EXPERIMENTAL STUDY OF VERTICAL THERMOSYPHONS FOR INDUSTRIAL HEAT EXCHANGER APPLICATIONS

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ABSTRACT

An experimental set-up was developed for testing thermosyphons to be used in a heat exchanger to be installed in one of the Petrobras Refineries in Brazil. The thermosyphon tested, made of carbon steel, is 2.2 m long, where 1 m corresponds to the condenser, 1 m to the evaporator and 0.2 m to the adiabatic section. Its external diameter is 50.80 mm. The experimental set-up consists of heater and of cooler systems, insulated form the environment. The heating system is made of five stacked copper cylinder blocks, which holds several cartridge heaters and the thermosyphon in its center. A cooler system, which consists of a metallic cylinder concentric with the thermosyphon condenser, removes the heat applied by the heater by means of water, which is temperature controlled by a thermal bath. It was observed that the vapor was not able to reach all the condenser length for the low power input cases, showing that the thermosyphon could be shorter. Also, it could be noted that the higher the power input, the lower the overall thermal resistances. For all the cases tested, the thermosyphon was capable to transfer the heat, not showing that any of the operational limits were close to be reached. Actually, the major concern in designing a heat exchanger is not the thermosyphon thermal behavior but its external heat transfer capacity. Therefore, the usual techniques to improve heat transfer should be applied (fins, tube arrangement, mass flow improvement, etc).

KEY WORDS: Thermosyphons, heat pipes, heat exchangers.

1. INTRODUCTION

The world nowadays faces a serious energetic crisis which forces the largest companies to invest money and efforts to save energy. In this scenery, heat exchangers using the heat pipes or thermosyphons represent an interesting alternative for the substitution of equipment built with other less efficient technology.

The petroleum treatment process use high temperature air, which is heated by means of a heater, usually feed by burning oil. After being used, the exhaustion gases are released at high temperature levels (approximately 300 °C). The rejected heat can be used to pre-heat the clean air, saving combustion oil.

The Satellite Thermal Control Laboratory of the Federal University of Santa Catarina, Brazil, is developing a heat exchanger using the thermosyphon technology. This is a very promising technology, with applications that have been constantly increased in the last decade, especially in petrochemical plants, as observed in China (Zhang and Zhuang, 2002).

In the present work it is described and discussed the results of an experimental study conducted in a set-up for testing the thermosyphons to be used in a heat exchanger which will be installed in a petrochemical plant of the Brazilian oil company, Petrobras. Figure 1 shows a schematic of the heat exchanger under development, which is composed by seven independent moduli.

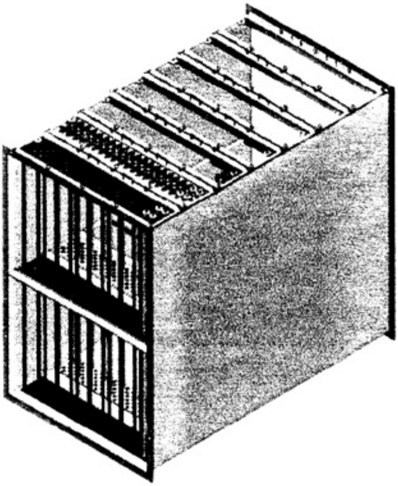

Figure 1. Schematic of the heat exchanger under development.

2. THERMOSYPHON DESCRIPTION

The thermosyphon tested, made of carbon steel (ASTM A-179), presents 2.2 m of length, 2 inches (50.80 mm) of external diameter and wall thickness of 3.76 mm. The evaporator and condenser lengths are of 1 m each, with an adiabatic section of 0.2 m. Before being charged, the tube must be carefully cleaned and their tips sealed by soldering two metal disks. In one of the disks, a small tube (1/8 inch) is perpendicularly soldered for inside tube cleaning and working fluid charging. An amount of 900 ml of dionized water is used as working fluid, representing about 60% of the total volume of the evaporator (Dunn and Reay, 1994 and Chi, 1976). The geometry and material of the tube were selected according to the safety recommendations established in the ASME Standards.

