [6]. They have investigated their study in turbulent conditions and found correlations to achieve the Nusselt number and pressure loss. In their correlations, studied parameters were summarized base on the Reynolds number. Wang et al. [7] have done an experimental and numerical investigation to evaluate the flow characteristics and heat transfer performance within shell side of a shell and tube heat exchanger with fold baffles. They observed an enhancement in heat transfer performance. The heat transfer characteristics and the pressure drop in a small shell and tube heat exchanger with defining conditions are studied numerically by Ozden and Tari [8]. They investigated the

* Corresponding author.
E-mail address: mamourian@um.ac.ir (M. Mamourian).

https://doi.org/10.1016/j.enconman.2018.08.103
Received 7 June 2018; Received in revised form 29 August 2018; Accepted 30 August 2018
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Nomenclature

A	Area (m^2)
C_p	specific heat at constant pressure (J/kg K)
D_i	the tube inside diameter (m)
ΔP	pressure drop, Pa
f_t	the friction factor
h	convective heat transfer coefficient (W/m^2 K)
k	thermal conductivity (W/m K)
K	the coverage factor
L_{eff}	effective tube length
$\dot{m}$	mass flow rate (kg/s)
Nu	Nusselt number,
N_p	The number of the tube passes
N_t	The tube numbers
p	pressure (Pa)
Pr	Prandtl number,
Re	Reynolds number,
T	temperature (K)
TPF	The thermal performance factor
Re	Reynolds number,

Greek symbols

ρ	density (kg/m^3)
μ	dynamic viscosity (kg/m s)

Subscripts

c	cold
h	hot
i	inner
m	mean
s	shell side
t	tube side
o	outer
w	wall

effect of the baffle spacing to shell diameter ratio on the heat exchanger performance with changing the flow rate. Lei et al. [9] have investigated a numerical study to evaluated thermo-hydraulic performance of two novel shell and tube heat exchangers with louver baffles. They have also compared their results with a shell and tube heat exchanger with segmental baffles. They found that in their novel studied heat exchangers with louver baffles, the heat transfer coefficient per pressure drop is higher than exchangers with segmental baffles. Wen et al. [10] used a new design of shell and tube heat exchangers with ladder-type fold baffle to study the flow and heat transfer characteristics, numerically. They found that their modification leads to enhancement in flow and heat transfer characteristics. Yang et al. [11] carried out an experimental study to investigate the thermal performance in a combined serial two shell-pass shell-and-tube heat exchanger (CSTSP-STHX) with continuous helical baffles. They had a comparison between CSTSP-STHX with the double shell-pass shell-and-tube heat exchanger with segmental baffles (SG-STHX). They found that the CSTSP-STHX has better performance compared to SG-STHX. Wang et al. [12] have studied and optimized a shell and tube heat exchanger with staggered baffles. They found that from the heat transfer improvement point of view, the shell and tube heat exchanger with segmental baffles is not always the best option. Moreover, some other researchers such as Yang et al. [13] and Chen et al. [14] have carried out other studies in this field of heat exchangers.

Moreover, some researchers have presented some studies on thermo-economic and cost analysis in heat exchangers such as: Sadeghzadeh et al. [15] have done a numerical investigation to find techno-economically optimum condition in a shell-and-tube heat exchanger. They used Delaware method to estimate the heat transfer efficiency and the shell-side pressure drop. Yang et al. [16] have used a modified optimization method to present a theory for minimizing the function cost in shell and tube heat exchangers. They divided a shell-and-tube heat exchanger into several in-series heat exchangers. They found that their method can significantly decrease the total cost. A multi-objective optimization algorithm is used by Mirzaei et al. [17] to optimize simultaneously cost and effectiveness in a shell and tube heat exchanger. Their results showed an enhancement in thermal efficiency. Hadidi et al. [18] have used the imperialist competitive algorithm to minimize the total cost in shell and heat exchangers. Their results showed that the used algorithm has an effective benefit for designing a shell and tube heat exchanger with optimal design and it has higher accuracy in less computational time. Another optimization of shell and tube heat exchanger has been successfully done by DeVasconcelos Segundoa et al. [19] to minimize the total annual cost by Differential Evolution (DE) and a novel Differential Evolution variant, denominated Tsallis Differential Evolution (TDE). Some other researchers such as Yin et al. [20] and Hatami et al. [21] have survived in this field of heat exchangers.

Some other researchers surveyed on effect of tubes arrangements such as: The effects of tubes arrangements on the flow pattern in a shell and tube heat exchanger have been studied numerically by Labbadlia et al. [22]. They found that the studied parameters have an important effect on the flow pattern.

Some other studies are focused on novel methods such as injection of air flow, insert of twisted tapes or using new structure of tubes such as coiled tubes to increase heat transfer. For example: Ayub et al. [23] have carried out an experimental study to evaluate the thermal performance of a shell and tube heat exchanger with interstitial twisted tapes. They used the propylene glycol/water solution as a working fluid and compared their heat exchanger with a same sized shell and tube exchanger, but with single segmental baffles. They found that tube heat exchanger with interstitial twisted tapes has better thermal enhancement against the one with single segmental baffles. El-Said and Alsood [24] have done an experimental investigation to study the air injection effects on enhancement of the thermal performance within the shell side of the shell and tube heat exchangers. Their results showed that the thermal performance increases by injection of air flow. Dizaji et al. [25] have done an experimental study to investigate the influences of flow, thermodynamic and geometrical characteristics on exergy loss in shell and coiled tubes heat exchangers. Sadighi Dizaji et al. [26] have investigated a shell and tube with corrugated tube to analyze the exergy. They have used various arrangements of convex and concave corrugated tubes. Their results showed that, heat exchanger with corrugated tubes have more exergy loss and NTU than heat exchanger with smooth tubes. Sepehr et al. [27] have done a numerical study to investigate the heat transfer, pressure drop and entropy generation in shell and helically coiled tube heat exchangers. They found some correlations for estimating of the Nusselt number and friction factor in the shell side. Moreover, they studied about the thermal effectiveness, NTU and the entropy generation rate relations.

According to the literature review, it can be concluded that most of the researches have been done on baffles with less consideration on the tubes structure. Accordingly, the researchers decided to develop their research on the tubes structure. Therefore, the novelty of the present study lies on this fact that the structure of tube bundle in heat exchangers with cosine corrugated tubes is considered for first time. On the other hand, as much as the authors know, the thermal performance factor (TPF) on the tube side of the shell and tube heat exchanger with

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