Instability of a Two-Phase Loop Thermosyphon

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The instability of two-phase loop thermosyphons was investigated experimentally and analytically. Three orifice type inserts were used to study the effect of change in the pressure drop in the flow channel of the TLT on the flow instability and temperature fluctuation. It is observed that a decrease in the size of the orifice insert from 3.7 mm (no insert) to 0.71 mm drastically reduced the fluctuation of the temperature, especially at the evaporator section of the TLT. With the orifice type insert of 0.71 mm for the TLT, the overall temperature fluctuation was almost completely eliminated, especially at higher power input to the TLT. The analysis based on the Kelvin-Helmholtz instability theory seems to predict reasonable well the loop stability state of the TLT with experimentally determined constant factors.

Key Words: Instability, Two-phase Loop Thermosyphon, Kelvin-Helmholtz Instability, Orifice Type Insert

Nomenclature

A_1 : Experimental constant
c : Wave velocity (m/s)
k : Wave number (m^{-1})
l : Length (m)
m : Film thickness (m), mass flow rate (kg/s)
$\bar{m}$: Mean film thickness
$\hat{m}$: Amplitude of wave on the interface (m)
p : Pressure (Pa)
Q : Heat transfer rate (W)
R : Resistance (°C/W)
r : Radius (m)
t : Temperature (°C)
t_{air} : Surrounding air temperature (°C)
t_c : Coolant temperature (°C)
Δt_{h-c} : Temperature difference between the heater and air (°C)
TLT : Two-phase loop thermosyphon
u : Velocity
V : Volume (m^3)
V_{WF} : Amount of working fluid (ml)
WF : Working fluid
x : x axis
y : y axis

Greek Letter Symbols

ϕ : Diameter (m)
δ : Thickness (m), perturbation
λ : Wave length (m)
μ : Viscocity (kg/m-s)
π_{ng} : Normal stress exerted by the gas phase on the interface (kg/m^2s)
π_{nl} : Normal stress exerted by the liquid phase on the interface (kg/m^2s)
ρ : Density (kg/m^3)
σ : Surface tension (N/m)
ψ : Stream function, function defined in Appendix E

Subscrbpts

air : Surrounding air
c : Cold section
$cond$: Condensation, condenser section
$conv$: Convection
dis : Disturbance
ev : Evaporation, evaporator

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g : Gas, vapor state
h : Heater, hot
hot : Heating section
i : Inner
l : Liquid
$loop$: Thermosyphon loop
max : Maximum
T : Total
t : Tube
tp : Two-phase
tr : Transporting section

1. Introduction

A two-phase loop thermosyphons (TLT) is a heat transfer system in which the fluid flow is driven by thermally generated density gradients so that pumping is not required. This is sometimes called as a natural circulation loop, a natural convection loops or a separate loop heat pipe. These various names are derived from the fact that a two-phase loop thermosyphon is working on natural convection mode without any external power supply.

The fluid flow in a TLT is created by buoyancy forces as a result of the differences in fluid density induced by the temperature variations between the hot (evaporator) and the cold (condenser) sections. Hence, the fluid in the vicinity of the heat sink is cooled becoming denser, and thus tends to move downward. Conversely, the fluid in the vicinity of the heat source is heated causing it to become lighter and rises upward. As a result of this motion, the temperature distribution is altered and the total buoyancy force is correspondingly changed. Nevertheless, as long as this force continues to act in the same direction, the fluid velocity continues to increase. This process does not go on indefinitely, however, since a retarding force due to viscous friction is developed. This force acts in the direction opposite to the direction of the fluid motion, and its magnitude increases as the fluid velocity increases. When the velocity has become large enough so that the frictional force becomes equal to the buoyancy force, the net force acting on the fluid in the direction of flow is zero. Therefore, there is no further acceleration of the fluid, and the flow rate remains constant thereafter under steady applied thermal conditions at the heat source and heat sink.

