Heat transfer analysis of the DOT 4 brake fluid using a double pipe heat exchanger

C Sharma, M Siddiqui, Md Imran and G Manikandaraja

Department of Mechanical Engineering, SRM Institute of Science and Technology, Kattankulathur, Chennai, Tamilnadu, India

Email: pandat.bhardwaj97@gmail.com

Abstract. An important factor in the heat exchanger is the enhancement of the heat transfer rate. Heat exchangers succumb to numerous losses resulting because of convection, conduction, and radiation from the experimental set-up which hinders its performance. This project focuses on developing a parallel flow model for the analysis of DOT4 brake fluid considering the numerous energy losses based on experimental results. Various parameters like mass flow rate, inlet temperature on the overall heat transfer rate, and their effects are studied. Basis of the results, parameters are considered for better performance which has been taken into consideration for doing theoretical calculations. This project aims at analyzing the brake fluid both experimentally and theoretically by fabrication of the heat exchanger using mild steel and copper, henceforth experimenting to obtain the analysis of the fluid.

1. Introduction

Energy is a well-known sector for determining the economics of countries that mainly rely on the techniques used. Most of the energy sector utilizes heat exchangers to transfer the heat efficiently. The utilization of energy is a primary factor that readily decreases abundant costs in the energy sectors. Hence heat exchanger used should have a higher energy conversion. Some of the heat transfer mediums used in heat exchanger - ethylene glycol, engine oil, water, etc., which can be employed well in many heat exchangers. Double heat exchangers or pipe in pipe heat exchangers are compact and easy to fabricate which can be effectively placed suitably in most of the applicants. Double pipe heat exchangers are commonly used in compact devices for transferring heat from one source to another with substantially improved performance results. When large quantities of fluid need to be heated or cooled, concentric tube or double-pipe heat exchangers are employed to withstand high temperature and pressure and therefore most of the parts of the IC engines which still subjected to high temperature or medium temperature in which heat needs to be removed often to conduct better operations use double pipe heat exchangers. Some parts of the IC engines which need a high rate of heat transfer are radiators, jacket circulating water, the oil used in lubrication, and oil used for braking systems.

The effectiveness of heat exchangers can be achieved by enhancing the thermal properties of the flowing medium. A series of tubes bundled together in a specific orientation is what defines a double-pipe heat exchanger. The fluid has to be either heated or cooled runs through the tubes. The governing fluid that will either provide heat or absorb heat runs through the concentric space. The designing of
heat exchangers depends upon flow arrangements and incorporate numerous designs depending upon the desired outcome. Concentric tube or double-pipe within which one pipe is concentric with the other in which two fluids are flowing from entry region to exit region and all the flows can flow either in the same direction as parallel flows or in opposite directions as counter flow.

The present investigation of our project includes the detailed study of the heat transfer process for parallel flow and the study of characteristic graphs. Here we used double pipe heat exchangers in which the inner pipe is copper-base, whereas the outer pipe is a mild-steel base for best results. Characteristic graphs show the performance of our designed heat exchanger.

