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Heat Recovery & Renewable Energy Applications of Pulsating Heat Pipes Systems: A Literature Review

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***Abstract*-- Recent advancement in the field of computational analysis has ease the complexities involve with the conventional experimental method. With the availability of various design & analysis software it is now become quite convenient to evaluate heat pipe with different arrangement, flow regime & working fluid.**

Our review paper aims to evaluate such heat pipe arrangements as heat recovery & renewable energy unit. A wide variety of heat pipe form conventional tabular heat pipe to micro heat pipes are considered for comparison. Different governing parameters like temperature range, working fluid & number of turns were also taken care. This review paper evaluates that pulsating tube shows promising potential to be consider for further investigation with new geometries & working fluid.

***Keywords*-- Computational Fluid Dynamics for Heat Recovery System, Pulsating Heat Pipes (PHP), Computational Fluid Dynamics (CFD), CFD Simulations, Heat Transfer, Pulsating Heat Pipes geometries & working fluid etc.**

I. INTRODUCTION

To accommodate the transfer of heat from one end to another heat pipes are one of the best choices available today. These heat pipes found application over a wide range of industrial process. Latent heat of vaporization and condensation is the driving force to behind this heat transfer.

Heat pipes are hollow cylindrical pipes containing working fluids at different fill ratio. These pipes may have single or multiple turns. Working fluid inside these tubes under phase change from liquid to vapor (gaining heat from source) & again vapor to liquid (releasing heat to sink). Selection of material of tube depends upon its compatibility of with the working fluid for example copper is selected for water heat pipes and aluminum for ammonia heat pipes.

Tube used is divided into three sections the evaporator section at one end, where heat is absorbed and the fluid is vaporized; a condenser section at the other end, where the vapor is condensed and heat is rejected; and the adiabatic section in between, where the vapor and the liquid phases of the fluid flow in opposite directions.

Typically, a vacuum pump is used to remove the air from the empty heat pipe. The heat pipe is partially filled with a working fluid and then sealed. The working fluid mass is chosen so that the heat pipe contains both vapor and liquid over the operating temperature range.

The working pressure and the working fluid inside the heat pipe rely to a great extent upon the working temperature of the heat pipe. For instance, if a heat pipe with water as a working liquid is intended to eliminate heat at 343 K, the pressure inside the heat pipe must be kept up at 31.2 kPa, which is the boiling pressure of water at this temperature. In spite of the fact that water is an appropriate liquid to use in the moderate temperature range experienced in electronic gear, different liquids are utilized in the assembling of heat lines to permit them to be utilized in cryogenic just as high-temperature applications. The thermal conductivity of a heat pipe encourages heat to be shipped at high productivity over enormous separations. Therefore, heat pipes have been expansively utilized in different energy stockpiling frameworks because of their reasonableness in the part of heat conveyance and aloof activity. The extraordinary technique for activity of heat pipes including stage change materials (PCMs) give a superior productivity design over traditional heat exchangers in significant tasks remembering temperature definition for boiling water storage tanks.

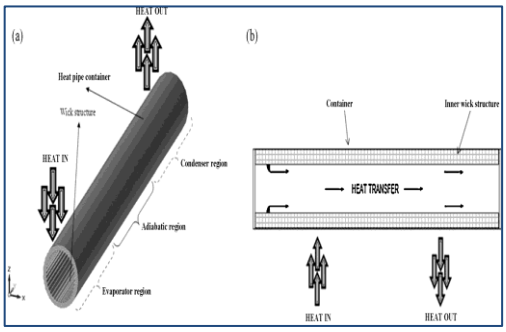

Figure 1.1: Basic working principle associated with a heat pipe (a) isometric view (b) sectional view

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II. LITERATURE REVIEW

The review of associated literature includes the role of heat pipes in heat recovery and energy conservation. The interest for using heat pipes in sustainable power frameworks alongside building heat recuperation, featuring novel ideas and necessities is expanding. A few earthbound applications going from sunlight-based concentrators to warm exchangers utilize heat pipes for higher and more efficient heat move rates. Heat pipes offer particular focal points over other warm exchange mechanical assembly because of its aloof and minimized strategy for activity alongside the different business sizes accessible going from miniature to a broader cluster making the gadget reasonable for most applications requiring a temperature differential.

