Model Design, Construction and Test of a Prototype of Heat Exchanger using Two-Phase Thermosyphons

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Abstract
This paper presents the design, building and test of a two-phase thermosyphon heat exchanger, using water as the working fluid. A conceptual design was carried out for a gas- liquid heat exchanger using two-phase thermosyphons, and also it was developed a mathematical model for dimensioning thermosyphons and the heat exchanger. In synthesis the prototype built has 33 thermosyphons and was made with copper pipe type L of 3/8" of nominal diameter (12.7 mm outside diameter), with a length of 280 mm practically without adiabatic zone, with an effective length of evaporator of 165 mm and an effective length in the condenser of 75 mm. The employment of the two-phase thermosyphons permitted to couple the region of the gases and the region of the liquid with a heat transfer area relation of 2.2, being obtained a compact unit. The performance of some two-phase thermosyphons and the heat exchanger were evaluated, and under the conditions of the test, very significant results related to the heat recovery were observed presenting each two-phase thermosyphon a heat transport capacity around 50W.

Keywords
Two-phase thermosyphon, heat pipe, heat recovery, heat exchangers, energy saving.

1. 1. Introduction

The importance of the improvement of the energy efficiency is soported by the continuous increment of the energy demand associated to social and economic development.Also it is important due to financial restrictions to expand the energy offer, the need to achieve a greater international competitiveness and the efforts to reduce the environmental impact of the energy technologies.

The employment of the heat pipes and two phase close termosyphons offer interesting opportunities in this sense that deserve to be studied in order to reduce fuel comsumption and to improve the global conversion energy efficiency.

The topics of the heat pipes and two-phase thermosyphons are new in Colombia and their study and development just begin in continuous and effective way, although in the past it had been carried out some academic and investigative works, as well as some intents to introduce some commercial applications. From 1999, the EAFIT University has been working the topics of two-phase thermosyphons and heat pipes in continuous form. Nowadays it has been done several works focused to develop the construction capacity and get some application of this technology. The EAFIT University has carried out a project sponsored by the Colombian agency for Science and Technology, COLCIENCIAS, to study and develop some heat pipes and/or thermosyphons for heat recovery applications.

These topics have been treated in the academic and industrial domains with very good acceptance. This paper shows some parts of the realizations, specifically in the aspects of conceptual design, construction and evaluation of these devices

A heat exchanger prototype with two-phase close thermosyphons was developed to be employeed in heat recovery processes. Information concerning to Heat pipes, two-phase thermosyphons and heat exchangers were collected. It was found that several universities, centers of investigation, industries and people in general around the world are involved in these themas.

2. Two phase Thermosyphons

The term heat pipe describe a "synergistic engineering structure which, within certain limitations on the manner of use, is equivalent to a material having a thermal conductivity greatly exceeding that of any known metal" as was published by Grover in 1964 (Peterson, 1994). This device can be seen as a close system, having 3 main elements: a working fluid with vapor and liquid phases, a container and a structure or mechanism for pumping liquid, i.e. a wick in a capillary driven heat pipe, or the gravity in the case of two-phase close thermosyphon. The heat pipe can be coupled between a high and a low temperature zones in order to transfer a significant amount of thermal energy. The heat pipe design process mainly consists in determine the geometry (shape and size), the type and amount of fluid, and the material of the container in order to meet the requirements of heat transfer capacities at defined temperatures, in safety and durable way and a lower cost possible. It is used a conceptual design to outline some alternatives and variants and then evaluate and select an alternative according with some criteria.

A two phase Thermosyphon, gravity assisted Heat Pipe or wickless Heat Pipe, is considered a close system, because it has a fixed amount of fluid inside the container. The fluid can be change of phase by evaporation and condensation due to heat flows, transferring by this means high amount of thermal energy.

The operation and behavior of a two phase thermosyphon is better understood when it is divided in tree zones: evaporator, adiabatic zone, and condenser (figure 1). The heat input is located in the bottom part, which is the evaporator, where some liquid lays in the liquid pool and some is coming from the condenser. There the liquid is evaporated again due to heat delivery at high temperature. The vapor generated in the evaporator at higher pressure and temperature flows through the core of the tube, passing by the adiabatic zone, to the condenser where the pressure and temperature are lower. Then, in the condenser, the vapor changes to liquid delivering the latent heat and flows down assisted by gravity forming a liquid film until it reaches the evaporator at the bottom of thermosyphon, beginning the cycle again.

