Int. J. Mech. Eng. & Rob. Res. 2012

International Journal of Mechanical Engineering and Robotics Research

ISSN 2278 – 0149 www.ijmerr.com
Vol. 1, No. 2, July 2012

Review Article

REVIEW OF UNSOLVED MATTER RELATED TO PULSATING HEAT PIPES

Prafull V Shahare[1]* and K K Jain[1]

Corresponding Author:* ***Prafull V Shahare,* ✉ *prafullshahare@gmail.com*

pulsating (or oscillating) heat pipes (PHP or OHP) are new two-phase heat transfer devices that rely on the oscillatory flow of liquid slug and vapor plug in a long miniature tube bent into many turns. The unique feature of PHPs, compared with conventional heat pipes, is that there is no wick structure to return the condensate to the heating section; thus, there is no counter current flow between the liquid and vapor. Significant experimental and theoretical efforts have been made related to PHPs in the last decade. While experimental studies have focused on either visualizing the flow pattern in PHPs or characterizing the heat transfer capability of PHPs, theoretical examinations attempt to analytically and numerically model the fluid dynamics and/or heat transfer associated with the oscillating two-phase flow. The existing experimental and theoretical research, including important features and parameters are discussed. Progresses in flow visualization, heat transfer characteristics, and theoretical modeling are reviewed. Finally, unsolved issues on the mechanism of PHP operation, modeling, and application are discussed.

Keywords: Pulsating heat pipe, Oscillating heat pipe

INTRODUCTION

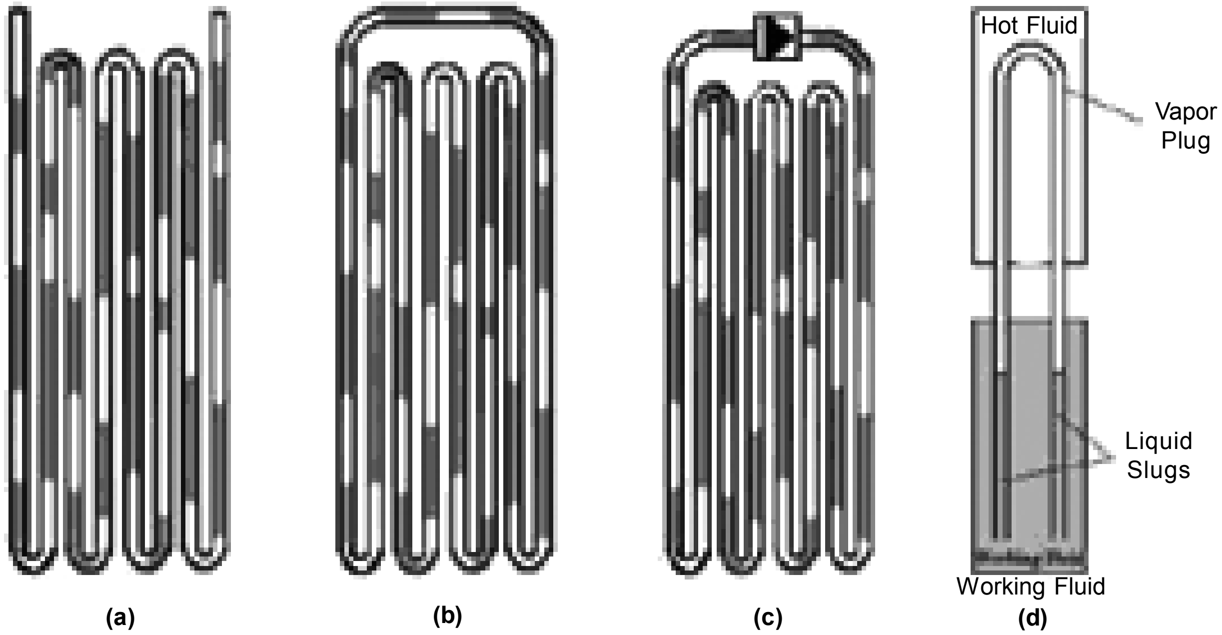
True development of Conventional Heat Pipes (CHP) began in the 1960s; since then, various geometries, working fluids, and wick structures have been proposed (Faghri, 1995). In the last 20 years, new types of heat pipes such as capillary pumped loops and loop heat Pipes—were introduced, seeking to separate the liquid and vapor flows to overcome certain limitations inherent in conventional heat pipes. In the 1990s, Akachi *et al.* (1996) invented a new type of heat pipe known as the pulsating or oscillating heat pipe (PHP or OHP). The most popular applications of PHP are found in electronics cooling because it may be capable of dissipating the high heat fluxes required by next generation electronics. Other proposed applications include using PHPs to preheat air or pump water. A typical PHP is a small meandering tube that is partially filled