3. EXPERIMENTAL APPARATUS

The experimental apparatus consists basically of a heater, which provides controlled thermal energy for the thermosyphon; a cooler where heat is removed by means of cooling water; thermocouples for temperature readings and a data acquisition system. Figure 2 shows a schematic of the experimental apparatus with the location of the thermocouples used to monitor the thermal behavior of the thermosyphon. Two thermocouples are especially important for the present study, which are those that monitor the saturated vapor and liquid temperatures. They are installed inside needles located in the vapor and in the liquid regions of the thermosyphon.

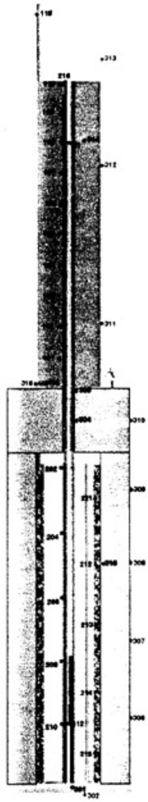

Figure 2. Schematic of the experimental apparatus.

The apparatus was designed to simulate the several operation conditions observed in a thermosyphon in the heat exchanger: the tubes located in the first line are subjected to a higher temperature differences between hot and cold gases, while the tubes in the rear position are subjected to lower temperature differences. The set-up was also designed to accommodate tubes of different diameters.

The heating system is constituted of 5 stacked cooper cylinders with a central hole of 2.5 inches of diameter. The whole set receives 36 stainless steel cartridge resistances of 750 W each. Figure 3 shows a picture of the cooper cylinder with the thermal resistances fitted. To lodge thermosyphons of different diameters, a set of adapting cylindrical sleeves where designed to fit inside the central hole and to hold tubes of 1.0, 1.5, 2.0 and 2.5 inches of diameter. The cooper cylinders are insulated from the environment by means of heat insulation. The electrical circuit is fed by two alternative power systems, a 0-220, 220-0 V Variac, used for power inputs lower than 1500 W and three Triacs Sintex of 4.2 kW each, for test inputs higher than 1.5 kW.

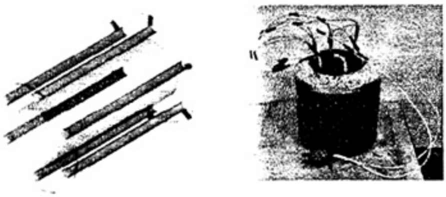

Figure 3. Heater composed by a cooper cylinder which holds cartridge resistances and the thermosyphon in its center.

To remove heat from the condenser, refrigerating water from a thermal bath circulates within a vertical tube of 5 inches of diameter and 2.5 m of height, located in a concentric position along the condenser.

4. EXPERIMENTAL TESTS AND RESULTS

For the experimental study of the thermosyphon described in Section 2, the following parameters were varied: dissipated power (4 levels), cooling water temperature (three levels) and water mass flow rate (2 levels). Table 1, in the first three columns, presents the parameter levels used in the tests. Figures 4, 5, 6 and 7 shows the temperature reading curves as function of time for some selected cases described in Table 1, as there is not enough room here to present all the cases studied. The case presented in each figure is briefly described in the figure caption. As one can observe, the only parameter varied among the graphs is the power input level, while all the other parameters were kept constant. Actually, the power input showed to be the most relevant parameter tested. In these figures, the red curves represent the temperature readings of the cooper block heaters, the orange curves represent the evaporator temperatures, the green curves the adiabatic section, the light blue curves the condenser temperatures and the dark blue curves the temperature readings of the saturated vapor (upper curves) and of the saturated liquid (lower curves). The vapor temperatures are not available for Figs. 5 and 6.

In all these figures, large temperature variations in the condenser and in the adiabatic section can be observed. The amplitude of these temperature variations decreases with the increasing power dissipation. This behavior can be justified by the boiling phenomena, where, at low power inputs, the vapor bubbles grow slowly, becoming large (Carey, 1992). The large bubbles, in its ascending way, are able to carry considerable amount of water over them. When they find the condenser colder tube wall, there is a break-up and the water carried up is suddenly released. The coefficient of heat transfer of the water flow in touch with the internal wall is high. Therefore, the liquid efficiently exchanges heat with the condenser, cooling itself down. This phenomena, according to Faghri (1995) is denominated Geyser effect and can be observed by the quickly decrease in the temperature levels of the wall temperature readings. As the temperature increases, the bubble formation rate is much larger>these bubbles remain small, not being able to carry water over then and therefore the oscillations decrease.