The right operation of the two phase thermosyphon requires that the heat input must be at bottom where the temperature is high, and the heat output must be at the top where the temperature is low, otherwise it does not operate, that is why it is called a thermal diode.

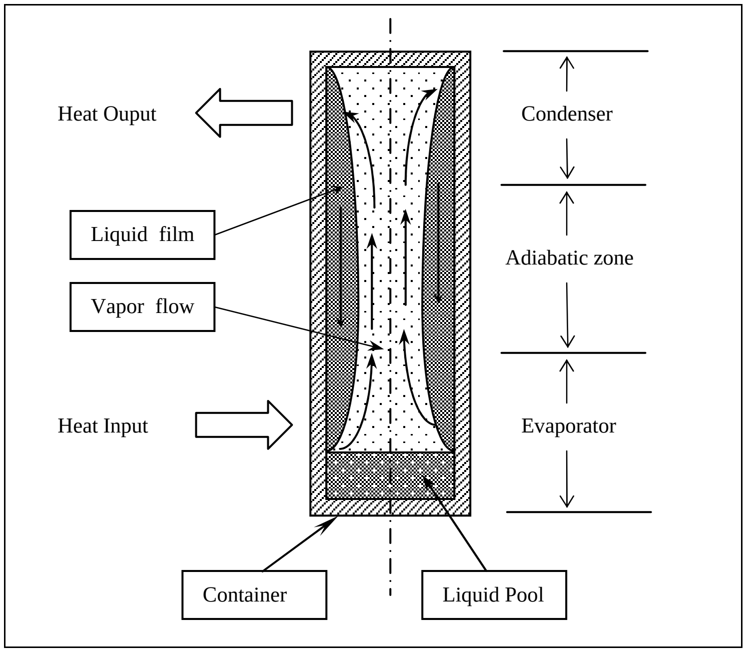

Figure1. Two-Phase Close Thermosyphon.

3. Design of Two phase close thermosyphons and heat exchanger with thermosyphons.

The design process and requirements assumed are described to dimensioning the two phase thermosyphon and the heat exchanger. Conceptual designs and sketches of thermal calculation models are presented.

3.1 Conceptual design of Heat pipes and two-phase thermosyphons

The first step is to establish the main function of a heat pipe or a two-phase close thermosyphon. It is considered as a system and the flows of mass, energy and signal (information) from or to the environment, crossing the limits or boundaries of the system, are analyzed. Normally, heat pipes and thermosyphons do not exchange mass with the environment, they only exchange energy.

3.1.1 Main Function of Heat pipes or Two-Phase thermosyphons.

The heat pipe and thermosyphon main function is to transport thermal energy from high to low temperature zone, and the principal flow is Energy (Paris, 2004). This is represented in a form of black box in figure 2.

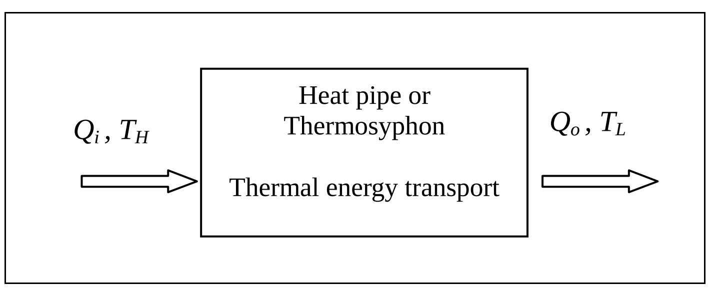

Figure 2. Heat Pipe / Thermosyphon black box

3.1.2 Functional synthesis for Heat pipes or Two-Phase thermosyphons.

Next step is to decompose the black box into secondary functions obtaining the functional structure. As can be seen in figure 3, there are several sub-functions associated with mass and energy flows inside the heat pipe or two-phase thermosyphon. Each sub-function is associated with an element or physical carrier

