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Numerical studies on combined parallel multiple shell-pass shell-and-tube heat exchangers with continuous helical baffles

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A combined parallel multiple shell-pass shell-and-tube heat exchanger with continuous helical baffles (CPMP-STHX) is developed to improve heat transfer performance of shell-and-tube heat exchangers (STHXs). The CPMP-STHX is compared with the conventional STHX with segmental baffles (SG-STHX) by Computational Fluid Dynamics method. The numerical results indicate that, for the same mass flow rate in the shell side, the heat transfer coefficient, the overall pressure drop, and heat transfer coefficient per pressure drop of the CPMP-STHX are 17.8 %, 13 % and 13.2 % higher than those of the SG-STHX, respectively. For the same overall pressure drop in the shell-side, the heat transfer coefficient of the CPMP-STHX has 20% increases than that of the SG-STHX. Based on these results, it can be concluded that the CPMP-STHX might be used to replace the conventional STHX with segmental baffles in industrial applications.

1. Introduction

Shell-and-tube heat exchangers are widely used in oil refining, chemical engineering, environmental protection, electric power generation and refrigeration, etc (Gulyani, 2000). In order to further enhance heat transfer between the shell-side and tube-side fluids, baffles are set up in the shell pass. In addition, the baffles can provide supports for the tube bundles. However, the most commonly used segmental baffles have many disadvantages, such as high pressure drop, low shell-side mass flow velocity, low heat transfer efficiency, short operation time and so on (Master et al.,2006). The idea of shell-and-tube heat exchangers with helical baffles is firstly proposed by Colston (1925), and has been developed by other researches. Many investigators have carried out experimental researches on these helical baffles (Stehlik et al., 2002). In addition, the effectiveness of heat exchangers with helical baffles is proven on test units in industry applications (Kral et al., 1996). Helical baffled heat exchangers, which are

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commercially produced by ABB Lummus (2004), are now accepted by their outstanding advantages. In the past two years, Wang et al. (2009, 2010) have invented two combined multiple shell-pass shell-and-tube heat exchangers with continuous helical baffles. The main improvements of these STHXs are as follows: there are two or more shell passes in the shell side of STHXs, where the outer shell-passes are set up with continuous helical baffles and the inner shell-pass can be equipped with other kinds of baffles, such as segmental baffles, discontinuous helical baffles, disk-doughnut baffles, rod baffles and so on, which could be manufactured and installed easily. If the working fluid flows through the inner and outer shell-passes simultaneously, the STHX is called combined parallel multiple shell-pass helical baffled STHX(CPMP-STHX), and if the working fluid flows through the inner and outer shell passes sequencely, the STHX is called combined series multiple shell-pass STHX with helical baffles (CSMP-STHX). As to each individual shell-pass, the flow area is reduced, the velocity of the fluid is increased and the heat transfer performance can be improved. In addition, the continuous helical baffles can reduce the pressure drop and mitigate fouling in the shell side. In this study, the combined parallel multiple shell-pass STHXs with continuous helical baffles (CPMP-STHX) and a conventional STHX with segmental baffles (SG-STHX) are proposed. Computational Fluid Dynamics (CFD) commercial software FLUENT was used to study the flow and heat transfer characteristics in the shell side.

2. Models of shell-and-tube heat exchangers

2.1 Physical models

The physical model of the studied CPMP-STHX is presented in Figure 1(a). It has two shell passes in the shell side, the inner shell-pass and the outer shell-pass, the inner shell-pass and the outer shell-pass are separated by a central tube. The inner shell-pass is set with segmental baffles and the outer shell-pass is constructed by completely continuous helical baffles. The inner shell-pass and the outer shell-pass have the same inlet and outlet on both ends of the shell side. There are five continuous helical baffled sections in the outer shell-pass and five segmental baffled sections with 50% cutoff window in the inner shell-pass. In the SG-STHX, there are five segmental baffled sections with 25% cut off window in the shell pass.T he material of the heat exchange tubes and baffles is aluminium, which has a density ρ= 2719kg/m^3, thermal conductivity λ= 202.4 W/ (m K), specific heat c_p =871J/ (kg K). The working fluid is water. Its thermal properties depend on the temperature. Detailed geometrical parameters of the computation models can be observed in Figure 1.

