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Pulsating Heat Pipes: Thermo-fluidic Characteristics and Comparative Study with Single Phase Thermosyphon

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Abstract

This paper presents an experimental study of Pulsating Heat Pipes (PHP), having potential applications in microelectronics thermal management [1]. The PHP is made of 10 parallel glass tubes (ID: 2 mm, OD: 4.2 mm, 100mm long) forming the adiabatic section, interconnected alternately by copper U-tubes forming part of the water-cooled condenser and the electrically heated evaporator section. Working fluids employed are water and ethanol. Thermal response and operational characteristics of the device are studied under different operating regimes. Internal flow pattern visualization is done and various bubble/slug sizes and patterns are characterized, having an important effect on the performance. Although a PHP is recognized as a two phase heat transfer device, for comparative studies it is operated as a single phase system by filling it 100% with the working fluid. This comparison has resulted in a better understanding of the underlying principles of the PHP operation. The fundamental thermo-fluidic processes occurring in the device operation are explained in detail. It is concluded that significant information is yet to be extracted until a complete theory of PHP operation may be proposed. This paper attempts to bridge the gap.

1. Introduction to pulsating heat pipes

A closed loop pulsating or oscillating heat pipe consists of a metallic tube of capillary dimensions wound in a serpentine manner and joined end to end as shown in Fig. 1. It is first evacuated and then filled partially with a working fluid, which distributes itself naturally in the form of liquid-vapor plugs and slugs inside the capillary tube. One end of this bundle of tubes receives heat transferring it to the other end by a pulsating action of the liquid-vapor system. There may exist an optional adiabatic zone in between. A PHP is essentially a non-equilibrium heat transfer device, performance success of which primarily depends on the continuous maintenance or sustenance of these non-equilibrium conditions within the system. The liquid-vapor slug transport is due to thermally driven pressure pulsations in the respective tubes. There is no external power source required for fluid transport as in the case of DREAM Pipes [1,2].

Consider a case when a PHP is kept throughout isothermal. In this case the liquid and vapor phases in the PHP must exist in equilibrium at a saturation pressure corresponding to the fixed isothermal temperature. In Fig. 2, points A and B represent the thermodynamic state of all the liquid and vapor plugs respectively, irrespective of their sizes and positions. Let the temperature of the entire PHP be quasi-statically increased to a new fixed value. Then the liquid-vapor slug system will slowly come to a new corresponding saturation pressure, point A' and B'. In doing so, there will be some evaporation mass transfer from the liquid until new equilibrium is reached again. A similar phenomenon will be observed if the system is quasi statically cooled to new equilibrium points A" and B" (exaggerated for clarity). In an actual working PHP, there exists a temperature gradient between heater and cooler. Temperature differences also exist amongst the U-bends of the heater and the condenser due to local non-uniform heat transfer rates, always expected in real systems. The net effect of all these temperature gradients is to cause non-equilibrium pressure conditions, which is the primary driving force for thermo-fluidic transport. The heating process in the evaporator continuously tries to push the point A upward on the liquid saturation line. Simultaneously point B is forced to move downwards on the vapor saturation curve. In this way a sustained non-equilibrium state exists between the driving thermal potentials and the natural causality which tries to equalize the internal pressure. Further, inherent perturbations present in real systems cause pressure fluctuations in the heater and condenser. Thus self-sustained thermally driven oscillating flow is obtained.

