To Study and Analysis on Heat Transfer Performance of a New Parallel-Flow Shell and Tube Heat Exchanger with Different Structure Using RSM Analysis

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Abstract: In this paper we have proposed and analyzed a new parallel-flow shell and tube heat exchanger with clamping plate baffles and sinusoidal wavy tapes. We have employed the response surface methodology (RSM) method to investigate the turbulent heat transfer performance of a new parallel-flow shell and tube heat exchanger with clamping plate baffle (CPB) and sinusoidal wavy tapes (STHX-CPBSWT). 25 CFD runs are adopted to study the effect of four parameters (tape pitch, tape amplitude, tape width and *Re*) on thermal-hydraulic performance based on central composite design of RSM. MATLAB 9.1 as a simulation tool has been used for implementing the equation and for the designing of STHX-CPBSWT system. The flow structures are shown and the heat transfer mechanism is revealed. The results show that the sinusoidal wavy tapes make the fluid flow in a wavy manner and induce many distinct longitudinal swirling vortexes than the conventional round rod baffle, CPB and equilateral triangle cross sectioned wire coil. The sinusoidal wavy tape can enhance heat transfer as effectively as the equilateral triangle cross sectioned wire coil does in turbulent regime. In the investigated range, the average *Nu*, *f* and *PEC* of STHX-CPBSWT are 2.2%, 25.2% and 0.5% larger than those of STHX-CPBETWC respectively

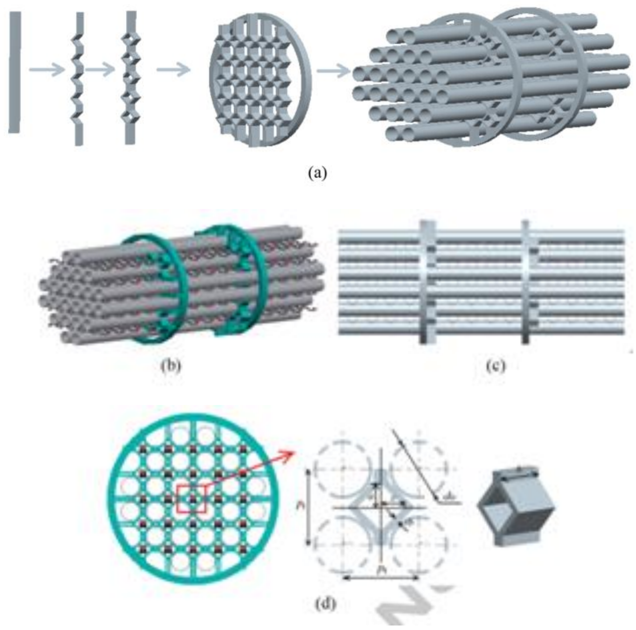
Keywords: *Parallel-Flow; Shell And Tube Heat Exchanger; Sinusoidal Wavy Tape; Heat Transfer; RSM*

