Analysis of heat transfer characteristics of induced vibration of elastic tube beam of heat exchanger

Xinyang Yu *

Harbin Engineering University

Abstract. Elastic tube bundle heat exchanger uses fluid induced elastic tube bundle vibration to achieve passive enhanced heat transfer. Due to the structural characteristics of traditional flat elastic tube bundle, the heat exchange area per unit volume in the heat exchanger is small and the comprehensive heat transfer performance is low, which makes the overall efficiency of the heat exchanger poor. Based on the design concept of fluid-induced vibration to enhance heat transfer and the structural characteristics of traditional shell and tube heat exchangers, a spiral elastic tube heat exchanger is proposed to make it efficient, reliable and flexible, taking miniaturization, lightweight and compact as the basic design criteria.

Key words: heat exchanger; Helical elastic tube bundle; Vibration response; Heat transfer performance; Structural improvement.

1. Introduction

Traditional shell-and-tube heat exchangers [1] transfer heat energy to the cylinder through closed heat pipes. They are by far the most commonly used heat exchangers. The internal heat transfer element of this heat exchanger is usually made of stainless steel, which is characterized by low cost and large effective heat transfer area, but its disadvantages are low overall heat transfer capacity, large footprint, easy scaling and short service life. The traditional shell and tube heat exchanger [2-5] assembles two tubes of different diameters concentrically together to form a certain closed space, so that the two kinds of thermal working medium flow in the opposite direction (or the same direction) in the jacket. / On the pipe side. The purpose of achieving heat exchange is shown in Figure 1. It has simple structure, small footprint, and can freely increase or decrease the heat transfer area (multiple groups are used in series), but it also has disadvantages such as low overall heat transfer capacity, easy scaling, and short service life. . The vibration caused by the flow will lead to fatigue failure of the heat exchange tube of the heat exchanger, thus shortening its service life. Damage to the heat exchange tube bundle due to liquid-induced vibration is one of the most significant problems encountered in heat exchangers. Design and use of heat exchangers [6-8]. In addition, the vibration caused by fluid is a negative factor affecting the fatigue life of heat transfer tubes, and it is also a positive factor to improve heat transfer. The elastic tube bundle heat exchanger [9-10] changes the internal heat exchange tube from the original rigid structure (stainless steel) to the elastic structure (copper), and uses fluid impact to vibrate the internal elastic tube bundle to achieve the purpose of enhancing heat exchange.

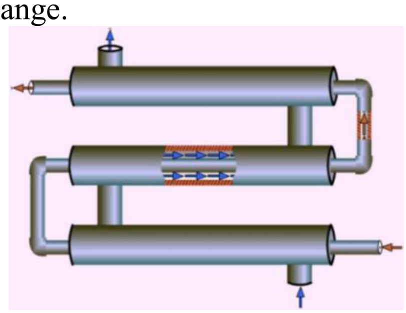


Figure 1. Tube heat exchanger

In the flexible tube bundle heat exchanger, the fluid causes the vibration of the heat transfer element to achieve the purpose of improving the heat transfer effect, without consuming additional energy, which has great advantages in energy saving and consumption reduction, and has automatic descaling function, which belongs to the category of passive technology enabling, is the subject of current academic research. However, a large number of studies have shown that this flexible tube bundle heat exchanger has the following shortcomings:

Flexible tube bundle heat exchanger is bulky, covers a large area and has low application flexibility. Affected by the structural characteristics of the internal copper heat transfer elements, the heat transfer area per unit volume in the heat exchanger is small and the overall heat transfer efficiency is low, which makes the overall performance of the heat exchanger not significantly improved [11], which is also the technical bottleneck that cannot be overcome in the design, testing and application of the flexible tube bundle heat exchanger.

