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Effect of Bond Number on Thermophysical Properties of Working Fluid Used in 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]Department of Mechanical Engineering, Prof. Ram Meghe Institute of Technology & Research Badnera-Amravati, Sant Gadge Baba Amravati University

Abstract: ***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. As an important parameter for the proper pulsating heat pipe operation, the critical bubble diameter is directly related to the selected working fluid and can be estimated from the Bond number. The Bond number has strong influence on the thermal performance of closed loop pulsating heat pipe hence there is need to study the effect of Bond number on thermophysical properties of working fluid used in closed loop pulsating heat pipe.***

Keywords: Heat pipe, thermal performance, working fluid.

1. Introduction

The closed-loop pulsating heat pipe (CLPHP) is a small heat transfer device with a very high thermal conductivity. It was invented to meet the requirement for smaller heat transfer devices. It can transfer sufficient heat for heat dissipation applications in modern electronic devices. The Closed loop pulsating heat pipe is made of a long copper capillary tube, bent into an undulating tube and connected at the ends to form a closed-loop with no internal wick structure [1]. Working fluid is partially filled in the tube. The closed loop pulsating heat pipe has a condenser, evaporator section and adiabatic section. As any other two-phase passive thermal control device, heat is acquired from the source through the evaporator section transferring it to the working fluid where the slug/plug pumping action will be generated. The fluid then flows by the adiabatic section towards the condenser section. On a closed loop configuration, the fluid is allowed to circulate and after being condensed, the fluid returns to the evaporator section to complete the loop. The tube is evacuated and consequently partially filled with working fluid. Since an inner diameter of the tube is very small and then meets a capillary scale, the inside working fluid forms into liquid slugs alternating with vapour plugs along the entire length of the tube [2].

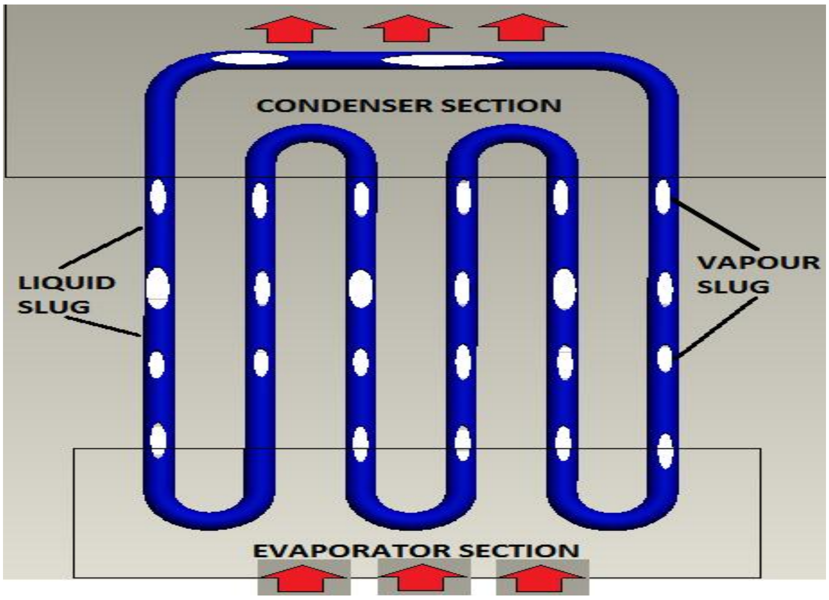

Figure 1: Closed loop pulsating heat pipe (CLPHP).

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 liquid slug form, will evaporate, expand, and move through the no heat transferring zone, or „adiabatic section‟, toward a cooler Section, „condenser section‟ . Then, the vapour plugs will condense, collapse, and release the heat into the 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 a cycle. The structure of the closed loop pulsating heat pipe is as shown in Figure 1.

2. Diameter As Defining Parameter for Operation of Closed Loop Pulsating Heat Pipe

The diameter plays vital role in the selection of the heat pipe because it affects the performance of CLPHP. A large hydraulic diameter results in a lower wall thermal resistance and increases the effective thermal conductivity. The capillary tube inside diameter must be small enough such that: If $d < d_{max}$ surface tension forces dominate and stable liquid plugs are formed. However, if $d > d_{max}$ the surface tension is reduced and the working fluid will stratify by gravity and oscillations will cease. Also the selection of tube material is important; the different type materials have their own coefficient of heat transfer. The pulsating action (plug/slug) is the motion force for the pulsating heat pipe, which is directly influenced by the inner tube diameter. The factors that influence the plug/slug formation in reduced diameters must be observed for this application, such as the correct working fluid selection, surface tension and shear stress effects, etc. Without this pumping action, the device will operate as a solid bar conducting heat from one end to another [14].

