Research of the Heat Transfer Characteristic for Compound Hollow Heat Pipe

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Abstract: **In order to solve the engineering problems of a large number of low-quality flue gas waste heat recovery and acid dew point corrosion leading to failure of the device easily, a new kind of heat transfer component named a compound hollow heat pipe was proposed. Its structure and working principle was introduced. Its internal heat transfer mechanism is analyzed, and its start-up characteristics, isothermal temperature performance and heat transfer properties were studied. The results show that compound hollow heat pipe can start and work fast while the outer tube wall temperature is 30 ℃ within 2 min heating time. And in the natural air convection cooling conditions, it has good isothermal characteristics. The heat transfer coefficient of the compound hollow heat pipe increases with the cooling water Reynolds number. When the heating steam temperature is below 125 ℃ and the cooling water Reynolds number is 6650, the heat transfer coefficient of the compound hollow heat pipe is1350 W.m^{-2}.℃$^{-1}$. Experimental results of the compound hollow heat pipe provide the basis of engineering applications for heat exchanger.**

Keywords: *the compound hollow heat pipe; waste heat recovery; saving energy; enhancement of heat transfer characteristic*

1 INTRODUCTION

Heat pipe is a thermal element of high heat transfer characteristic [1]. In all of the heat pipes, two-phrase closed thermosyphon has more simple structure and excellent characteristic so that it is made of heat pipe air preheater, heat pipe waste heat boiler, heat pipe economizer and other energy-saving equipments, and they play an important role in recycling industrial waste heat[2-8]. However, heat pipe exchangers have some problems in industry, for example, gray block in the fin, acid dew point corrosion and so on. In order to avoid acid dew point corrosion, the flue gas temperature is generally controlled at above 180℃. There is massive low quality flue gas of which the temperature is below 180℃ in the industry. In order to use waste heat of 180 ℃ below low quality flue gas and avoid acid dew point corrosion, the compound hollow heat pipe was proposed. It can enhance the flow of vapor phase and liquid phase in heat pipe, and make temperature of the tube wall of flue gas side keep relatively high, which can avoid acid dew point corrosion and improve equipment reliability. The heat transfer efficiency, startup characteristic, isothermal characteristic and heat transfer characteristic of compound hollow heat pipe were studied by experiment. The results can provide reference for industrial applications of compound hollow heat pipe.

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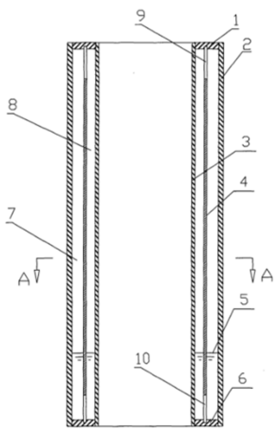
2 THE HEAT TRANSFER CHARACTERISTIC OF COMPOUND HOLLOW HEAT PIPE

2.1 Structure and Working Principle

The structure and working principle of compound hollow heat pipe are shown in figure 1. It is composed of the inner tube, outer tube and intermediate tube. The outside circular chamber is encircled by outer tube and intermediate tube around and the inside circular chamber is encircled by intermediate tube and inner tube around. The outside circular chamber and the inside circular chamber are connected by the upper and lower notch, and both ends of the inner tube and outer tube are sealed by shell cover. Some of the working media are filled in the tube which is pumped into vacuum. When the inner wall of the inner tube is heated, the working media in the inside circular chamber will be vaporized and vapor will go through upper notch from the inside circular chamber to the outside circular chamber due to pressure difference function. Vapor will be condensed in outside circular chamber and condensed water flow back to the inside circular chamber through the lower notch, then it will be vaporized and condensed again, this process is circulated continuously. The heat of flue gas of inner tube is transferred continuously to cool water of the outer tube.



1.upper seal cover ;2.outer tube; 3.inner tube; 4.middle tube; 5.working media; 6.under seal cover; 7.outer annular chamber; 8. inner annular chamber; 9. upper notch; 10. under mouth;

Fiureg1. The structure and work principle of complex hollow heat pipe

2.2 Analysis of the Enhanced Heat Transfer Mechanism

When the compound hollow heat pipe works, nucleate boiling is the main vaporization form in evaporation section, and the nucleate boiling heat transfer mechanism shows liquid overheated boundary layer plays a decisive role in the bubble growth process [9], and the micro-relaxation model thinks that the overheated layer around the lower side of the bubble plays a decisive role in the growth of the bubble of heating wall. H* is distance between overheated liquids layer to the wall, H is the height of bubble and θ is the wetting angle in figure 2. The temperature and thickness of overheated liquids layer will change with growth process of the bubble, so this called relaxation microlayer. The overheated liquids layer will provide heat to bubble evaporate through thermal conductivity.

