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Effect of Height Difference on the Performance of Two-phase Thermosyphon Loop Used in Air-conditioning System

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ABSTRACT:

Two-phase thermosyphon loops (TPTLs) are widely used in air-conditioning field for heat recovery and free cooling utilization in recent years. The height difference between the condenser and the evaporator is always considered as the driven force of thermosyphon. However, experiments show the cooling capacity of the TPTLs is not linearly improved with the increase of the height difference. So, the influence mechanism of height difference on the performance of TPTLs is not clear and needs more deep investigation. In this study, a visual experimental setup is established, and the effect of height difference and circulation resistance on the performance of TPTL is investigated. The results shows that with the increase of the height difference, the liquid head rises continuously until remain stable approximately. Therefore, the liquid head is less than the height difference in some cases, which means that the downcomer is partially liquid filled. Consequently, with the increase of height difference, the circulation flow rate and thermal performance firstly increases then remains constant, rather than continuous increase in the traditional understandings.

1. INTRODUCTION

Two-phase thermosyphon loops (TPTLs) are highly effective devices for spontaneously transferring heat through a relatively long distance. Therefore, TPTLs are extensively used in various fields, such as cooling of electronic components(Garrity et al., 2007; Khodabandeh, 2005), light water reactors(Nayak et al., 2006; Rao et al., 2006), etc., owing to their simplicity, flexibility, high heat transfer efficiency, and passive nature.

Recently, the TPTL has also been found to be an effective way to recover heat or utilizing free energy in air-conditioning systems for energy saving. For example, Liu (Liu et al., 2006) used TPTL heat exchanger to recover heat from exhaust air or waste water for free; Tu (Tu et al., 2011) developed a TPTL heat exchanger for telecommunication base stations to eliminate the heat rejection spontaneously in cold seasons; Han (Han et al., 2012) integrated the TPTL with vapor compression into one device. The integrated air-conditioner was used in the spaces with large heat rejection, and showed significant energy-saving effect. As a whole, TPTL shows bright prospects in the field of air-conditioning.

A typical TPTL consists of an evaporator, a riser (gas tube), a condenser, and a downcomer (liquid tube). The condenser is higher than the evaporator by a certain height difference. The TPTL is powered by the gravity, which means the liquid head, caused by the height difference and density difference of the liquid in the downcomer and the vapor or vapor/liquid mixture in the riser, is the key factor affecting the circulation flow rate and energy performance of TPTLs.

In the traditional ideas, the liquid head is considered to be equal to the height difference between the condenser and the evaporator based on the underlying assumption: the downcomer is fully liquid filled (Garrity et al., 2007; Haider et al., 2002; Imura et al., 1989; Khodabandeh, 2005). According to that, the TPTL will perform better with a larger height difference, since driving force becomes larger. The conclusion is correct in the cases with large temperature difference and heat flux, such as in the field of cooling of electronic and light water reactors. However, when the TPTL is used in air-conditioning system, which has quite small temperature difference and small heat flux, the behavior of TPTL is different. The preliminary research indicated the heat transfer rate does not always increase with the increase of the height (Lee et al., 2009). What happened to the TPTL in air conditioning application? Is the “common sense” of the downcomer fully filled correct? Does the liquid head always keep consistent with the height difference? These are the fundamental questions that required answers before using TPTLs in air conditioner field.

In this study, a visual experimental plant is established, the behavior of the liquid head in the downcomer is observed and the effect of height difference and circulation resistance on the performance of TPTL is investigated experimentally.

2. EXPERIMENTAL SETUPS

Figure 1 shows the visual experimental plant of TPTL heat exchanger. The TPTL is a water-to-water type heat exchanger, and consists of an evaporator, a condenser, a riser, and a downcomer. A high-temperature water tank and a low-temperature water tank are set to create required temperature conditions.