The fluid entering the heated flow channel always is at a constant temperature and at the same time the velocity of the flow stream is governed by the density difference between the hot and the cold sections of a fluid flow loop. Under certain conditions, this system may be unstable; that is, a small deviation from the equilibrium temperature distribution or the equilibrium velocity may be propagated in space or time with increasing amplitude. This description illustrates the normally expected operation of a loop. Nevertheless, the mechanisms described above are adequate for the discussion of the operation of a TLT. A TLT mainly consists of the evaporating, the transporting and the condensing sections, and the returning section of the condensed working fluid. The buoyancy force is the main driving force of a TLT. The void distribution in a TLT in turn is a function of the local heating and cooling rates and the fluid velocities within the loop.

Annular two-phase flow in a flow channel can be characterized by the flow in which the interface between the phases is not smooth but covered with a complex pattern of waves. So far it has been reported that interfacial waves exist over the whole range of conditions (Hewitt, 1970). The waves observed vary widely in wavelength and in amplitude, some amplitudes being several times greater than the mean film thickness, and this waviness of the interface dominates a number of important phenomena in an annular flow. Although the effect of waves to the pressure drop is not as yet clearly understood, it is clear that the pressure drop is inevitably strongly dependent on the waves.

Experimental and theoretical studies of wave behaviour and their influence on other phenomena in annular flow are still at a very early stage of development. And, therefore, in this present study, the Kelvin-Helmholtz interfacial instability approach is applied to the two-phase annular flow region of the transporting section of the TLT systems as an attempt to obtain some quantitative results.

2. Experimental

The experimental apparatus, illustrated in Fig. 1, consists of the main TLT assembly, the cooling system for the condenser section, the heat generation section and the charging system. The main TLT assemblies used in the study are made of three parts; the evaporation section, the long smooth transporting section, and the finned condenser section. The essential dimensions of the test assembly are shown in the figure.

The test assembly shown in Fig. 1 was manufactured with a cooling capacity of up to 12 W/cm^2 with the maximum surface temperature of the evaporator section of 75°C and the ambient air temperature of 25°C, resulting the overall temperature difference of about 50°C. The evaporator section was made from the copper plate with the dimensions of 35 mm×35 mm×9.5 mm (thickness). The effective surface area (heat transfer surface) is 35 mm×35 mm.

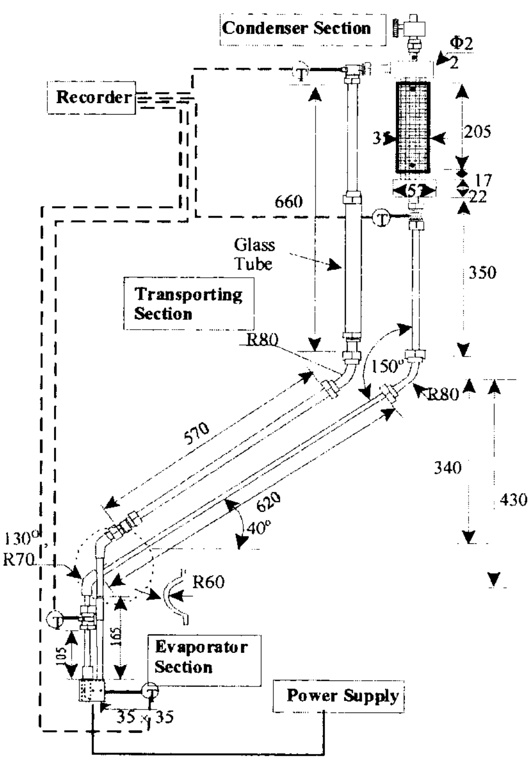

Fig. 1 Experimental Setup

The evaporator was designed to simplify the manufacturing process. The cavity in the evaporator was created simply by having eight holes of 5.6 mm drilled; four from the top and the other four from the side. Two holes were drilled through the upper side into the cavity for the transporting tubes which connect the evaporator section with the condenser section. A square thin copper plate (thickness 2 mm) was silver soldered on the cavity to create a box. Two brass tubes were silver soldered into the holes. The tube has an extension tube for the condensate return as illustrated in Fig. 1. The evaporator was tested under pressure and vacuum for leaks. The condenser consists of finned tubes; 63 fins with the pitch of 3.2 mm. These fined tubes were soft soldered into two parallel horizontal headers made of copper. Swagelok fittings were used for connecting the header with the transport tubing for the vapor and condensate.