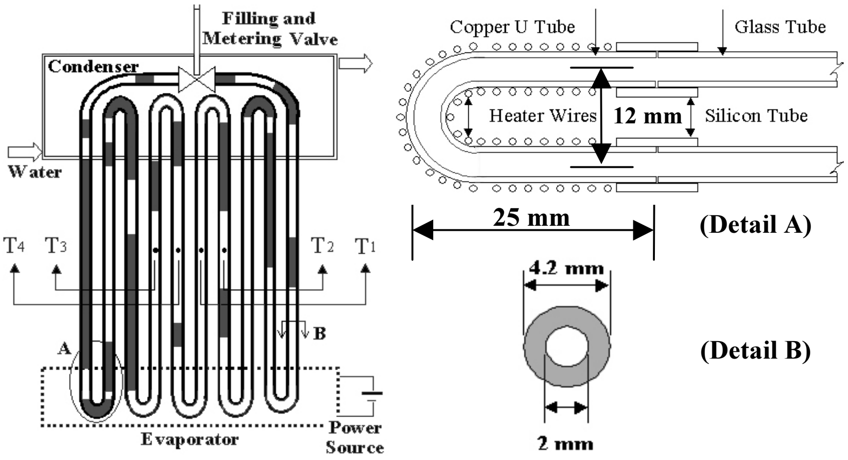


Figure 1: Fabricated PHP structure details

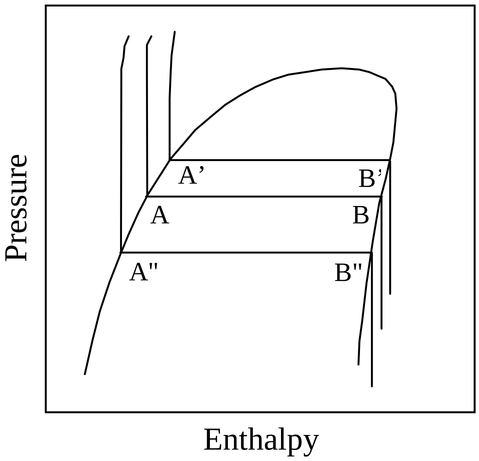


Figure 2: Typical p-h diagram

2. Scope and description of experimental set-up

The setup consisted of a closed-loop pulsating or oscillating heat pipe (PHP), a water-cooling bath, an electrical power input source, a temperature data logger and a PC. The PHP is made of five looped turns, each in the heater zone and the condenser and of 10 parallel glass tubes (ID: 2 mm, OD: 4.2 mm, length 10 cm and inter-tube axial distance 12 mm) forming the adiabatic section. These tubes were interconnected alternately by copper U-turn tubes (ID: 2 mm OD: 3 mm) in condenser and evaporator section with the help of flexible silicon tubes as detailed in Fig.1. Resistance wires, wrapped around the copper U-turns on one side formed the heater section. The U-turns of the other side were routed through a cooling box, supplied by coolant water. The adiabatic section was covered from all sides by transparent (for proper visualization) PE foil at a distance of about 10 mm from the glass tubes so that convective losses were minimized. The U-turn height for heater and cooler was 25 mm and 20 mm respectively. Four thermocouples (protected K type 0.5 mm at locations T1, T2, T3 and T4) were used to measure the adiabatic tube temperatures (Fig. 1), two thermocouples each were placed in the condenser section and on the evaporator U-tubes to measure the average temperatures respectively. The PHP was mounted on a tiltable frame. The evacuation and filling was done via a T-connector and valve integrated inside the condenser, which could be fitted to a vacuum pump and metering arrangement. (for details refer [4])

3. Two extremities of PHP operation

A given PHP has two operational extremities with respect to the filling charge, i.e. 0% filled or an empty device and 100% filled equivalent to a single-phase thermosyphon with no pulsations. It is important to understand the fundamental characteristics and differences of these operational modes to fully appreciate the PHP operation.

It is obvious that at 0% fill charge, a PHP structure with only bare tubes and no working fluid, is a pure conduction mode heat transfer device and obviously has a very high undesirable thermal resistance.

A 100% fully filled PHP is identical in operation to a single-phase thermosyphon. Since there exist no bubbles in the tube, 'pulsating' effect is obviously nonexistent but substantial heat transfer can take place due to liquid circulation in the tubes by thermally induced buoyancy. Referring to Fig. 3, when the 100% filled PHP is working in vertical orientation (inclination angle 90°, heater down) and at 45° inclination angle, the tubes in the adiabatic section are always alternately hot and cold i.e.T1 and T3 are higher than T2 and T4. Moreover, just after switching on the heating, PHP achieves a rapid steady state after the short initial transient. Thereafter, the inter-tube temperature difference of adiabatic section tubes, the alternating hot and cold phenomenon, is continually maintained. This inter-tube temperature difference clearly suggests that there is a thermally driven directed fluid flow pattern in the PHP tubes which was also confirmed by seeding the flow with glass tracer particles. As the inclination angle is changed from vertical to 45°, the adiabatic temperature difference and so also the net thermal resistance slightly increases. After that, when the orientation is changed to horizontal, all adiabatic tube temperatures tend to equalize and the thermal resistance drastically increases to very high undesirable values. Bulk circulation of the fluid stops perpendicular to the gravity vector and heat transfer takes place purely by axial conduction.

