Effect of Dimensionless Number on Thermal Performance of Closed Loop Pulsating Heat Pipe: A Review

Roshan D. Bhagat[1], K.M.Watt[2]

[1]Student M.E.Thermal Engineering, Prof. Ram Meghe Institute of Technology & Research Badnera-Amravati
Sant Gadge Baba Amravati University

[2]Professor, Department of Mechanical Engineering, Professsor Ram Meghe Institute of Technology & Research Badnera-Amravati,
Sant Gadge Baba Amravati University

Abstract: ***The objectives of this paper is to study effects of dimensionless numbers on thermal performance of the closed-loop pulsating heat pipe and to establish a correlation to predict the thermal performance of the closed loop pulsating heat pipe the heat pipes are made of long copper capillary tubes. Both ends were connected together to form a loop. Acetone, ethanol, methanol can be used as working fluids with constant filling ratio of 30 to 70 % by total volume. Thermal performance of closed loop pulsating heat pipe represented by Kutateladze number (Ku) and it depends on Prandtl number of liquid working fluid (Prl), Karman number (Ka), Bond number (Bo), Jacob number (Ja), and Aspect ratio (Le/Di). Moreover, thermal performance can be successfully established by analyzing all dimensionless numbers that have effect on the thermal performance of the closed loop pulsating heat pipe.***

Keywords: closed-loop pulsating heat pipe, working fluid, thermal performance, dimensionless parameter

1. Introduction

The closed loop pulsating heat pipe is a heat exchanger with very high thermal conductivity it was firstly invented by akachi [1]. The closed loop pulsating heat pipe is made of copper capillary tube with internal diameter not to exceed the critical value [2]. The copper tube is bent into number of turns both the ends of tube connected together to form a closed loop. The tube is evacuated and consequently filled with a working fluid partially to its volume. Since the inner diameter of the tube is very small and then meets capillary scale, the inside working fluids forms into slugs of liquid alternating with the vapour plug along the entire length of the tube.

When one end of the closed loop pulsating heat pipe called evaporator section is subjected to heat or high temperature the working fluid which is in slug form will evaporates and expands and moves through no heat transferring length of copper tube called adiabatic section towards the cooler section called as condenser section. The vapour plug will condense and collapsed and release the heat into environment. Therefore the vapour plug evaporating in the evaporator section will consequently flow to replace the vapour plug collapsing in the condenser section due to this mechanism the working fluid can circulate and continuously transfer heat in the cycle.

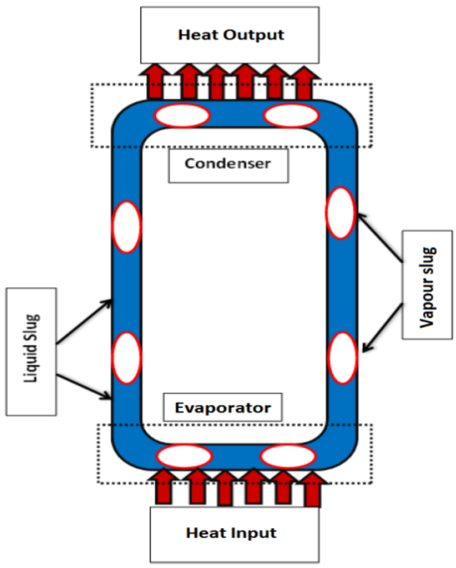

Figure 1: Schematic diagram of closed loop pulsating heat pipe

it can be seen from the above mention that working fluid is important factor which significantly influence the thermal performance of closed loop pulsating heat pipe since working fluid acts as transferring medium between that source and sink. Thermal performance of the pipe significantly depends on thermodynamic properties of working fluid inside the heat pipe. The thermodynamic properties involving two phase flow heat transfer consist of latent heat, specific heat capacity, viscosity, surface tension etc.