Based on the basic idea of vibration strengthening heat transfer of flexible tube bundle heat exchanger, combined with the design advantages of the existing shell and tube heat exchanger and sleeve heat exchanger, it has the characteristics of miniaturization, lightweight and compact. The new type of flexible tube bundle heat exchanger not only meets the basic design criteria, but also has the characteristics of high efficiency, reliability and flexibility, which is the key to break through the technical bottleneck of heat exchanger. Therefore, it is urgent to optimize the flat vortex structure of the existing heat transfer tube to achieve the high efficiency and flexibility of the heat transfer device, which has important guiding significance for the development of the heat transfer device, energy saving and consumption reduction.

2. spiral elastic tube bundle heat exchanger vibration-heat transfer numerical calculation method

2.1 Connotation of elastic tube bundle heat exchanger

At present, the traditional plane elastic bundle is affected by its structural properties. The heat exchange surface area per unit volume is small, and the overall heat transfer capacity is low, resulting in poor overall performance of the heat exchanger. There is an urgent need for optimization. Compared with the flow of the tubular process fluid in the heat exchange tube, the flow of the shell process fluid is more complicated and changeable due to the influence of the tube bundle in the heat exchanger tube. In this paper, a helical elastic bundle heat exchanger is developed. The bundle structure model and shell flow model are established, and the grids of the structure model and shell flow model are divided accordingly. In addition, by comparing the calculated results of this paper with the experimental results obtained in the public literature, the correctness of the numerical simulation strategy proposed in this paper is verified, and the foundation is laid for the subsequent analysis. The current flat elastic tube bundle has some shortcomings due to the copper plane eddy current structure, which leads to low unit volume heat transfer coefficient and poor overall heat transfer performance. However, the coil bundle can be installed multiple times. The spiral coil group solves the shortcomings of the existing plane elastic tube bundle. Based on the design concept of the existing elastic tube bundle heat exchanger to improve heat transfer through fluid-induced vibration, combined with the advantages and disadvantages of the traditional shell and tube heat exchanger, to achieve miniaturization and portability based on the basic design criteria, a spiral elastic tube bundle heat exchanger is proposed, and its main structure is shown in Figure 2. It is mainly composed of a left and right end, a left and right tube plate, a simplified body and a heat transfer component. The heat transfer element is composed of a number of copper spiral tubes with two sections fixed on the tube plate.

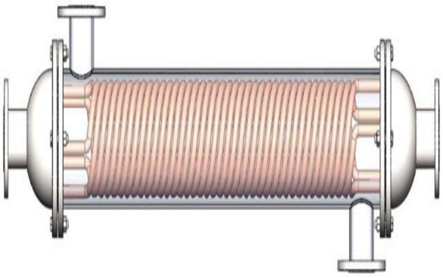


Figure 2 Components of spiral elastic tube bundle heat exchanger

For the existing shell-and-tube heat exchangers, the heat transfer parts are affected by the impact of the working medium, and fatigue failure is easy to occur. If its structure is improved, it can not only achieve the purpose of strengthening heat transfer by fluid-induced vibration, but also will not cause the failure of heat transfer components. In this case, the vibration caused by fluid action is worth making full use of. According to the core idea of improving heat exchange through vibration of heat exchange components, the structure of the heat exchange tube inside the traditional heat exchanger was improved, and an elastic tube bundle structure [78-80] was proposed, which was used as a heat exchange component. Figure 3 shows its structure. The proposed planar elastic tube bundle is composed of a number of copper vortex tubes and two stainless steel mass blocks (III and IV), as shown in Figure 3, and the end faces of the I and II tube bundles are set as fixed constraints. When the heat exchanger is in normal operation, the working medium of the pipe enters from the port of I, flows through the channel in the mass block III and the mass block IV, and flows out from the port of II.

The results show that the low intensity vibration of shell/tube working medium in heat exchanger can greatly improve the heat transfer performance of tube bundle at low flow rate. In addition, the fatigue failure caused by high-intensity vibration is avoided, and the noise can be reduced to a certain extent. In addition, the vibration of the elastic tube bundle also has a remarkable descaling effect.

