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EXPERIMENTAL STUDY ON SEMI-OPEN HEAT PIPES AND ITS APPLICATIONS

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Abstract: Semi-open heat pipes were studied experimentally in this work. A new kind of semi-open heat pipe with fluid swirl backflow was developed on the basis of the traditional semi-open heat pipe. Heat transfer characteristics during operation and start-up of closed heat pipe、traditional semi-open heat pipe and swirl flow semi-open heat pipe were investigated. The swirl orifice's backflow effect on enhancing the working limitation was obtained. Heat exchangers or waste heat boilers made of swirl flow semi-open heat pipes and semi-open heat pipes have been successfully used in high or variable gas temperature engineering applications.

Key words: semi-open heat pipe，swirl flow semi-open heat pipe，heat transfer limitation
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INTRODUCTION

Heat pipes are widely used in waste heat recovery systems. Traditional gravity heat pipe（CHP）is composed of inside working fluid and outside closed shell with high vacuum state inside it. Some problems were found during the industrial applications of closed heat pipes（Au et al.，2000；Lin et al.，2000；Tu et al.，1989；Tu et al.1990）included:

1. Carbon-steel-water heat pipe is used mostly in industry. But because of the incompatibility between the carbon-steel shell and the inside water，the treatment of the heat pipes' inner surface should be especially of first class.

2. The production cost of heat pipe heat exchangers is much higher than that of the ordinary heat exchangers because of the special surface treatment and vacuumization.

3. The working temperature and pressure will rise suddenly and cause the heat pipe to break when the condensing segment does not cool effectively and the heating segment continues to absorb heat from the heat source.

4. The existence of non-condensable gas in the closed heat pipe system is inevitable because of unavoidable quantitative fluctuation during manufacturing and the complexity of installation and running conditions. Sometimes it becomes the important factor lowing heat pipe performance.

Use of closed heat pipes in waste heat boiler leads to the following problems:

（1）To prevent leakage，heat pipes should be welded to the wall of the drum，but the inside surface membrane of the heat pipe will be destroyed during welding.

（2）There should be enough water in the boiler's drum，otherwise，the heat pipe will explode when working temperature inside the CHP rises to beyond 300 ℃.

（3）To keep heat pipe work normally and safely，the threshold of gas temperature must not exceed 650 ℃.

In view of the above problems，we developed the semi-open heat pipe（SOHP）and the swirl flow semi-open heat pipe（SFSOHP）further，as shown in Fig.1. The SOHP or SFSOHP need not be vacuumized and the treatment of the surface is quite simple，so the production cost is decreased greatly. The non-condensable gas generated in operation can be discharged from the top orifice at any time, and pipe explosion at high temperature or fierce fluctuation of heat source temperature will not occur. When working under high temperature, the swirl flow semi-open heat pipe can keep the working fluid flow back to the heating section to counter the increase of wall temperature and avoid the dry-out limitation. So the working limitation of heat pipes are improved apparently. But studies on such kind of heat pipes are few and most of them were done by us (Tu et al., 1987; Tu et al., 1988; Tu et al., 1989; Tu et al., 1990; Zhu et al., 1991; Zhu et al., 1992; Zhu et al., 1993).

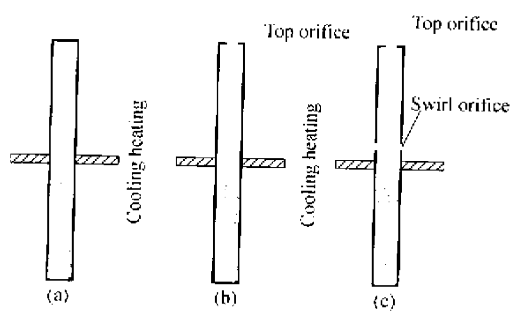

Fig.1 Kinds of gravity heat pipes
(a) The closed heat pipe (CHP);
(b) the semi-open heat pipe(SOHP);
(c) the swirl flow semi-open heat pipe(SFSOHP)

EXPERIMENT OF FLOW PATTERNS

Flow pattern is the major factor affecting the flow and heat transfer performance of fluids. The heated flow inside a semi-open heat pipe is two-phase flow; and liquid and vapor inside the heated heat pipe can form various patterns under different conditions. So it is very important to investigate the performance and mechanisms of heat transfer of a system by analyzing its flow patterns or geometrical figures. Presently, flow pattern determination is by direct observation, high-speed photography, ray measurements, and so on. To study two-phase flow at low speed, direct observation through a transparent channel that is accurate and easy is often used. For two-phase flow at high speed, high-speed photography can be used to improve resolution. But reflection and refraction will occur at the interface. X-ray photography is helpful for reducing the distortion of ordinary photography and for investigating through the opaque channel of a heated wall. Moreover, some kinds of probes can be used to get some indirect information from which to infer flow patterns(Katto et al., 1991; Kusuda et al., 1973).