I. INTRODUCTION

As far as the industry is concerned heat exchanger plays very important role. Comparing with the conventional cross-flow STHXs, parallel-flow STHXs are more promising because they can behave better in overall thermal-hydraulic performance and can prevent fouling more effectively and so on [4]. Due to above mentioned merits, many applications of parallel-flow STHXs can be found in newly built super-critical power plants, nuclear plants and solar heat power plants. For heat exchangers, the heat transfer enhancement technique is always attractive to researchers [5]. In the past a few decades, different heat transfer enhancement inserts used in the tube were invented such as coiled wires [6], twisted tapes [7], helical screw-tapes [8], vortex rods [9], conical strips [10], etc. Among these inserts, the coiled wires and twisted tapes are two attractive inserts to improve the convective heat transfer coefficient due to their broad source and low cost [11]. As the coiled wires are concerned, Promvonge [12] experimentally studied the thermal performance of a tube with square cross sectioned coiled wires, and compared the results with that obtained from circular cross sectioned wires. It was found that the coiled square wire provided higher heat transfer rate than the circular one under the same conditions. Gunes et al. [13] experimentally investigated the heat transfer and pressure drop of tube inserted with equilateral triangle cross sectioned coiled wires in turbulent flow regime using Taguchi method. It was found that the Nusselt number increased with the decrease of the coil pitch. Bovand et al. [14] numerically explored the forced convective heat transfer of Al2O3–water nanofluid over an equilateral triangular obstacle with three different orientations (side, vortex and diagonal facing flows). Results showed that the heat enhancement of the vortex facing flow orientation was better than that of the side facing flow orientation when the nanoparticles were not available. As the twisted tapes are concerned, different twisted tapes are proposed and learned, such as twin and triple twisted tapes [15], serrated twisted tapes [16], broken twisted tapes [17], delta-winglet twisted tapes [18] and short-length twisted tapes [19], etc. In most cases, the shell side flow of STHXs is working in turbulent regime. It is well recognized that the twisted tapes are not suitable for enhancing turbulent heat transfer. Wang and Sunden [20] compared the thermal and hydraulic performance between twisted tapes and coiled wire inserts. It was found that the coiled wire provided better overall enhancement than the twisted tapes. In addition, Keklikcioglu and Ozceyhan [21] suggested that the coiled wire should not be placed too close to the tube wall, as it may cause contamination over time and resulted in additional resistance to heat transfer. Wavy-shape configurations have been widely applied to heat exchangers [22-26]. They can produce secondary flow and vortexes in ducts such that greatly improve the heat transfer performance. Lin et al. [27] experimentally and numerically explored the laminar heat transfer characteristics of internally finned tube with sinusoidal wavy fin under uniform heat flux condition. Zhu et al. [28] numerically investigated a novel wavy-tape insert configuration for pipe heat transfer augmentation with *Re* ranging from 200 to 2200. The effects of tape amplitude and tape width on the thermal-hydraulic performance were learned. However, the effect of the tape pitch was not learned. Celik et al. [29] experimentally studied the heat transfer and pressure drop of a tabulated heat exchanger with corrugated tapes with *Re* ranging from 10000 to 17000 using Taguchi method and grey relational analysis. The effects of thickness, width and pitch of these tapes on the thermal-hydraulic performance were examined. It was found that the most strength parameter on average Nusselt number was *Re*, followed by the width, pitch and thickness and the most strength parameter on friction factor was the thickness, followed by the width, *Re* and the pitch. However, the effect of tape amplitude was not investigated. Considering the enormous time consumption and costs of experiments, it is necessary to adopt some experiment design methods based on statistics to save time and costs, such as uniform design, Taguchi method, and response surface methodology (RSM), etc. RSM is a collection of mathematical and statistical techniques, which can establish a mathematical model between independent variable and dependent variable. In the past a few years, RSM has been widely and successfully applied to the study of various heat exchangers. Khalajzadeh et al. [30] numerically explored the thermal-hydraulic performance of a vertical ground heat exchanger based on RSM. Han et al. [31] numerically studied the heat transfer characteristic, resistance characteristic and overall heat transfer performance for the corrugated tube using RSM. Seok-Jin Oh et al. [32] numerically predicted the performance of a single-phase parallel-flow heat exchanger with respect to selected design parameters over the design domain using RSM. For the parallel-flow STHXs, the baffles play the role of supporting the tube bundle on the one hand, on the other hand, they determined the thermal-hydraulic performance. In the past decades, different baffles used in parallel-flow STHXs are proposed and explored, such as rod baffle [33], small and large hole baffle [34], trefoil hole baffle [35], etc. Among these baffles, the clamping plate baffle (CPB) (see Fig.1) is wildly used in nuclear power station because it can provide a better anti-vibration effect on flow induced vibration [36]. Yu et al. numerically [37] studied the turbulent heat transfer of a parallel-flow shell and tube heat exchanger with CPB and equilateral triangle cross sectioned wire coil ETWC). It was found that the coil pitch and coil diameter have a significant effect on thermal-hydraulic performance while the baffle width has a trivial effect. In present study, a new parallel-flow STHX with CPB and sinusoidal wavy tapes (SWT) (STHX-CPBSWT) is proposed and illustrated. The effects of geometrical parameters such as tape amplitude, tape pitch, tape width, etc. on the thermal-hydraulic performance are numerically explored using RSM with flow in the turbulent regime. In addition, the thermal-hydraulic results of STHX with ETWC (STHX-CPBETWC) are also obtained using RSM to make a comparison. Finally, the heat transfer mechanism is revealed from flow structure and field synergy analysis [38].

