16th International Heat Pipe Conference (16th IHPC)
Lyon, France, May 20-24, 2012

A TWO-PHASE LOOP THERMOSYPHON WITH NAPHTHALENE AS WORKING FLUID

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ABSTRACT

This work presents an experimental study on a stainless steel loop thermosyphon with naphthalene as the working fluid. A prototype was tested in a hot gas stream with temperatures ranging between 335 and 450°C with the thermal resistance of the thermosyphon ranging from $1.9x10^{-2}$ to $5.7x10^{-3}$ m^2K/W, respectively. The evaporator and the condenser are connected by vapor and liquid lines which are 5.8m long. In order to operate properly, the thermal losses of the vapor line connecting the evaporator to the condenser must be eliminated, which was accomplished during the tests by using auxiliary heating. Without the auxiliary heating to the vapor lines, pure saturated vapor does not reach the condenser, and the thermosyphon does not operate properly.

KEY WORDS: Loop thermosyphon, Naphthalene.

1. INTRODUCTION

Loop thermosyphon heat exchangers, also known as separated heat pipes, have been applied in industrial waste heat recovery systems. Figure 1 presents a schematic drawing of a typical loop thermosyphon heat exchanger. Dube et al. (2004) also studied this kind of system previously. Both the evaporator and the condenser are geometrically very similar. They consist of two horizontal headers (upper and lower) connected by several vertical tubes in parallel. The two upper headers (condenser and evaporator) are connected by the vapor tube. The two lower headers are connected by the liquid return line. In the evaporator, during operation, the liquid level must be such that the internal walls remain wet.

The concept shown in Fig. 1 normally employs water as the working fluid. However, for applications at higher temperatures, water is not appropriate and other working fluids are needed. The authors are studying the use of this type of loop-thermosyphon with naphthalene as the working fluid.

The main concern about using naphthalene as the working fluid is related to the solidification in cold parts of the loop, such as the liquid return line. This problem is especially important during start-up, when the system is at room temperature. If the working fluid becomes a solid, it obstructs the liquid return line and the system ceases to operate. To prevent that from happening, external heating must be applied on the liquid return line.

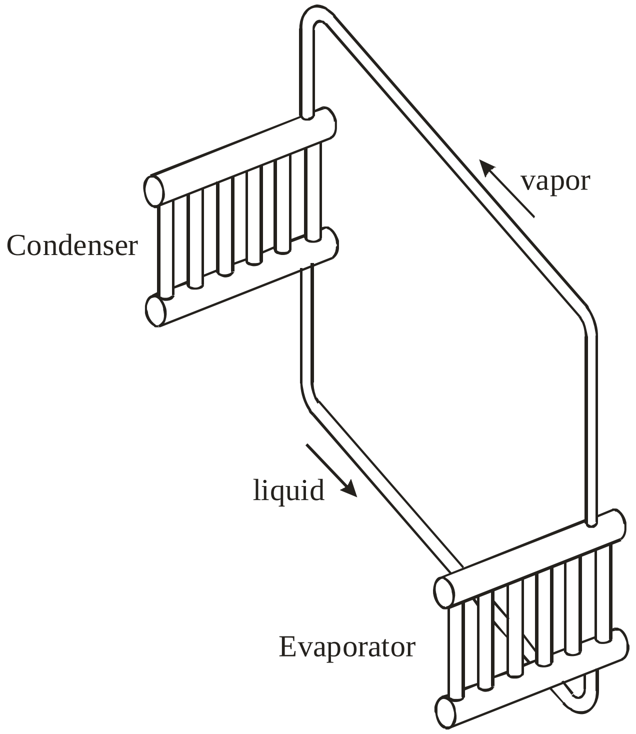

Figure 1. Loop thermosyphon heat exchanger.

External heating is also necessary in case of long vapor lines because of the condensation due to heat losses to the ambient. Even with thermal insulation, the relatively low value of condensation enthalpy of the naphthalene leads to intense condensation inside the vapor tube, which may obstruct the vapor flow. Therefore, an auxiliary heating is necessary to minimize or neutralize the heat loss from the vapor tube.

