Thermal Science and Engineering (2022) Volume 5 Issue 2
doi:10.24294/tse.v5i2.1538

ORIGINAL RESEARCH ARTICLE

Study on performance of heat collecting evaporator of direct expansion solar heat pump

Jinzhou Yan, Kunhai Wang, Lin Xing, Xin Guan*

College of Energy and Power Engineering, University of Shanghai for Science and Technology, Shanghai 200093, China. E-mail: cindy_guan@hotmail.com

ABSTRACT

The heat collection evaporator was modeled based on equilibrium homogeneous theory, and the Runge-Kutta calculation method was used to analyze and solve the flow in the heat collection evaporator. The influence of environmental factors such as solar irradiance, ambient temperature and wind speed on the variation of refrigerant pressure in two kinds of heat collecting evaporator was analyzed under the set working conditions. The results show that the solar energy irradiance has a great influence on the pressure drop in the tube of serpentine heat collecting evaporator, and the maximum pressure drop of the refrigerant in the tube is 16.3%, minimum pressure drop is 7.8%. However, it has little influence on the pressure drop of the tube sheet evaporator. The maximum pressure drop in the refrigerant tube of the tube sheet evaporator is 4.8%, minimum pressure drop is 1.8%. When the irradiance reaches 800 W/m^2, the refrigerant in the serpentine-tube evaporator has been completely vaporized at 6 m, it's completely vaporized at 3 m.

Keywords: Direct Expansion Solar Heat Pump; Heat Collecting Evaporator; Equilibrium Homogeneous Theory; Pressure Drop

ARTICLE INFO

Received: 27 September 2022
Accepted: 1 November 2022
Available online: 17 November 2022

1. Introduction

Direct expansion solar heat pump technology has the advantages of high efficiency, energy saving and no pollution, and is widely used in many fields such as construction, chemical industry and environmental protection. Studies show that the average COP performance of direct expansion solar heat pump is significantly higher than that of traditional air source heat pump system, especially in winter[1]. The heat collecting evaporator is used as a direct expansion solar heat pump, and the performance of energy absorption components directly affects the performance of direct expansion solar heat pump system.

In terms of the research on heat collection evaporator, the research abroad started earlier. Chaturvedi *et al*.[2] carried out theoretical analysis on different types of solar heat collection evaporator. According to the two-phase flow homogeneous flow theory, the heat collection the flow of refrigerant in evaporator tube is modeled, and the glass cover plate, bare plate heat collector evaporator and six different refrigerants are used to heat direct expandable solar heat pump system respectively performance impact.

Domestic scholars Chen *et al*.[5] analyzed the relationship between the thickness of the air interlayer and the natural convection heat transfer coefficient, and then determined the optimal distance of the air interlayer of the flat-type heat collecting evaporator. Zhang *et al*.[6] made a detailed analysis of fluid flow in flat-plate heat collection evaporator through experimental analysis and theoretical research. Aiming at the research of refrigerant pressure drop in collecting tube of evaporator, Liu *et al*.[7] used two methods to study the refrigerant pressure drop in the collector tube of heat collecting evaporator. The phase flow theory establishes the mathematical model of solar heat collection evaporator, puts forward some assumptions to simplify the flow in the heat collection tube, theoretically analyzes the pressure drop in the heat collection evaporator, and explores the heat collection. Effects of structural parameters such as evaporator area, type and arrangement on performance of direct expansion solar heat pump system. Yang *et al*.[8] carried out experimental research and theoretical calculation on the performance of various solar heat collection evaporators, and finally analyzed the relationship between the fluid temperature at the collector inlet and the heat collection efficiency. Zhao *et al*.[9] established a two-phase flow model of solar heat collection evaporator by using the equilibrium homogeneous theory, and verified the reliability of the model through experiments. Kong *et al*.[10] established the distributed parameter homogeneous flow model of solar heat collector evaporator and condenser and the centralized parameter model of compressor and expansion valve according to the performance of different working medium, and compiled the performance simulation program of direct expansion solar heat pump water heater system to study direct expansion solar heat pump water heater. It is found that the calculated values of the theoretical model are in good agreement with the experimental results in the literature, which verifies the mathematics. Reliability of the model. Liu *et al*.[11] used Fluent software to analyze the heat transfer characteristics of different flow channel units of solar heat pump heat collector evaporator, and made a theoretical analysis on the optimization method of heat collector evaporator. Analysis and practical application.

