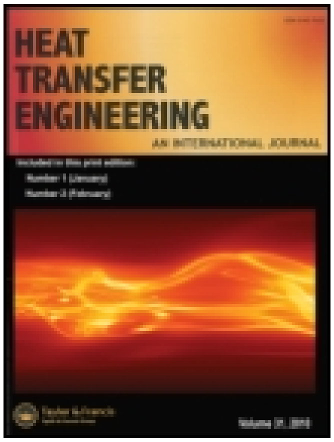

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Investigation of Geyser Boiling Phenomenon in a Two-Phase Closed Thermosyphon

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In this paper, geyser boiling phenomenon (GBP) in a two-phase closed thermosyphon has been investigated experimentally. Here, the effects of the inclination angle, filling ratio, input heat rate, mass flowrate of coolant, and inside diameter of the tube on the GBP have been discussed. Three copper thermosyphons with inside diameters of 14 mm, 20 mm, and 24 mm and a length of 1000 mm were employed. Distilled water was used as the working fluid. A series of experiments was carried out to investigate the effect of the inclination angle range of 5° to 90°, the input heat rate range of 50 to 312.4 W, the coolant mass flow rate range of 0.00389 to 0.0164 kg/s, and the filling ratio range of 15 to 45%. The GBP has been investigated by analyzing the time variations of the evaporator and adiabatic wall temperature and outlet water temperature from condenser jacket. The results show that the period of GBP was longer for higher inclination angles and filling ratios. Furthermore, it was discovered that the GBP did not take place for inclination angles of less than 15°.

INTRODUCTION

Two-phase closed thermosyphons are a group of heat pipes known as wickless heat pipes, so named because there is no wick inside the pipes. It consists, as a rule, of an evacuated-closed pipe filled with a certain amount of a suitable pure working fluid. The two-phase closed thermosyphon has three main parts: the evaporator, adiabatic, and condenser sections (see Figure 1). When heat is added in the evaporator section, the working fluid inside the pipe vaporizes and carries heat from the heat source to the condenser section, where heat is rejected to the heat sink. The condensate working fluid returns to the evaporator section by gravity. For this reason, the condenser section of the pipe must be positioned above the evaporator section.

Due to effective latent heat transfer associated with the phase change processes, a large quantity of heat is transferred from the evaporator section to the condenser section with a relatively small temperature difference.

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The thermosyphon is widely used in various industrial applications, such as in heat exchangers, solar collectors, extraction of geothermal energy, cooling of gas turbine blades, cooling of electronic equipment, and preservation of permafrost in arctic regions [1].

During the normal operation of two-phase closed thermosyphons, instability often occurs. These unstable phenomena include near-dry out oscillation for small filling ratios, geyser boiling phenomenon (GBP) for large filling ratios and small heat inputs, and unstable operation due to flooding.

When the tube is filled with a large quantity of working fluid under certain thermal conditions, GBP occurs (see Figure 2). Depending on the internal conditions, the bubble will grow quickly, first filling the pipe diameter, then expanding, and finally propelling the liquid to the condenser end, which creates a characteristic sound. When the overheated liquid and the vapor bubbles reach the condenser, heat has been removed by the cooling jacket, collapsing the bubble and at the same time sub-cooling the liquid. Consequently, the liquid returns to the evaporator by gravitational forces and the GBP continues [1].

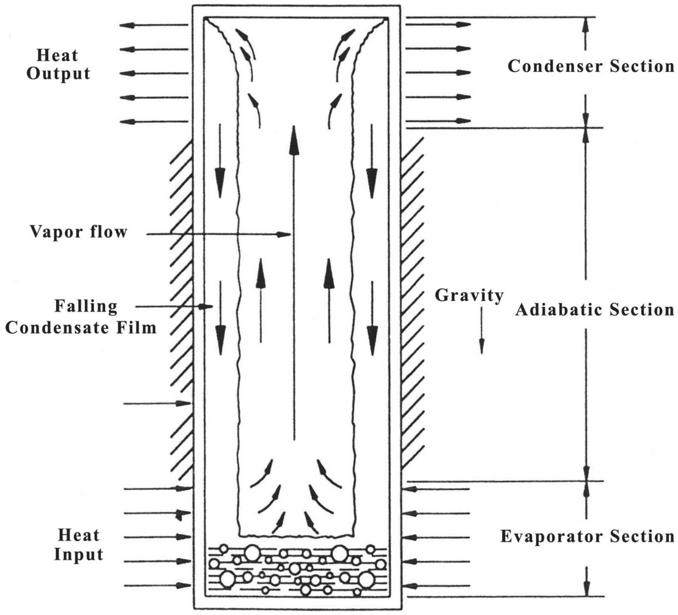

Figure 1 Working mechanism of a two-phase closed thermosyphon.

