Study on the Effect of Inclination Angle on Heat Transfer Enhancement of a Ferrofluid and Kerosene in a Closed Loop Oscillating Heat Pipe

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Abstract: This paper elaborates on the findings of study on the effect of Fe_2O_3/Kerosene nanofluid to the copper closed-loop oscillating heat pipe under the magnetic field for inclination angles ranging from 0° to 90° under different heat inputs (10–90 W). The heat pipe's heat transfer coefficient was measured without and with the magnetic field. Moreover, the vapor temperature was assessed directly at the center of the oscillating heat pipe by exposing the ferro-nano particles to a magnetic field. It was shown that Fe_2O_3 nanoparticles could improve the thermal resistance and subsequently thermal performance as well as the pipe's heat transfer coefficient, especially under the magnetic field. The heat pipe's heat transfer coefficient increased as the input heat flux increased. The results also demonstrated that the heat pipe's inclination angle had a significant effect on performance of heat pipe. The critical angle was 75° as the heat transfer coefficient increased due to higher inclination angle.

1. Introduction

Better thermal management is needed as electronic devices with higher performance are introduced, their heat output of which may surpass the heat transfer potentials of the existing heat pipe designs. Oscillating Heat Pipes (OHPs), also known as Pulsating Heat Pipes (PHPs), can remove higher heat fluxes due to better heat spreading performance. OHPs, developed by Akachi [1], do not necessitate a pump or extra power to work, because they are passive heat transfer devices. The long meandering tube of OHPs is heated and chilled at several locations along its length. The oscillation principle for the working fluid constitutes the basis of these devices, and the capillary tube undergoes a phase change phenomena. The tube diameter should be as small as possible so that the vapor and liquid plugs are still present. Heat transfer is the result of fluid's normal oscillations between the condenser and evaporator sections. OHPs, unlike classic heat pipes, do not require a wicking assembly for liquid transfer and are able to work at greater heat fluxes. Compared to conventional heat pipes, their performance is higher and they may be employed to solve the upcoming LED [2], electronic cooling [3], drying [4], heat recovery [5] and fuel cell [6] problems.

A number of investigations concerning the horizontal OHP have been done from both theoretical and applied point of view [7,8]. Most of the OHPs are made vertically and a large number of research studies have explored vertical OHP [9–11]. However, the studies by Khandekar, Schneider, Schafer, Kulenovic and Groll [12] and Lotfi and Shafii [13] showed that efficiency as well as thermal resistance of an OHP depend on the orientation, filling ratio,

inner diameter and number of OHP bends. On the other hand, the experimental studies of Taslimifar, Mohammadi, Afshin, Saidi and Shafii [14] and Mohammadi, Taslimifar, Saidi, Shafii, Afshin and Hannani [15] demonstrated that magnetic field results in flow circulation that can improve heat transport owing to thermomagnetic convection changes and effects in ferrofluid's magnetic properties as temperature changes. Ferrofluids are called smart functional fluids because of their exceptional characteristics, establishing concurrent magnetic and fluid properties. That is why these are used in bioengineering, aerospace and mechanical engineering [16,17]. The previous studies imply that ferrofluids are good coolants [18,19]. Yet, the ferrofluids' convection heat transfer in an inclined OHP requires more investigations. Hence, in the present study, a ferrofluid comprising of Kerosene and Iron (III) oxide was applied to an inclined, closed-loop OHP at the presence of the magnetic field to evaluate the thermal efficiency of the system and find the critical OHP angle. This is the angle at which the maximum heat transfer is achieved [20]. The changes of thermal resistances, difference in vapor temperature between the evaporator and the condenser as well as heat transfer coefficient in different angles at a filling ratio of 50% were analyzed. Also, two semi-empirical correlations for Nusselt number have been derived in presence or absence of the magnetic field. The outcomes of the current investigation are expected to assist the readers to design more efficient OHPs, charged with nanofluid.

2. Literature review

Annamalai [1] discussed about experimental studies on porous wick flat plate heat pipe. In this study, the experimental analysis of the thermal performance of flat plate heat pipe of dimensions 133×133×35 mm was carried out for various heat input rates with different working fluids. Quantity of working fluid charged into the heat pipe is varied and its influence on performance was obtained. Different working fluids have been tested with heat pipe and their performance has been compared. At lower heat flux (1.38-2.73 W/m2) the fluids such as acetone, ethanol, and methanol are better than water, whereas at higher heat flux (6.38 W/m2) water is best candidature among these fluids considered. Water being more economical and easy availability will be a suitable choice of working fluid for high heat flux applications.

K. Mozumder [2] discussed about performance of Heat Pipe for Different Working Fluids and Fill Ratios. An attempt is made to design, fabricate and test a miniature heat pipe with 5 mm diameter and 150mm length with a thermal capacity of 10 W. Working fluids such as water, methanol and acetone were studied and compared. The performance of the heat pipe was quantified in terms of thermal resistance and overall heat transfer coefficient. The amount of liquid filled was varied and the variation of the performance parameters for varying liquid inventory is observed. Acetone with 100% fill ratio of evaporator volume shows the best result with minimum temperature difference across the evaporator and condenser. In case of water it was observed that it shows maximum value of heat transfer co-efficient and minimum value of thermal resistance at 85% fill ratio.

R.A. Hossain [3] presented the works on the Design, Fabrication and Experimental Study of Heat Transfer Characteristics of a Micro Heat Pipe. In this study the heat transfer characteristics, a micro heat pipe (MHP) of circular geometry having inner diameter 1.8mm and length 150 mm is designed and fabricated. An experimental investigation is carried out also to investigate the performance of the MHP with different experimental parameters like inclination angle, coolant flow rate, working fluid and heat input. Three different types of working fluids are used; acetone, ethanol and methanol. For each working fluid, heat transfer characteristics are determined experimentally for different inclination angle and different coolant flow rate at different heat input. Acetone is proved to be better as working fluid.

Paisarn Naphon [4] presented work on experimental investigation of titanium nano fluids on the heat pipe thermal efficiency. In this study the enhancement of heat pipe thermal efficiency with nano fluids with titanium particles was presented. The heat pipe is fabricated from the straight copper tube with the outer diameter and length of 15mm and 600 mm, respectively. The heat pipe with the de-ionic water, alcohol, and nano fluids (alcohol and nano particles) are tested. The mixtures of the pure alcohol and nano particles with the concentration of 0.01, 0.05, 0.10, 0.50 and 1.0% by volume are prepared using an ultrasonic homogenizer. The titanium nano particles with diameter of 21 nm are used in the present study which the mixtures of alcohol and nano particles are prepared using an ultrasonic homogenizer. Thermal efficiency of heat increases and reaches maximum upto a tilt angle of 60° for de-ionic water and 45° for alcohol. For de-ionic water thermal efficiency as a function of heat flux increases and reaches maximum when the percentage charge of water is 66%. For mixture of alcohol and titanium nano particles the optimal concentration of nano particles was 0.10 % for maximum efficiency. The maximum efficiency ranges from 65-70%.

3. Mathematical Modeling and Numerical Simulation

1. Temperature – Here we have found out the temperature variation along cross-section.
We have to select all the layers of the model of uniform flow of the particles in it.

