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Heat Distribution of Micro Turbocharger Cooling System for Motorcycle Application

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Abstract: The heat produced in turbocharger has the potential to destroy the bearing system and the oil piston ring. For the past years, the researchers have focused on heat transfer of micro turbocharger. The lack of research on the cooling system of the turbocharger has motivated the author to publish this paper. In this paper, the electrical water pump with air blower is used to reduce the heat effect. The impact of adding electric water pump o heat distribution on turbocharger has been discovered by conducting experimental research. The experimental research was conducted on one cylinder, two-stroke with Lifan engine 160 cc equipped with the turbocharger. The temperatures of the turbine, bearing housing, coolant inlet and outlet are measured and analyzed in this turbocharged engine test rig.

Index Terms: cooling system, electrical water pump (EWP), turbocharger

I. INTRODUCTION

Many people hear about a motorcycle turbocharger and assume that it must be a powerful tool for increasing the overall power of a motorcycle without genuinely realizing how it functions. Thus, to prove the turbocharger engine performance, an engine test rig is used. It is a facility used to determine the characteristics and functions of engines, such as power, rotational speed, fuel consumption, temperature, operating performance, and exhaust emission. Nevertheless, the turbocharger that installed on the motorcycle engine requires the cooling system, as shown in Fig. 1 to prevent the performance of it being affected. Therefore, this project purposes of investigating the effect of heat distribution when applying an electrical water pump cooling. Turbochargers are devices known in the art that are used for forcing or increasing the intake airflow to a combustion chamber of the engine, by using the heat and volumetric flow of exhaust gas leaving from the engine. Specifically, the exhaust gas takes off the engine is routed into a turbine housing of a turbocharger in a means that causes an exhaust gas-driven turbine to spin within the house. The exhaust gas-driven turbine is attached to one end of a shaft which is common to a radial compressor blade mounted onto an opposite end of that shaft.

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Thus, the rotary action of the turbine blade also causes the compressor blade to spin within a compressor housing of the turbocharger. The bearing system that supports the rotor assembly, which is the turbine, shaft, and compressor, resides in the turbocharger centre housing. The bearing system must reliably position and support the rotor from zero up to speeds that can approach the higher revolutions per minute.

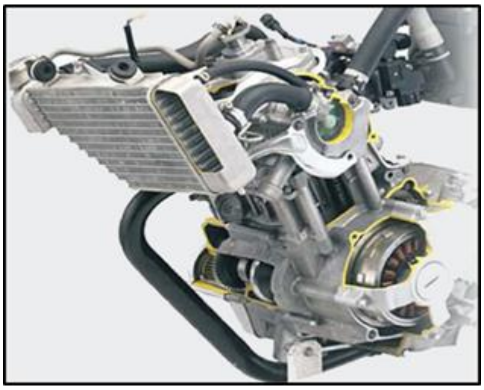

Fig. 1: Cooling system in turbocharger motorcycle engine

As an addition to the rotating loads on the bearings, it can be substantial thrust loads in either direction, depending on operating conditions. The bearing system also influences on critical rotor speeds, vibration and shaft instability. The temperature of the turbocharger environment also presents a challenge to the bearing system. If the engine is shut down immediately following a run at high power output, the turbine, and turbine housing temperatures are toward their upper limits, and suddenly all gas flow through the turbine stops and all oil flow through the centre housing stops. All that heat must go somewhere, and an easy path is into the centre housing. The heat stored in the turbine housing and exhaust manifold "soaks back" into the centre section which is the housing in the area of the bearings. The resulting temperatures can quickly cook the oil to a solid and will cause the bearing damage which potentially disastrous results on the next run.

II. LITERATUREREVIEW

The research conducted by [1] examined the results of many turbocharger tests with different heat transfer rates from the turbine to compressor in a turbocharger test machine. For this purpose, the tests were carried out with and without the cooling water of the bearing housing. These results indicate the high impact of heat transfer on the efficiency of the compressor and turbine, especially at low speeds and flanges, but the effect of heat transfer on the overall performance of the turbocharger is negligible since it does not affect the compressor and turbine compression ratio. In the investigations by [2], heat transfer was simulated from the turbine to the compressor, and it was assumed in the simulation that external heat transfer was merely from the turbine housing to the environment.