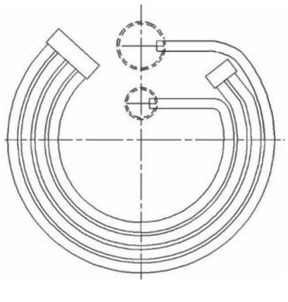


Figure.3 Structure diagram of plane elastic tube bundle

2.2 Basic governing equations

In the calculation of this study, the influence of physical degeneration and the heat loss between the heat exchanger and the environment are ignored. Fluid flow and heat exchange obey the basic law of conservation of energy.

Mass conservation equation:

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

Where,ρ -- density:
t -- Time:
x, y, z - three-dimensional coordinate axes:
U, v, w- the flow rate of the fluid in the x, y, and z directions.

Momentum conservation equation:

$$\rho\frac{du}{dt}=\rho f_x-\frac{\partial\rho}{\partial x}+\frac{\partial}{\partial x}\left\{\mu\left[2\frac{\partial u}{\partial x}-\frac{2}{3}\left(\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}\right)\right]\right\}+\frac{\partial}{\partial y}\left[\mu\left(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}\right)\right]+\frac{\partial}{\partial z}\left[\mu\left(\frac{\partial w}{\partial x}+\frac{\partial u}{\partial z}\right)\right] \quad (2)$$

$$\rho\frac{dv}{dt}=\rho f_y-\frac{\partial\rho}{\partial y}+\frac{\partial}{\partial y}\left\{\mu\left[2\frac{\partial v}{\partial y}-\frac{2}{3}\left(\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}\right)\right]\right\}+\frac{\partial}{\partial z}\left[\mu\left(\frac{\partial v}{\partial z}+\frac{\partial w}{\partial y}\right)\right]+\frac{\partial}{\partial x}\left[\mu\left(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}\right)\right] \quad (3)$$

$$\rho\frac{dw}{dt}=\rho f_z-\frac{\partial\rho}{\partial z}+\frac{\partial}{\partial z}\left\{\mu\left[2\frac{\partial w}{\partial z}-\frac{2}{3}\left(\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}\right)\right]\right\}+\frac{\partial}{\partial x}\left[\mu\left(\frac{\partial x}{\partial x}+\frac{\partial u}{\partial z}\right)\right]+\frac{\partial}{\partial y}\left[\mu\left(\frac{\partial v}{\partial z}+\frac{\partial w}{\partial y}\right)\right] \quad (4)$$

Where, μ -- dynamic viscosity:

p -- Pressure:

fxf,f: -- The component of the fluid force in the x, y, : directions.

2.3 Grid independence verification

In order to test the dependence of the numerical results on the mesh density, the heat transfer coefficient h and pressure drop △P of the tube under different mesh numbers were calculated. Taking the model with a spiral diameter of 110mm as an example, when the inlet flow rate is 1.0m/s, the influence of four different mesh quantities on the numerical results is shown in Table 1. When the grid number is 3.76 million, the relative errors of pressure drop and heat transfer coefficient are less than 5.0%. It can be considered that a solution independent of mesh density has been obtained.

Table 1 Grid independence verification

serial number	Grid number	pressure drop		heat transfer coefficient	
		numerical value	Relative error （%））	numerical value	Relative error （%））
1	1, 865, 549	180. 60	4.65	994.43	3.53
2	2, 378, 675	176. 27	2.14	1012.16	1.81
3	3, 186, 464	174. 12	0.89	1022.99	0.76
4	2, 789, 718	763. 33	--	1362.85	--

Based on the conical spiral tube bundle vibration test bench in reference [1] and the single row elastic tube bundle vibration test bench in reference [2], two numerical models are established. The experimental data are the vibration frequency and acceleration amplitude measured by the acceleration sensor at different inlet flow rates in the above two experiments. Using the above grid setting and numerical simulation methods, the experimental results are compared with the numerical results, and the results are shown in Table 3. It can be seen from Table 3 that the numerical results obtained by the solution are basically consistent with the experimental results in the literature, and the maximum relative error is only 6.59%. It can be seen that the vibration results calculated in this study meet the requirements of subsequent analysis.