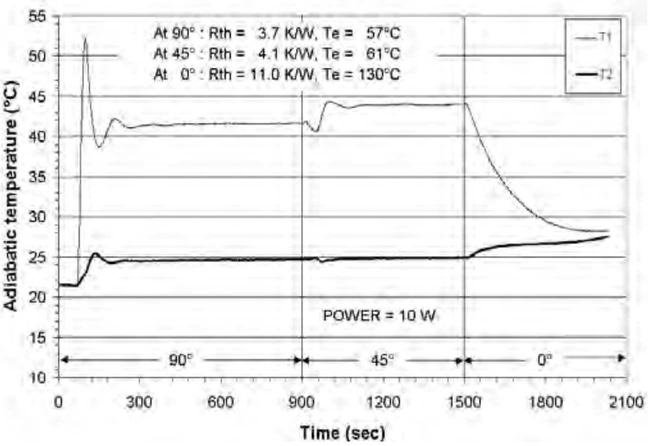


Figure 3: Adjacent tube temperature in adiabatic zone
Fill charge = 100%, Power input = 10 W

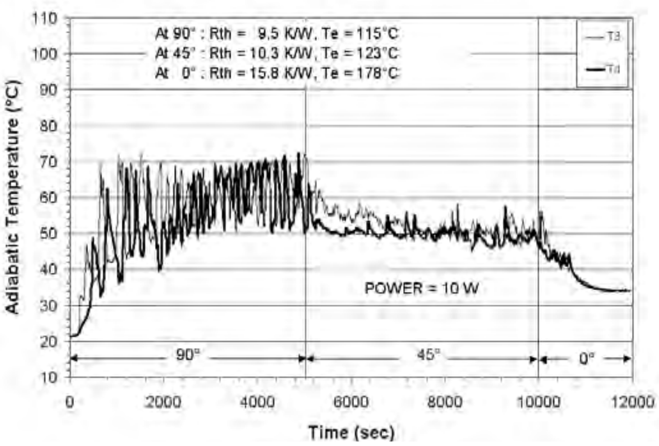


Figure 4: Adjacent tube temperature in adiabatic zone
Fill charge = 50%, Power input = 10 W

4. 'Pulsating' mode of operation

A certain amount of heat transfer is achieved in the single-phase thermosyphon mode of PHP operation. If this heat transfer rate has to be augmented, a logical step is to introduce a two-phase flow regime rather than a single-phase system. For example, a certain performance augmentation is obviously achieved in case of a two-phase thermosyphon because of latent heat transfer. In between the operational extremities (0% and 100% fill charge) although a PHP is a two-phase device, the obvious advantages as achieved in a two-phase thermosyphon, may not be always guaranteed, primarily because of the type of two-phase flow regime. Flow in a PHP is broadly classified as slug flow. Due to capillary dimensions of the PHP tubes, alternating liquid and vapor plugs are always present, in contrast to a two-phase thermosyphon where a clear liquid-vapor interface exists with no slugs. By partially filling the PHP it is expected that (a) there will be a latent heat advantage due to the evaporation and condensation of bubbles, (b) the temperature gradient between heater/cooler coupled with bubble growth and collapse will generate self-sustaining pressure perturbations, as explained earlier, causing liquid plug transport and thus sensible heat transfer. This feature is also expected to make the PHP performance to be orientation independent.

In the pulsating operational mode too there exist three distinct regions:

(a) Nearly 100% fill charge: In this mode there are only very few bubbles present rest being all liquid phase. These bubbles are not sufficient to generate the required perturbations and the overall degree of freedom is very small. The buoyancy induced liquid circulation, which was present in 100% filled PHP, gets hindered due to additional surface tension generated friction of the bubbles. Thus the performance of the devise is seriously hampered and the thermal resistance much higher than for the 100% filled PHP.

(b) Nearly 0% fill charge: In this mode there is very little liquid to form enough distinct slugs and there is a tendency towards dry-out of the evaporator. The operational characteristics are unstable and undesirable.

(c) PHP true working range: Between about 10% to 90% fill charge the PHP operates as a true pulsating device. The exact range will differ for different working fluids, operating parameters and construction. More the bubbles (lower fill charges), more is the degree of freedom but simultaneously there is less liquid mass for sensible heat transfer. Less bubbles (higher fill charges) cause less perturbations and the bubble pumping action is reduced thereby lowering the performance. Thus an optimum fill charge exists.