The evaporator and condenser are connected with two transporting lines as seen in Fig. 1; one for the two-phase flow from the evaporator to the condenser, and the other for the condensate return from the condenser to the evaporator. The flow channel for the two-phase flow is made of the brass tube (7.9×0.4 mm) with bending at the mid section at an angle of 40° to horizontal plane. The inclined section is about 650 mm in length. A glass tube (ϕ=12.7×2.5 mm and 310 mm in length) is provided in the upper vertical section of this line. The flow channel for the condensate return is also made of the brass tube with bending in the mid section at an angle of 40° to horizontal plane. The inclined section is about 800 mm in length.

A temporary closure of the loop thermosyphon was made with a NUPRO vacuum valve (B4HK-TW, SWAGELOK Co.). The valve was connected to the upper header through a brass tube. To measure the temperature distribution along the length of the loop thermosyphon, several types of the thermocouples (No. 1: ready-made insulated thermocouples, TT-T-30-36, No. 2: OMEGA subminiature thermocouple probes, KMQSS-040-G-6, No. 3: OMEGA subminiature thermocouple probes, KMTSS-062-G-6, and No. 4: ready-made insulated thermocouples, GG-K-24-36) were used. All the thermocouples (T and K-types) used were calibrated in situ and connected through two rotary selector switches to two digital thermometers, respectively. For the measurement of temperature fluctuation, three FISHER Recordall Series 5000 devices were used together with a PC for the digitizing of the results.

A fan (Archer 273-242 with a rated sound level-38 dB) was used for the cooling of the condenser section. The finned parts of the TLT's were installed into the channel (290 mm long and in cross section-rectangular with the dimensions: 201.5×35 mm) made from transparent acrylic (sheets with 6 mm thickness).

The heater, consisted of a heating element made from BeO on a ceramic sheet plate with metal as an electrical conductor from one side and covered with thin layer of electrical insulating material and a copper box. The heating element of 38×38 mm was installed into the copper box (50 mm$\times$50 mm$\times$10.2 mm) with the cut opening (35 mm$\times$35 mm$\times$8 mm) and the heating layer facing into the box.

The test section with the heater was installed on the vertical desk board and covered with thick insulation to prevent heat loss to environment.

To find the working fluid most suitable for the system, refrigerants such as R-11, R-113, ethanol, water, FC-72, FC-87, and acetone were tried under various test conditions. For investigating the loop instability, water, acetone, and FC-87 were used as the working fluids. The test TLT was thoroughly cleaned by washing with ethanol and then with distilled water. It was then vacuum dried, tested for vacuums and leaks checked. The TLT was connected to a vacuum pump to remove the inside air and other non-condensable gases. The pump usually reached to the magnitude of 5×10^{-3} torr for a dry system. After the TLT was evacuated, a known amount of the working fluid was charged into the tube using the charging system.

The power to the evaporator heating section was increased carefully in steps to the desired heat flux. To reach the steady state, it took usually approximately 30 minutes. Voltage was seen to fluctuate within a range of ± 0.2 V. By using the thermo-anemometer, the air flow velocity and air temperature in the condenser section were measured.

To determine the effect of a change in the pressure drop in the flow channel of the TLT on the flow instability and temperature fluctuation, three orifice type inserts (cylindrical : $d=5.5$ mm and 6 mm in height, $d_{orifice}=0.51$, 0.71 and 1.2 mm) were used. These inserts are placed inside the condensate return line using a Tee connector situated near the evaporator section (140 mm from the upper edge of the evaporator).

At the start of this investigation, the transient temperature variation of the test TLT was recorded on three X-Y pen-recorders (FISHER RECORDALL Series 5000, LINEAR model: 1201-0000 and BBC GOERZ). The transient temperature variation could be recorded on the papers (LINEAR model: 1201-0000 and BBC GOERZ: feeding speed was 1 cm per minute at 2.5 mV range, FISHER RECORDALL Series 5000: feeding speed was 2.5 cm per minute at 10 mV range). All recorders were calibrated before the experiments. The noise was specified to be a maximum of $\pm 2\%$ rms.

3. Analysis of Instability

The major aspect of the Kelvin-Helmholtz instability applied to a TLT is that the outlet velocity of the fluid from the evaporator section must be higher than the critical velocity to sustain stable annular flow in the transport section. The outlet velocity of the fluid can be prevented to rise by the effect of surface tension or liquid entrainment etc.