Table 2 Comparison of numerical data

document	Inlet velocity (m/s)	Frequency f/Hz		Relative error （%）	Acceleration amplitude		Relative error （%）
		numerical result	experimental result		numerical result	experimental result	
[1]	0.260	19.4	19.0	2.11	0.093	0.098	5.10
	0.312	19.9	19.0	4.47	0.374	0.396	5.56
[2]	0.3	29.6	29.0	2.07	0.156	0.167	6.59
		30.8	30.0	2.67	0.179	0.188	4.79
	0.5	28.5	28.0	1.78	0.721	0.747	3.48

3. Result verification

Considering the accuracy of the numerical calculation method in this study, a quantitative comparison was made with the experimental data of Salimpour[3] under the same conditions of thermophysical properties and geometric parameters. Salimpour [3] analyzed the shell side heat transfer characteristics of a spiral tube heat exchanger by establishing a heat transfer test bench, and the experimental setting process is shown in Figure 3. In this device, hot water flows in the tube and cold water flows in the shell. The main components of the experimental device are spiral tube heat exchanger, centrifugal pump, water storage tank and electric heater. The spiral tube heat exchanger comprises a spiral copper tube and an insulating shell. The flow of cooling water and hot water is controlled by ball valve and globe valve respectively. The inlet and outlet temperatures of hot and cold water are monitored by four RTD thermocouples inserted into small holes in the inlet and outlet pipes of the heat exchanger.

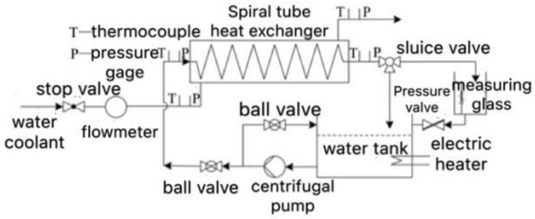
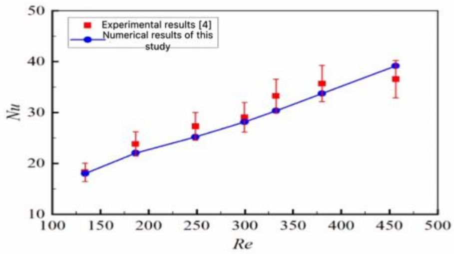


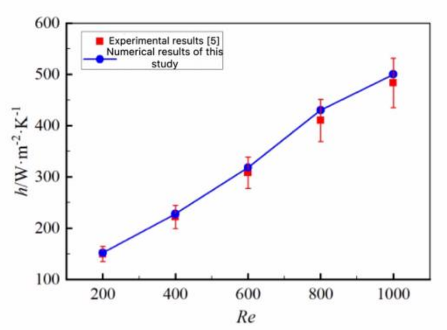
Figure. 3 Flowchart of experiment setup

The helical elastic tube bundle used in this analysis has the same material, structure size and fluid flow condition as the heat transfer tube used in the experiment in literature [4]. The structural parameters of middle heat exchanger 1 were selected, and the spiral coil heat exchanger was simulated with the numerical calculation method in the range of shell water flow 0.019-0.136 m^3/s. Based on experimental conditions, Nu at different Re were obtained, and the corresponding results were represented by a 10% error line in Figure 4. Compared with the experimental data, the deviation of Nu is 1.37%~8.66%. These small differences are attributed to the simplification of the model and the inevitable measurement errors. This shows that the accuracy of the numerical calculation results in this study can meet the needs of subsequent analysis.

In addition to comparison with experimental data, this study is also compared with numerical results from Duan et al. [5]. Elastic bundle heat exchangers with tube spacing of 20mm and tube row spacing of 50mm in literature[5]. were selected as the research object. The average heat transfer coefficient h of the tube bundle at different Reynolds numbers Re was calculated, and the corresponding results were represented by a 10% error line in Figure 4. Compared with the simulated data, the deviation of h is 1 1.37%~8.66%. This further indicates that the accuracy of the numerical calculation results in this study meets the needs of subsequent analysis.