Based on the results, the heat transfer conditions, such as the turbine inlet temperature, oil discharge, or water flow from the turbocharger, affect the temperature of the simulated turbine to the compressor. In addition to the mentioned parameters, the air passing through the turbine in the car or the cooling fan position in the test room also affects. Based on the research results of [2], the temperature of the compressor wall is influenced by the temperature of the bearing housing and the turbine wall temperature.

The temperature of the bearing housing is also regulated by the inlet water temperature, while in the absence of the drainage path; the temperature of the bearing housing is directly affected by the oil inlet temperature were investigated by [3]. Although the temperature of the turbine wall is highly dependent on the temperature of the turbine inlet gas, the change in heat transfer displacement will significantly change the temperature of the turbine wall was carried out by [4]. [5] and [10] has investigated on the turbocharger's external heat transfer, and five temperature sensors were installed on five axial planes of the turbocharger as shown in Fig. 2 to check the turbocharger heat transfer temperature. The reason for this is the information that the turbine tank is hot, and its exterior is high. In the compressor housing, external heat transfer may be reversed, according to the working conditions and heat may be absorbed or repelled. An essential part of the absorption of the compressor condenser is the radiation induced by the outer surface of the turbine housing.

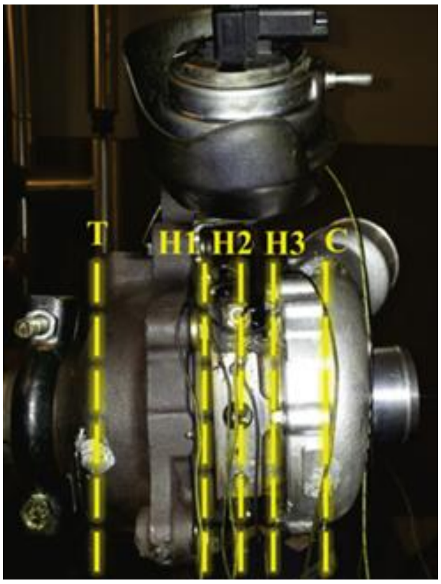

Fig. 2: Axial positions for temperature sensors

According to research conducted by [6] indicated that once the engine stalls, the turbocharger temperature would significantly increase to 200 °C due to the uncirculated cooling liquid. This higher temperature may cause the engine oil coking. [6] analyzed the turbocharger bearing temperature increased from 95 °C to 340 °C within 40 seconds when the engine stalls. After 90 seconds, the bearing temperature would cause a reduction to about 135 °C, if the temperature of the turbocharger is higher than 204 °C, which may result in damage to the oil quality and it may cause oil coke. This is supported reserach by [7] which reveal that on the stagnant fluids in mechanisms such as the injectors and bearings become exposed to excessive heat which spreads by conduction, radiation and natural convection through the engine, and potentially leading the oil to decompose and to form a build-up of carbon through a phenomenon called "oil coking". The heat soak-back occurring in engines under post-shutdown conditions is by no means a new problem. The high pressure, high-velocity airflow causes convective heating, which in turn raises the temperature of the fuel before it is sprayed into the combustion chamber. On the one hand, the combustion process can benefit from this increase in temperature since a lower viscosity for the fuel promotes finer atomization. Keeping in mind that heat flows naturally from hot to cold, the heat starts flowing from the hot components to the colder air after the engine shut down and transferring to colder components was studied by [7]. This phenomenon happens when the turbocharger bearings are deprived of the lubricating oil cooling effects because the engine was shut down immediately after operating in a high load condition was investigated by [8]. Authors said it as a heat absorption condition called the heat soak phenomenon that affecting turbocharger performance. Heat flowing from the turbocharger housing and turbine wheel to these uncooled bearings and can raise bearing temperatures over 300°C. At these temperatures, lubricating oil remaining in the bearing become carbonized causing the bearings to stick and prematurely wear. Consequently, the turbocharger service life is severely reduced. The finding is consistent with findings of past studies by [9], which heat stored in the exhaust manifold and turbine housing is “soaks back” into the centre section of the turbocharger after shutdown. “Heat soak back” is the greatest turbo killer and should be taken seriously by turbocharger engineers and turbo users alike. This destructive heat originates from the exhaust system. During hard usage, the higher exhaust gas temperatures dump massive amounts of heat into the exhaust manifold, turbine housing, and turbine wheel. These parts are designed to handle very high temperatures through careful design and materials selection. The author found that a small amount of heat will be transmitted to the surrounding air through the radiation and convection, but the most significant majority will be transferred from the turbine housing into the centre housing since the centre housing is at the lower temperature. Also, some of the heat will flow from the turbine wheel into the shaft and out towards the bearing system. During the phase of the turbine and exhaust cool down, as the heat is “soaking back” into the turbocharger centre section as shown in Fig. 4. The larger turbine housing size worsens this effect due to the more heat is stored in the housing during operation. Therefore, there is a higher risk for damage to the turbocharger during heat soak back after engine shutdown.