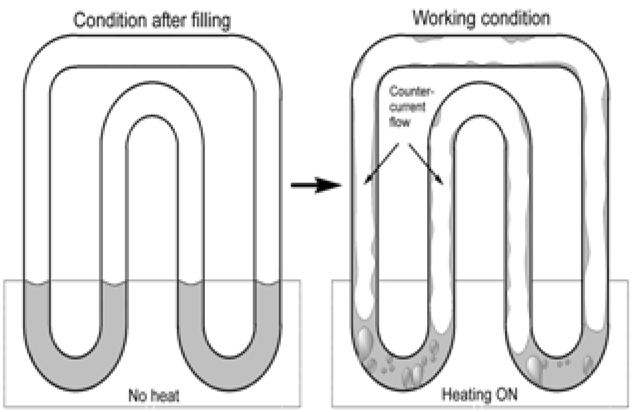

Figure 2: Diameter of CLPHP ($D \gg D_{critical}$) very much greater than critical diameter.

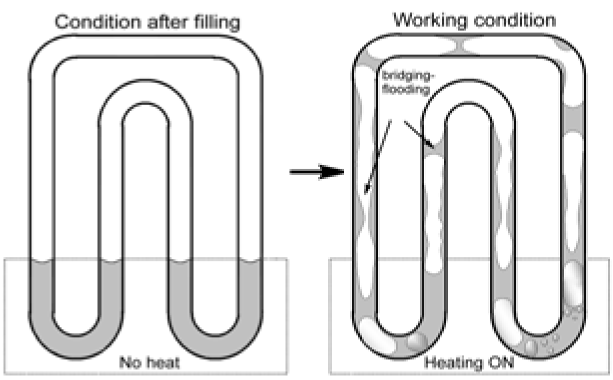

Figure 3: Diameter of CLPHP ($D \geq D_{critical}$) greater than or equal to critical diameter.

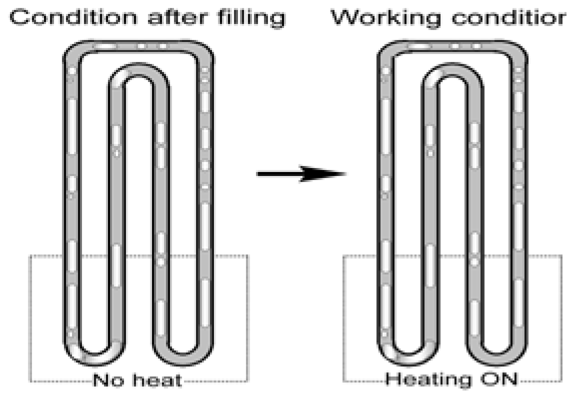

Figure 4: Diameter of CLPHP ($D \leq D_{critical}$) less than or equal to critical diameter.

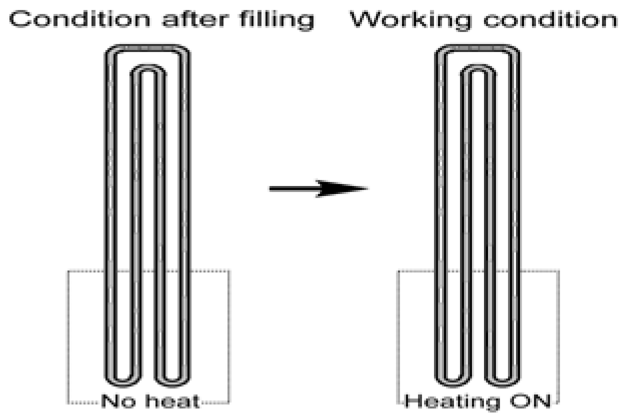

Figure 5: Diameter of CLPHP ($D \ll D_{critical}$) very less than critical diameter.

