Simulation study of heat transfer characteristics of a biomimetic honeycomb CO_2 gas cooler

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Abstract. CO_2 air source heat pumps are widely used because of their advantages of energy saving, high efficiency and clean. Gas cooler is one of the key components of CO_2 heat pump system, while its heat transfer effect will affect the energy efficiency of the whole system. In order to improve the heat transfer efficiency, a biomimetic honeycomb gas cooler is proposed in this paper, the steady-state simulation model of the biomimetic honeycomb gas cooler is established by using MATLAB software, and the reliability of the model is verified by literature data. In addition, the heat transfer performance of the biomimetic honeycomb gas cooler is compared with that of the tube-in-tube gas cooler. The results showed that, under the same working condition, compared with the tube-in-tube gas cooler, the outlet temperature of the biomimetic honeycomb gas cooler with 1st, 2nd and 3rd level increased by 9.7℃, 25.4℃ and 27.3℃, and heat transfer can be increased by 55.5%, 205.4% and 220.6% respectively. This research is helpful to provide the reference for the design and optimization of this type of gas cooler, and is conducive to the popularization of CO_2 air source heat pump.

1 Introduction

At present, the rapid development of modern society relies on a large amount of energy consumption, which not only leads to the shortage of traditional fossil energy resources, but also makes problems of environmental pollution and climate change increasingly prominent. Achieving carbon neutrality by the middle of the 21st century is the most fundamental measure to deal with energy and environmental problems globally[1]. CO_2 air source heat pump is considered as the most promising environmental protection product in reducing CO_2 emissions and reducing dependence on fossil fuels[2,3]. CO_2 air source heat pump takes air as a low temperature heat source, which is inexhaustible, and uses CO_2 as the refrigerant, which has stable chemical properties, non-toxic, non-flammable and large temperature slip[4].

However, there are still some problems in the application of the CO_2 heat pump[5]. The supercritical heat transfer of CO_2 in gas cooler is a typical irreversible process. The poor heat transfer effect of gas cooler will lead to the increase of irreversible loss, and then affect the energy efficiency of the CO_2 heat pump system. Research shows that exergy loss rate of gas cooler is 25% ~29.6%, second only to compressor[6]. In addition, for microchannel heat exchangers, uneven flow distribution and gas blockage lead to reduced heat transfer efficiency, resulting in a large amount of energy loss. Structural innovation and optimization and thermal performance analysis of gas cooler are the focus of domestic and foreign scholars[7,8,9]. At present, in addition to the conventional tube-in-tube gas cooler, there are small tubes in a large tube, spiral tube and other forms. Zhang Xianping et al.[10] conducted sensitivity analysis on the structural parameters of the tube-type gas cooler used in CO_2 heat pump water heater, and the results showed that when there are multiple tubes in the tube, the performance of three tubes is optimal. Microchannel heat exchanger refers to heat exchanger with channel equivalent diameters ranging from 10μm to 1000μm, which are first applied in refrigeration systems and mostly used in automobile air conditioners in the form of air conditioning[11]. Jiong Li et al.[12] proposed a carbon dioxide integrated finned microchannel gas cooler for automobile air conditioning, and analyzed the effects of finned geometry and poor air side distribution on heat exchanger performance. Dandong Wang et al.[13] improved the heat exchange capacity of the high-pressure side of the system by using gas cooler in series.

To sum up, gas cooler is one of the key components of CO_2 heat pump system, while its performance and different structural forms will directly affect the performance of the whole CO_2 heat pump system. The poor heat transfer effect of gas cooler will lead to the increase of irreversible loss, and then affect the energy efficiency of the CO_2 heat pump system. In order to solve this problem and improve the heat transfer efficiency, a biomimetic honeycomb gas cooler is proposed in this paper, the steady-state simulation model of the biomimetic honeycomb gas cooler is established by using MATLAB software, and the reliability of the model is verified by literature data. In addition, the heat transfer performance of the biomimetic honeycomb gas cooler is compared with that of the tube-in-tube gas cooler. This

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2 Model of honeycomb CO_2 gas cooler

2.1 Geometric construction

Honeycomb structure in nature is composed of hexagonal cells, which has the advantages of material saving and high strength. Figure 1 shows the diagram of imitation honeycomb fractal network constructed. CO_2 flow channel and water channel distribute alternately, one layer of CO_2 flow channel and one layer of water channel are collectively called the first level network structure. The innermost channel is the CO_2 flow channel. Figure 2 shows the schematic diagram of the 3rd level honeycomb CO_2 gas cooler. The flow type of CO_2 and water is countercurrent.