The evaporator is a double-pipe heat exchanger with three parallel pipes, and made of copper. The refrigerant flows in the inner pipe with a diameter of 12 mm, and the water flows in the outer pipe with a diameter of 16 mm. A transparent pipe is set in parallel with the evaporator to observe the liquid level before experiments. A ball valve is set at the outlet of the evaporator to change the circulation resistance in the experiment. The condenser uses the similar structure as the evaporator. The condenser is fixed on a lifter, which falls or rises to change the height difference between condenser and evaporator from 0 m to 1.5 m. The outer surfaces of the evaporator and the condenser are in good thermal insulation, and the heat loss can be neglected. In order to observe the flow pattern and liquid level in the riser and downcomer, a transparent pipe, made of PU, is selected to act as the riser and downcomer. The detailed specifications of the TPTL are presented in the Table 1.

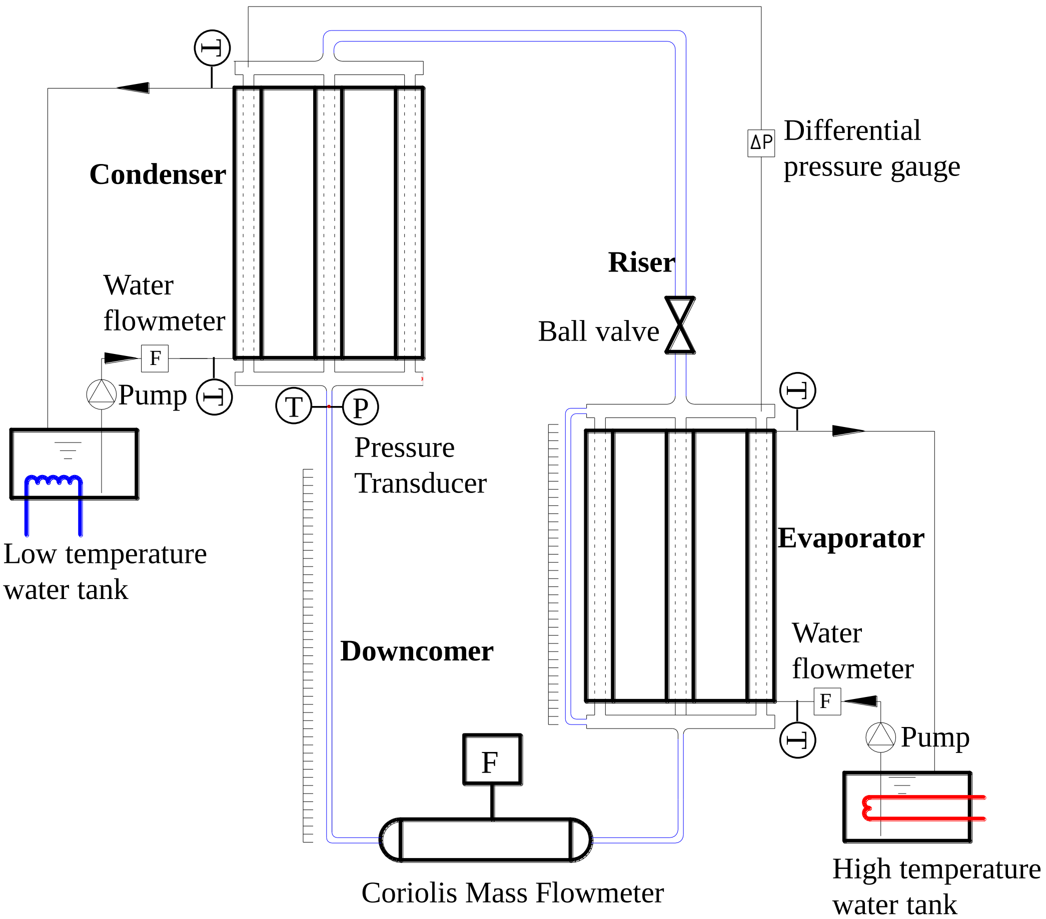


Figure 1: Schematic diagram of the experimental setup

Table 1: Specifications of the TPTL heat exchanger

Items	**Specifications**
Evaporator	3 parallel double pipes; Pipe length: 0.45 m Diameter of inner pipe: 12 mm; Diameter of outer pipe: 16 mm;
Condenser	3 parallel double pipes; Pipe length: 0.45 m Diameter of inner pipe: 12 mm; Diameter of outer pipe: 16 mm;
Riser	Length: 2.0 m; Inner diameter: 12 mm
Downcomer	Length: 2.0 m; Inner diameter: 12 mm
Height difference	0-1.5 m
Refrigerant	R134a

