Effect of Inclination Angle on Heat Transfer Characteristics of Closed Two-Phase Thermosyphon*

By

P. TERDTOON**, M. SHIRAISHI*** and M. MURAKAMI**

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Summary: The paper presents the results of effect of inclination angle on heat transfer characteristics of thermosyphon. The steel–R113 thermosyphon system was used to investigate with the filling ratio of 80%, 50% and 30%. The heat transfer characteristics of the thermosyphon is obtained in the range from 90 deg. to the horizontal position. It is found from the experiments that there is a tendency that the transported heat at any inclination angle is higher than that of the vertical state. The ratio of critical heat transfer rate at any inclination angle and that of the vertical state reaches the maximum value of 1.6 in the case of filling ratio of 50%. The range of the isothermal operating state depends deeply on the filling ratio. From the preliminary consideration, the effect of inclination angle can be divided into 4 major regions, which are described thoroughly.

1. INTRODUCTION

The simple closed two-phase thermosyphon is an effective heat transfer device. Its working principle of obtaining a large amount of heat from the evaporator section by means of the evaporation mechanism and releasing the heat out of the condenser section by means of the condensation phenomena is widely acknowledged. Simply say, it is a wickless heat pipe under the effect of the gravitational force.

There are some limitations concerned with the heat transfer capacity of the thermosyphon, for instance, burn-out phenomena, dry-out limitation, entrainment limitation etc. Moreover, the heat transport capability of the thermosyphon is highly affected by the gravity effect, in other word, the inclination angle of the thermosyphon. There are few researches concerned with the investigation of the heat transfer characteristics of the inclined thermosyphon. The property of water and ethanol filled inclined thermosyphon was studied by Negishi and Sawada(1) with the conclusion that, in order to obtain a high heat transfer rate, the appropriate inclination angle had to be between 20 and 40 deg. for water and more than 5 deg. for ethanol. Hahne and Gross(2) conducted the experiment with the steel–R115 thermosyphon and yielded the result that the highest heat transport rate occurred at the inclination of around 40 deg. Bontemps et.al(3) tested the toluene thermosyphon and found that the critical heat flux depended little on the filling ratio and had the maximum value at 30 deg. of inclination angle. Groll and Spedel(4) investigated the long copper-water thermosyphon and concluded that the maximum performance could be considerably increased for inclination angles greater than 10 deg.

** Institute of Engineering Mechanics, University of Tsukuba, Ibaraki, Japan.
*** Mechanical Engineering Laboratory, Tsukuba, Ibaraki, Japan.
However, the effect of inclination angle has not been clarified in the previous researches. Furthermore, the effect of filling ratio, on which the maximum heat transfer rate depends, on the inclined thermosyphon has not been sufficiently studied up to present.

The purpose of this paper is to conduct the detail investigation of the heat transfer characteristics of the thermosyphon from the vertical state down to the horizontal position by taking into account of the filling ratio. It is expected that, if the accurate results of the inclination angle and the filling ration for the best heat transfer characteristics of the thermosyphon are obtained, the results can be applied to the design of the improved heat pipe heat exchanger, which employs the inclined pipe thermosyphon instead of an ordinary vertical pipe thermosyphon.

2. Experimental Apparatus

In this research, stainless steel thermosyphon is employed. Inside diameter of the stainless steel pipe is 21 mm. As shown in Figure 1, the total length of the thermosyphon is 146 mm., the length of evaporator section is 34 cm. while the condenser section is 50 cm. long. Freon 113 is used to be the working fluid. The heat input device is designed to exploit the pipe itself as the heat generator. That is, electrical power is passed through the pipe (only in the evaporator section) via the copper electrodes which are connected at both ends of the evaporator section. Because of the resistance of the pipe itself, the homogeneous heat flux is applied into the working fluid. An accurate variable transformer is used to control the amount of heat input. Water is used as the cooling substance at the condenser section. It is pumped from the water bath, where its temperature is kept constant by mean of a refrigerating unit, and circulates though the

![Figure 1: Experimental Apparatus.](image-url)
water jacket of the condenser. The water flow rate could be read out by using the float type flow meter. Twenty-seven points at the evaporator section, 2 points at the adiabatic section, and six points at the condenser section of thermocouple sensor are used to monitor any points' temperature at any time. The thermosyphon is well designed to be easily rotated from the 0 deg. (horizontal) to the 90 deg. (vertical) and the exact position can be read clearly. All of the data needed are logged into two 30-channel data loggers and the computer is used to record the data into the external memory at any specified time.

Concerned parameters are as follows:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range of variation</th>
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<tbody>
<tr>
<td>Filling Ratio</td>
<td>80%, 50%, 30%</td>
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<tr>
<td>Inclination Angle</td>
<td>0–90 deg.</td>
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</table>

In this experiment there were two types of the operating state, i.e. isothermal and non-isothermal state. The isothermal state was the case that when the heat input was charged into the thermosyphon, the always existing initial dry-out phenomena took place due to the initial small rate of circulation of the condensate. The heat input was, however, increased to some appropriate amount, the circulation rate of the condensate would accordingly increase, then the initial dry-out phenomena disappeared. The temperatures of all parts of the evaporator section were, eventually, in the steady isothermal state condition. After that gradually increased heat would be supplied to the thermosyphon. The required data would be recorded when the system entered the steady isothermal state at each of the heat input value. Final data had to be obtained at the point at which local temperature rose rapidly. The selected data would be, however, the data at which the minimum thermal resistance of the thermosyphon existed. The quantity of heat that can be transported through the thermosyphon at the selected point is called “critical heat” or $Q_{critical}$. All of the experiments were conducted very near to the boiling point of the working fluid.