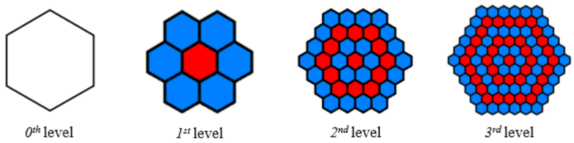

Fig. 1. Schematic diagram of section structure of honeycomb CO_2 gas cooler with different levels.

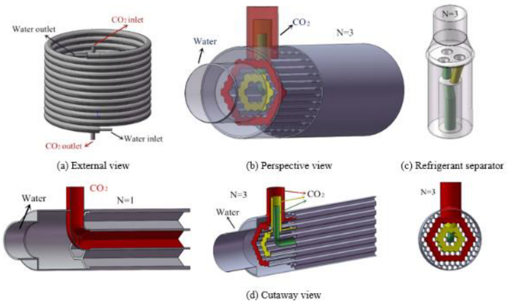

Fig. 2. Structure schematic diagram of honeycomb CO_2 gas cooler.

Assume that the 0th level is a regular hexagon, and the length of the side is *a*. If the diameter of 0th level hexagonal outer circle remains unchanged, its equivalent diameter *de* remain the same. Make the equivalent diameter of each microchannel hexagon in 1st level is 1/3 of that in 0th level, the side length of each microchannel hexagon in 1st level is also 1/3 of that in 0th level; The equivalent diameter of each microchannel hexagon in 2nd level is 1/7 of that in 0th level, and the side length of each microchannel hexagon in 2nd level is 1/7 of that in 0th level. Similarly, the side length of each microchannel hexagon in the nth level structure is 1/(4n-1) of that in the 0th level.

Table 1 shows the relationship between the side length of microchannel, the number of channels for water and CO_2, and the heat transfer area with the level. When the honeycomb CO_2 gas cooler is nth level structure, the number of water flow channel is $6n^2$; the number of CO_2 flow channel is $1+6(n^2-n)$; and the total heat transfer area is $(6+24(n^2-n))aL$. Where, *a* is the side length of microchannel of 0th level structure, and *L* is the tube length of gas cooler.

Table 1. The relationship between the side length of microchannel, the number of water and CO_2 flow channel, and the heat transfer area with the level.

Level	Side length of microchannel	Number of water flow channel	Number of CO2 flow channel	Heat transfer area
0th	a			
1st	a/3	6	1	6aL
2nd	a/7	24	13	54aL
3rd	a/11	54	37	150aL
…	…	…	…	…
nth	a/(4n-1)	6n2	1+6(n2-n)	(6+24(n2-n))aL

2.2 Mathematical model

In order to further understand the fluid flow and heat transfer process in honeycomb CO_2 gas cooler, it is necessary to establish a model to analyze it. Because the physical property of CO_2 changes dramatically in the quasi-critical region, the gas cooler is modeled by steady-state distributed parameter model, that is, the gas cooler is divided into many micro-elements, and each element is modeled according to the centralized parameter method. In order to simplify the model calculation, the following assumptions are made for each micro-element: (1)Steady state operation; (2)There is no heat conduction along the axial direction of the pipe; (3)Ignore heat loss; (4)The axial flow of refrigerant along the pipe is one-dimensional; (5)Ignore the pressure drop of water; (6)The flow and temperature of refrigerant and water are evenly distributed.

The specific calculation process of honeycomb CO_2 gas cooler is as follows: the gas cooler is divided into N elements of equal length along the flow direction of refrigerant. The more the elements is, the more accurate the calculation will be. In each micro-element, the refrigerant and cooling water are in the state of countercurrent heat exchange, and the outlet state of the previous micro element is the inlet state of the next micro element, as shown in Figure 3.

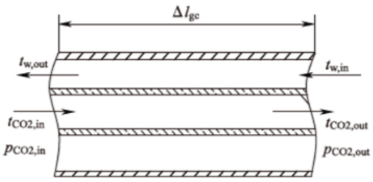

Fig. 3. Schematic diagram of honeycomb CO_2 gas cooler element.