II.SYSTEM STRUCTURE

For a STHX-CPBSWT with tubes in parallel layout, the sketch of the tube bundle is illustrated in Fig. 1 (a). As can be seen from this figure, for one baffle, it consists of CPBs and a rigid ring. The SWTs are placed between tubes to enhance the heat transfer as Fig. 1 (b) shows. The parameter definition of CPB and sinusoidal wavy tape is shown in Fig. 1 (d) and (e) respectively. In addition, Fig.1(c) illustrates the same tube bundle with ETWCs. The parameter definition of ETWC is shown in Fig. 1 (f).



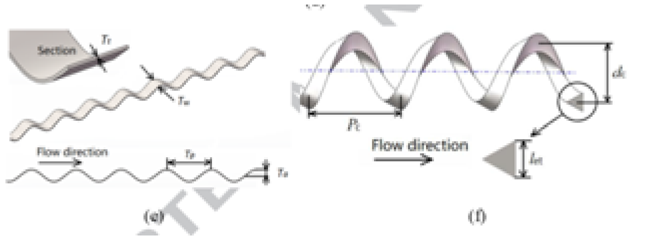


Fig.1. Sketch of STHX-CPBSWT and STHX-CPBETWC

III. RSM METHOD

The RSM is an empirical modeling approach for determining the relationship between input parameters and responses with the various desired criteria [41]. The quadratic polynomial model of RSM is used in this study. It can be expressed as follows:

$$Y = b_0 + \sum_{I=1}^{N}(b_I X_I) + \sum_{I=1}^{N-1}\sum_{J=I+1}^{N} b_{I,J} X_I X_J + \sum_{I=1}^{N}(b_{I,J} X_I^2) + \varepsilon$$

where Y is a response variable; XI and XJ are the factors or variables with which we wish to correlate and the symbols b0, bI, bI,J and bI,I are constants; N is the number of the factors or variables; and ε is the statistical error. In present paper, three objectives (*Nu*, *f* and *PEC*) are selected to study the turbulent heat transfer performances of STHX-CPBETWC. The *Nu* and *f* can reflect the heat and flow characteristics of the heat exchanger, while the *PEC* can evaluate the overall thermal-hydraulic performance. The *PEC* can be expressed as follows:

$$PEC = \frac{Nu}{(f)^{1/3}}$$

IV. RESULTS

It can be observed from the results that the *Nu*SWT/*Nu*RRB is in the range of 1.1638~1.8097; the *f*SWT/*f*RRB is in the range of 4.078~16.062; the *PEC*SWT/*PEC*RRB is in the range of .6593~0.7706. It can be seen from Table 6 that the *Nu*ETWC/*Nu*RRB is in the range of 1.1885~1.8254; the *f*ETWC/*f*RRB is in the range of 4.401~14.982; the *PEC*ETWC/*PEC*RRB is in the range of .6579~0.7783. This means that the heat transfer enhancement of STHX-CPBSWT and STHX-CPBETWC is better than that of the STHX-RRB. This is achieved with a large expense of pump power. As a result, the overall thermal-hydraulic performance of STHX-CPBSWT and STHX-CPBETWC is worse than that of the STHX-RRB.

In the investigated range, the average *Nu*SWT is 318.80, which is 2.2% larger than the average *Nu*ETWC. The average *f*SWT is 0.7014, which is 25.2% larger than the average *f*ETWC. The average *PEC*SWT is 363.97, which is 0.5% larger than the average *PEC*ETWC. This means that the SWT is as effectively as the wire coil in enhancing the turbulent heat transfer. It is worth noting that the raw shape of SWT is the same as the twisted tape. In turbulent heat transfer application, the SWT can be used to replace the ETWC.

