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Heat Generation Inside Turbocharger Without External Heat Source

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ABSTRACT

Recently, many vehicle manufacturers started to invest in new technology to reduce the emission produced by their engines. Due to the emission regulations that become more stringent and the rising demand for highly efficient vehicles, many new technologies were introduced to achieve the demand. One of the technologies that gain popularity in modern vehicles is applying force induction systems such as turbocharging and supercharging the engine. By using the turbocharger, two major advantages can be achieved which are increasing engine efficiency and engine size reduction. However, turbocharger performance will be affected by the amount of heat that is generated due to friction inside the bearing, air compression process and also the heat transfer from the exhaust gas that has high temperature and pressure. In this paper, the heat generation inside the turbocharger unit without any external heat source was measured and analysed. A turbocharger unit from Garrett Turbocharger where the model is GT2056 was used for this experiment. The operating speed in the study is recorded between 20 000 rpm until 70 000 rpm and the temperature at the turbine inlet and compressor inlet is at room temperature. The parameters that were measured are the temperature difference at the turbine side, bearing housing and also compressor side. From the results obtained, it can be concluded that the bearing housing produces a higher amount of heat compared to the compressor side while the turbine side will experience heat loss.

1. Introduction

In the modern world, the number of motorized vehicles that run on internal combustion engines is increasing. According to the statistics that were produced by the Ministry of Transportation Malaysia (MOT) [1], in the year 2020 as many as 1,169,320 new land vehicle was registered even though during the year, Malaysian Government are enforcing the Movement Control Order (MCO) that affect the economic activity within the country. This statistic shows that the number of new vehicles that registered remains high from year to year. All of these vehicles are powered by an internal combustion engine where it uses fossilized fuel as a source of power [2]. One of the major disadvantages of an internal combustion engine is, it emits exhaust gas as a product of its

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combustion. This exhaust gas will pollute the environment, and also causes a bad effect on human health.

One of the solutions that are currently being implemented to reduce the emission level is by enforcing more stringent emission regulations [3,4]. Moreover, there are many new technologies that have been introduced aiming to produce highly efficient vehicle that is able to extract as much as possible energy that contained inside the fuel while saving as much fuel as possible. Among the examples of new technology includes combustion cylinder deactivation (CDA) [5-7], gasoline direct injection (GDI) [8-10], variable valve timing and lift [11,12]. Some manufacturer even introduces more radical solutions to decrease the emission and obtain more energy efficient vehicle through introduction to electric hybrid vehicle and fully electric vehicle [13-17]. Other than that, car manufacturers also use downsized engine to achieve lower emission level together with lower fuel consumption. The advantages of a small size engine include producing lower emission, less mechanical losses, less pumping losses and also less weight [18]. However, a small size engine can produce a limited amount of output thus compromising the driving quality of the vehicle itself. Hence, to overcome this problem, a forced induction system is equipped for this small size engine. A forced induction system generally is a system consisting of an air pump that pumps compressed air into the intake manifold. This air pump is either driven by exhaust gas or belting that attached to the crankshaft pulley [19]. A forced induction system that is driven by exhaust gas is known as a turbocharger and the system driven by belting is known as a supercharger. The purpose of the forced induction system being used in an internal combustion engine is to increase the degree of intake air boosting thus producing higher system efficiency [20]. A forced induction system also forces a higher amount of airflow that is being channelled into the intake manifold thus increasing the engine output [21].

The turbocharger system is driven by the exhaust gas that has a high temperature. Besides having a high amount of energy, this high exhaust gas temperature can affect turbocharger performance. The high temperature of the exhaust gas will cause heat transfer across the components of the turbocharger. However, the common practice of turbocharger performance measurements ignores the heat transfer effect to the turbocharger performances [22-25]. Since the heat transfer plays a significant effect on the turbocharger performance as stated by Gao *et al.,* [26], several researches have been conducted to investigate the effect of heat transfer on the turbocharger performance.

Tanda *et al.,* [27] investigated the effect of internal heat transfer on the compressor efficiency. The compressor efficiency was evaluated at various compressor inlet pressure, compressor speed and inlet mass flow rate. The investigation was conducted by using infrared thermography to evaluate the heat transfer from the turbine to the compressor. Moreover, the aim of the paper that measures the internal heat transfer inside a turbocharger is to provide a general understanding of the heat transfer mechanism occurring in turbochargers and the relationship for heat transfer mechanism occurring in turbochargers. This research also presents about relationship for the heat transfer rate that is useful to derive the real adiabatic efficiency. Based on the results, a novel procedure to evaluate the internal heat transfer from the turbine to the compressor has been developed and reliable results have been obtained by comparing the efficiency map during diabatic tests with the quasi-adiabatic conditions.