Therefore, the major parameters concerning the analysis are the outlet velocities of the two-phase flow from the evaporator, u_g and u_l. The density and velocity conditions vary markedly along the evaporator section of a TLT. The density is highest at the evaporator inlet and the flow velocity is highest at the evaporator outlet. The effect of a small perturbation in the inlet velocity is to change the whole distribution.

The Kelvin-Helmholtz instability theory is well described in the book by Hewitt, (1970). Also Kelvin-Helmholtz instability is well known theory. The Kelvin-Helmholtz instability was developed to define the interface phenomenon between two inviscid fluids of different densities. The application of the theory to two-phase flows seems to be very rare and it appears that none has been applied to any TLT systems. One theoretical approach of Kelvin-Helmholtz instability for a two-phase closed thermosyphon (TCT) is by Teng (1999).

The instability resulting from the pressure drop in a TLT must be from the annular flow state because if an oscillatory flow rate is to be possible, the driving force would not be generated in the evaporator section but in the vertical riser above the evaporator. Any kind of forces and state which would prevent the flow can induce a pressure drop and flow unstable.

The annular flow state in a flow channel is expressed as a mixed state between the vapor flow and the liquid flow. Consider the basic flow of two incompressible inviscid fluids of different velocities and densities separated by a vertical interface in a TLT transport section on which a regular train of waves of wavelength, λ_w, are moving with velocity, c, as shown in Fig. 2 which was modified to apply for the present TLT analysis from . To illustrate the mechanisms and concepts of this kind of instability, it is needed to work through a classic problem that demands little of mathematics.

Figure 2 shows the streamlines of a flow with a mean velocity of, u_g, in the vapor phase and, u_l, in the liquid. It can be noted that the amount of distortion to the streamlines decreases with increasing distance from the interface. As the vapor flows around the curves of the streamlines, centrifugal forces are set up and these must be balanced by a pressure gradient in the direction normal to the streamline. Since the vapor velocity is roughly the same at all points, the magnitude of the pressure gradient will decrease with increasing distance from the interface in accordance with the decrease in the curvature of the streamlines, ultimately falling to zero at infinity, where the pressure and velocity fields are undisturbed.

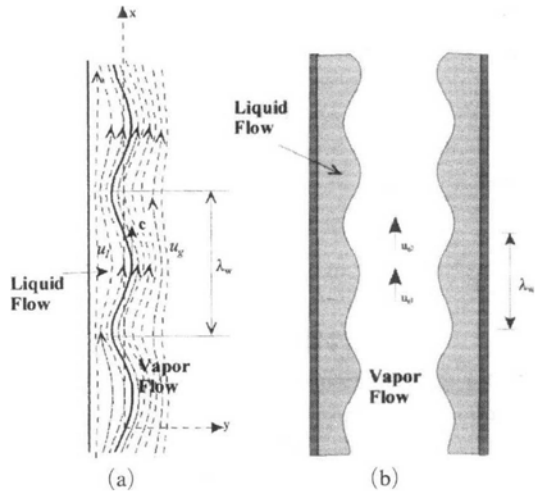

Fig. 2 Instability Model

In the annular flow region in a TLT, the liquid flows in a thin film enclosing the vapor phase in a cylindrical core. It is interesting to consider the effect of this change of geometry has on the stability problem, assuming the mean velocities of the two phases and the shape of the interface remain unchanged.

The unstable feature of a TLT system is when the annular flow is disturbed because of the unbalance in the normal stress between the liquid and the vapor interface. This unbalance will lead to cut off the flow stream or some chaotic flow situation and also lead to velocity and pressure perturbation. Finally this unbalance will induce a large pressure drop. When the annular flow in the riser is stable, the pressure drop is just induced from the pipe wall friction.

Considering Kelvin-Helmholtz instability in an annular flow, the problem of interfacial stability can thus be considered as the determination of these values of the flow and fluid parameters which make c (wave velocity) positive for a given value of the wave number k (wave number). Simply in a pipe flow, the wave disturbance can be assumed to be axisymmetric. The Kelvin-Helmholtz instability in an annular flow is mainly the relationship between the liquid flow and the vapor flow. Therefore, the behavior of the vapor phase will be considered first followed by the liquid phase.