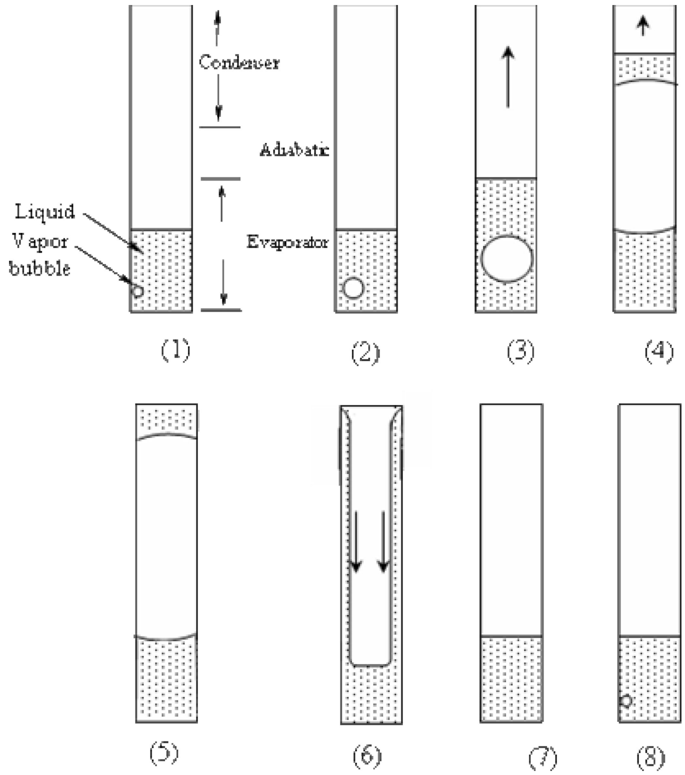

Figure 2 Geyser boiling phenomena in a two-phase closed thermosyphon.

In this article, the effects of the inclination angle, input heat rate, mass flow rate of coolant, inside diameter of tube, and filling ratio on the characteristics of the GBP under normal operating conditions were studied.

REVIEW OF PREVIOUS WORK

Semena and Kiseelev [2] found that the undeveloped boiling occurred at the heat supply zone at a low heat load, while at a high heat load, developed boiling prevails. Negishi and Sawada [3] made an experimental study on heat transfer performance of an inclined two-phase closed thermosyphon, with water and ethanol as working fluids. They discovered that the highest heat transfer rates are obtained when the filling ratio is between 25 and 60% for water and between 40 and 75% for ethanol. The inclination angle was between 20° and 40° for water, and more than 5° for ethanol. Also, they observed that at filling ratios of over 70%, GBP occurred.

Imura et al. [4] carried out visual experiments to qualitatively describe the boiling and two-phase flow patterns in vertical industrial heat pipes. Negishi [5] found that the period of GBP depends on the length of the condenser section and applied heat load in the evaporator. A longer period of time was needed for a longer condenser section. As the heat load increased, the period of GBP decreased, and the severity of the slug striking the end cap lessened. Negishi [6] used a glass-water thermosyphon to determine the frequency of the GBP as a function of the distance into the condenser section that the liquid slug reached. He found that maximum heat transfer occurs at an inclination angle of 50° from the horizontal axis.

Based on the 2529 data points, Gross [7] classified the heat transfer process in the evaporator into a two-phase natural convective regime (undeveloped boiling) and a nucleate boiling regime (developed boiling). Furthermore, Liu and Wang [8] investigated pulse boiling in a glass/water thermosyphon. They focused on the pulse boiling frequency for the determination of flow patterns. Lin et al. [9] experimentally studied GBP in a vertical annular two-phase closed thermosyphon. They found that the GBP was shorter for a higher heat load, with a smaller liquid fill and a shorter evaporator length.

Imura et al. [10] conducted experimental studies on the conditions that led to the geyser and developed boiling. They used the same dimensions of evaporator and condenser sections in a vertical two-phase closed thermosyphon and tested several cooling temperatures and heat flux for different filling ratios and working fluids. Lei et al. [11] investigated the mechanism of the GBP in a vertical gravity heat pipe. In a simplified analysis, they derived quantitative correlations for the height of the vapor plug and the volumetric flow with the pressure between two sides. Abreu and Colle [12] focused on the experimental analysis of the thermal behavior of two-phase closed thermosyphons solar collectors having unusual geometries. They observed GBP at start-up period.