However individual working fluid type has different quantity in each property. Identification on working fluid type by only one thermodynamic property cannot be done successfully. It can be found from the literature studies that effect of working fluid on thermal performance of closed loop pulsating heat pipe frequently defined the latent heat as quantitative property to identify the type of working fluid because the heat transfer mechanism inside the heat pipe can be maintained due to evaporation and condensation of working fluid which relates directly to latent heat.

However it is found that when the latent heat of working fluid increased, the thermal performance of closed loop pulsating heat pipe has possibility to change in both ways ie. Increase or decrease. The effect of latent heat on thermal performance of closed loop pulsating heat pipe is not clear as mention above ie it may increase or decrease. This is because there are other thermodynamic property that strongly influence on the heat transfer mechanism and circulating of each working fluid. In addition the geometrical parameter of closed loop pulsating heat pipe also influence on thermal performance depending on the working fluid type. In addition the geometrical properties of closed loop pulsating heat pipe also influence on thermal performance depending on the working fluid type [3].

Therefore there is need to study the group of dimensionless number containing different thermodynamics properties of working fluid and the geometrical parameter of heat pipe and dimensionless number have no unit or no dimension so the correlation is valid for any type of working fluid with wider condition. In order to investigate the effect of dimensionless number on thermal performance of closed loop pulsating heat pipe and to establish the correlation to predict the thermal performance of closed loop pulsating heat pipe. According to working fluid from all corresponding dimensionless number, these become significance and objective of the study. This correlation is very useful for designer, industries and people who are interested in the application of closed loop pulsating heat pipe. Since the correlation is the mathematical tool for selecting working fluid ie suitable for individual application.

Kutateladze number (K_u)

working fluid used in closed loop pulsating heat pipe has different “critical heat flux” the highest thermal performance that heat pipe can transfer before dry-out of liquid working fluid inside the evaporator section will occur, comparison in thermal performance of each working fluid through the heat flux is not reasonable. The working fluid with relatively low critical heat flux generally has lower transferred heat flux than the higher one. In order to normalize the experimental data, Kutateladze number (Ku) was chosen to be a representative of the thermal performance. Ku is a well known dimensionless number involving in heat transfer in the heat pipe.

$$K_u = \frac{\dot{q}_c}{\rho_v h_{fg}\left[\sigma g\left(\frac{\rho_l-\rho_v}{\rho_v{}^2}\right)\right]^{1/4}}$$

$\dot{q}_c$ *heat flux*
g *acceleration due to gravity*
ρ_l *is the liquid density*
ρ_v *vapour density*
h_{fg} *latent heat*
σ *surface tension*

Effect of dimensionless number on the thermal performance

Prandtl number: (P_r)

Prandtl number is the dimensionless number involved with the working fluid properties. It is implied to the ratio between the kinematic viscosity to the thermal diffusion of the working fluid. Prandtl number involve two phase ie Prandtl number of liquid working fluid and Prandtl number of vapour working fluid. From the literature studies it was found that the Prandtl number of vapour working fluid rarely had an effect on thermal performance and hence could be neglected.

$$P_{rl} = \frac{\mu_l C_{pl}}{k_l}$$

C_{pl} *liquid specific heat capacity*
μ_l *liquid viscosity*
k_l *liquid thermal conductivity*

Working fluid with higher liquid specific heat capacity can transfer higher quantity of heat since the working fluid carries the higher quantity of heat from evaporator to release at condenser section comparing within the same working fluid mass. This causes the thermal performance to increase. Moreover increase in liquid viscosity lead flow velocity of working fluid to be retarded therefore time duration that the working fluid receives and release heat in the evaporator and condenser section is longer, respectively and the thermal performance consequently increase.