The mobile phase of refrigerant in heat collecting evaporator is complicated. The flow of refrigerant in the tube is gas-liquid mixture, so that its pressure and dryness change in real time. Solar radiation, ambient temperature and wind speed are several factors that cause the variation of refrigerant flow in the tube. In order to analyze the influence of different factors on the performance of the heat collector evaporator in detail, this paper modeled the heat collector evaporator based on the equilibrium homogeneous theory. The Runge-Kutta calculation method is used to analyze and solve the flow in evaporator.

2. Model of solar collector evaporator

The flow of refrigerant in the tube follows the continuity equation, momentum equation and energy equation. According to the above assumptions, the steady-state equation of refrigerant flow in the heat collection evaporator can be established.

Equation of continuity:

$$G = \rho_m u = \text{const} \tag{1}$$

Momentum equation:

$$-\frac{dp}{dz} = \frac{\frac{2C_f}{D_i}(v_f + x v_{fg}) + v_{fg}\frac{dx}{dz}}{\frac{1}{G^2} + x\frac{dv_{fg}}{dp} + (1-x)\frac{dv_f}{dp}} \tag{2}$$

Energy equation:

$$m_r \frac{dx}{dz} = \frac{WF'}{h_{fg}}\left[S\tau(\alpha) - U_L(T_f - T_a)\right] \tag{3}$$

Thereinto:

$$v_m = \frac{1}{\rho_m} = \frac{x}{\rho_g} + \frac{1-x}{\rho_f} \tag{4}$$

In the above formula, ρ_m is the average density of refrigerant two-phase flow in the tube, kg/m^3; u is the flow velocity of refrigerant in the heat collecting evaporator tube, m/s; p is the pressure in the tube of refrigerant in the collecting tube of heat evaporator, Pa; h is the enthalpy of refrigerant in the heat collecting evaporator tube, J/kg; G is the mass flow rate of refrigerant on the cross-sectional area of unit collector tube of heat collecting evaporator, kg/(m·s); C_f is the friction coefficient of refrigerant flowing in the heat collecting evaporator tube; D_i is the inner diameter of the collecting tube of the heat collecting evaporator, m; m_r is the refrigerant in the set Mass flow in thermal evaporator tube, kg/s; x is the dry amount of refrigerant Degree; ρ_g and ρ_f indicate that the refrigerant is saturated in gas and liquid, respectively Density of kg/m^3; W is the distance between collector tubes, m; F' is the efficiency factor of heat collecting evaporator; S is solar irradiance, W/m^2; $\tau(\alpha)$ is the absorption rate of heat collecting plate in heat collecting evaporator; T_f is the temperature of refrigerant in the collector tube, °C; Ta is the ambient temperature, °C.

3. Solving the simulation process

Runge-Kutta calculation method is widely used in engineering, and its accuracy is very high, using a single step algorithm, mainly used for numerical calculation to solve differential equations. Runge-Kutta calculation method has high precision and some measures are taken to effectively control the error, so its calculation principle is complicated. The calculation method is built on the basis of mathematical theory. The Lagrange mean value theorem can be used to solve the differential equation for the first-order Runge-Kutta calculation method. The simulation solution process of the flow in the evaporator is shown in **Figure 1**.