---

[1] Mechanical Engineering Department, Shri Ram Institute of Technology, Jabalpur, Madhya Pradesh, India.

with a working fluid, as seen in Figure 1 (Rittidech *et al.*, 2003). The tube is bent back and forth parallel to itself, and the ends of the tube may be connected to one another in a closed loop, or pinched off and welded shut in an open loop (see Figure 1a and 1b). It is generally agreed by researchers that the closed-loop PHP has better heat transfer performance (Gi *et al.*, 1999; and Zhang *et al.*, 2004). Although an addition of a check valve (see Figure 1c) could improve the heat transfer performance of the PHPs by making the working fluid move in a specific direction, it is difficult and expensive to install these valves. There has been some exploration into pulsating heat pipes in which one or both ends are left open without being sealed (see Figure 1d) (Dobson and Harms, 1999; Zhang and Faghri, 2002; and Dobson, 2005). Due to the simplicity of the structure of a PHP, its weight is lower than that of conventional heat pipe, which makes PHP an ideal for space application.

Figure 1: Different PHPs: (a) Closed-End, (b) Closed-Loop, (c) Closed-Loop with Check Valve, and (d) PHP with Open Ends



(a) (b) (c) (d)

PRINCIPLES OF OPERATION

Thermodynamic Principles

Heat addition and rejection and the growth and extinction of vapor bubbles drive the flow in a PHP. Even though the exact features of the thermodynamic cycle are still unknown, Groll and Khandekar (2003) described it in general.

Fluid Dynamic Principles

Fluid flow in a capillary tube consists of liquid slugs and vapor plugs moving in unison. The slugs and plugs initially distribute themselves in the partially filled tube. The liquid slugs are able to completely bridge the tube because surface tension forces overcome gravitational forces. There is a meniscus region on either end of each slug caused by surface tension at the solid/liquid/vapor interface. The slugs are separated by plugs of the working fluid in the vapour phase. The vapor plug is surrounded by a thin liquid film trailing from the slug.

Heat Transfer Principles

As the liquid slugs oscillate, they enter the evaporator section of the PHP. Sensible heat is transferred to the slug as its temperature increases, and when the slug moves back to the condenser end of the PHP, it gives up its heat. Latent heat transfer generates the pressure differential that drives the oscillating flow. The phase change heat transfer takes place in the thin liquid film between the tube wall and a vapor plug and in the meniscus region between the plug and slug, which requires complex analysis.

FLOW PATTERNS

Gi *et al.* (1999) performed the flow visualization experiment on a PHP made from a Teflon tube strung between hot and cold water jackets. The PHP has 20 parallel channels, is filled with R142b, and was videotaped with an 8 mm camera to record the flow. The description of the flow patterns does not adequately explain what was observed, and little information can be derived from the flow visualization portion of the experiment. Cai *et al.* (2002) built a PHP made of quartz and filled with ethanol, and used high-speed video to record the flow pattern. The video showed the propagation of bubbles in the liquid, some of which moved to the cooled section of the PHP and condensed to extinction. Other bubbles grew large enough to become fully developed vapor plugs with a thin liquid film along the wall. Local dryout was observed in the evaporator, but liquid soon returned to the evaporator from the condenser. Xu *et al.* (2005) visualized flow in a closed-loop glass PHP charged with methanol or water by videotaping at 125 frames per second. The fluid circulated during testing but also exhibited a phenomenon called “local flow direction switch,” which involves the flow in some of the channels to go the opposite direction of bulk fluid circulation. For methanol, it was observed that the bubble displacement followed a quasi-sine wave. When water was used, the bubble displacement exhibited a quasi rectangular oscillating motion. This difference was attributed to the difference in latent heats of vaporization. Yu-Hsing *et al.* (2008) reports on the preliminary experimental results of using polydimethylsiloxane (PDMS) to manufacture a visual pulsating heat pipe with use of methanol and ethanol as working fluids. A fix filled ratio (about 60%) and different heating power values (3-8 W) were used to test the thermal performance. The experiment shows that methanol, in a vertical orientation, shows the most efficient results. When the heating power is 3 W, the thermal resistance is more than 4.5 °C/W below the value for ethanol as the working fluid. For a heating power of 4 W, the average temperature decreases to 15 °C in the evaporator. Also, gravity will have an impact on the PHP performance: the vertical orientation is better as compared to the horizontal orientation.