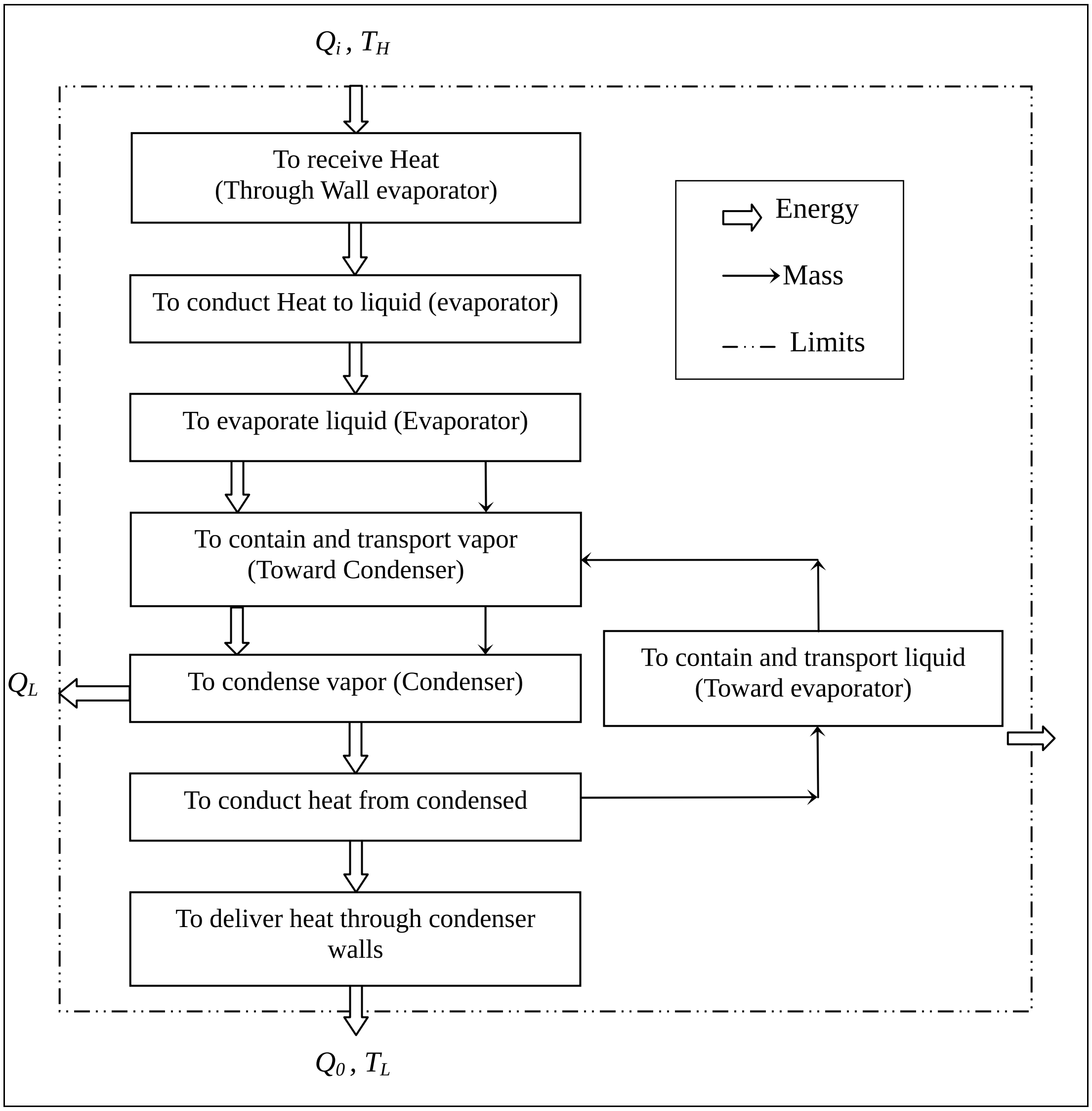

Figure 3 Functional synthesis of a Heat Pipe or two-phase close thermosyphon

3.2 Main Function and functional synthesis of the Heat Excahger.

The main function of a heat exchanger is to transport both mass and thermal energy from a hot fluid to a cold one (Duque, 2004). This is represented in a form of black box in figure 4-, and figure 5 shows the functional synthesis of a heat exchanger

