Performance investigation on shell-and-tube heat exchangers with different baffles based on fluid-structure interaction

J. Xiao¹, J. Wang¹, G. Jian¹, S. Wang¹, J. Wen²
¹School of Chemical Engineering and Technology
Xi’an Jiaotong University, Xi’an 710049, China
²School of Energy and Power Engineering
Xi’an Jiaotong University, Xi’an 710049, China

SUMMARY
Thermo-hydraulic performance and mechanical properties were discussed using numerical simulation method for three kinds of shell-and-tube heat exchangers with segmental baffles, plain helical baffles and fold helical baffles based on thermal fluid-structure interaction. When the shell-side volume flow is $14m^3/h \sim 30m^3/h$, the shell-side pressure drop, overall heat transfer coefficient, $Nu_f^{1/3}$ and equivalent stress all go from highest to lowest under same shell-side volume flow rate in the following order: fold helical baffles, plain helical baffles and segmental baffles. In addition, the results of stress linearization at danger location in elastic stage show that membrane stress, and sum of primary stress and secondary stress are in range of corresponding stress intensity for all three kinds of STHxS. Hence, the comprehensive thermal-structural performance of shell-and-tube heat exchangers with fold helical baffles is best, which provide the theoretical guidance for design and choice of shell-and-tube heat exchangers with different baffles.

INTRODUCTION
Heat exchangers play an important role to heat mass transfer in a lot of engineering applications, for instance, petrochemical progress, electric power production, food industry, environmental protection, waste heat recovery, refrigeration and so on. What’s more, shell-and-tube heat exchangers (STHXs) hold the dominant position with more than 35%~40% of heat exchangers in the world [Huminic 2012; Master et al. 2007; Bhatta et al. 2012]. STHXs have many advantages: simple manufacturing, robust construction and adaptability operation conditions. Baffles are used to support heat transfer tubes and control shell-side flow distribution, which have a significant effect on heat transfer enhancement and thermal-hydraulic performance of heat exchangers.

The shell-and-tube heat exchangers with segmental baffles (STHxSB) are typical in conventional STHXs, which has been standard production in designing institutes and industries. STHxSB are characterized by high pressure drop, flow dead zone, leakage flow in large quantities, easy fouling and flow induced vibration under high velocity, etc [Gawande et al. 2011; Maakoul et al. 2016; Movassag et al. 2013], which have disadvantages on flow and thermal performance of heat exchangers. Hence, many researchers had put forward to improving measures based on segmental baffles [Wang et al. 2004; Singh et al. 2013]. In addition, a new type of shell-and-tube heat exchangers with helical baffles (STHEsHB) was proposed to overcome the shortcomings of STHxSB.

STHXsHB were proposed by Lutcha and Nemcansky (1990) and realized industrialization by ABB Lummus in 1994. At present, STHxSB are mainly discontinuous helical baffles with four fan-shaped plain baffles form one helical pitch due to the manufacture of continuous helical baffles is difficult. STHXsSB have plenty of advantages, such as: enhancing shell-side heat transfer; decreasing pressure drop; reducing shell-side fouling, prolonging the running time and avoiding flow-induced vibration [STEHLÍK et al. 1994; Master et al. 2004; Wang et al. 2010]. As a consequence, STHXsHB are most possibly considered to replace STHxSB, hence, researchers had investigated the influence factors of performance and compared with STHxSB [Zhang et al. 2013; Gao et al. 2015; Taher et al. 2012]. However, discontinuous STHXsHB have the triangle leakage zones between two adjacent baffles that decreases radial flow rate and reduces the flow and heat transfer performance.

In order to solve the problem of triangle leakage zones, there are many useful methods to block. Wang et al. (2014) proposed a new type of shell-and-tube heat exchangers with fold helical baffles and Wen et al. (2015) proposed a novel type of shell-and-tube heat exchangers with ladder-type fold baffles. However, it is a pity that the flow and heat transfer performance is just concerned and mechanical properties are neglected when improving performance of heat exchangers. Therefore, it is not certain that mechanical properties satisfy the requirement of design and manufacture when thermal-hydraulic performance is best, due to fluid-induced vibration and fatigue failure in shell-and-tube heat exchangers.

