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Numerical Investigation on the Heat Transfer Characteristics of Dimple Jacketed Heat Exchanger in the Chemical Post-processing Integrated Equipment

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Abstract - Dimple Jacketed Heat Exchanger (DJHE) is the heat transfer unit of Chemical Post-Processing Integrated Equipment (CPPIE) during its crystallization and drying process. In this paper, based on the field synergy principle, the mechanism of heat transfer enhancement of DJHE is analysed. Then, the heat transfer characteristics of DJHE are numerically analysed by Fluent6.3. With the standard k-ε turbulent model, the three-dimensional numerical model of DJHE is developed and the superiority is verified by comparing the flow and temperature field with the traditional jacketed heat exchanger. In addition, triangular and square arranged structures of dimples on the DJHE are analysed. The analysis result can give some advices to the design work of DJHE in CPPIE.

***Keywords*:** Numerical analysis, Heat transfer, Dimple jackets, Heat exchanger.

1. Introduction

Chemical reaction, crystallization, filtration, washing and drying are the typical processes in chemical engineering. In order to improve process efficiency, reduce pollution and energy consumption, our institute develops the new equipment, Chemical Post-Processing Integrated Equipment (CPPIE), which can deal with all above processes by changing the position of the tank (Zhang Q.K. 2010). Without the transfer of products during the chemical processes, CPPIE has a significant advantage compared with the conventional equipment. The main structure of CPPIE is shown as Fig. 1., and Fig. 1.(a) shows its position during crystallization and drying; Fig. 1.(b) shows its position of filtration and washing; Fig. 1.(c) shows its position when it pours out the products.

Chemical reaction is generally accompanied by the exothermic or endothermic process. Thus, the temperature must be adjusted to maintain the steady conditions. Crystallization requires the temperature difference to control the crystal precipitation or dissolution. Drying the products also needs extra heat. Therefore, the heat transfer unit is one of the key units in CPPIE.

Jacket heat exchanger is widely used in the chemical engineering. In 1990s, Dimple Jacket Heat Exchanger (DJHE) is developed, and due to its excellent mechanical properties and heat transfer performance, DJHE is utilized widespread immediately. In CPPIE, DJHE is adopted as the heat transfer unit and its structure is shown as Fig. 2(b).

DJHE has been investigated by numerous researchers focus on the structural parameters design and heat transfer characteristics. Based on analysis of similar none uniform flow, Garvin J. (2001) estimated the heat transfer and friction in dimple jackets. Fan Q. and Yin X. (2008) investigated the effect of geometrical parameters on thermal performance of DJHE in thin-film evaporator by the 3-D simulation. Li Y. et al. (2011) analysed the DJHE by field synergy theory and compared the fluid flow and heat transfer characteristics of outer and inner jackets. Heat transfer model of DJHE was developed and both experimental and numerical analysis was researched by Cadavid Y. et al. (2013). In addition, during these years, lots of researchers investigated the heat transfer and fluid flow characteristics on the dimpled surfaces by numerical and experimental methods (Mahmood G.I., Ligrani P.M. 2002, Nishida S. et al., 2012, Chung H. et al., 2014).

However, due to the newly designed equipment, there is no related literature dealing with the parameters and heat transfer characteristics of DJHE in CPPIE. In this paper, the mechanism of heat transfer enhancement of DJHE is analysed based on the field synergy principle. Then, the heat transfer characteristics of DJHE are numerically investigated by Fluent6.3. With the standard k-ε turbulent model, the three-dimensional numerical model of DJHE is developed and the superiority is verified by comparing the flow and temperature field with the traditional jacketed heat exchanger. In addition, triangular and square arranged structures of dimples on the DJHE, which are shown in Fig. 2(c) and (d), are analysed. This work can give some advices to the following design work of DJHE in CPPIE.