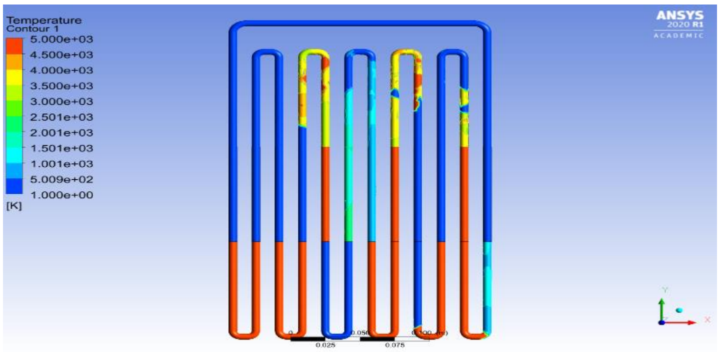


Figure 15: selection of layers for the Temperature variation

2. Surface heat transfer coefficient – Here we have found out the surface heat transfer coefficioent values in a similar way as the above pressure variation. For the surface heat transfer coefficient analysis also we have done the same way as Temperature analysis.

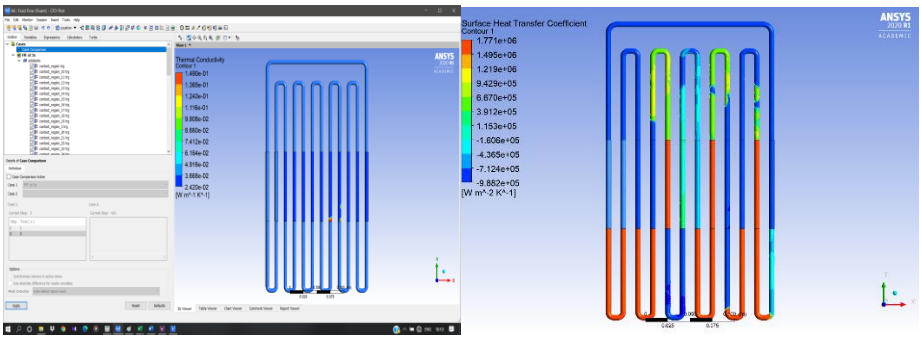


Figure 17: Surface heat transfer coefficient Analysis

3. Inner wall temperature – Here we have found out the inner wall temperature values in a similar way as the above pressure variation. For the inner wall temperature analysis also we have done the same way as Temperature analysis.

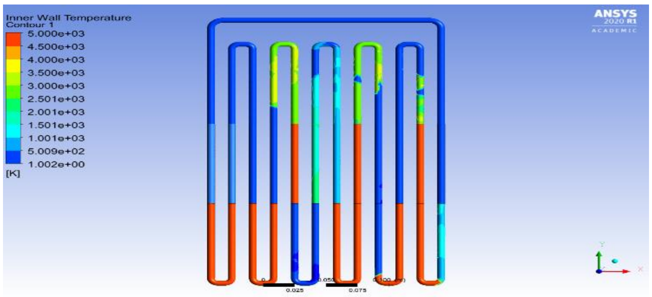


Figure 18: Inner wall temperature Analysis

4. Mass transfer rate – Here we have found out the mass transfer rate values in a similar way as the above pressure variation. For the mass transfer analysis also we have done the same way as Temperature analysis.

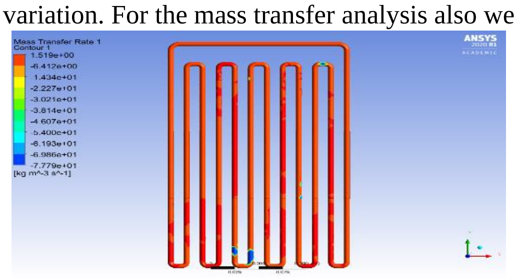


Figure 19: Mass transfer rate Analysis

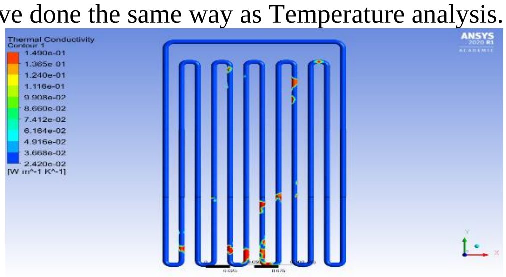


Figure 20: Thermal conductivity Analysis

4. **Thermal conductivity** – Here we have found out the thermal conductivity values in a similar way as the above pressure variation. For the thermal conductivity analysis also we have done the same way as Temperature analysis.

4.

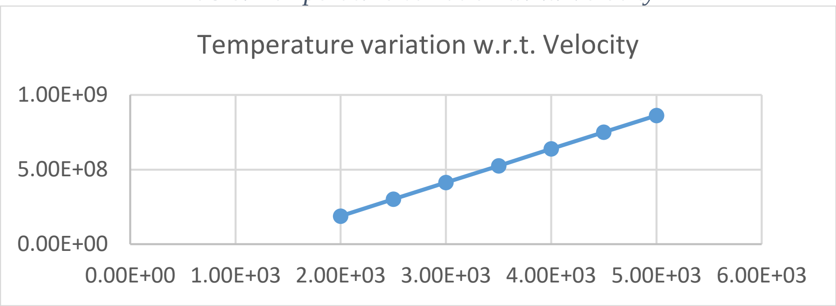
5. Results and Data

1. Temperature variation w. r. t. Velocity

TEMPERATURE	VELOCITY
5.00E+03	8.62E+08
4.50E+03	7.50E+08
4.00E+03	6.38E+08
3.50E+03	5.25E+08
3.00E+03	4.13E+08
2.50E+03	3.01E+08

2.00E+03	1.88E+08

Table: *Temperature variation w.r.t. Velocity*

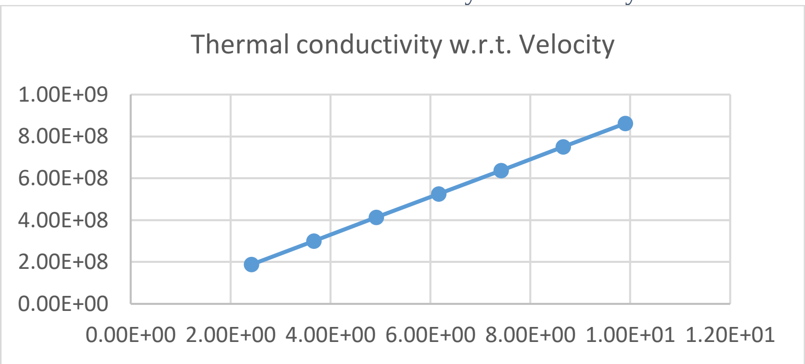


Graph 1: Temperature variation w.r.t. Velocity

2. Thermal conductivity w. r. t. Velocity

Thermal conductivity	Velocity
9.90E+00	8.62E+08
8.66E+00	7.50E+08
7.41E+00	6.38E+08
6.16E+00	5.25E+08
4.92E+00	4.13E+08
3.67E+00	3.01E+08
2.42E+00	1.88E+08