It is worth mentioning that for equal volumes of coexisting saturated liquid and vapor, the former has substantially more mass than the latter (under normal operating conditions as encountered in PHPs referred in literature). Therefore, comparing on an equal volume basis, net enthalpy carried by the vapor bubble, although inclusive of the latent heat is considerably less than the net sensible enthalpy carried by the liquid plug. So, if proper advantage of bubbles is to be availed then following essential requirements should be met:

1. The vapor bubbles must get a chance to loose their entire latent heat in the condenser thereby collapsing in size. This requires that the residence time of the bubble in the condenser should be sufficient for complete condensation of the vapor bubble.
2. Since each bubble carries a relatively small amount of enthalpy, more and more bubbles should get an opportunity to loose their latent heat in the condenser so that their integrated effect exceeds the frictional disadvantage caused by their presence in the tubes.
3. There should be enough liquid plugs in the system for substantial sensible heat transfer.

5. Results for partially filled PHP

For 50% fill charge although the thermal resistance decreases with increasing the thermal power input, in no case it was found to be better than the single-phase thermosyphon mode of PHP operation (Figs. 5 and 6). For 30% fill charge the combination of bubble dynamics and latent heat advantage coupled with the sensible heat transport of the liquid plugs was sufficient to get the pulsating mode advantage. This occurred at lower input power for ethanol than water. It is to be noted that for a given temperature gradient between the heater and cooler, ethanol has a higher saturation pressure gradient than water. It also suggests that there is a critical input power below which the pulsating effect of the system provide no special advantage.

In general, it is observed that the overall thermal performance is nearly comparable for vertical and 45° inclination. The amplitude of oscillations of adiabatic wall temperatures also decreases when the PHP is turned to 45° from vertical orientation (Fig. 4). At higher loads e.g. 15W, the effect of change in thermal performance in these two cases is less pronounced as also the amplitude of adiabatic temperature variation is comparable in magnitude.

As the PHP is turned to horizontal position, a sharp increase in thermal resistance is observed (Figs. 4, 5 and 6). All the temperatures of the adiabatic section rapidly equalize and no macro movement of bubble plugs is seen. Bubbles only oscillate about a mean position with high frequency and the input power has to be stopped for safety. The comprehensive underlying reasons for such a phenomenon are still not clear but it is believed that:

1. Although surface tension predominates in capillary dimension tubes used in the experiments, the very fact that PHP has stopped operation in horizontal position suggests that gravity force is not insignificant. The effect of gravity may be further reduced by using smaller diameter tubes (at a cost of higher pressure drop). A complete operational characterization with respect to tube diameter is therefore required.

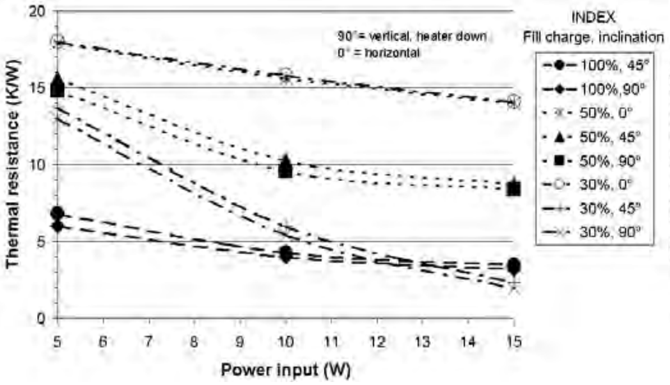


Figure 5: Thermal performance vs inclination angle and fill charge for water

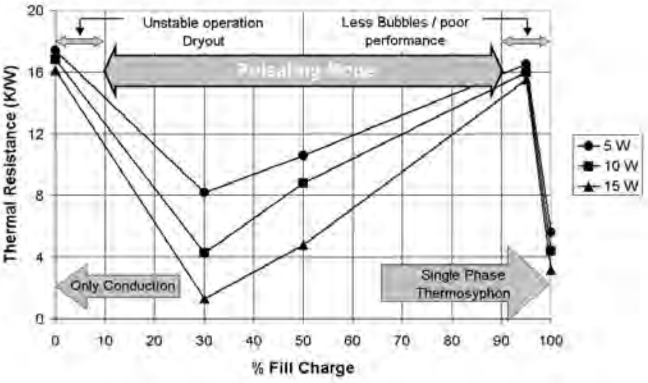


Figure 6: Thermal performance vs fill charge for ethanol, vertical position, heater down.