2.2 Boundary conditions and numerical methods

The main focus of the present study is the flow and heat transfer performance in the shell-side of STHXs. Following assumptions are acceptable: (i) The flow and heat transfer is steady and turbulent; (ii) The working fluid is incompressible; (iii)·The thermal-physical properties of the working fluid are considered as temperature dependent; (iv) The thickness of baffles is neglect.

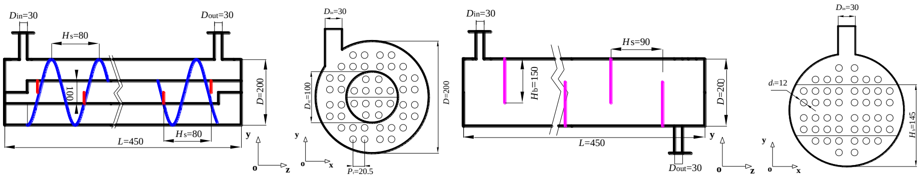
The boundary conditions are described as follows:

(1)The shell side inlet: velocity inlet, u=w=0, v=const, T_{in}=300 K (27 °C) (uniform inlet temperature), inlet turbulence intensity, I=1 %.

(2)The shell side outlet: outflow outlet, $\frac{\partial u}{\partial n}=\frac{\partial v}{\partial n}=\frac{\partial w}{\partial n}=0$, $\frac{\partial T}{\partial n}=0$, $\frac{\partial k}{\partial n}=0$, $\frac{\partial \varepsilon}{\partial n}=0$.

(3)The heat exchange tube wall surfaces: non-slip boundary, u=v=w=0, T_{w} =373K (100℃) (hot tube walls).

(4)Other wall surfaces: non-slip boundary, u=v=w=0, $\frac{\partial T}{\partial n}=0$.



(a) *(b)*

Figure1: Geometrical parameters the STHXs. (a)CPMP-STHX; (b)SG-STHX (unit:mm)

The computational domains are meshed with unstructured Tet/Hybrid grids, which are generated by the commercial code GAMBIT and the cell number is about 9.8×10^{6}. The computational process is carried out using FLUENT (2003) a commercial Computational Fluid Dynamics (CFD) code which is based on the finite volume method. The governing equations were iteratively solved by using SIMPLE pressure–velocity coupled algorithm. This numerical approach stores scalar variables at the centre of the control volume. The face values of scalar variables are also required for the convection terms and their values are gained from interpolation. The QUICK scheme with Second Order Upwind precision is used for the numerical simulation. All computations are performed on a service park with 16GB RAM and Intel® Xeon(R) 2.66GHz CPU. Each simulation took approximately 48-50 CPU h to converge.

2.3 Validation of model

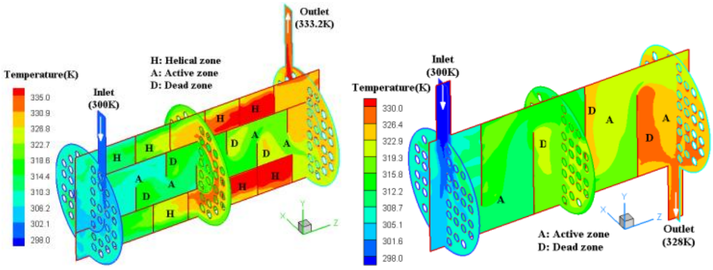
The Bell-Delaware design method (Bell, 1988) was used to calculate the heat transfer coefficient h in the shell side of the STHX with segmental baffles. It is found that the biggest difference is less than 10% and average deviation of the heat transfer coefficient between present results and Bell-Delaware design results is about 7.8%. It is acceptable in numerical simulation, so it can be concluded that the present model can give a close prediction.