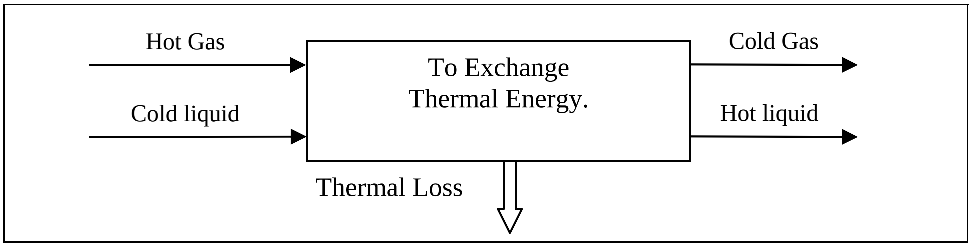

Figure 4 Heat Exchanger Black Box

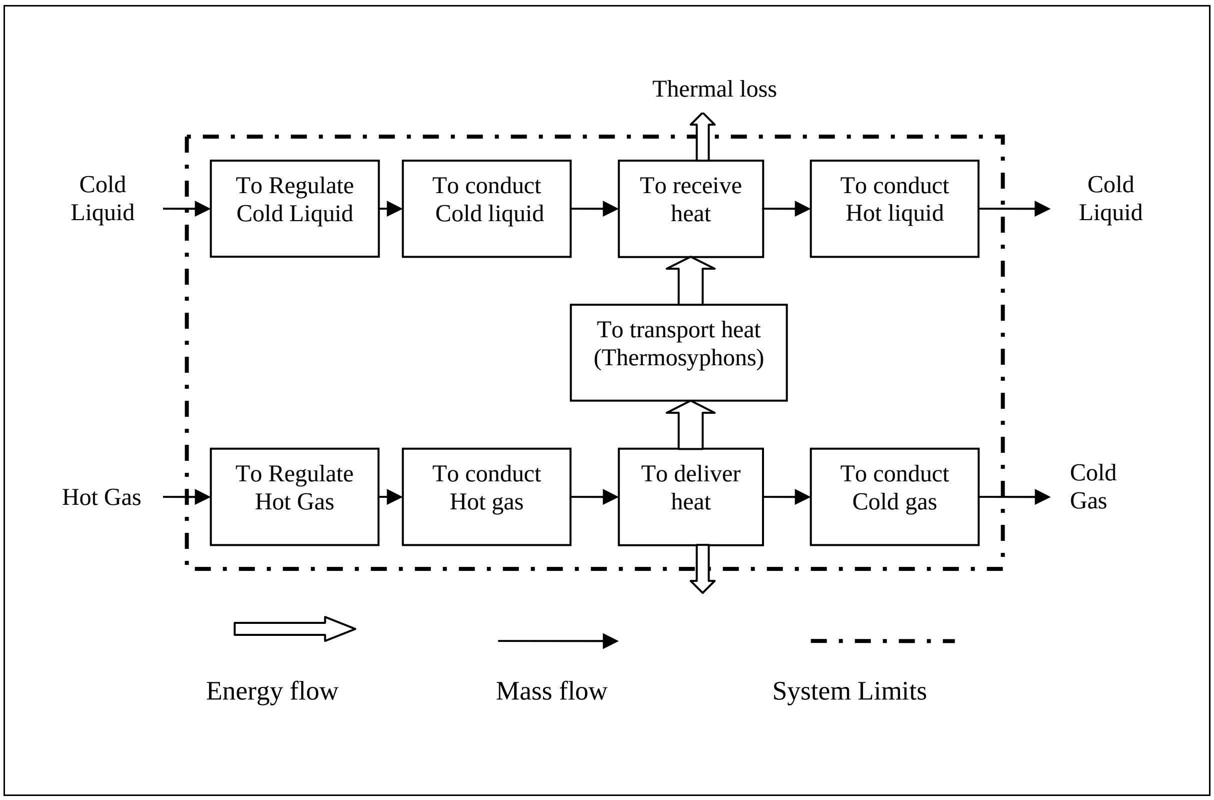

Figure 5 Functional synthesis of a Heat Exchanger

3.3 Thermal design of two-phase close thermosyphons

In general, Heat pipe models are quite complex and depend on many assumptions, properties and variables. What it is pretended is to calculate some parameters like the amount of fluid, the size of specific kind of wick, and some operational limits. Several authors and researchers (Dunn, 1976, Faghri, 1995, Peterson, 1994, Silverstein, 1992) have proposed formulas and equations to calculate the amount of fluid, the maximum heat flow at some operating limits (Viscous, capillary, sonic, boiling, entrainment limits, etc.) as a function of the operation temperature. These models let dimension and delimit the region where the heat pipe or thermosyphon can work well, and can be used to estimate geometric and functional considerations.

There are several factors that have to be considered to design a thermosyphon like the compatibility between materials involved, the operating temperature range, the size (diameter and length of the different zones), the thermal power, thermal resistance, working fluid, orientation, operating limits (boiling, sonic, thermodynamic, entrainment). Out of these limits the thermosyphon does not work well.