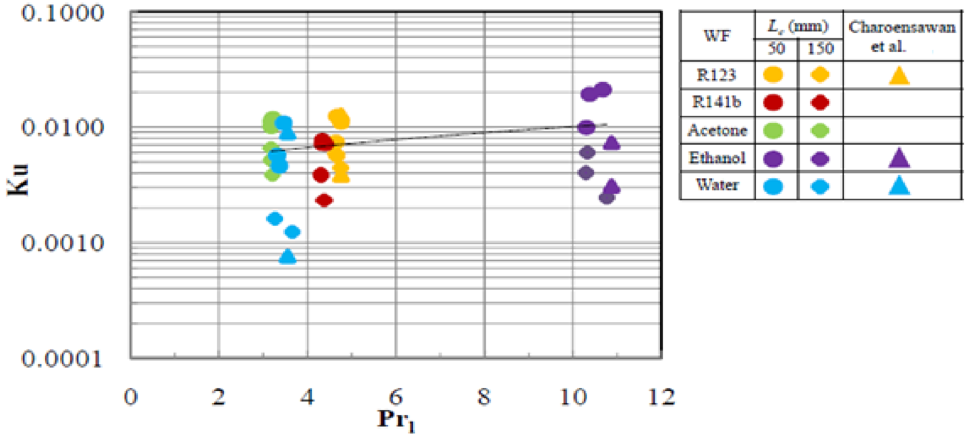

Figure 2: Effect of Prandtl number on thermal performance of closed loop pulsating heat pipe [4]

However when the working fluid with higher thermal conductivity is used, the heat will freely diffuse in the liquid slug with high portion compared with remaining portion of heat that causes evaporation, then the thermal performance decreases.

These are the physical reason to support when Prandtl number for liquid working fluid increases, thermal performance of closed loop pulsating heat pipe increases. from literature studies it was observed that ethanol has highest Prandtl number of liquid working fluid as compared to other this causes the closed loop pulsating heat pipe with ethanol as working fluid to give highest thermal performance.

Effect of Bond Number on Thermal Performance

Bond number is the dimensionless number involved with working fluid properties and geometry of the heat pipe. It is implied to the ratio between buoyancy force and the surface tension force of the working fluid.

$$B_o = \frac{g(\rho_l - \rho_v)}{\sigma_s} \times D_i^{\,2}$$

g acceleration due to gravity
ρ_l density of liquid
ρ_v density of vapour
σ_s surface tension
D_i internal diameter of the tube

It was found from the study that when bond number increases the thermal performance decreases. However the obtained relation is in opposite direction to that of found in some literature study [4].

