Performance of a small diameter two-phase closed thermosyphon in geyser boiling condition

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Abstract. In the present article, the geyser boiling phenomenon is experimentally investigated in a small diameter two-phase closed thermosyphon. The studied thermosyphon has an inner diameter of 4.8 mm and total length of 918 mm. Three specific filling ratios and four temperatures for the thermal bath used to provide cooling water to the condenser were tested. Power was inputted in steps of 20 W, up to 100 W. Variation of the temperatures on the walls of the evaporator, adiabatic and condenser sections as well as variations on pressure, obtained from a pressure transducer installed on the thermosyphon, indicated the presence of Geyser boiling. The results show that the studied variables affect directly the intensity and periodicity of the geyser boiling phenomenon.

1. Introduction

Two-phase closed thermosyphons are high conductance thermal devices. Basically, a thermosyphon can be considered as a closed evacuated container, where a certain amount of working fluid is inserted. It has three sections: evaporator, condenser and adiabatic regions. Heat is inputted in the evaporator and rejected in the condenser section. The working fluid evaporates in the evaporator and the resulting vapor is transported, due to pressure differences, to the condenser region, where heat is then rejected, causing the vapor condensation. The condensate returns to the evaporator region due gravity action, closing the cycle. This heat transfer process is cyclic and passive as it does not require the use of pumps or other active devices, being driven only by temperature differences between evaporator and condenser, which can be quite small. It is imperative that the evaporator section remains under the condenser, as the gravity must be responsible for returning the condensate from the condenser to the evaporator. As stated by Faghri [1], the high thermal conductance of the thermosyphons is directly associated with the high convection coefficients of the evaporation and condensation observed internally the device. These characteristics make thermosyphons attractive solutions to improve the efficiency of heat exchangers, for instance.

However, the same physical phenomena which allow the thermosyphon to work, also limit its maximum heat transfer capacity. These operational limits are important parameters to consider when designing such devices. The literature reports several models and correlations developed to predict the maximum admissible heat power according to the physical phenomena that limits the heat transfer. Many of these correlations are shown in Table 1. Some of these heat transfer limits are resulting from the interaction between the counter flows of the liquid and vapor phases, inside the thermosyphons. By analyzing the equations presented in Table 1, it is observed that these limits are functions of the thermophysical properties of the liquid-vapor phases and of the geometrical properties of the tube. From Table 1 equations, it is also detected that the inner diameter (d_i) is a highly influential parameter.

However, during the tests, it was observed that the geyser boiling phenomenon (from now on referred as GBP) occurred before any other operational limits were reached. Even if it does not represents a limitation to the heat transfer capacity of the thermosyphon, the GBP must be avoided, as it may cause strong vibration and/or may damage the end cap of the condenser if maintained for large periods of time, as stated by Faghri [1].

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In the present paper, the heat transfer performance of a small diameter thermosyphon is studied, with special attention to the occurrence of the GBP.

### 2. Literature review

As stated by Faghri [1], the GBP happens when the input power on the evaporator is insufficient to allow constant nucleate boiling. In this case, the temperature of the liquid pool increases until it becomes superheated. A vapor bubble then nucleates, somewhere in the liquid pool and its size quickly increases up to the inner diameter of the tube. This vapor bubble separates a portion of the working fluid from the rest of the pool. The bubble continues to grow until it is inside pressure is enough to impel this portion of fluid upwards, which reaches the top of the condenser. Then, a liquid slug returns to the evaporator in the form of subcooled liquid film over the wall. This subcooled liquid cools down the temperature of the liquid pool. This cycle configures the GBP. Afterwards, a certain time is required until the liquid pool can reach superheated condition again and a new cycle of the GBP can happens. A representation of GBP is shown in Figure 1.

![Coaxial thermosyphon](image_url)

**Figure 1. Geyser Boiling Phenomenon [6].**

Gross [7], based in 2529 experimental points, studied pool boiling in a thermosyphon. The heat transfer was classified in two categories: two-phase natural convection regime (undeveloped boiling) and nucleated boiling (developed bubble boiling). His results agreed with those of Semena and Kisselev [8], who associated the undeveloped boiling with low input power and the developed bubble boiling with high input power levels.
breaks in steady streams as it runs down the inner walls of the thermosyphon. The wall high temperature cause nucleation of bubbles as these streams approach the evaporator, inducing instabilities in the streams.