This literature review clearly indicates that the effects of various parameters on the GBP are still poorly understood. In particular, the effect of inclination angle in GBP into a water-copper thermosyphon is not well known.

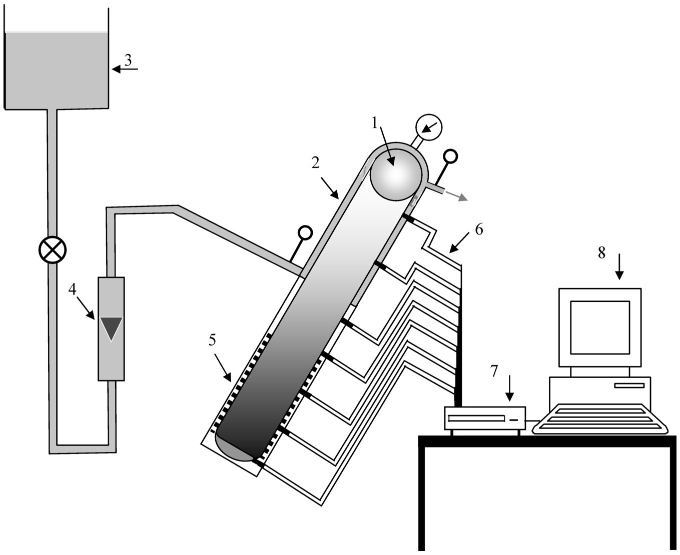

Figure 3 The experimental test rig: (1) thermosyphon, (2) water jacket, (3) liquid tank, (4) rotameter, (5) electric heater, (6) thermocouples, (7) data logger, and (8) computer.

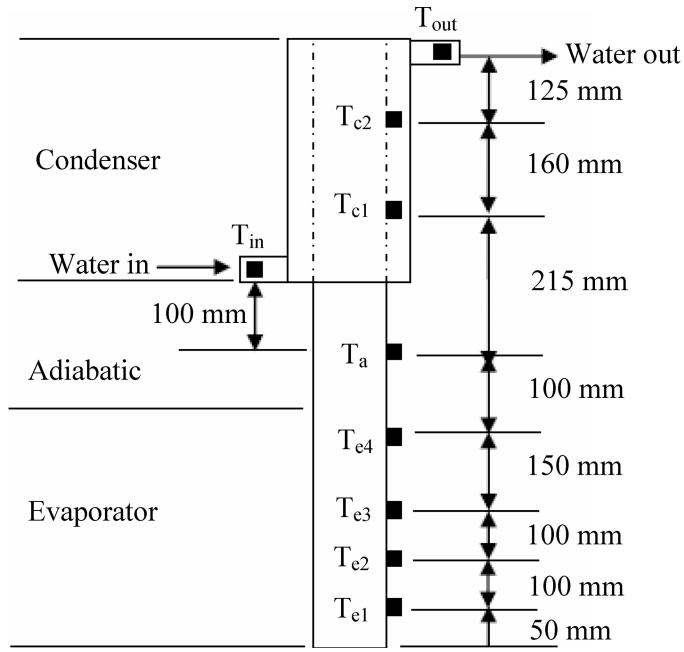

Figure 4 Location of thermocouples.

Experimental Setup and Procedure

In order to study the thermal performance of the two-phase closed thermosyphon, a special experimental set up has been designed. The schematic of the experimental test rig is shown in Figure 3.

The thermosyphon is a copper tube 1000 mm long, 16 mm OD, and 2 mm thick. To investigate the effect of the diameter, two other tubes (22 mm OD and 26 mm OD) and 2 mm thick were also employed. For both tubes, the lengths of the evaporator, adiabatic, and condenser sections were 410 mm, 180 mm, and 410 mm, respectively. Water was used as a working fluid. A 410 mm-long water jacket surrounded the condenser section, and cooling water flowed through the annular passage of the jacket. The water inlet and outlet temperatures of the jacket were measured by two digital "TESTO" thermometers. A constant head tank was placed two meters above the head of the thermosyphon and connected to the cooling section through a plastic pipe. The flow rate of cooling water was measured by a rotameter. The electric heater of the evaporator section was made of a nickel-chrome wire with a nominal power of 1000 W. The electric heater was covered by an electrical insulating tape and 32 mm thick rock wool insulation. The other sections of the thermosyphon were covered by the rock wool to reduce the heat loss to the environment.

