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Numerical simulation of heat transfer enhancement by strip-coil-baffles in tube-bundle for a tube-shell heat exchanger

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Abstract: A novel strip-coil-baffle structure used to enhance heat transfer and support the tube bundle for a tube-shell heat exchanger is proposed. The new structure can sleeve the tubes in bundle alternatively to create a vortex flow in a heat exchanger. The numerical simulation on the flow and heat transfer characteristics for this new structure heat exchanger is conducted. The computational domain consists of two strip-coil sleeved tubes and two bare tubes oppositely placed at each corner of a square. The velocity and temperature fields in such strip-coil-baffled channel are simulated using FLUENT software. The effects of the strip-coil-baffles on heat transfer enhancement and flow resistance in relation to the Reynolds number are analyzed. The results show that this new structure bundle can enhance the heat transfer coefficient up to a range of 40% to 55% in comparison with a bare tube bundle; meanwhile, higher flow resistance is also accompanied. It is believe that the strip-coil-baffled heat exchanger should have promising applications in many industry fields.

Key words: heat transfer enhancement; strip-coil-baffle; tube-shell heat exchanger; vortex flow; numerical simulation

An improvement of the shell-side structure of a tube-shell heat exchanger is a hot research topic in the thermal engineering field due to its shortcomings such as dead zones and vibration problems for a traditional bow-baffled tube bundle[1–6]. Rod baffle[3] and helical baffle[4] are some of the solutions. The rod baffle heat exchanger has good anti-vibration characteristics, but its heat transfer efficiency is sometimes limited by low velocity at shell side. While the helical baffle heat exchanger has good performance, but it is difficult to fabricate.

Vortex or spiral flow can keep a fluid flow curved motion with unchanged direction when consuming minimum energy to overcome the flow resistance. Therefore, producing a vortex flow is an economical and efficient way to enhance heat transfer in a tube-shell heat exchanger. Strip-coils and twisted strips have already been widely applied as vortex generators inside the tubes of the heat exchanger[5–7]. Nevertheless, they have seldom been used in the shell-side of heat exchangers so far.

Mei et al. proposed a novel strip-coil-baffle scheme for a tube-shell heat exchanger, which sleeves some tubes in a bundle with strip-coils to create vortex flow for heat transfer enhancement in the shell side as well as to support the tube bundle itself[8]. It is different from the finned tube scheme[9] in that the coil has greater pitch, and the strip-coils are not used to extend heat transfer surface but to induce or guide a vortex flow. The flow and temperature fields in a strip-coil-baffled concentric channel were simulated using FLUENT software[8]. However, there is a great disparity between the real strip-coil-baffled heat exchanger and a single strip-coil-baffled concentric channel. Especially, the vortex flow induced by a strip-coil can not only enhance heat transfer of its sleeved tube but also its adjacent tubes sleeved by an other strip-coil or a bare one. Because it is too difficult to simulate the whole heat exchanger field, a simplified model is necessary. The object of this paper is to build up a simplified calculated model and simulate the flow and heat transfer behaviors for the heat exchanger as well as to catch the detailed information of the reciprocity of vortex flows in the shell side.

1 Physical and Mathematical Model

Fig. 1 shows a part of a typical square arranged

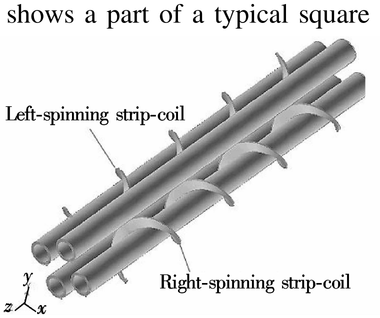

Fig. 1 A part of the tube bundle of a strip-coil baffle heat exchanger

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tube bundle in a strip-coil baffle heat exchanger. Two tubes are sleeved by one left-spinning and one right-spinning strip-coil, and the other two are bare and tangential to the neighboring coils. The area around the tubes is selected as the computational domain to be calculated.

1.1 Basic assumptions

To build up a mathematical model for the flow and heat transfer in a strip-coil baffle heat exchanger, the following basic assumptions are made: ① The working medium in shell side is air, and it is a fully developed turbulent flow in the channel; ② The working medium inside the tube is saturated steam, and the wall temperature can be treated as constant; ③ The strip-coils are considered as an insulating structure that guide only a vortex flow, and neglect convection heat transfer between the fluid and strip-coils and their temperatures are uniform.

1.2 Governing equations

The governing equation to describe the flow and heat transfer is

$$\mathrm{div}(\rho U\phi) = \mathrm{div}(\Gamma_\phi \mathrm{grad}\phi) + S_\phi$$

where ϕ is a scalar variable representing component velocities u, v or temperature T; Γ_ϕ is a general diffusion coefficient; S_ϕ is a general source. The governing equations corresponding to different representations of Γ_ϕ and S_ϕ as well as boundary and initial conditions are given in Ref. [10].

