Review on Closed Loop Oscillating Heat Pipe

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***Abstract*—Heat pipe is a passive two phase heat transfer device. It is being used to manage heat transfer between two solid interfaces for that heat pipe combines the principle of both thermal conductivity and phase transition. Over the last few decades, several factors motivated researchers to develop new and more efficient types of heat pipe such as; flat plate heat pipe, variable conductance heat pipe, oscillating/pulsating heat pipe, micro loop heat pipe etc. The main reason for this development in heat pipe is increasing its commercial applications like solar thermal water heating, computer cooling system, space craft etc. Oscillating/Pulsating heat pipe (OHP/PHP) is the most recent developed heat pipe among various other types of heat pipes. It is more efficient than conventional heat pipe with respect to its construction and operation. The two basic features of oscillating/pulsating heat pipes which differentiate it from rest of the other heat pipes are; it uses no external power for its operation and there is no wick structure inside it which is generally present in most other types of heat pipes. In this paper, a review is established on the work done by various researchers on closed loop oscillating/pulsating heat pipes for improving its efficiency by using various system parameters.**

***Keywords*— Heat Pipe, Oscillating/Pulsating heat pipe**

I. INTRODUCTION

Heat Pipes are the passive two phase heat transfer devices capable of transporting heat without consuming any external power. They mostly used as a thermal management system in various electronic systems. As modern electronic systems become more and more compact, more heat is generated within very small space e.g. computer processor etc., to transfer this heat out of the system, some reliable solutions are required for their thermal management. In such cases, heat pipes can be prominent and reliable solution. First Heat pipe was developed in 1839 by Angier March Perkins who worked on only single phase heat transfer. Many researchers worked on heat pipes and single phase heat transfer principle but important evolution in heat pipe started in 1936; Jacob Perkins, descendant of Angier March Perkins developed Perkins tube [1]. In Perkins tube water was used as the working fluid which travelled to and from the evaporator and condenser sections through the twisted metal tubes. It was the basic two phase heat transfer model for the development of conventional heat pipes. Actual development in conventional heat pipe (CHP) began in 1960; many spacecraft industries started their research on heat pipes. They developed and used heat pipes for managing heat in space craft. During last two decades, lots of work is going on overcoming drawbacks of conventional heat pipes [2] which include liquid and vapor flow separation, design of wick structure, orientation of tubes, size and weight of heat pipe etc. It results into development of some new and more efficient types of heat pipes such as loop heat pipe, capillary pumped loop heat pipes, miniature heat pipe etc. Akachi et al. [3] in 1990 developed new type of heat pipe known as oscillating or pulsating heat pipe (OHP or PHP). OHP has wide range of applications in modern electronics systems due to its capability of dissipating high heat flux. This review article will describe the construction and operation of oscillating heat pipe and summarizes the work done by various researchers on oscillating heat pipes for improving its efficiency.

A. Heat Pipe

Heat pipe is a passive two phase heat transfer device which required no external power for its operation. It has good flexibility, simple construction and easy control. Conventional heat pipe as shown in fig. 1 consists of a sealed container, wick structure and working fluid [4]. In heat pipes, mainly container having cylindrical structure is used however it can be of any shape and size. Heat pipe is divided into three main sections: Condenser, Evaporator and Adiabatic section. On the inner periphery of the container there is wick structure, which is a porous structure through which working fluid translates from condenser to the evaporator and vice versa. There are various types of working fluid [5] which can be used in heat pipe as a heat transfer medium e.g. water, acetone, methanol, different refrigerants etc. Selection of working fluid mainly depends on the temperature range for which it is to be use. Heat pipes can have single or multiple heat sources and heat sinks. Adiabatic section mainly works as a transport passage for the working fluid. Working fluid in the evaporator section, takes heat from the cylinder wall and wick structure, with the help of that working fluid gets evaporated and vapor pressure rises. Vapor pressure developed in the container drives the working fluid from the evaporator region to the condenser section where it loses its heat to the condensate and again gets converted into liquid. Pressure that developed in the wick structure, pumps this liquid again in the evaporator region, in this way the cycle gets completed and the same cycle is repeated again and again for the transfer of heat from evaporator to the condenser section.