As an important parameter for the proper pulsating heat pipe operation, the critical bubble diameter is directly related to the selected working fluid and can be estimated from the Bond number as

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

$g -$ acceleration due to gravity

$\rho_l -$ density of liquid

$\rho_v -$ density of vapour

$\sigma_s -$ surface tension

$D_i -$ internal diameter of tube

The Bond number should be less than or equal to 2 this variable should be used as an upper limit for the maximum tube inner diameter, as an important parameter for the vapour plug formation. If the conditions for the vapour plug formation are satisfied, the pulsating heat pipe would present a satisfactory operation [5].

3. 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. 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 [13]. 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 CLPHP 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.

Table 1: Thermophysical properties of Acetone

Acceleration due to Gravity m/s^2	Density of liquid kg/m^3	Density of vapour kg/m^3	Surface tension of liquid $N/m \times 10^2$	Internal diameter m	Bond number	Temperature in^0C
9.81	860	0.03	3.1	0.002	0.010885556	-40
9.81	845	0.1	2.76	0.002	0.012012274	-20
9.81	812	0.26	2.62	0.002	0.012157511	0
9.81	790	0.64	2.37	0.002	0.013069404	20
9.81	768	1.05	2.12	0.002	0.01419581	40
9.81	774	2.37	1.86	0.002	0.016278904	60
9.81	719	4.3	1.62	0.002	0.017311622	80
9.81	689.6	6.94	1.34	0.002	0.01999073	100
9.81	660.3	11.02	1.07	0.002	0.023810979	120
9.81	631.8	18.61	0.81	0.002	0.029705649	140