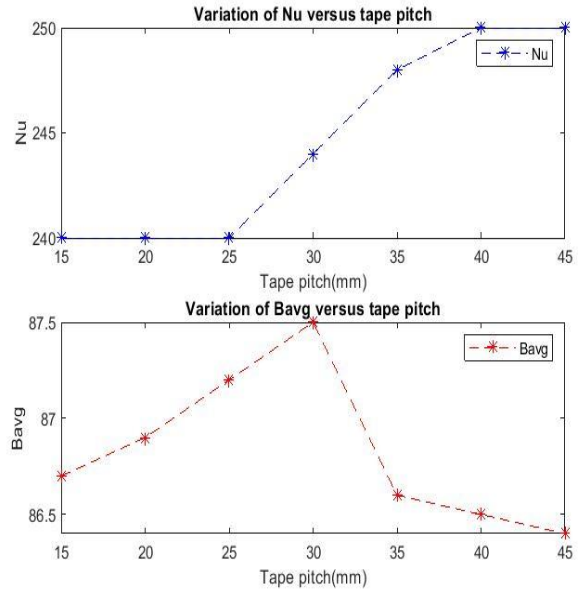


Figure 1.Variation of N_u and B_{avg} with tape pitch

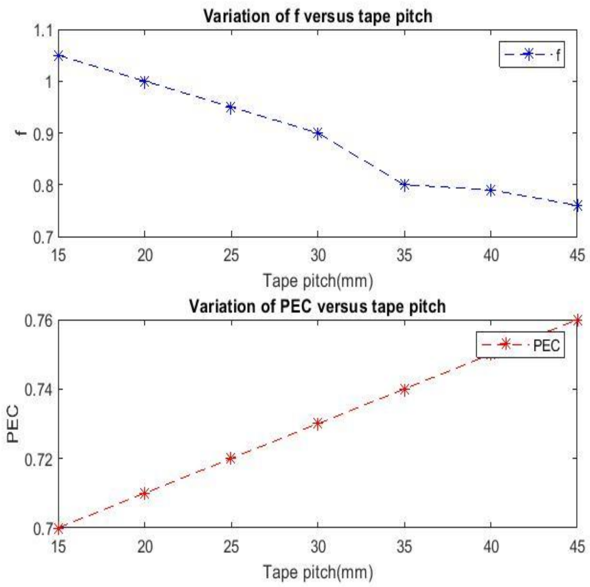


Figure 2 Variation of f and PEC with tape pitch

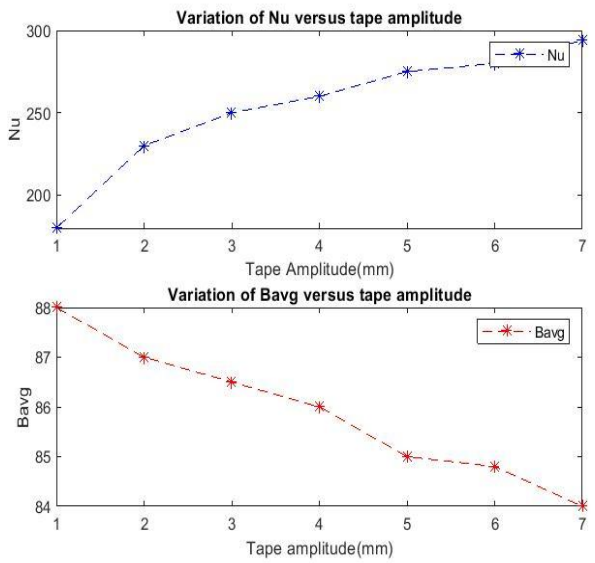


Figure 3 Variation of N_u and B_{avg} versus tape amplitude

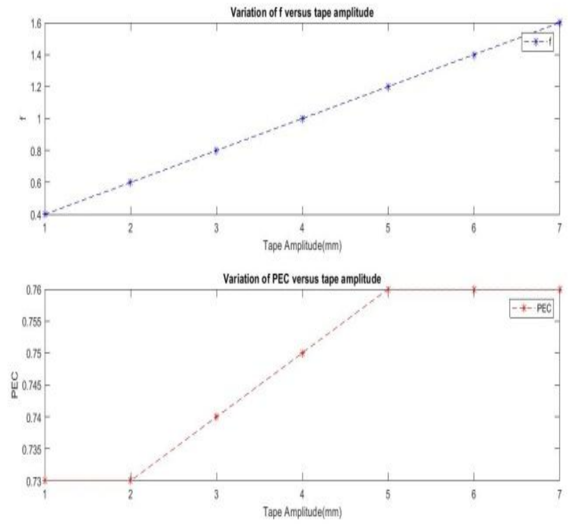


Figure 4 Variation of f and PEC versus tape amplitude

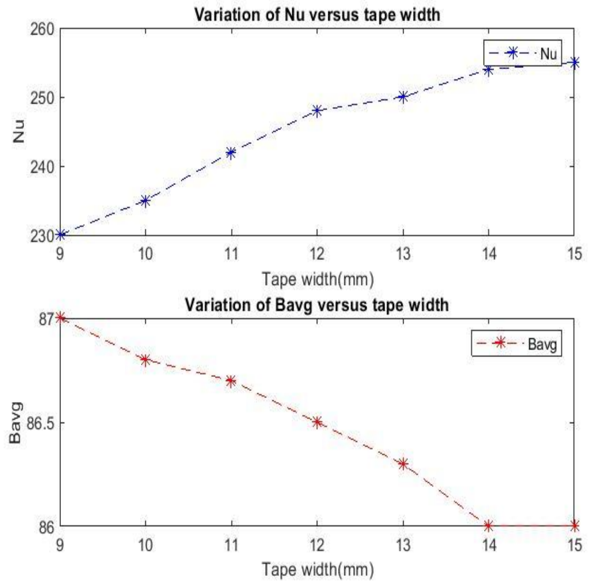


Figure 5: Variation of N_u and B_{avg} versus tape width

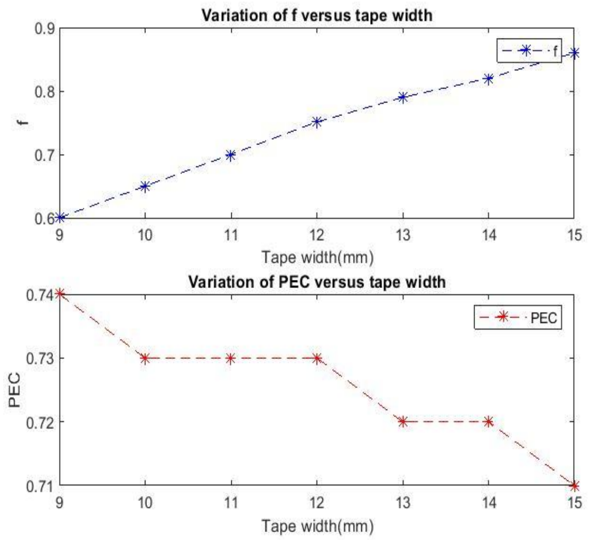


Figure 6: Variation of f and PEC versus tape width

CONCLUSION

Some main conclusions are drawn as follows: (1) In the investigated range, the *Nu*SWT/*Nu*RRB is in the range of 1.1638~1.8097; the *f*SWT/*f*RRB is in the range of 4.078~16.062; the *EC*SWT/*PEC*RRB is in the range of 0.6593~0.7706. The *Nu*ETWC/*Nu*RRB is in the range of 1.1885~1.8254; the *f*ETWC/*f*RRB is in the range of 4.401~14.982; the *PEC*ETWC/*PEC*RRB is in the range of 0.6579~0.7783. The average *Nu*, *f* and *PEC* of STHX-CPBSWT are 2.2%, 25.2% and 0.5% larger than those of STHX-CPBETWC respectively. This indicates that in turbulent heat transfer application, the SWT can be used to replace the ETWC.(2) It can be deemed that the heat transfer mechanism in STHX-CPBSWT is that the swirling vortexes generated by the sinusoidal wavy tape which thins the thickness of thermal boundary and enhances the heat transfer. It can be expected that the STHX-CPBSWT can behave better in preventing fouling than STHX-RRB because of the strong vortexes all over the fluid zone. (3) It is found that the *Nu*, *f*, and *PEC* of STHX-CPBSWT increase with the increase of tape amplitude and tape width; the *f* decreases with the increase of tape pitch; the *PEC* increases with the increase of tape pitch and tape width. However, the *Nu* of STHX-CPBSWT does not vary with the variation of tape pitch monotonically. It is found that there may exist an optimum tape pitch which can obtain the maximum of *Nu*.

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