Direct observation was chosen to investigate the flow patterns and working processes of the semi-open heat pipe. Three different diameter semi-open heat pipes using water as working fluid were made with glass tube. The heating section was heated by glycerol, and the condensing section was cooled by water in a glass-jacket. As the smoothness of the glass would cause instability of boiling, which made it impossible to mimic metal, the inner wall of the glass tubes was specially treated to make the boiling process stable and perfect.

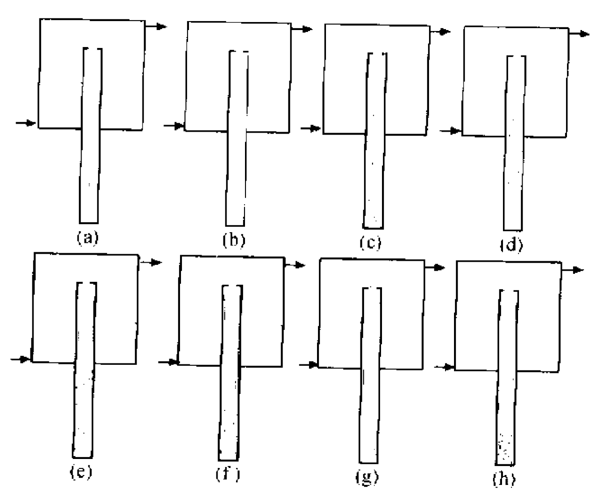

Fig.2 Working process of SOHP
(a),(b)working fluid auto filling process;
(c),(d)startup process;
(e)operating stage(low working state);
(f)operating stage(the ideal state);
(g)operating stage(high working state);
(h)heat transfer limitation

Fig. 2 shows the complete working process and flow patterns of the semi-open heat pipe. Where,

(a) and (b) show the first stage, that is auto filling of working fluid. Heat pipe is completely dry at first. Air inside is discharging when the heating section of SOHP is heated and then the SOHP is filled with water.

(c) and (d) show the second stage, that is startup. During continous heating in the heating section, vapor bubbles generate、expand、rise and merge; the liquid column above the big vapor bubble strikes the top of the heat pipe. The boil hot heating section contains vapor bubbles. In the cooling section, it is just single phase heat transfer. So, the heat flow rate of the SOHP at this time is very small.

(e) to (g) show the third stage, that is operating normally. Heat is transferred effectively by SOHP at this stage. In the heating section, a certain amount of vapor is generated mainly by nucleate boiling. Vapor condenses on the wall in the cooling section. At stage (e) in Fig.2, an upper cooling section whose length is justified by its heat loading is not used because of the shortage of vapor at the low working state. At stage (g) in Fig.2, film boiling is magnified in the upper heating section and a small amount of vapor condenses directly in the water seal above the top orifice as the thermal load increases. In summary, Fig.2(e) shows the working condition before the first turning point (low working state). Fig.2(f) shows the working condition just at the first turning point (the ideal state). Fig.2(g) shows the working condition after the first turning point (high working state). Fig.2(h) is the SOHP at its heat transfer limitation. It is the second turning point of SOHP, the state of "dry out". If the heat flow rate in the heating section is too large, the liquid surface of the boiling pool will fall to a low level that causes the breaking of the liquid film on the pipe wall in the heating section.

THE INVESTIGATION OF STARTUP PROCESS

The experimental setup is shown in Fig.3. The semi-open Φ 25 × 2.5 heat pipe is used.

Fig.4 shows the variations of working pressure inside the SOHP and the amount of heat transfer with time. P_1 is the pressure inside the SOHP near the top orifice. P_1 increases during startup and equals ambient pressure during normal working state. P_2 is pressure in the middle of the cooling section which is the center of the vapor column, so it stays at a certain value when the SOHP is working normally in certain states. P_3 is pressure at the end of the cooling section remains at vacuum state as vapor condenses during the operating stage.

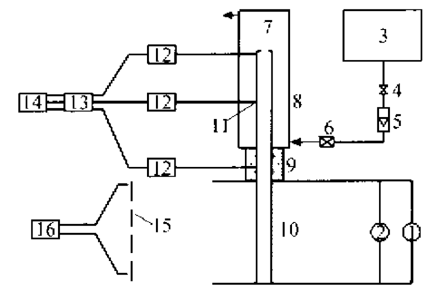

Fig.3 Experimental setup

1. power supply; 2. power meter; 3. water tank; 4. stop-valve;
5. rotameter; 6. regulator vavle; 7. liquid seal;
8. water-jacket; 9. insulator layer; 10. electric heater;
11. pressure transmitter; 12. resistance bridge box;
13. electrical resistance strain gauge; 14. oscilloscope;
15. thermocouple system; 16. data collecting device