For each element, there are the following conservation equations of energy and mass:

Water side:

$$Q_j = m_{w,j} C_{p,w} (t_{wo,j} - t_{wi,j}) \tag{1}$$

CO$_2$ side:

$$Q_j = m_{r,j} [h(t,p)_{i,j} - h(t,p)_{o,j})] \tag{2}$$

Heat transfer between CO$_2$ side and water side:

$$Q'_j = \frac{[(t_{ri,j} - t_{wo,j}) - (t_{ro,j} - t_{wi,j})] / \ln(\frac{t_{ri,j} - t_{wo,j}}{t_{ro,j} - t_{wi,j})})}{\frac{1}{h_{r,j} A_{r,j}} + \frac{\delta}{\lambda A_{r,j}} + \frac{1}{h_{w,j} A_{w,j}}} \tag{3}$$

where， Q_j is the heat transfer of the micro element, W; $m_{w,j}$, $m_{r,j}$ are the mass flow rate of water and CO$_2$ respectively, kg/s; $C_{p,w}$ is the specific heat capacity of water, J/kg·℃; $t_{wi,j}$, $t_{wo,j}$ are the inlet and outlet temperature of water in the micro-element respectively, ℃; $h(t,p)_{i,j}$, $h(t,p)_{o,j}$ are the enthalpy of import and export of CO$_2$ in the micro-element respectively, J/kg; $h_{w,j}$, $h_{r,j}$ are the heat transfer coefficients of water side and CO$_2$ side respectively; $A_{w,j}$ is heat exchange area, m^2; δ is the wall thickness, m; λ is the thermal conductivity of the wall, the material of pipe is copper, 398W/ (m^2·℃).

For the calculation of heat transfer coefficient of CO$_2$ in supercritical tube cooling, this paper adopts the heat transfer correlation equation proposed by Yoon S H et al. Based on MATLAB software, the simulation program of honeycomb CO$_2$ gas cooler model under supercritical condition is designed in this paper. The calculation process is shown in Figure 4.

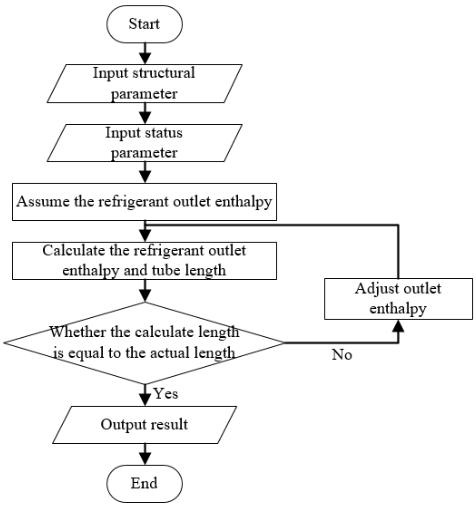

Fig. 4. Flow chart of tube length calculation of honeycomb CO2 gas cooler.

2.3 Validation of model

The structure of the 1st level gas cooler mentioned in this paper is similar to that of the tube-in-tube gas cooler. In order to verify the correctness of the Matlab simulation model, the data in literature [14] are used for simulation verification. Figure. 5 shows the variation trend of water and CO$_2$ fluid temperature along tube length It can be seen that the simulated value fits well with the literature data, and the maximum error is less than 3%. The comparison results verify the correctness and reliability of the model.

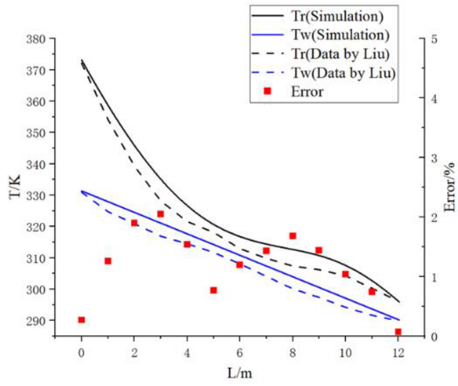

Fig. 5. Schematic diagram of fluid temperature along tube length in the gas cooler.

3 Results and discussion

The simulated operating parameters are as follows: the inner diameter of the outer tube is 22mm, the wall thickness is 0.8mm, the tube length is 8m, the inlet pressure of CO$_2$ is 9.0MPa, the flow rate of CO$_2$ and water is 0.02 and 0.03kg/s, and the inlet temperature of CO$_2$ and water is 90℃ and 20℃, respectively.