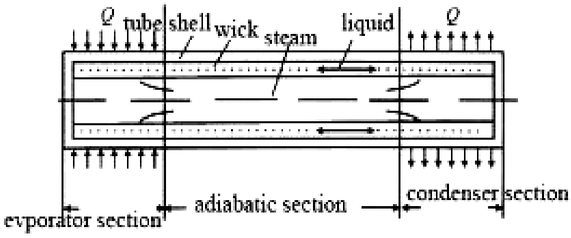

Fig.1. Heat Pipe [4]

Vapor pressure in the heat pipe varies mainly due to friction, inertia effect, formation of vapor in evaporator section and transformation of vapor to liquid in condenser section while liquid pressure varies mainly due to the effect of friction only.

Conventional heat pipe (CHP) as explained above though has various advantages like simple construction, flexibility and easy control etc. it has some drawbacks also which includes; difficulties in design of wick structure, mixing of vapor and liquid streams of working fluid, efficiency etc.. Many researchers worked on heat pipe for removing its limitations and improving its efficiency with that they developed some new types of heat pipe [2]. Two-Phase Closed Thermosyphon, Capillary-Driven Heat Pipe, Annular Heat Pipe, Vapor Chamber, Rotating Heat Pipe, Gas-Loaded Heat Pipe, Loop Heat Pipe, Capillary Pumped Loop (CPL) Heat Pipe, Pulsating Heat Pipe, Micro and Miniature Heat pipes, Inverted Meniscus Heat Pipe, Nonconventional Heat Pipes etc. These are various types heat pipe developed by various researchers depending on particular application and operational limit. This paper mainly focuses on pulsating or oscillating heat pipes which can be given as follows:

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B. Pulsating or Oscillating Heat Pipe (OHP/PHP)

Oscillating or Pulsating Heat Pipe is a new type of two phase heat transfer device. It consists of meandering capillary tubes arranged parallel to each other. OHP as in CHP divided into three main sections; Evaporator section, adiabatic section and Condenser section. It differs from CHP in many ways like;

- No wick structure,
- Multiple turns of capillary tubes,
- High heat transfer rate etc.

OHP can be designed in at least three ways:

(I) Closed loop known as closed loop oscillating/pulsating heat pipe (CLOHP/CLOHP). In this two ends of capillary tubes are usually closed either at two separate ends (b) or by joining two ends at a common point (a).

(II) Open loop known as open loop oscillating/pulsating heat pipe (OLOHP/OLPHP). In this, two ends of tubes are open to the surroundings.

(III) Closed loop with flow control valve. In this, flow control valve is use to control flow of working fluid.

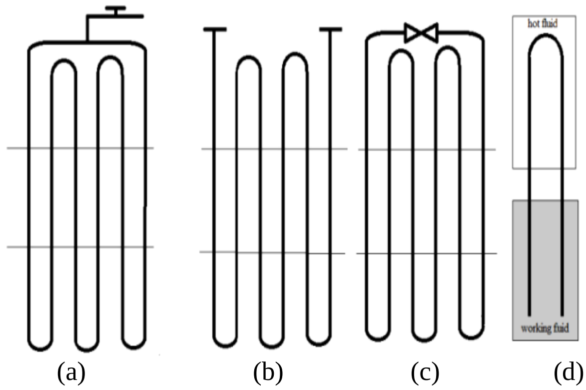

Fig. 2 . Types of pulsating heat pipes (PHP's):
(a) closed-end, (b) closed –loop, (c) closed-loop with check valve, (d) PHP with open end. … [2]

Review and past work on OHP shows that CLOHP is more efficient than other types of oscillating heat pipes. Construction of LOHP is very easy but the working principle of CLOHP can be understand by understanding its thermodynamics principle, fluid dynamic principle and heat transfer principle [6] which is quite difficult to understand. CLOHP's simple working principle and its various design parameters are explained as follows:

C. General working principle

OHP works on the principle of oscillation of working fluid and phase change phenomena inside a capillary tube. This review article mainly focuses on closed loop oscillating heat pipe (CLOHP). CLOHP consists of close loop of meandering tubes, through which working fluid flows for the heat transfer. Meandering capillary tube generally arrange in U-shape which are placed parallel to each other. These tubes are basically divided into three main sections: Evaporator section, Condenser section and middle adiabatic section. Working fluid with appropriate filling ratio (generally 30%-70%) is used in CLOHP which circulates through all the three section of CLOHP [5]. A vacuum is created inside an OHP tubes followed by charging of working fluid with proper filling ratio; so that after the charging gets complete, there is definite proportion of liquid and vapor form of working fluid, which is known as liquid slug and vapor bubbles. In the Evaporation section heat is added, with the help of that liquid slug gets converted into vapor bubbles and pressure of vapor gets increases. Vapor bubbles of fluid are then transferred to the Condenser section through adiabatic section. In the condenser section with the help of cooling fluid, vapor bubbles of fluid gets converted into liquid slug, which results into drop in pressure and as a result liquid fluid again come back to evaporator section through the adiabatic section, in this way the cycle gets completed. Working fluid in the OHP oscillates from evaporator region to the condenser region mainly due to pressure difference created inside the tubes by the formation and breaking of vapor bubbles which is the only reason for the transfer of heat from evaporator to the condenser section.

For the case when the OHP is isothermal throughout [7], the liquid and vapor phases of the OHP exist in equilibrium at a saturation pressure corresponding to the fixed isothermal temperature. In Figure 3, OHP Pressure-Enthalpy Diagram, point A represents the average thermodynamic state of the OHP. During operation, there is a temperature gradient between the evaporator and condenser, which causes a non-equilibrium pressure condition. The heat transfer to the evaporator causes the bubbles in the evaporator to grow continuously and tries to move to point B from point A at a higher pressure and temperature. This moves the liquid column towards the condenser. Simultaneously, the condenser located at the opposite end of the OHP further enhances the pressure difference between the two points, forcing point A to move to point C, at a lower pressure and temperature. This results in the development of a non-equilibrium condition between the driving thermal potentials, with the system trying to stabilize the internal pressure. Due to the inner-connection of the tube, the motion from the liquid slugs and vapor bubbles at condenser of one section also leads to the motion of the slugs and bubbles in another section near the evaporator. The interaction between the driving and restoring forces leads to the oscillation of vapor bubbles and liquid slugs in the axial direction. However, unlike traditional heat pipes, it is not possible for an operating OHP to reach steady-state pressure equilibrium.

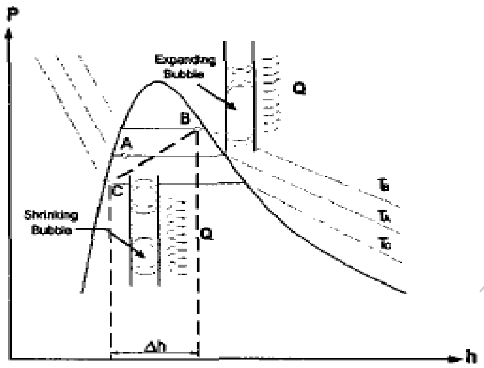

Fig.3. OHP: Pressure-Enthalpy diagram [7]

D. OHP Performance

The performance on an OHP depends on its structure, shape, material and length. A major criterion for thermal performance is the temperature drop (ΔT) along the heat pipe for a required heat load Q:

$$Q = \frac{\Delta T}{R_{th}} \quad \text{..... [8]}$$

E. OHP Resistances

The overall resistance is composed of several components, starting from the evaporator to the condenser. There are two conductive thermal resistances in the wall (R_{wall}), thermal resistance due to the evaporation and condensation at the evaporator and condenser (R_{evap} and R_{cond}), and a thermal resistance along the heat pipe length ($R_{l\text{-}v}$), which includes the conductive thermal resistance along the wall and the thermal resistance due to fluid head capabilities, and two thermal resistances ($R_{cont.}$) which are associated with the contact resistances due to the surface roughness. It is important to note, that for wicked heat pipes, additional thermal resistance needs to be added to the wall resistance to compensate for the wick structure.

The heat transfer capacity, Q, for an OHP can be estimated as

$$Q = \frac{\Delta T}{\frac{L_{eff}}{k_{eff} \times A_{cross}}} \quad \text{......... [8]}$$

Where ΔT is the overall temperature difference between the heating and cooling section, k_{eff} and L_{eff} are the effective thermal conductivity and length and A_{cross} is the cross sectional area of the OHP. A design goal of an OHP is to minimize all the resistances in equation given by [8] in order to obtain maximum heat throughout the OHP for a given ΔT.