2.1 Kim, W. and Kim, S.J., (2020) In this examination, the impact of a stream conduct is considered to figure out which sort of a throbbing warmth pipe (PHP) performs better between a shut circle throbbing warmth pipe (CLPHP) and a shut end throbbing warmth pipe (CEPHP). The warm exhibitions of a CLPHP and a CEPHP are tentatively assessed and analyzed. For this, MEMS strategies are utilized to create silicon-based PHPs with ten turns. Pyrex glass covers the carved silicon wafer to imagine the stream conduct inside the PHPs. The PHPs have rectangular channels with a water powered width of 923μm. Ethanol and R-134a are used as the working fluids. Based on the experimental data, a criterion of a diameter ratio ($D_h/D_{h,\ crit}$) is proposed to quantify the effect of a flow behavior on the thermal performance of two types of PHPs. A CEPHP performs better than a CLPHP when $D_h/D_{h,\ crit} < 0.5$. In the case of PHPs filled with ethanol ($D_h/D_{h,\ crit} = 0.29$), the CEPHP shows 33% lower thermal resistance and 20% higher maximum allowable heat flux than the CLPHP. In this case, an oscillation mode is observed inside both types of PHPs. In contrast, a CLPHP performs better than a CEPHP when $D_h/D_{h,\ crit} > 0.5$. In the case of PHPs filled with R-134a ($D_h/D_{h,\ crit} = 0.69$), the CLPHP shows 72% lower thermal resistance and 117% higher maximum allowable heat flux than the CEPHP. For this situation, a flow mode is seen inside the CLPHP, while a swaying mode is seen inside the CEPHP. To clarify why one sort of PHP performs in a way that is better than the other, a normal volumetric part is presented. A normal volumetric portion in the condenser segment is tentatively demonstrated to be a significant supporter of the warm presentation; an expansion of the normal volumetric part in the condenser segment prompts an improvement of the warm exhibition because of upgraded idle warmth move in the condenser area.

2.2 Li, Q., Wang, C., Wang, Y., Wang, Z., Li, H. and Lian, C., (2020) In this paper, a mathematical model of the Pulsating Heat Pipe (PHP) is set up, in view of the two-stage stream hypothesis and the Volume of Fluid (VOF) technique in Computational Fluid Dynamics (CFD). Under the condition that the structure, fluid Filling Rate (FR) and warming intensity of the PHP stay unaltered, the impact of the length and the convective warmth move coefficient of the adiabatic area on the beginning up execution, heat move execution and hostile to dry-out capacity of the PHP are concentrated by changing the adiabatic segment boundaries. The outcomes show that, with the expansion of the adiabatic segment length, the beginning up season of the PHP becomes more limited, however the warm opposition increments and the counter dry-out capacity is debilitated. At the point when the adiabatic segments assimilate heat from an external perspective, with the expansion of the convective warmth move coefficient, the switch of the beginning up time is generally little, however the warm obstruction increments, and the counter dry-out capacity is debilitated. At the point when the adiabatic segments disseminate warmth to the outside, with the expansion of the convective warmth move coefficient, the switch of the beginning up time is moderately little, yet the warm obstruction diminishes, and the counter dry-out capacity is improved. Nearly, while considering the warmth trade between the adiabatic segments and the climate, lower surrounding temperature is more helpful for improving the counter dry-out capacity of the PHP.