$$p_{i+1} = p_i + \frac{h}{6}(k_1 + 2k_2 + 2k_3 + k_4) \tag{5}$$

$$x_{i+1} = x_i + hz_n + \frac{h^2}{6}(k_1 + k_2 + k_3) \tag{6}$$

$$k_1 = f(z_n, p_n, x_n) \tag{7}$$

$$k_2 = f\left(z_n + \frac{h}{2}, p_n + \frac{h}{2}z_n, x_n + \frac{h}{2}k_1\right) \tag{8}$$

$$k_3 = f\left(z_n + \frac{h}{2}, p_n + \frac{h}{2}z_n + \frac{h^2}{4}k_1, x_n + \frac{h}{2}k_2\right) \tag{9}$$

$$k_4 = f\left(z_n + h, p_n + hz_n + \frac{h^2}{2}k_2, x_n + hk_3\right) \tag{10}$$

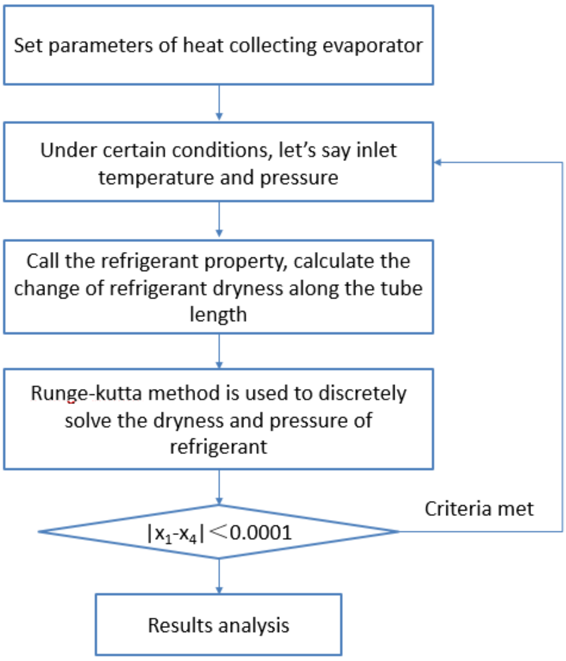

Figure 1. Flow simulation solution process in heat collecting evaporator**.**

4. Analysis of simulation results

4.1 Influence of solar irradiance on pressure and dryness

As shown in **Figures 2** and **3**, the solar energy irradiance directly affects the length of the heat collecting evaporator and the change of pressure in the heat collecting evaporator. Under the initial design condition, when the evaporation temperature, condensation temperature, ambient temperature and wind speed are fixed, the initial state of refrigerant is the same. By observing the change of irradiance, it can be found that the initial pressure in the tube is 412.5 kPa when the solar irradiance is 100 W/m^2, and the pressure of refrigerant when it is completely vaporized is 380.3 kPa. While the initial pressure in the tube is 412.5 kPa when the solar irradiance is 800 W/m^2. As the irradiance increases, the refrigerant in the tube absorbs heat. As the amount increases, the tube length becomes shorter and the pressure drop becomes smaller and smaller when the refrigerant is completely vaporized. When the solar irradiance is 100 W/m^2, the maximum pressure drop of the refrigerant in the tube is 16.3%. When the solar irradiance is 800 W/m^2, the minimum pressure drop of the refrigerant in the tube is 7.8%. Compared with the serpentine-tube evaporator, the maximum pressure drop in the refrigerant tube is 4.8%, while the minimum pressure drop is 1.8%. As shown in **Figures 4** and **5**, for the flow state, when the irradiance reaches 800 W/m^2, the refrigerant in the serpentine-tube heat collector evaporator has been completely vaporized at 6 m, while the refrigerant in the tube-plate heat collector evaporator, it's completely vaporized at 3 m. When the irradiance is 100 W/m^2, the refrigerant in the serpentine-tube heat collection evaporator should reach 12.8 m that can completely vaporize. While the refrigerant in tube-plate heat collection evaporator is in 2.8 m to vaporize completely. This is because that with the increase of solar radiation, the heat absorption of the refrigerant in the tube increases, and the refrigerant vaporization is accelerated, can be vaporized in a shorter tube length, the refrigerant pressure drop is reduced. Compared with the serpentine-tube evaporator, the tube-plate evaporator evaporates faster under the flow rate in a single tube, so the refrigerant completely vaporizes under the shorter tube length.