To monitor heat transfer performance of the TPTL, a couple of thermocouples and a water flowmeter are set to measure the inlet/outlet water temperature and flow rate of water. A Coriolis mass flowmeter with relatively small circulation resistance is selected to measure the flow rate of refrigerant. A differential pressure transducer is used to measure the pressure difference along the riser. In order to monitor the thermodynamic state in the downcomer, a thermocouple and a pressure transducer are used to measure the temperature and pressure of the refrigerant at the outlet of condenser. The detailed information of the transducers are presented in Table 2.

Table 2: Specifications of transducers

Items	Range	Uncertainty	Type
Thermocouple	-10-50 °C	<0.1 °C	T type
Pressure transducer	0-2.5 MPa	<0.2%	UNIK 5000
Differential pressure transducer	0-50 kPa	<0.2%	UNIK 5000
Coriolis mass flowmeter (for refrigerant)	0-1000 kg/h	<0.05%	MASS 6000
Flowmeter (for water)	0-10 m^3/h	<0.1 m^3/h	LXSR-E

During the test, each measuring point lasts 20 minutes after the operation condition keep steady. All the signals from the transducers (thermocouples, pressure transducer, flow meters) are transferred to a data acquisition unit , then analyzed in a computer.

The uncertainties of the measurement instruments are presented in Table 2. The method to calculate the heat transfer rate Q_e in the evaporator and its uncertainty are given in Eq. (1) and Eq. (2).

$$Q_e = c_P \rho V (t_{in} - t_{out}) \tag{1}$$

$$\frac{\delta Q_e}{Q_e} = \sqrt{\left(\frac{\delta V}{V}\right)^2 + \frac{\delta t_{in}^2 + \delta t_{out}^2}{(t_{in} - t_{out})^2}} \tag{2}$$

3. RESULTS AND DISCUSSION

3.1 Partially Liquid-Filled Phenomenon in the Downcomer

As mentioned before, most of the researchers believe that the downcomer is full of liquid. From our experiments, it is found that in some cases, the downcomer does be fully liquid filled; but in some cases, the downcomer is partially liquid filled rather than fully liquid filled. At that time, the lower part of the downcomer is full of liquid while the upper part is only surrounded by a hollow liquid film, shown in Figure 2. In that case, the temperature and pressure of the refrigerant are measured, and the measured temperature keeps consistent with the saturation temperature corresponding to the measured pressure, shown in Figure 3, which means that it is just the saturation state.