Table: Thermal conductivity w.r.t. Velocity

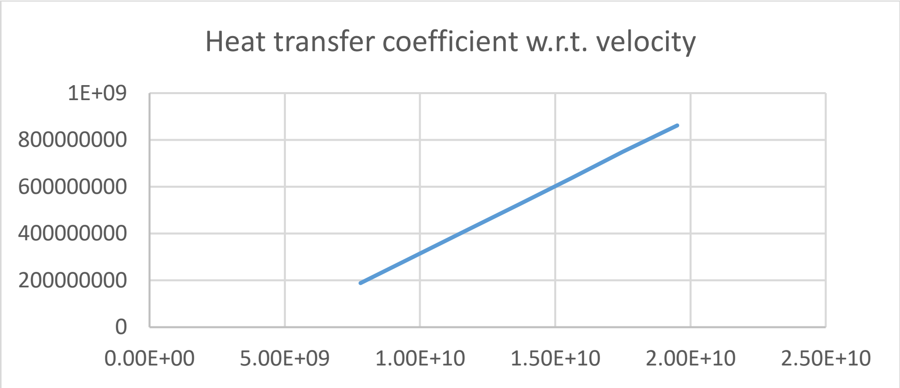


Graph 2: Thermal conductivity w.r.t. Velocity

3. Heat transfer coefficient w.r.t. velocity

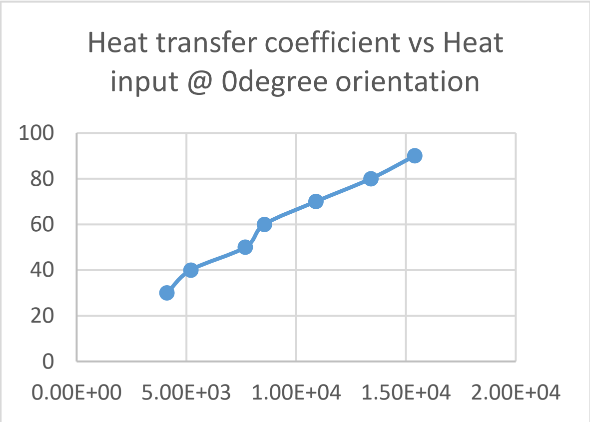
Heat transfer coefficient	Velocity
1.95E+10	8.62E+08
1.75E+10	7.50E+08
1.56E+10	6.38E+08
1.37E+10	5.25E+08
1.17E+10	4.13E+08
9.75E+09	3.01E+08
7.80E+09	1.88E+08

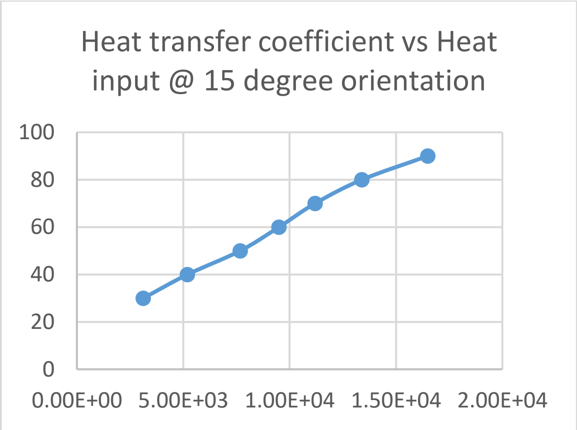
Table: *Heat transfer coefficient w.r.t. Velocity*

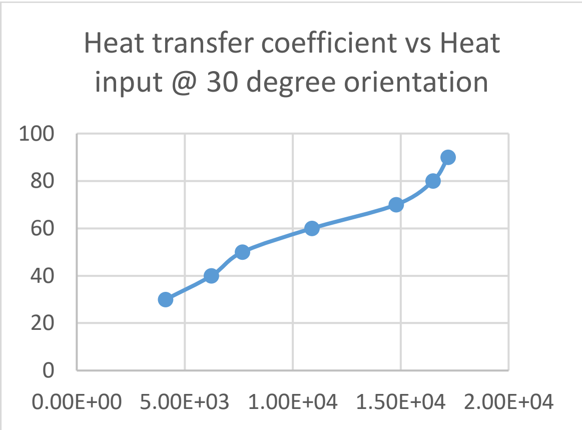


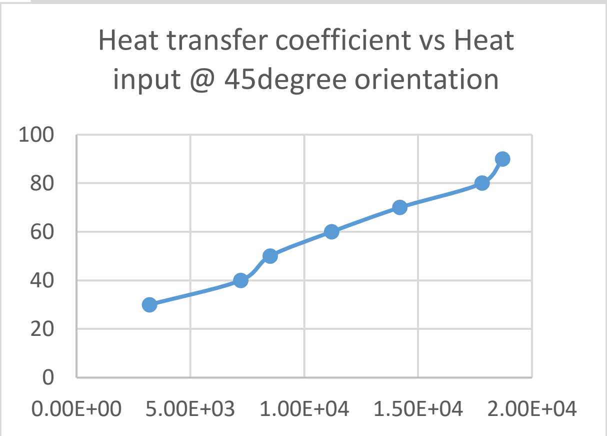
Graph 3: Heat transfer coefficient w.r.t. Velocity

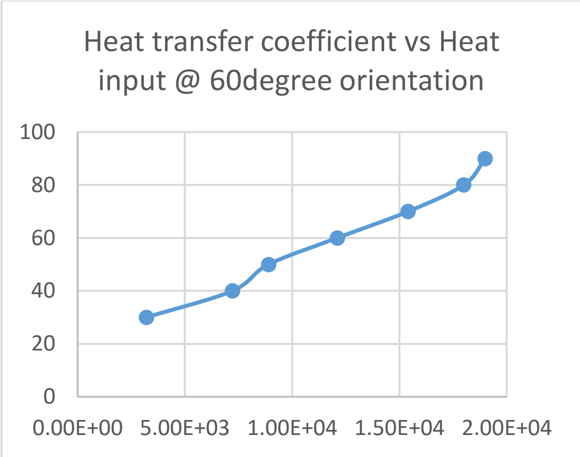
Heat transfer coefficient w .r. t. Heat input at different orientations for Kerosene fluid

