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Feasibility Study on Designing a Flat Loop Heat Pipe (LHP) to Recover the Heat from Exhaust of a Gas Turbine

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***Abstract*—**A theoretical study is conducted to design and explore the effect of different 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 a 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 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. By finding the results, it showed that we can use the LHP as a very high efficient device to recover the heat even in high amount of loads(exhaust of a gas turbine). The sizes of all parts of the LHP were obtained using the developed algorithm.

***Keywords*—**Loop Heat Pipe, Head Load, Liquid-Vapor Interface, Heat Transfer, Design Algorithm

I. Introduction

THERMAL management is an important factor for many engineering systems such as cooling electronics, computer processors, drill tips, aircraft tips, cryogenic applications, 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. 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. 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].Capillary pumped loops (CPLs) and loop heat pipes (LHPs) are emerging as the baseline of thermal control systems for space applications because of their higher efficiency compared to conventional heat pipes. CPLs were first conceived in the USA (NASA) in late 60's [1] whereas LHPs appeared in former Soviet Union in the early 1970s [2] and [3]. Critical reviews were carried out with CPLs and LHPs showing their similarities and differences [4] and [5]. LHPs and CPLs are the key apparatuses of thermal control in GLAS, EOS-Chemistry, GOES, SWIFT spacecraft and some communications satellites. While the CPL and LHP technologies have reached a certain level of maturity, many issues still remain as the subjects of active researches. The reason lies in the complex behavior of the two-phase fluid in these devices, which unites conjugate processes of heat transfer, flow through porous structure, eventual dry-out, flooding, condensation, evaporation and bubble formation, fast liquid phase redistribution in the loop, among others. It also yields several operation modes and possible types of failure. Those LHP behavior modes actually are studied experimentally, where the start-up issues of CPLs have been particularly investigated [7,8] among others as well as pressure oscillations were investigated [9,10,11]. Also there were several attempts to develop the model to design the LHP. Sasin et al. in 1990 published one of the first descriptions of the LHP numerical model, in which the nodal methodology was adopted [12]. Brienert and Wolf in 1995 used the same approach for their LHP model [13]. Kaya and Hoang [14] made advance in the LHP steady-state model.

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II. General Operating Principles of Loop Heat Pipe

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 sub cooled. 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.

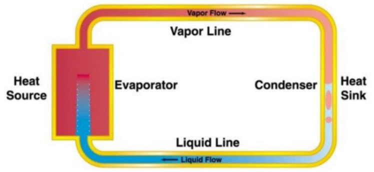

Fig. 1 Schematic Diagram of a LHP

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 [4].

III. Algorithm Selection to Design a Loop Heat Pipe

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 can not 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, any one 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.

IV. Defining Equations, Parameters and the Method of Solution

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:

$$Q = Q_{in} = Q_{out} \quad (1)$$

$$Q = q_{latent} + q_{v,sensible} + q_{l,sensible} \quad (2)$$

The simple iteration is used to configure the solution way by considering the assumptions. The major independent design parameters that should be considered in the design 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:

$$\Delta P_t = \frac{8\mu_{l,c}\dot{m}(l-l_v)}{\pi\rho_{l,c}r^4} + \frac{8\mu_{v,c}\dot{m}l_v}{\pi\left[\frac{\rho_{v,c}+\rho_{v,h}}{2}\right]r^4} + \frac{8\mu_{l,c}\dot{m}L}{A\varepsilon\rho'_{l,c}r^2} \quad (3)$$

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

The system of equations that was developed earlier, can be solved by simple numerical iteration until the solution converges. Utilizing the data given in table1, the set of equations is solved by numerical iteration which leads to the following graphs. The solution at first started by running the equations to produce the condenser conditions. The perturbation term was introduced by calculating the initial mass flow rate by $\dot{m} = Q/h_{fg}$ [5].

The developed algorithm is depicted by figure 2.

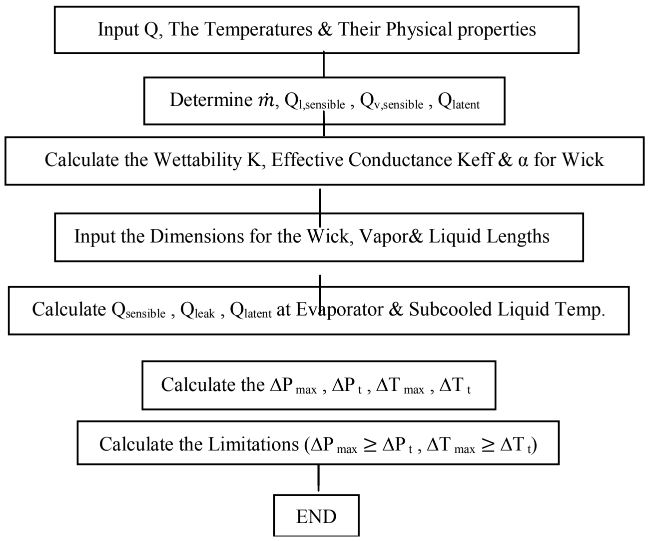

Fig. 2 The new algorithm developed to design the whole LHP

$$\Delta P_{MAX} = \frac{2\sigma}{r} \qquad \text{The Capillary limit} \quad (5)$$

$$\Delta T_{max} \approx \frac{\left[\frac{2\sigma}{R} - P_g\right]T_{sat}}{\rho_v h_{fg}} \qquad \text{The Nucleate Boiling Limits} \quad (6)$$