On the other hand, the non-isothermal state was the case that when the initial dry-out phenomena occurred, no matter how much the heat input was increased, the initial dry-out still existed because the returning condensate did not thoroughly distribute inside the evaporator section. The previously explained phenomena could not, therefore, be defined, neither the $Q_{critical}$. All of the results presented in the paper were based on the isothermal state experiment.

3. Experimental Results and Discussion

In order to completely understand the characteristics of the thermosyphon at the critical state, both of the $Q_{critical}$ and the thermal resistance of the thermosyphon were taken into account. The thermal resistance of the thermosyphon is the result of an equation:

\[
\text{thermal resistance} = \frac{t_{evap} - t_{cond}}{Q_{critical}}
\]

at the critical state

Results of the experiments were presented in the forms of heat transfer characteristics and thermal resistance.
3.1 Effect of Inclination Angle

In order to consider only the effect of inclination angle without other properties' influences, the ratio of Qcritical at any inclination angles and Qcritical at 90 deg. were calculated. Figure 2 shows the ratio of Qcritical/Q90 of Freon 113 with filling ratio of 80%. It can be noticed that, there exists the range of the inclination angle at which the amount of heat is much more higher than that of 90 deg. The ratio reached the maximum value of approximately 1.4 at about 50 deg. At the very small inclination angle, the non-isothermal state happens (see detail in section 3.3.4). The thermal resistance of the same condition can be seen in Figure 3. The minimum point also accordingly occurred at about 50 deg.

3.2 Effect of Filling Ratio

Figure 4 shows the Qcritical/Q90 of any filling ratio of Freon 113. There are 3 major points that can be observed here:

- the range of isothermal operation state depends deeply on the filling ratio. The more the filling ratio, the wider is the range of the isothermal operating state. For example, filling ratio of 80% produces the widest range of isothermal experiment (starts from 90 deg. down to 5 deg.), but the narrowest range of isothermal operating state occurs in the case of filling ratio of 30% (down to 30 deg. only).

![Fig. 2. Ratio of Q_{critical}/Q90 at any inclination angle of R-113 (filling ratio 80%).](image1)

![Fig. 3. Thermal resistance at any inclination angle of R-113 (filling ratio 80%).](image2)
Fig. 4. Ratio of $Q_{\text{critical}}/Q_{90}$ at any inclination angle of R-113.

Fig. 5. Thermal resistance at any inclination angle of R-113.

Fig. 6. Characteristics of $Q_{\text{critical}}/Q_{90}$ of R-113.
3.2.2 the maximum value of the Qcritical changes from one value of filling ratio to another. Filling ratio of 50% holds the highest value of about 1.6, filling ratio of 80%, on the other hand, reaches the highest value of 1.4 only.

3.2.3 the angle at which the highest values of any filling ratio occurred differs from the other. Filling ratio to 50% and 30% reached the highest values at approximately 45 deg. while that of 80% is 50 deg.

The variation of thermal resistances of 3 types of filling ratio are shown in Figure 5. The noticeable point is the minimum thermal resistance happens accordingly in the case of filling ratio of 50%.

3.3 Preliminary Consideration of the Effect of Inclination Angle

Careful investigation of all of the results leads to an important consideration in figure 6. The pattern of Qcritical/Q90 can be divided into 4 main regions as follows:

3.3.1 region 1: vertical state-about 70 deg. In this region the Qcritical increases with the decrease of inclination angle and the ratio does not depend on the filling ratio, i.e. only one line appears here.

3.3.2 region 2: 70 deg.-about 50 deg. The Qcritical also increases with the decrease of inclination angle, then it reaches the maximum value. The filling ratio, however, has the influence on the Qcritical/Q90, different filling ratio pursues different curve here in this range.

3.3.3 region 3: 50 deg.-minimum angle of the isothermal operating state. In this region the Qcritical decreases with the decrease of inclination angle, and the filling ratio has a large effect on the Qcritical/Q90 and the minimum angle.

3.3.4 region 4: minimum angle-limiting angle of operation. All of the experiments in this region are the non-isothermal state, i.e. local dry-out phenomena always exits and the Qcritical cannot be defined. The limiting angle of operation is the inclination angle at which no working fluid left inside the evaporator section before the operation. The heat can not be, accordingly, transported through the thermosyphon.

In order to understand clearly about the phenomena inside the thermosyphon, the study of flow pattern of all of the four preliminary consideration regions are expected to be conducted very soon.

4. Conclusions

The effect of inclination angle on the thermosyphon system was made clear in this paper. The detailed characteristics of the effect of inclination angle was investigated, and could be divided into 4 major regions. At the maximum ratio of Qcritical/Q90, the thermal resistance was also minimum. Filling ratio had a large effect on the heat transfer characteristics. It can be noticed from the experimental results that there is the case that the Qcritical at any inclination angle is higher than that of the vertical state. The maximum quantity of the transported heat, which is 1.6 time of the Q90, occurs at the angle of 45 deg. in case of 50% filling ratio.
5. REFERENCES