2. Literature survey

(1) done the optimal design of the tube in tube heat exchangers for corrugated helical tube and he found out that heat transfer has inversely proportional to the diameter of the shell with significant pressure drop and that heat transfer is mainly improved by the fluid impact to the wall with little effect of the spiral flow. The heat transfer performance is linearly decreased with the increase in shell diameter, but the pressure drop is sharply decreased when the shell diameter equals to 38 mm, which is the best design for comprehensive consideration. (2) found that employing the nanoparticle additives such as Al₂O₃-TiO₂ increases the heat transfer and it also increases the exergy efficiency of the tube in heat exchangers. He conducted the statistical analysis to improve the heat transfer efficiency with the help of the nanofluid and found out that when nanoparticles volume concentration increases, increasing the Reynolds number, reducing the twist ratio can significantly raise the exergy efficiency. Also, due to the random motions of nanoparticles mainly near the walls of the tube, leads to high axial pressure drops of the flow inside the tube as the momentum increases between particles. (3) uses the porous medium in double pipe heat exchangers to progress the heat transfer. The corrugated double pipe heat exchangers have the roughness of the surface of the heat exchangers which enhances the rate of heat transfer. It also shows that the sensitivity of the heat exchanger effectiveness enhances with the increases in the Reynolds number and ΔT. The sensitivity to the Reynolds number is positive but negative to the Darcy number. (4) found that heat pipes are passive systems that require no power to operate, heat pipe heat exchanger has great potential for applications in both commercial and industrial markets. He also observed that there was no cross leakage between heating and cooling streams in the heat pipe heat exchanger. An important factor contributing to the higher heat transfer rates seen in heat pipe heat exchangers is due to the forced convection between the hot and cold streams and the evaporator sections of the heat pipes. While the hot and cold streams must be in direct contact (through a separating surface) in a conventional heat exchanger, a heat pipe heat exchanger can transfer heat between two media located remotely from each other, promoting considerable design flexibility and finally, the incorporation of heat pipes into heat exchangers had large temperature differences between hot and cold source and they increased the overall heat transfer co-efficient in addition to having ease of assembly, versatility, scalability, and adaptability amongst the other attributes. (5) dimensionless design parameters are identified where each parameter has a different impact on the temperature distribution of the different fluid streams and a detailed analysis is required whenever a change is observed.

In the literature survey, many experiments were done using a double pipe heat exchanger which shows a detailed analysis of the performance of the heat exchanger which can be used as a reference for our work.
3. Methodology and theoretical analysis

3.1. Materials
The material used is the Mild Steel tube, Copper tube, Heater, 4 J types Thermocouple, K type multichannel temperature indicator, L joint coupling, and a Male to Male connector and valves. The Mild Steel pipe of (1") and Copper tube of (3/8") is used for the heat transfer from hot DOT 4 brake fluid to cold water which is kept at room temperature. Thermocouples are used for sensing the change in temperature on both inlet and outlet of both DOT 4 brake fluid and water (mainly for brake fluid). The multimeter is used for displaying the temperature and is connected by the thermocouple. A heater of 1500W power is used for heating the brake fluid.

3.2. Methodology
Firstly, we need to heat the brake fluid in the heater and after attaining the desired temperature the brake fluid flows from the heater to an entry region of the heat exchanger where we place the first thermocouple for sensing the inlet temperature of the brake fluid and fluid flows from entry region to exit region where the second thermocouple is placed for sensing the outlet temperature of the brake fluid. Water flows from another entry region of the heat exchanger where the third thermocouple is placed for sensing the inlet temperature of the water, which is mainly kept at room temperature and from there the water flows to the exit region of the heat exchanger where the fourth thermocouple is placed which senses the outlet temperature of the water. The flow inside the heat exchanger is a parallel flow, i.e. both the fluids (DOT 4 brake fluid and Water) flow in the same direction. When both fluid flow from an entry region to an exit region of the heat exchanger, the heat transfer takes place where heat energy flows from brake fluid to water, i.e. from high temperature to low temperature thus reducing the brake fluid temperature while increasing the water temperature as the water absorbs the heat energy due to the high specific capacity of water. Valves are used to open or close the passage of water, thus reducing the leakage of water.

![Figure 1. Schematic figure of a double pipe heat exchanger.](image)

Figure 1 shows the schematic figure of a double pipe heat exchanger showing the flow diagram of both fluids from inlet to outlet valves of the heat exchanger and it also shows the places where all four thermocouples are placed at the valves of the heat exchangers for temperature measurement.
4. Fabrication
Procurement of Mild Steel Tube, Copper tube, 4 J type Thermocouples, 2 L joint couplings, K type multi-channel temperature indicator, and heater. The tubes were welded together using Arc Welding and also with L joint couplings. Joints were attached to both the inlets and outlets that were connected to heater and water ports to reduce the cost of the manufacturing of the heat exchanger. Thermocouples were attached to both the inlets and outlets which were further attached to the temperature indicator.