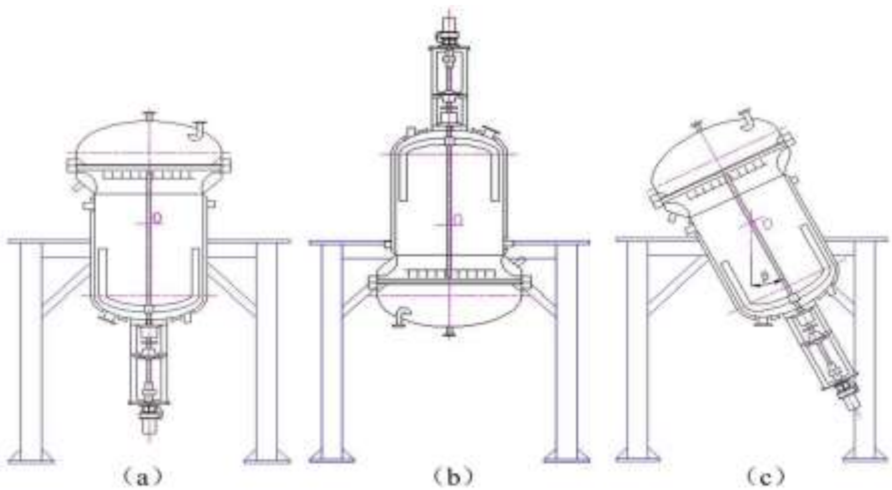

Fig. 1. Main structure of CPPIE and different positions during different processes.

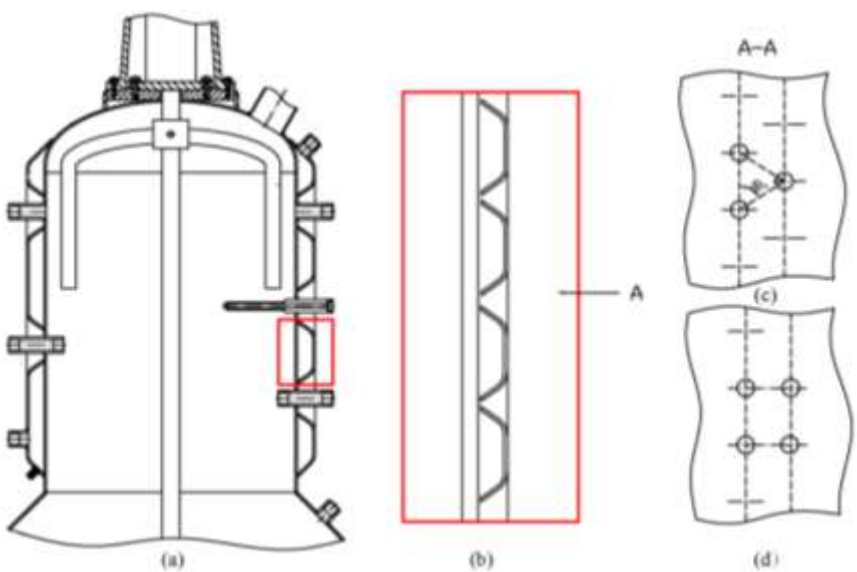

Fig. 2. Main structure of DJHE in CPPIE .

2. Field Synergy Analysis

The field synergy principle of boundary-layer flow is proposed by Guo Z.Y. et al. (1998, 2005) and co-works (Tao W.Q. et al., 2002). It explains that convective heat transfer not only depends on the thermal physics properties, the temperature difference between fluid and wall, and the fluid flow velocity, but also depends on the angle between the velocity vector and the temperature gradient. Reducing the intersection angle between the velocity and the temperature gradient is the basic mechanism for enhancing convective heat transfer, which means that optimizing the coordination of velocity and temperature gradient can improve the heat transfer coefficient. With the same speed and temperature boundary conditions, the better their level of collaboration, the better heat transfer performance is.

Conventional jacketed heat exchanger and its heat transfer process, it can be considered as a parallel plate heat exchanger channels. The velocity of the fluid is parallel to the wall, so the angle between the velocity vector and the temperature gradient close to 90°. Therefore, the coordination degree of velocity and temperature fields is inadequate, so is the heat transfer performance. In the DJHE, especially near the dimple points, they force the fluids to change its flow direction and produce a large number of vortices, which in turn results an increase of the synergistic angular velocity and temperature gradient, so is the heat transfer coefficient.

Based on the theoretical analysis above, adding dimples to conventional jacketed heat exchanger is a benefit to the synergy velocity and temperature fields, which in turn can improve the heat transfer coefficient of jacketed heat exchanger. Here field synergy principle is well applied to explain the mechanism of heat transfer enhancement of DJHE.

