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Design analysis and performance evaluation of heat pipe embedded oil cooler with enhanced staggered fins

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Abstract*: Hydraulic coolers are most commonly preferred cooling source in industry. The progress in past few years have offered high efficiency and reliable hydraulic component, yet hydraulic cooling circuit design is often neglected part of development. One aspect of the hydraulic cooling circuit design is prevention of overheating hydraulic oil. Allowing oil temperature rise beyond particular limit can increase the power consumption and reduce the life of a system due to poor lubrication, higher internal leakage, higher risk of cavitation's and damage component. Now-a-days shell and tube type oil coolers with water as the cooling medium are used as hydraulic oil cooler, these are extremely bulky and running cost is high hence it is needed to be replaced by another system that will be air cooled to make provision for lower space consumption and cost reduction. This paper discusses the design and development of innovative oil cooler heat extraction system using heat pipe. Designs of fins preferred are namely the straight fin system with fins projected outward in eight channels. The equipment developed is first model using Unigrafix Nx-8 and steady state thermal analysis of fins is done in Ansys workbench 16.0. A simple, compact, high efficiency, low cost device is developed, also a new technology of heat pipe embedded oil cooler is learnt in this present work. This paper discusses the performance of heat pipe embedded oil cooler in terms of LMTD, overall heat transfer coefficient and effectiveness. Further it discusses the performance evaluation of the straight fin setup.

***Keyword*—Hydraulic oil cooler, straight fin system, steady state thermal analysis, etc.**

I. INTRODUCTION

In hydraulic equipment most common problem is overheating. The hydraulic system is overheated due to inefficiencies. Inefficiencies leads to losses in input power due to which the heat is generated. In hydraulic systems heat load is equal to the total power loss through inefficiencies. Total power loss is the summation of power loss in pump, valve, plumbing and actuators. Hydraulic system is overheated when the total input power loss is greater than the heat dissipated. Hydraulic oil cooling with application of heat pipe was done by Marjapure et al.,[1].

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From the experimentations outcomes they concluded that heat pipe technology was used to reduce the overheating problems in hydraulic system. If the oil flow rate was constant it could be effectively used in hydraulic oil cooling application. Heat dissipation was improved by using the heat pipe with attached fins.

In hydraulic equipment if the fluid temperature is high that is above 82^0c (180^0f) this will accelerate degradation of the oil and damage most seal compounds. To obtain the stable fluid temperature in hydraulic system, heat dissipation must be greater than its heat load. The overheating problem can be solved in two ways either increase the heat dissipation or decrease the heat load. This paper discusses the design development and performance evaluation of heat pipe embedded oil cooler with enhanced staggered fins. This equipment is used to increase the heat dissipation to solve the overheating problem. The heat exchanger ability to dissipate heat is dependent on the temperature and flow rate of both the hydraulic fluid and the cooling air circulating through the exchanger.as per the performance of oil cooling circuit, components are replaced as required.

The oil cooler using embedded heat pipe is cost-effective solution in oil cooling application. Embedded heat pipes provide efficient thermal management for applications that are space constrained. Embedding heat pipe into the existing heat sink or applying a spiral radial fin structure to heat sink increases its heat spreading and rejection efficiency, this can be achieved without a costly product design. A review of heat pipe application including new opportunities was done by Mochizuki et al.,[2]. They took detail review of heat pipe applications ranging from computer electronics to renewal energy. They concluded that heat pipe can effectively transfer the heat from heat source to dissipation area and it also helps to reduce the thermal spreading at the base of metal. The ideas for using of heat pipe is to make those abundant natural energy source useful which are unlimited. The configuration proposed for the oil cooler is copper heat pipe with sintered powder metal wick with water as cooling fluid. This allows round, shaped, heat pipe configured to fit into the tightest of application. For the best thermal contact, heat pipes are press fitted or adhesively bonded into the metallic heat sinks. Making them strong enough to withstand and survive the toughest extreme temperature and vibration environment.