Research on OHP can be categorized in either experimental or theoretical. Experimental research focuses on either flow visualization or characterizing the heat transport capabilities of heat pipes. While experimental research mainly focuses on mathematical modeling of OHP.

II. DESIGN PARAMETERS OF OHP

There are various design parameters of OHP on the basis of that OHP is usually designed and it also affects its performance. Various design parameters of OHP are given as follows:

1. Geometric parameters
2. Working fluid
3. Working fluid properties
4. Number of turns
5. Orientations of tubes
6. Evaporator and condenser section etc.

Researchers worked on OHP for improving and enhancing its performance. Work done by various researchers on design parameters of OHP is given as follows:

A. Geometric parameters

The inner diameter of PHP must be decided carefully so that gravitational force of the working fluid can be overcome by surface tension forces. The critical diameter of PHP occurs when the value of bond number is equals 4. Bond number is the ratio of gravitational force to the surface tension force. It can be given as:

$$Bo = \frac{g(\rho_1 - \rho_v)D}{\sigma} \quad \text{.......... [2]}$$

From this equation, Chien et al [9] developed effective range of tube diameter for PHP, it is given as:

$$0.7\sqrt{\frac{\rho}{(\rho_{liq} - \rho_{vap})g}} \leq D \leq 1.8\sqrt{\frac{\rho}{(\rho_{liq} - \rho_{vap})g}} \quad \text{... [9]}$$

Where σ, g, ρ_{liq}, and ρ_{vap} represent the surface tension, gravitational constant, density of liquid and Density of vapor. Tubes diameter within this range ensures that there will be a separate liquid slug and vapor bubbles formation inside the OHP.

Study shows that, if the diameter is reduced from its critical value its performance gets decreased due to increase in frictional pressure head on the other hand if diameter is greater than that of critical value, it no longer remains OHP as there will be interconnected array of two phase thermosyphon.

Lin et al [10] investigated the effect of heat transfer length and inner diameter on the heat transport capability of oscillating heat pipes. They designed four different heat pipes with different diameters and with different heat transfer lengths. They found that, increasing inner diameter or decreasing heat transfer length is beneficial for the startup of OHP. also for high heating power, the thermal performance of OHP can only approach up to that of sintered heat pipes in horizontal heating mode, while exceed it in vertical bottom heating mode.

The operational limitation of CLOHP, which includes the effects of inner diameter, filling ratio, operational orientation and heat input flux on thermal performance of OHP was studied by Yang et al [11]. They found that, 2mm ID tubes giving best performance in the vertical orientation while CLOHP with 1 mm ID tubes have same performance in all the orientations. They calculate heat flux required to cause dry out and they found that, heat fluxes in the vertical bottom heat mode with axial heat transport is better than that of radial heat input.

B. Working fluid

Working fluid selection in OHP depends on the temperature range for which it is to be designed. Nagvase et al. [12] explained temperature range of various working fluids which can be useful for the selection of required working fluid, some commonly used working fluid having range above 0^0C can be given as:

TABLE I–TEMPERATURE RANGE OF DIFFERENT WORKING FLUIDS

Working Fluid	Boiling point at Atm. Temp. (^{0}c)	Useful range (^{0}c)
Helium	-261	-271 to -269
Nitrogen	-196	-203 to -160
Ammonia	-33	-60 to 100
Acetone	57	0 to 120
Methanol	64	10 to 130
Flutec PP2	76	10 to 160
Ethanol	78	0 to 130
Water	100	30 to 200
Toluene	110	50 to 200
Mercury	361	250 to 650
Sodium	892	600 to 1200
Lithium	1340	1000 to 1800
Silver	2212	1800 to 2300

For the proper working fluid selection, the Clausius-Clayperon relation could be applied.

$$\left(\frac{dP}{dT}\right)_{sat} = \frac{i_{lv}}{T_{sat} v_{lv}} \quad \text{....[25]}$$

Where, high values for the magnitude of the derivative $(dP/dT)_{sat}$ (slope) must be achieved. This represents that a small change in the saturation temperature will result in a large influence in the saturation pressure, which will directly affect the pumping forces of the PHP during its operation. Other important parameters should also be evaluated, such as: Latent heat of vaporization (i_{iv}): high values of i_{lv} desirable and important regarding the Clausius- Clayperon relation, which can reflect little temperature drop driving force. On the other hand, this parameter should present a reduced value in order to result in faster bubble generation and collapse.