3. Computational Model and Equations

3. 1. Model and Assumptions

Turbulent flow is a highly complex flow, where *k*-*ε* model has been validated many times. In this this model, due to the complex structure inside the DJHE, *k*-*ε* model is adopted for simulation in Fluent 6.3. Here we simplify the actual problem with the following assumptions: fluid flow inside is steady state turbulence; the fluid inside is Newtonian fluid; the density of fluid is regarded as a constant with no sharply change of temperature; the fluid satisfies the no-slip wall condition.

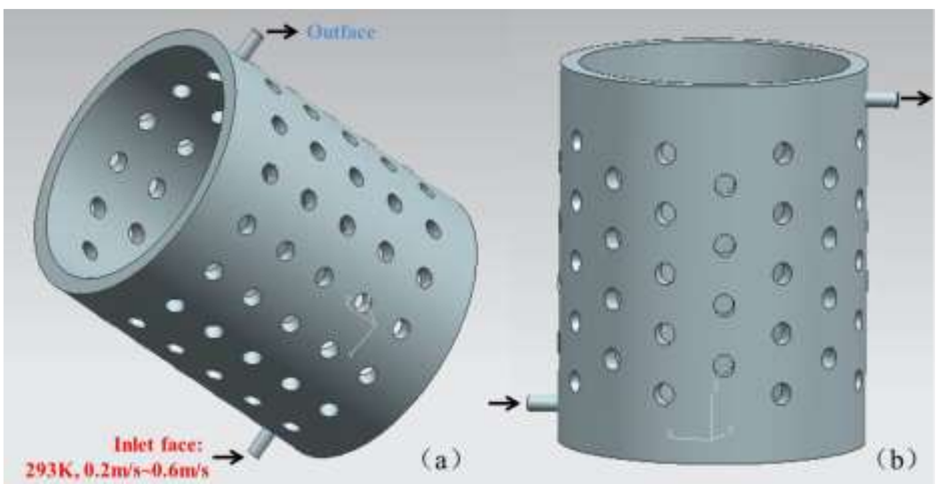

Fig. 3. Two different dimple arrangement model.

As is shown in Fig. 3, the inside diameter is 706mm; outside diameter is 800mm; and the height is 940mm. In Fig. 3(a), dimples are square arranged and in Fig. 3(b) they are triangular arranged. The diameter of all the dimples is 55mm and there are totally 16 rows (vertical direction) of dimples.

3. 2. Control Equations

The governing equations in Cartesian coordinate of turbulent flow can be written as follows:

$$\frac{\partial \rho}{\partial t}+\frac{\partial(\rho u)}{\partial x}+\frac{\partial(\rho v)}{\partial y}+\frac{\partial(\rho w)}{\partial z}=0 \qquad (1)$$

$$\frac{\partial(\rho u)}{\partial t} + div(\rho u\mathbf{u}) = div(\mu\ grad\ u) - \frac{\partial \mathrm{p}}{\partial x} + F_x$$
$$\frac{\partial(\rho v)}{\partial t} + div(\rho v\mathbf{u}) = div(\mu\ grad\ v) - \frac{\partial \mathrm{p}}{\partial y} + F_y \quad (2)$$
$$\frac{\partial(\rho w)}{\partial t} + div(\rho w\mathbf{u}) = div(\mu\ grad\ w) - \frac{\partial \mathrm{p}}{\partial \mathrm{z}} + F_z$$

$$\frac{\partial(\rho T)}{\partial t} + div(\rho \mathbf{u} T) = div(\frac{k}{c_p} grad\ T) + S_T \quad (3)$$

where: ρ represents density; t represents time; u, v, w represent velocity of three directions. p represents pressure. F_x, F_y, F_z represent body force; C_p represents heat capacity; T represents temperature; k represents heat transfer coefficient of the fluid; S_T represents viscous part.

3. 3. Boundary Conditions

Here, we set the fluid in DJHE liquid water, and the temperature is 293K; the velocity of inlet liquid water changes from 0.2m/s to 0.6m/s; the outface is set as outflow. The temperature of inside fluid is 343K, and the heat transfer coefficient between inside liquid and inner face is 4981.61$Wm^{-2}K^{-1}$. And the out face is set as no heat transfer to the atmosphere.