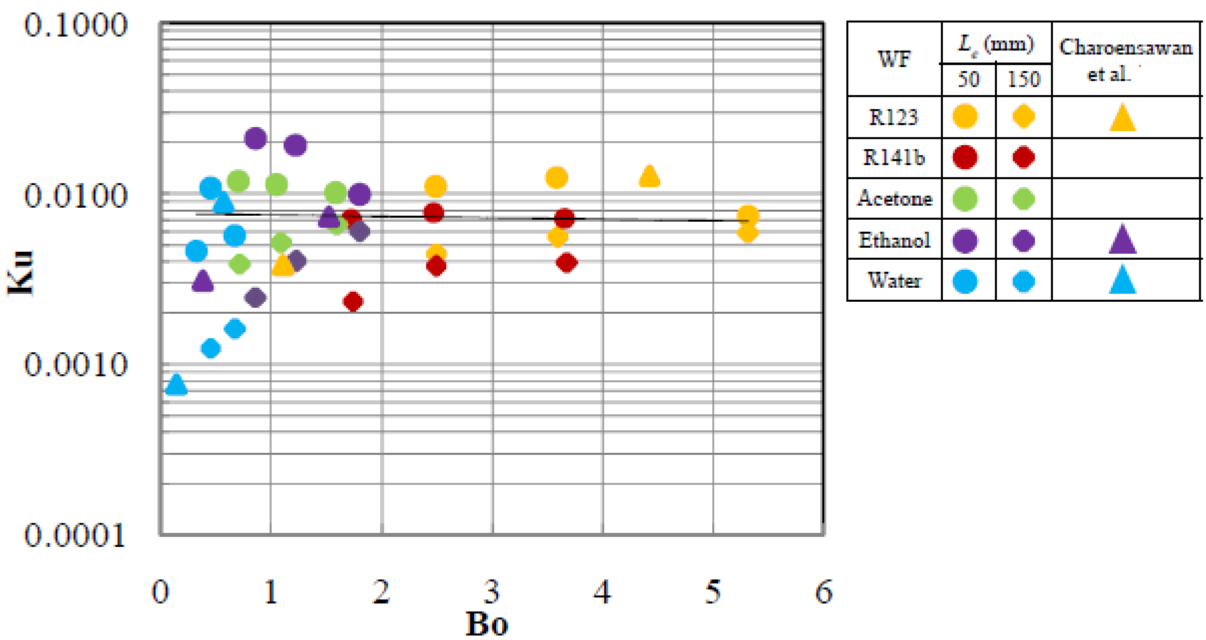

Figure 3: Effect of bond number on thermal performance [4]

This argument occurs according to difference in number of variables parameter such as working fluid type geometry of the heat pipe and also the experimental condition. Nevertheless the physical reason can be theoretically explain to support both tendencies.

Case I: In case the relation between the bond numbers increases and the thermal performance decreases. This is primarily affected from decrease in surface tension appearing in denominator of bond number.

When surface tension decreases the vapour bubble tends to form a smaller bubble instead of long vapour plug since smaller bubble have lower vapour mass than longer bubble. This situation can be implied that heat in the evaporator section transfer out from the tube surface by means of evaporation with lower quantity in case of smaller bubble. This causes the working fluid to transfer heat less continuously and thermal performance consequently lower.

Case II: on the other had another tendency was found from the past study that when bond number increases thermal performance increases. This is the major effect due to buoyancy force when difference between the liquid and vapour density increases it can be implied that vapour plug is obviously lighter than the liquid slug compared in the same volume. This causes the buoyancy force to be higher and vapour plug can flow from evaporator to condenser section which locates at the top of closed loop pulsating heat pipe with shorter time duration.

Moreover an increase in internal diameter of heat pipe promotes the working fluid circulation throughout the heat pipe since the crossectional area of flow passage is wider and frictional force at contact surface between the working fluid and the inside tube wall decreases. The working fluid transfer heat more actively and thermal performance consequently increases. It is mention from the above that the effect of bond number is not clear. Thus one more dimensionless number that has strong influence on thermal performance is possibly existed. Both the thermodynamic properties of working fluid and geometry of heat pipe must involve in the dimensionless number.

Effect of Karman Number on the Thermal Performance ($\boldsymbol{Ka}$)

Karman number is the dimensionless number involved with working fluid properties and geometry of the heat pipe which is similar to B_o. It represents a ratio between driving force and frictional force of working fluid [5].

$$K_a = \frac{\rho_l \times (\Delta P)_{sat}{}^{e-c} \times D_i{}^3}{\mu_l{}^2 \times L_{eff}}$$

ρ_l *density of liquid*

$(\Delta P)_{sat}{}^{e-c}$ *difference of pressure between evaporator and condenser*

D_i *internal diameter of tube*

μ_l *liquid viscosity*

L_{eff} *effective pipe*

$$L_{eff} = 0.5\, L_e + L_a + 0.5 L_c$$

When Karman number increases the thermal performance increases, exponential to ethanol since the thermal performance for ethanol isolates from data. Nevertheless relation between Karman and thermal performance are very well agreed with the result from the past studies.