![Figure 2. Real-time image of heat exchanger setup.](image)

Figure 2 shows the real-time image of the heat exchanger setup and shows all the L-joints, couplings, tubes, pipes, valves, and heater connected. This shows all the materials used to fabricate the double pipe heat exchanger.

5. Methodology Specification of Heat Exchanger
1) Length – 0.45 m
2) Inner Diameter – 3/8” pipe
3) Outer Diameter – 1” pipe
4) Specific heat capacity of brake fluid – 0.9 KJ/Kg K
5) Specific heat capacity of the water – 4.2 KJ/Kg K
6) The viscosity of brake fluid – 2.1369*10^{-3} m²/sec
7) Heater – 1500 watts
8) DOT 4 Brake Fluid – 1 Litre

6. Experimentation and Formulas
The setup is prepared, fabricated, and cleaned with all the joints attached. The thermocouples are attached to both the outlets of oil and water and are further attached to the temperature indicator. The brake fluid is preheated to the desired temperature and measured by a temperature indicator along with water temperature. The brake fluid and water are made to enter the respective inlets and flows out through the respective outlets which have a preinstalled thermocouple to it to measure the readings. The readings are taken through the temperature indicator, tabulated and then the necessary calculation and analysis made. The same steps are followed for 3 different temperatures of brake fluid. Tabulations made and calculations done. Finally, the results are plotted. Various formulas are used for plotting graphs, and those formulas are :-
The mass flow rate of brake fluid,

\[ m = \frac{Q}{C_p \Delta T} \]  \hspace{1cm} (6.1)

where \( Q \) is the heat energy, \( C_p \) is the specific capacity of brake fluid, \( \Delta T \) is the change in temperature of brake fluid, and \( m \) is the mass flow rate of brake fluid.

The velocity of brake fluid,

\[ V = \frac{m}{\rho \times A} \]  \hspace{1cm} (6.2)

where \( A \) is the area of the copper tube \((A=\pi r^2)\), \( r \) is the radius of the inner tube, \( \rho \) is the density of the brake fluid and \( V \) is the velocity of brake fluid in the heat exchanger. Velocity is required to measure Reynolds number which tells us whether the flow is laminar or turbulent.

Reynolds number of brake fluid,

\[ Re = \frac{\rho \times V \times d}{\mu} \]  \hspace{1cm} (6.3)

where \( d \) is the diameter of the copper tube (inner tube), \( \mu \) is the dynamic viscosity of the brake fluid. After calculating the Reynolds number we found out that its value is more than 2300 and therefore the flow is turbulent. Thus heat energy transfer is more rapidly done in the heat exchanger.

Logarithmic Mean Temperature Difference,

\[ \text{LMTD} = \frac{(\Delta T_1 - \Delta T_2)}{\ln \left( \frac{\Delta T_1}{\Delta T_2} \right)} \]  \hspace{1cm} (6.4)

where \( \Delta T_1 \) is the difference in inlet temperature of brake fluid and outlet temperature of water and \( \Delta T_2 \) is the difference between the outlet temperature of brake fluid and inlet temperature of the water. LMTD is used to assume the rate of change of temperature of both fluids i.e. the more the LMTD, the higher the rate of heat transfer from one fluid to another.

Heat transfer coefficient for Outer pipe,

\[ h_o = \frac{Q}{A \times \Delta T} \]  \hspace{1cm} (6.5)

where \( A \) is the area of Mild Steel pipe \((A=\pi R^2)\), \( \Delta T \) is the temperature difference of water, \( Q \) is the heat energy of the heat exchanger and \( h_o \) is the heat transfer coefficient for outer pipe (the pipe which has bigger diameter). The heat transfer coefficient is used to determine the heat transfer from the fluid.