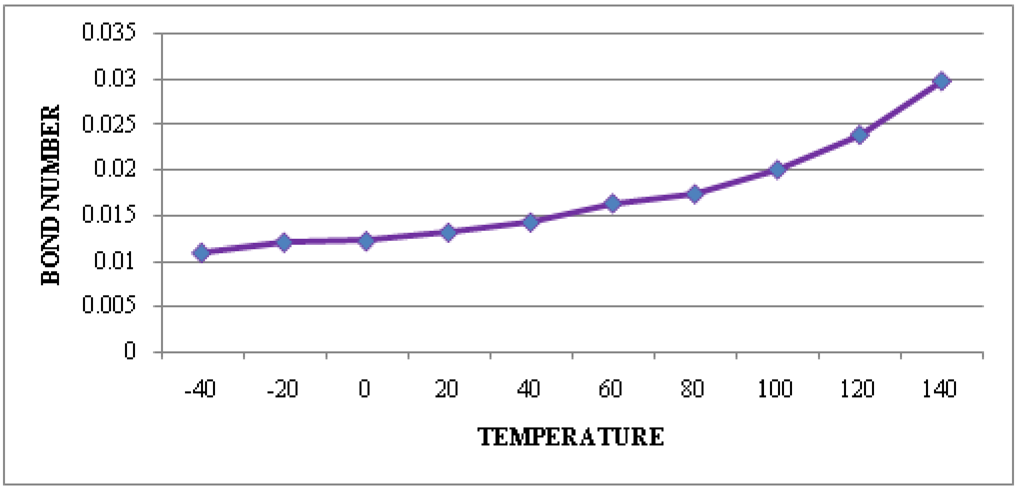

Figure 6: Effect of Bond number on temperature for Acetone

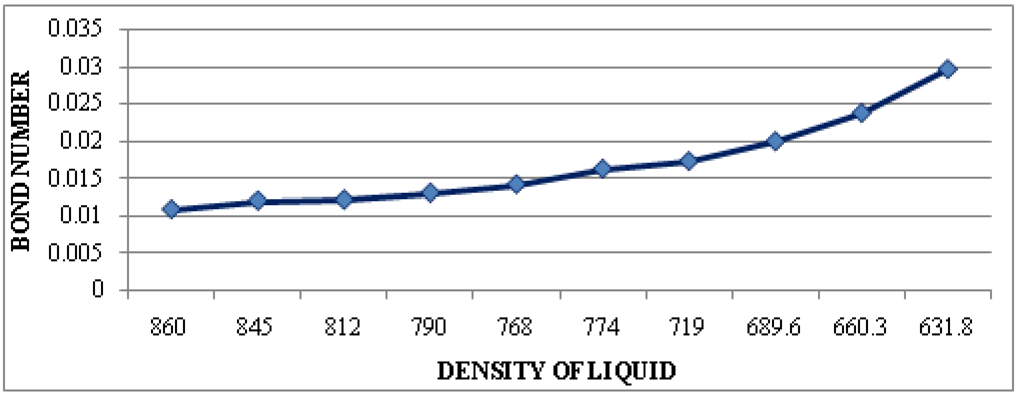

Figure 7: Effect of Bond number on density of liquid for Acetone

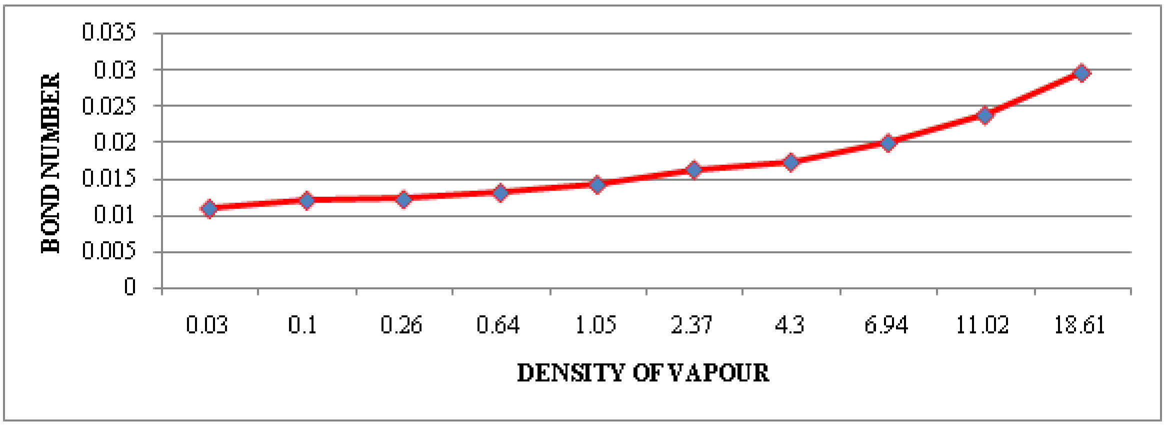

Figure 8: Effect of Bond number on density of vapour for Acetone.

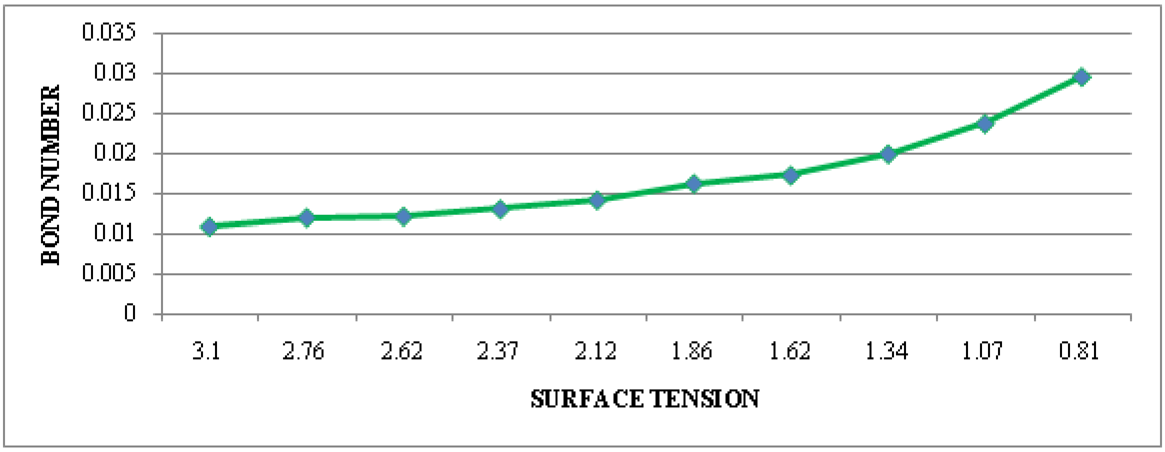

Figure 9: Effect of Bond number on surface tension of liquid for Acetone

Table 2: Thermophysical properties of Methanol

Acceleration due to Gravity m/s^2	Density of liquid kg/m^3	Density of vapour kg/m^3	Surface tension of liquid $N/m \times 10^2$	Internal diameter m	Bond number	Temperature in^0C
9.81	843.5	0.01	3.26	0.002	0.010152929	-50
9.81	833.5	0.01	2.95	0.002	0.01108683	-30
9.81	818.7	0.04	2.63	0.002	0.012214532	-10
9.81	800.5	0.12	2.36	0.002	0.013308013	10
9.81	782	0.31	2.18	0.002	0.01407042	30
9.81	764.1	0.77	2.01	0.002	0.014902024	50
9.81	746.2	1.47	1.85	0.002	0.015796327	70
9.81	724.4	3.01	1.66	0.002	0.017052617	90
9.81	703.6	5.64	1.46	0.002	0.01875887	110
9.81	685.2	9.81	1.25	0.002	0.021201843	130
9.81	653.2	15.9	1.04	0.002	0.024045819	150