4. Results and Discussion

4. 1. Simulation Results

In order to determine the appropriate computing grid, the conventional jacket heat exchanger (no dimple) is meshed with 0.8mm, 1.5mm, 2.0mm, 2.5mm. Then, acting in accordance with boundary conditions, take 0.2m/s inlet velocity. The simulation results indicate that its outlet temperature improvements have no more than 0.5% differentiation. Thus, we take 2.5mm and consider it has met the accuracy of simulation. Fig. 4 (a) shows the grid of conventional jacket heat exchanger. Then, three different structures are defined with the inlet velocity as: 0.2m/s, 0.3m/s, 0.4m/s, 0.5m/s, 0.6m/s, and 15 simulations are completed. For the following analysis, we regard outlet temperature as a major evaluation of the heat transfer performance. The simulation results are shown in Table. 1.

Table 1. Simulation results of average temperature in the outface.

inlet velocity	no dimple	square arranged	triangular arranged
0.2m/s	304.26K	308.25K	308.38K
0.3m/s	301.75K	304.57K	304.72K
0.4m/s	300.47K	302.54K	302.57K
0.5m/s	299.66K	301.18K	301.25K
0.6m/s	299.00K	300.26K	300.35K

4. 2. Compared with Traditional Jacked Heat Exchanger

As is shown in Table. 1., the heat transfer performance of conventional jacket heat exchanger is always poorer than DJHE, especially when there is a lower inlet velocity. With 0.2m/s inlet velocity, the heat transfer amount is lower than DJHE by 26.4%. Fig. 3(b) indicates the temperature contour when the inlet velocity is 0.2m/s. When the inlet velocity increases, the temperature gap between them decreases, because turbulence inside the jacket increases with the velocity and this decreases the effects of dimples, which are shown in Fig. 4(b).

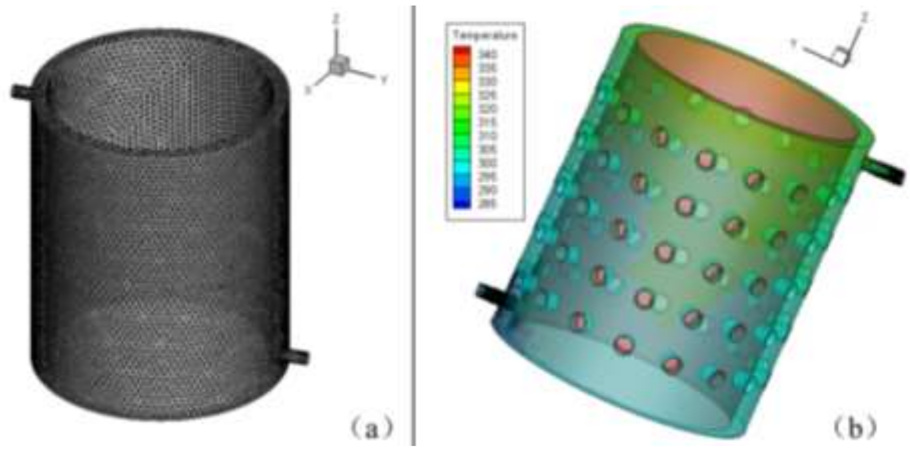

Fig. 4. (a) Mesh of jacket heat exchanger; (b) Temperature contour of square arranged at 0.2m/s.

4. 3. Triangular and Square Arranged Structures Comparison

Fig. 5(a) shows, dimples which are square arranged and triangular arranged have the similar heat transfer performance and the outface temperature line is nearly coincide.

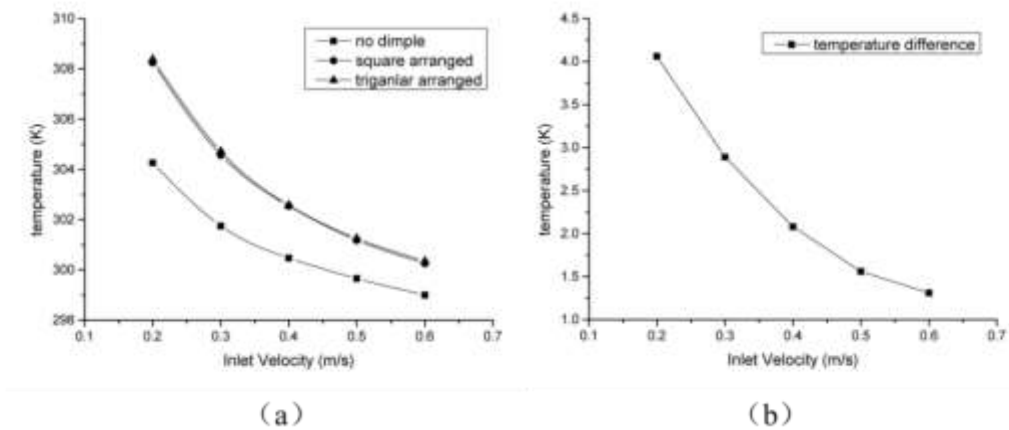

Fig. 5. Outfaces average temperature and temperature difference between them.