Figure. 6 shows fluid temperature variation along tube length of honeycomb gas cooler and tube-in-tube gas cooler. Be located at 0m of pipe length is the inlet of the refrigerant side (i.e., the outlet of the water side). The temperature of CO$_2$ and water decreases along the direction of CO$_2$ flow, and the reduction amplitude becomes smaller and smaller, that is, the temperature difference between cold and hot fluids becomes smaller and smaller. Under the same condition, the outlet temperature of tube-in-tube, 1st level, 2nd level and 3rd level is 306K, 316K, 331K and 333K respectively. The latter three are 10K, 25K and 27K higher. Compared with tube-in-tube gas cooler, the temperature difference between CO$_2$ and water in the honeycomb gas cooler and is smaller, and the temperature matching is better. This is because a large number of honeycomb structures are distributed in the whole gas cooler, which not only increases the heat transfer area, but also makes the two fluid fully contact and exchange heat. In addition, each wall of the flow channel can be used as fins of other flow channels (i.e. "common-rib effect"), and the local vortex formed can effectively impact and destroy the boundary layer, accelerate the rate of convective heat transfer, and thus strengthen the heat transfer.

Figure. 7 shows the comparison of heat transfer capacity and pressure drop between the honeycomb gas cooler and the tube-in-tube gas cooler. Under the same condition, the heat transfer capacity of the four types of gas cooler is 1580W, 2457W, 4826W and 5065W respectively. The heating effect of honeycomb gas coolers with 1st level, 2nd level and 3rd level is improved by 55.5%, 205.4% and 220.6%. Although there is little difference between the heat transfer capacity Q of 2nd level and 3rd level, however, to achieve the same heat transfer capacity, only 8m tube length are needed for the 3rd level while 10m for the 2nd level. At the same time, the pressure drop of tube-in-tube gas cooler, 1st level and 2nd level honeycomb gas cooler has little change, while the pressure drop of 3rd level structure is almost five times of the former. This is because when the outer pipe diameter is unchanged, the equivalent diameter *de* of the micro-channel decreases with the increase of the number of levels. The equivalent diameter of the1st level honeycomb gas cooler is about 5.6mm, and the equivalent diameter of the 3rd level honeycomb gas cooler can be reduced to 0.9mm. When the flow rate is constant, the equivalent diameter decreases and the flow velocity increases, so the pressure drop of the 3rd level increases sharply.

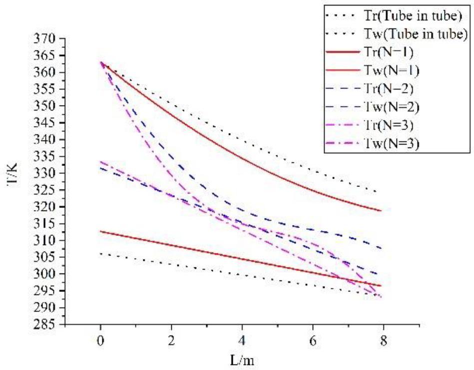

Fig. 6. Schematic diagram of fluid temperature variation along tube length of honeycomb gas cooler and tube-in-tube gas cooler.

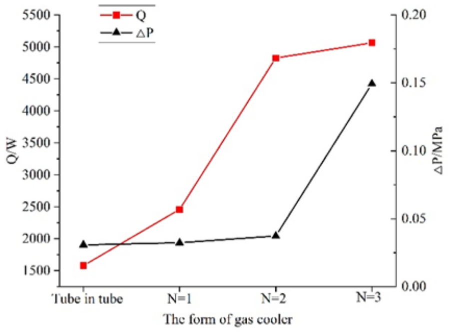

Fig. 7. Comparison of heat transfer capacity and pressure drop between honeycomb gas cooler and tube-in-tube gas cooler.

4 Conclusions

In this work, a biomimetic honeycomb gas cooler is proposed, the model of the gas cooler is established by using MATLAB software. Several conclusions can be drawn:

1) The reliability of the model is verified by literature data, and the maximum error is less than 3%
2) Under the same working condition, compared with the tube-in-tube gas cooler, the outlet temperature of the biomimetic honeycomb gas cooler with 1st, 2nd and 3rd level increased by 9.7℃, 25.4℃ and 27.3℃, and heat transfer can be increased by 55.5%, 205.4% and 220.6% respectively.

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