HEAT TRANSFER PERFORMANCES

Cai *et al.* (2006) presented an experimental investigation of heat transfer characteristics of PHPs versus operating temperature. The PHP with 12 turns is made of stainless steel or copper and charged with water at three filling ratios: 40%, 55%, and 70%. They found that minimal temperature difference and fluctuation appear at operating temperatures between 120 and 160 °C. Khandekar *et al.* (2008) were reported that a single loop pulsating heat pipe exhibits multiple operational quasisteady states. Four distinct quasi-steady states has been observed in experimental runs. A temporal scaling analysis is presented to estimate the order of magnitude of the equilibrium frequency of phase change and ensuing oscillations. These order-of-magnitude estimates closely match with the experimentally observed frequencies. The spectral contents of each quasi-steady state are analyzed and it is found that dominant frequencies of flow oscillations are in the range of 0.1 to 3.0 Hz with each quasi-steady state exhibiting a characteristic power spectrum. This provides the necessary velocity scaling estimates, primary information needed for any progress in design of pulsating heat pipes. Yang *et al.* (2008) were presents an experimental study on two flat plate closed loop pulsating heat pipes in a thermal spreader configuration. The influence of various operating parameters, including volumetric filling ratio of the working fluid, input heat flux and operating orientation, on the thermo-hydrodynamic performance, was investigated. Successfuly operation at all orientations with respect to gravity was achieved. From this paper explores the possibility of embedded pulsating heat pipe as an integrated structure or heat spreader, so as to render higher overall thermal conductance to the host substrate. Wang *et al.* (2009) were conducted an experimental investigation to explore the heat-transport capability of Pulsating Heat Pipes (PHP) working with functional thermal fluids (FS-39E microcapsule fluid and Al_2O_3 nano-fluid), by comparing them with pure water. The results show that the heat-transport capability of PHP can be enhanced by using FS-39E microcapsule fluid and Al_2O_3 nanofluid as working fluid under specific conditions. When using vertical bottom heat mode, FS-39E microcapsule fluid is the best working fluid and its best concentration is 0.1 wt%; when using horizontal heat mode, Al_2O_3 nano-fluid is the best working fluid and its best concentration is 0.1 wt%.

MODELING

Shafii *et al.* (2001) developed a theoretical model to simulate the behavior of liquid slugs and vapor plugs in both closed- and open-loop PHPs with two turns (Figure 1). The model solves for the pressure, temperature, plug position, and heat transfer rates. The most significant conclusion is that the majority of the heat transfer (95%) is due to sensible heat, not due to the latent heat of vaporization. Latent heat serves only to drive the oscillating flow Khandekar and Gupta (2007) modeled heat transfer in a radiator plate with PHP embedded using a commercial package FLUENT. However, oscillatory flow and heat transfer of the PHPs were not modeled. The contribution of PHPs on the heat transfer in the radiator plate was considered using an effective thermal conductivity obtained from experiment. Qu *et al.* (2009) were investigated the chaotic behaviour of wall temperature oscillations in a closed-loop pulsating heat pipe using non-linear analyses on temperature data.

Ethanol was selected as the working fluid with different filling ratios. Wall temperature fluctuations were recorded under three different heating power inputs. Various methods, including pseudo-phase-plane trajectories, correlation dimensions (DE), Lyapunov exponents, and recurrence plots, were used to analyze the non-linear dynamics characteristics of temperature oscillation data. Three types of attractors were identified under different power inputs. The increase of the power input augments the correlation dimensions and contributes to the improvement of the thermal performance of the PHP. The average time of the temperature oscillation stability loss, i.e., the inverse of the largest Lyapunov exponent, decreases as the power input increases. Ping-Hei *et al.* (2008) were present mathematical models for a Closed Loop Pulsating Heat Pipe (CLPHP) with multiple liquid slugs and vapor plugs. The model considers the effect of thermal instability in different sections of a CLPHP at different operational conditions. Based on a neural network, an approach of nonlinear autoregressive moving average model with exogenous inputs (NARMAX) can be applied to the thermal instability of CLPHP. A Multi-Input Single-Output (MISO) strategy is adopted in this study to approximate nonlinear behavior of CLPHP. The development of nonlinear identification technique will be helpful to optimize and understand the heat transfer performance of thermal instability in the different designs of CLPHP.