Negishi and Sawada [10] experimentally studied the thermal performance of an inclined two-phase closed thermosyphon. The involucre was composed by a 330 mm long copper tube with an inner diameter of 13 mm. Water and ethanol were selected as the working fluids. The inclination angle varied between 20° and 40° for the water-filled and between 25° and 45° to the ethanol-filled thermosyphons. According to their results, filling ratios (ratio between working fluid volume and evaporator volume) from 25 to 60% for water and from 40 to 75% for ethanol yielded the better heat transfer rates. They also concluded that GBP takes place for filling ratios greater than 70 percent.

Negishi [11] observed that the periodicity of the GBP depends on the condenser section length and on the input power at the evaporator. He observed that longer condenser sections yielded GBP with longer periods. In turn, as the input power in the evaporator increased, the GBP period decreased, and the intensity with which the fluid hit the condenser top was also attenuated. Lin et al. [12] confirmed that smaller filling ratios and shorter evaporator lengths make the periodicity of the GBP shorter, declining almost linearly with the input power increase. The amplitude of the oscillations was also found to decrease as input powers increase.

Mantelli et al. [13] experimentally studied the behavior of a two-phase closed thermosyphon. Water was used as the working fluid. The involucre was made of a 1220 mm long stainless steel tube with an inner diameter of 17.05 mm. The results confirmed the occurrence of GBP for input powers lower than 25 W. On the other hand, for higher input powers, nucleated pool boiling intensified and GBP disappeared. These results agree with Faghri [1], who stated that, even if GBP cannot be qualified as a thermosyphon limit, it is a startup phenomenon, which affects its performance.

Kunkoro et al. [14] studied the geysering mechanism in a two-phase closed thermosyphon. A 2507 mm long, transparent glass tube was used to observe the phenomenon. It was discovered that the temperature distribution or the internal-energy storage pattern might play an important part on the GBP onset. The temperature distribution depends on the geometry of the system, on the physical properties of the working fluid and on the heat transfer process. They justified the GBP mainly to the superheating of the fluid. During the nucleated boiling, the GBP could still be observed even with the vapor pressure rising.

Khazaee et al. [15] studied the influence of four parameters on GBP: filling ratio, input power, mass flow rate through the condenser refrigeration system and aspect ratio (ratio between evaporator length and tube inner diameter). They observed that, increasing the filling ratio, the period and the intensity of the oscillations also increased. However, for filling ratios smaller than 30 percent, the GBP disappears. Moreover, with an increase in the input power, the period and the intensity of the oscillations decreased, until they disappeared completely. For smaller aspect ratios and mass flow rates through the condenser refrigeration system, the period of oscillation increases.

Xia et al. [16] observed that the heat transfer instabilities in the thermosyphon evaporator are mainly caused by the behavior of bubbles, fluid physical properties and operating pressures. They classified the heat transfer in the thermosyphon in three modes: natural convection, intermittent boiling (GBP) and fully developed nucleated boiling.

Smith et al. [17] proposed the first multiphase flow map for closed two-phase thermosyphons, identifying four types of flow: Geyser Flow, Slug/Plug Flow, Churn Flow and Bubbly Flow. The map was designed according to the degree of confinement and the rate of steam production, establishing four zones with the four boiling regimes. Intermittent boiling was observed in high levels of confinement and high heat flows, in which relatively large bubbles are characteristics of the Geyser Flow regime. However, in conditions of low confinement at high steam production rates, the boiling regimes are similar to those observed in the pool boiling (Bubbly Flow). Small diameter thermosyphons show boiling regimes different from those commonly reported for the conventional thermosyphons (pool nucleation and film condensation).

3. Experimental procedure
The thermosyphon studied in the present work was made from a 918 mm long copper pipe with an inner diameter of 4.8 mm. Its three regions: evaporator, adiabatic and condenser, had the lengths: 200, 90 and 628 mm, respectively. The working fluid was chosen according to the suggestion of Reay et al. [18], who affirmed that working fluids with a high merit number should be preferred to minimize the gradient of temperature over the thermosyphon. For the operating temperature range of this thermosyphon, water was selected as working fluid because it exhibited the highest merit number. Four cartridge electric resistances were inserted in an
aluminum block in close contact with the evaporator, to provide the thermosyphon input power by means of a power supply (MEC 1310). The evaporator and adiabatic sections were thermally insulated from the environment using expanded vermiculite. The heat rejected by the condenser is dissipated to a water jacket. The condenser section and the water jacket form a tube and shell heat exchanger. The water jacket is also connected to a rotameter (Omega FL1504A) and a waterbath (Lauda RUK-40S). These devices are responsible for keeping the cooling fluid mass flow rate and the temperature constant. Figure 2 depicts the diagram of the workbench.