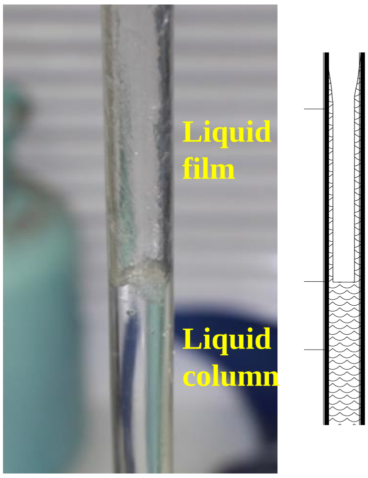


Figure 2: Partially liquid-filled phenomenon observed in experiments

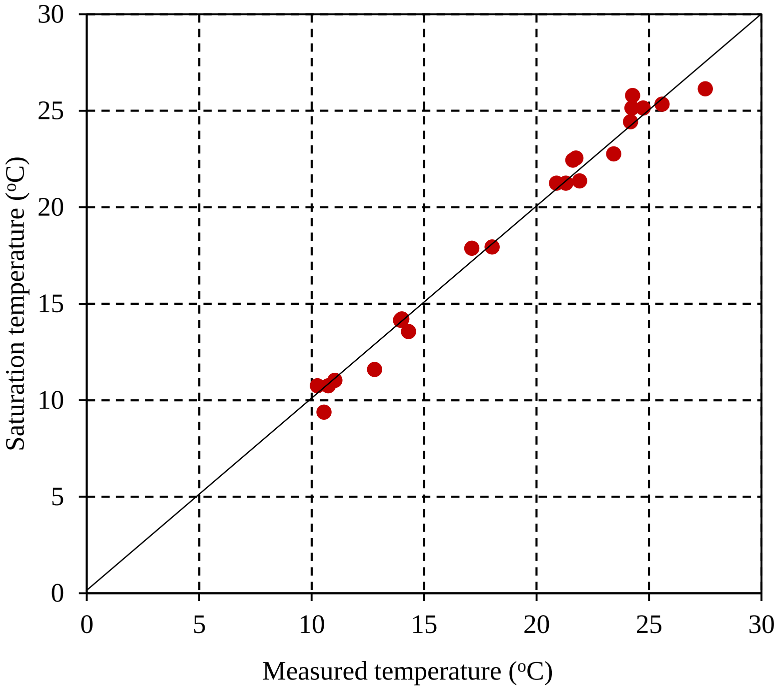
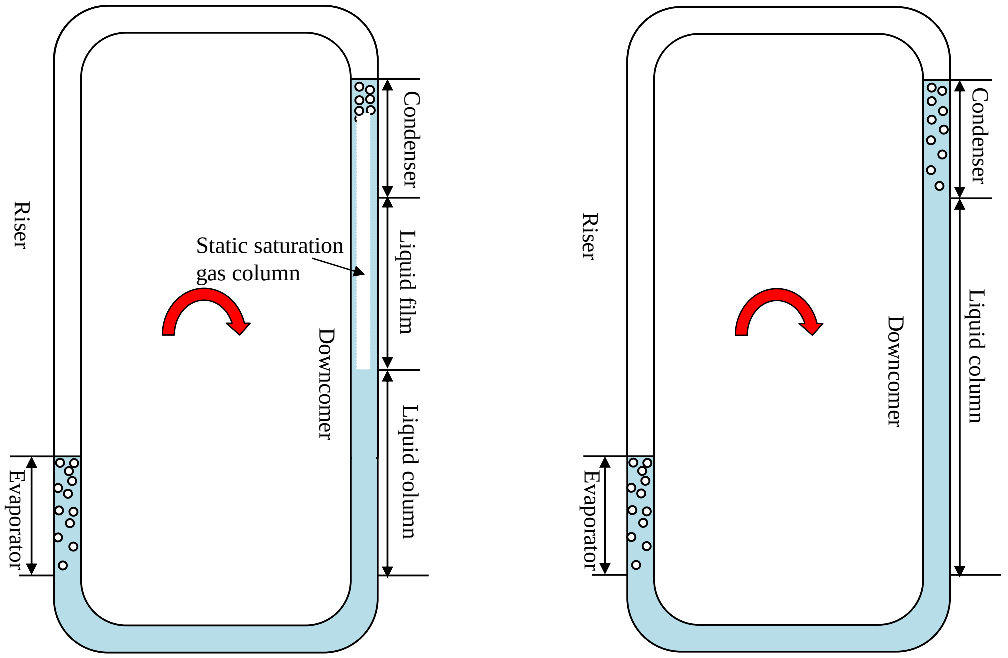


Figure 3: The measured temperature and the saturation temperature corresponding to the measured pressure at the outlet of condenser when the downcomer is partially liquid filled

From the measurement, it can be concluded that there are two possible scenarios for downcomer: fully liquid filled (Figure 4(b)) and partially liquid filled (Figure 4(a)). In the fully liquid-filled case, the liquid head is equal to the height difference. When the downcomer is partially liquid filled, there is a static saturation gas column, surrounded by a layer of liquid film in the upper part of the downcomer. In the static gas column, the pressure remains constant, corresponding to the saturation temperature. The liquid film flows down along the inner wall, and it does not provide the driving force. In the lower part of the downcomer, there is a liquid column full of liquid, which provides the driving force for circulation.