In Figs. 4, 5 and 6, the vapor temperatures always represent a lower limit for the thermosyphon temperatures, following all the major temperature oscillations. Actually, the needle that holds the thermocouple receives directly the vapor coming from the evaporator, when it is able to reach it. When the external heat exchange is very efficient or the heat input is not large enough, all the vapor formed is able to condensate before reaching the needle, so that the upper part of the condenser just assume the cooling bath temperature level. This means that this region of the condenser is useless and that not all the thermosyphon length is properly used. As the power input increases for the sameexternal condenser heat exchange conditions, the vapor temperature reaches larger values than the condenser wall temperatures, as it can be observed in Fig. 7. The vapor column height inside the condenser is observed in Table 1 for all cases studied. One can observe that the higher the power input, the higher is the vapor column inside the condenser.

The adiabatic section, for all cases analyzed, always presents intermediate temperature levels between the condenser and the evaporator. The temperature difference between the cooper heater and the saturated liquid is considerable, showing that the internal resistance of the evaporator is considerable larger than that of the condenser.

In all these figures it is possible to observe the transient behavior of the thermosyphon. In the beginning all the temperatures are in the same level. As the power is turned on, vapor starts to be formed, reaching first the lower parts of the condenser. The vapor front can be easily observed especially in Fig. 7, where the temperature represented by the light blue curves start increasing their level one by one. One can also observe that, as the power input increases, the thermosyphon temperature level also increases.

Table 1. Description of the test configuration and some results

Pot. (W)	Temp. (°C)	Flow (L/min)	Case number	Height of the vapor column	Time start up
200	17	14	A	140	2.80
	15	**15**	**B**	**140**	**2.80**
400	10	10	C	150	2.50
		15	D	150	2.10
	25	10	E	130	2.40
		15	**F**	**130**	**2.60**
	40	10	G	130	2.20
		15	H	130	2.00
600	10	10	I	220	1.20
		15	J	190	1.50
	25	08	K	190	1.50
		10	L	190	1.00
		15	**M**	**220**	**0.50**
	40	10	N	190	1.80
		15	O	190	1.50
1500	25	10	P	190	1.60
6500	10	10	Q	220	0.40
		15	R	220	0.30
	25	10	S	220	0.25
		12	T	220	0.20
		15	**U**	**220**	**0.25**
	40	10	V	220	0.18
		15	W	220	0.20

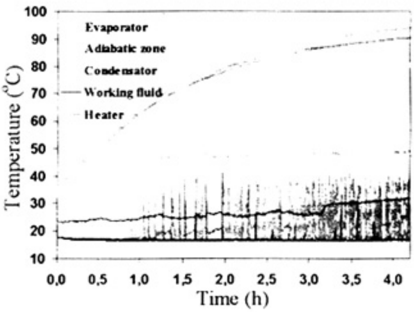

Figure 4. Test B, power input of 200 W, cooling water temperature of 15 °C and refrigerating fluid flow mass of 15 L/min.

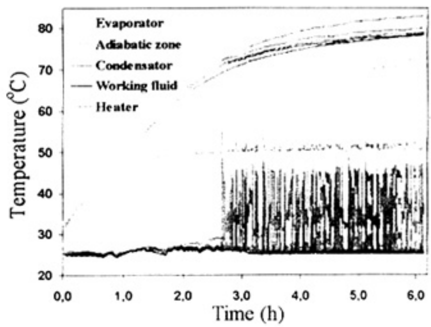

Figure 5. Test F, power input of 400 W, cooling water temperature of 15 °C and refrigerating fluid flow mass of 15 L/min.

The "start up" in this study was defined as the time required for the vapor to reach the condenser, after boiling regime takes place in the evaporator. Table 1 also presents the time required for the start up to take place. As one can observe, the higher the power input, the faster the thermosyphons starts up.

The steady state conditions for all cases analyzed are reached much faster by the condenser and adiabatic section than by the evaporator, since, for the present experimental set-up, the temperature of the cooper heaters tends to keep increasing slowly as the time goes by. If any kind of heater active temperature control was adopted for the evaporator, as it is used in the condenser, the steady state conditions would be reached much faster.