The disturbance to the interface is accompanied by velocity and pressure fluctuations in the vapor. Since the flow is axisymmetric, the velocities can be related to a Stokes stream functions of the form,

$$\psi=\bar{\psi}(r)+\delta\psi(r) \tag{1}$$

The pressure can be expressed in a similar form as,

$$p=\bar{p}(y)+\delta p(r) \tag{2}$$

where the first terms are the steady state stream function and pressure, respectively, and the second terms is the perturbations induced by the wavy interface. This perturbation can be expressed as exponential forms of $\delta\psi(r)=\hat{\psi}(r)e^{iky}$, and $\delta p(r)=\hat{p}(r)e^{iky}$. When these relationships are applied to the equations of motion in a cylindrical coordinate, the normal stress exerted by the vapor phase on the interface is,

$$\pi_{ng}=-k\hat{m}\rho_g(\bar{u}_g-c)^2\left[\frac{I_o(k\bar{r}_i)-1}{I_i(k\bar{r}_i)}\right] \tag{3}$$

The similar procedure can be applied to the liquid film. The functions I_0, I_1 is known as the modified Bessel functions for the first kind, of order zero and first. In this case, the liquid film is assumed to be thin enough, and thus we can get the normal stress in the liquid film interface as,

$$\pi_{nl}=k\hat{m}\rho_l(\bar{u}_l-c)^2\left[\frac{\cosh k\bar{m}-1}{\sinh k\bar{m}}\right] \tag{4}$$

The instability of the interface will occur due to the unbalance between π_{ng} and π_{nl}. This instability directly leads to the unstable state of the TLT. Therefore, we need to find the stable state between the interfaces. The stable state of interface can be found by relating the surface tension, as

$$\pi_{nl}-\pi_{ng}=\sigma k^2\hat{m}e^{iky} \tag{5}$$

Thus, we can obtain the stable velocity state expression as,

$$(\bar{u}_g-\bar{u}_l)\geq\sqrt{\frac{2\sigma}{\bar{m}\rho_g}\left(\frac{1}{2}k\bar{m}+\frac{\rho_g}{\rho_l}\right)} \tag{6}$$

The stability relationship in a vertical annular flow is now reduced to a simple formula. But this relationship cannot explain the whole system instability because the TLT system instability can be explained only by the whole system phenomena.

Table 1 Constant A_1

Working Fluid	A_1
Water	0.62
Acetone	0.21
FC-87	0.21

The simple relationship above could not reach the exact instability criteria and would not satisfy different geometrical effects and the effects of various working fluids. In the present analysis, the instability criteria is compared with experimental results by the relationship as shown in Eq. (8) with constant A_1.

The empirical constant A_1 obtained from the present TLT is given in Table 1. The constant A_1 is obviously different for different geometries and working fluids. The stable length, k_s is defined as;

$$k_s=\sqrt{\frac{(\rho_l-\rho_g)g}{\sigma}} \tag{7}$$

and mean film thickness, $\bar{m}$ is calculated by a simulation procedure given as.

$$(\bar{u}_g-\bar{u}_l)\geq A_1\sqrt{\frac{2\sigma}{\bar{m}\rho_g}\left(\frac{1}{2}\left(\frac{(\rho_l-\rho_g)g}{\sigma}\right)\right)^{1/2}k_s+\frac{\rho_g}{\rho_l}} \tag{8}$$

In the present analysis, this instability criterion is a part of the computer program and liquid film thickness, entrainment and other parameters in Eq. (8) are calculated. This criterion is related to other two-phase flow parameters.

The present analysis (simulation) is based on the thermal resistance network of TLT system. The TLT system resistance, R_{loop}, must be determined through various tow phase flow parameters involved. The detailed simulation logics are described by Rhi et al. (1998), Lee et al (1999), and Rhi (2000).

4. Results and Discussion

Two-phase loop thermosyphon systems (TLT) are often subjected to flow instabilities which are undesirable for obvious practical reasons. In the experimental program of the present study, the parameters such as pressure drop, the amount of working fluid in a TLT, the insert size, heat flux etc which affect the stability of a TLT have been investigated.