II. LITERATURE REVIEW

A case study of oil cooler model for heat pipe design, development, manufacturing was done by Chavan et.al., [3]. The study showed that as there is rise in rate of oil flow it increases the total heat rejection. On oil cooler a test was carried out at constant flow rate for increasing inlet oil temperature. At low temperature this unit is more efficient. Cooling efficiency can be improved by changing the material of heat pipe and increasing number of heat pipe. Heat transfer rate was improved by using heat pipe with fins over the forced convection. Design and thermal analysis of hydraulic oil cooler by using computational fluid dynamics was done by Patil et al., [4]. They found that overall heat transfer coefficient increased up to 110 $W/m^{20}K$ for maximum mass flow rate (0.123 Kg/s). Hence system was safe and will not be overheated. They found that the highest effectiveness was 0.725.

Hydraulic oil cooler equipped with the heat pipe cores was developed by Kamthane et al., [5]. Components in the reservoir were secured by shrouding the equipment's with bracers, brackets and fans. The article showed that to investigate the characteristics of heat pipe the modules of heat pipe were tested. Since for oil cooling the model was developed and over a temperature difference of 45^0c to 80^0c of inlet and outlet of oil test were carried out. By single module, heat dissipated was found near about 200watt, and with natural convection it will be 120watt. Ansys based FEM model had been developed by Wang et al.,[6] for heat pipe cooled piston crown and correlating, the numerical results with experimental measurement. For annular heat pipe the effective thermal conductance was found to be 3980 W/m^0c about 240 times that of the crown material. In hydraulic motor pump for heat dissipation the research had been done in this area using heat pipe.

Fu et al., [7] had designed the heat pipe radiator model. Using Ansys software the results in terms of temperature were simulated. The results showed that it was difficult to transfer the heat generated only through the natural cooling. The average of oil temperature was found to be 150.08^0c. When the heat pipe radiator model was used the average oil, temperature was found as 73.844^0c. It showed that the heat pipe radiator ensured the working of hydraulic motor pump in an appropriate range. It also helped to reduce the temperature gradient. Experimental applications of heat pipe in hydraulic oil cooler was performed by Wankhede et al.,[8]. from the experimentation they concluded that for constant mass flow rate the heat transfer rate increased up to 0.70KJ/S. According to them heat can be transferred effectively by using blower and at the given flow rate of oil the overall heat transfer rate was increased. For the given flow rate of oil, the outlet temperature was decreased. Testing and analysis of enhanced-cross flow heat pipe hydraulic oil cooler was performed by Wahile et al., [9]. They conclude that in industry for many applications for effective heat transfer the heatpipe device was used. Influence of wick characteristics on heat pipe performance was done by Mwaba et al., [10]. They studied the influence of wicking structure on performance heat pipe by developing the numerical model. Under the investigated condition they found that heat pipe having wick structure with coarse and fine pores gave the best performance. It was showed such a wick can enhanced heat pipe performance up to factor.

After careful study of various papers and literature it is clear that liquid cooled heat exchangers using heat pipe are sparse and have being rarely researched. No specific research was found to be dedicated to study the effect of change in geometry of heat exchanger on the performance of liquid cooled heat exchanger. Given the specific application in liquid cooling the heat pipe cooled device are becoming increasingly popular research in this area. The project work aims at design development and study of one such liquid cooled heat exchanger using heat pipe of sintered copper. The objective of research will be design and develop the system for liquid cooling for application of hydraulic cooling. The project work embodies the system development, thermal analysis using Ansys software and experimental performance evaluation and comparative evaluation of performance of the device.

