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Experimental study on transient behavior of semi-open two-phase thermosyphon

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Abstract: An experimental system was set up to measure the temperature, pressure, heat transfer rate and mass flow rate in a semi-open two-phase thermosyphon. The behaviors of a semi-open two-phase thermosyphon during startup, shutdown and lack of water were studied to get complete understanding of its thermal characteristics. The variation of wall temperature, heat-exchange condition and pressure fluctuations of semi-open two-phase thermosyphons showed that the startup of SOTPT needs about 60~70 min; the startup speed of SOTPT is determined by the startup speed of the condensation section; the average pressure in the heat pipe is equal to the environmental pressure usually; the shutdown of SOTPT needs about 30~50 min; a semi-open two-phase thermosyphon has good response to lack of water accident.

Keywords: Semi-open two-phase thermosyphon (SOTPT), Transient heat transfer, Startup, Lack of water, Shutdown
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INTRODUCTION

A semi-open two-phase thermosyphon (SOTPT) has advantages of simple structure, good performance, easy manufacture and safe operation, and is widely used in heat recovery systems and other fields of heat-exchange. The SOTPT shown in Fig.1a has a structure similar to that of a closed two-phase thermosyphon (CTPT); but differs from a CTPT by having a top orifice enclosed by a water seal that secludes the room inside heat pipe from the outer atmosphere. At present, the characteristics and applications of SOTPTs have been thoroughly researched (Tu *et al*., 1989; Zhu *et al*., 1992; 2001). The startup dynamics of a standard heat pipe and the variation of transient pressure in the course of steam condensation have been studied experimentally and theoretically (Ivanovaki, 1987; Wedekind and Bhatt, 1989). The transient heat transfer characteristics of closed two-phase thermosyphon had been researched experimentally and theoretically (Farsi *et al*., 2003), but research on the transient heat transfer characteristics of SOTPT remains blank.

EXPERIMENT METHOD

SOTPTs with outside diameter of 25 mm and wall thickness of 2.5 mm are made of copper. The length of the evaporator section is 650 mm; the length of the adiabatic section is 200 mm, and the length of the condensation section is 500 mm. Three types of SOTPT are used: mixed type (SOTPTM), separated type (SOTPTS), with internal tube type (SOTPTI). The structures of the three SOTPT types are shown in Fig.1a. Water is the working liquid. Fourteen pairs of chromel-constantan thermocouples were used with measurement accuracy of ±0.5 °C. The cooling water was supplied by high level tank and the mass flow rate was measured by an LZB-6 rotameter flowmeter with measurement accuracy of ±2.5%. Power provided by an electric heater is measured by a D26-W wattmeter, a D26-A amperemeter and a D26-V voltmeter, with measurement accuracy of ±0.5%. The pressure was measured by BPR-10 pressure transmitters, whose signals are magnified by a YD-15 electrical resistance strain gauge, and the pressure wave is shown by a SC16 oscilloscope. The test system is shown in Fig.1b.

RESULTS AND DISCUSSION

SOTPT startup analysis

In Fig.2, T_1 shows the temperature distribution after 5 min heating up by an electric heater. When the evaporator section temperature begins to rise, and the condensation section temperature remains unaffected, there is still free convection inside the heat pipe. T_2 shows the temperature distribution after 10 min heating up when the evaporator section has turned into a nucleate boiling state, while the condensation section discharge excess water, gradually forms a vapor chamber. T_3 shows the temperature distribution after one hour heating up, and the condensation section, from which discharge of excess water through the top orifice has stopped, has turned into a steady vapor chamber, when, in general, the startup of the semi-open two-phase thermosyphon has come to an end.

In Fig.3, SOTPTM has nearly the same speed of startup as SOTPTS. The latter is a little faster than the former during the early phase of the startup because its water seal has little influence on the operation inside the heat pipe. Compared with the other two types, SOTPTI has the fastest startup speed because of the internal tube, which has the following effects: first, it rapidly changes the state of free convection; second, it enhances capillary effects which promote the heat transfer from evaporator section to condensation section and water seal; finally, it accelerates the discharge of excess water. Its startup speed as well as heat flux is up to twice that of the other two SOTPTs, but the time needed to fully reach steady state is about the same as that of SOTPTM.