Temperature distribution along the external surface of the thermosyphon was measured by seven Ni-Cr thermocouples mechanically attached to the surface of the pipe. The thermocouples were glued by a high conductive epoxy. The operating pressure was measured by a pressure transducer connected to the upper part of the thermosyphon. For temperature measurement in the condenser section, thermocouples were mounted on the water jacket but pressed against the external surface of the inner pipe of the thermosyphon through a screw arrangement. All thermocouples were connected to a data-logger, which was connected to a computer for displaying data. The accuracy of measurements was approximately $\pm 1^\circ$C for temperatures of the external surface pipe, $\pm 0.1^\circ$C for input and output water, $\pm 4\%$ for water flow rate, and $\pm 2\%$ for pressure.

Before charging the pipe, the tube was thoroughly cleaned to remove any grease or oil from the inner surface. After charging the working fluid and confirming the absence of non-condensable gases in the tube, the thermosyphon was set for the experiments. The thermosyphon was vacuumed down to 0.001 mm Hg. A series of experiments was carried out for the investigation of the effect of the inclination angle range of $5^\circ \leq \Phi \leq 90^\circ$, input heat rate range of $50 \leq Q_{in} \leq 312.4$ W, coolant mass flow rate range of $0.00389 \leq \dot{m}_c \leq 0.0164$ kg/s, and filling ratio range of $15\% \leq \text{FR} \leq 45\%$. The locations of the thermocouples are shown in Figure 4.

Calculation of Input and Output Heat Transfer Rate

The following calculations were carried out to determine the input and output heat rate of the thermosyphon. The actual input heat rate to the evaporator section was obtained from Eq. (1).

$$Q_{in} = \text{VI} - Q_{loss} \quad (1)$$

where Q_{loss} is the sum of heat losses from the evaporator section by radiation and free convection. The heat loss from heater surface was evaluated by measuring the temperatures across the insulation layer over cylinder [13].

The heat transmitted from the condenser section is equal to the rejected heat to coolant water in the jacket, and was calculated as:

$$Q_{\text{out}} = \dot{m}_{c_{p,w}}(T_{o,w} - T_{i,w}) \quad (2)$$

EXPERIMENTAL RESULTS AND DISCUSSION

In this work the effects of the following parameters within their operating range were studied.
Fixed parameters:

- working fluid: distilled water
- condenser length: 410 mm
- evaporator length: 410 mm
- material of tube: copper

Variable parameters:

- filling ratio: $15\% \leq \text{FR} \leq 45\%$
- inclination angle: 5, 15, 30, 45, 60, 75, 90°
- inside diameter: 14, 20, 24 mm
- coolant mass flow rate: $0.0032 \leq \dot{m}_c \leq 0.012$ kg/s
- input heat rate to evaporator section: $50 \leq Q_{\text{in}} \leq 312.4$ W

A series of experiments was carried out to find the effect of inclination angle, filling ratio, coolant mass flow rate, input heat rate, and inside diameter on the characteristics of GBP in a two-phase closed thermosyphon. The results were compared with a previous work [3].

Inclination Angle

Figure 5 shows the temperature changes of the four thermocouples (see Figure 4) in the evaporator section for $\Phi = 75°$, FR = 30%, $Q_{\text{in}} = 50$ W, and ID = 14 mm. It is obvious from Figure 4 that none of the thermocouples, except the number 1, shows significant variations. This is because the liquid level in the thermosyphon is 123 mm, and only the thermocouple number 1 is below the liquid level. The generation of bubbles in GBP occurs close to the bottom of the thermosyphon (evaporator section), and therefore the thermocouple (T_{e1}) is only considered in the discussions that follow.

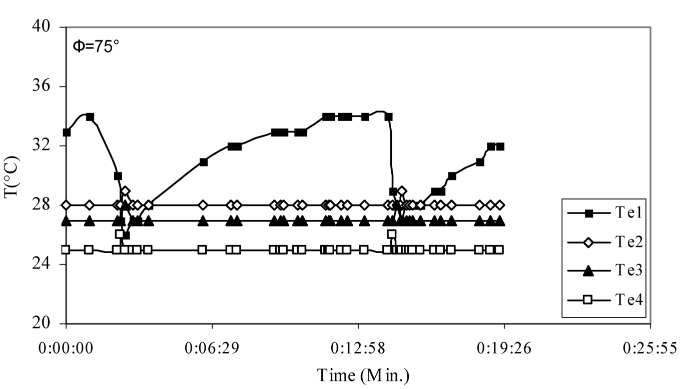

Figure 5 Temperature variation of the thermocouples in the evaporator section for $\Phi = 75°$, FR = 30%, $Q_{\text{in}} = 50$ W, and ID = 14 mm.