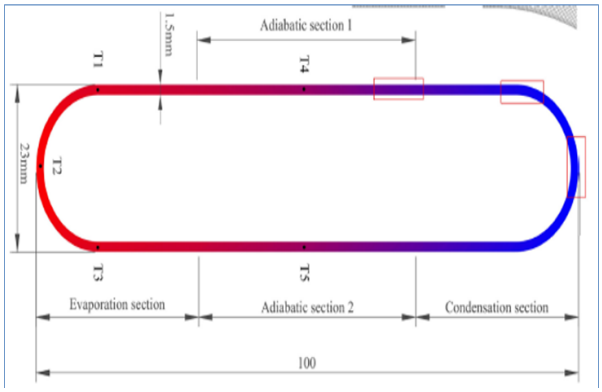

Figure 2.1: Schematic Diagram of CFD model of PHP [2]

2.3 Sedighi E, Amarloo A, Shafii B. (2018) In addition to some approaches, for example, changing the working liquid or number of turns in a level plate pulsating heat pipe (FP-PHP), mathematical changes are additionally engaging for upgrading the heat execution of this sort of heat pipes.

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The fundamental thought of this examination is to build heat move rate by expanding stream dissemination of working liquid. By setting extra branches in the evaporator area, auxiliary air pocket siphons were made which improved the flow of liquid inside the FP-PHP. To examine the effect of these extra branches, two comparative four-turn aluminum FP-PHPs were created. One of them was the regular FP-PHP and the other had four extra branches and is named extra branch FP-PHP (AB-FP-PHP). Warm exhibitions of these two kinds of warmth pipes were researched at various filling proportions (40, 50, 60, and 70%) and heat contributions (from 40 to 200 W). Results indicated that the heat opposition of the AB-FP-PHP was 11–20% below normal contrasted with the heat obstruction of the traditional FP-PHP at various analyzed filling proportions. Furthermore, for heat contributions around 80 W or more, heat exhibitions of the two gadgets were better at 50 % filling proportion. Besides, stream perception demonstrated that extra branches influence the stream system and upgrade stream dissemination in PHPs. Likewise, a mathematical method was directed for the two-stage framework before the exploratory examination to show the job of extra branches in accomplishing a superior course of the working liquid.

2.4 Bhramara, P., (2018) Pulsating Heat pipes (PHPs) are uninvolved warmth move gadgets where the heat move is a lot higher when contrasted with the overall warmth move gadgets, for example, metal balances. The primary explanation behind this is the two-stage wonder occurring inside PHPs with the oscillatory movement of the air pockets. It tends to be utilized in different applications, space satellites, workstations or whatever other spot where you need heat move to be extremely high in a little temperature drop. CFD examination for the PHP is tried with various working liquids double blends like water-methanol and water-ethanol for half fill proportion viz., for various inward measurements of 2mm and 3mm. At evaporator limit, heat transition that is comparable to 10 W to 70 W is provided and the condenser limit is set as warmth motion of reach 1000 W/m2 and in the adiabatic area heat motion is zero. A CFD displaying is done in ANSYS CFX with two turns of PHP. The temperature dissemination across the warmth pipe was estimated. The exhibition boundaries, for example, temperature contrast among evaporator and condenser, warm opposition assessed. CFD results exhibit the warmth move qualities noticing the presentation of PHP is a mathematical methodology. The CFD examination is performed and the yields of the reenactments are plotted in diagrams and shapes.

2.5 E. R Babua (2018) Pulsating heat pipe is a compelling technique for heat move through inactive two stage system. In the current exploration work, trial contemplates were performed on throbbing warmth pipe produced using copper tube having inside and outside distance across of 2 mm and 3 mm individually. The throbbing warmth pipe is accused of CH3)2CO as working liquid with various filling proportions of half, 60%, 70%, 80%, and 90% of its volume. The evaporator zone is electrically warmed by methods for mica warmer with a scope of 10 to 60 Watt and condenser segment is cooled by methods for cooling water at a consistent stream rate. The impact of filling proportion on warm execution of shut circle throbbing warmth pipe was explored. The outcome shows that, the warm opposition diminishes quickly with the expansion in the warming info and it is seen that lower estimation of warm obstruction is gotten at a filling proportion of 60%. Thus CH3)2CO displays better execution at a filling proportion of 60%.