As shown in Figs.4–5, the SOTPT evaporator section is very fast in startup and transition, but the condensation section is fairly slow. The reason is that at the beginning, the condensation section is full

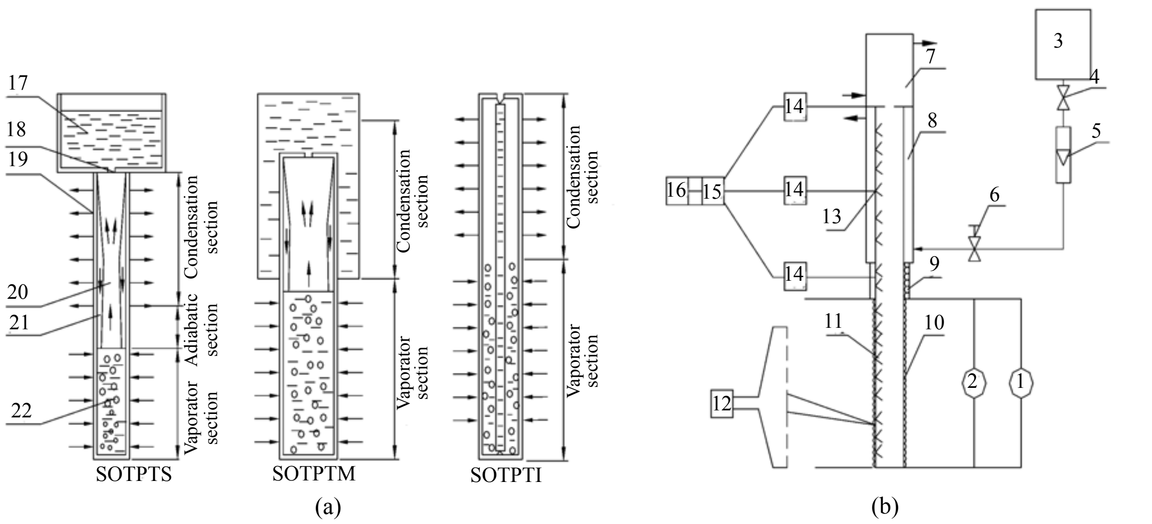

Fig.1 SOTPT structure and the schematic diagram of experimental apparatus
1: power supply; 2: power meter; 3: water tank; 4: stop valve; 5: rotameter flowmeter; 6: regulator vavle; 7: liquid seal; 8: water-jacket; 9: insulator layer; 10: electric heater; 11: thermocouple; 12: data collecting device; 13: pressure transmitter; 14: resistance bridge box; 15: electrical resistance strain gauge; 16: oscilloscope; 17: liquid seal; 18: top orifice; 19: pipe shell; 20: vapor flow; 21: condensate film; 22: water pool