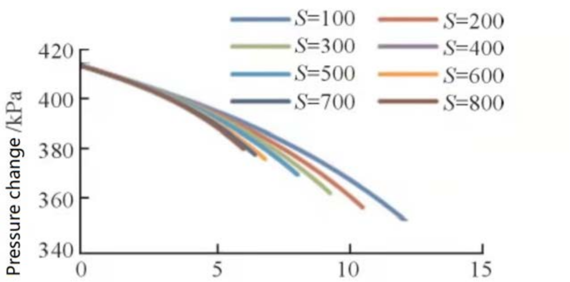

Figure 2. Evaporation of serpentine tube heat collector by solar irradiance**.**

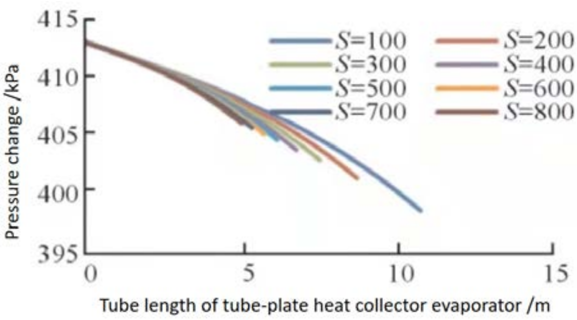

Figure 3. Evaporation of tube-plate heat collector by solar irradiance**.**

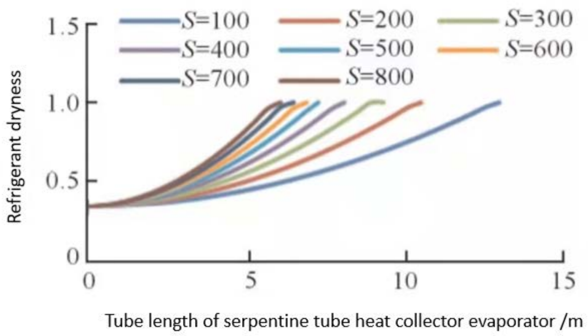

Figure 4. The dryness of refrigerant in serpentine tube heat collector evaporator changes along the tube length**.**

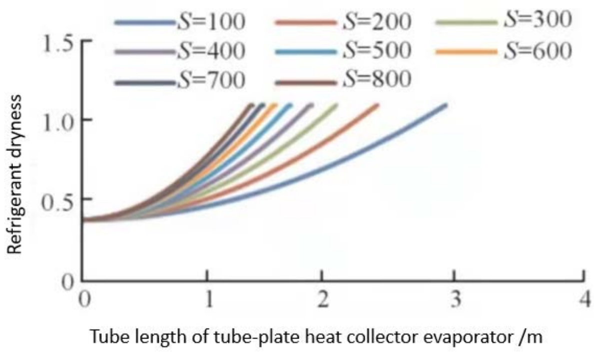

Figure 5. Tube plate heat collecting evaporator tube refrigerant dryness varies along tube length**.**

4.2 Influence of ambient temperature on pressure and dryness

In the initial design condition, when solar irradiance, condensation temperature and wind speed are constant, and the difference between ambient temperature and evaporation temperature is 5 °C, and the initial state of refrigerant is no longer the same. Observe the ambient temperature (Ta), for the serpentine-tube heat collection evaporator, it can be found that when the ambient temperature is 0 °C, the pressure in the tube is from the initial 242 kPa to 157.3 kPa when the complete vaporization, with pressure drop of 35%. When the ambient temperature is 25 °C, the pressure in the tube changes from 569 kPa initially to 540 kPa at complete vaporization, with a pressure drop of 5% (see **Figure 6**). When the ambient temperature increases, the evaporation temperature of the design parameter increases, so the initial pressure of the refrigerant in the tube increases. Therefore, it is necessary to choose reasonable evaporation temperature and ambient temperature when designing the heat-collecting evaporator. For tube-plate heat collection evaporator, the pressure drop is much smaller than that of serpentine-tube, and the average pressure drop is less than 5%, which can be basically ignored (see **Figure 7**). For the flow state, the state of the refrigerant inlet in the heat collecting evaporator is different, and the pipe length of the heat collecting evaporator is basically the same. When the refrigerant completely vaporizes in each working condition, at the same design condition, the initial condition is the same and the total flow in the tube is the same, but the flow in the single tube of the tube is small. Under the simulation condition, when the tube length is 1.7 m, it has almost completely vaporized (see **Figure 9**).