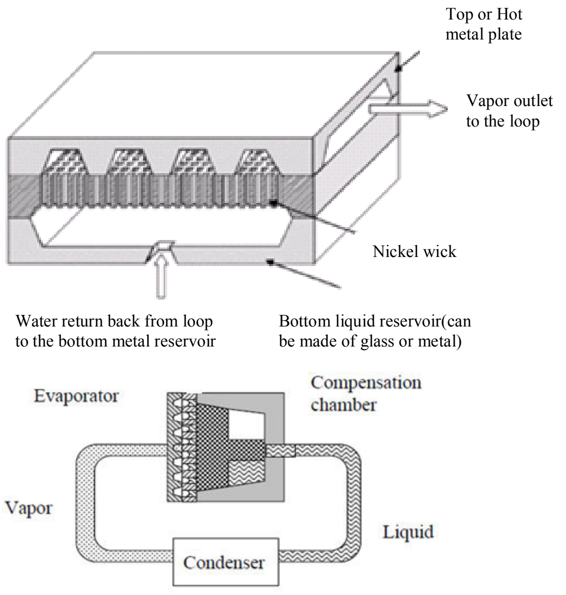

Fig. 3 A schematic view of (a)The Evaporator and Compensation chamber ,(b)The LHP cycle

V. Obtained Results

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 an actual 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 in a gas refinery. As the amount of heat lost from exhaust of a gas turbine is so high, to use the design algorithm as applicable as possible, the total heat load is divided to smaller values(about 10 kW). Therefore any LHP is designed for every heat load part and finally the total numbers of LHPs were found for that total heat load. The other parameters are obtained from the calculating hand books [6].
As it's shown on the following graphs, the heat leaked from the evaporator to the compensation chamber(Q_{leak}) and the latent heat because of the latent heat of vaporization inside the evaporator(Q_{latent}) are changing suddenly when the wick thickness reaches to 0.002m. But the best choice for this thickness is about 0.007 as the latent heat reaches to the value about 0.93 times or more than the heat load applied to the evaporator(Q) [1]. At the end of the paper, one can see that the prepared algorithm can be utilized to design most types of loop heat pipes such as general and micro ones with different heat load values which is so useful and important for industrial applications.

TABLE I
(A)LHP SPECIFICATIONS OBTAINED BY THE NEW ALGORITHM

LHP Specification	
Working Fluid	Water
Whole LHP Body Material	S.S 304
Evaporator:	
- Active Area(m^2)	1.00E-02
- Wick Pore Radius(m)	2.00E-05
- Wick Porosity (%)	50
- Wick Thickness(m)	0.007
- Nickel Conductivity	73.269
Vapor Line:	
- Diameter(m)	0.047
- Radius(m)	0.0235
- Length(m)	0.7
Liquid Line:	
- Diameter(m)	0.047
- Radius(m)	0.0235
- Length(m)	1

TABLE II
(B)LHP INPUT PARAMETERS USED BY ALGORITHM

Input	
Tair(K)	300
Q(kW)	10
Th(K)	473
Tc(K)	373
Ts(K)	343
Ks.s at 308K	15.7
K_{Ni} at 343K	73.269
σ(N/m)	0.05886

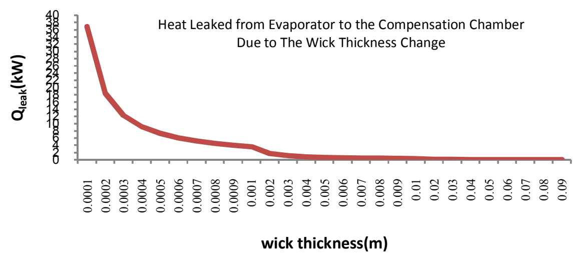

Fig. 4 Heat Leaked from Evaporator to the Compensation Chamber due to the Wick Thickness Change