III. EXPERIMENTAL SETUP

Fig.1. shows the experimental setup of heat pipe embedded oil cooler with enhanced staggered fin. In this setup the tank contain oil which is heated by immersion rod heater up to desired temperature (say 80^0 C -90^0 C) to cool this hot oil we design this heat pipe embedded oil cooler with enhanced staggered fin setup. Hot oil flows through flow control valve (1/4 " BSP) from tank to the heat pipe embedded tower cooler. Note this hot oil inlet temperature (T_{hi}). This hot oil enters into the heat pipe embedded tower cooler, heat of oil is extracted by heat pipe. Then the heat pipe transfers the heat to the fins and fins further dissipates the heat into air. Cooling fan is mounted above the fins. The inlet air temperature (T_{ai}) and outlet air temperature (T_{ao}) are measured. After the heat dissipation the oil in tower cooler get cooled that temperature is oil outlet temperature (T_{ho}). This oil is collected in flow measurement beaker. Measure, stop watch time required to fill 100 ml oil in beaker. Change the valve opening to record other readings. This system Increases the heat transfer rate by extracting latent heat which is 100% more than the sensible heat extracted by previous system. Thermostat used in the tank is Capillary type 30^0c to 300^0c

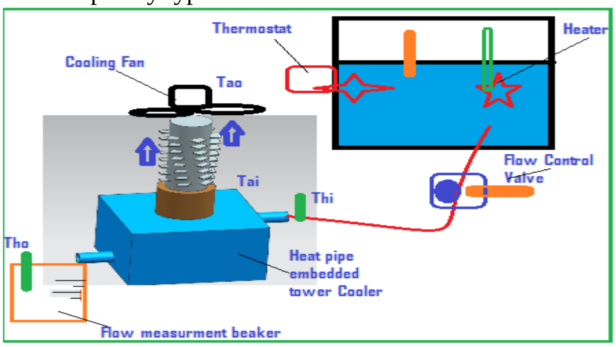

Fig.1 Experimental setup of heat pipe embedded oil cooler with enhanced staggered fin.

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Table.1 Inlet and outlet temperature readings of air and oil

Sr. No.	Cold air Inlet Temp. $(T_{ci})^0C$	Cold air outlet Temp $(T_{co})^0C$	Hot oil Inlet Temp. $(T_{hi})^0C$	Hot oil Outlet Temp. $(T_{ho})^0C$
1	30.2	31.5	81	76
2	31	32.5	80	68.4
3	30.5	31.3	80.5	61.3
4	30	33.2	80	57.5
5	31	34.8	79.5	51.2
6.	30.5	35.4	80.5	49.6

Table 1. shows the inlet and outlet temperature readings of air and oil, taken during the experimentation. Number of readings are taken by changing the valve opening. In Table.2 readings of volume of beaker and time are mentioned and by using this reading mass flow rate is calculated.

Table.2 Mass flow rate of hot oil

Sr. No	Volume in Beaker (ml)	Time (Sec)	Mass Flow Rate (Kg/sec)
1	100	38	0.0022
2	100	32	0.0026
3	100	28	0.0030
4	100	24	0.0035
5	100	20	0.0042
6	50	7	0.0060

The reading taken from the experimentation are used to calculated LMTD, overall heat transfer coefficient and effectiveness of this hydraulic oil cooler. LMTD (logarithmic mean temperature difference) shows the appropriate average temperature difference between the hot oil and cold air streams which drive the heat transfer. LMTD (ΔT_{lm}) can be calculated by using this formula,

$$\Delta Tlm = \frac{\Delta T2 - \Delta T1}{Ln(\Delta T2/\,\Delta T1)} \quad (1)$$

where ΔT_1 and ΔT_2 depend on heat exchanger configuration.
ΔT_1 = Hot oil inlet temperature (T_{hi}) ^0C – Cold air outlet temperature (T_{co}) ^0C.
ΔT_2 = Hot oil outlet temperature (T_{ho}) ^0C – Cold air inlet temperature (T_{ci}) ^0C.
Overall heat transfer coefficient expresses the total resistance experienced as the heat is transferred between oil and air. The overall heat transfer coefficient (U) is calculated by dividing the heat flux (q/A) by the temperature difference between the oil and air (ΔT_{lm}) where heat is being transferred, can be written as:

$$U = \frac{q}{A\Delta Tlm} \quad (2)$$

Effectiveness (ε) is the ratio of actual heat transfer in heat exchanger (q) to the maximum possible heat transfer (q_{max}), can be written as:

$$\varepsilon = \frac{q}{qmax} \quad (3)$$

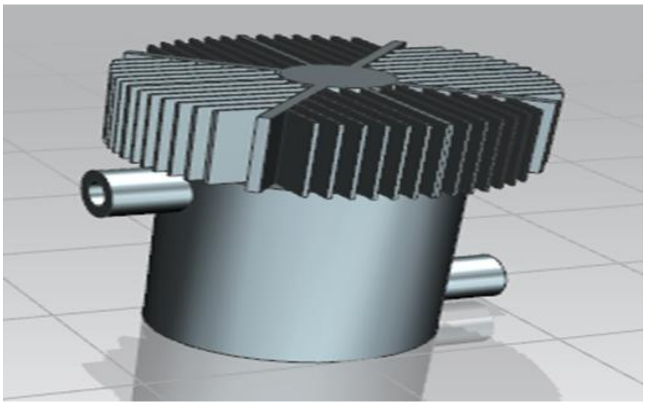

Fig.2 Assembly design of heat pipe Embedded oil cooling system drawn in Unigrafix Nx-8 software

This Heat pipe embedded oil cooler is designed in Unigrafix Nx-8 software. The above Fig.2 shows the assembly design of helical spiral radial fin, inlet and outlet pipe, tank and heat pipe which is embedded at the Centre of inner surface of fin. Tank is made up of base block made from aluminum, hollow at the Centre receives the heat pipe at the top and inlet hole is at the bottom of back end whereas oil exits from front top end. The central concept of the model is to extract the latent heat from the heat source hence we use the heat pipe. Copper heat pipe is used in this system which have sintered copper wick structure. The material of wick is copper having water as a working fluid. Diameter of pipe is 12mm and length is 50mm. Filling ratio is 50% of volume of pipe. The fins used in this system provide the maximum surface area in given 100 x 100 mm space that will increase the heat dissipation ability improving the efficiency of system. The structure of fins allows maximum permeability of air there by allowing maximum air flow over the fins which will enhance the heat transfer rate. A ready central hole mounting with 12 mm bore which makes the mounting of the round heat pipe with ease and low cost of manufacturing, maximum surface contact on the evaporator section.

IV. STEADY -STATE THERMAL ANALYSIS OF FINS

Solid model of fin structure and heat exchanger was developed using Unigraphix Nx-8 software and the steady state thermal Analysis of fins was done in Ansys workbench 16.0. In Ansys first the meshing was done and then the generate command was used to apply it, the mesh parameter set by the workbench are nodes-33375, Element-15403. To obtain the results two boundary conditions are applied on fins as shown in Fig.3 and Fig.4.

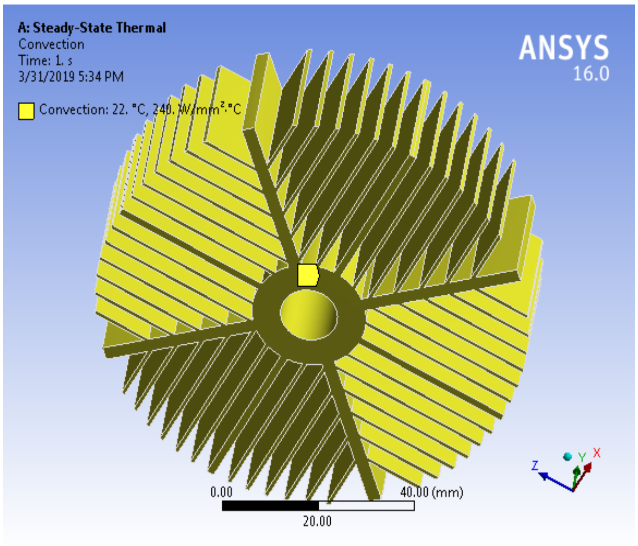

Fig.3 First boundary condition applied on fin.