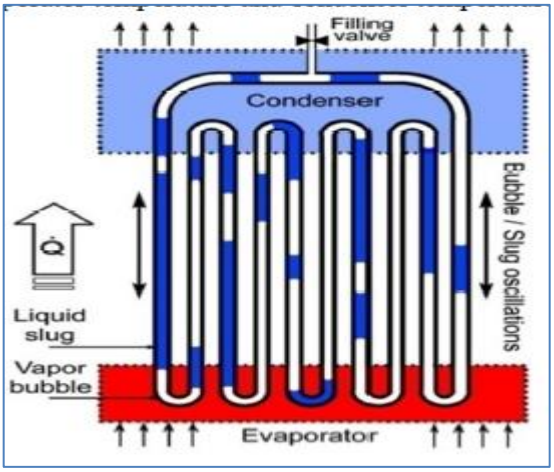

Figure 2.2: Effect of Filling Ratio on Thermal Performance of Closed Loop PHP [5]

2.6 Bae J, Lee SY, Kim SJ (2017) In the current examination, a one-dimensional mathematical model for throbbing warmth pipes (PHPs) is introduced. The equilibrium conditions of mass, force, and energy were addressed for fluid slugs, fume plugs and furthermore for fluid movies, alongside the warmth conduction condition for the cylinder divider. The spatial and transient varieties of the fluid movie thickness were straightforwardly recreated, and the film was permitted to dry out when the nearby thickness diminished to the unpleasantness stature of the cylinder divider.

The mathematical outcomes indicated great concurrence with the trial information, for a vertical PHP as well as for level and slanted PHPs with different various boundaries, including number of turns, working liquid, filling proportion, and working temperature. Moreover, the impact of the elements of the fluid film on stream conduct and warmth move was inspected mathematically. It was affirmed that the wavering movement of the liquid inside an even PHP can't be totally anticipated when the film elements are disregarded. For a vertical PHP, then again, flowing movement was anticipated paying little mind to the film elements, and the job of the film elements on the forecast of warm execution was not critical. The current model is viewed as the first to anticipate the warm execution of an even PHP without presenting any fitting boundaries.

2.7 Giulia Spinato, Navid Borhani, John R (2016) Synchronized warm and visual examination was completed on a solitary turn channel CLPHP utilizing R245fa as the working liquid. The tests were done at filling proportions from 10 to 90% and warm contributions from 2 to 60 W for vertical and slanted directions. An efficient examination of the stream designs, their advances and warm opposition estimations recommends a solid coupling between the two-stage stream design and the framework warm conduct. The impact of the stream elements on the framework warm execution was likewise subjectively and quantitatively surveyed and introduced as 'operational guides'. Nearby time-found the middle value of warmth move coefficients were separated by applying a-best in class unthinking model for the vanishing of lengthened air pockets in the CLPHP miniature channels utilizing the stream estimations. The acquired nearby and found the middle value of results were then used to subjectively survey and record for the warmth move qualities in the CLPHP evaporator U-turn for the distinctive stream designs. In view of this investigation, dainty film dissipation was discovered to be the prevailing warm system, while heat move into the swaying fluid slug and restricted nucleate bubbling were of auxiliary significance.

2.8 Xiaoyu Cui, Ziqian Qiu, Jianhua Weng, Zhihua Li, (2016) In this paper, a trial study is introduced on the warm opposition qualities of shut circle throbbing warmth pipes (CLPHPs) with methanol-based twofold combinations. The working liquids were methanol blended in with deionized water, CH3)2CO and ethanol. The volume blending proportions utilized were 2:1, 4:1 and 7:1, and the warming force went from 10 W to 100 W with filling proportions of 45%, 62%, 70% and 90%.