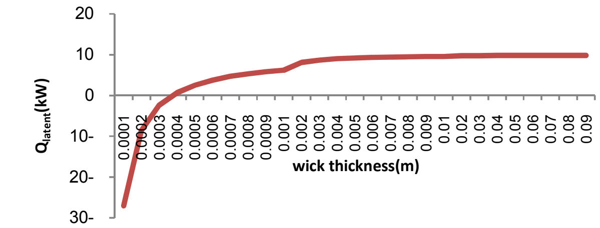

Fig. 5 Latent Heat Inside Evaporator due to the Wick Thickness Change

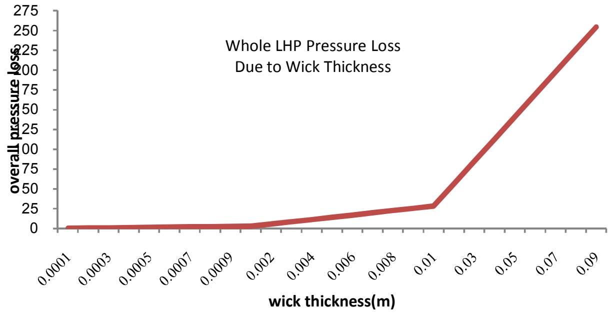

Fig. 6 Whole LHP Pressure Loss Due to the Wick Thickness Change

VI. Conclusion

The results of the current global model have shown operating condition of current steady state LHP device which is used to recover the heat from the exhaust of a typical gas turbine. The study shows that in order to have an operating loop, the nickel wick should be able to hold a saturated temperature difference which would represent a saturated pressure difference. The system can operate due to the high thermal resistance induced by the compensation chamber. The pressure-temperature gradient depends on operating temperature and the working fluid. A LHP with short pumping distance and large tube size is better than other loop with larger pumping system and smaller tube size because it cause high pressure loss which cause less mass flow rate to be circulated in the LHP. In case of the steady state, most of the heat will be carried by the latent heat. The leaked heat will cause vapor bubble to occur underneath the wick and step by step it covers the wick and prevents the LHP from operating. If the leaked heat was enough to initiate a bubble, the sub-cooled liquid circulating in the LHP will be able to suppress such action. Still many phenomena in the LHP operation need more exploration such as interface oscillation, the dryness of the wick,… . Therefore study on the Loop Heat Pipe operation is still continuous and most of the relations are not recognized yet.

References

[1] M. Hamdan, F. M. Gerner, H. T. Henderson, "Steady State Model of a Loop Heat Pipe(LHP) with Coherent Porous Silicon(CPS) Wick in the Evaporator", *Int. J. Heat Mass Transfer*, Vol. 35, (2003).

[2] Yu.F. Maydanik, "Loop heat pipes", Institute of Thermal Physics, Ural Branch of the Russian Academy of Sciences, Amundsen St. 106,Ekaterinburg 620016, Russia, *Applied Thermal Engineering* 25 (2005) 635–657.

[3] Faghri. A "Heat pipe science & Technology", Taylor and Francis publication (1984).

[4] Po-Ya Abdel Chuang,(2003), "An Improved steady state model of Loop Heat Pipes based on Experimental and Theoretical Analysis", *PHD Thesis*, Mechanical and Nuclear Engineering Department, The Pennsylvania State University, Pennsylvania.

[5] G. Van Wylen, R. Sonntag, C. Borgnakke, "Fundamentals of Classical Thermodynamics", 4th Edition, John Wiley & Sons, INC., New York, (1998).

[6] M. Ebrahimi, "Hand Book of Thermodynamic Tables", Koleyni Pub., Tehran, May (1985).

[7] D. Butler, T. Hoang, "The enhanced capillary pumped loop flight experiment: a prototype of the EOS platform thermal control system", AIAA Paper 91-1377, in: *Proceedings of the 26th AIAA Thermophysics Conference*, Honolulu, 1991.

[8] J. Ku, L. Ottenstein, D. Butler, "Performance of CAPL 2 flight experiment", SAE Paper 961432, in: Proceedings of the *26th International Conference on Environmental Systems*, Monterey, CA, 1996.

[9] T. O'Connell, T. Hoang, J. Ku, "Investigation of power turn down transients in CAPL-1 flight experiment", AIAA Paper 95-2067, in: Proceedings of the *30th AIAA Thermophysics Conference*, San Diego, CA, 1995.

[10] A.M. Kiper, T.D. Swanson, R. McIntosh, "Exploratory study of temperature oscillations related to transient operation of a capillary pumped loop heat pipe", in: Proceedings of the *ASME National Heat Transfer Conference*, Houston, 1988, pp. 353–359.

[11] K.R. Kolos, K.E. Herold, "Low frequency temperature and fluid oscillations in capillary pumped loops", AIAA Paper 97-3872, in: Proceedings of *National Heat Transfer Conference*, Baltimore, MD, 1997.

[12] V.Ya. Sasin, A.I. Zelenov, V.G. Zuev, E.Yu. Kotlyarov, "Mathematical Model of a Capillary Loop Heat Pipe with a Condenser-radiator", *SAE Paper No. 901276*, 1990.

[13] W.B. Bienert, D.A. Wolf. "Temperature control with loop heat pipes: analytical model and test results, in: Proceedings of the Ninth International Heat Pipe Conference (IHPC)", *Albuquerque, NM, USA*, 1995.

[14] T.T. Kaya and T.T. Hoang, "Mathematical modeling of loop heat pipes and experimental validation", *Journal of Thermophysics and Heat Transfer* 13 (3) (1999), pp. 314–320.