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Theoretical Algorithm Obtained to Design a Typical Flat Loop Heat Pipe for Heat Recovery Purposes

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ABSTRACT

A theoretical study is conducted to explore the effect of difference parameters such as heat loads, the tube size of piping system, wick thickness, porosity and hole size on the performance and capability of a Loop Heat Pipe (LHP). This paper presents a steady state model that describes the different phenomena inside an LHP. Loop Heat Pipes (LHPs) are two-phase heat transfer devices with capillary pumping of a working fluid. By their original design comparing with heat pipes and special properties of the capillary structure, they're capable of transferring heat efficiency for distances up to several meters at any orientation in the gravity field, or to several meters in a horizontal position. This theoretical model is described by different relations to satisfy important limits such as capillary and nucleate boiling. An algorithm is developed to predict the size of the LHP satisfying the limitations mentioned above for a wide range of moderate to high applied loads. Finally, to assess and evaluate the algorithm and all the relations considered, we have used to design a new kind of LHP to recover the heat from the exhaust of an actual Gas Turbine.

KEYWORDS: Loop Heat Pipe, Head Load, Heat Recovery, Heat Transfer, Design Algorithm.

1. INTRODUCTION

The temperature control is an important factor for many engineering systems such as cooling electronics, computer processors, space matters, aircraft tips, cryogenic application, space applications, heat recovery applications and other engineering applications. Different heat exchangers were developed to produce better convection heat removed. Recently, thermal engineers utilize the phase change, latent heat, to cool such devices [1]. Loop Heat Pipes were developed to efficiently transport heat that is generated by a highly localized concentrated heat source and then to discharge this heat to a convenient sink where, no pump is needed [2]. The working fluid is circulating by passive forces such as capillary effect, osmotic effect, viscosity effect and expansion effect to create a driving force gradient to circulate a working fluid in the loop [3].

2. Overall Operating Cycle of Loop Heat Pipe

To describe the whole cycle of the loop heat pipes, it's necessary to know some general information about them. A LHP consists of five key components: an evaporator, a reservoir, a condenser, a liquid line, and a vapor line. Surface tension developed in a porous material is the source of the pumping force used to circulate the fluid. A schematic diagram of a typical LHP illustrating the fluid direction inside and its different parts is shown in Fig. 1. When heat is applied to the evaporator body, it is conducted into the primary wick. Due to capillary action and surface tension, the liquid at the outer surface of the primary wick is vaporized and collected in the vapor channel. The amount of liquid vaporized depends on how much heat is applied to the evaporator. Because the vapor in the vapor channel has the highest pressure in the system, it flows through the vapor line to the condenser. In the condenser, where the heat is rejected, the vapor is condensed back to liquid and slightly subcooled. The liquid then flows through the liquid line back to the evaporator. In the evaporator/reservoir assembly, the liquid line is referred to as the primary wick, which directs the liquid all the way to the closed end of the evaporator. After the liquid exits the primary wick into the evaporator core, most of the liquid wets the primary wick and the secondary wick. The excess liquid goes back to the reservoir through the non-wick flow path. This completes the flow cycle in a LHP. The primary wick is usually made of sintered metal with very fine pores (on the order of 1 μm) to increase the pumping capability of the system [4].

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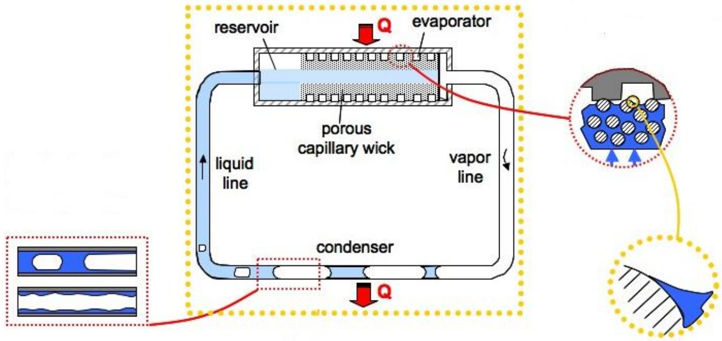

Figure1. Schematic Diagram of a LHP

Because the evaporator and the condenser are separated by smooth and flexible transportation lines, the pressure drop for the liquid returning to the evaporator is much less than that in a traditional heat pipe. Excess liquid and vapor inside the evaporator core flow back to the reservoir following the non-wick flow path. Since the reservoir contains both liquid and vapor, it remains at saturation temperature while the LHP is operated [5].