3. Results and discussion

3.1 Temperature and velocity fields

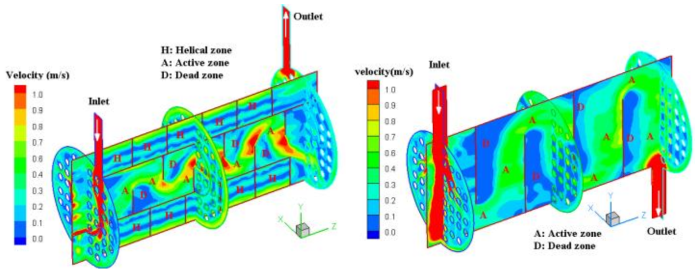
The temperature distributions for the combined parallel multiple shell-pass STHX with continuous helical baffles and the single shell-pass segmental baffled STHX are shown in Figure 2. From Figure 2, the difference of the temperature in close helical zones is every small. Because the continuous helical baffles and more heat exchange tubes located in the outer shell-pass, the working fluid has 35 ℃ increase in the outer shell-pass and 18 ℃ increase in the inner shell-pass. From this point, the inner shell-pass has relatively poor performance on heat transfer than the outer shell-pass. As to the inner shell-pass, disadvantages of segmental baffles cannot be erased completely in this

CPMP-STHX. There are “Dead zones” (marked by “D”) in the inner shell-pass. Dead zones have lower local heat transfer coefficient, because it cannot exchange heat with the “Activity zones” (marked by “A”) freely. The same reason results in temperatures in these “Dead zones” are higher than the activity regions nearby.



(a) (b)

Figure 2: Temperature distribution on different sections. (a)CPMP-STHX; (b)SG-STHX



(a) (b)

Figure 3: Velocity distribution on different sections. (a) CPMP-STHX; (b)SG-S

Take the advantages of continuous helical baffles into consideration; it is valuable to separate the shell side into two different shell-passes. The existence of inner shell-pass increases the scale of the inner helix and simplifies the manufacturing of continuous helical baffles. It also makes use of the space in the central pole, which is used to form the inner helix in the single shell pass STHX with continuous helical baffles. Segmental baffle is still a better choice for the inner shell-pass, because it can be manufactured and installed easily in a relatively small space. It can be seen from Figure 3, the velocity field in the “Helical zones” (marked by “H”) nearly have no back flow regions existed in the outer shell-pass. On the one hand, helical flow increases the heat transfer by rush the heat exchange tubes with an inclination angle. On the other hand, it avoids abrupt turns of the flow, so it can reduce pressure drop in the shell side. In the inner shell-pass, the fluid flows cross the heat exchange tubes and rushes toward the shell and baffles in a tortuous, zigzag manner. Back flow regions formed at the place where the baffles are attached to the shell wall.

3.2 Heat transfer and pressure drop characteristics

Figure 4 shows the heat transfer performance of the two STHXs. It can be found that the overall heat transfer rates Q were linear with the mass flow rate m in both STHXs. The maximum deviation of the overall heat transfer rate Q between these two STHXs was 17.8%. From the this point, it can be concluded that the CPMP-STHX had better heat transfer performance than that of the STHX with segmental baffles for the same mass flow rate *m* in the computation models. Variation of the overall pressure drop △*p* versus mass flow rate *m* in the shell side is shown in Figure 5. As shown in Figure .5, the overall pressure drop △*p* increases with the increase of the mass flow rate *m* in both STHXs. The overall pressure drop △*p* in the CPMP-STHX is bigger than that of the segmental baffled STHX for the same mass flow rate. The overall pressure drop △*p* of the CPMP-STHX is about 13% higher than that of the STHX with segmental baffles for the same mass flow rate *m* .From this point, we can predicate that the CPMP-STHX has worse pressure drop performance than that of the STHX with segmental baffles. The heat transfer coefficient *h* and pressure drop △*p* cannot be used independently to evaluate the performance of STHXs. In this paper, the heat transfer coefficient per pressure drop *h*/△*p* is introduced to evaluate the comprehensive performance of the STHXs. As can be seen from Figure 6, the *h/*△*p* of the CPMP-STHX is 13.2% higher than that of STHX with segmental baffles. The variation of the heat transfer coefficient *h* with the overall pressure drop △*p* is shown in Figure 7. The results indicate that in the low overall pressure drop region, the heat transfer rate *h* has a fast increasing with the increase of overall pressure drop, while in the high pressure drop region, this increase becomes smaller. For the same overall pressure drop, the difference of the heat transfer coefficient for the STHXs is very small in the low pressure drop region. However, in the high pressure drop region, the heat transfer coefficient *h* in the CPMP-STHX is obviously higher than that in STHX with segmental baffles at the same overall pressure drop △*p*. The heat transfer coefficient *h* in the CPMP-STHX is about 20% higher on average than that of the STHX with segmental baffles.