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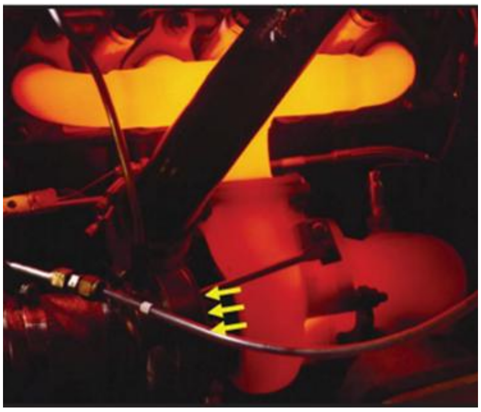

Fig. 4 Heat soak back into the turbocharger centre housing.

III. METHODOLOGY

In order to investigate the heat trapped in the centre section of the turbocharger, the examination required exact measurements, not only across the centre section but also all over the part of the turbocharger. The engine used for this work is a single-cylinder, two-stroke with the engine displacement of 160 cc equipped with the water-oil-cooled turbocharger. The experiments will be performed in three situations to analyze the heat distribution in the turbocharger system. These situations are used to be able to study heat transfer and change its condition on the turbocharger:

1) Turbocharger running with or without the cooling system.
2) Cooling system running methods after the engine shut down.
3) Turbocharger running with a different coolant flow rate of the cooling water system.

The first and second situations have four similar methods that will be applied on the turbocharger, but the difference is the first situation uses the cooling system when the engine is working, and for the second situation, the cooling system will be applied after the engine is turned off. Four similar methods are used to examine heat transfer:

1) The first method is cooling water and blower will not be used to cool down the turbocharger.
2) The second method is the water will be allowed passes into the water passage in the bearing housing to reducing the heat in the centre section of the turbocharger.
3) The third method is a blower will be placed on the front of the turbocharger to change the air velocity around it and the situation of convection heat transfer.
4) The last method is the cooling water and blower used to provide the maximal cooling medium to cool down turbocharger parts.

The third situation will be conducted when the turbocharger running at the constant speed, and as the centre housing reaches the temperature of 150 °C, the electric water pump will be turned on. The voltage regulator used to regulate the coolant flow rate and five different flow rates that would be controlled and examined in this experiment, which consist of 4.5, 5.5, 6.5, 7.5 and 8.5 LPM. Several thermocouple probes have been measuring the temperature of the turbine, centre housing, inlet and outlet of water port to analyze the temperature distribution on the turbocharger. The layout configuration of the micro-turbocharger cooling system as illustrated in Fig. 5.

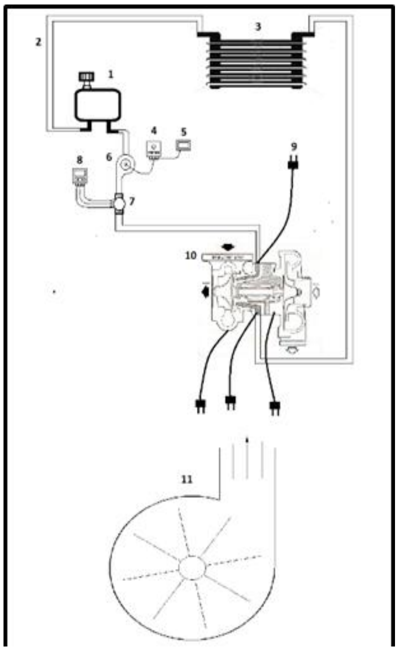

Fig. 5 Layout configuration of micro-tuQrbocharger cooling system

IV. RESULTS & DISCUSSION

In this section, the result presentation will be divided into three subsections. The first section, the turbocharger running with or without cooling system. The second section, results are demonstrated the effect of cooling system after the engine shut down. The final section contains the results and comparisons of the water flow rate of the water pump that will affect the turbocharger temperature.