And previous experiments also show that the downcomer is more likely to be partially liquid filled, when the refrigerant charge and temperature difference (or heat flux) is relatively small, which may be the reason why the phenomenon are not found in the field of cooling of electronic and light water reactors, where large refrigerant charge is need to avoid dryout in the evaporator.



(a) Partially liquid-filled case (b)Fully liquid-filled case

Figure 4: Two possible cases for the downcomer

3.2 Effect of Height Difference and Circulation Resistance on the flow and heat transfer performance of TPTL

In this study, effect of height difference and circulation resistance on the performance of TPTL have been studied experimentally. The height difference between the condenser and the evaporator ranges from 0 m to 1.5 m. There are three different openings of the ball valve at the outlet of the evaporator, 25%, 50%, 100%, on behalf of different circulation resistance. The inlet water temperature of the evaporator keeps 35°C, and the inlet water temperature of condenser keeps 5°C. There are 0.48 kg refrigerant in the system, and the static liquid level is 0.9 m before experiment, the refrigerant charge is selected by the optimization of refrigerant charge based on heat transfer performance.

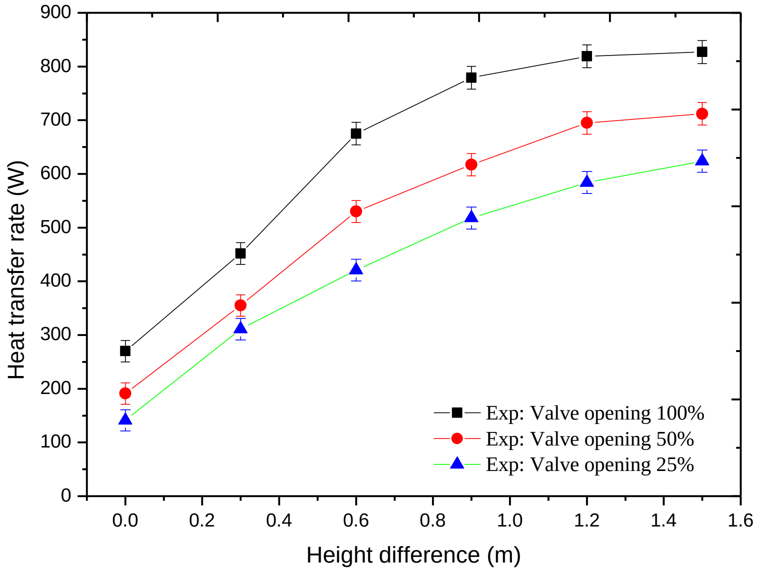


Figure 5: Heat transfer rate as a function of height difference between the condenser and evaporator

Figure 5 presents the heat transfer rate as a function of height difference between the condenser and the evaporator. As shown in Figure 5, on the whole, the heat transfer rate rises with the increase of height difference. But for the loop with lower circulation resistance (Valve opening 100% and 75%), with the increase of height difference, the heat transfer rate first increases sharply, then increases slowly, finally remains constant. While for the loop with higher circulation resistance (Valve opening 25%), with the increase of height difference the heat transfer rate increases continuously. Moreover, the TPTL performs worse with larger circulation resistance. The reasons for these behaviors can be found in Figure 6 and Figure 7.