The outcomes indicated that adding other working liquids to methanol could change the warm obstruction qualities of a PHP. At a low filling proportion (45%), adding water to methanol could forestall dry-out at a high warming force; when ethanol was added to methanol, the warm opposition of the CLPHP was between that with unadulterated methanol and ethanol; when CH3)2CO was added, the warm obstruction of the CLPHP was somewhat lower than that with unadulterated methanol and CH3)2CO. At a high filling proportion (62%, 70%, 90%), the warm obstruction qualities of CLPHPs with methanol-based blends were very little unique in relation to those with unadulterated liquids aside from methanol–water combination where the warm opposition was more prominent than that with unadulterated methanol and unadulterated water. It tends to be derived that the warmth move exhibitions of CLPHPs with methanol-based twofold combinations are identified with the warm actual properties of the working liquids, fume fluid stage change properties, sub-atomic collaborations and the extra protection from mass exchange

2.9 Ebrahimi M, Shafii M, Bijarchi M. (2015) An ideal circulatory stream in level plate shut circle throbbing warmth pipes (FP-CLPHPs), which may enhance electronic warm administration, was accomplished by utilizing the groundbreaking thought of interconnecting channels (ICs) to diminish stream opposition one way and increment the absolute warmth move of liquid. To tentatively explore the impacts of the IC, two aluminum level plate warm spreaders—one with ICs (IC-FP-CLPHP) and one without them—were manufactured. The FP-CLPHPs were accused of ethanol as working liquid with filling proportions of 35%, half, 65%, and 80% by volume. Execution of interconnecting directs in various warmth inputs was investigated, and the outcomes showed the better of throbbing warmth pipes with ICs in examination with heat pipes without them in a wide scope of warmth sources of info and filling proportions. It has been seen that the most productive exhibition of IC-FP-CLPHP happened at the filling proportion of 65%. Stream perception demonstrated that interconnecting channels influence the stream system and improve stream course and warmth move in CLPHPs. In promotion of examining the reasonability of the thought, mathematical strategy has been followed on a solitary stage fluid to show the job of interconnecting diverts in accomplishing single direction stream.

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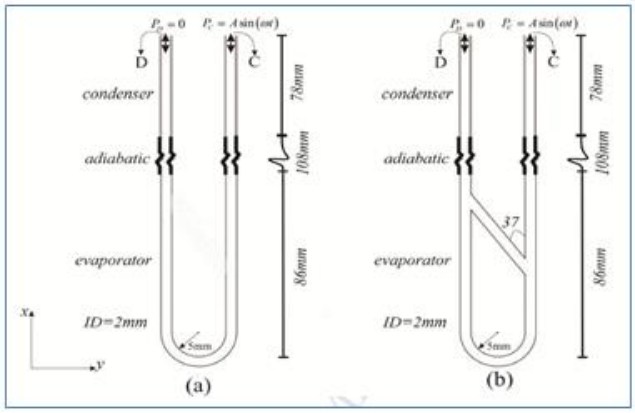

Figure 2.3: Closed-loop pulsating heat pipes with interconnecting channels [9]

2.10 M Lutfor Rahman, Rasel A Sultan1, T Islam, Noor M Hasan, Mohammad Ali (2015) in their test work on shut circle throbbing warmth pipe (CLPHP) made of copper with 2 mm ID and 2.5 mm OD with blade in the condenser area is utilized in the current work to assess the warmth move exhibitions where the vanishing segment is 50 mm, adiabatic segment is 120 mm and buildup segment is 80 mm. The endeavor is to dissect and think about the consequences for the warmth move exhibitions of CLPHP with finned and un-finned condenser segment with tendency point of 00 (vertical), 300 and 450. Methanol is utilized as working liquid with half filling proportion in CLPHP with 8 circles during the experimentation. The test results demonstrate a solid impact of gravity and bottle actual properties of the working liquid on the exhibition of the CLPHP concentrated with various direction and warmth load. The outcomes show the impact of blade utilized in condenser segment, the info heat motion, tendency point direction and physiochemical properties of the working liquid on the warm exhibition of the gadget.

2.11 X.H. Wang, H.C. Zheng, M.Q. Si, X.H. Han, G.M. Chen, (2015) An exploratory examination was led to research the warmth moves execution of a throbbing warmth pipe (PHP) accused of deionized water and surfactant arrangement. The inward measurement of the PHP was 2 mm. The surfactant was sodium stearate, and the convergences of sodium stearate arrangements were 10, 20 and 40 ppm. The exploratory outcomes showed that the warmth move execution of the PHP was extraordinarily affected by the surfactant arrangement, and the impact was subject to the charge proportion and the convergences of the arrangements.