C. Working fluid properties

Work done by [12-13] suggests that the working fluid employed for oscillating heat pipes should have the following properties:

- High value of $(dP/dT)_{sat}$: It ensures that if there a small change in temperature difference, there will be a large change in saturated pressure inside the bubbles which can affect the bubble pumping action i.e. it can change heat transfer performance of OHP.
- Dynamic viscosity should be small so that it will generate lower shear stress.
- Latent heat of working fluid must be low so that there will quick bubble generation and collapse, It also reveals that sensible heat is the predominant heat transfer mode.
- High specific heat can compliment low latent heat of working fluid.
- Low surface tension may create additional pressure drop.

Working fluid selection directly related to working fluid properties. The properties of working fluid affects heat transfer rate of OHP. Along with these properties of working fluid, compatibility of working fluid with the heat pipe tube material is also very important. If working fluid is not compatible with the tube material then it can cause various adverse effects on the performance of OHP. Compatibly of some working fluids with different tube materials are given as:

TABLE II – COMPATIBILITY OF WORKING FLUID WITH DIFFERENT TUBE MATERIALS

Tube Material	Working fluid		
	Water	Acetone	Ammonia
Copper	RU	RU	RU
Aluminum	GNT	RL	RU
Stainless steel	GNT	MC	RU
Nickel	MC	MC	RU

Where, RU- recommended by past successful usage; RL-recommended by literature; MC- may compatible GNT- generation of gas all temperatures. [13]

Wallin [5] presented a review on selection of working fluid for heat pipe. He graphically explained various operational parameters on the basis of which proper working fluid can be selected for specific condition. This graph will change for different operational conditions.

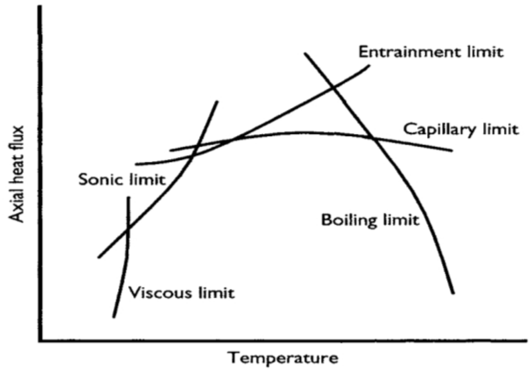

Fig.4. Operational limits of working fluid for OHP [5]

He concluded that, as water has better capillary limit than acetone and methanol thus water can give best performance as compared to acetone and methanol.

D. Filling ratio of Working fluid

Filling ratio of working fluid is the ratio of volume of working fluid charged inside the tube to the total volume of OHP tubes. If the filling ratio is too low, there will not be enough liquid slugs in the evaporator region to start oscillation of fluid and evaporator may dry out. If the filling ratio is too high, there will not be enough vapor bubbles to pump the liquid and heat pipe may act as a single phase thermosyphon. Thus, filling ratio in OHP must be selected carefully. In general, filling ratio of working fluid between 20%-80% is preferred for designing various types of OHP.

Wilson et al. [14] visualized and investigated four OHP to observe fluid flow of vapor bubbles and liquid slug in an OHP and its effect on the temperature distribution and heat transfer performance in an OHP. They used open end and closed end OHP with acetone and water as working fluid. They found that both the working fluid in closed loop OHP has reduced movement in the connecting turns. They found same flow pattern in closed loop and open loop OHP with water as a working fluid. They concluded that, to enhance the performance of OHP, flow in connecting turns must be improve.

E. Number of turns of oscillating heat pipe

Number of turns of pulsating heat pipe tubes can affect thermal conductivity of OHP and it can also minimize the effect of gravitational force. If the numbers of turns are more, less heat will be taken by each turn of tube and there will be either vapor bubbles or liquid slug in the tubes. The heating to these tubes creates pressure difference which is the basic working principle of OHP. If the numbers of tubes are fewer then OHP cannot operate in all orientation but if numbers of tubes are more in numbers then it can operate in all the orientations.