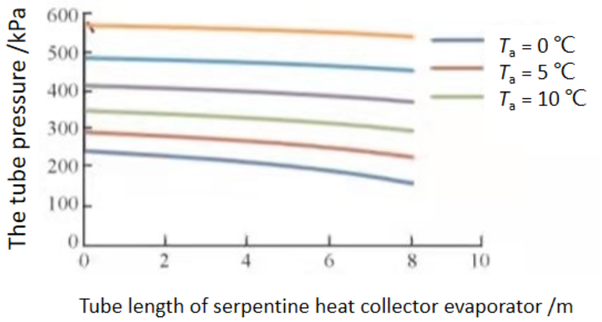

Figure 6. Evaporation of serpentine tube by ambient temperature.

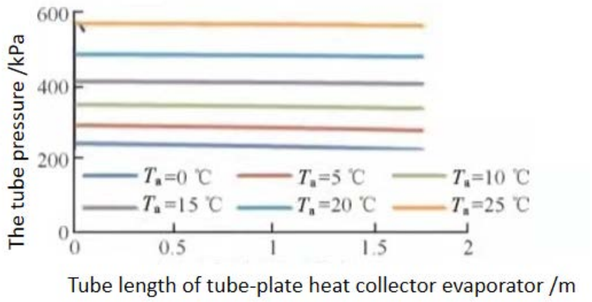

Figure 7. Simulation results of influence of ambient temperature on pressure in tube-plate collector evaporator.

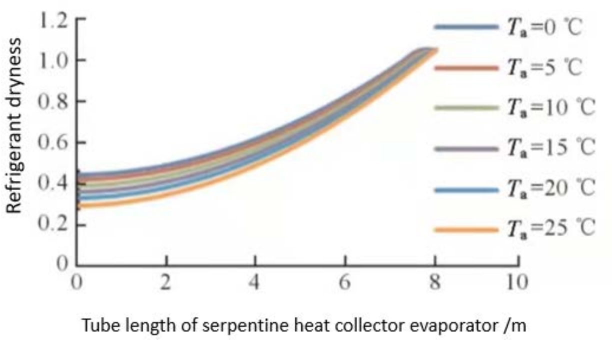

Figure 8. The dryness of the refrigerant in the serpentine tube heat collecting evaporator changes along the tube length.

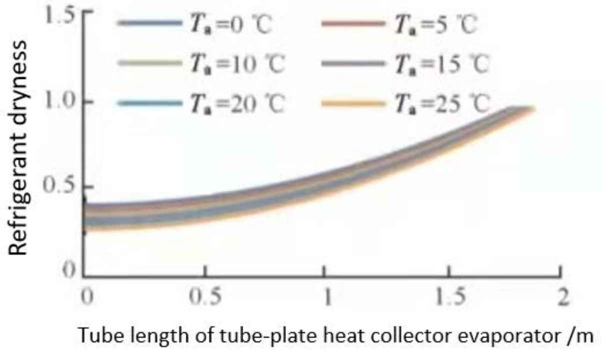

Figure 9. The refrigerant dryness changes along the tube length of the tube-plate heat collecting evaporator.

4.3 Influence of wind speed on pressure and dryness

When the wind speed is different and other external factors are the same, the initial state of the refrigerant in either the serpentine-tube heat collecting evaporator or the tube-plate heat collecting evaporator is basically the same as the pressure drop of the coolant changes very little. As the state lines of the image are too dense, no image.