Heat transfer coefficient for Inner pipe,

\[ h_i = \frac{Q}{A \times \Delta T} \]  \hspace{1cm} (6.6)

where \( A \) is the area of the Copper tube \((A=\pi r^2)\), \( \Delta T \) is the temperature difference of brake fluid, \( Q \) is the heat energy of heat exchanger, and \( h_i \) is the heat transfer coefficient for inner pipe (the pipe which has smaller diameter). The heat transfer coefficient is used to determine the heat transfer from the fluid.
Effectiveness,

$$
\varepsilon = \frac{m \times C_p \times \Delta T_1}{C_{min} \times \Delta T_2}
$$

(6.7)

where \(m\) is the mass flow rate of brake fluid, \(C_p\) is the specific heat capacity of brake fluid, \(C_{min}\) is the product of mass flow rate and specific heat capacity of brake fluid, \(\Delta T_1\) is the temperature difference of brake fluid and \(\Delta T_2\) is the temperature difference between the inlet temperature of brake fluid and inlet temperature of the water. Effectiveness is used to determine the performance of the heat exchanger.

Overall heat transfer coefficient,

$$
\frac{1}{U \times A_o} = \frac{1}{h_i \times A_i} + \frac{\ln \left( \frac{R}{r} \right)}{2 \times \pi \times L \times k} + \frac{1}{h_o \times A_o}
$$

(6.8)

where, \(h_i\) is the heat transfer coefficient of brake fluid, \(h_o\) is the heat transfer coefficient of water, \(R\) is the diameter of the outer pipe, \(r\) is the diameter of the inner pipe, \(k\) is the thermal conductivity of copper pipe (inner pipe), \(A_i\) is the area of the Copper tube (inner pipe), \(A_o\) is the area of Mild Steel pipe (outer pipe). The overall heat transfer coefficient is used to determine the heat transfer through all the mediums in the heat exchanger.

Number of transfer units,

$$
N = \frac{U \times A}{C_{min}}
$$

(6.9)

where \(U\) is the overall heat transfer coefficient, \(A\) is the area of the Copper tube \((A = \pi r^2)\), \(C_{min}\) is the product of mass flow rate and specific heat capacity of brake fluid. NTU is used to determine the effectiveness of the heat exchanger.

Effectiveness,

$$
\varepsilon = \frac{[1-\exp\{-N(1 + C_r)\}]}{1 + C_r}
$$

(6.10)

where, \(C_r = C_{min}/C_{max}\). \(C_{min}\) is the product of mass flow rate and specific heat capacity of brake fluid, \(C_{max}\) is the product of mass flow rate and specific heat capacity of water, \(N\) is the number of transfer units. Effectiveness is used to determine the performance of the heat exchanger.

7. Results and discussions

As it is difficult to discuss every result of the calculations, it is decided to discuss the numerical values of the different temperature distributions of the two fluids under the influence of parallel flow in the heat exchanger. The temperature of brake fluid ranges between 375K – 340K and the temperature of water range 295 K – 305 K are taken into consideration in this paper. The velocity of both fluids is taken as same for simpler calculations.
The values of effectiveness which are obtained from correlations as discussed earlier and the resulting temperature distributions are shown in Figure 3. One can observe from the graph that as the temperature decreases the effectiveness increases thus it means that the heat energy transfers from hot brake fluid to cold water rapidly and effectively. Figure 5 also shows the characteristic changes in temperature of both the fluids as there is a significant downfall in the brake fluid temperature while the temperature of water almost remains the same thus showing the high heat capacity of water.

Since the effectiveness of the heat exchanger increases, the rate of heat transfer also increases which increases the efficiency of the heat exchanger. The values of efficiency were obtained and are plotted at various temperature distributions for both fluids in Figure 4. As we can see, the results are within our estimation, the temperature of brake fluid decreases rapidly while there is an increase in efficiency, thus we can say that the heat transfer is taken place from brake fluid to water with ease and at a fast pace. We can also see that there is a huge change in brake fluid temperature while the efficiency increases at a significant pace.
Figure 5. Temperature Vs Efficiency.