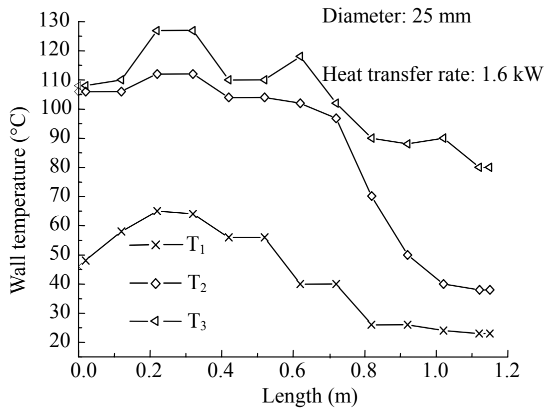

Fig.2 SOTPT wall temperature distribution with time

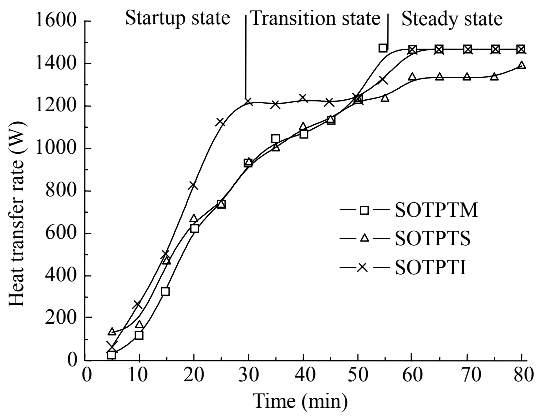

Fig.3 The energy transfer change of SOTPT during startup

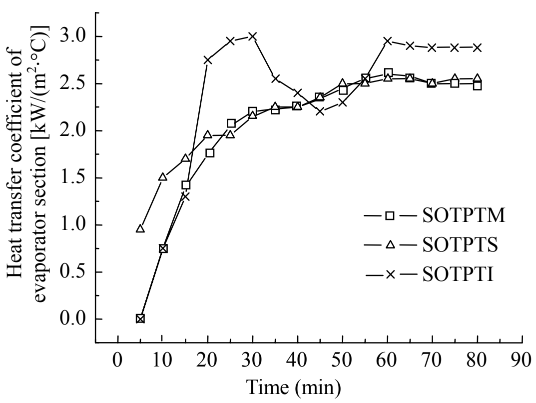

Fig.4 Variation of the evaporator section heat transfer coefficient during startup

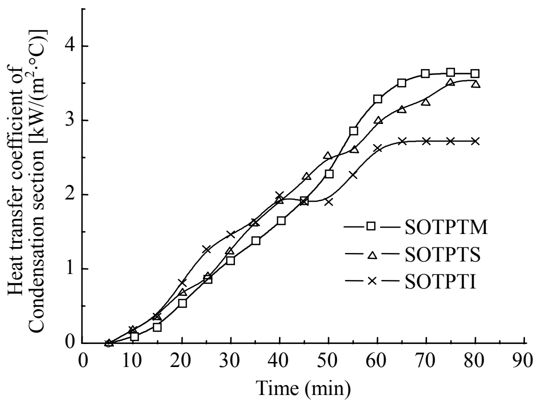

Fig.5 Variation of the condensation section heat transfer coefficient during startup

of cold water, needs time to discharge excess water and forms a steady state vapor chamber after startup. The SOTPT startup speed is mainly determined by the startup speed of its condensation section. The heat transfer performance of SOTPTM and SOTPTS are very similar, but different from those of SOTPTI, where the evaporator section's liquid boundary film becomes thinner because of the presence of the inner tube, so the startup and transition of the evaporation section are very rapid; and the heat transfer performance of the evaporation section is also better than that of the other two type semi-open thermosyphon. SOTPTI's heat transfer performance of the condensation section is a little better than that of SOTPTM and SOTPTS in the midst of the startup, but worse than that of SOTPTM and SOTPTS after becoming steady.

Fig.6 shows the evolution of pressure and heat transfer rate with time during the startup of SOTPTM. P_1 is the pressure near the top orifice. P_2 is the pressure at the center of the condensation section. P_3 is the pressure of the adiabatic section. The environmental pressure is a norm of P_1, P_2 and P_3, which are all relative, averaged pressures. As can be seen from the figure, P_3 increases rapidly with the rapid startup of the evaporator section. Bubbles emerge rapidly after the startup of the evaporator section, and the vapor chamber lies in adiabatic section at first, which causes the rapid increase of pressure in the adiabatic section. The vapor chamber then moves out of the adiabatic section to the evaporator section. So P_2 increases gradually. Owing to the discharge of liquid at the beginning of startup, P_1 influenced by the bubbles and liquid plugs increases gradually. When P_1 has reached quasi-steady state, the large-scale liquid discharge stops and the vapor chamber tends to become steady. P_1 decreases gradually to the environmental pressure after reaching its maximum. P_3 decreases gradually with the upward movement of the vapor chamber. P_3 reaches quasi-steady state, negative pressure. The reason is that the vapor mass flow rate increases along the evaporator section, and reaches its maximum at the entrance to the adiabatic section. At the same time, P_3 reaches its minimum. Moreover, because the SOTPTM is separated from the environment by a water seal only, in general, SOTPTM works under environmental pressure. So, the pressure is negative and a little less than the environmental pressure.