3. Achieving to the Proper Algorithm for Loop Heat Pipe Design

At this paper, a theoretical model for a loop heat pipe with stainless steel body and a wick which is made by sintered nickel is analyzed. A proper algorithm is obtained by this study by describing its strength points. To study and select this algorithm, it's important to pay attention to this point that it must be capable to execute in experimental ways and it should be as complete as possible. By studying the different papers, it could determine that most of them have some incompletion to design the components of an LHP, therefore by having just an algorithm; one cannot have a complete design of all LHP parts. This complete design is consist of solving the continuity, momentum and energy relations to predict the operation conditions of a LHP and also the inside and outside facts effects on it. Also by having this new algorithm, anyone can illustrate the size of the pre mentioned LHP.

During creating the algorithm structure, the effects of different parameters such as evaporator temperature, working fluid total mass, wick thickness, porosity and holes size on LHP operation and each part designation will be studied. After finishing comparing all the existence algorithms with their strength and weakness points, the final algorithm will get prepared completely [4].

4. Major Equations to Algorithm Development

The selected loop heat pipe consists of a flat evaporator and reservoir which they're equipped with a wick. The condenser is a cylindrical type with the same size compared with the vapor and liquid tubes but in different length. As the operation of the LHPs is complex and some of its specifications are not recognized yet, therefore to calculate, solve and making the related algorithm, some assumptions are considered to simplify more the relations. The most important equations to create and solve this algorithm are as follows [4]:

$$Q = Q_{in} = Q_{out} \tag{1}$$

The above mentioned Q is the overall heat load absorbed from a heat source. At the moment of heat load entranced to the evaporator, it divided to three parts which are the latent heat inside the evaporator, the sensible heat inside the vapor and liquid lines of the loop which can be obtained by the simple thermodynamic and heat transfer formulas [6]. The simple iteration is used to configure the solution way by considering the assumptions. The major independent design parameters that should be considered to design this algorithm are (1) the saturation condition inside the compensation chamber, (2) the different phenomena inside the condenser, and (3) the total mass charge (m). To design the LHP by using this new algorithm, the method starts with finding the mass flow rate inside the LHP by different heat loads. The named different phenomena are liquid, vapor and two phase region. After finding these different phenomena, and also the sizing values obtained by them, they can help us to design the other components of the whole LHP step by step. Through all the working fluid values, only the vapor densities varies with the different conditions and most the other values, considered constant. An overall view of the designed algorithm is illustrated below. Finally, to verify all the different specifications determined before, the two-important limitations which discussed before, will be added to the end part of the algorithm, which the ultimate results will be obtained after solving these limitations and comparing the last results with them. As it's described before, these limitations are capillary and nucleate boiling as following:

$$\Delta P_t = \frac{8\mu_{l,c}\dot{m}(l-l_v)}{\pi\rho_{l,c}r^4} + \frac{8\mu_{v,c}\dot{m}l_v}{\pi\left[\frac{\rho_{v,c}+\rho_{v,h}}{2}\right]r^4} + \frac{8\mu_{l,c}\dot{m}L}{A\varepsilon\rho_{l,c}r^2} \tag{2}$$

$$\Delta T_t = \left[\frac{\vartheta_{fg,c}T_c}{h_{fg,c}}\right]\left[\frac{8\mu_{l,c}\dot{m}(l-l_v)}{\pi\rho_{l,c}r^4} + \frac{8\mu_{v,c}\dot{m}l_v}{\pi\left[\frac{\rho_{v,c}+\rho_{v,h}}{2}\right]r^4} + \frac{8\mu_{l,c}\dot{m}L}{A\varepsilon\rho_{l,c}r^2}\right] \tag{3}$$

Where, ΔP_{max}, ΔP_l, ΔP_v, ΔP_w, σ, R, $\mu_{l,c}$, l, l_v, $\rho_{l,c}$, r, $\mu_{v,c}$, L, $\rho_{v,c}$, $\rho_{v,h}$, $\rho_{L,c}$ and ε are defined respectively as maximum capillary head, pressure drop inside liquid line, pressure drop inside vapor line, pressure drop inside wick, surface tension, wick radius, viscosity of fluid in condenser liquid part, total length of liquid and vapor paths, length of vapor part, density of fluid in condenser liquid part, radius of vapor & liquid parts tube, viscosity of fluid in condenser vapor part, wick thickness, density of fluid in condenser vapor part, density of fluid in evaporator, density of fluid at wick and porosity of wick [4]. Whole LHP pressure loss due to the variations of wick thickness is shown at figure 4.
The system of equations that was developed earlier can be solved by simple numerical iteration until the solution converges.
The developed algorithm is depicted by figure 2.