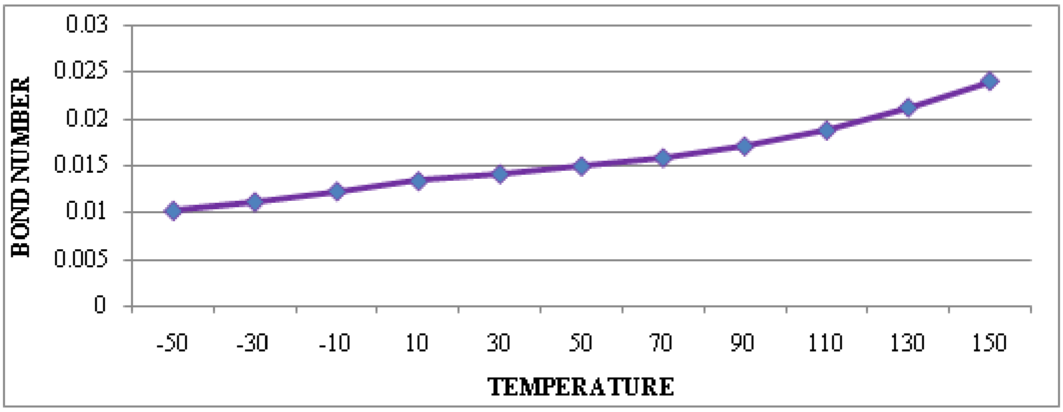

Figure 10: Effect of Bond number on temperature for Methanol

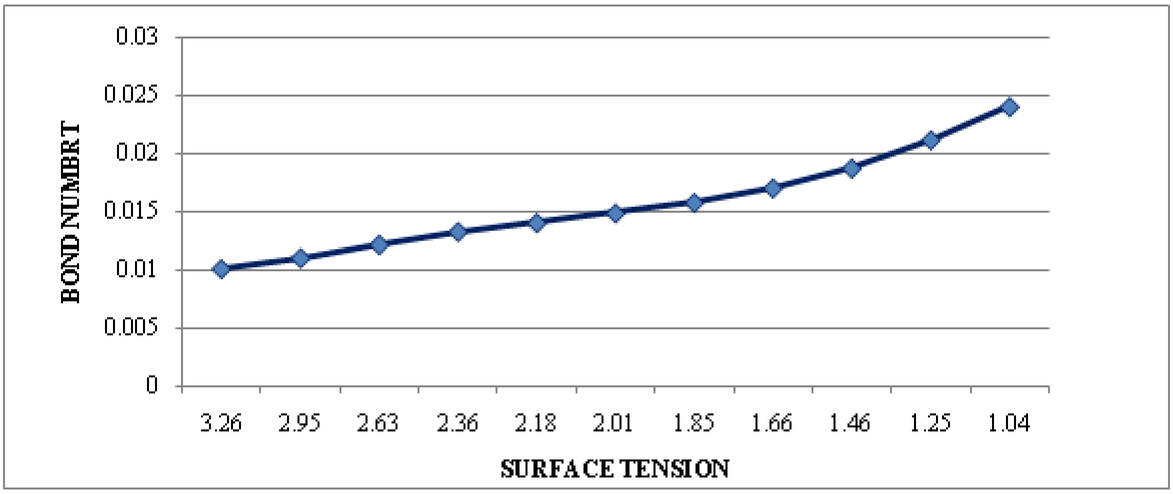

Figure 11: Effect of Bond number on surface tension of liquid for Methanol

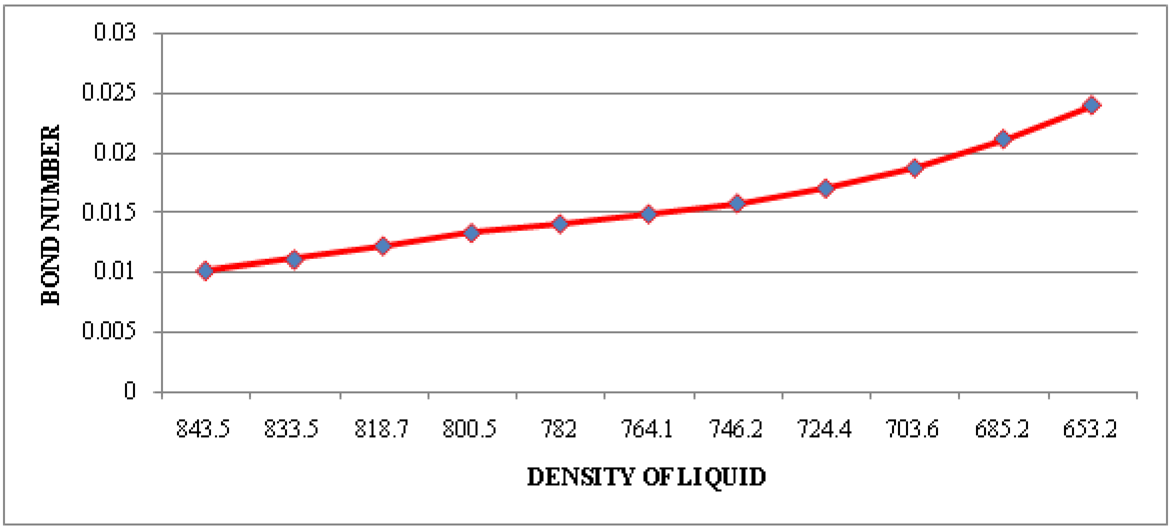

Figure 12: Effect of Bond number on density of liquid for Methanol

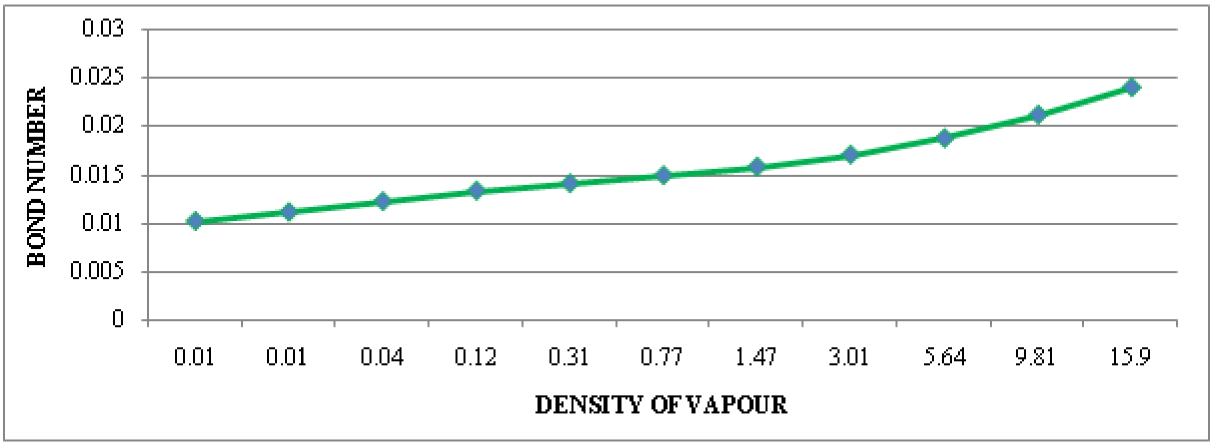

Figure 13: Effect of Bond number on density of vapour for Methanol

Table 4: Thermophysical properties of Ethanol

Acceleration due to Gravity m/s^2	Density of liquid kg/m^3	Density of vapour kg/m^3	Surface tension of liquid $N/m \times 10^2$	Internal diameter m	Bond number	Temperature in^0C
9.81	825	0.02	2.76	0.002	0.011729063	-30
9.81	813	0.03	2.66	0.002	0.011992836	-10
9.81	798	0.05	2.57	0.002	0.012183486	10
9.81	781	0.38	2.44	0.002	0.012553905	30
9.81	762.2	0.72	2.31	0.002	0.012935271	50
9.81	743.1	1.32	2.17	0.002	0.01341357	70
9.81	725.3	2.59	2.04	0.002	0.013901539	90
9.81	706.1	5.17	1.89	0.002	0.014552642	110
9.81	678.7	9.25	1.75	0.002	0.015010982	130