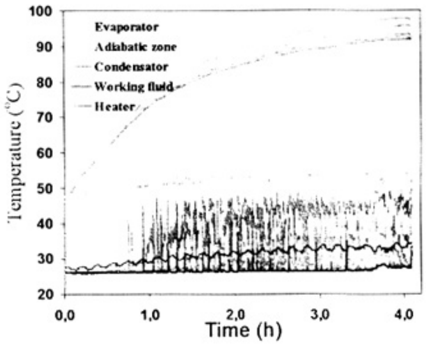

Figure 6. Test M, power input of 600 W, cooling water temperature of 15 °C and refrigerating fluid flow mass of 15 L/min.

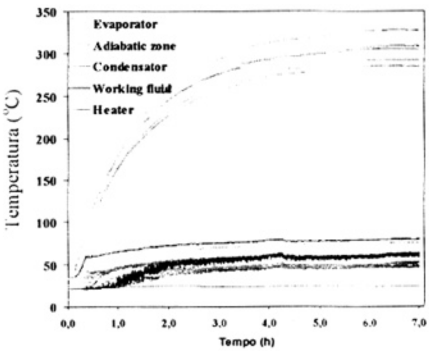

Figure 7. Test U, power input of 6500 W, cooling water temperature of 15 °C and refrigerating fluid flow mass of 15 L/min.

Figure 8 shows the temperature distribution (temperature as a function of distance, starting from the evaporator end) for the cases presented in Figs. 4 to 7. The thermosyphon thermal resistances, defined as the ratio between the evaporator and condenser temperature difference and the power dissipated can be determined from this figure. For the present case, these resistances varied from 0.025 °C/W, for heat input around 6500 W, going through 0.06 for power inputs of 1500W and 0.08 for power input of 600 W, up to the value of 0.35 °C/W for 200 W dissipation.

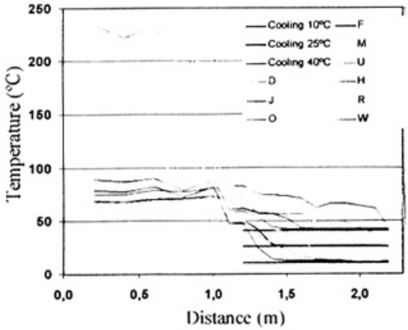

Figure 8. Temperature distribution as a function of the distance, starting from the evaporator end.

The experimental set-up presents heat losses, which were carefully determined and discounted from the power input. They varied from 3.5 to 5% of the total power input, which can be considered a small amount, showing that the experimental apparatus thermal insulation was well designed.

An experimental uncertainty analysis was performed. The temperature was obtained with an uncertainty of ±2 °C, according to the manufacturer. The power input was measured with an experimental uncertainty of ± 5W. The uncertainty for the thermal resistance determination is always lower than ± 0.0018 °C/W.

5. CONCLUSIONS

The following conclusions can be obtained from the experimental work performed:

- In all cases studied, the thermosyphon was able to transfer the heat input.
- The thermosyphons operational limits (Peterson, 1994), including drying, drag, boiling, etc, were never achieved in any of the cases studied.
- The higher is the heat input, the better is its thermal performance.

- The design of the thermosyphons should include consideration about the external conditions of heat exchange. Large condenser areas may be useless if the external coefficient of heat transfer is in the same other of magnitude of the internal coefficients or higher. In these cases the thermosyphon could be much shorter.
- The thermal performance of a heat exchanger using thermosyphon technology is very dependent on the tube external heat transfer conditions. In other words, the main concern during the design of this equipment is to guarantee that the heat is able to be transferred to the thermosyphon working saturated liquid in the evaporator and also to be removed from the working fluid vapor in the condenser. Therefore, the usual techniques to improve the external heat transfer should be applied (fins, tube arrangement, mass flow improvement, etc).
- The geometry of the studied thermosyphon was over-dimensioned for the lower power dissipation levels tested.
- For the thermosyphon working in ideal conditions, the internal heat transfer coefficient of the evaporator is at least one order of magnitude lower than that of the condenser. This observation agrees with correlations from the literature (Kaminaga et al., 1992, Brost, 1996 and Groll and Rösler, 1994).

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