Having determined the working fluid, which could be water, some alcohol, some refrigerant, etc., it is necessary to calculate the amount of fluid selected, in order to fulfill the requirements for a given conditions. Faghri recommends an expression to estimated the minimum volume of fluid (Faghri, 1995):

$$Vt = \left[\frac{4(Lc+Le)}{5} + La\right]\left[\frac{3Q\mu_L(\pi D)^2}{(\rho_L)^2 g h_{fg}}\right]^{1/3} + \frac{\pi L_P D^2}{4}$$

Where sub index *c, e, a,* are related to condensation, evaporation and adiabatic zones respectively, and *p* and *L* refers to the pool and liquid respectively. *Q* is the rate of heat flow, *D* is the internal pipe diameter, μ is absolute viscosity, h_{fg} is fluid vaporization enthalpy and g is the gravity acceleration.

3.4 Thermal design of heat exchanger with two-phase close thermosyphons

The heat exchanger selected is an arrange of several two-phase thermosyphons, placed in two ducts with a horizontal separation between hot gases and cold liquid, in such a way that the heat is transported from hot fluid to cold one by means of thermosyphons.

In the constructed prototype, the hot fluid (Gas) flows trough a tube bank in bottom part (evaporation zone of thermosyphons), while the cold fluid (Liquid) flows in top part (condenser). Due to the temperature differences, thermosyphons are activated transferring heat between two fluids. Figure 6 shows a prototype sketch.

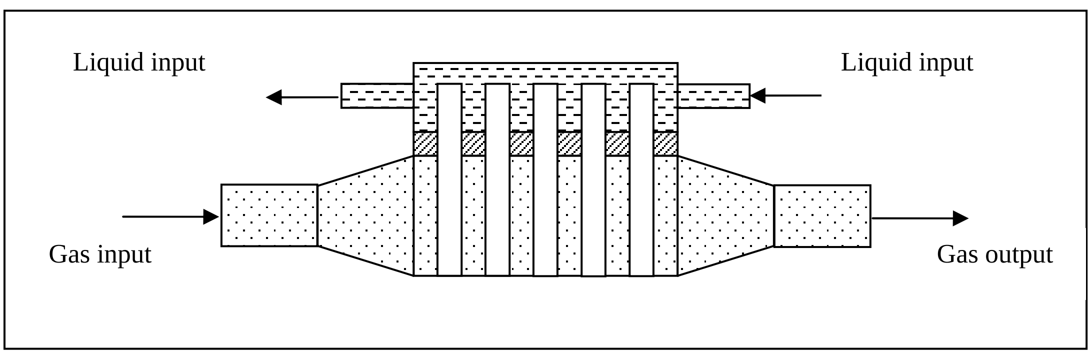

Figure 6. Sketch of heath exchanger

Knowing the prototype operation conditions, the geometric and thermal issues must be computed, i.e, temperatures, heat transfer coefficients, heat transfer areas, arrange and number of thermosyphons required, etc. Global steady state energy balance is applied to get relations between thermal energy flow from hot fluid (gas) to cold fluid (liquid), and heat transfer equation, assuming that there are not heat loss and phase changes during the process:

$$\dot{Q} = \dot{m}_H C_{pH}(T_{Hi} - T_{Ho})$$
$$\dot{Q} = \dot{m}_C C_{pC}(T_{Co} - T_{Ci})$$
$$\dot{Q} = UA(\Delta T_{ml})$$

Where subscripts *H* and *C* mean hot and cold fluid respectively, *i* and *o* mean inlet and outlet conditions, C_p is the specific heat of fluid, *m* is the mass flow of fluid, *T* is the fluid temperature at each specific location, *U* is the global heat transfer coefficient, *A* heat transfer area, and ΔTml is the log mean temperature difference.

The heat transfer process from hot fluid to cold fluid is considered in two stages: one from hot fluid to the thermosyphon evaporation zone and the other from the thermosyphon condensation zone to cold fluid, assuming constant temperature. In this sense there are two heat transfer processes couple by thermosyphon, (Silverstein 1992). Depending on operation conditions and design the temperature difference could be around 10 C between evaporation and condensation zones of thermosyphons. Figure 7 shows a general sketch of Heat exchanger design process used to find the number and arrange of thermosyphons required to fulfil thermal requirements.