Triangular arranged is a bit better than square arranged according to the simulation results. Because triangular arranged structure breaks the parallel flow channels on the circular direction. Therefore, it improves the turbulence inside the jacket, and turns out a better synergistic angular and the heat transfer coefficient. However, all the arrangement schemes shall consider the possibility of the manufacture possibilities, especially when there is miniature heat transfer difference.

5. Conclusion

Compared to conventional jacketed heat exchanger, DJHE have an apparent performance of heat transfer enhancement. It is well applied in CPPIE as the heat transfer unit. Field synergy theory can explain the mechanism of heat transfer enhancement of DJHE because of the improvement of the synergistic angular velocity and temperature gradient.

Based on the simulations results, the heat transfer performance of conventional jacket heat exchanger (no dimple) is always poorer than DJHE, especially when there is a lower inlet velocity. With 0.2m/s inlet velocity, the heat transfer amount is lower than DJHE by 26.4%. However, improving the inlet velocity can decrease the gap between conventional jacket heat exchanger and DJHE, since the turbulence inside the jacket increases with the velocity.

On the face of DJHE, dimples which are square arranged and triangular arranged have the parallel heat transfer performance. And triangular arranged is somewhat better than square arranged according to the simulation results. This is because triangular arranged structure breaks the parallel flow channels on the circular direction, which can be further increased the turbulence and the heat transfer coefficient.

In addition, further research work of more detail arrangement of dimples, such as the spacing between two dimples and the diameter of the dimple, can benefit the design work of DJHE in CPPIE. However, all the arrangement schemes shall consider the possibility of the manufacture possibilities.

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References

Cadavid Y., Amell A., Cadavid F. (2013). Heat transfer model in recuperative compact heat exchanger type honeycomb: Experimental and numerical analysis. Applied Thermal Engineering, 57(1), 50-56.

Chung, H., Kim, K. M., Kwon, H. G., Lee, S., Kim, B. S., & Cho, H. H. (2014). Heat Transfer and Fluid Flow on Dimpled Surface With Bleed Flow. Heat Transfer Engineering, 35(6-8), 641-650.

Fan Q., Yin X. (2008). 3-D numerical study on the effect of geometrical parameters on thermal behavior of dimple jacket in thin-film evaporator. Applied Thermal Engineering, 28(14), 1875-1881.

Girvan J. (2001). Estimate heat transfer and friction in dimple jackets. Chemical Engineering Progress. 97 (4) 73–75.

Guo Z.Y., Li D.Y. Wang B.X. (1998). A novel concept for convective heat transfer enhancement. International Journal of Heat and Mass Transfer, 41(14), 2221-2225.

Guo Z.Y., Tao W.Q., Shah R.K. (2005). The field synergy (coordination) principle and its applications in enhancing single phase convective heat transfer. International Journal of Heat and Mass Transfer, 48(9), 1797-1807.

Li Y., Wu J., Zhang L., Kou L. (2011). Comparison of fluid flow and heat transfer behavior in outer and inner half coil jackets and field synergy analysis. Applied Thermal Engineering, 31(14), 3078-3083.

Mahmood G.I., Ligrani P.M. (2002). Heat transfer in a dimpled channel: combined influences of aspect ratio, temperature ratio, Reynolds number, and flow structure. International Journal of Heat and mass transfer, 45(10), 2011-2020.

Nishida S., Murata A., Saito H., Iwamoto K. (2012). Compensation of three-dimensional heat conduction inside wall in heat transfer measurement of dimpled surface by using transient technique. Journal of Enhanced Heat Transfer, 19(4).

Tao W.Q., Guo Z.Y., Wang B.X. (2002). Field synergy principle for enhancing convective heat transfer––its extension and numerical verifications. International Journal of Heat and Mass Transfer, 45(18), 3849-3856.

Zhang Q.K. (2010) Development and application research of the integrated equipment of raw material drug's post-processing production. Master Thesis, Zhejiang University.