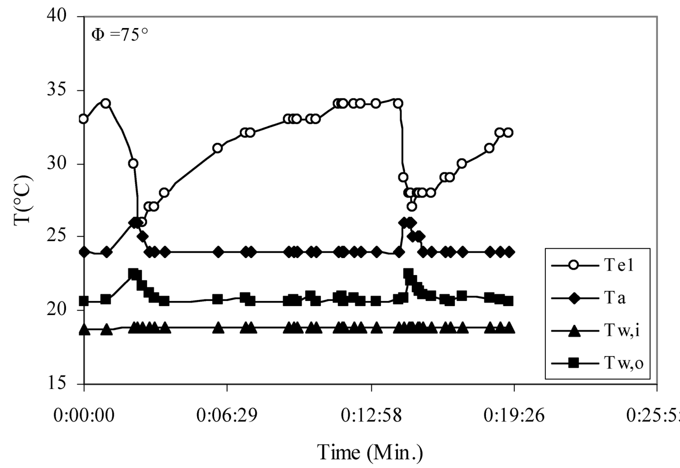

Figure 6 Temperature variation of the tube section for FR = 30%, AR = 29.3, and $\Phi = 75°$.

Temperature variations of the evaporator wall (T_e), adiabatic section (T_a), water inlet ($T_{i,w}$), and outlet ($T_{o,w}$) temperatures to and from the condenser jacket at FR of 30% and Φ of 75° are shown in Figure 6. Similar trends of temperature variation can be observed in Figure 7, where Φ is 45°.

Figures 6 and 7 show that the temperature variations versus time in the evaporator section are in the form of a bead edge rim, but the temperature in the adiabatic section and outlet water of jacket varies instantly. The inlet water temperature at condenser jacket was constant.

The following conclusions may be drawn from Figures 6 and 7:

- As expected, decreasing the inclination angle (Φ) decreases both the period of temperature oscillation and the range of temperature variation.
- Decreasing the inclination angle causes a significant reduction in the thermosyphon sound level (i.e., reduces the impact intensity at the end cap of the condenser section).

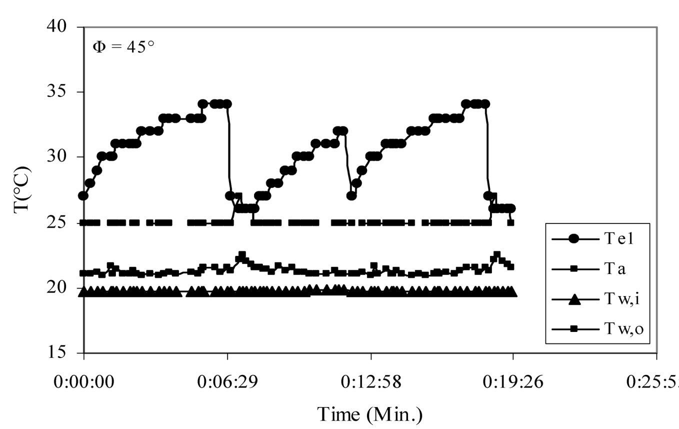

Figure 7 Temperature variation in various parts of tube for AR = 29.3, FR = 30%, and $\Phi = 45°$.

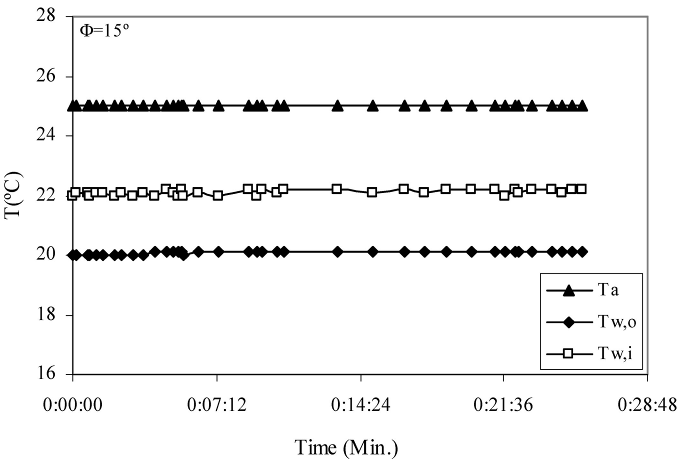

Figure 8 Temperature variation of the tube sections for AR = 29.3, FR = 30%, and $\Phi = 15°$.