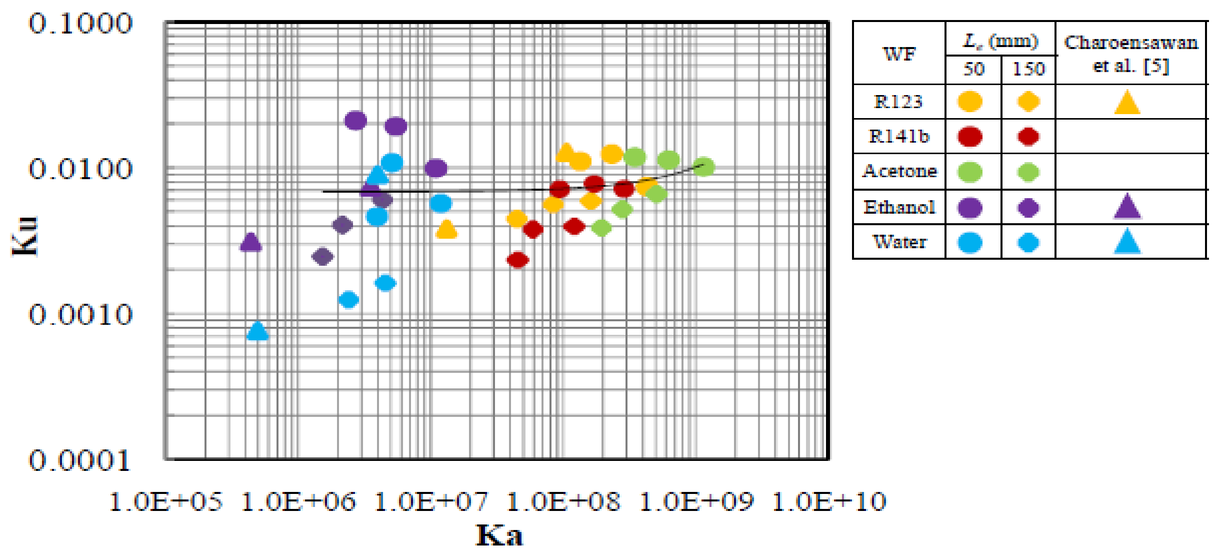

Figure 4: Effect of Karman number on thermal performance

Since the driving force is the main mechanism of working fluid circulation in closed loop pulsating heat pipe the working fluid flows forth and back between the evaporator and condenser section. Therefore when pressure difference increases Karman number increases the driving force increase. This causes the working fluid flow velocity and heat transfer quantity increases.

In addition when internal diameter increases pressure loss along flow passage between the evaporator and condenser decreases. Net pressure difference of closed loop pulsating heat pipe with bigger internal diameter is higher than that of smaller one. Since an increase in internal diameter strongly diminishes the effect of pressure difference when internal diameter increases Karman number increases obviously the thermal performance increases.

On contrary increase in length and liquid viscosity of heat pipe causes a decrease in Karman and thermal performance since the working fluid flow velocity decreases and the flow distance which directly affects to an increase in the pressure loss, increases respectively. These phenomenons originally are major causes of degradation in thermal performance.

Effect of Jacob Number on Thermal Performance ($\boldsymbol{Ja}$)

Jacob number is the dimensionless number involved with working fluid properties. It is implies to be the ratio of heat quantity that a heat pipe can transfer between two different mechanism latent heat and sensible heat. The former mechanism corresponds to the working fluid phase change the latter relates to the working fluid temperature change the Jacob number can be expressed as below

$$J_a = \frac{h_{fg}}{C_{pl}\,(\Delta T)_{sat}{}^{e-c}}$$

h_{fg} *latent heat*

C_{pl} *specific heat of liquid*

$(\Delta T)_{sat}{}^{e-c}$ *saturation temperature difference between evaporator and condenser*

It could be seen that when the Jacob number increases the thermal performance increases in case of closed loop pulsating heat pipe with evaporator section of length 50 mm on the other hand opposite tendency was found in case of closed loop pulsating heat pipe for longer evaporator section of length 150 mm. The relation is very well agreed with relation obtained from past studies.

Working fluid with high ration of latent heat to sensible heat or higher Jacob number causes the closed loop pulsating heat pipe to have higher thermal performance since working fluid transfer great quantity of heat by means of phase change from liquid to vapour in evaporator section relatively to remaining quantity of heat that is transferred by means of temperature change. This situation corresponds to heat transfer mechanism of closed loop pulsating heat pipe thus heat pipe operates near the theoretically optimized ability.