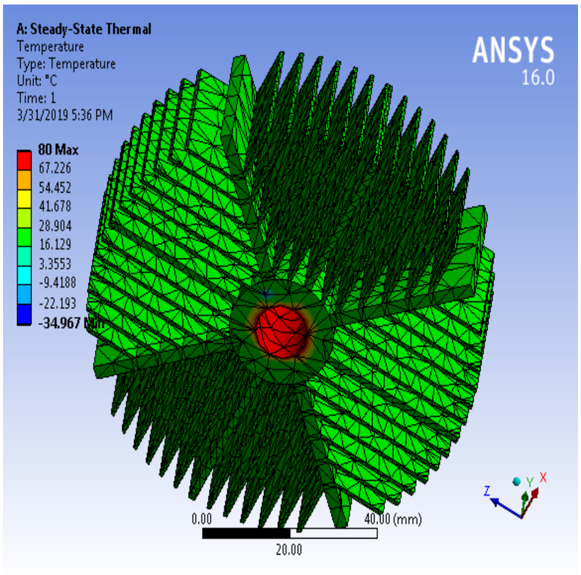

Fig.5 Temperature distribution of fin.

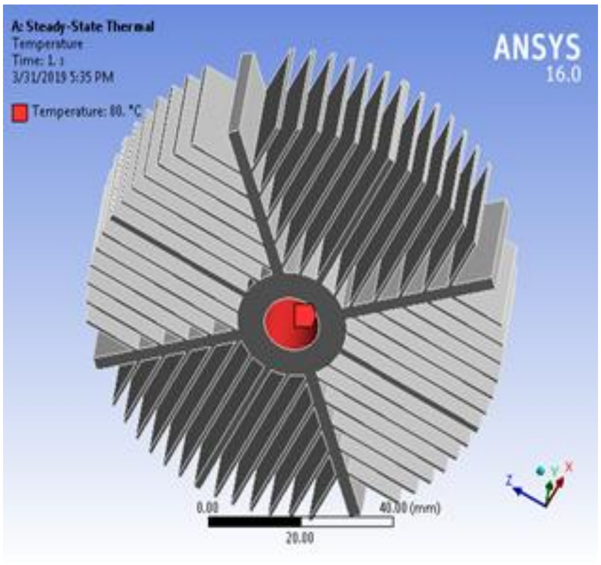

Fig.4 Second boundary condition applied on fin.

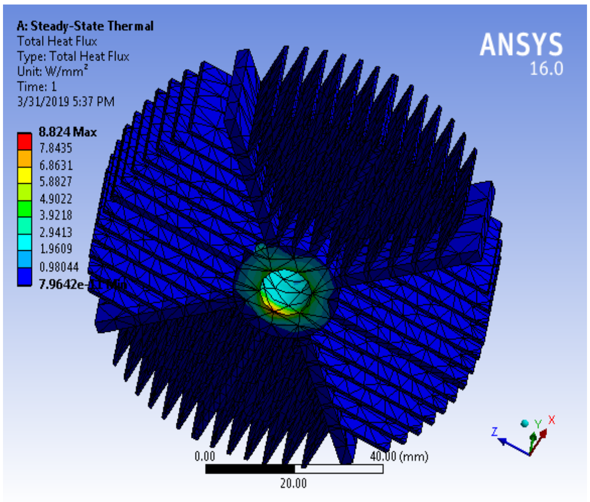

Fig.6 Total heat flux of fin.