The heat transfer coefficient of nucleate boiling for the compound hollow heat pipe is higher than that of the two-phrase closed thermosyphon. Because there is the middle tube in the compound hollow heat pipe, nucleate boiling becomes more intense. There are several reasons :(1) The spalt between the middle tube and inner tube can inhibite radial growth of the bubble and enhance horizontal growth of the bubble, it increases greatly the area of overheated liquids layer heating the bubble in figure 3. (2) During the growing process of the bubbles, the bubbles will collide with each other, which will disturb the liquid and strengthen the boiling heat transfer.

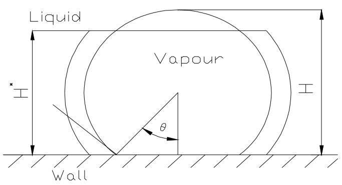


Figure2. The relaxation microlayer model of nucleate boiling

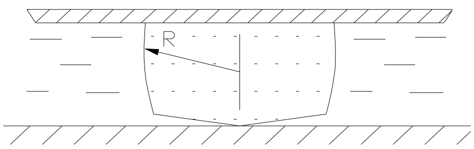


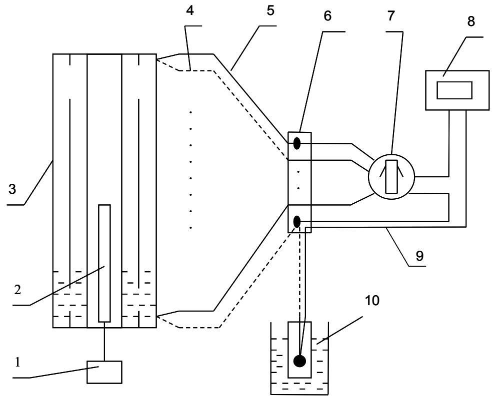
Figure.3. The grow of bubbles between middle tube and inner tube

3 EXPERIMENT AND METHODS

3.1 Experiment of Startup and Isotherm

The startup and isothermal characteristics are important indexes to weigh the heat transfer characteristic of compound hollow heat pipe. The size and material of compound hollow heat pipe for start-up and isothermal characteristics test are shown in table 1. And the compound hollow heat pipe is filled with a certain amount of special organic media as working fluid.

Experimental device is shown in figure 4. The compound hollow heat pipe is heated by electrical heating rod and cooled by air in the condition. Outer tube wall is furnished six pairs of K-type thermocouples and thermocouples are distributed in 200mm,400mm,600mm,800mm, 1000mm and 1150mm location from the top to the bottom of the compound hollow heat pipe. Another end of thermocouple is inserted in the mixture of ice and the temperature is recorded by a digital temperature indicator.



1. regulator 2. heater 3.complex hollow heat pipe 4.thermocouple 5.compensation wires 6.wiring board 7.switch 8.temperature indicator 9.copper wire 10. mixture of ice and water

Figure 4. The schematic diagram of experimental setup for isothermal characteristic test

3.2 Test of Heat Transfer Characteristics

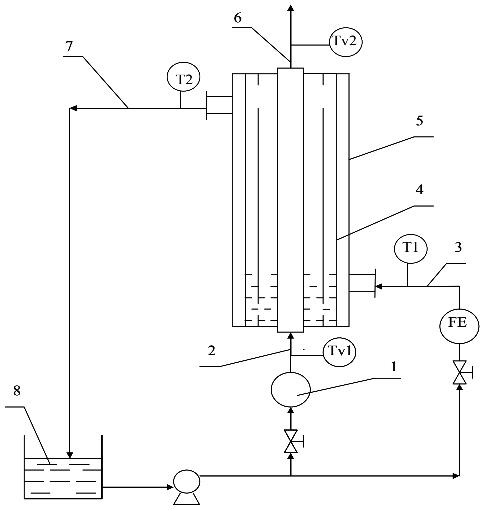
Experiment of heat transfer characteristic is to obtain thermal conductivity of the compound hollow heat pipe, while experimental device is shown in figure 5. And it is composed of compound hollow heat pipe, cooling water jacket, a steam boiler, water tanks, a pump and temperature and flow testing