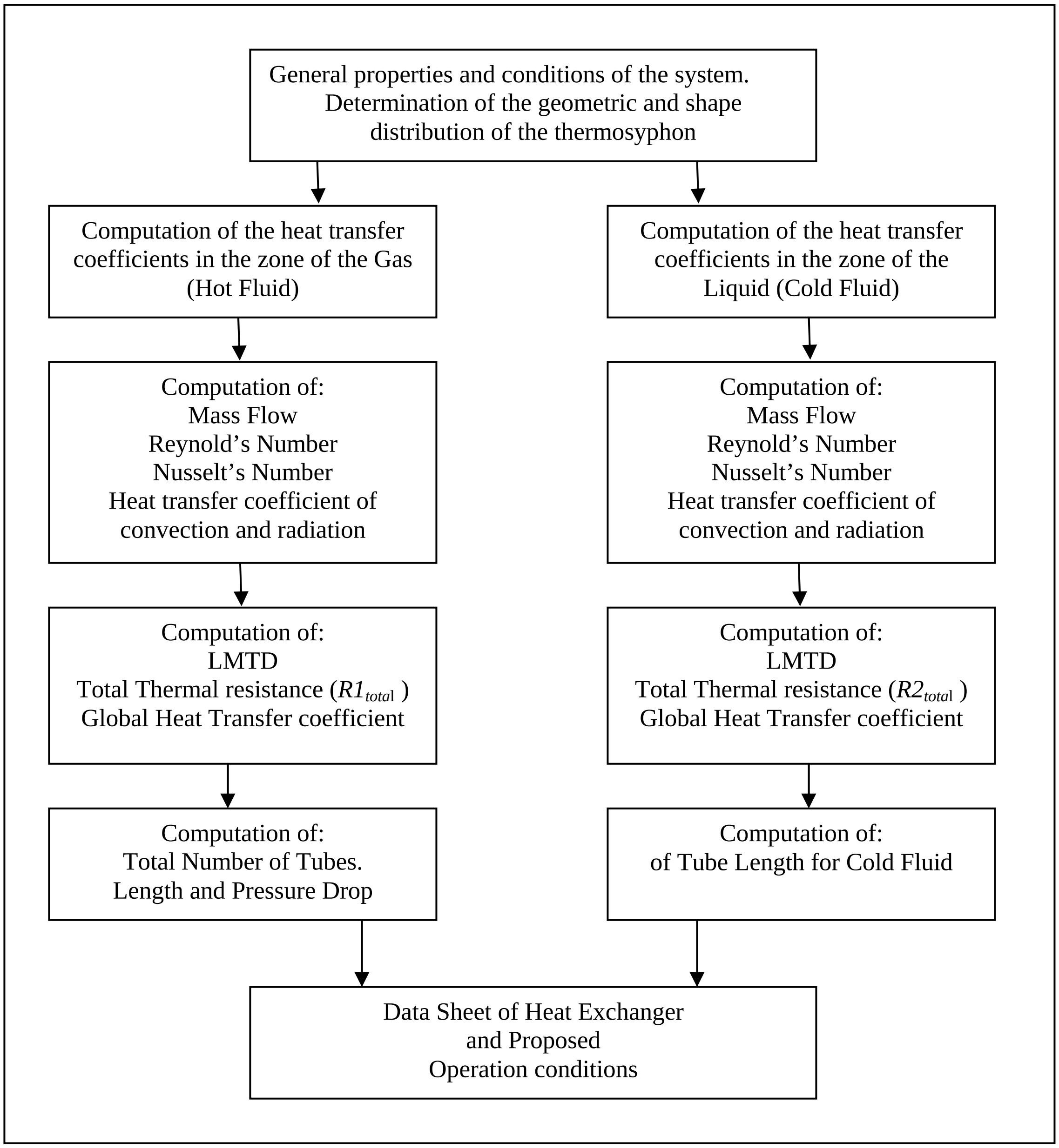

Figure 7 Sketch of Heat exchanger design process

4. Two-Phase Close Thermosyphon and heat exchanger prototype Manufacturing

The main aspects of manufacturing process of thermosyphons and the heat exchanger prototype are described.

4.1 Two-Phase Close Thermosyphon Manufacturing

Once the main mechanical and thermal parameters had been established, the next step is to construct the thermosyphon. Some factors have to take into consideration in order to obtain a very good quality two phase close thermosyphon. Cleaning process, charge of fluid, seal, are some of these factors.

4.1.1 Container

Type L copper tube was selected as container for thermosyphons. It has 12.7 mm outside diameter and 10.9 mm inside diameter. Copper caps were used as plugs at the ends. A 3 mm diameter capillary tube is attached to one cap to charge the fluid by means of the charge valve. Tube, caps and capillary tube were soldered after they were cleaned.