Figure 3 shows the effect of heat transfer rate, Q, on the heater temperature and the evaporator temperature from the point view of the instability. The temperatures of a TLT increases with increasing heat flux. Increasing heat flux leads to increase the operation pressure and void fraction, quality, saturation temperature and consequently the driving force will be increased. Obviously, the increased driving force leads to increase the stability as seen in the figure.

It is generally accepted that the amount of the working fluid in a system affects the system stability. The theoretical study of Ishii (1992) predicts that the system stability is decreased with increasing the amount of working fluid. However, the present experimental study shown in Fig. 4 indicates that this is not necessarily true. As seen in the figures, the best stable performance for the present TLT (for 30 ml, the heater temperature was over the design goal) is obtained when the amount of the working fluid is 40 ml which implies that the theory of Ishii could not predict the optimum working state.

Ishii's analysis (1992) predicts that the stability is decreased with increasing umax and lc. However, our experimental results shown in Figs. 5 and 6 indicate that the effect is very marginal.

As stated above, for the test TLT, three orifice type inserts (cylindrical: Outer diameter is 5.5 mm and 6 mm in height, dorifice=0.51, 0.71 and 1.2 mm, respectively) were used to study the effect of a change in the pressure drop in the flow channel of the TLT on the flow instability and temperature fluctuation. When the orifice insert is not installed, the inner diameter is 3.7 mm. These inserts are placed inside the condensate line using a Tee connector situated near the evaporator section (140 mm from the upper edge of the evaporator).

The instability in a fluid loop system has been extensively studied by many during the last 50 years. However, the most of the studies are limited to single phase flow or theoretical approach with limited experimental verifications.