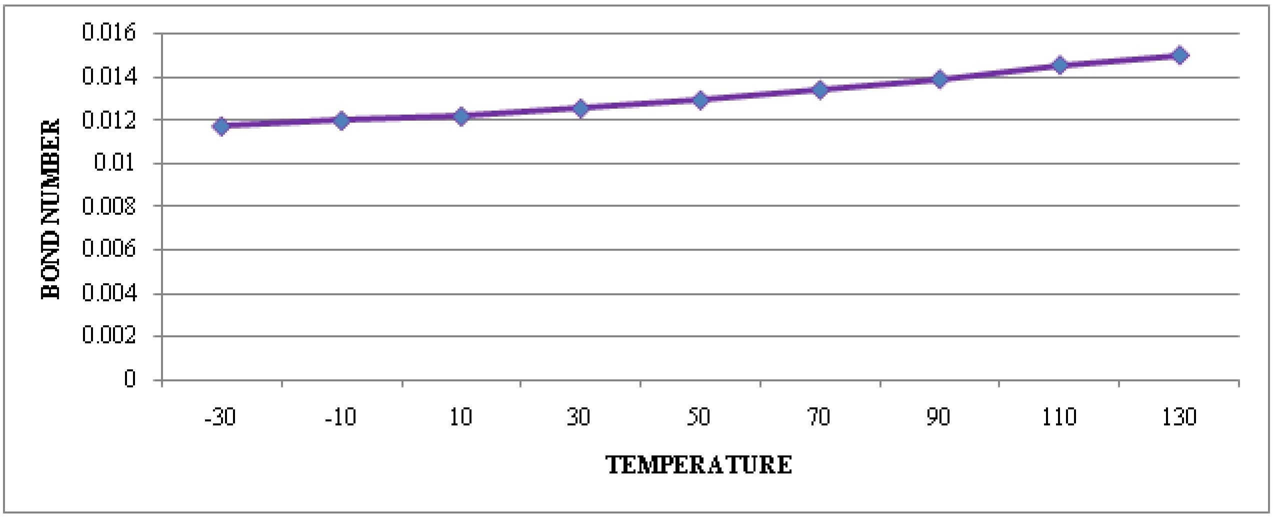

Figure 14: Effect of Bond number on temperature for Ethanol.

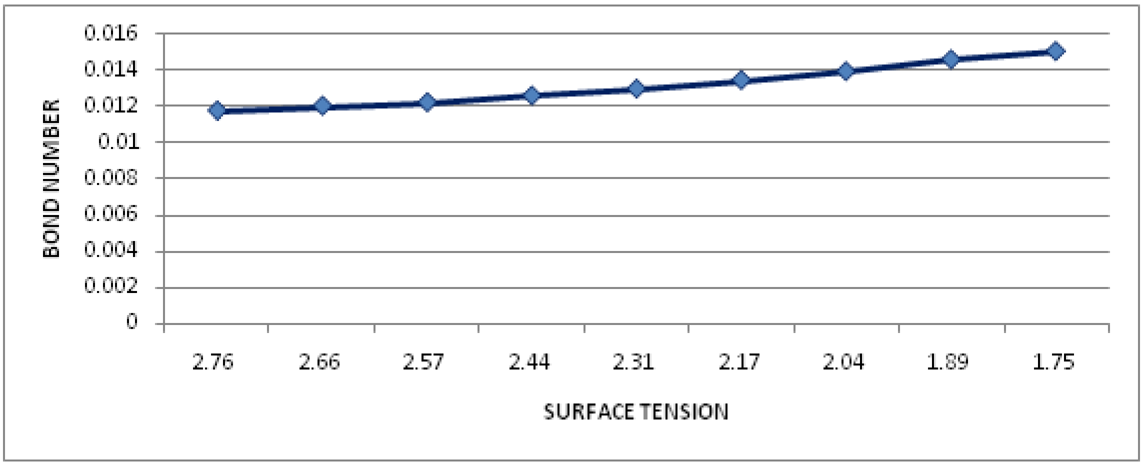

Figure 15: Effect of Bond number on surface tension of liquid for Ethanol.