1.3 Boundary conditions

1) Inlet: $u = v = 0$, $w = M/(\rho_a A_{in})$, $T_{in} = 300$ K.

2) Outlet: the static pressure $p_{out} = 0$.

3) On tube wall and strip-coils: $u = v = w = 0$, $T_w = 378$ K.

4) On the encircled boundary of the computational domain other than tube-wall: convection heat transfer coefficient $\alpha = 0$.

Where u, v, w are the component velocities in x, y, z directions, respectively (m/s); M is the mass flow rate (kg/s); ρ is the density of the fluid (kg/m^3); A is the area (m^2); p is the pressure (Pa); α is the heat transfer coefficient (kW/(m^2 · ℃));

1.4 Turbulent flow model

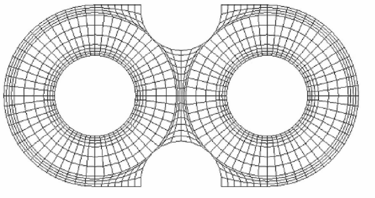
The RNG k-ε model is adopted for main flow area which is widely used by other researchers in this field, while the wall function is applied to treat the laminar flow zone near the wall.

1.5 Bare tube channel

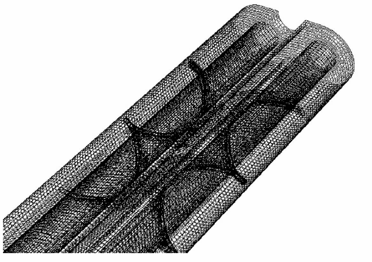
As a comparison object the four-bare-tube channel is also calculated. The assumption and boundary conditions are similar except that there is no limitation involving strip-coils.

1.6 Grids generation

The whole calculated area is divided into several sub-blocks to adopt different grid generation methods. Quadrangle nets are selected for some areas encompassed by the four tubes, while hexahedron nets are used for the channel outside of the sleeved tubes to ensure that the flow direction be perpendicular to the particular grid surfaces, thus preventing pseudo-diffusion of the solution. Fig. 2 shows the total grids of the strip-coil-baffled channel.



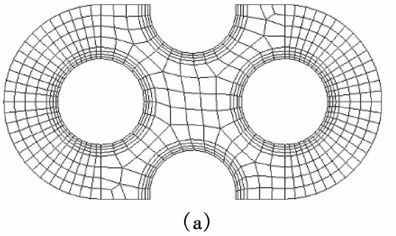
(a)



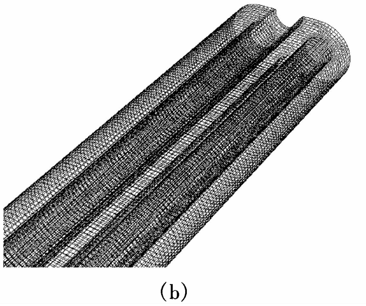
(b)

Fig. 2 Grids of four-tube channel with strip-coils. (a) Cross section view of the channel grids; (b) Stereoscopic view of the channel grids

The bare-tube channel as a comparison object is also divided to several sub-blocks using appropriate gridding. All the grids are hexahedron nets as shown in Fig. 3.



(a)



(b)

Fig. 3 Grids of four-bare-tube channel. (a) Cross section view of the channel grids; (b) Stereoscopic view of the channel grids

2 Analysis of Numerical Simulation Results

The outside diameters of the studied tubes and coils are $\phi 8$ and $\phi 16$, respective. The length of the tube channel is 125 mm, and the helix angle is 45°. The velocity and the temperature distribution are simulated when the Reynolds number is equal to 7 000.

2.1 Flow fields

Figs. 4(a) and (b) show the velocity distribution slices at $z = 20, 40, 60$ and 80 mm in a strip-coil-baffled channel and a bare tube channel, respectively. Obviously, spiral flow induced by the strip-coil accelerates the main flow by adding a tangential component. The disturbance in such a channel is more severe especially at the beginning. And it is very helpful for heat transfer enhancement because the thickness of the boundary layer near the wall is thinned down and there is no dead flow zone in the strip-coil-baffled channel. However, for the bare tube scheme it reveals that the flow velocity almost remains unchanged, and there is an obvious boundary layer effect near the tube wall.