Figures 7 to 9 indicate that with the orifice of

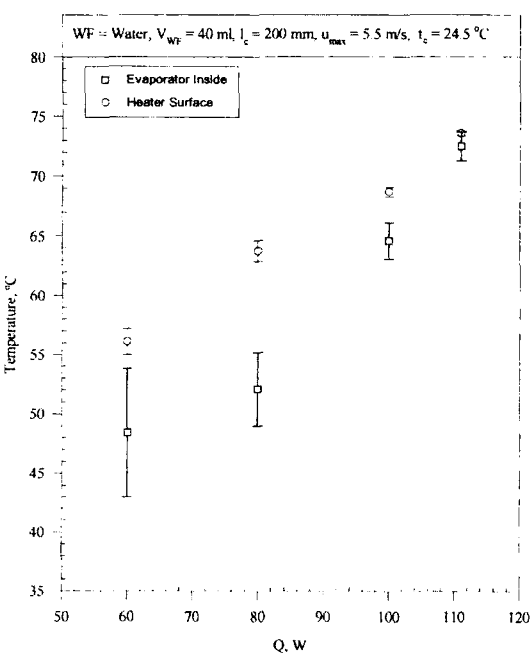

Fig. 3 Pulsation of Temperature vs. Heat Flux

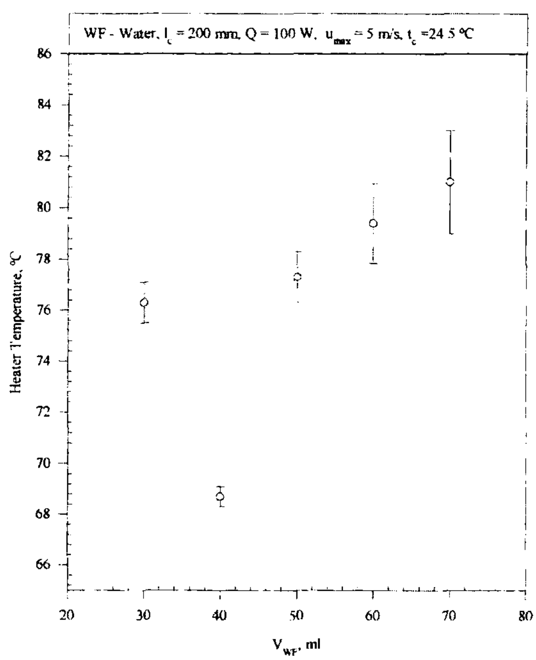

Fig. 4 Effect of VWF on Heater Temperature

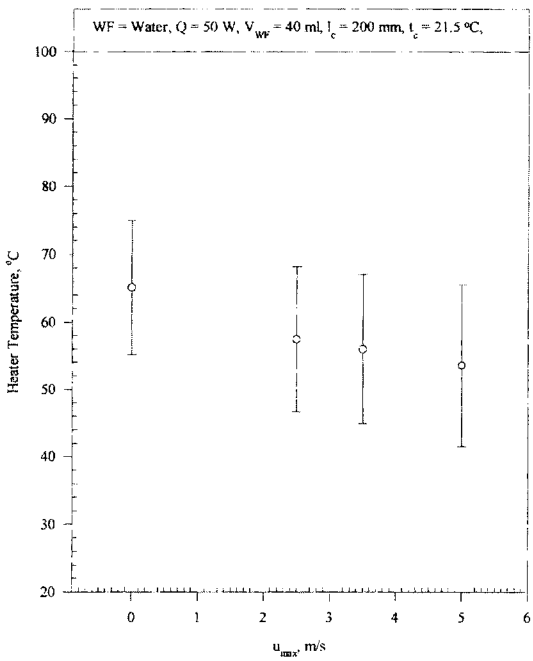

Fig. 5 Effect of u_{max} on Heater Temperature Fluctuation

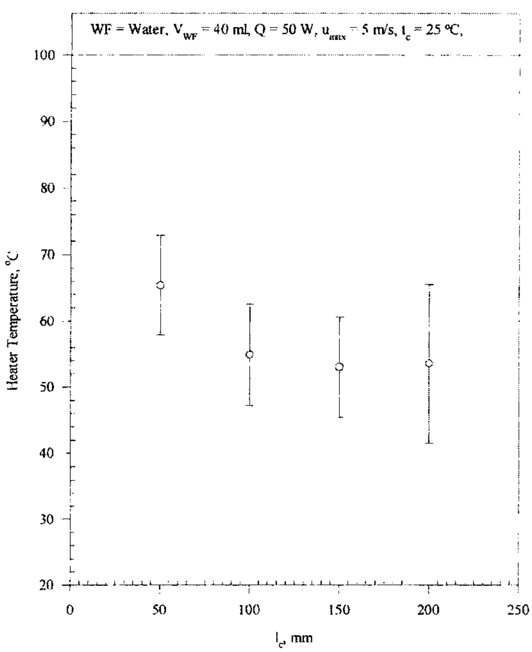

Fig. 6 Effect of lc on Heater Temperature Fluctuation

0.71 mm, the overall temperature fluctuation can be almost eliminated as the power to the TLT is

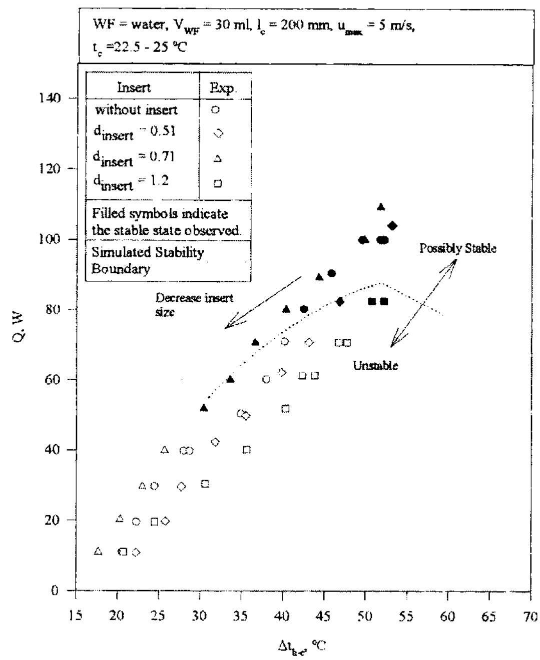

Fig. 7 Comparison Between Experiment and Simulation, Stability Boundary with Inserts, Water

increased. It could be expected that the smaller the size of the orifice, the larger the overall pressure drop of the system because of the insert, thus reducing the total mass flow rate which would have resulted in low heat transfer performance. The studies by Lorenzini (981) and Imura (1994) generally showed that the system instability decreased with decreasing the insert size. In Figs. 7 to 9, it is seen that the best heat transfer performance is obtained with 0.71 mm ID insert with acetone and water as the working fluids. However, it is interesting to note that with acetone as the working fluid, the differences in the performance with different inserts or even without any insert is relatively very small. On the other hand, with water as the working fluid, there seems to exist an optimum size of the inserts, namely 0.71 mm ID insert for the present TLT.