2. EXPERIMENTAL STUDY

In order to eliminate the problem of working fluid solidification in the liquid return line, a new lay-out was chosen for this experimental study. The liquid return line is inserted in the vapor tube, i.e., there are two concentric pipes. The liquid returns in the smaller pipe, while vapor flows in the annular duct between the two pipes. Figure 2 presents a drawing of the prototype. The liquid return line is surrounded by the saturated or slightly superheated vapor flowing in the annular channel. As a result, instead of heating both the liquid and the vapor lines, only the vapor line (external tube) is heated externally.

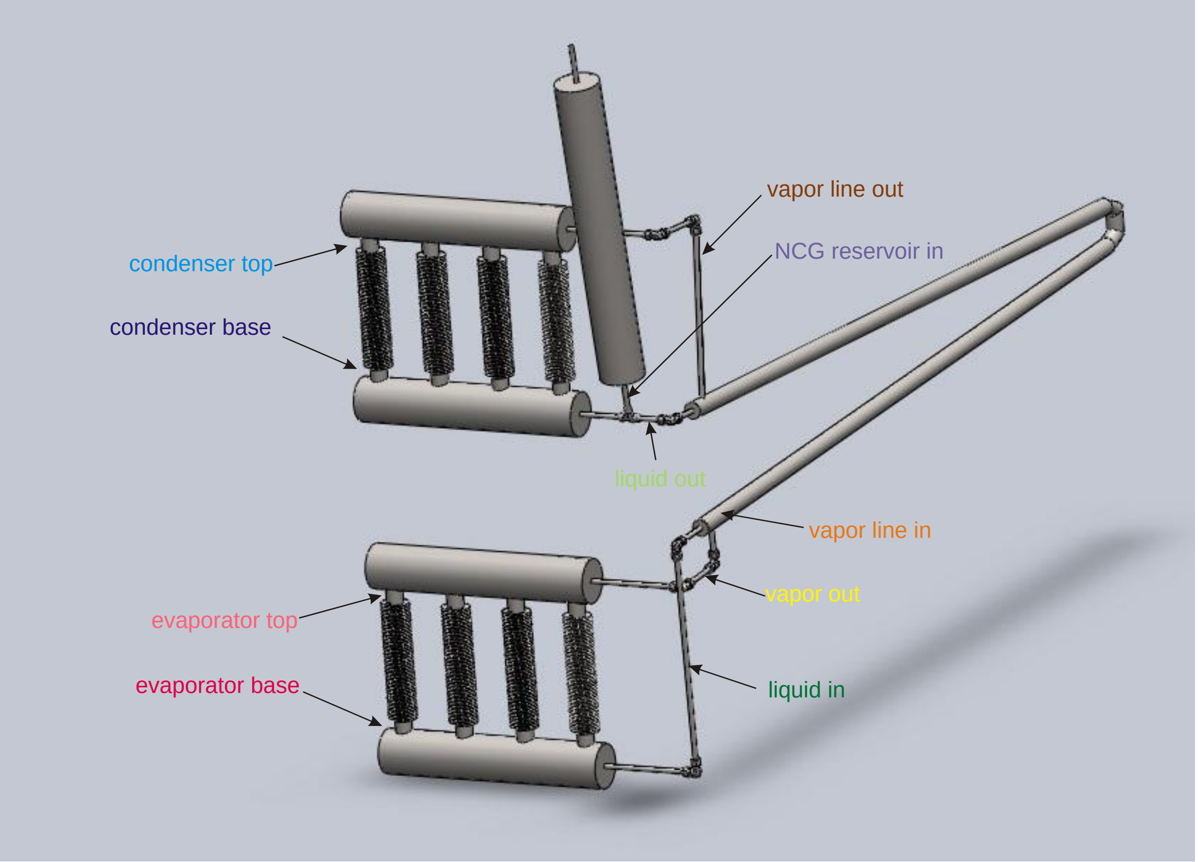

Figure 2. Two-phase loop thermosyphon under study.