4.1.2 Cleaning process

Rust, residual oil or grease, and strange contaminants, must be removed form pipe, caps, to assure purity of constituents, avoiding improper operation of the thermosyphon. When the working fluid is water, special care must be taken during cleaning process to have good wetability. The procedure used follows some recommendation given by Peterson to clean copper (PETERSON, 1994): Remove oil and grease from pipe surface by soaking and rinsing with acetone. Soak the tube and caps in a solution of phosphoric and acid and nitric acid in water during 15 minutes at room temperature. Rinse with the working fluid and leave it for an hour, then rinse with working fluid and finally dry with air or nitrogen. Also a test was done with a solution of 30% hydrochloric acid in water and rinse with abundant water with good results.

4.1.3 Fluid charging process

A charge station was built following some proposals and suggestions given by Dunn (Dunn, 1976) and Peterson (Peterson, 1994). This station allows putting the right amount of fluid inside the thermosyphon. This can be done evacuating the tube and then charging the fluid as a liquid or as a vapor through the system of valves and tubes. Both procedures have been tested with very good results until now. The liquid charge procedure was chosen to charge the thermosyphons.

4.1.4 Final characteristics of Thermosyphons constructed.

Thermosyphons were constructed with Copper tube type L of 12.7 mm outside diameter (3/8" of nominal diameter) , filled with a mass of 1 g of water as working fluid. The total length was 275 mm, with 75 mm for effective condensation zone, 165 mm for effective evaporation zone and 25 mm as cuasi-adiabatic zone when they were used in the heat exchanger prototype.

4.2 Construction of Two-Phase Close Thermosyphons Heat Exchanger

A heat exchanger prototype with 33 two-phase thermosyphons was constructed which basic characteristics are listed in table 1.

Table1: Main characteristics of heat exchanger prototype

Description	**Symbol**	**Value**	**Units**
Total number of thermosyphons	N	33	
Array		Triangular	
Nominal diameter of copper tubes	D_{nom}	3/8	in
Outside Diameter	D_o	12.7	mm
Inside Diameter	D_i	10.94	mm
Interior area of each thermosyphon	A_i	9.40E-05	m^2
Number of tubes in transverse sense	N_T	6	
Number of tubes in longitudinal sense	N_L	6	
Transversal step		0.035	m
Longitudinal step		0.035	m
Length of evaporation zone (effective)	L_e	165	mm
Evaporation area (Gas side)	A_e	0.217	m^2
Length of condensation zone	L_c	75	mm
Condensation Area (liquid side)	A_c	0.0987	m^2
Evaporation/condensation areas ratio	$A_{e/}A_c$	2.2	

5. Thermosyphons and Heat Exchanger Evaluation and Results

Some tests were made to thermosyphons and heat exchanger to know and evaluate their performance under some specific conditions.

5.1 Two-Phase Close Thermosyphon test.

Thermosyphon tests allow determine the heat transport capabilities, as well as operation temperatures and differences between evaporation and condensation zones. Also an equivalent thermal conductivity can be calculated. Evaluation processes were carried out in steady state, using electrical bands added to the thermosyphon evaporator to supply thermal energy.

A small heat exchanger was located in the condensation zone in order to withdraw the heat transported from evaporator by means of a water flow. Temperatures were measured by means of thermocouples, data acquisition equipment and a personal computer.

Some thermosyphons were tested with several power levels, between 20 W and 100 W. In this case, the evaporator length was 75 mm and the condenser length 180 mm immerse in water as a cool media to remove the heat transported. The effective equivalent thermal conductivity under test conditions was around 50 times greater than copper at 50 C (C_p~ 394 W/m-K)

Figure 8 shows the Temperature Distribution in Two-phase Thermosyphon and figure 9 shows a Typical Temperature difference (Evaporator-Condenser) variation with input heat flow in a constructed thermosyphon