The PHP with 10 ppm sodium stearate arrangement demonstrated preferable execution over the PHP with deionized water inside the entire test range (0–160 W). By and by, the upgrade impact of the warmth move was obvious just when the warmth motion was extremely high for the 40-ppm sodium stearate arrangement. Contrasted and the PHP with deionized water, the warm opposition and the temperature distinction between the dissipation segment and buildup segment could be diminished by 0.13 K/W and 20.8 K when the charge proportion, the warming force and the centralization of the arrangement was 58%, 160 W and 40 ppm, individually.

2.12 Tseng C-Y, Yang K-S, Chien K-H, Jeng M-S, Wang C-C (2014) The current examination inspects the exhibition of shut circle throbbing warmth pipes (CLPHPs) with an ID of 2.4 mm. The impact of uniform and rotating tube distance across on the exhibition is explored. The working liquids incorporate refined water, methanol and HFE-7100. Tests are performed with both flat and vertical game plan. For the flat game plan, when contrasted with uniform plan, the rotating channel configuration can be begun at a somewhat low warmth contribution with a lot more modest warm obstruction. Typically, the warm opposition is diminished with the ascent of warmth input and uncovers a base an incentive at a specific warmth input followed by shows a negligible ascent when the warmth input is expanded further. Both uniform and exchanging configuration uncovers the comparative pattern. For the vertical plan, the warm opposition is a lot of lower than that in even course of action. Unique in relation to that in flat plan, the warm obstruction shows a persistent decay against heat contribution for all the working liquids. For a low info power, CLPHP with HFE-7100 shows the un-warm obstruction. Paradoxically, CLPHP with refined water shows the littlest warm opposition when the information power is expanded more than 60 W.

2.13 Gi Hwan Kwon, Sung Jin Kim (2014) A series of experiments was performed to investigate the effect of a dual-diameter tube on the flow and heat transfer characteristics of single-turn pulsating heat pipes (PHPs). Various types of PHPs were made of glass capillary tubes with various inner diameters. Using thermometry and high-speed photography, experiments to quantitatively observe operational characteristics of the PHPs were performed with varying input power and inclination angle. The results show that circulating flow promoted by a dual-diameter tube reduces thermal resistance of the PHP by as much as 45%.

Based on experimental observations, a simplified model was developed to predict thermal performance of PHPs with circulating flow, and the results based on the model matched well with experimental data to within the error of 15%. The data calculated by the proposed model show that there is an optimum range of diameter difference where the thermal performance enhancement is maximized. The optimal range of the dimensionless diameter difference is found to be 0.25 < DD/Davg < 0.4.

2.14 Hua Han, Xiaoyu Cui, Yue Zhu, Shende Sun (2014) Throbbing heat pipe (PHP) is an inexorably encouraging innovation in the use of numerous modern fields, yet an extensive comprehension of its thermo-hydrodynamic instrument is still a long way from enough. This examination researched the wavering attributes and the warmth move execution of a shut circle PHP (internal distance across = 2 mm) accused of deionized water, methanol, ethanol and CH3)2CO, in order to single out the thermo-actual properties that generally influence the PHP's exhibition under assorted circumstances like distinctive warmth inputs (HI = 5–100 W) or/and diverse filling proportions (FR = 20–95%). It was discovered that at generally low HI, the warmth move relied exceptionally upon whether the wavering fired up or whether the stream was quick whenever began, and had a cozy relationship with dynamic thickness. With the expansion in HI, the impact of dynamic thickness on warmth move dwindled and that of working liquids' energy conveying capacity portrayed by fluid explicit warmth and dormant warmth of vaporization (LHV), particularly the last mentioned (LHV), improved steadily. Higher LHV was ideal for the warmth move at higher HI. At low filling proportion, the working liquids with lower limit, and lower LHV were simpler to dry out. There exists a warmth move limit, which is practically autonomous of the kind of the working liquids, yet generally relies upon the PHP itself (the material and the structure) and the cooling condition. Given certain PHP, it might in light of the fact that, after certain warming force, the equal warm opposition inside the cylinder divider got immaterial contrasted with the external warm obstruction of air convection.