(a) Comparison with experimental results



(b) Comparison with simulation results

Figure. 4 Verification of numerical calculation results of heat transfer

4. Conclusion

A spiral elastic bundle heat exchanger is proposed in this paper. The numerical calculation model of vibration-heat transfer of spiral elastic bundle is established. The numerical calculation method is determined and the boundary conditions are set. By comparing the calculated results with the experimental results, the accuracy of the vibration and heat transfer results is verified.

References

[1] Yuelin Li, Chao Sun, Shiqin Ai et al. Three-dimensional numerical simulation of beam induced vibration of elastic tube of heat exchanger considering two-way fluid-structure coupling [J]. Vibration and shock, 2022, 9 (17) : 63-72. The DOI: 10.13465 / j.carol carroll nki JVS. 2022.17.008.

[2] Yan-cai Su. Study on fluid-induced Vibration and Heat Transfer Characteristics of Elastic Tube bundle [D]. Doctoral Dissertation of Shandong University, 2012:45-49.

[3] Salimpour M R. Heat Transfer Coefficients of Shell and Coiled Tube Heat Exchangers [J].Experimental Thermal and Fluid Science, 2009,3(2): 203-207.

[4] Duan D R, GE P Q, BI W B, et al. Numeric al Investigation on Synthetical Performance ofHeat Transfer of Planar Elastic Tube Bundle Heat Exchanger [J]. Applied Thermal Engineering, 2016, 109:295-303.

[5] SATHYABHAMA A, PRASHANTH S P. Enhancement of Boiling Heat Transfer UsingSurface Vibration [J]. Heat Transfer—Asian Research, 2017, 46(1): 49-60.

[6] LU G, ZHOU G. Numerical Simulation on Performances of Plan e and Curved Winglet Type Vortex Generator Pairs with Punched Holes [J]. International Journal of Heat and Mass Transfer. 2016, 102:679-690.

[7] Lu G, Zhou G. Numerical Simulation on Performances of Plan e and Curved Winglet-pairVortex Generators in a Rectangular Channel and Field Synergy Analysis[J]. International Journal of Thermal Sciences.2016, 109:323-333.

[8] Tan X, Zhu D, Zhou G, et al. Experimental and Numerical Study of Convective HeatTransfer and Fluid Flow in Twisted Oval Tubes[J]. International Journal of Heat and Mass Transfer. 2012,55(17):4701-4710.

[9] De Liu,Jubao Liu,Qiubei Yue et al. Study on vortex-induced Vibration Characteristics of Double elastic tubes in shell-and-tube heat exchangers [J]. Chemical Machinery,2018,45(04):495-500+514.

[10] Zhao Li. Study on fluid elastic instability of an unequal frequency tube array [D]. Tianjin University,2018.

[11] Ruijia Cheng, Yanan Zhang, Qing Xiao et al. Numerical Simulation of Elastic Instability of fluid-induced Heat exchanger tube bundle [J]. Light Industry Machinery,2018,36(03):36-40+45.[12] GE Lei. Equivalent homogenization of plate-fin heat exchanger strength design [D]. China university of petroleum (east China), 2018. The DOI: 10.27644 /, dc nki. Gsydu. 2018.001291.

[12] Jiadong Ji,Peiqi Ge,Wenbo Bi et al. Fluid-induced vibration response of elastic tube bundle of heat exchanger with different combinations of tubes and rows [J]. Journal of Xi 'an Jiaotong University,2018,52(03):69-75.

[13] Derong Duan. Study on Fluid Induced Vibration Enhanced Heat Transfer and Fatigue Strength of Elastic tube bundle [D]. Shandong University,2017.

[14] Jiadong Ji, Peiqi Ge, Wenbo Bi. Heat exchanger in the line of the shell side of the elastic tube bundle more fluid induced vibration response of the numerical analysis [J]. Journal of vibration and shock, 2016, 35 (20) : 85-89 + 136. DOI: 10.13465 / j.carol carroll nki JVS. 2016.20.014.