Table 1 the Size and Material of Compound Hollow Heat Pipe for Start-up and Isothermal Characteristic Test

Name	Length (mm)	Outer tube (mm)	Inner tube (mm)	Middle tube (mm)	Upper notch (mm)	Under mouth (mm)	Working media	Materials
Compound hollow heat pipe	1200	Φ60×1.2	Φ38×2.2	Φ50×0.4	150	50	Organic media	Stainless steel

Table 2. the Size and Material of Compound Hollow Heat Pipe for Heat Transfer Characteristic Test

Name	Length (mm)	Outer tube (mm)	Inner tube (mm)	Middle tube (mm)	Upper notch (mm)	Under mouth (mm)	Working media	Materials
Compound hollow heat pipe	1080	Φ60×1.2	Φ38×2.2	Φ50×0.4	150	50	Organic media	Stainless steel



1. steam boiler 2. steam inlet 3.cooling water inlet 4.complex hollow heat pipe 5.cooling water jacket 5.steam outlet 6.cooling water outlet 7.circulating pool,8. water tanks. FE-cooling water flow measurement sensor, Tv1,Tv2, T 1,T2- inlet and outlet temperature of steam and cooling water separately

Figure5. The schematic diagram of experimental setup for heat transfer characteristic test

instruments. When experiment starts, superheated steam goes along the pipeline and water goes along water jacket. Temperature (inlet and outlet) of steam and jacket water are measured through the Pt-100 temperature sensor, while steam flow is regulated by the valve. And water flows are measured by the LWGY-25BBG type turbine flow sensor. The heat transmission of compound hollow heat pipe is similar to the sensible heat of water absorption in water jacket which is calculated by formula :Q=Cp.M.△t, and thermal conductivity is calculated by formula: Ki=Q/(Ai△tm), for them, Q is the heat transfer (KW), and Cp is specific heat capacity($kj.kg^{-1}℃^{-1}$),and also M stands for the cooled water flow($kg.s^{-1}$), △t: temperature difference between import and export cooled water(℃), Ki: thermal conductivity in base of compound hollow heat pipe inner tube surface ($W.m^{-2}.℃^{-1}$), Ai: inside surface area of inner tube(m^2), △tm: logarithmic-mean temperature difference(℃).

The size and material of compound hollow heat pipe are shown in table 2.

4 EXPERIMENTAL RESULTS AND ANALYSIS

4.1 Starting-up and Isotherm Performance Test Results and Analysis

Experimental results show that the compound hollow heat pipe starts very quickly. When the wall is heated about 2 minutes and temperature increases to 30 ℃ , a slight discontinuity sound is similar to the crisp sound which is produced by bullet hit the metal. This shows that the heat pipe has begun to start working. The working fluid can be easily

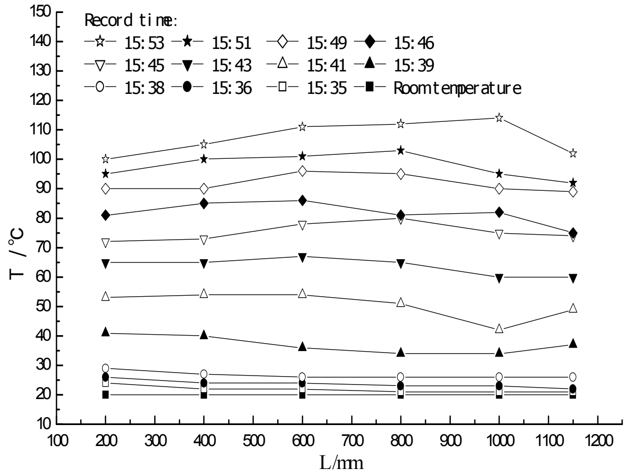


Figure 6. The outer tube wall temperature distribution curve of compound hollow heat pipe

evaporated under the vacuum state. The crisp metal crash is the sound of steam carrying with droplets impact of metal end cover. When the wall is heated about 4 minutes and temperature increases to 38℃, the crisp metal crash starts continuous, and it shows that the media exacerbates evaporation. When the wall is heated about 6 minutes and temperature increases to 50℃, the crisp metal crash becomes increasingly loud, and after continuing some time, the sound becomes smaller. When the wall is heated about 10 minutes and temperature increases to 70 ℃ , the sound almost disappears. In addition to hearing the sound similar to the crisp sound produced by bullet hit the metal, there is also a phenomenon top of the wall temperature rises rapidly.