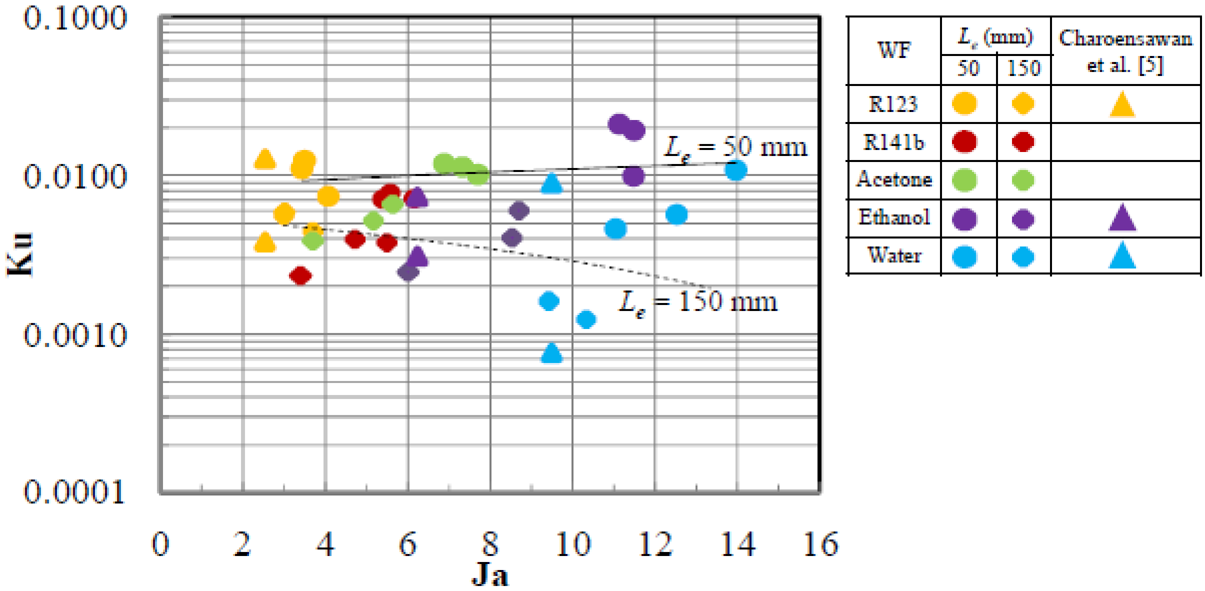

Figure 5: Effect of Jacob number on thermal performance [5]

However when the evaporator section length increases distance that the working fluid has to flow towards the condenser section increases. Frictional force and pressure loss increases. For this reason heat will transfer with uncontinuity. This causes the heat transfer through the closed loop pulsating heat pipe with higher Jacob number not to increase as usual.

This is obvious evidence to support that evaporator section length has significant effect on thermal performance. Therefore another dimensionless number which has influence over Jacob number involves with evaporator section length has to be further investigated [6].

In addition it was found from the past studies that when portion of sensible heat decreases the Jacob number increased the thermal performance decreased. Reason was discussed primarily realize that closed loop pulsating heat pipe transfer heat by means of temperature change mechanism rather than phase change. In recent days actual portion of heat transfer in closed loop pulsating heat pipe according to latent heat and sensible heat is still in black box. Therefore when Jacob number is increased the thermal performance can possibly increases in either direction [7].

Effect of aspect ratio on thermal performance

Aspect ratio is the dimensionless number involved with geometry of heat pipe. It represents ratio between evaporator section length (L_e) and internal diameter (D_i). It could be seen that when the aspect ratio increases thermal performance decreases. This result very well agreed with the result from the past studies. The evaporator section length and internal diameter simultaneously affects to the thermal performance of the heat pipe. Working flow pattern inside the tube depends on evaporator section length.