A. Turbocharger Running with or without Cooling System

In order to study the efficiency and effectiveness of the cooling system on the turbocharger, the micro-turbocharger which utilized on the motorcycle engine was measured in different heat transfer situations. Fig. 6 summarizes the temperature increment on the turbine for four different methods was conducted at the engine speed of 3000 rpm for 5 minutes. For the first method Fig. 6, it is the critical situation of the turbocharger on the engine, in which the water pump and blower were not used to cool down the turbocharger when it is running.

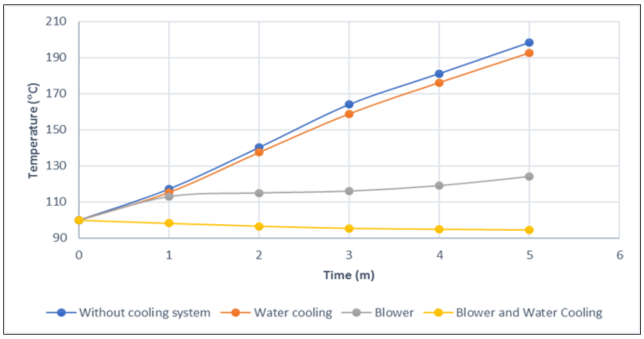

Fig. 6 Effect of different cooling methods on the turbine temperature

This method was achieved the highest percentage of temperature increase of the turbine by 49.6% due to the absence of a cooling system that aids the heat reduction process. The measurements were indicated that the turbine temperature mainly influences the bearing housing temperature. The highest heat transfer had obtained in this method that is 1010.7 W through the conduction. Hence, the rate of heat conduction through the turbine wall to the bearing housing temperature can be calculated by using formula in (1):

$$\dot{Q} = kA\frac{T_1-T_2}{L} \qquad (1)$$

When the water was allowed passes through the turbocharger bearing housing for the second method, it only reduces 2.9% of the heat increase in the turbine housing compared to the first method. This is because the cooling water passes in the passage is close to the bearing housing and the heat absorption was more to the centre housing and the heat transfer is very low by conduction between the centre section and turbine. The effect of having the water flows through the turbocharger bearing housing shows an effective way to reduce the heat trapped in the bearing housing by 17.9% compared to the first method, as shown in Fig. 7. Due to high heat absorption by the coolant in the passage of the centre housing, it had caused the temperature of the coolant that flows out from the bearing housing for the second method had the highest temperature increase approaching to 49 °C.

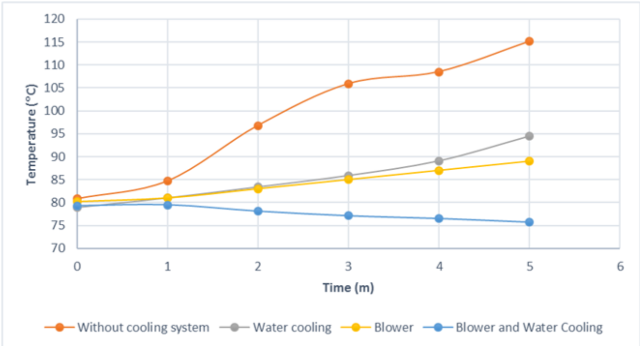

Fig. 7 Effect of different cooling methods on the centre housing temperature

The result on the third method was indicated that the effect of the blower to provide a cooling medium to the turbocharger is significant. This method was presented its effectiveness by reducing the heat increase in the centre housing that is 26.1 °C, as shown in Fig. 7 compared to the first method. The percentage of temperature increase in the centre housing is only 10% compared to the first method, which is 29.8%. The inlet coolant temperature of the centre housing increases to 37.8 °C when the engine was started running. However, after the engine was running for 5 minutes, the inlet coolant temperature was decreased to 37 °C, as shown in Fig. 8