- The evaporator temperature rises more rapidly than both the outlet water temperature of the condenser jacket and the temperature of the adiabatic section.

As can be seen from Figure 8, at $\Phi = 15°$, the temperature variation disappeared completely. By decreasing the inclination angle, the surface area of the bubble increases and causes the bubble to become unstable. Therefore, after the bubble moves a short distance, but before reaching the end cap, it will burst.

The Effect of Filling Ratio (FR)

Figure 9 shows the variation of temperature versus time at a constant rate of heat input (50 W) for filling ratios of 30 and 45%.

The GBP period increases from 12 to 15 minutes when the FR changes from 30 to 45%. Higher FR causes a substantial impact to the end cap. During the warming up of the water in the source, some vapor in the condenser section condenses. This causes an increase in pressure difference at both ends of the thermosyphon; thus, the impact intensity level is increased.

A sudden rise in temperature level at the adiabatic section and outlet water temperature at the condenser jacket is due to the escape of bubbles from adiabatic part to the condenser section and drops of liquid film from the condenser to the evaporator.

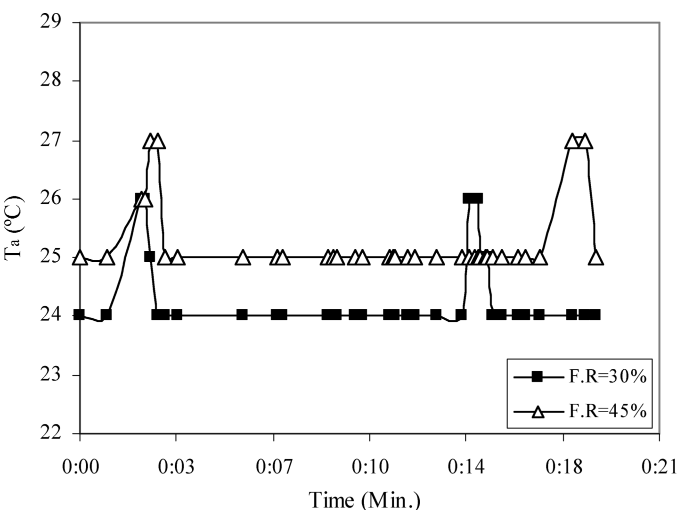

Figure 9 Temperature variation in adiabatic section for inlet heat rate of 50 W.

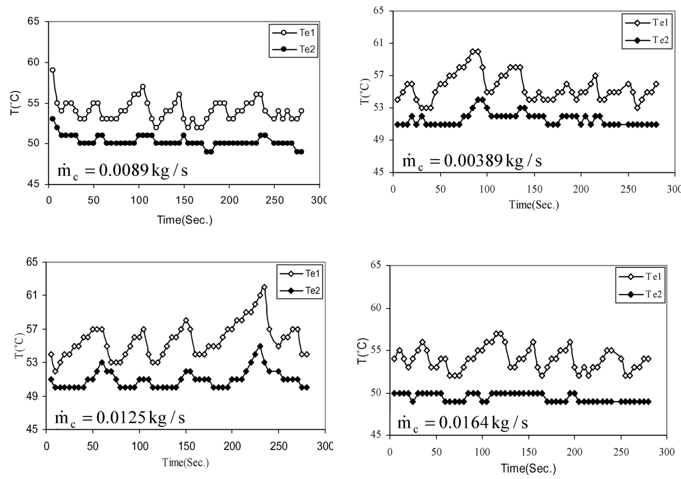

Figure 10 Temperature variation of evaporator for various coolant flow rates at $Q_{in} = 200$ W.

The Coolant Mass Flow Rate

Figure 10 illustrates the effect of the coolant mass flow rate on GBP at inlet heat rate of 200 W, FR of 45%, and aspect ratio (AR) of 29.3. The experiments were carried out only for two thermocouples, T_{e1} and T_{e2}. These curves indicate that by increasing the coolant mass flow rate, the T_{e1} and T_{e2} temperatures reduce slightly due to conductive heat transfer caused by the walls. Hence, the coolant mass flow rate has no significant effect on the behavior of the GBP.