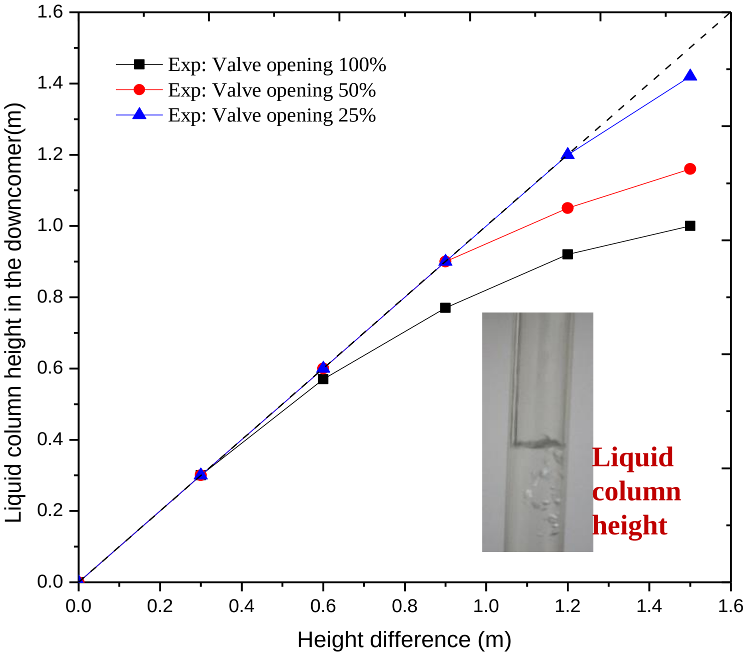


Figure 6: Liquid column height in the downcomer as a function of height difference between the condenser and evaporator

Figure 6 shows the liquid column height in the downcomer as a function of height difference and circulation resistance. As shown in Figure 6, when the height difference is relatively small, the liquid column height keeps consistent with the height difference between the condenser and evaporator, which means the downcomer is fully liquid filled, and the condenser outlet is subcooled; but when the height difference continues to increases, the liquid column height cannot keep up with the increase of height difference, which means the downcomer turns to be partially liquid filled at that time. Additionally, the loop with lower circulation resistance (larger opening of the valve) has lower liquid column in the downcomer, and the downcomer turns to be partially liquid filled at smaller height difference, which means the loop with lower circulation resistance are more likely to be partially liquid filled than that with larger circulation resistance. It can be explained like that, TPTL is a natural circulation driven by the liquid head, and the pressure drop in the cycle always equals to the liquid head caused by the density difference of the liquid in the downcomer and the vapor or vapor/liquid mixture in the riser, therefore the loop with larger circulation resistance requires higher liquid head (liquid column height) to drive the circulation. In summary, the height difference and circulation resistance jointly influence the behavior of the liquid head, and the liquid head always keeps balance with the pressure drop resulting from height difference and circulation resistance, which shows good self-regulation of TPTLs.

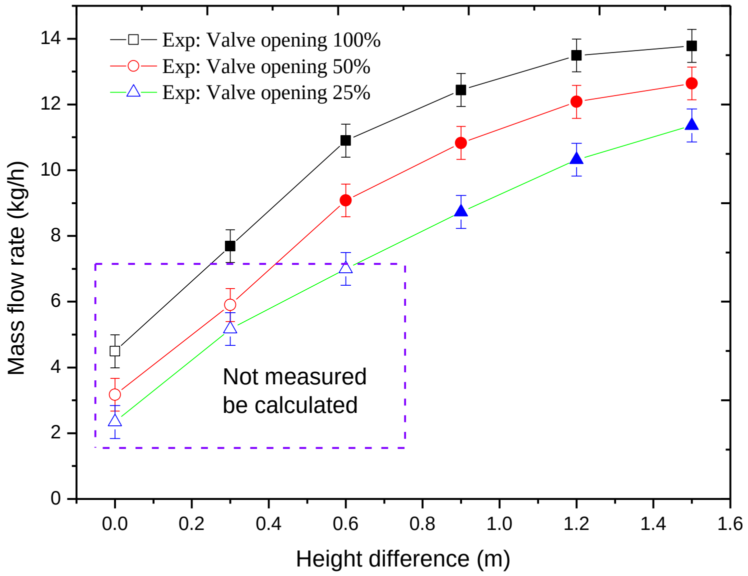


Figure 7: Refrigerant mass flow rate as a function of height difference between the condenser and evaporator