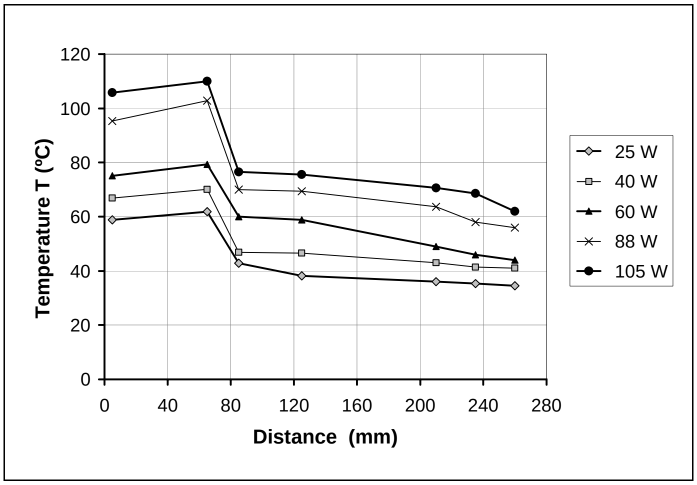

Figure 8. Temperature Distribution in Two-phase Thermosyphon
(Container: Copper tube *Di* = 10.9 mm *L*=280 mm Working fluid: 1 g water)

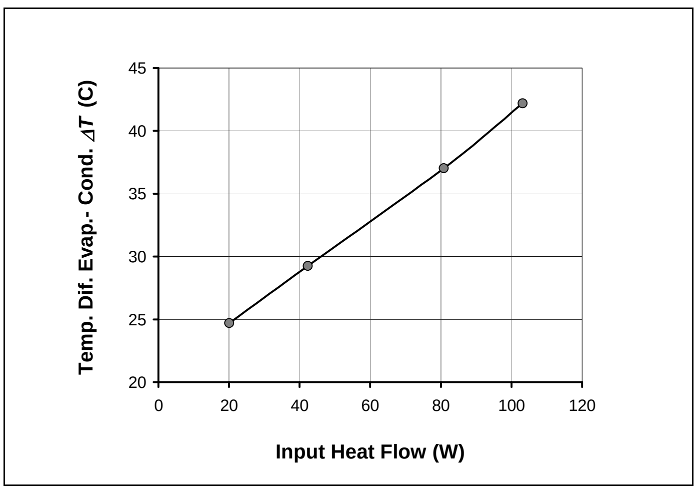

Figure 9. Typical Temperature difference (Evaporator-Condenser) variation with Input heat flow in a constructed Thermosyphon.

5.2 Thermosyphon Heat Exchanger test.

The 33 Thermosyphons Heat Exchanger prototype was tested in special device. It consists of a blower with air variable flow, a bank of electrical resistance (7 kW at 220 V and 60 Hz), to heat up the ambient air until the required temperature, and water circulation system to withdraw thermal energy from the prototype. Also a data acquisition system was employed to register temperatures and test results. Table 2 summarize the results for one of the cases tested, and figure 10 shows the thermosyphons heat exchanger prototype built.

Table 2: Test results of two - phase thermosyphon heat exchanger.

Description	Symbol	Value	Units
Air mass Flow	m_a	0.0347	kg/seg
Ambient temperature	T_o	28	C
Outlet air temperature	T_{ho}	165.4	C
Inlet air temperature	T_{hi}	229	C
Heat flow delivered by the air stream	Q_a	2284	W
Water mass Flow	m_w	0.0085	kg/seg
Outlet water temperature	T_{co}	76.2	C
Inlet water temperature	T_{ci}	23.2	C
Heat flow taken by the water stream	Q_w	1882	W
Thermal loss	Q_l	402	W
Effective thermal power transported by each thermosyphon (average)		57	W/tube
Heat recovered percentage in prototype	*Qw/Qmax*	24	%

Figure 10 The thermosyphons heat exchanger prototype.

6. Conclusion

A prototype of heat exchanger with thermosyphons was designed and built using 33 two-phase close thermosyphons. A computational model was developed to find the minimum amount of fluid required for the each thermosyphon as well as the geometry array and number of thermosyphons necessary to transport a determined amount of thermal energy at some temperature levels. The results obtained by tests fits well with theoretical. In practice there is a thermal loss due to non adiabatic heat exchanger.

According with tests, the prototype built could recover 26% of maximum energy transported by gas stream.

Colombia has no great experience and developed technology to construct heat pipes or thermosyphons and use them in specific application, but these kinds of works and projects allow us to get knowledge and experience to interact with others that have already developed and proved the heat pipe technology in several fields. Specifically some heat pipes and thermosyphons manufactured work very well, having high thermal equivalent conductivity and their performance is acceptable. Nevertheless, it is necessary more research, to improve the models, to automate the charge station, to standardize the construction procedure, to define protocols and quality standards, and to develop more industrial applications.

Acknowledgement

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