PARAMETERS AFFECTING PHP PERFORMANCE

The diversity of experiments and analyses make them difficult to compare directly. Nonetheless, the following issues require further investigation:

Sensible Heat vs. Latent Heat

Analyses by Shafii *et al.* (2001 and 2002) and Zhang and Faghri (2002) conclude that the majority of the overall heat transfer (greater than 90%) in a PHP is due to the exchange of sensible heat. Also, Groll and Khandekar (2003) showed that for ethanol the ratio of sensible enthalpy to total enthalpy is greater than 98% for the range of charge ratios in which PHPs operate. On the other hand, the role of latent heat becomes important when the flow pattern becomes annular directional flow. Further experimental evidence is needed to reveal the roles of sensible and latent heats under different conditions.

Optimum Charge Ratio

It has been shown that PHPs operate correctly with charge ratios ranging from 20-80%. Also, most researchers agree that for each PHP, some optimal charge ratio exists. Unfortunately, due to the differences in PHP geometry and the properties of various working fluids, the optimum charge ratio can reside anywhere within that range. There are no robust correlations or models that can accurately predict the best charge ratio for a given PHP. The model by Zuo *et al.* (2001) was capable of predicting the optimal charge ratio for their experimental setups within 10%, but the model was extremely simplified, and there is no proof that such a model could be applied to other PHPs.

Gravity/Inclination Angle

Most of the above theoretical investigations include gravity in their calculations, and they have found that its effects are dominated by surface tension forces. However, experiments show that gravity may yet play a significant role.

As the inclination angle is varied from vertical to horizontal, the thermal performance of many PHPs degraded, and some did not operate at all. Other PHPs, often with many turns, were able to perform satisfactorily independent of orientation. If the inner diameter of the PHP is decreased, it may also aid in the PHP's ability to perform at low inclination angles.

Number of Turns

The number of turns in a PHP and the associated flow perturbations in each turn may account for a PHP's ability to function in the horizontal orientation. Experimental results from Rittidech *et al.* (2003), who reported heat flux rather than heat transferred because PHP with evaporators of different sizes were compared, have shown that the heat flux decreases as the number of turns increases. It was proposed that some optimum number of turns might exist that would achieve maximum heat flux.

Losses at Bends

A typical simplifying assumption in many of the mathematical models is to neglect the pressure lost at each bend in the pipe. Because it has been shown experimentally that the number of turns affects a PHP thermal performance and its ability to operate at low inclination angles, it may not be totally valid to treat the PHP as a straight pipe. Perturbations at each bend may not be negligible, but including them in a numerical model greatly increases its complexity.

Onset Heat Flux/Temperature

PHPs are thermally driven non-equilibrium devices, and although they may be very effective heat spreaders, a temperature difference must exist between the evaporator and condenser to maintain their operation. In many cases, there was observed to be some minimum heat flux or differential temperature necessary to initiate oscillating flow. Like the optimum charge ratio, the onset heat flux was different for each experiment. Therefore, parametric investigation is required to fully understand this phenomenon.

Evaporator Dryout

Some investigators claim that PHPs have an advantage over conventional heat pipes because they are not limited by evaporator dryout, but others have observed local dryout, especially at low charge ratios. The oscillating flow should quickly return liquid to the evaporator, but dryout and the associated rise in local wall temperature should still be avoided.

Surface Tension

One of the most important properties of the working fluid used in a PHP is surface tension. Surface tension determines the critical diameter of the PHP, pressure drop along the PHP, and affects the flow within the PHP, but conflicting conclusions have been drawn as to whether higher or lower values of surface tension improve PHP performance. Analysis by Shafii *et al.* (2002) concluded that heat transfer increases as the surface tension of the fluid increases. However, Groll and Khandekar (2003) indicate that a low surface tension is desirable because it reduces the pressure drop necessary to drive the flow.

Capillary Wick

Typical PHPs have no internal capillary wick structure, but Zuo *et al.* (1999 and 2001) were able to achieve very high heat fluxes from a PHP with a sintered copper wick. The wick aids in the distribution of the liquid throughout the PHP and provides more nucleation sites for bubbles to form. However, except for the work by Zuo's group and Holley and Faghri (2005), little investigation has been performed in this area.