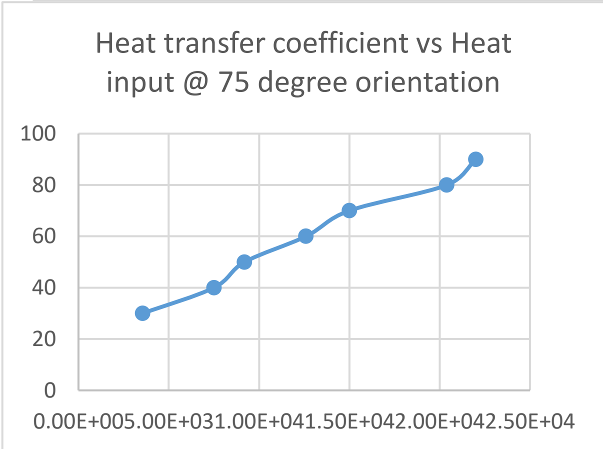


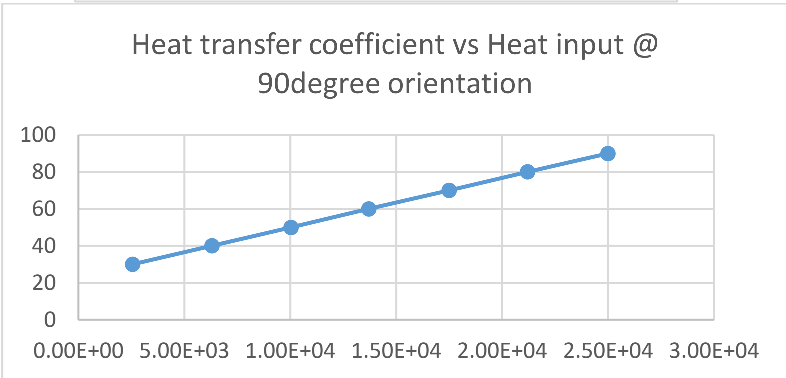












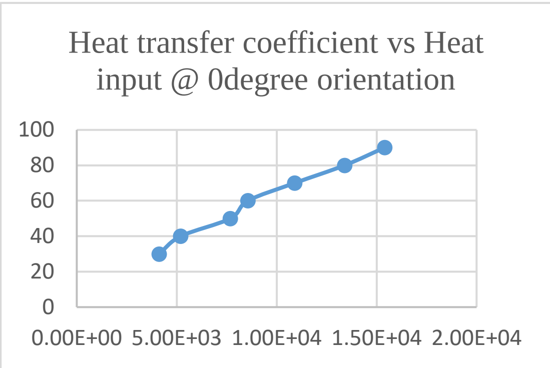
Tabulated results for Kerosene fluid:

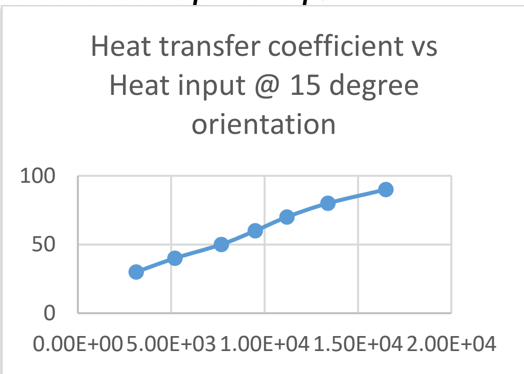
Orientation / **Heat input**	**0°**	**15°**	**30°**	**45°**	**60°**	**75°**	**90°**
90	1.34E+10	1.48E+10	1.58E+10	1.65E+10	1.75E+10	1.85E+10	1.95E+10
80	1.21E+10	1.36E+10	1.45E+10	1.55E+10	1.65E+10	1.75E+10	1.75E+10
70	1.13E+10	1.22E+10	1.31E+10	1.42E+10	1.52E+10	1.62E+10	1.56E+10
60	9.89E+09	1.17E+10	1.26E+10	1.32E+10	1.41E+10	1.41E+10	1.37E+10
50	9.01E+09	9.01E+09	1.01E+10	1.20E+10	1.10E+10	1.20E+10	1.17E+10
40	8.19E+09	8.19E+09	6.19E+09	7.69E+09	8.89E+09	9.89E+09	9.75E+09

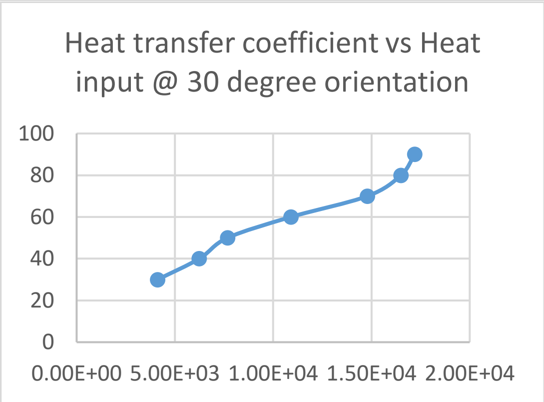
30	7.90E+ 09	7.90E+ 09	5.90E+ 09	6.90E+ 09	7.20E+ 09	8.20E+ 09	7.80E+ 09

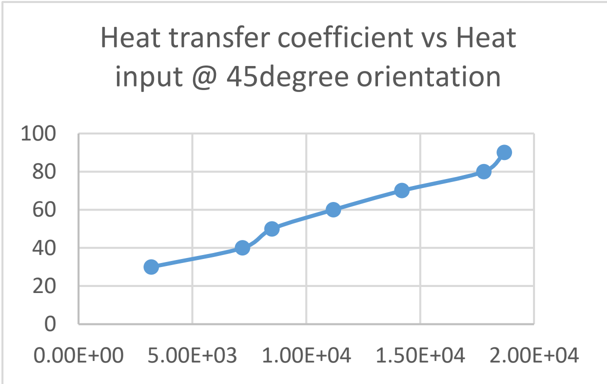
Table: *Heat transfer coefficient w.r.t. different orientations for kerosene fluid*

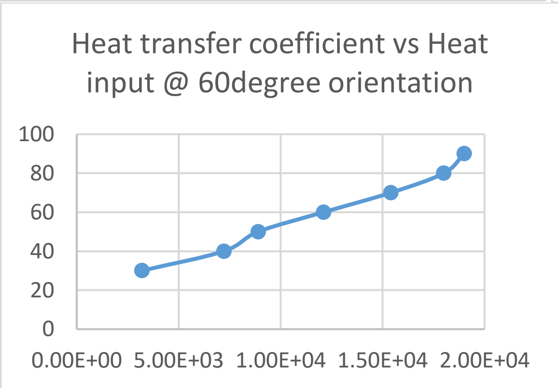
Heat transfer coefficient w .r. t. Heat input at different orientations for Ferro fluid