2. In the present experiments, the number of turns may have been too small for the PHP to operate satisfactorily in all the orientations with respect to the gravity vector. The dependence of PHP performance on increasing the number of turns is attributed to the fact that the overall degree of freedom is increased. A higher number of turns are instrumental for generation of more pressure imbalance chambers within the system. This enhanced instability is expected to make the device work in the horizontal orientation, without buoyancy assisting the pulsations.

6. Bubble patterns observed in PHPs

Bubble pattern recognition, characterization and issues like formation of thin liquid film around the vapor bubbles will provide important direction to mathematical modeling of PHPs [3]. With this view, visualization of the setup was carried out with high-speed video camera. Following important aspects were recorded:

6.1 Bubble size

- Frequently it is observed that, as the liquid slugs pass the heater U-bends, a small amount of liquid is always left behind. Boiling phenomenon qualitatively comparable to nucleate pool boiling within this small amount of entrapped liquid is observed, producing bubbles smaller than the tube diameter (Fig. 7(a)).
- Bubbles whose size is nearly equal the tube diameter, the difference being attributed to the liquid thin film between the bubble and the tube, are more predominantly produced.
- Bubble length may or may not be comparable to the overall length of the PHP.

6.2 Bubble contact angle

- Depending on the physical properties of the working fluid and the tube material, the leading and lagging contact angles of the vapour liquid interface may be different as is predominantly seen in water compared to ethanol. This effect has a significant contribution towards the overall frictional resistance of the flow [4].

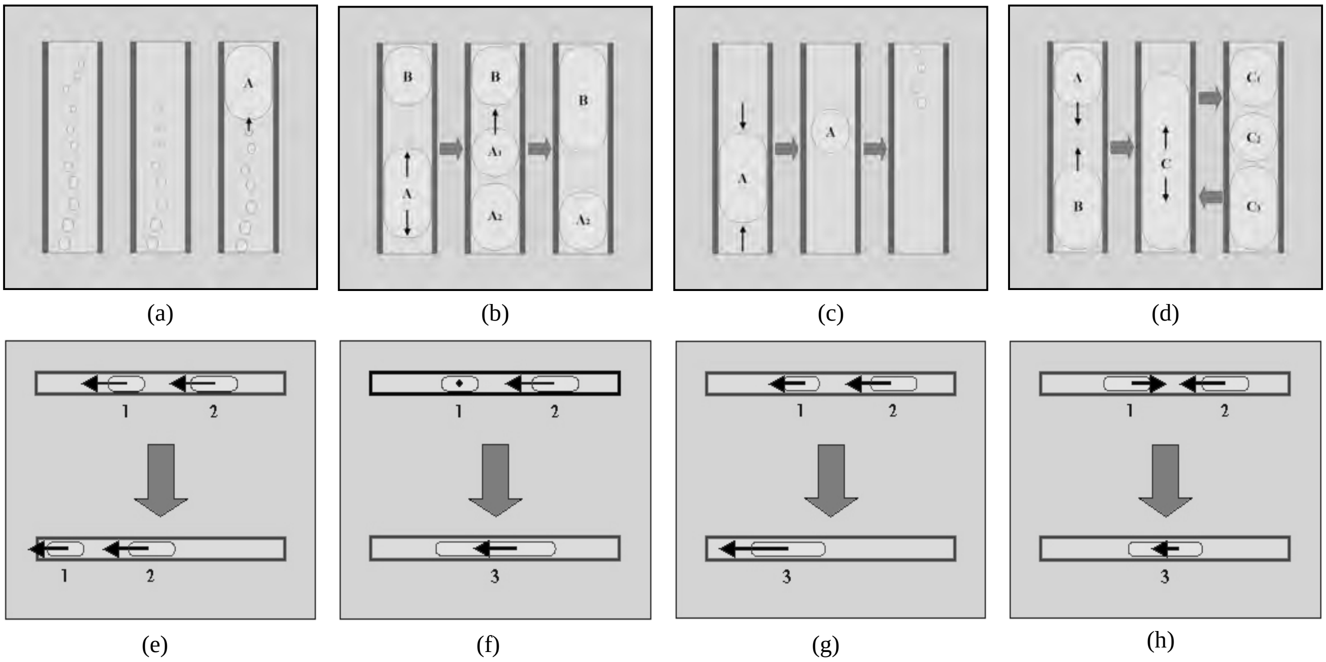
6.3 Bubble merging and breaking patterns