![Workbench diagram](image)

**Figure 2.** Workbench diagram.

A pressure transducer was installed on the thermosyphon (Omega PX409-015V5V), along with fourteen type T thermocouples, as shown in Figure 3. The workbench also counts with three more thermocouples: one installed on the aluminum block and other two on the entry and exit of the water jacket.

![Thermocouples distribution](image)

**Figure 3.** Thermocouples distribution.
All measurement instruments were calibrated aiming to obtain an accurate evaluation of the thermosyphon behavior. The uncertainties related to each measurement device used during the experiments are showed in Table 2. The propagation of these errors for indirect measurements was determined according to equation 1, following the methodology of ISO/IEC GUIDE 98-3:2008 [19].

\[
u_c(f) = \sqrt{\sum_{i=1}^{N} \left(\frac{\partial f}{\partial x_i}\right)^2 u^2(x_i)}
\]  

In this equation, \(x_i\) represents each variable, on which the function, \(f\), is dependent. The errors derived from input power \(q_w\) and thermal resistance calculations using the Eq. (1) were 2.8%.

| Measurement | Device | Experimental uncertainty |
|-------------|--------|--------------------------|
| Temperature | Omega T-type thermocouple | ±1.5 °C |
| Pressure    | Omega pressure transducer  | ±1.8% |
| Voltage & Current | MEC 1310 power supply | <0.2% |
| Rotameter   | Omega FL1504A               | ±2.0% |

The curves for correlations, obtained using the expressions presented in Table 1 that predict the operational limits of the studied thermosyphon, are depicted in Figure 4. From this figure, it is possible to observe that the entrainment limit is the first to be reached.

For the present experimental work, the input powers ranged from 20 to 100 W with increments of 20 W. Each power step was kept constant until steady state conditions were reached.

Three filling ratios were selected: 35%, 66% and 90%, with which the liquid pool upper level reached the thermocouples Evp1, Evp2 and Evp3, respectively (see Figure 3).
The water, which circulates through the water jacket, was kept at a constant flow rate of 4.62 l/min, and the tests were carried out for two different temperatures: 20 and 30 °C. Table 3 presents an overview of the test conditions.

| Test | Filling Ratio [%] | Water jacket temperature [°C] |
|------|-------------------|-----------------------------|
| 1    | 35                | 20                          |
| 2    | 35                | 30                          |
| 3    | 66                | 20                          |
| 4    | 66                | 30                          |
| 5    | 90                | 20                          |
| 6    | 90                | 30                          |

4. Results and discussion

Figure 5 presents the obtained data of temperature and pressure as a function of time, for each one of the six tests. The temperature range (vertical axis) is the same for all plots while small changes can be observed for the time range (horizontal axis). The thermocouples are labeled according to Figure 3. Besides, Twin and Twout are the inlet and outlet water bath temperatures, Tresist is the electrical resistance temperature and P_trans is the working fluid pressure.

In the beginning of test 2, it is perceived that the pressure peaks at near 3000 Pa and then, suddenly decreases. This happens because the temperature of the thermal bath (Twin and Twout) and the temperature of the condenser are higher than the temperatures of the evaporator and adiabatic sections. Under this condition, the thermosyphon cannot work and the heat input merely increases the vapor pressure. When the temperatures of the evaporator and adiabatic sections reach the temperature of thermal bath, the device reaches thermal equilibrium and, at this point, the pressure also lowers until it reaches a equalized level.

This condition of non-operation is also observed in tests 1, 4 and 6. However, for these cases, pressure only grows. For the aforementioned tests, the condition of non-operation is temporary. Therefore, in the present analysis, only the phenomena that happen after the operation conditions are reached (all thermosyphon temperatures are above Twin and Twout) will be analyzed.

From Figure 5, it is possible to observe that in tests 3 to 6, the temperature and pressure data present very short period oscillations. In order to better understand this behavior, Figure 6 shows a data window of the 5th test (see Table 3) for the 40 and 100 W input power levels. It is noted that, at around 8500 seconds, the first sudden increase in the condenser pressure and temperatures is observed, at the same time that Evp3 shows a sudden temperature drop. The combination of these effects evidences the GBP. The sudden increase in pressure occurs because, due to its high pressure, the vapor within a bubble bursts, propelling a portion of liquid upwards with a great deal of momentum. Before bursting, the superheated liquid slug located above the bubble which volume is increasing, reaches its higher height in the condenser, evidenced by the continuous increase of the Cnd1 to Cnd5 temperatures with time. Due to the bubble burst, the liquid above the bubble is expelled and reaches the cooled condenser wall, cooling down quickly. After the bubble burst, the subcooled liquid occupies the previous vapor bubble space in the evaporator wall. This is evidenced by the temperature drop on thermocouple Evp3. The GBP is also observed with greater or lesser extent for tests 3 to 6.