Up to now, researchers have rarely meanwhile studied the thermal-hydraulic performance and mechanical properties of shell-and-tube heat exchangers. In this paper, three kinds of heat exchangers of shell-and-tube heat-exchangers with segmental baffles, plain helical baffles and fold helical baffles will be compared in terms of thermal-structural performance combing computational fluid dynamic (CFD) and finite element method (FEM) based on fluid-structure interaction (FSI) theory. Fluid-structure interaction is mainly applied to, but not limited to, sedimentation, turbulence, aerodynamic, bio-fluid and bio-mechanics, and the application of FSI in existing literatures can prove FSI meet the demand of actual engineering design [Hou et al. 2012; Hu et al. 2013; Simonneau et al. 2011; Yan et al. 2010]. The shell-side pressure drop, shell-side heat transfer coefficient and $Nu_f^{1/3}$ will be presented for thermal-hydraulic performance, and the stress classification and equivalent stress linearization will be performed to discuss the result of stress distribution of tube bundle.
METHODS

The geometry construction of STHXs with plain helical baffles, fold helical baffles and segmental baffles are shown in Figure 1. The shell diameter of STHXs is 250 mm and tube bundle is 1250 mm in length. There are 40 tubes with the diameter of 19 mm, which are arranged squarely with the tube pitch of 25 mm. Besides, 12 spacer tubes are set to fix baffles and increase flow disturbance in the shell side. The thickness, helical angle and overlapped degree of shell-and-tube heat exchanger with helical baffles are respectively 6 mm, 18° and 50%.

Figure 1. Tube bundle of STHEs with different baffles

Using indirect bundle temperature form fluid dynamics to solid dynamics for mechanical analysis. Due to the temperature gradient, external constraints or internal deformation compatibility requirements, the additional stress, namely thermal stresses, is generated. Solving the thermal stress according to thermoelastic theory, it needs to satisfy basic hypothesis, such as material uniformity, continuity, completely elasticity, isotropy and small deformation. Hence, governing equations mainly include fluid dynamics equations and solid mechanics equations.

As the physical model depicted before, there are three domains in shell-and-tube heat exchanger, two fluid domains (heat-conducting oil in shell side and water in tube side) and the solid domain (tube bundle). Hexahedral grids were used in the tube side while unstructured grids were used in the shell side and solid domain. To improve the accuracy of the calculation, adaptive grid technique was used and grid independence was verified. Figure 2 presents the local grid of STHXs with fold helical baffle and Table 1 shows the detailed data of grids.

The RNG k-ε model is adopted in the simulation. The boundary conditions of tube-shell side inlet and outlet were set as velocity inlet and pressure outlet, respectively. The shell-inlet temperature was 337.15 K. The tube-inlet velocity was 1.18 m s⁻¹ and temperature was 303.15 K. Non-slip, impermeable and adiabatic boundary conditions were adopted on the wall except fluid-solid interface with coupled wall. Pressure-Velocity coupling algorithm was SIMPLE and second-order upwind scheme was adopted for solving the mass, momentum, energy and turbulent kinetic energy equation. The convergence criterion was that the normalized residuals are less than 1 × 10⁻⁶ for all equations. In the solid domain, material was structural steel. Density is 7854 kg m⁻³, heat conductivity is 60.5 W m⁻¹ K⁻¹, specific heat capacity is 434 J kg⁻¹ K⁻¹ and the allowable stress is 147 MPa when temperature is in the range of 30°C–70°C.

Figure 2. Local grid of heat exchanger with fold baffle

Table 1. Mesh details and metrics

<table>
<thead>
<tr>
<th>Baffles type</th>
<th>Elements</th>
<th>Average skewness</th>
<th>Average element quality</th>
<th>Average orthogonal quality</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plain</td>
<td>25128983</td>
<td>0.23577</td>
<td>0.83009</td>
<td>0.85112</td>
</tr>
<tr>
<td>Fold</td>
<td>19895942</td>
<td>0.24684</td>
<td>0.82391</td>
<td>0.84575</td>
</tr>
<tr>
<td>Segmental</td>
<td>26227443</td>
<td>0.22724</td>
<td>0.83748</td>
<td>0.85654</td>
</tr>
</tbody>
</table>