Numerical Simulations

The existing theoretical models of PHPs are mainly lumped, one-dimensional, or quasi-one-dimensional, and many unrealistic assumptions are often introduced. In order to significantly advance the understanding of oscillatory flow and heat transfer in PHPs, transient evaporation and condensation of thin film, effect of surface ension, and heat transfer in directional annular flow at high heat flux must be considered. In addition, the modeling of flow pattern transition, transient evaporation/ boiling, and condensation in PHPs with more advanced techniques, such as the Volume Of Fluid (VOF) model (Zhang and Faghri, 2001; and Zhang *et al.*, 2001) to simulate 2-D/3-D two-phase flow and heat transfer, will be very helpful to obtain a more realistic description of transient flow and heat transfer in the PHPs.

Non-Dimensional Parameters

Nearly all current PHP studies rely on the dimensional parameters that were already discussed, which makes the development of general design tools challenging. If PHP performance can be correlated with certain non dimensional parameters, it would provide a better understanding of the complex phenomena governing PHP operation. Rittidech *et al.* (2003) attempted to do so with Kutateladze and Prandtl numbers, but this correlation is limited to open-loop PHPs in the horizontal heat mode over a certain temperature range. Khandekar *et al.* (2003) also developed a semi-empirical model based on the Reynolds, Karman, liquid Prandtl, and Jakob numbers. The resulting function is only valid for charge ratios of 50%. Zhang and Faghri's model (2003) does well to describe the motion of the two-phase flow while taking various parameters such as number of turns and charge ratio into account, but it does not predict heat transfer performance. Obviously, further investigation is required to expand such semi-empirical models.

CONCLUSION

Since their invention, there have been a considerable number of studies relating to pulsating heat pipes, and their ability to transfer heat at very low effective thermal resistances has been proven. The work compiled here significantly increases the understanding of the phenomena and parameters that govern the thermal performance of pulsating heat pipes. Many unsolved issues still exist, but continued exploration should be able to overcome these challenges. The development of comprehensive design tools for the prediction of pulsating heat pipe performance is still lacking.

REFERENCES

1. Akachi H, Polasek F and Stulc P (1996), "Pulsating Heat Pipes", Proc. 5th International Heat Pipe Symposium, pp. 208-217, Melbourne, Australia.
2. Cai Q, Chen C L and Asfia J F (2006), "Operating Characteristic Investigations in Pulsating Heat Pipe", *ASME J. Heat Transfer*, Vol. 128, pp. 1329-1334.
3. Cai Q, Chen R and Chen C L (2002), "An Investigation of Evaporation, Boiling and

Heat Transport Performance in Pulsating Heat Pipe", Proc. ASME International Mechanical Engineering Congress & Exposition, New Orleans, Louisiana, USA.