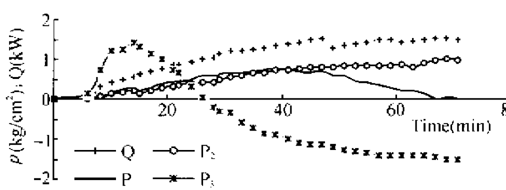

Fig.4 Variations of working pressures (p) and heat flow (Q) inside the SOHP

EFFECT OF SWIRL ORIFICE ON HEAT TRANSFER PERFORMANCE

Our investigation showed that there was pressure decrease inside the SOHP, as was the case with the CHP (Rohani et al., 1974; Wedekind et al., 1989) because of the similar process of phase change during operation although the two heat pipes were seemingly different in configuration. Therefore, it is practical in theory to bore a set of orifices on the pipe wall near the bottom of condensing section to backflow the filling liquid when the heating section lacks working fluid. Such kind of semi-open heat pipe is called swirl flow semi-open heat pipe. An experimental setup similar to that in Fig.3 was used to study the effect of backflow and the influence on the heat transfer performance of the SFSOHP with a pair of orifices. The effect on heat transfer is shown in Fig.5. For ordinary SOHP, the second turning point, "dry out", occurs earlier than in SFSOHP. The region of operation is extended in SFSOHP. Fig.6 shows wall temperature distributions along SFSOHP、SOHP and CHP , all of which were of the same length.

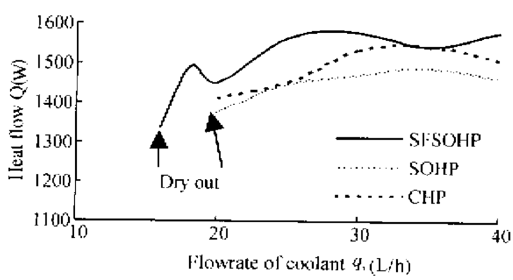

Fig.5 Comparison of heat flow in CHP、SOHP、SFSOHP

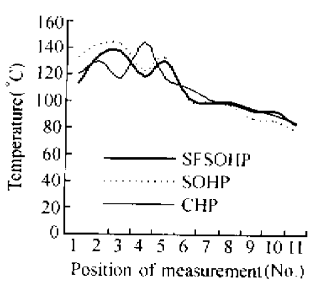

Fig.6 Comparison of wall temperature distributions

At working condition before or around the first turning point, the backflow effect of the swirl orifices was faint and had no influence on the wall temperature. When the working condition reached the second turning point, the wall temperature rose and the backflow effect of the orifices became gradually obvious. The noise of the absorbed liquid could occasionally be heard, but the outlet temperature of cooling water kept constant. When working condition reached and then exceeded the second turning point, the backflow effect of the swirl orifices was notable, and the periodical noise of the absorbed liquid could be heard. Its frequency rose with the increase of heat load. The wall temperature at the broken water film's position in the heating section fluctuated periodically while the other wall temperatures still remained steady or fluctuanted lightly(according to the strength of backflow), and outlet water temperature was also steady (Fig.7). The undulating period of wall temperature was inversely proportional to heat load, while the area and amplitude of fluctuation were directly proportional to heat load.

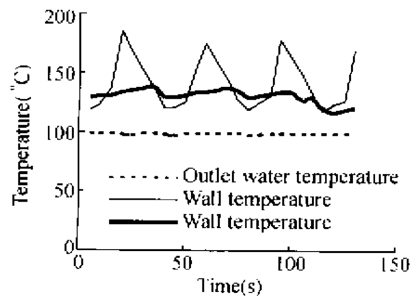

Fig.7 Variations of temperature with time

CONCLUSIONS

The above test results showed that SOHP and SFSOHP can operate normally as conventional heat pipes. SFSOHP can bear higher heat flow rate and heating temperature than SOHP.

APPLICATIONS

Semi-open heat pipe is widely used in gas-water heat exchangers、gas-gas heat exchangers、gas-gas-water heat exchangers and waste heat boilers. When gas temperature is high enough (700℃ ~ 900℃ or more) or the change of gas temperature is great, heat exchangers using swirl flow semi-open heat pipes will perform ideally as shown in the above tests and also by industrial applications. Fig.8 shows its application in

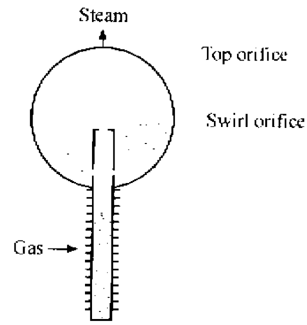

Fig.8 Applications of SFSOHPs in waste heat boilers

waste heat boiler. It can be used independently, and also used together with ordinary semi-open heat pipe、closed heat pipe and so on. There are several of this kind of heat exchangers and waste heat boilers used in steel industry and industrial furnaces. They all operate normally and have good performance.

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