The numerical results compared with the experimental data for the shell-and-tube heat exchangers with plain helical baffles where helical angle was 18° and the overlap was 50% from the reference [Chen et al. 2015], as shown in Figure 3. The figure shows that simulated and experimental values agreed well. The maximum relative error of pressure drop in inlet and outlet was less than 15% with an average value of 14.7%. Hence, it can be concluded that the numerical method is reliable. At the same time, the numerical pressure drop was less than the experimental values. The deviations may attribute to some simplification made in the physical model and some un-avoidable measurement error.
RESULTS
Flow performance
Due to the different structural forms of baffles, the shell side streamline differed apparently. As shown in Figure 4, the streamlines of the three types of heat exchangers are plotted. By comparison, it is found that in STHXs with helical baffles, fluid flows in an obvious spiral way. And STHXs with fold helical baffles can make fluid flow spirally and more easily, since that flowing is better in designed helical channel. In addition, in STHXs with fold helical baffles, streamlines in the center along the axis of the shell are denser than that in STHEs with plain helical baffles, as well as higher mass flow rate and velocity. The reason is that fold helical baffles effectively plug the triangle leakage zone between baffles and shell. However, due to the zigzag flow pattern, STHXs with segmental baffles have obvious dead zones, which result in high pressure drop and low heat transfer efficiency. Figure 5 shows the shell side pressure drop in three kinds of heat exchangers. It is found that total pressure drop in STHXs with fold helical baffles is the maximum, while shell-side pressure drop in STHXs with segmental baffles is the minimum.

Heat transfer performance
Figure 6 shows the temperature distribution of tube bundle in the three types of heat exchangers when the shell-side volume rate is 14m$^3$·h$^{-1}$. As can be seen in Figure 6, the temperature of baffle, located at the entrance in the shell side, is almost as high as the heat-conducting oil temperature. The temperature of spacer tubes and tubes is distributed uniformly, and the temperature of spacer tubes is higher because cooling water does not pass through spacer tubes. However, the conjunction of baffles and tubes has a large temperature gradient, because the baffles, located in the shell side, on the one hand, baffles have heat convection with shell-side flow, and baffles have conduction with tubes on the other hand, which causes the temperature of baffles is between temperature of heat-conducting oil and water. What's more, the temperature near spacer tubes is higher than the temperature near the tubes. In the shell-and-tube heat exchangers, external constrain will cause thermal stress when temperature is uneven.

The effect of volume flow rate on the heat transfer coefficient is shown in Figure 7. As depicted in Figure 7, with the volume flow rate increasing, the heat transfer is also enhanced. When the volume flow rate is same, the heat transfer coefficient of STHXs with fold helical baffles is higher than two other types of heat exchanger, and heat transfer coefficient of STHXs with segmental baffles is the minimal. When the volume flow rate increases from 14m$^3$·h$^{-1}$ to 30m$^3$·h$^{-1}$, the heat transfer of coefficient STHXs with fold helical baffles increases 14.7%~17.3% compared to that of STHXs with plain helical baffles, while compared to that of STHXs with segmental baffles, the heat transfer coefficient of STHXs with fold helical baffles enhanced 20.3%~27.8%. In STHXs with helical baffles, flowing is spiral and has no dead zones, therefore the heat transfer coefficient is higher than
STHXs with segmental baffles, and fold helical baffles effectively plug the leakage zone between baffles and shell so that the flow velocity in the center increases and the heat transfer is enhanced.

**Comprehensive performance**

In fact, there are many comprehensive performance evaluation indexes of heat transfer enhancement in heat exchangers. Considering the heat transfer coefficient and resistance coefficient are not the same order of magnitude, and the effect of pressure drop on economic losses and energy consumption is only small part, therefore $Nu^{-1/3}$ is selected to evaluate comprehensive performance of three types of heat exchangers. The effect of volume flow rate on the $Nu^{-1/3}$ is shown in Figure 8. At the same volume flow rate, the PEC number of STHXs with fold helical baffles is the maximal, while that of STHXs with segmental baffle is the minimal. When the volume flow rate increases from $14 m^3/h$ to $30 m^3/h$, the $Nu^{-1/3}$ of STHXs with fold helical baffles increases 9.7%~10.2% compared to that of STHXs with plain helical baffles, and it enhances 107.2%~110.6% compared with STHXs with segmental baffles.