Figure 7 shows the refrigerant mass flow rate as a function of height difference between the condenser and the evaporator. The refrigerant mass flow rate shares the similar behavior with the heat transfer rate (shown in Figure 5). When the downcomer is fully liquid filled, with the increase of height difference, the refrigerant mass flow rate and the heat transfer rate increase sharply, since the liquid head increases sharply (shown in Figure 6). But when the downcomer turns to be partially liquid filled, with the increase of height difference ,the refrigerant mass flow rate and the heat transfer rate rise slowly even remain constant, since the liquid head risers slowly even keeps constant (shown in Figure 6). It should be noteworthy that there are some points (hollow points in the dashed rectangle) cannot be measured in the experiments, and they are calculated by the ratio of heat transfer rate and latent heat of vaporization. Because in these cases, the horizontal liquid tube (connecting the Coriolis mass flowmeter and the evaporator) turns to be partially liquid filled (just like a brook) rather than fully liquid filled, and the Coriolis mass flowmeter does not work at that time.

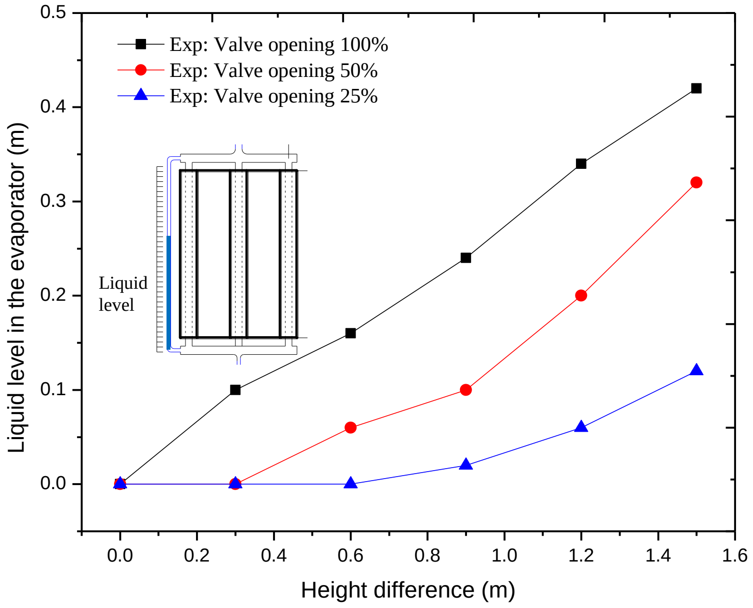


Figure 8: Liquid level in the evaporator as a function of height difference between the condenser and evaporator

To present the distribution of refrigerant at different height difference, liquid level in the evaporator (observed in the transparent pipe in parallel with the evaporator) is plotted in Figure 8. Corresponding to the points which can not be measured in Figure 7, the liquid level in the evaporator stays at 0 m approximately, which indicates that there are nearly little refrigerant for boiling in the evaporator at that time, that is also the reason for worse performance with smaller height difference. As shown in Figure 8, when the height difference is small, especially for the loop with larger circulation resistance, the liquid level in the evaporator is very low and much refrigerant stays in the condenser, since the liquid head is not sufficient to drive the refrigerant to the evaporator, therefore the TPTL performs badly. With the increase of height difference, the liquid level in the evaporator rises, which means the boiling region gets larger, so the TPTL performs better.

4. CONCLUSIONS

To find out the effect of height difference on the performance of TPTL, a visual experimental setup is established, a water-to-water type TPTL with the height difference from 0 to 1.5 m is investigated experimentally. The following conclusions can be drawn:

1) The downcomer can be partially liquid filled rather than always fully liquid filled, and the condenser outlet is just saturated when the downcomer is partially liquid filled;
2) With the increase of height difference, the heat transfer rate and circulation flow rate first increases sharply, then increases slowly, finally remains constant, since the downcomer turns to be partially liquid filled, and the liquid head stops rapid rise;
3) The loop with larger circulation resistance shows worse heat transfer performance and is more likely to be fully liquid filled.

NOMENCLATURE

The nomenclature should be located at the end of the text using the following format:

c_P	specific heat	(kJ/(kg ºC))

V	volumetric flow rate	(m^3/s)
Q	heat transfer rate	(kW)
t	temperature	(^oC)
ρ	density	(kg/m^3)

Subscript

e	evaporator
in	inlet
out	outlet

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