4. Dobson R T (2005), "An Open Oscillatory Heat Pipe Water Pump", *Applied Thermal Engineering*, Vol. 25, pp. 603-621.
5. Dobson R T and Harms T M (1999), "Lumped Parameter Analysis of Closed and Open Oscillatory Heat Pipes", Proc. 11th International Heat Pipe Conference, pp. 12-16, Tokyo, Japan.
6. Faghri A (1995), "Heat Pipe Science and Technology", *Taylor and Francis*, Bristol, Pennsylvania, USA.
7. Gi K, Sato F and Maezawa S (1999), "Flow Visualization Experiment on Oscillating Heat Pipe", Proc. 11th International Heat Pipe Conference, pp. 149-153, Tokyo, Japan.
8. Groll M and Khandekar S (2003), "Pulsating Heat Pipes: Progress and Prospects", Proc. International Conference on Energy and the Environment, Vol. 1, pp. 723-730, Shanghai, China.
9. Holley B and Faghri A (2005), "Analysis of Pulsating Heat Pipe with Capillary Wick and Varying Channel Diameter", *International Journal of Heat and Mass Transfer*, Vol. 48, pp. 2635-2651.
10. Khandekar S and Gupta A (2007), "Embedded Pulsating Heat Pipe Radiators", Proc. 14th International Heat Pipe Conference, April 22-27, Florianopolis, Brazil.
11. Khandekar S, Charoensawan P, Groll M and Terdtoon P (2003), "Closed Loop Pulsating Heat Pipes, Part B: Visualization and Semi Empirical Modeling", *Applied Thermal Engineering*, Vol. 23, No. 16, pp. 2021-2033.
12. Khandekar S, Gautam A P and Sharma P K (2008), "Multiple Quasi-Steady States in a Closed Loop Pulsating Heat Pipe", *International Journal of thermal Sciences*, Vol. 48, pp. 535-546.
13. Ping-Hei Chen, Ya-Wei Lee and Tien-Li Chang (2008), "Predicting Thermal Instability in a Closed Loop Pulsating Heat Pipe System", *Applied Thermal Engineering*, Vol. 29, pp. 1566-1576.
14. Qu J, Wua H, Cheng P and Wang X (2009), "Non-Linear Analyses of Temperature Oscillations in a Closed-Loop Pulsating Heat Pipe", *International Journal of Heat and Mass Transfer*, Vol. 52, pp. 3481-3489.
15. Rittidech S, Terdtoon P, Murakami M, Kamonpet P and Jompakdee W (2003), "Correlation to Predict Heat Transfer Characteristics of a Closed-End Oscillating Heat Pipe at Normal Operating Condition", *Applied Thermal Engineering*, Vol. 23, pp. 497-510.
16. Shafii M B, Faghri A and Zhang Y (2001), "Thermal Modelling of Unlooped and Looped Pulsating Heat Pipes", *ASME Journal of Heat Transfer*, Vol. 123, pp. 1159-1171.
17. Shafii M B, Faghri A and Zhang Y (2002), "Analysis of Heat Transfer in Unlooped and Looped Pulsating Heat Pipes",

International Journal of Numerical Methods for Heat & Fluid Flow, Vol. 12, No. 5, pp. 585-609.

18. Wang S, Lin Z, Zhang W and Chen J (2009), "Experimental Study on Pulsating Heat Pipe with Functional Thermal Fluids", *International Journal of Heat and Mass Transfer*, Vol. 52, pp. 5276-5279.
19. Xu J L, Li Y X and Wong T N (2005), "High Speed Flow Visualization of a Closed Loop Pulsating Heat Pipe", *International Journal of Heat and Mass Transfer*, Vol. 48, pp. 3338-3351.
20. Yang H, Khandekar S and Groll M (2008), "Performance Characteristics of Pulsating Heat Pipes as Integral Thermal Spreaders", *International Journal of Thermal Sciences*, Vol. 48, pp. 815-824.
21. Yu-Hsing Lin, Shung-Wen Kang and Tsung-Yu Wua (2008), "Fabrication of Polydimethylsiloxane (PDMS) Pulsating Heat Pipe", *Applied Thermal Engineering*, Vol. 29, pp. 573-580.
22. Zhang X M, Xu J L and Zhou Z Q (2004), "Experimental Study of a Pulsating Heat Pipe using FC-72, Ethanol, and Water as Working Fluids", *Experimental Heat Transfer*, Vol. 17, No. 1, pp. 47-67.
23. Zhang Y and Faghri A (2001), "Numerical Simulation of Condensation on a Capillary Grooved Structure", *Numerical Heat Transfer, Part A*, Vol. 39, No. 3, pp. 227-243.
24. Zhang Y and Faghri A (2002), "Heat Transfer in a Pulsating Heat Pipe with Open End", *International Journal of Heat and Mass Transfer*, Vol. 45, pp. 755-764.
25. Zhang Y and Faghri A (2003), "Oscillatory Flowin Pulsating Heat Pipes with Arbitrary Numbers of Turns", *AIAA Journal of Thermophysics and Heat Transfer*, Vol. 17, No. 3, pp. 755-764.
26. Zhang Y, Faghri A and Shafii M B (2001), "Capillary Blocking in Forced Convective Condensation in Horizontal Miniature Channels", *ASME J. Heat Transfer*, Vol. 123, No. 3, pp. 501-511.
27. Zuo Z J, North M T and Ray L (1999), "Combined Pulsating and Capillary Heat Pipe Mechanism for Cooling of High Heat Flux Electronics", Proc. ASME Heat Transfer Device Conference, pp. 2237-2243, Nashville, Tennessee, USA.
28. Zuo Z J, North M T and Wert K L (2001), "High Heat Flux Heat Pipes for Cooling of Electronics", *IEEE Transactions on Components and Packaging Technologies*, Vol. 24, No. 2, pp. 220-225.