The effects of internal diameter, gravity, working fluid and number of turns on the thermal performance of oscillating heat pipe were investigated by Charoensawan et al. [15]. They found that, gravity certainly have affect on the performance of OHP also there must some critical number of turn to bridge gap between vertical and horizontal orientations.

F. Evaporator and Condenser section

These parameters have greater influence on the performance of OHP and can change the flow patterns within heat pipe. If evaporator is not getting enough heat fluxes at the onset, then oscillating motion of working fluid will not start and if condenser is not dissipating enough heat then it will reduce the heat transfer from the OHP.

A fluctuation in heating and cooling section temperature and its effect on the performance of oscillating heat pipe was studied by Kim et al. [16]; they applied periodic fluctuations and random noises to the temperatures of the heating and the cooling sections. They investigated Effects of amplitude and frequency of the periodic component and some standard fluctuation of the random components on the heating and cooling sections. They found that, the frequency of the liquid slug oscillation decreases with increasing amplitude and frequency of the periodic fluctuation of the wall temperature. However, the change of different standard deviations did not have any effect on the performance of the PHP.

G. Configuration and orientation of tubes

Configuration of OHP tubes can have closed end or open end. Closed end oscillating heat pipe gives better performance, as circulation causes increase in velocity of working fluid and sensible heat. OHP can be inclined, horizontal or vertical. Inclination of tubes may or may not have effect on the performance of OHP but, experimental study shows that, vertical OHP can run with fewer turns also while horizontal OHP required more number of turns to work properly. Here bottom heating OHP consider as a vertical and horizontal heating mode is assume to be horizontal OHP.

Tung and Torii [17] designed an oscillating heat pipe and investigated its heat transfer performance and effect of inclinations. They found that heat transfer performance of the heat pipe in the case of 100% of fill charge ratio is higher than that of 30% of fill charge ratio also The effective thermal conductivity of this heat pipe with the conditions of experiment and in the case of 100% of fill charge ratio was 18958 W/mK, which was much higher than that of copper 401W/mK 47 times

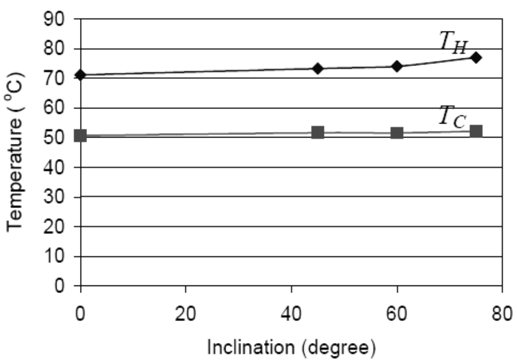

Fig.5. Effect of inclination on temperature of heating and cooling side. [17]

III. WORK ON MATHEMATICAL MODELING

CLOHP have wide range of commercial applications due to which lots of researchers are working on improving its efficiency and developing a suitable mathematical model for understanding its operational characteristics. Work done by some researchers on mathematical modeling on CLPHP is as follows:

Zhang and Faghri [18] proposed models for heat transfer in the evaporator and condenser sections of a PHP with one open end by analyzing thin film evaporation and condensation. They developed relations for liquid film thicknesses in the evaporator and condenser sections. They consider that phase changes over this film drive the oscillatory flow in the PHP; heat transfer in the evaporator is the sum of evaporative heat transfer in the thin liquid film and at the meniscus. They also consider sensible heat transfer to the liquid slug. They found that the overall heat transfer is dominated by the exchange of sensible heat, not by the exchange of latent heat.

Barua et al [19] did Mathematical Modeling of Change of Temperature in a Pulsating Heat Pipe with Multiple Turns. They used two hypothesis, There first hypothesis was that for multiple turns, temperature T decreases exponentially in time τ following, where α and β are parameters to be estimated, $\alpha > 0$ and $\beta < 0$, and C is the controlled temperature beyond which there would be no more cooling possible. They used regression analysis for their study and concluded that, temperature decreases exponentially with respect to time in pulsating heat pipes with multiple turns in the evaporator section. They also established that the instantaneous failure rate $\varphi = -\beta$ increases when the number of turns in the evaporator section increases and that their second hypothesis was that this increment is exponential in nature, with the help of log linear regression equation they validated statistically that the, instantaneous failure rate increases exponentially as the number of turns increases.