The temperature variation contour is obtained when given boundary condition are applied to the problem shown in Fig.5.The results obtained from ANSYS software simulation for temperature contour. From this Fig.5 we can say that as fluid entered into aluminum block firstly it comes in contact with inner member therefore maximum temperature exists there. After that it is entered the fin section where heat is dissipated. The Fig.6 show that the heat flux carried by the fin system which is nearby 8.84 watt very close to the required heat dissipation ability of the system.

V. RESULTS AND DISCUSSION

Table.3. shows the results for hydraulic oil cooler with shell and tube heat exchanger is used for cooling the hot oil (Existing system). Table.4 shows the results for the heat pipe embedded oil cooler with enhanced staggered fins used for cooling the hot oil. (New system). The LMTD, Overall heat transfer coefficient and effectiveness are calculated by using the inlet and outlet temperature of hot oil and cold air.

Table.3 Shell& tube heat exchanger results:

Sr. No	Hot oil Inlet temp (Thi)	Hot oil outlet temp (Tho)	Cold air Inlet temp (Tci)	Cold air Outlet temp (Tci)	LMTD	Effectiveness	Overall HTC (U)
1	81	78	30.2	30.8	48.97	0.059	1.765
2	80	73	31	31.6	45.09	0.142	2.382
3	80.5	67	30.5	32.1	42.05	0.27	8.277
4	80	61	30	32.4	38.48	0.38	15.60
5	79.5	58.2	31	32.8	35.71	0.439	14.38
6	80.5	55.6	30.5	33.4	34.45	0.498	23.91

Table.4 Heat pipe embedded oil cooler results:

Sr. No	Hot oil Inlet temp (Thi)	Hot oil outlet temp (Tho)	Cold air Inlet tem p (Tci)	Cold air Outlet temp (Tci)	LMTD	Effecti-veness	Over-all HTC (U)
1	81	76	30.2	31.5	47.62	0.098	3.934
2	80	68.4	31	32.5	42.24	0.236	6.362
3	80.5	61.3	30.5	31.3	39.28	0.384	4.442
4	80	57.5	30	33.2	36.29	0.45	22.18
5	79.5	51.2	31	34.8	30.84	0.583	35.51
6	80.5	49.6	30.5	35.4	30.26	0.618	46.68

Various tests are performed in the experimental setup for different mass flow rate. For the different mass flow rate various parameters like effectiveness, LMTD and overall heat transfer coefficient are calculated and plotted on graph. From these graphs we compare the performance of previous system that is shell & tube heat exchanger and new system that is heat pipe embedded oil cooler for different mass flow rate. These graphs are as follow:

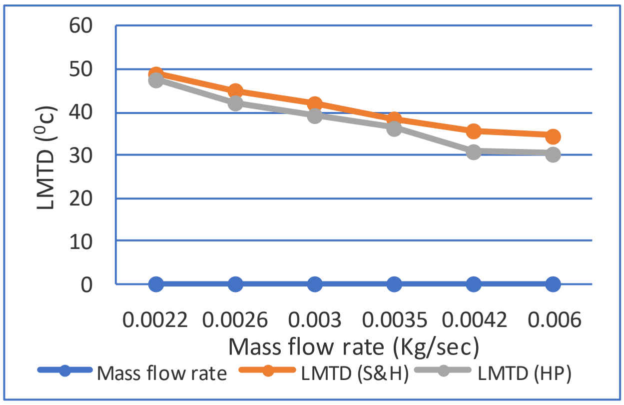

Fig.7 Comparative graph of LMTD Vs mass flow rate.