The temperature distribution curve with the compound hollow heat pipe outer wall in different locations at different times in the natural air convection cooling conditions is shown in figure 6. It can be seen that the compound hollow heat pipe has not only good isothermal characteristic but also start-up characteristic from figure 6. The length of test heat pipe is 1200 millimeters, and electrical heating rod is 50 millimeters. Environmental temperature is 21℃, and electric heating rods start at 15:35. The wall temperature of heat pipe increases to 40 ℃ quickly for upside and downside locations. With the increasing of time, the wall temperature is also rising. It also repeatedly finds that temperature has a little fluctuation for 1000mm measuring point position (the fifth point from top to bottom). Calculated by liquid-filled, this point is likely to stay interface of vapor-liquid. The temperature fluctuations reflect in heat pipe with the compound phase change heat transfer and mass transfer process at the gas-liquid interface. In the condition of natural air convection cooling, recorded time is at 15:49, 15:51, 15:53. With the improvement of heating power, it is difficult for steam to be cooled. So the temperature gradually increases relatively fast in central location (600mm, 800mm and 900mm measuring point) of compound hollow heat pipe.

4.2 Experimental Results and Analysis of Heat Transfer Characteristics

The relation-curve between heat transfer coefficient and Reynolds number of cooling water is shown in figure 7. It can be seen that the heat transfer coefficient of the compound hollow heat pipe increases with the increasing of cooling water Reynolds number from figure 7. When the Reynolds number is around 2000(transition flow), the heat transfer coefficient is about 900W.m^{-2}.℃$^{-1}$. When the Reynolds number is around 4000 (turbulence flow), the heat transfer coefficient rapidly increases to 1300W.m^{-2}.℃$^{-1}$, and average growth rate is 17.5%. When the Reynolds number increases more than 4000, the flow fully develops into turbulence, and now the increasing rate of heat transfer coefficient becomes smaller. When the Reynolds number is around 6650, the heat transfer coefficient is about 1350W.m^{-2}.℃$^{-1}$, and average growth rate is 5%.

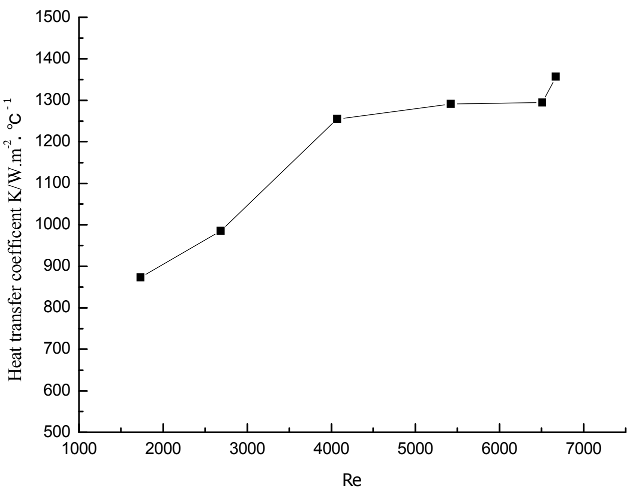


Figure 7. The relation curve between heat transfer coefficient and Re number of cooling water

5 CONCLUSIONS

The compound hollow heat pipe can start and work fast when the outer tube wall temperature is 30 °C. And in the natural air convection cooling conditions, it has good isothermal characteristic. The heat transfer coefficient of the compound hollow heat pipe increases with the improvement of Reynolds number of cooling water. When the temperature of superheated steam is below 125 °C and the Reynolds number of cooling water is 6650, the heat transfer coefficient of the compound hollow heat pipe is1350 W.m^{-2}.°C^{-1}. In addition, it is necessary to adopt further exploration, for example, visualization, PIV flow field measurement or numerical simulation, to research the micro-channel evaporation and mechanism of phase-change heat and mass transfer with condensation of compound hollow heat pipe.

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