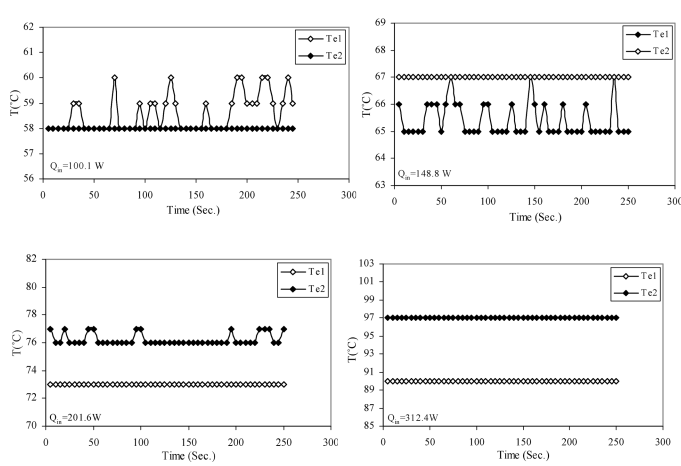

Figure 11 Temperature variation in evaporator section for FR = 45% and AR = 29.3.

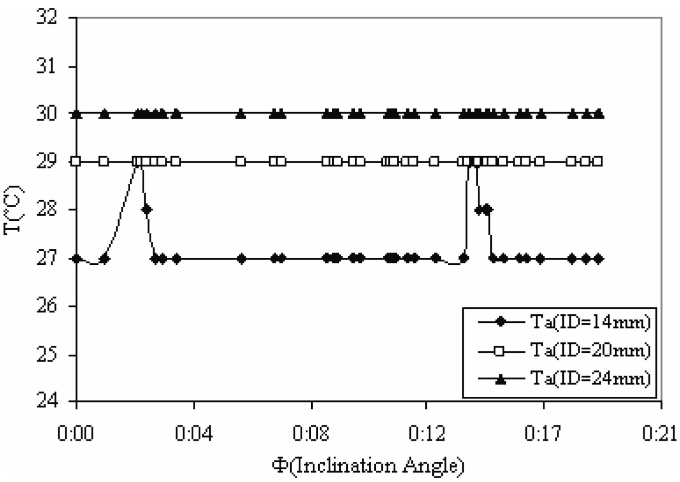

Figure 12 The effect of inside diameter of thermosyphon on geyser boiling phenomena.

Input Heat Rate

The effect of input heat on behavior of GBP in the range of 100 to 312.4 W can be seen in Figure 11. For the input heat rate of 100 W (see Figure 11a), the temperatures of both thermocouples (T_{e1}, Te$_2$) are nearly the same, while the temperature of T_{e1} oscillated from 1 to 2°C in regular period. At 148.8 W (see Figure 11b), T_{e2} is higher than T_{e1}, even though the temperature variation for T_{e1} existed.

By increasing the inlet heat rate to 201.6 W (see Figure 11c), the thermal oscillation of T_{e1} completely disappeared, but for T_{e2}, this oscillation increased. This is due to the displacement of bubble region. When the inlet heat rate reaches 312.4 W (see Figure 11d), the vapor pressure in the thermosyphon increased; hence, it was not possible for the bubbles to form to the size of inside diameter of tube. Therefore the GBP did not take place.

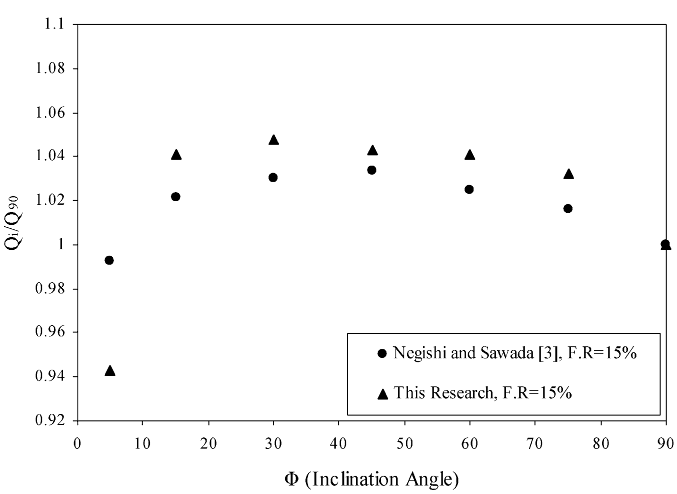

Figure 13 Comparison results of the present work with Negishi and Sawada [3] for FR = 15%.