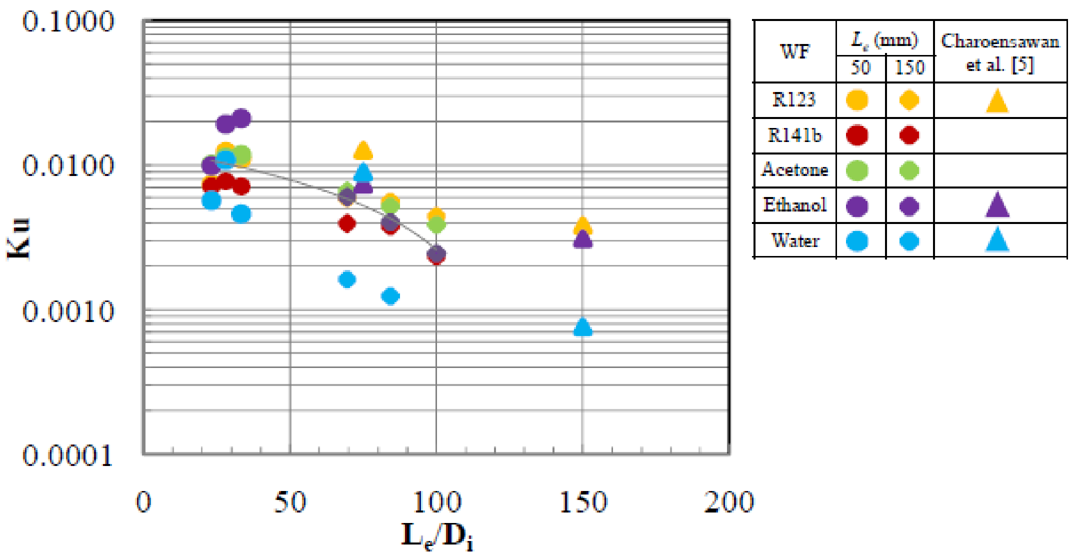

Figure 6: Effect of aspect ratio on thermal performance [5]

The working fluid with slug flow pattern can be observed when the evaporator section length is short i.e. for ex 50mm as in study. Vapour plug in slug flow form in a core of tube surrounding with liquid film. Since the liquid films contacts around the tube wall in the evaporator section, heat input can be transferred to the liquid film directly and evaporation rate consequently increases. This causes the thermal performance to increase.

On contrary working fluid flow pattern in closed loop pulsating heat pipe with longer evaporator section length will change into churn flow in which the vapour shape is not stable liquid working fluid can be entrained as droplet into vapour core. Heat input cannot conduct through vapour core to liquid droplet easily. The thermal performance according to the flow pattern will be low.

In addition it was found that an increase in internal diameter not only causes heat transfer area between the heat pipe and working fluid to increase but also causes the crossectional area of the working fluid flow inside close loop pulsating heat pipe increases. When closed loop pulsating heat pipe has larger internal diameter or wider crossectional are of the flow passage vapour plug evaporating in evaporator section consequently flow towards condenser section more continuously with higher working fluid quantity. The pressure loss of working flow decreases. From this physical reason closed loop pulsating heat pipe can transfer more heat and thermal performance increases. it can be seen from experimental results that geometrics of heat pipe strongly influence on thermal performance of closed loop pulsating heat pipe. The closed loop pulsating heat pipe with low aspect ratio has higher thermal performance.

Approximation to Predict the Thermal Performance

The method of dimensional analysis is used to get the approximate solution for the given problem as all the dimensionless number discussed above can be correlated so as to get more precise thermal performance for closed loop pulsating heat pipe.

$$K_u \, is \, function \, of \, (Pr, Bo, Ja, Ka, Li/Di)$$

$$\mathrm{K_u} = \mathrm{f(Pr, Bo, Ja, Ka, Li/Di)}$$

2. Conclusion

Effects of dimensionless numbers on thermal performance of the closed-loop pulsating heat pipe have been thoroughly investigated. Thermal performance was represented in a term of Kutateladze number (Ku), which is a dimensionless number involving in the heat transfer in heat pipes. It can be concluded that when Prandtl number of liquid working fluid (Prl), and Karman number (Ka) increases, thermal performance increases. On contrary, when Bond number (Bo), Jacob number (Ja), and Aspect ratio (Le/Di) increases, thermal performance decreases.

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