2.15 Mauro Mameli, Vincenzo Manno, Sauro Filippeschi, Marco Marengo (2014) A multi-turn Closed Loop Pulsating Heat Pipe (CLPHP) made of copper (I.D. 1.1 mm, O.D. 2 mm), loaded up with FC-72 is tentatively examined. The examination centers specifically around the consolidated impact of the tendency point (gravity) and the filling proportion at various warmth input levels on the gadget activity strength and the warm exhibitions.

Results show that this CLPHP is a lot of delicate to the gravity head and that the vertical activity is influenced by shaky activity at high warmth input levels. Then again, the CLPHP in the flat position is less effective, however it doesn't go through any presentation drop regarding the warmth input level until the greatest warmth input level is reached. The repeatability investigation, performed for the flat and vertical activity possibly, uncovers that the higher inconsistencies happen when the PHP works in vertical situation toward the beginning up warmth input levels while the insecurity happening at high warmth loads is repeatable and doesn't rely upon the past warmth power input level. This conduct is affirmed at various filling proportions, and the ideal one is 0.5.

2.16 Qu J, Wang Q (2013) Exploratory examinations were performed to research the warm execution of three shut circle swaying heat pipes (CLOHPs) working at the vertical base warmth mode with warming force contribution to a scope of 15–127 W. The tried CLOHPs are completely produced using copper hair like cylinders with inward distances across (IDs) of 1.2, 2, and 2.4 mm. Two working liquids, unadulterated water and ethanol, were utilized with filling proportions of 40%, half, and 60% by volume. The evaporator of each CLOHP was electrically warmed with alterable lengths, while the condenser was fluid cooled with a steady length. Trial results show that the warm execution of the CLOHPs relies upon the formation impacts of working liquid, filling proportion, internal distance across, evaporator length, and warming force input. The 2 mm ID and 2.4 mm ID CLOHPs would be wise to warm execution when accused of water as contrasted and ethanol, while ethanol was favored for the 1.2 mm ID CLOHP. The warm execution of these CLOHPs was upgraded at the moderately lower filling proportions (40% and half). An ideal evaporator length comparing to the least warm obstruction was demonstrated. At last, an exact relationship dependent on 510 arrangements of accessible exploratory information both from the current examination and different writings was proposed to anticipate the warm execution of vertical CLOHPs. The proposed relationship concurred with the test information inside a deviation of around ±40%.

2.17 Kuo-Hsiang Chien, Yur-Tsai Lin, Yi-Rong Chen, Kai-Shing Yang, Chi-Chuan Wang, (2012) this study presents a novel pulsating heat pipe (PHP) concept that is functional even when PHP is with fewer turns and is operated horizontally.

Two heat pipes were made of copper capillary tubes with an overall size of 122 mm × 57 mm × 5.5 mm is investigated, one had 16 parallel square channels having a uniform cross-section of 2 mm × 2 mm (uniform CLPHP), and the other had 16 alternative size of parallel square channels (non-uniform CLPHP; a cross-section 2 mm × 2 mm and a cross-section of 1 mm × 2 mm in alternating sequence). Test results showed that the performance of PHP rises with the inclination but the uniform channel CLPHP is not functional at horizontal configuration whereas the proposed non-uniform design is still functional even at horizontal arrangement. The thermal resistance for uniform PHP is relative insensitive to change of inclination when the inclination angle exceeds certain threshold value.

III. Conclusion

The evolution of computational analysis software provides us a new platform for performing various experiments with different operating parameters.

The use of heat pipes for efficient & passive heat recovery systems has increased rapidly over the past few years.

This review paper considers a wide variety of heat pipes, operating under the different classes of boundary conditions.

The study concludes that pulsating tube with its wide operating temperature range, working fluid & geometry can be considered for further investigation.

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