2.1 Experimental Set-up

A naphthalene-stainless steel two-phase loop thermosyphon prototype, as shown in the drawing of Fig. 2, was built and tested. Both the condenser and the evaporator consist of four finned 1 ¼" ASTM A106 vertical tubes. The finned tubes are 300 mm long. The four headers are standard 4" ASTM A106 with a length of 700 mm. The liquid return pipe is made of stainless steel with 10 mm i.d. and 12 mm o.d. and the vapor pipe is also made of stainless steel with 38 mm i.d. and 42 mm o.d. The length of both the liquid and the vapor return line is 5.8 m. The device was designed to transfer 4 kW of heat.

The prototype was tested in an air-air heat exchanger test rig. The test rig was built recently at the Heat Pipe Laboratory (LABTUCAL) of Federal University of Santa Catarina-Brazil. It can be used to test two-phase thermosyphon heat exchangers. The rig consists of two gas ducts, one with hot exhaustion gases from a 60 kW gas burner and one with ambient air.

In the test section, the flows are countercurrent, with the hot gas stream in the bottom and the ambient air stream at the top. Both the hot gases and the ambient air flow through a rectangular 300 x 700mm cross section duct. The evaporator finned tubes are inserted in the hot exhaustion stream, while the condenser tubes are inserted in the air stream.

As the test rig was designed for standard vertical two-phase thermosyphon heat exchangers, the condenser and the evaporator have to be aligned, one on the top of the other. The vertical distance between the top of the evaporator and the bottom of the condenser is only 300 mm. However, in real loop thermosyphon heat exchanger applications, the evaporator and the condenser could be several meters apart from each other. In the present work, the prototype was designed and built so the liquid and vapor lines are 5.8 m long. They have a "U" shape in order to fit between the evaporator and the condenser. That corresponds to a thermosyphon with a horizontal distance of 5.8 m between evaporator and condenser.

The prototype has also a non-condensable gas reservoir coupled to the liquid return line, right after the condenser lower header (see Fig.2). The reservoir is 800 mm long and has an internal diameter of 102.2 mm. As the thermosyphon was not evacuated prior to charging with the working fluid, the objective of the reservoir is to accommodate the air present in the system during operation. The reservoir was designed based on the procedure also used by Dube et al. (2004). These authors also showed that the exit of the condenser lower header is the best place for the non-condensable gas reservoir in this type of loop thermosyphons. This procedure was also employed successfully by the present authors in other experimental studies, such as Milanez and Mantelli (2010).

As mentioned, heating is provided to the external wall of the vapor pipe. The heating is obtained by wrapping a flexible belt shaped electric heater from Omega® around the tube. The electrical heater is connected to a DC source and the power supply was regulated so it compensates the external thermal loses to the ambient, estimated between 800 and 1000 W, depending on the operation temperature level. The prototype was instrumented with 21 K type thermocouples placed as shown by the arrows of Fig. 2. The temperature of the hot gas and the air streams were measured with RTD probes.

The main objective of this experimental study is to assess whether a naphthalene loop thermosyphon could operate properly. The thermosyphon total thermal resistance was measured, and the importance of the external heating for the vapor line was also analyzed.

3. RESULTS

Figure 3 presents the temperature readings as a function of time during the test. In this test, the system was operating properly with the help of the auxiliary heating to the vapor lines. The black line is the temperature of the hot gas stream reaching the evaporator. The red, yellow, orange and blue lines correspond to the thermocouples attached to the loop thermosyphon, according to Fig. 2.

The red lines correspond to the evaporator, the yellow/orange/brown lines correspond to the vapor tube, the blue lines correspond to the condenser and the green lines correspond to the liquid return tube. Note that there are several red lines. Three of them are close to each other, below the black line. These three light red lines correspond to the thermocouples placed on the condenser top (see Fig. 2). Initially, four thermocouples were attached to the four evaporator tubes, but one of them did not work after the assembly was completed. There are also four dark red lines, placed bellow the three light red. These four dark red lines correspond to the condenser base (see Fig. 2). As one can see, there is a considerable difference of temperature between the base and the top of the condenser, (50 to 100°C), which shows that the evaporation resistance is relatively large.