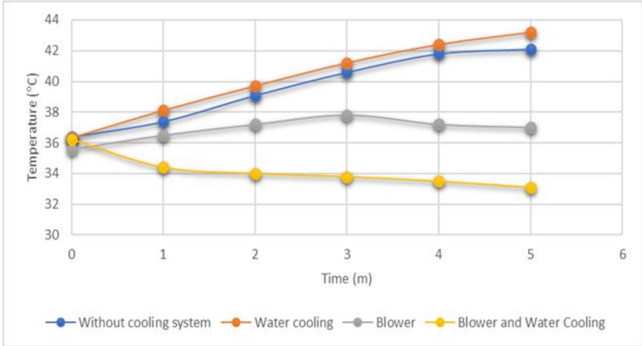

Fig. 8 Effect of different cooling methods on the coolant inlet temperature

The combination of the blower and water cooling in the final method is the most significant factor that affects the temperature of the turbine and bearing housing, as presented in Fig. 9. From the data was collected, the temperature on the turbocharger part did not undergo heat absorption from the exhaust gas, but instead, it only decreasing the temperature when this method had been implemented. The turbine and bearing housing temperature had been reduced after engine running in 5 minutes, which are 5.5 °C and 3.6 °C. The blower had increases the order of magnitude of the external heat transfer of the turbine housing to surrounding and the cooling water had to change the internal heat transfer on the bearing housing. This method had proven it is an effective and efficient way compared to other cooling processes to reduce oil coking of the lubricant and reduce the possibility of heat soak back to the turbocharger centre housing.

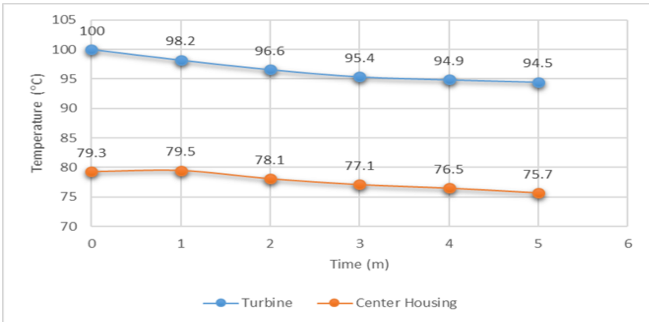

Fig. 9 Turbine and centre housing temperature when running with blower and water cooling

B. Cooling System Running Methods after the Engine Shut Down

The critical experimental situation of this project is to analyze the behaviour of the temperatures in the turbocharging system when the engine is shut down, using different cooling methods to reduce the possibilities of coke formation and heat soak back. The coke formation could lead to severe turbocharger bearing damage, and it is produced at extremely high oil temperatures. The maximum oil temperature is expected to happen after the engine shut down inside the bearings system.

This heat transfer analysis with four different methods performing on the turbocharger after the engine was shut down, was conducted through experimental. In the experiment, the engine initially worked at a working speed of 3500 rpm and after stabilizing the running condition, the engine speed is reduced for 20 seconds, and the engine is turned off. Before the engine was shut down, the turbine body temperature should reach 200 °C and thermocouple sensors reading were recorded.

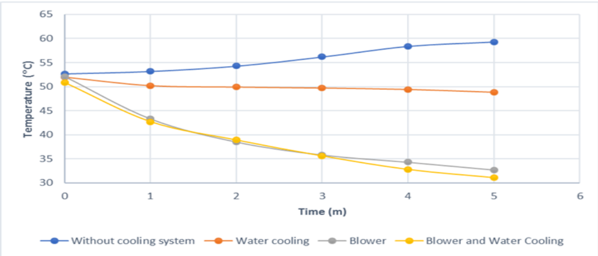

Fig. 10 Coolant inlet temperature on a different cooling methods

Fig. 10 shows the representative experimental results for four different methods at the coolant inlet. Firstly, the heat transfer test was performed without using the water pump and blower. After the engine was shut down approximately 5 minutes, the temperature of the coolant inlet was increased by 6.6 °C. Since there was no water flow into the passage of centre housing, the heat was transferred nearby through the convection heat transfer. The heat from the turbine was transmitted to the bearing housing, and the coolant inside the passage had absorbed the excessive heat from the bearing housing. This phenomenon called as heat 'soak back' from the turbine into the centre housing by conduction heat transfer. It is because a small amount of heat was transferred to the surrounding via radiation and convection. However, the tremendous excessive heat was generated from the turbine housing into the centre housing, since the centre housing is at a lower temperature than the turbine housing.