It is also gathered from Figure 6, 40W, that, before the steady state conditions are reached, some of the condenser thermocouples still do not feel the vapor presence, as they remain at water cooling bath temperatures (around 20o C). However, as the evaporator temperature increases, the vapor reaches high levels in the condenser, observable by the one by one thermocouple temperature increase, which follows the order of their installation in the condenser, from the bottom to the top. Until the 7500 seconds instant, only the Cnd1 thermocouple followed the trend of the adiabatic section (steady increase in temperature). The Cnd2 thermocouple presented a pulsating reading, showing that the GBP effect reached this thermocouple height. At Cnd3 height and above, the temperatures present the same behavior as the adiabatic section. Thermocouples Cnd4 to Cnd6 sporadically presented the pulsating behavior characteristics.
Furthermore, when analyzing the temperature readings for the 100 W input power level (Figure 6 right plot), it is possible to observe intense and high frequency oscillations of the temperature readings, for all the thermocouples of the condenser section.

Figure 5 also shows that, despite of the reading oscillations, significant temperature differences between the condenser and thermal bath are observed for the thermosyphon under tests configuration 3, 5 and 6, indicating that the vapor reaches the superior end of the device. This means that the thermosyphon works better under these operation conditions, with lower thermal resistances. The temperature data of test 6 configuration shows that, in this case, the full potential of the condenser section is reached (all the condenser is heated by the vapor). Therefore, the thermal resistance is lower and, as a consequence, the temperatures reached in all the sections are lower.
Figure 6. Test 5th for 40 and 100 W of input power.

As depicted in Figure 5, the steady state for the 40W power step of the test 4 presents similar behavior as the one observed in test 6. However, as the input power increased to 60W, the behavior becomes unstable with a drop of condenser’s temperature readings, as well as an increase of temperature readings of the adiabatic section and evaporator. After approximately 13000 seconds of test run, it is observed that all of the temperature readings of the condenser section present the value as the temperature readings of the water bath, regardless of input power.

In order to help understanding these phenomena, the thermodynamic state of the working fluid was analyzed, as depicted in Figure 7.

As previously mentioned, test 6 presents the best thermal performance. By analyzing the thermodynamic state of the working fluid for this test, it is observed that the points representing the condenser section show that the working fluid is subcooled, while the points for adiabatic section are found over the saturation line and the ones for evaporator, over the superheated vapor region of the chart. This distribution represents the best thermosyphon operation conditions.

For the thermodynamic state of tests 3 and 5 (see Figure 7), the evaporator and adiabatic section points show a rightward shift in the graphs with increment in power. This causes the adiabatic section to move away from the saturation line. Simultaneously the points of the condenser, located near to the saturation line, are also displaced rightwards, leading them to a more unstable region. This would explain the reason for GBP being characterized by the chaotic and intermittent phase changes.

The thermodynamic state of test 4 explains the steady state condition found for the 40W power step, where the thermosyphon exhibits satisfactory operation. By analyzing this point, it is observed that the condenser and the adiabatic section are on the saturation line. However with increase of input power, these two sections, together with the evaporator, present a thermodynamic state of superheated steam. This shows the blockage of the thermosyphon.

The thermosyphon blockage is also observed in tests 1 and 2. Figure 5 shows that the condenser thermocouples readings presented the same temperature as thermal bath, while the ones pertaining adiabatic and evaporator sections increased their readings, with the increase of the input power. By analyzing this phenomena, in light of the thermodynamic states (see Figure 7), the working fluid in all three sections of the thermosyphon is indicated to be in superheated vapor state. This results in a blockage of the thermosyphon, thus preventing thermal exchange.
Figure 7. Thermodynamic state of the tests.

Figure 8 presents the thermal resistance as a function of the input power for all of the six tests.

Figure 8. Thermal resistance of the tests.
In Figure 8, it is observed that test 6 presents average values of 0.08 C/W of thermal resistance, for the input powers of 40 and 80W. Furthermore, some instabilities are presented at the 60W of input power, with the thermal resistance being calculated as 0.13 C/W. For the 100W of input power, its value reaches 0.3 C/W. This sudden increased can be explained by the tendency of the thermosyphon to dryout, even when GBP (See Figure 5, test 6) is still present.