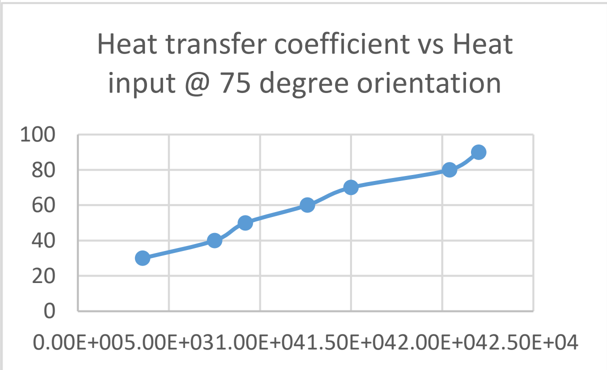


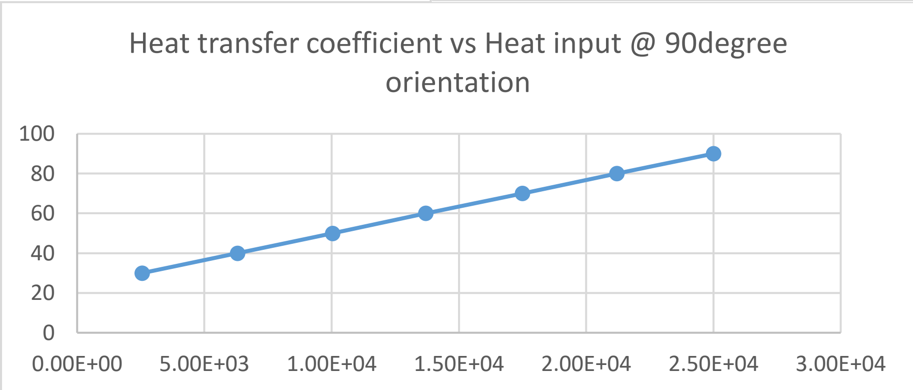










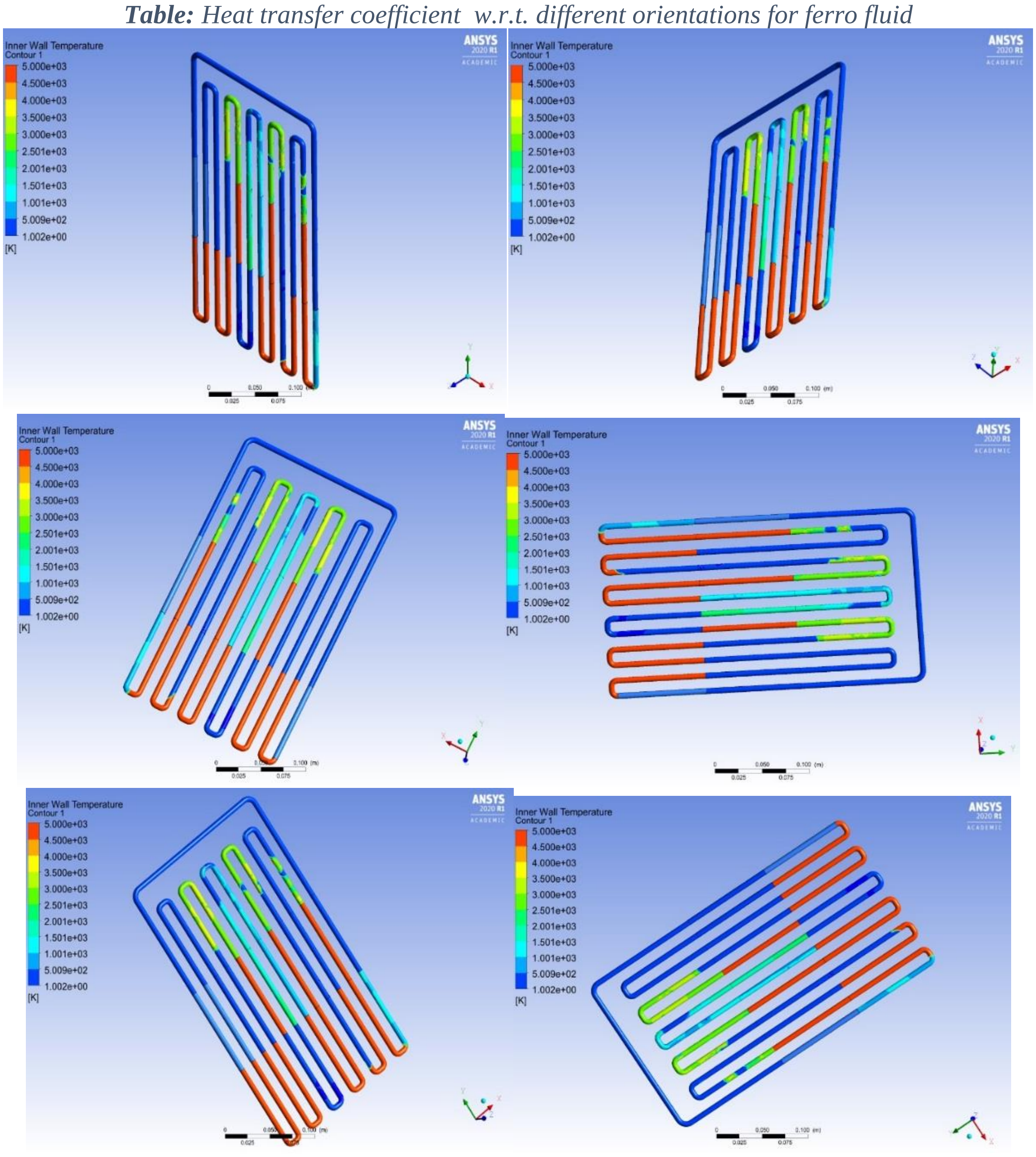


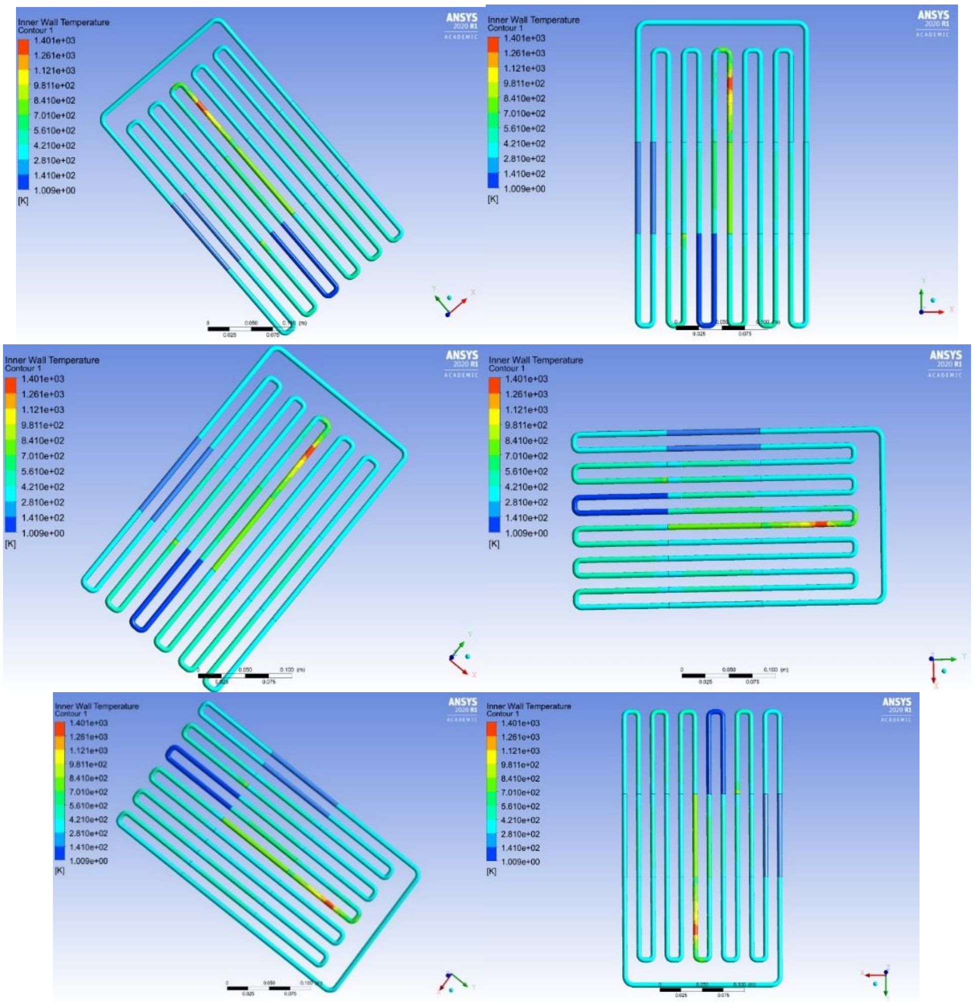
Tabulated results for Ferro fluid:

Orientation	**0°**	**15°**	**30°**	**45°**	**60°**	**75°**	**90°**
Heat input							

90	1.54E+10	1.65E+10	1.72E+10	1.87E+10	1.90E+10	2.20E+10	2.50E+10
80	1.34E+10	1.34E+10	1.65E+10	1.78E+10	1.80E+10	2.04E+10	2.12E+10
70	1.09E+10	1.12E+10	1.48E+10	1.42E+10	1.54E+10	1.50E+10	1.75E+10
60	8.56E+10	9.50E+10	1.09E+10	1.12E+10	1.21E+10	1.26E+10	1.37E+10
50	7.68E+09	7.68E+09	7.68E+09	8.50E+09	8.90E+09	9.20E+09	1.00E+10
40	5.20E+09	5.20E+09	6.24E+09	7.21E+09	7.21E+09	7.50E+09	6.30E+09
30	4.12E+09	3.12E+09	4.12E+09	3.20E+09	3.20E+09	3.56E+09	2.56E+09

Table: *Heat transfer coefficient w.r.t. different orientations for ferro fluid*





Comparison of Heat transfer coefficient VS Heat input for Kerosene liquid and Ferro fluid:

Tabulated results for Kerosene fluid:

Orientation / **Heat input**	**0°**	**15°**	**30°**	**45°**	**60°**	**75°**	**90°**
90	1.34E+10	1.48E+10	1.58E+10	1.65E+10	1.75E+10	1.85E+10	1.95E+10
80	1.21E+10	1.36E+10	1.45E+10	1.55E+10	1.65E+10	1.75E+10	1.75E+10
70	1.13E+10	1.22E+10	1.31E+10	1.42E+10	1.52E+10	1.62E+10	1.56E+10
60	9.89E+09	1.17E+10	1.26E+10	1.32E+10	1.41E+10	1.41E+10	1.37E+10
50	9.01E+09	9.01E+09	1.01E+10	1.20E+10	1.10E+10	1.20E+10	1.17E+10
40	8.19E+09	8.19E+09	6.19E+09	7.69E+09	8.89E+09	9.89E+09	9.75E+09
30	7.90E+09	7.90E+09	5.90E+09	6.90E+09	7.20E+09	8.20E+09	7.80E+09

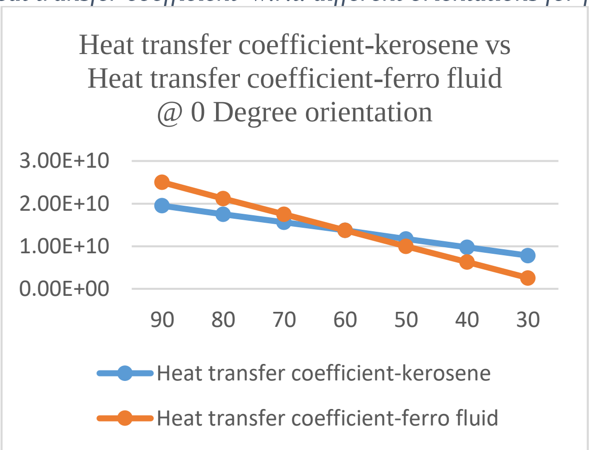
Table: *Heat transfer coefficient w.r.t. different orientations for kerosene fluid*

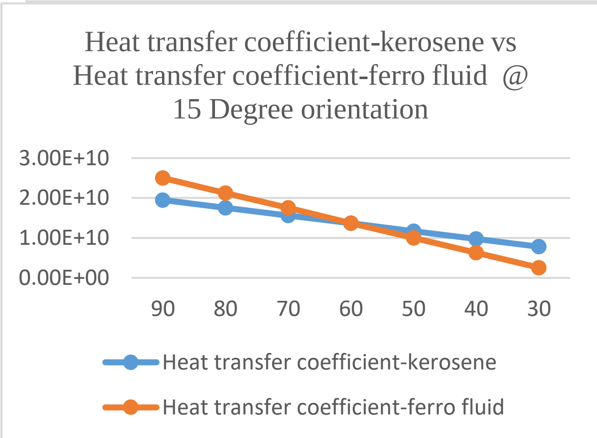
Tabulated results for Ferro fluid:

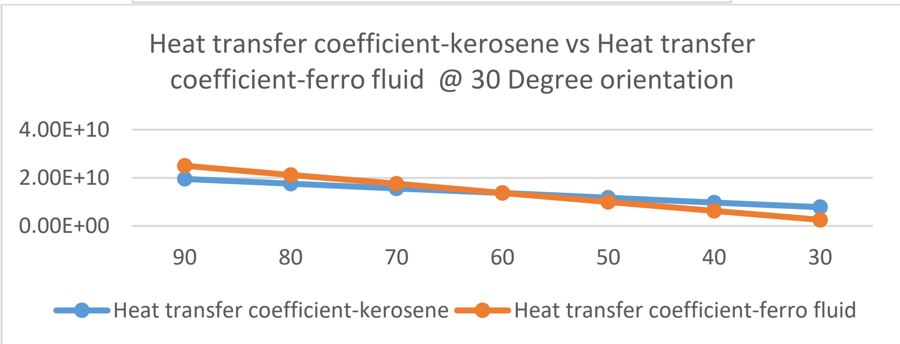
Orientation / **Heat input**	**0°**	**15°**	**30°**	**45°**	**60°**	**75°**	**90°**

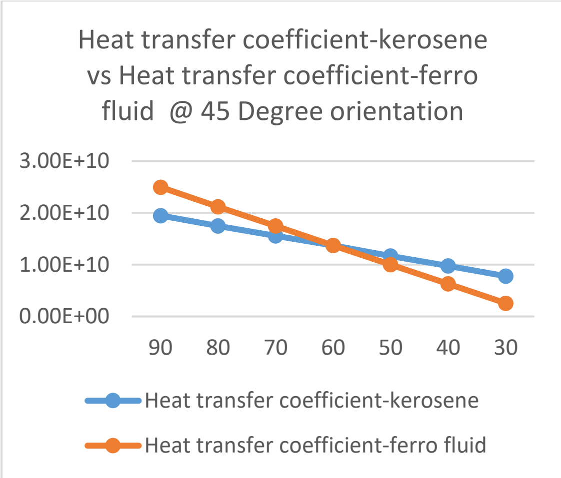
90	1.54E+10	1.65E+10	1.72E+10	1.87E+10	1.90E+10	2.20E+10	2.50E+10
80	1.34E+10	1.34E+10	1.65E+10	1.78E+10	1.80E+10	2.04E+10	2.12E+10
70	1.09E+10	1.12E+10	1.48E+10	1.42E+10	1.54E+10	1.50E+10	1.75E+10
60	8.56E+10	9.50E+10	1.09E+10	1.12E+10	1.21E+10	1.26E+10	1.37E+10
50	7.68E+09	7.68E+09	7.68E+09	8.50E+09	8.90E+09	9.20E+09	1.00E+10
40	5.20E+09	5.20E+09	6.24E+09	7.21E+09	7.21E+09	7.50E+09	6.30E+09
30	4.12E+09	3.12E+09	4.12E+09	3.20E+09	3.20E+09	3.56E+09	2.56E+09

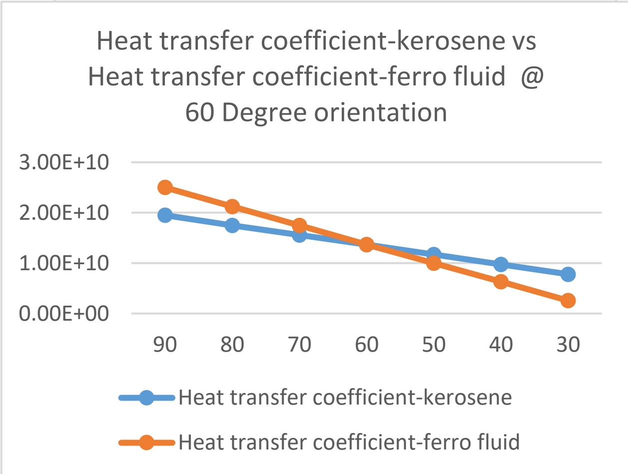
Table: *Heat transfer coefficient w.r.t. different orientations for ferro fluid*