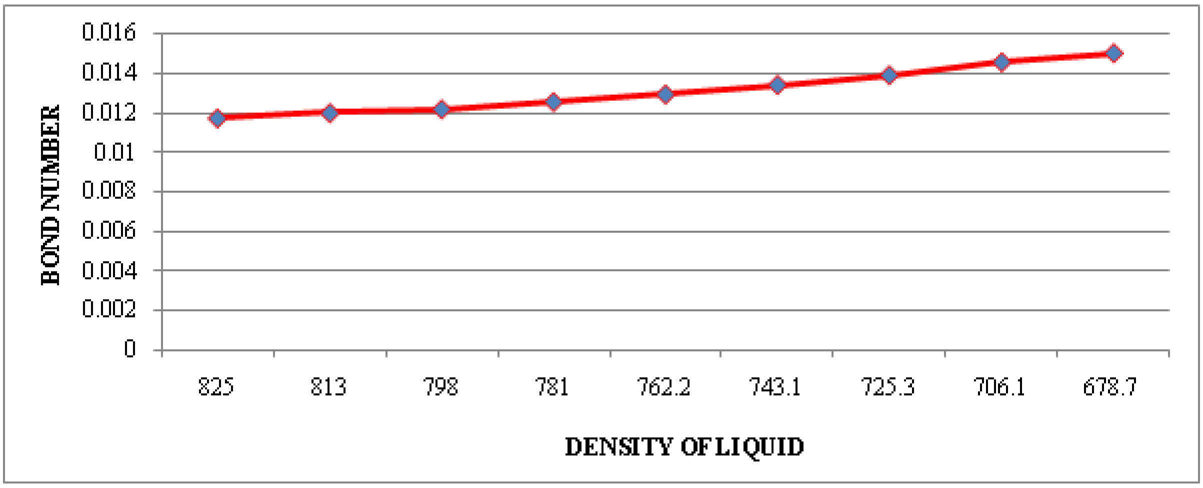

Figure 16: Effect of Bond number on density of liquid for Ethanol.

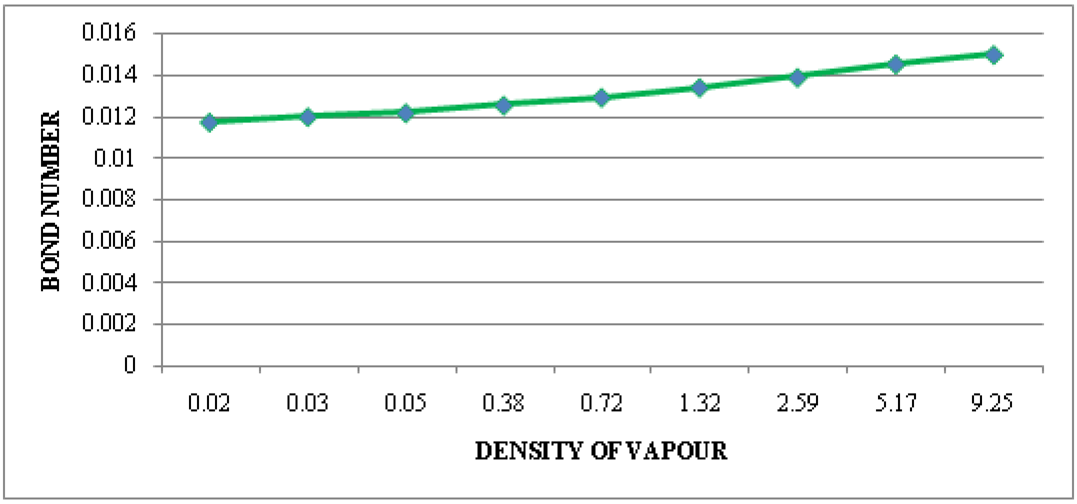

Figure 17: Effect of Bond number on density of vapour for Ethanol.

4. Conclusion

For acetone the value of Bond number varies from 0.01 to 0.03 there is increase in temperature and density of vapour. Whereas for this variation of Bond number the density of liquid and surface tension of liquid decreases. For Methanol the value of Bond number varies from 0.01 to 0.025 there is increase in temperature and density of vapour. For this variation of Bond number the density of liquid and surface tension of liquid decreases. For Ethanol the value of Bond number varies from 0.02 to 0.016 there is increase in temperature and density of vapour. For this variation of Bond number the density of liquid and surface tension of liquid decreases. In all the above cases the value of bond number is less than 2 each working fluid has different variation of bond number depending on the Thermophysical properties of working fluid and the operating ranges of working fluid used in closed loop pulsating heat pipe.

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