Its maximum pressure drop is no more than 2%, which is basically negligible. The refrigerant import state is the same, with the increase of wind speed, the dryness of the refrigerant in the tube increases slowly. When the wind speed is less than 1 m/s, the length of the tube-plate heat collector evaporator reaches 8.4 m, the refrigerant is completely vaporized, and then under the condition of increasing wind speed, the length of the refrigerant is basically 8 m. Wind speed has little influence on the tube-plate heat-collecting evaporator. Under the setting condition, when the pipe length reaches 1.8 m, it has completely vaporized.

5. Conclusion

The equilibrium homogeneous theory is used to model the heat collection evaporator, and Runge-Kutta mathematical method is used to analyze and solve the flow in the collector evaporator. Under the set working conditions, we analyzed the influence of environmental factors such as solar irradiance, ambient temperature and wind speed on the pressure change and flow state of the refrigerant in the two heat collecting evaporators. The results show that:

(1) The solar irradiance has a great influence

on the pressure drop of the serpentine tube heat collector, while little influence on the tube-plate evaporator. When the irradiance reaches 800 W/m^2, the refrigerant in the serpentine-tube evaporator has completely vaporized at 6 m, and the refrigerant in the tube-plate evaporator is at 1.3 m;

(2) For the serpentine-tube heat collection evaporator, when the solar irradiance is 100 W/m^2, the maximum pressure drop of the refrigerant in the tube is 16.3%. When the solar irradiance is 800 W/m^2, the minimum pressure drop of the refrigerant in the tube is 7.8%.

(3) Compared with the serpentine-tube evaporator, the maximum pressure drop in the tube of the tube-plate evaporator is 4.8%, while the minimum pressure drop is 1.8%;

(4) The influence of ambient temperature and wind speed on the pressure drop and flow state of the refrigerant in the heat collecting evaporator is very little, and can be basically negligible.

Conflict of interest

The authors declare that they have no conflict of interest.

References:

1. Sun X, Dai Y, Novakovic V, *et al*. Performance comparison of direct expansion solar-assisted heat pump and conventional air source heat pump for domestic hot water. Energy Procedia 2015; 70: 394–401.
2. Chaturvedi SK, Chen DT, Kheireddne A. Thermal performance of a variable capacity direct expansion solar-assisted heat pump. Energy Conversion and Management 1998; 39(5): 189–196.
3. Ito S, Miura N, Wang K. Performance of a heat pump using direct expansion solar collectors. Solar Energy 1999; 65(3): 189–196.
4. Chata GFB, Chaturvedi SK, Almogbel A. Analysis of a direct expansion solar assisted heat pump using different refrigerants. Energy Conversion and Management 2005; 46(15-16): 2614–2624.
5. Chen Z, Ge X. Theoretical and experimental investigations on determination of the optimum air layer spacing of the flat-plate solar collector with small convective heat loss. Acta Energiae Solaris Sinica 1985; 6(3): 287–296.
6. Zhang Y, Yu Y. Optimal spacing determination of air layers for the flat plate solar energy collector. Journal of Hebei Institute of Technology 1992; 21(2): 101–109.
7. Liu L, Yin P. Study on the performance of a direct expansion solar assisted heat pump system. Journal of Shanghai Fisheries University 2008; 17(2): 247–250.
8. Yang X, Wu X, Liu A. Performance computation of a few kinds of solar collectors and comparison among them. Journal of Chongqing Jianzhu University 1997; 19(5): 98–101.
9. Zhao J, Liu L, Li L, *et al*. Investigation into the use of R134a in a direct expansion solar assisted heat pump. Journal of Tianjin University 2000; 33(3): 302–305.
10. Kong X, Li J, Li Y. Performance analysis of three different refrigerants in a direct-expansion solar-assisted heat pump water heater. Journal of Shanghai Jiao Tong University 2016; 50(4): 506–513.
11. Liu R, Wu J, Sun X. Analysis of collector/evaporator for direct expansion solar assisted heat pump water heater. Chinese Journal of Refrigeration Technology 2014; 34(2): 1–6.