It is important to mention that these thermocouples do not face the hot gas stream. Only the finned portions of the evaporator pipes are subjected to the hot gas stream. The thermocouples are actually attached to a small (20 mm) smooth portion of the pipes below and above the finned length, as pointed by the arrows of Fig. 2. Also, these small portions where the thermocouples are attached are thermally insulated from the environment. The upper and lower headers are also insulated from thermal losses to the ambient. Therefore, the temperature readings of the evaporator thermocouples are more closely related to the working fluid temperature inside the pipes than the hot gas stream. The same is valid for the thermocouples of the condenser.

It can be also observed from Fig. 3 that the orange/brown lines are very close together and also close to the dark red lines of the condenser base. One can conclude that this is the temperature of the saturated vapor inside to thermosyphon. As the naphthalene evaporates at the bottom and flow upwards, it gets superheated (condenser top, light red lines) and flows out of the evaporator still slightly superheated (yellow line). Then it comes back to saturation as it enters in the annular vapor line and flow out of it (orange/brown). The vapor temperature suffers another temperature drop from the vapor line (brown) to the condenser (blue), indicating a relatively large condensation resistance. Note that the condenser is approximately isothermal as the four light blue lines, which correspond to the condenser top and the dark blue lines (condenser base) are close to each other.

The liquid coming out of the condenser (light green) is at the same temperature as the condenser. The liquid then is heated up to the saturation temperature because the liquid return pipe flows inside the annular vapor duct (orange/brown). As one can see, the dark green line (liquid into the evaporator) is at the same temperature of the saturated vapor.

During the test of Fig. 3, the temperature of the hot gas stream (black line) varies with time. Initially, when 5.0 < time < 5.4 h, the temperature of the hot gas stream is approximately 370°C. After time=5.4 the temperature was lowered to a set point of approximately 335°C and then, after time=7.4 h, raised to 450°C. During this time interval, the loop thermosyphon was operating properly, with a total thermal resistance ranging from a minimum of $2x10^{-2}$ to a maximum of $6x10^{-2}$ K/W. The heat transfer rate ranged from 1.8 to 4 kW, respectively. The total thermal resistance of the thermosyphon is defined here as the difference between the temperatures of the evaporator and the condenser divided by the heat transfer rate through the thermosyphon. The auxiliary heat of the vapor line, ranging between 800 and 1000 W, is not taken into account for calculation of the thermal resistance because the auxiliary power works as a guard heater, i.e., it neutralizes the heat loss to the environment through the vapor tube thermal insulation.

The importance of the auxiliary heating of the vapor lines can be easily visualized in Fig. 4. It presents the test result when the auxiliary heating was turned off (time=3.5h). As one can see the yellow/orange/brown lines start to drop one after the other as time passes. Also, the green lines, i.e., the liquid return line, drop below the evaporator base temperature, which is, as already mentioned, believed to be the saturated vapor temperature. As a consequence, the condenser temperatures (blue lines) start to drop. The auxiliary heating was turned on again at time=4 h. As one can see, after that time, the temperatures of the vapor tube (yellow/orange/brown) start to increase again and, finally, after time=4.5 h, the blue lines of the condenser start to increase too. At this point, the thermosyphon was back to normal operation. That shows that the thermal losses to the ambient need to be eliminated in order for the thermosyphon to operate properly. It is convenient to mention that the time scale of Fig. 4 is the same as of Fig. 3, i.e., the test when the auxiliary heating was turned off (Fig. 4) actually took place before the test when the auxiliary heating was on (Fig. 3).

4. CONCLUSIONS

A stainless steel loop thermosyphon was designed, built and tested with naphthalene as the working fluid. In the lay-out tested here, the liquid return line is placed inside the vapor line so the condensate does not become solid due to thermal losses to the ambient.