Performance comparative graph of LMTD Vs mass flow rate in shown in Fig.7.In this graph LMTD (log mean temperature difference) is seen to drop with increase in the flow rate of oil. LMTD for the heat pipe heat exchanger is lower as compared to that of the shell tube heat exchanger. In shell and tube heat exchanger, initially for the mass flow rate of 0.0022 Kg/sec the LMTD is 48.97 and finally it becomes 34.45 for mass flow rate 0.006 Kg/sec. The value of LMTD decrease by 14.52. In case of heat pipe heat exchanger initially for mass flow rate of 0.0022 Kg/sec the LMTD is 47.62 and finally it becomes 30.26 for mass flow rate 0.006. In this case LMTD decrease by 17.36. Hence Fig.7 shows the performance of LMTD is better in case of heat pipe as compare to shell and tube heat exchanger. the minimal flow rate is likely to result in better LMTD given that the oil is in contact with heat pipe

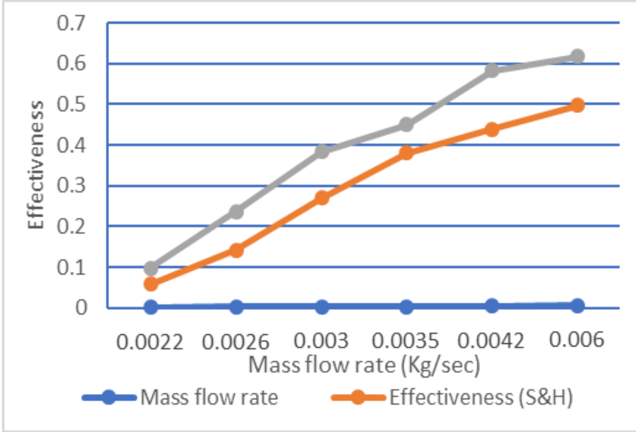

Fig.8 Comparative graph of Effectiveness Vs mass flow rate.

Fig.8 shows the performance comparative graph of effectiveness vs mass flow rate. The effectiveness of the heat pipe heat exchanger is better than the shell tube heat exchanger thus it requires lesser space and operating cost. the effectiveness of the heat exchanger increases steadily with increase in flow rate of oil again this is due to combined effect of the increased heat extraction ability of the heat pipe which increases with increase in mass flow rate.

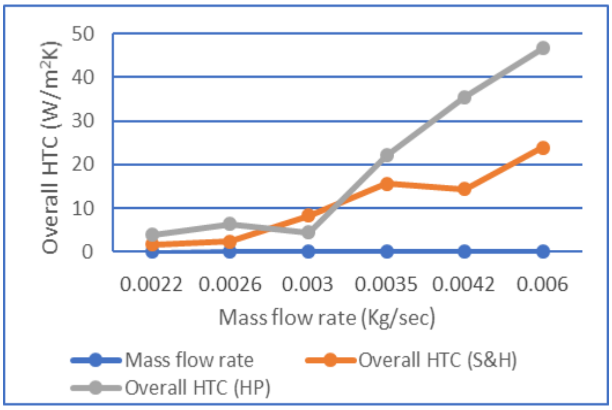

Fig.9 Comparative graph of Overall HTC Vs mass flow rate.

Fig.9 shows the comparative graph of overall heat transfer coefficient (HTC) vs mass flow rate of heat pipe and shell and tube. The overall heat transfer coefficient of the heat exchanger increases steadily with increase in mass flow rate of oil. The overall heat transfer coefficient of the heat pipe system is better than that of the shell & tube, hence the heat pipe system is recommended over the Shell &Tube system.

VI. CONCLUSION

The following conclusion are drawn from the present research work:

i. LMTD is seen to drop with increase in the flow rate of oil in either cases.

ii. Effectiveness increases steadily with increase in mass flow rate.

iii. Overall heat transfer coefficient increases with increase in mass flow rate.

iv. Optimal performance of the Sintered copper heat pipe system with staggered fins is obtained when the mass flow rate of oil is 0.006 kg/sec.

v. A simple, compact, high efficiency, low cost device is developed, so new technology of heat pipe embedded oil cooler is learnt in this present work. This project provide industry with a new device to solve over heat problems in many machines and applications.

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