Table 1 Comparison of the Geometry and Other Conditions with Those of Negishi and Sawada [3]

	L_t (mm)	L_e (mm)	L_c (mm)	T_a (°C)
Negishi and Sawada [3]	330	150	150	55
This work	1000	410	410	25

Inside Diameter

The effect of inside diameter on the GBP is shown in Figure 12. The temperature of adiabatic section shows a regular oscillation when the inside diameter of tube is 14 mm, FR of 45%, and input heat rate of 54 W. However, by changing inside diameter of tube to 20 mm and 24 mm, the oscillation stops.

As we know in GBP, some conditions occur that enable a bubble in a point over the internal surface of the evaporator section to grow up to internal diameter of the pipe. Because the critical diameter of the bubble is inversely proportional to vapor pressure inside the bubble and also the liquid above the bubble, by increasing the diameter of the bubble, the driving force for moving the bubble decreases and the bubble abruptly disappears.

Comparison with Previous Work

As explained earlier, the experimental results of this work can be compared with the study carried out by Negishi and Sawada [3]. Figure 13 shows variation of heat transfer ratio of inclined to vertical thermosyphon (Q_i/Q_{90}) versus the inclination angle for a filling ratio of 15%. As shown in Figure 13, a good agreement (around 2% deviation on average) was observed between the results of this work and those of Negishi and Sawada [3].

GBP occurred in the present work at FR greater than 30%, while in the work of [3], it occurred at FR greater than 70%. The reason behind this difference can be the result of the difference of the working temperature (T_a) and geometry. The results obtained from the two experimental setups have been compared in Table 1.

CONCLUSIONS

A series of experiments was carried out to find the effect of inclination angle, filling ratio, coolant mass flow rate, and input heat rate and inside diameter on characteristics of GBP in a two-phase closed thermosyphon. Based on these results, the conclusions are as follows:

1. For filling ratios of 30% and higher, for a thermosyphon with 14 mm inside diameter, GBP occurs. To prevent this phenomenon, the filling ratio should be less than 30%.
2. A substantial variation of temperature was only observed for evaporator temperature, T_{e1} (see Figure 4), which is the most probable place for growing bubbles.

3. By reducing the inclination angle to a value below 15°, the impact intensity applied to the end cap of evaporator was reduced. Also, the variation of temperature period as well as temperature variation range becomes smaller.
4. Increasing the filling ratio from 30 to 45% increases the period of GBP and the intensity of impact on the end cap of the condenser as well.
5. The coolant mass flow rate in condenser jacket has no effect on the behavior of GBP.
6. Up to an input heat rate of about 149 W in evaporator section, the period of GBP becomes shorter. At an input heat rate of about 202 W, the generation of bubbles occurs near the surface of the fluid source. At inlet heat rate of about 312 W, the GBP completely disappears.
7. The geyser boiling phenomenon and experimental results of present work at filing ratio of 15% are in good agreement with the results of Negishi and Sawada [3].

NOMENCLATURE

AR	aspect ratio, ratio of the evaporator length to inside diameter of the tube
$c_{p,w}$	specific heat of water at constant pressure, J/kg · °C
FR	filling ratio, ratio of volume of working fluid to volume of evaporator section, %
I	current, A
ID	inside diameter of tube, m
L_c	length of condenser section, m
L_e	length evaporator section, m
L_t	total length of thermosyphon, m
$\dot{m}_c$	coolant mass flowrate of water, kg/s
Q_{90}	output heat transfer rate at vertical position, W
Q_i	output heat transfer rate at inclined situation, W
Q_{in}	input heat rate into the evaporator section, W
Q_{loss}	sum of heat losses from the evaporator section by radiation and free convection, W
Q_{out}	transmitted heat from the condenser section, W
T_a	temperature of adiabatic section, °C
T_e	temperature of evaporator section, °C
$T_{i,w}$	inlet water temperature of condenser, °C
$T_{o,w}$	outlet water temperature of condenser, °C
V	voltage, V

Greek Symbol

Φ	inclination angle, measured against horizontal

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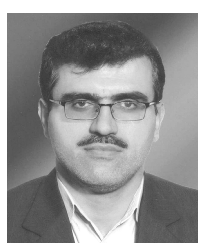

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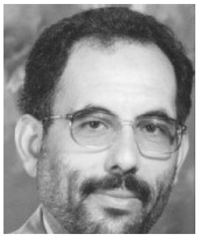

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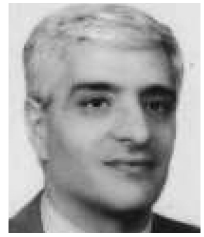

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