Then, the experiment was repeated by applying the water-cooling method to cool down the turbocharger after the engine shut down. The results of this experiment are more acceptable than the first one. Based on the results of this test, the maximum temperature of the coolant was decreased from 52 °C to 48.8 °C after 5 minutes, the engine was shut off. This indicates that the heat stored in the centre housing was reduced by 6.2% and the possibility of the heat soak and oil coke to occur can be avoided. The effect of this method indicates that the water has an essential purpose in cooling the turbocharger and acts as a heat sink.

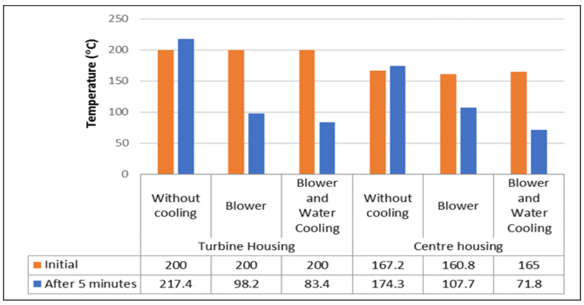

Fig. 11 The temperature difference between initial and after engine shut down

After the engine was cold down using the third and last methods for 5 minutes, respectively, the turbine and centre housing temperatures show the temperature drop drastically from the initial temperature, as shown in Fig. 11. From the result observation that since the turbine and bearing housing in front of the blower, the air velocity had increased the temperature drop. Experimental results show that the heat transfer by forced convection is the efficient way than the measured heat from free convections. The effect of utilizing the blower indicate that increasing air velocity flows to the turbocharger had a maximal impact on the turbine and centre housing temperatures. The percentage of the temperature drop in the turbine housing is 50.9%, and the centre housing is 33% after using the blower. The oil temperature reading inside the bearing housing cannot be obtained due to the thermocouple probe cannot be installed. Although the oil temperature inside the bearing system is unknown, it should be correlated with the bearing housing temperature, the reduction of the temperature should lead to the decrease in maximum oil temperature, and thus, the coke formation could be avoided. The results of the centre housing temperature drop using different cooling methods were shown in Fig. 12, and only the first method shows that the temperature was increased. The highest percentage of temperature drop was obtained by the combination of the blower and water cooling after the engine shut off that is 56.5%. This cooling method was shown the more significant impact of the cooling method on the temperature distribution of the bearing housing. After comparing the experimental results of the use of a blower and the combination of the blower and water cooling, both results show a positive effect in reducing the temperature of the turbine and centre housing. Thus, the results obtained on these experimental methods can be used to represent for the future application.

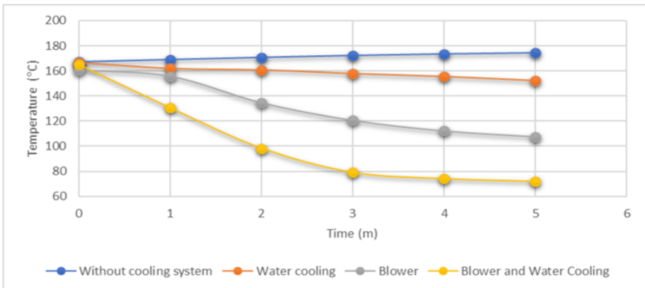

Fig. 12 Centre housing temperature on different cooling methods

C. Turbocharger Running with Different Water Flowrate of Water Pump

The effect of the different water flow rate was studied in engine running speed at 3500 RPM, and the water pump was turned on after the centre housing temperature reaches 150 °C and the water flow rates had controlled using the voltage regulator. Five different water flow rates, which consist of 4.5, 5.5, 6.5, 7.5 and 8.5 LPM were examined in this experiment. Once the centre housing achieves the initial temperature (T_1) of 150 °C, the EWP will start running for 2 minutes (T_2), and the temperature readings on the turbocharger would collect for the analyses. After going through the comparison process of the temperature on different water flow rate mentioned above, the result is shown in Table 1.