From Figure 8, it is also possible to conclude that when the thermosyphon reaches the blockage conditions (such as the ones from tests 1, 2 and from test 4 after 40W input power), the thermal resistance remains at an average value of 0.5 C/W.

For tests 3 and 5, where GBP is evident, the values of the thermal resistances range from 0.2 to 0.45 C/W. This indicates that even though the GBP is not a phenomenon that limits heat transfer, it does hamper its performance and efficiency.

As discussed above, in analyzing the temperature versus time results, Figure 5, it is possible to ensure that in tests 3 to 6 the GBP is present. However, when comparing these data with the global thermal resistances, it is possible to associate that, for higher values of resistance, a greater oscillation of the data of temperatures and pressures occurs. On the other hand, lower power inputs yield longer periods of GBP. This is justified since in low input power rates, more time is necessary for the overheating of the pool of liquid. For higher input power, the GBP period decreases, as there is more active boiling inside the pool. This causes more liquid to be blown into the condenser, resulting in a decrease in the pool level. This leads to higher thermal resistance values for higher input powers.

By comparison of the results, it was observed that, for higher condenser temperatures, the liquid blown by the GBP can reach the total height of the condenser section (Cnd8). This increases the condenser area available for thermal exchange. As a consequence, there is a decrease in the thermal resistances for both filling ratios. However, when comparing both filling ratio operation conditions, it is perceived that increasing the fill rate, from 66% to 90%, decreases the thermosyphon's thermal resistance.

5. Conclusions

After the six tests presented in this paper, with the prescribed filling ratios and condenser temperatures as shown in Table 3, it was found that, for all tests with a 35% filling ratio (tests 1 and 2), the thermosyphon did not work. This happens because the working fluid was found to be in the superheated vapor state in all sections of the thermosyphon. The remaining four tests showed that the thermosyphon did work. However, in all these tests, Geyser Boiling Phenomenon was present.

GBP is a mechanism that disturbs the thermosyphon’s capacity of transfer heat. Due to its chaotic and intermittent characteristics, it causes an abrupt change in the internal pressure of the tube and in the temperatures of the three regions of the thermosyphon. This causes the evaporator to overheat and the thermal resistance of the device to rise.

It has been shown that with increasing the water jacket temperature, the vapor front is able to reach higher positions on the condenser. This causes the exchange area to be larger, enhancing the heat transfer.

Contrary to the work of Negishi and Sawada [10] the GBP was present in all filling ratios and not only in filling ratios higher than 70% as they claim. However, it must be taken into account that the diameter tested in this work is 4.8 mm, much smaller diameter than the 13 mm used in their thermosyphon.

The small internal diameter makes it easier for the bubble to occupy the cross-section area of the evaporator, which facilitates the occurrence of the GBP. Therefore, in the present thermosyphon, this phenomenon was present in all of the tests that brought together the thermodynamic conditions for it to operate as such. Unlike Lin et al. [12], Mantelli et al. [13] and Khazaee et al.[15] who affirm that this phenomenon occurs only at low heat flows, the present results show that the Geyser boiling phenomenon is always present due to the confinement effect caused by the small thermosyphon diameter, which was also observed by Smith et al. [17].

Of all the tests performed, only in three power levels did the thermal resistance reached values smaller than 0.1 °C/W. For these conditions, the GBP is almost imperceptible. Although the GBP does not limit the operation of the thermosyphon, it does hinder the efficiency of this equipment. Therefore, more in-depth studies are necessary to understand this phenomenon, how it occurs and what are the factors which influence its generation.
6. Nomenclature

$q_w$ : Heat rate (W)

$C_w$ : Experimental constant

$d_i$ : Internal diameter (m)

$h_{lv}$ : Enthalpy of vaporization (J/kg)

$\rho_v$ : Specific mass of the vapor (kg/m³)

$\rho_l$ : Specific mass of the liquid (kg/m³)

$g$ : Gravitational constant (m/s²)

$\sigma$ : Surface tension (N/m)

$B_0$ : Bond number

$A_v$ : Cross-sectional steam area (m²)

$p_v$ : Steam pressure (Pa)

$r_v$ : Radius of the steam area (m)

$\mu$ : Dynamic viscosity (Pa.s)

$l_{ef}$ : Effective length (m)

$A_e$ : Radial evaporator area (m²)

$u_c$ : Combined uncertainty

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