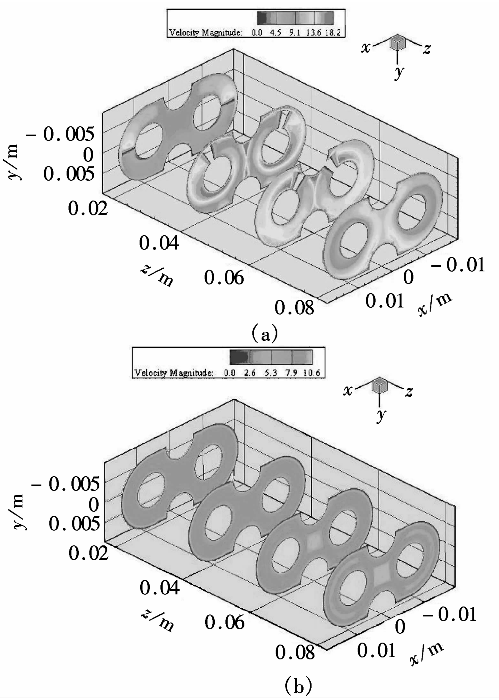


Fig. 4 Velocity distribution slices. (a) Strip-coil-baffled channel; (b) Bare-tube channel

Fig. 5 illustrates different strip-coil effects at different flow sections on the heat transfer enhancement: ① The disturbance of flow by the strip-coil is more severe at the inlet than at the rest part of the channel; ② The spiral flow induced by the strip-coil diffuses gradually to peripheral; ③ Adjacent counter-revolution flows splice at center zone without disturbing each other; ④ Non-sleeved-tubes are tipsily scoured by neighboring helix flows, thus augmenting their heat transfer coefficient.

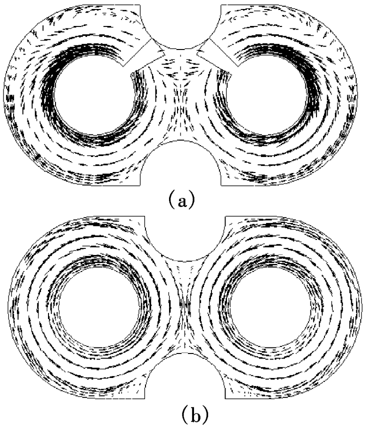


Fig. 5 Distribution of velocity vectors in four-tube channel with strip-coils. (a) Inlet cross section; (b) Outlet cross section

2.2 Temperature fields

Figs. 6 (a) and (b) show temperature distributions at $z = 20, 40, 60$ and 80 mm in both the strip-coil-baffled channel and the bare tube channel, respectively. From Fig. 6 the following characteristics can be seen: ① The fluids go away from the sleeved tube wall due to the centrifugal force induced by the helix flow and mix with each other sufficiently, thus resulting in an even temperature distribution; ② The temperature of fluid around the non-sleeved tube also tends to be uniform by the tipsy scouring of neighboring helix flows; ③ In the bare-tube channel, the boundary layer effect is much obvious that causes hot

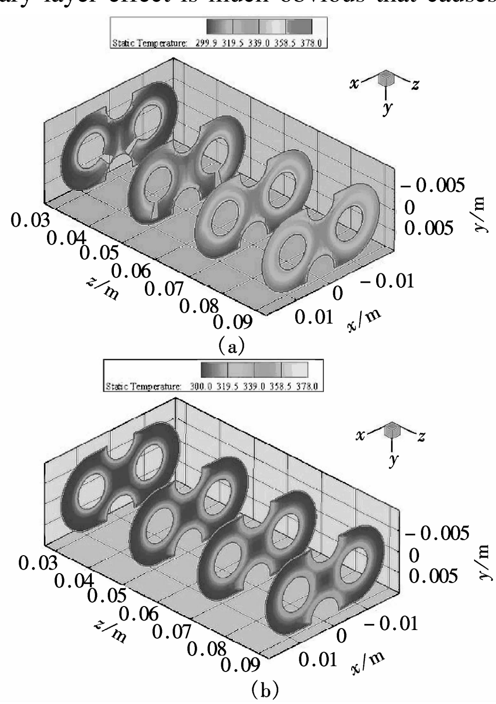


Fig. 6 Temperature distribution slices. (a) Strip-coil-baffled channel; (b) Bare-tube channel

fluid elements to accumulate near the wall and decreases the temperature difference between the tube wall and the nearby fluid, while the fluid temperature far away from the wall is still low, even at the outlet cross section.

2.3 Heat transfer enhancement and flow resistance

Fig. 7 shows the variation of local heat transfer coefficients along both the strip-coil-baffled channel and the bare tube channel when the Reynolds number is equal to 7 000. From Fig. 7 it can be seen that the local heat transfer coefficients vary slightly along the strip-coil-baffled channel, but decrease obviously along the bare tube channel. Also the heat transfer enhancement factor α/α_b for strip-coil increases along the flow direction. Therefore, the longer strip-coil has a better effect on the heat transfer enhancement by thinning the fluid boundary layer.