The attempts to simulate the system instability are shown in Figs 7 to 9. The instability calculation with the correction factors given in Table 1 agrees rather well with the experimental results. The simulation based on Kelvin-Helmholtz instability theory can reasonably describe the insta-

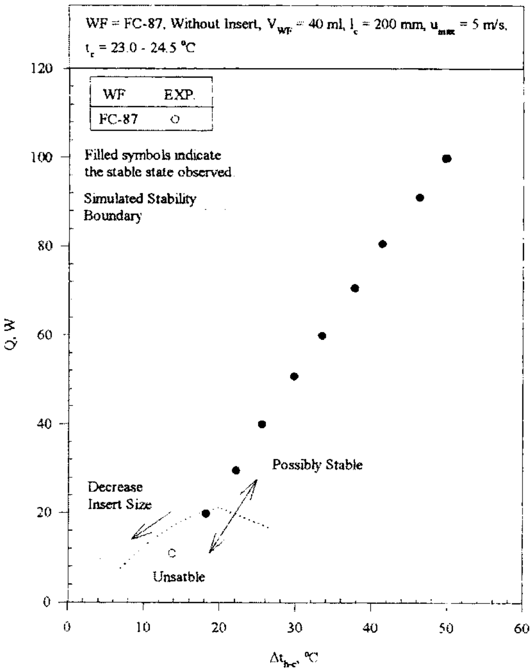

Fig. 8 Comparison Between Experiment and Simulation, Stability Boundary with Inserts, FC87

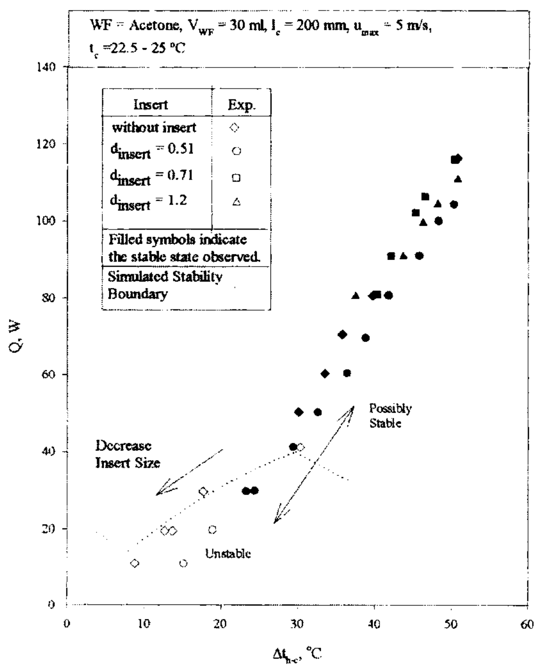

Fig. 9 Comparison Between Experiment and Simulation, Stability Boundary with Inserts, Acetone

bility boundary of the system.

5. Conclusion

An experimental and analytical study was carried out on the instabilities for a two-phase loop thermosyphon (TLT).

(1) The various parameters which would affect the instability state operation of the TLT such as Q, u_{max}, l_c, V_{WF} were experimentally investigated. With acetone, water and FC-87 as the working fluids, it was seen that the TLT instabilities are affected by the charge and kind of the working fluids, heat flux, and insert size. The experimental results also showed that an insert before the evaporator inlet of the TLT significantly affect the temperature fluctuations in the loops, especially when the working fluid is water. It was also noticed that as the heat flux was increased, the temperature fluctuations were reduced.

(2) An analysis based on the Kelvin-Helmholtz instability theory for a TLT showed that the critical velocity accompanied with empirical correction factors can predict the system instability boundary to a certain extent and that the theory agrees relatively well with the experimental results of the present test TLT.

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