**Mechanical properties**

Figure 9 shows the equivalent stress of three types of heat exchangers when the volume flow rate is $14 m^3/h$. As depicted, the equivalent stress of spacer tubes is maximal, and at the contact position of baffles and tubes, the equivalent stress is larger than other parts of baffles, since high temperature space tubes, large temperature gradient and local stress concentration caused by discontinuous construction. The maximum of equivalent stress of STHXs with fold helical baffles is 109.07 MPa, that of STHXs with plain helical baffles is 105.56 MPa, and that of STHXs with segmental baffles is 105.45 MPa. Due to the STHXs with fold helical baffles has the best heat transfer performance, large temperature difference resulted to large corresponding thermal stress. The effect of volume flow rate on the equivalent stress is presented in Figure 10. It is noted that the maximum equivalent stress is smaller than the yield strength of the material that is 250 MPa, which indicates the tube bundle are still in elastic range.
to primary stress plus secondary stress. Figure 12 shows the results of equivalent stress linearization at same stress evaluation path. It noted that the membrane stress of STHXs with fold helical baffles is maximal, while that of STHXs with plain helical baffles is minimal. The sum of primary stress and secondary stress along the thickness direction from interior node1 to exterior node 2 decreases first and then increases. What’s more, the maximum is at exterior node 2, and the minimum is near the middle face. The result of stress evaluation is represented in Table 2. As shown, the design satisfies the strength requirement.

![Figure 11. Stress evaluation path](image1)

![Figure 12. Results of stress linearization at same path](image2)

<table>
<thead>
<tr>
<th>Heat exchanger</th>
<th>$P_l$/Mpa</th>
<th>Max $P_l+P_b+Q$/Mpa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plain</td>
<td>44.782</td>
<td>56.862</td>
</tr>
<tr>
<td>Fold</td>
<td>41.927</td>
<td>52.134</td>
</tr>
<tr>
<td>Segmental</td>
<td>42.128</td>
<td>45.745</td>
</tr>
<tr>
<td>Criterions</td>
<td>$P_l\leq1.5S_m=220.5$</td>
<td>$P_l+P_b+Q\leq3S_m=441$</td>
</tr>
</tbody>
</table>

**Conclusions**

Based on thermal fluid-structure interaction, the thermal-hydraulic performance and mechanical properties were discussed among shell-and-tube heat exchangers with plain helical baffles, fold helical baffles and segmental baffles. The research results can provide theoretical guidance of design, manufacture and processing.

1. Through the comparison of flow performance, it can be found that flowing is zigzag in STHXs with segmental baffles, while in STHXs with helical baffles, fluid flows spirally. And STHXs with fold helical baffles can conduct spiral flowing more easily. When the volume flow rate is in the range of $14m^3\cdot h^{-1}-30m^3\cdot h^{-1}$, pressure drop in STHXs with fold baffles is the maximal, while pressure drop in the segmental baffle heat exchanger is the minimal.

2. Through the comparison of heat transfer performance, it can be seen that when the volume flow rate increases from $14m^3\cdot h^{-1}$ to $30m^3\cdot h^{-1}$, the heat transfer coefficient of STHXs with fold helical baffles enhanced 14.7% ~ 17.3% and 20.3% to 27.8% respectively compared to that of STHXs with plain helical baffles and STHXs with segmental baffles. In addition, The PEC number of STHXs with fold helical baffles is increases 9.7% ~ 10.2% and 107.2% ~ 110.6% respectively, compared to that of STHXs with plain helical baffles and STHXs with segmental baffles.

3. Using stress classification and equivalent stress linearization method, equivalent stress is large at the contacting positing of baffles and spacer tubes, and the maximum equivalent stress of STHXs with fold baffles is maximal at the same conditions, but stress satisfies strength requirement. Therefore, the thermal-structural performance of STHXs with fold helical baffles is best.
Based on the thermal fluid-structure interaction theory, heat transfer performance and mechanical properties can be efficiently compared, which provide a guidance to select heat exchangers with superior thermal-structural performance.

ACKNOWLEDGEMENT
This work is supported by the National Natural Science Foundation of China (No. 51676146)

REFERENCES