The evaporator and the condenser consist basically of vertical finned pipes that are immersed in gas streams at different temperatures. The temperature of the hot gas stream flowing around the evaporator tubes ranged between 335 and 450°C during the tests, while the thermal resistance of the thermosyphon ranged from $1.9x10^{-2}$ to $5.7x10^{-2}$ m^2K/W, respectively.

The results of the experiments showed that the naphthalene loop thermosyphon works well if the thermal losses of the vapor line that connects the evaporator to the condenser are eliminated. However, as there is no perfect thermal insulator, the only way to accomplish that is by using auxiliary heating to the vapor lines. Without an auxiliary heating, like a guard heater, pure saturated vapor does not reach the condenser, and the system ceases operation.

ACKNOWLEDGEMENT

The author would like to acknowledge the support of PETROBRAS, the Brazilian Petroleum Company, for their financial support during the development of this work.

REFERENCES

Dube, V., Akbarzadeh, A., and Andrews, J. (2004), *The effects of non-condensable gases on the performance of loop thermosyphon heat exchangers*, Appl. Therm. Eng., vol. **24**, pp. 2439–2451.

Milanez, F.H. and Mantelli, M.B.H. (2010), *Heat Transfer Limit Due to Pressure Drop of a Two-Phase Loop Thermsyphon*, Heat Pipe Science and Technology, An International Journal, Vol. 1 (3), pp. 237-250.

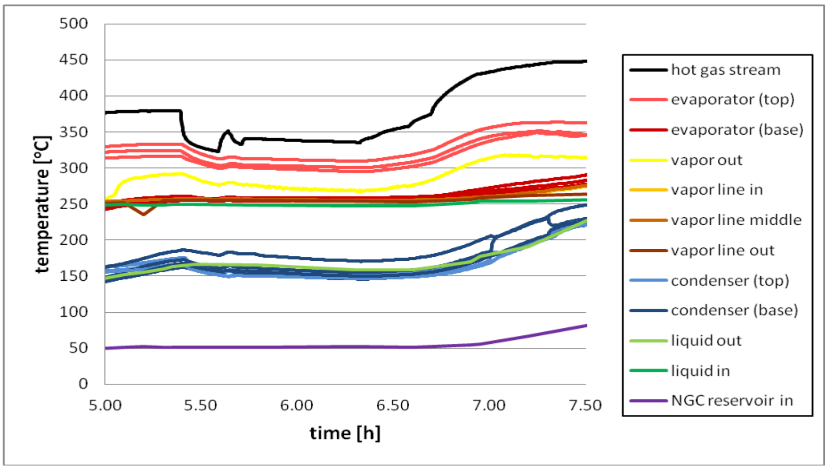

Figure 3. Test results: normal operation, auxiliary heating turned on.

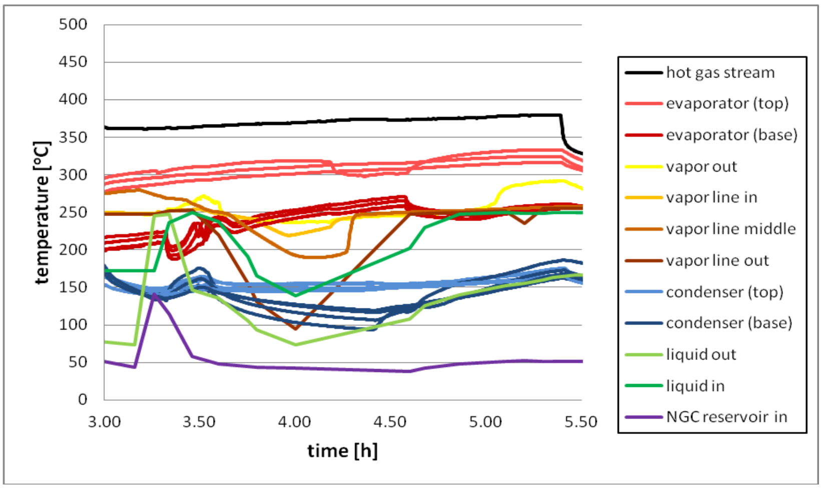

Figure 4. Test results: auxiliary heating tuned off.