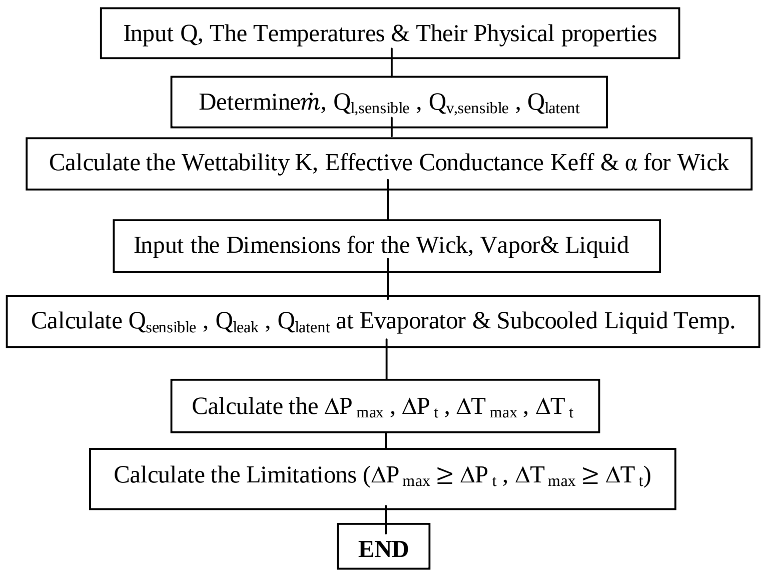

Figure2. The new algorithm developed to design the whole LHP

As it mentioned before, the most important relations are the limits which have directly effects on the loop operation conditions. The main limitations are in two types: the capillary limit and the nucleate boiling limit. The capillary limit occurs due to the pressure losses across the whole LHP. To come over to these losses, the total pressure created by the wick inside evaporator, should be greater than this limitation. Also to solve the nucleate boiling limit, the fluid at the outlet of the condenser should be completely in subcooled condition. Any vapor bubble is not permitted inside the liquid line between condenser and compensation chamber.

$$\Delta P_{max} = \frac{2\sigma}{r} \qquad \text{The Capillary Limit} \tag{4}$$

$$\Delta T_{max} \approx \frac{\left[\frac{2\sigma}{R}-P_g\right]T_{sat}}{\rho_v h_{fg}} \qquad \text{The Nucleate Boiling Limit} \tag{5}$$

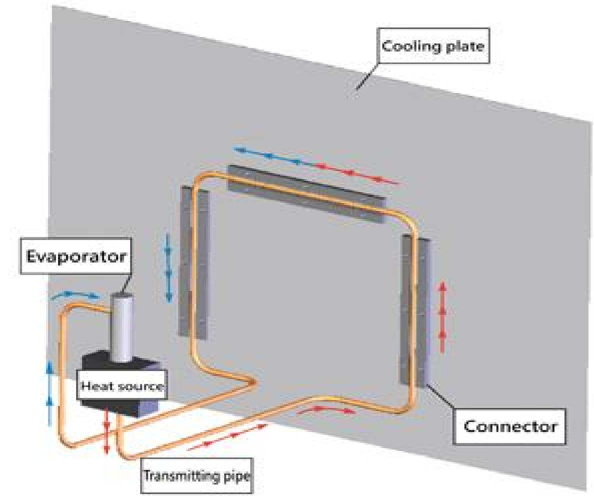

Figure3. Typical suggested arrangement of the Loop Heat Pipe

5. CONCLUSION

During working and analyzing on this new algorithm, it was determined that any change specially in wick thickness, have most effects on an LHP design conditions and specially they're so important to satisfy the limitations mentioned before. To evaluate this algorithm and the results obtained through it, we have used it to design a Loop Heat Pipe to recover a typical gas turbine exhaust heat loss. The available data were including the gas turbine exhaust heat loss flow rate and the heat load rate. By considering these values, we have tried to design a new LHP by considering this fact that all heat lost from the exhaust is planned to recover. This gas turbine is used to generate the electrical power about 1.8 MW to operate some facilities for a plant.

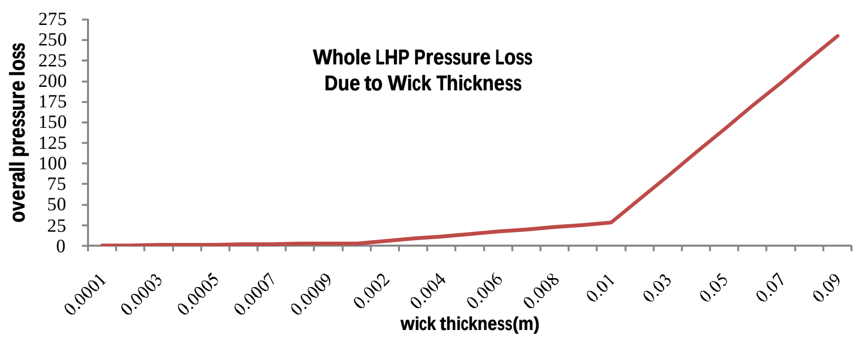

Figure 4. Variation of total ΔP with wick thickness

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