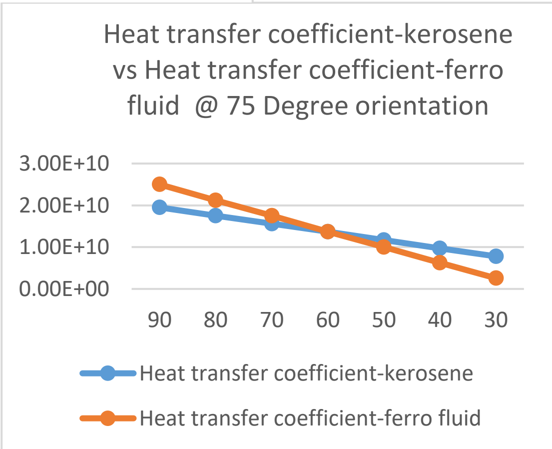


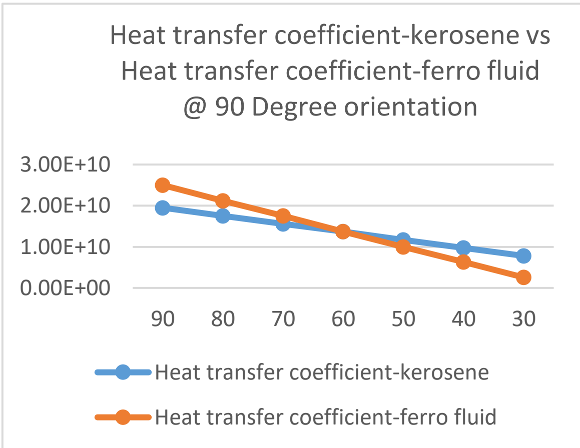




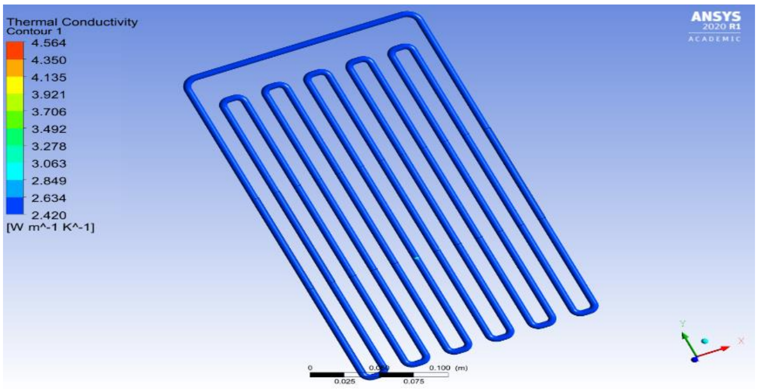








Thermal Resistance:



Tabulated results for Thermal resistance for Kerosene fluid:

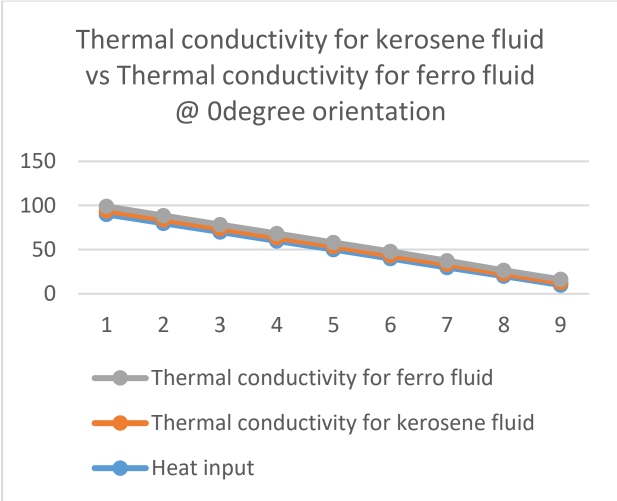
Orientation / Heat input	0°	15°	30°	45°	60°	75°	90°
90	3.985	4.055	4.165	4.275	4.394	4.464	4.564
80	3.851	3.904	4.095	4.164	4.264	4.35	4.35
70	3.761	3.828	3.875	3.974	3.981	4.015	4.135
60	3.654	3.726	3.795	3.801	3.752	3.891	3.921
50	3.589	3.641	3.656	3.621	3.534	3.706	3.706
40	3.421	3.498	3.523	3.462	3.362	3.592	3.492
30	3.30	3.312	3.329	3.208	3.248	3.348	3.278
20	2.741	2.806	2.875	2.971	2.871	2.963	3.063
10	2.621	2.751	2.613	2.665	2.765	2.749	2.849

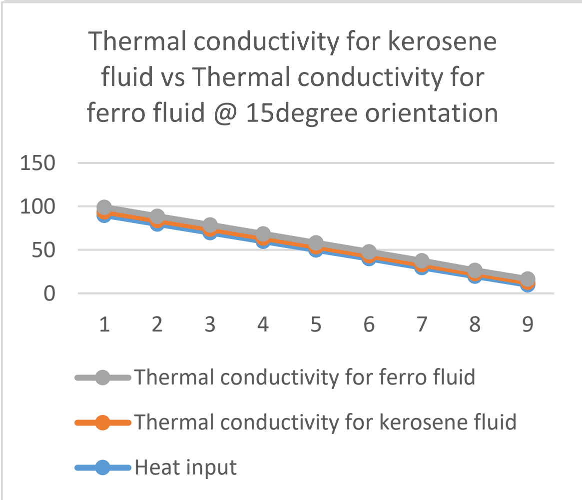
Table: *Thermal resistance w.r.t. different orientations for kerosene fluid*

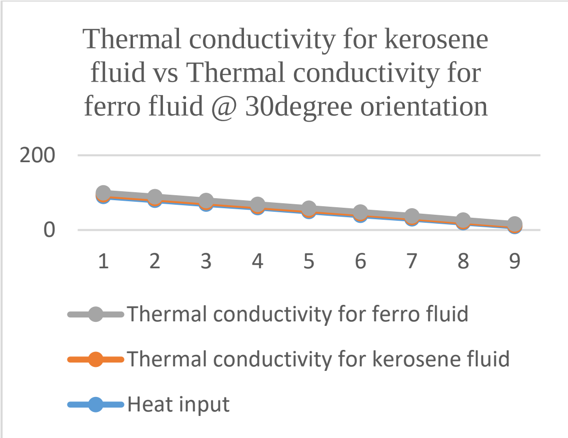
Tabulated results for Thermal resistance for Ferro fluid:

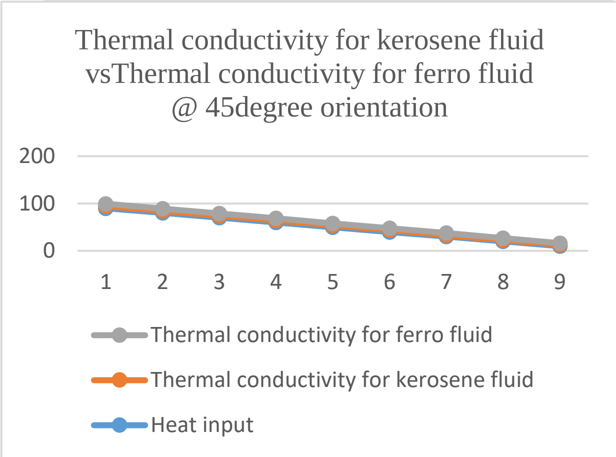
Orientation / Heat input	0°	15°	30°	45°	60°	75°	90°
90	4.984	5.051	5.115	5.215	5.294	5.444	5.524
80	4.851	4.914	5.098	5.166	5.214	5.350	5.450
70	4.712	4.821	4.871	4.979	4.981	5.015	5.135
60	4.631	4.726	4.799	4.805	4.752	4.891	4.921
50	4.551	4.648	4.655	4.624	4.534	4.706	4.706
40	4.425	4.491	4.524	4.466	4.362	4.592	4.492
30	4.312	4.316	4.326	4.219	4.248	4.348	4.278
20	3.768	3.801	3.875	3.976	3.871	3.963	4.063
10	3.649	3.755	3.614	3.624	3.765	3.749	3.849

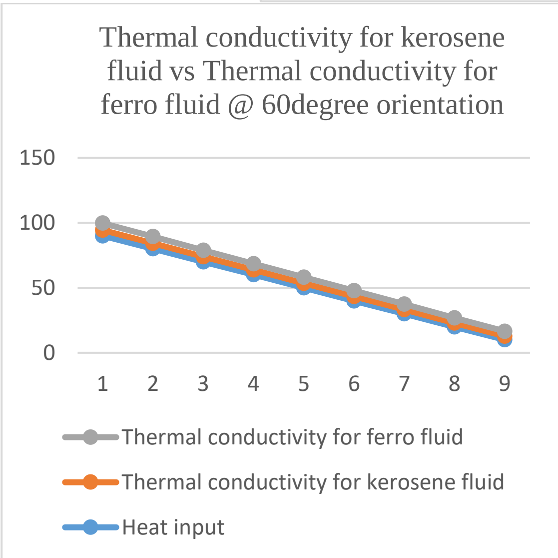
Table: *Thermal resistance w.r.t. different orientations for ferro fluid*

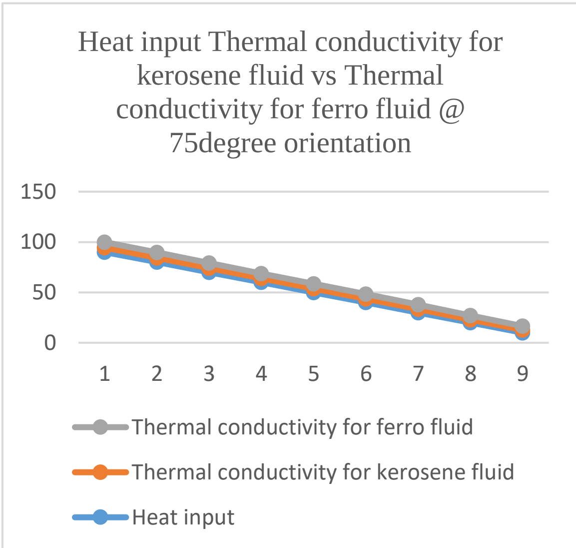

Thermal conductivity for kerosene fluid vs Thermal conductivity for ferro fluid @ 0degree orientation
150
100
50
0
1
2
3
4
5
6
7
8
9
Thermal conductivity for ferro fluid
Thermal conductivity for kerosene fluid
Heat input

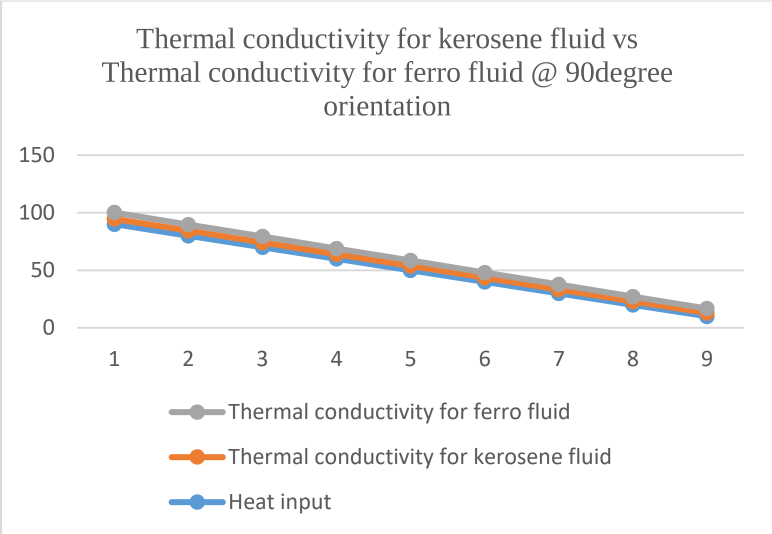

Thermal conductivity for kerosene fluid vs Thermal conductivity for ferro fluid @ 15degree orientation
150
100
50
0
1
2
3
4
5
6
7
8
9
Thermal conductivity for ferro fluid
Thermal conductivity for kerosene fluid
Heat input


Thermal conductivity for kerosene fluid vs Thermal conductivity for ferro fluid @ 30degree orientation
200
0
1 2 3 4 5 6 7 8 9
Thermal conductivity for ferro fluid
Thermal conductivity for kerosene fluid
Heat input


Thermal conductivity for kerosene fluid vsThermal conductivity for ferro fluid @ 45degree orientation
200
100
0
1 2 3 4 5 6 7 8 9
Thermal conductivity for ferro fluid
Thermal conductivity for kerosene fluid
Heat input


Thermal conductivity for kerosene fluid vs Thermal conductivity for ferro fluid @ 60degree orientation
150
100
50
0
1 2 3 4 5 6 7 8 9
Thermal conductivity for ferro fluid
Thermal conductivity for kerosene fluid
Heat input


Heat input Thermal conductivity for kerosene fluid vs Thermal conductivity for ferro fluid @ 75degree orientation
150
100
50
0
1 2 3 4 5 6 7 8 9
Thermal conductivity for ferro fluid
Thermal conductivity for kerosene fluid
Heat input



6. Conclusions

The heat pipe is fabricated from the straight copper tube with the outer diameter and length of 15mm and 600 mm, respectively. The heat pipe with the de-ionic water, alcohol, and nano fluids (alcohol and nano particles) are tested. The mixtures of the pure alcohol and nano particles with the concentration of 0.01, 0.05, 0.10, 0.50 and 1.0% by volume are prepared using an ultrasonic homogenizer. The titanium nano particles with diameter of 21 nm are used in the present study which the mixtures of alcohol and nano particles are prepared using an ultrasonic homogenizer. Thermal efficiency of heat increases and reaches maximum upto a tilt angle of 60° for de-ionic water and 45° for alcohol. For de-ionic water thermal efficiency as a function of heat flux increases and reaches maximum when the percentage charge of water is 66%. For mixture of alcohol and titanium nano particles the optimal concentration of nano particles was 0.10 % for maximum efficiency. The maximum efficiency ranges from 65-70%.

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