The values of overall heat transfer coefficients are obtained from correlations as discussed earlier and the resulting temperature distributions are shown in Figure 5. One can observe that at a high temperature, the overall heat transfer coefficient is more, therefore, more amount of heat energy transfers from brake fluid to water takes place at high temperatures. One can observe that as the temperature distribution of brake fluid decreases, the overall heat temperature coefficient also decreases so low-temperature heat transfer takes place at a very slow speed.

Figure 6. Temperature Vs C_{min}.

The values of C_{min} are obtained from correlations as discussed earlier and the resulting temperature distributions are shown in Figure 6. One can observe that at a high temperature, C_{min} is more while at low temperature, C_{min} is less. This shows that more heat can store at high temperatures due to high specific heat capacity of oil and therefore brake fluid is a good lubricant used in storing heat energy.
The values of NTU are obtained from correlations as discussed earlier and the resulting temperature distributions are shown in Figure 7. One can see that as the temperature decreases, the number of transfer units increases therefore as the heat energy transfers from high-temperature brake fluid to low-temperature water the number of transfer units increases, and therefore the rate of heat transfer increases in the heat exchanger.

8. Conclusion
An experimental analysis of DOT 4 brake fluid using double pipe heat exchanger was performed over a range of temperature distributions and yielded the following inference; as the temperature increases, the rate at which heat is transferred from the hot fluid to the cold fluid also increases which is because, in double pipe heat exchangers, the efficiency is higher which is evident from the graph and therefore has a direct relation to the rate of heat transfer.

We also noticed from the temperature distribution, there was a direct impact on the number of transfer units, as the temperature decreases, the number of transfer units increases which increased the heat transfer rate.

From the graph between temperature and $C_{\text{min}}$, it is evident that brake fluid is an excellent lubricant, with an increase in temperature, the value for $C_{\text{min}}$ also increased which is a direct indication of the amount of heat energy the oil can store thus making it a perfect candidate.

The advantage that we had to conduct such an experiment with much ease was the due fact that we went for a double pipe heat exchanger and a parallel flow which not only helped us in manufacturing but also while testing as there were no leakages and since the flow was parallel, we had ample amounts of time to study the heat transfer between the hot and cold fluid.

Thermal characteristics were also taken into consideration while doing this experiment, graphs of which have been plotted along with an explanation in addition to the other graphs which show the performance characteristics of the heat exchanger.

The mass flow rate and Reynolds number were used to determine the flow of the fluid as that helped us in studying the effectiveness of the heat exchanger, theoretical calculations were done by both the LMTD method and the NTU method both indicating an increase in efficiency over higher temperatures. After doing both theoretical as well as practical analysis of the heat exchanger, the results were within estimated counts and the fabricated heat exchanger worked efficiently.
9. References

[1] Wang W 2019 Optimal design of a double pipe heat exchanger based on the outward helically corrugated tube. *International Journal of Heat and Mass Transfer*. 135 706-716.

[2] Maddah H 2018 Factorial experimental design for the thermal performance of a double pipe heat exchanger using Al2O3-TiO2 hybrid nanofluid *International Communications in Heat and Mass Transfer* 97 92-102.

[3] Shirvan K M 2017 Heat transfer and sensitivity analysis in a double pipe heat exchanger filled with a porous medium *International Journal of Thermal Sciences* 121 124-137.

[4] Shabgard H 2015 Heat pipe heat exchangers and heat sinks: Opportunities, challenges, applications, analysis, and state of the art *International Journal of Heat and Mass Transfer* 89 138-158.

[5] Quadir G A 2014 Numerical investigation of the performance of a triple concentric pipe heat exchanger *International Journal of Heat and Mass Transfer* 75 165-172.