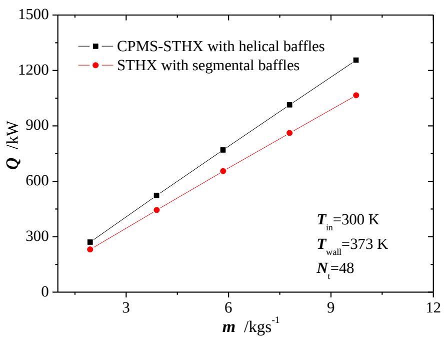


Figure 4 Heat transfer rate comparisons

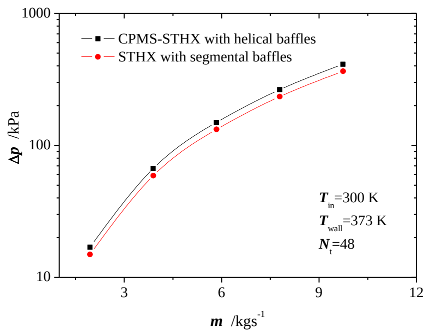


Figure 5: Overall pressure drop comparisons

In this paper, a combined parallel multiple shell-pass STHX with continuous helical baffles (CPMP-STHX) was investigated with CFD method. The numerical simulation results are compared with the conventional STHX with segmental baffles. The conclusions are summarized as follows: (1) In the CPMP-STHX, fluid has higher velocities in the outer shell-pass than that in the inner shell-pass. (2) For the same mass flow rate *m*, the overall heat transfer rate *Q* and pressure drop △*p* of the CPMP-STHX are 17.8% and 13% higher than those of the segmental baffled STHX. (3) For the same mass flow rate *m*, the comprehensive performance, which evaluated by heat transfer coefficient per pressure drop *h*/△*p* of the CPMP-STHX is nearly 13.2 % higher than that of conventional segmental baffled STHX. For the same overall pressure drop $\triangle p$, the heat transfer rate h of the CPMP-STHX is nearly 20% higher than that of the STHX segmental baffles.

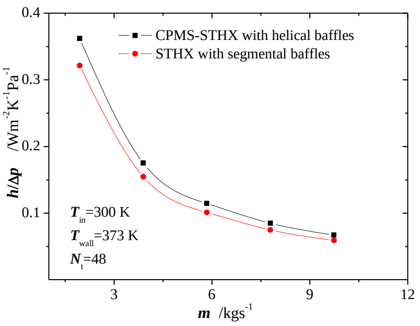


Figure 6: Heat transfer coefficient per pressure drop comparisons

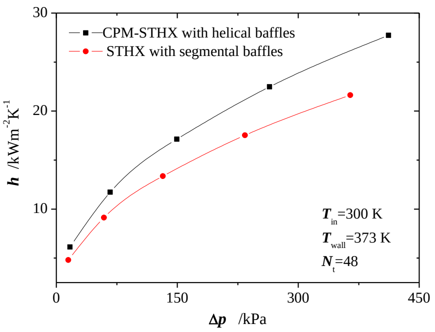


Figure 7: Heat transfer coefficient h versus pressure drop Δp

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