- Small bubbles, produced as a result of nucleate pool boiling in the evaporator section, rise in the adiabatic section of the tubes. Depending on the bubble rise velocity, relative movement of the bulk fluid, geometry of the heat pipe and local heat transfer characteristics these bubbles may reach the condenser section with reduced sizes or may completely collapse due to condensation while in transit. If a larger bubble is encountered on the way, these smaller bubbles usually merge with it as shown in Fig. 7(a).
- A part of an expanding bubble breaks away from it and travels further to merge with another bubble encountered in the way as shown in Fig. 7(b).
- A large bubble shrinks due to condensation and may sometimes become smaller than the tube diameter and immediately floats up due to buoyancy as shown in Fig. 7(c).
- Two or more large expanding bubbles usually coalesce to form larger bubbles that in turn may get subdivided again into smaller components as shown in Fig. 7(d).

6.4 Bubble displacement patterns on micro and macro level

- Vapour plugs may oscillate / vibrate with comparatively higher frequency and small amplitude about a mean position. These oscillations may or may not be superimposed by a macro displacement of the bubble.
- Two typical vapour plugs, 1 and 2 travel in the same direction with nearly same velocities taking along the liquid slug which is trapped between them, comparable to piston movement of the bubbles (Fig. 7(e)).
- Vapour plug 1 is nearly stationary and plug 2 expands or alternatively travels with a velocity finally merging with plug 1 to form a bigger plug 3 which continues to travel. It is clearly observed that the vapour plug 2, instead of acting as a ‘piston plug’ pushing the liquid plug completely, travels through the liquid slug thereby displacing in-between liquid which eventually passes through the thin layer around the bubble (Fig. 7(f)).

- Vapour plugs 1 and 2 are both moving in same direction, with simultaneous expansion, and finally merge to form a larger vapour bubble 3 which continues to travel in the same direction (Fig. 7(g)).
- Vapour plugs 1 and 2 are both moving in the opposite direction, with simultaneous expansion, finally merge together to form a larger bubble 3 that continues to travel in the resultant direction (Fig. 7(h)).



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

(e) (f) (g) (h)

Figure 7: Bubble patterns observed in PHP

7. Conclusions

Pulsating Heat Pipe, an apparently simple and promising cooling device, is considerably intriguing for theoretical and experimental investigations alike. Although PHPs are being used in various industrial applications and may prove to be a viable option for future microelectronics thermal management, the physical understanding of the device operation is still at a primary stage. Important insight into the physical phenomenon occurring in a PHP has been gained by this study. Operational characteristics and working regimes have been identified and described in detail. Comparison with a single-phase thermosyphon mode of operation has resulted in deeper understanding of PHP operation. Various types of bubble patterns in the PHP tubes have been identified and categorized. These bubble patterns have an important effect on the overall system dynamics and so on the thermal performance. This research bridges the gap in the present stare of understanding of the PHP and opens the way for a detailed parametric study.

8. Acknowledgements

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9. References

1. H. Akachi, F. Polášek and P. Štulc, Pulsating Heat Pipes, Proc. 5th International Heat Pipe Symposium, Melbourne, Australia, pp. 208-217, 1996.
2. M. Hosoda, S. Nishio, R. Shirakashi, Study of Meandering Closed-Loop Heat-Transport Device (Vapor-Plug Propagation Phenomena), JSME International Journal (B), Vol. 42/4, pp. 737-744, 1999.
3. S. Khandekar, M. Schneider and M. Groll, Mathematical Modeling of Pulsating Heat Pipes: State of the Art and Future Challenges, Proc. 5th ASME / ISHMT Int. Heat and Mass Transfer Conference, Calcutta, India, 2002.
4. S. Khandekar, M. Schneider, P. Schäfer, R. Kulenovic and M. Groll, Visualization of Thermofluiddynamic Phenomena in Flat Plate Closed Loop Pulsating Heat Pipe, Proc. 6th Int. Heat Pipe Symposium, Chiang Mai, Thailand, 2000.