Sakulchangsatjatai et al. [20] modeled the heat transfer characteristics equations of a closed-end oscillating heat pipe (CEOHP) and CLOHP at normal operating condition using the explicit finite element method. They applied mass, momentum and energy equation with some assumptions on individual vapor bubbles and liquid slug. The principles and theories of internal friction flow, basic governing equations and a finite difference scheme were applied to evaluate the heat transfer rate. The predicted heat transfer rate, obtained from the model, was compared to the existing experimental data. The effects of the working fluid, evaporator length and inner diameter on the performance of a CEOHP and a CLOHP were also investigated. They found that, there developed mathematical model for heat transfer is reliable and valid.

Shafii et al. [21] also developed analytical models for both unlooped and PHP with multiple liquid slugs and vapor plugs. They solved the governing equations using an explicit finite difference scheme to predict the behavior of vapor plugs and liquid slugs. They found that, gravity does not have significant effect on the performance of unlooped PHPs with top heat mode, Heat transfer in both looped and unlooped PHPs is due mainly to the exchange of sensible heat, role of evaporation and condensation on the performance of the PHPs is mainly due to the oscillation of liquid slugs and with increasing the diameter of the PHP both looped and unlooped, the total average heat transfer increases.

A transient model to predict the thermal and hydrodynamic behavior of a standard loop heat pipe was developed by Launay et al [22]. The model of the loop has been divided into subsystems, for which transient mass, energy, or momentum conservation laws have been developed they found that, there model have ability to accurately predict the frequencies , amplitudes and affect of various design parameters on loop heat pipe.

Though lots of research work is going on understanding the working phenomenon of CLOHP, it is quite difficult to develop mathematical model for CLOHP.

IV. WORK ON SOME UNTRADITIONAL CONCEPTS IN OSCILLATING HEAT PIPE

Along with the study on designing geometrical parameters for CLOHP and modeling of OHP, few researchers also worked on some newly evolved concepts like understanding Taylor bubble flow, effect of acoustic waves on the performance of OHP, effect of nanofluids on OHP performance, use of phase change materials etc.

Khandekar et al [23] worked on understanding oscillating Taylor bubble flows. They suggested that Local hydrodynamic characteristics such as velocities, lengths, shapes and profiles of bubbles and slugs, their dynamic contact angles, thickness of the liquid film that surrounds the bubbles, enhanced mixing/ flow circulation within the liquid slugs and net pressure drop along the flow, etc., are needed to predict local heat transfer and thus, the global thermal performance of OHP. They worked on experimental, analytical and modeling methodologies to calculate global thermal performance of OHP. They concluded that the study of oscillating Taylor bubble flows can be useful for understanding and modeling of OHP.

The ultrasonic sound effect on oscillating motion and heat transfer in an oscillating heat pipe (OHP) is investigated by Zhao et al. [24]. They used piezoelectric ceramics for the generation of ultrasound. After the application of ultrasound on OHP they found that when an ultrasonic sound with a total electric power of 4.48 mW is added, the input power needed to start the oscillating motion can be reduced from 30W to 18W and the effective thermal conductivity is increased from 672.8 W/mK to 1254.7 W/mK.

Wannapakhe et al [25] used silver nanofluid as a working fluid with different concentration ratio, they found that the heat transfer rate of the CLOHP/CV using silver nanofluid as a working fluid was better than that the heat transfer rate when pure water is used because the silver nanofluid increases the heat flux by more than 10%.

V. CONCLUSION

It is obvious from this article that, lots of work is going on CLOHP either for improving its performance and understanding its working principle or for developing and calculating its heat transfer characteristics with the help of mathematical modeling. In this paper, simple operation and working of CLOHP, various design parameters of CLOHP and work done by various researchers on particular design parameter is explained. Along with this some newly evolved concepts are also motioned for future work. It is concluded that OHP have a huge scope of research in various part like improving its geometry, developing accurate and common relation for OHP to calculate its heat transfer capabilities, applying external effects like acoustic waves, understanding Taylor's bubble flow etc.

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