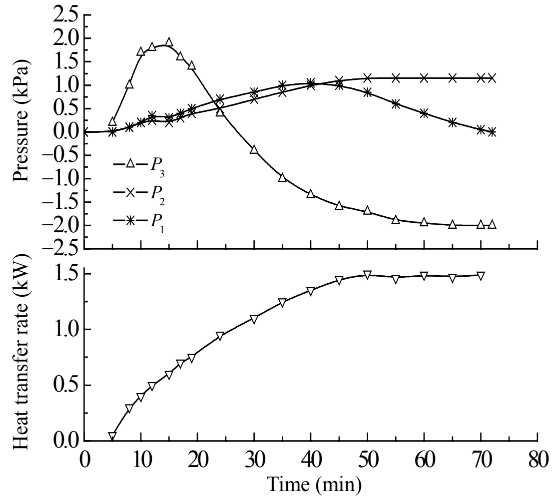

Fig.6 Variation of SOTPTM pressure and heat transfer rate during startup

SOTPT accident analysis due to lack of water

As is the case with closed two-phase thermosyphon, the semi-open two-phase thermosyphons cannot blast when there is not enough liquid to be continued and the heat input cannot be removed at nominal temperature. When such an accident happens, the heat transfer performance is suppressed, an enormous amount of vapor is let out through the top orifice, and the temperature of the evaporator section will rise rapidly. In the test, the cooling water was stopped and the heat transfer rate kept at 1.6 kW. As shown in Fig.7, SOTPT can endure 4~5 min lack of water condition without a rapid rise of the local evaporator wall temperature. After about 5 min, the local evaporator wall temperature will rise rapidly, and the dry-out area will increase. So, when the accident happens, cooling water should be provided rapidly within the time limitation, then, the heat transfer characteristics of SOTPT will not be affected.

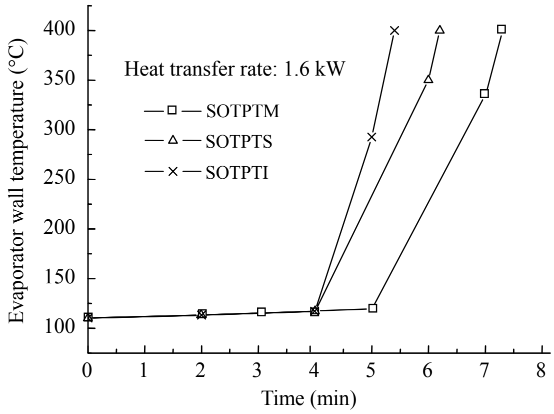

Fig.7 Variation of SOTPT evaporator wall temperature due to lack of water accident

SOTPT shutdown analysis

The shutdown of SOTPT was researched for the conditions of the steady-state heat input being stopped and the mass flow rate being kept constant. Fig.8 shows that the heat transfer rate and the working temperature inside the heat pipe decrease with time. The shutdown of the semi-open thermosyphon is fairly fast and the time of shutdown lasts about 40~50 min. The shutdown of SOTPTI is

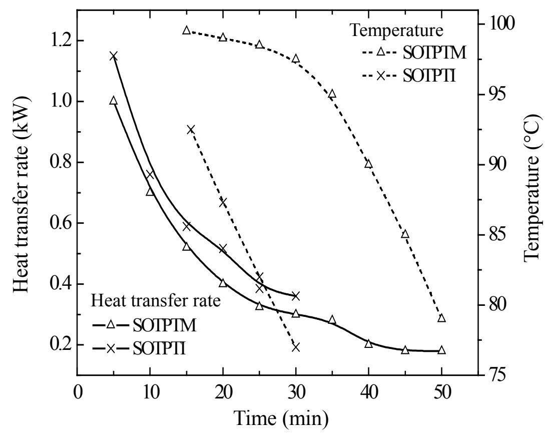

Fig.8 Variation of the inner temperature and heat transfer during shutdown

faster and the time of shutdown lasts about 30 min.

CONCLUSION

The startup of SOTPT needs some time in order to discharge excess water and to stabilize the vapor-liquid interface at the top. Generally, a whole startup process needs about 60~70 min. The startup speed of SOTPT is determined by the startup speed of the condensation section. The evaporator section has the highest startup speed. In the process of startup, the pressure variation of SOTPT is different from that of a CTPT. The average pressure in the heat pipe is equal to the environmental pressure in general. The shutdown of SOTPT needs about 30~50 min, which is much shorter than that for startup. A semi-open two-phase thermosyphon shows a rather good response to a lack of water accident. The critical time is 4~5 min, in which SOTPT can be brought back to normal operation by replenishment with cooling water or it has to be shut down.

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