Table 1 Comparison of the temperature difference in different water flow rate

Voltage (Volt)	Water Flow Rate (LPM)	Center Housing Temperature			Coolant Outlet Temperature		
		T_1	T_2	ΔT(°C)	T_1	T_2	ΔT(°C)
6.65	**4.5**	150	152.2	2.2	48.2	49.2	1.0
7.80	**5.5**	150	151.7	1.7	48.4	49.7	1.3
9.15	**6.5**	150	151.0	1.0	48.2	49.7	1.5
10.56	**7.5**	150	149.1	- 0.9	48.3	50.7	2.4
11.72	**8.5**	150	149.8	- 0.2	48.1	50.1	2.0

Based on the experimental result, the temperature of the centre housing decrease with increasing coolant flow rate through the turbocharger until it found the suitable flow rate. The result of this examination shows the high flow rate of the coolant needed to reduces the temperature. However, the process of increasing the coolant flow rate to cool down the bearing housing still had a limitation. Due to the coolant flow rate has a corresponding passage diameter to flows and absorbs the excessive heat from the bearing housing. The only effective flow rate would be cool down the turbocharger when it is running. Increasing the WFR from zero to 7.5 litres per minute resulted in a very significant reduction in the temperature of the bearing housing which is 0.9 °C and had the highest result of the internal heat convection inside the passage. Therefore, the optimal flow rate would be 7.5 LPM, because it has a higher coolant temperature to remove the heat from the centre housing without higher electricity consumption and to correspond to flow through inside the passage of bearing housing. The highest heat transfer had obtained in this experiment that is 1196.6 W through the internal convection. The heat transfer inside water passage of bearing housing can be obtained by using the formula in 2.

$$\dot{Q} = \dot{m}C_p\left(T_{c,out} - T_{c,in}\right) \qquad (2)$$

where mass flow rate, $\dot{m}$ as equation 3

$$\dot{m} = \rho_c\dot{V} \qquad (3)$$

V. CONCLUSION

The purposes of this project are to develop and analyze the micro turbocharger cooling system. The experimental investigation was conducted on the Lifan engine equipped with a water-oil cooled turbocharger. This experiments had performed in three situations to analyze the heat distribution in the turbocharger system. From the analysis of the results, the conclusion can be found as follows:

1) Firstly, the experiment results show that the maximum turbine temperature of turbocharger rises to 198.4 °C during the engine running with the absence of a cooling system that helps the heat reduction process. This result may cause bearing damage and reduces oil quality due to high heat transfer to the bearing housing from the turbine by means of conduction.
2) Then, the experiment was repeated by applied the EWP to cool down the turbocharger during the engine running and after shutting down. The examination results show that the maximum centre housing temperature was decreased. The effect of application EWP indicates that the coolant has an essential purpose of cooling down the turbocharger and acts as a heat sink.
3) Next, the impact of the blower to provide a cooling medium to the turbocharger is significant. Based on the result, the turbine and centre housing temperature had reduced after the engine was shut down by 50.9% and 33%, respectively. The experiment results show that the heat transfer by forced convection is seven times more than the evaluated heat transfer from free convections.
4) The last situation to analyze the effectiveness of the cooling method by using a combination of the blower and water-cooling. This method is the most significant factor that affects the temperature of the turbine and bearing housing. The external convection heat transfer had acted on the turbocharger to increases the temperature drop by raising the air velocity around the turbocharger, and internal convection heat transfer that occurs inside the bearing housing had successfully to reduce the centre housing temperature.
5) Finally, the thermal study of the turbocharger takes place by control the water flow rate inside the passage of the bearing housing. The different flow rates of 4.5, 5.5, 6.5, 7.5 and 8.5 LPM, were used to evaluate the significant effect on the temperature difference of the centre housing. The test results indicated the changing the coolant flow rate on the turbocharger could significantly alter the temperatures of the centre housing walls. The most effective and efficient flow rate of coolant is 7.5 LPM due to it had reduced the centre housing temperature by 0.9 °C during water cooling running in two minutes.

As a conclusion, the functional and the operational of the project is successful in analyzing the heat trapped inside the centre housing of the turbocharger. The results from this experiment show that the temperatures of the turbocharger walls are predictable. The turbine wall temperature very clearly affects the bearing housing temperature through the conduction heat transfer. Then, the coolant had governed the bearing housing temperature by absorbing the excessive heat. As a final point, the positive impact is shown after the EWP and blower used on the turbocharger had reduced the heat distribution on the turbocharger parts and this application can be used for the future work.

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