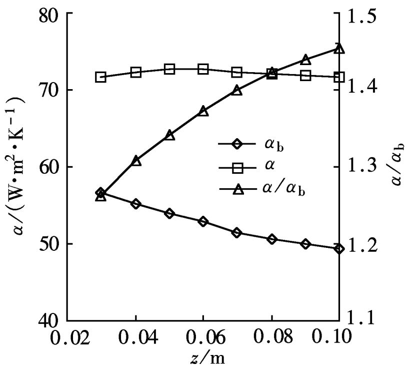


Fig. 7 Local heat transfer coefficients along channels

Fig. 8 and Fig. 9 show the heat transfer coefficients and flow resistance of shell-side of both the strip-coil-baffled channel and the bare tube channel vary with the Reynolds number. The following features can be seen: ① The heat transfer coefficients for both channels increase with the increase of the Reynolds number, but the value in the strip-coil-baffled channel is higher than that in the bare-tube channel; ② The heat transfer enhancement factor α/α_b for strip-coil has peak value with the Reynolds number;

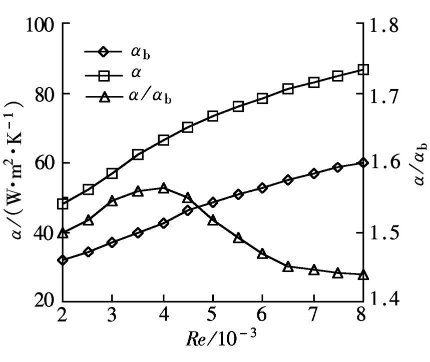


Fig. 8 Heat transfer coefficients at shell-side of both strip-coil-baffled channel and bare-tube channel

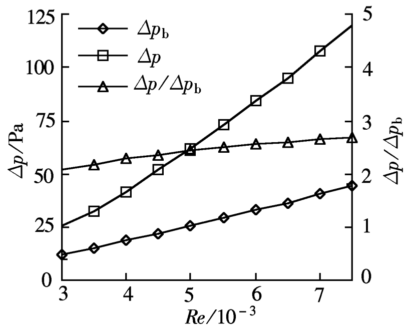


Fig. 9 Flow resistances at shell-side of both strip-coil-baffled channel and bare-tube channel

③ The flow resistances in both channels increase with the increase of the Reynolds number, but the value in the strip-coil-baffled channel is also much higher than that in the bare tube channel; ④ The ratio of $\Delta p/\Delta p_b$ increases rapidly at a smaller Reynolds number, but gradually level off at a larger Reynolds number.

3 Conclusions

1) The numerical simulation of flow and temperature fields in the shell side of the four-tube-model reveals that the strip-coils can not only induce helix flow to raise the flow velocity and decrease the thickness of the boundary layer near the wall of the sleeved tube, but also form coupled counter-revolution spiral flows which splice at center zone and tipsily scoure the adjacent non-sleeved-tubes. Additionally, the centrifugal force due to helix flow can enhance the mixing processes of the fluid near the wall and those in mainstream, thus keeping a relatively larger temperature difference for heat transfer. All of these might augment the heat transfer coefficient.

2) Each strip-coil can not only enhance heat transfer but also support the tubes. It is easier to manufacture individual strip-coils than to do curve-shaped helix-baffle. The strip-coil-baffled heat exchangers have good heat transfer performance as well as moderate flow resistance at shell side. They can also be combined with other heat transfer enhancements and tube support schemes such as rod-baffles, so that they can remedy the defect of lower velocity of fluid at shell side in such kinds of longitudinal flow heat exchangers.

3) Although the four-tube-model used in this paper still does not cover all the details of the shell side of a strip-coil-baffled tube-shell heat exchanger, but the results of heat transfer performance and pressure drop features convince us that the strip-coil-baffled heat exchanger scheme should have promising applications in many industry fields.

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螺旋折流片强化管壳式换热器内管束传热数值模拟

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摘要：介绍了一种用于强化管壳式换热器壳侧传热和支撑管束的螺旋折流片新型结构，该结构是对换热器管子相间地套上螺旋折流片以产生旋涡流动. 研究模型是在正方形布置的 4 个管子中的 2 个对角管子套上螺旋折流片后形成的通道，利用 FLUENT 软件对该上述四管通道模型的流场和温度分布情况进行了数值模拟；分析了四管通道模型中螺旋折流片对强化传热和流动阻力随雷诺数的变化关系的影响. 算例结果显示该新型结构可比相同尺寸的光管通道中的情形传热系数提高约 40% ~55%，同时也将伴随较高的流动阻力. 可以相信螺旋折流片式换热器将会在许多工业领域有良好的应用前景.

关键词：强化传热；螺旋折流片；管壳式换热器；涡旋；数值模拟

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