Romagnoli *et al.,* [28] have made comprehensive reviews on the heat transfer in turbochargers. The reviews that have been made is about the previous and current research about the turbocharger and future suggested research area of turbocharger heat transfer. In the article, it is stated that three research methods were used to describe the heat transfer in turbocharger through the experimental method, three-dimensional modelling and one-dimensional modelling. Based on all of the extensive review, a conclusion has been made which concludes that the heat transfer effect cannot be neglected in turbocharger-engine matching.

Aside from turbine casing that is considered one of the major sources of heat transfer for turbocharger unit, the bearings that supports the turbocharger shaft also contributes to the heat transfer for turbocharger unit as investigated by Li *et al.,* [29]. In the investigations, the author conducted experiments and numerical simulations to investigate the thermohydrodynamic (THD) performance of a turbocharger rotor-bearing system. A transient three-dimensional THD model of oil film was built, and the temperature field in the solid parts was simulated. The model that was developed was validated through the experiment conducted. The results obtained from the experiment shows that the solid part played a significant role in the heat transfer of the lubrication system. The temperature of the rotor and rings changes in large amplitude as the rotor speed changes.

Serrano *et al.,* [4] studied the internal convection that took place in the small turbocharger. In the study, the author measured and analysed different convective heat transfer phenomena inside turbochargers. Moreover, general correlations for these flows, based on dimensionless numbers are fitted and validated in three different turbochargers. At the end of the study, it was concluded that heat losses in turbine side grow with turbine enthalpy drop, but relative to it has a high influence only at low loads. Similar conditions were observed at the compressor side where adiabatic behaviour can be considered at medium to high loads since in those points relative importance of heat transfer is almost negligible due to the low residence time of the fluid. Finally, heat transfer on compressor side should be concentrated at compressor outlet since none of heat should arrive at the compressor inlet.

Moreover, Serrano *et al.,* [30] also studied the heat transfer losses using lumped capacitance model coupled with one-dimensional whole-engine simulation software. The data from the simulations have been compared with experimental measurements performed in an engine test bench. The study that was conducted is focused on the influence of turbocharger outlet temperature and predicting the engine performance output. The results obtained from the study shows improvement in the prediction of both compressor and turbine outlet temperatures. The results obtained also enable predictions of the heat transfer losses split in the turbocharger and quantifying the importance of heat transfer phenomena in turbocharger efficiency at full load conditions and as a function of engine speed.

In this paper, the experimental study was conducted to investigate the heat generation inside the turbocharger unit without any external heat source. The aim of this study is to investigate the parts that generate the heat, where if this heat is added to the heat applied to the turbine inlet, it will influence the turbocharger output. The temperature of the air that enters the turbine inlet is at room temperature. Different turbocharger speed was applied and the temperature at the different significant point was measured.

2. Experimental Setup and Testing Details

The experiment was conducted using a turbocharger gas stand test rig. The complete schematic diagram of the turbocharger gas stand test rig was shown in Figure 1. The turbocharger gas stand test rig used in the experiment consists of a compressed air stored inside a pressurised tank. The pressurised air is channelled to the turbocharger unit through a piping. The flow rate was controlled using an air valve that was mounted just after the compressed air tank. A heater was mounted at the pipeline just before the compressed air enters the turbocharger unit. However, in the experiment, the heater was not activated.

The turbocharger that was used in the experiment is from Garrett Turbocharger and the model used was GT2056. This turbocharger was mounted to the compressed air piping using a custom mounting. A speed sensor was mounted to the turbocharger compressor side to measure the turbocharger speed. The speed was determined by measuring the speed of the compressor wheel tip. The speed of the turbocharger was varied by controlling the flow rate of the air that enters the turbine casing.

A lubricating system was equipped to the turbocharger system to provide the lubrication purpose. It consists of a positive displacement gear pump that provides the pressurised lubricating oil. The gear pump was driven by a three-phase electric motor that act as an actual engine drives the pump. The motor rotates at a constant speed of 1492 rpm. The electric motor is connected to the pump by a flexible coupling. The pressurised oil was pumped into the bearing housing to lubricate the turbocharger bearing. The pressure generated by the gear pump was controlled by a valve mounted at the gear pump outlet. The heated lubricating oil that comes out from the bearing housing was cooled using a cooling radiator and fan.

A number of thermocouples, pressure transducer and mass flow-rate sensors were mounted to a specific point at the test rig. The listing of the sensors that used in the test rig was listed in Table 1. The numbers shown in the figure denotes the thermocouple, mass flow sensor and pressure transducer that are mounted to measure the required data. Several data collected during the experiment need to be processed by the data processing unit. The measured data signal will be processed by the data acquisition unit (DAQ) and the results will be shown on the computer screen. The DAQ system consists of one unit of power supply cable, signal-processing unit and USB cable that is connected to the computer.

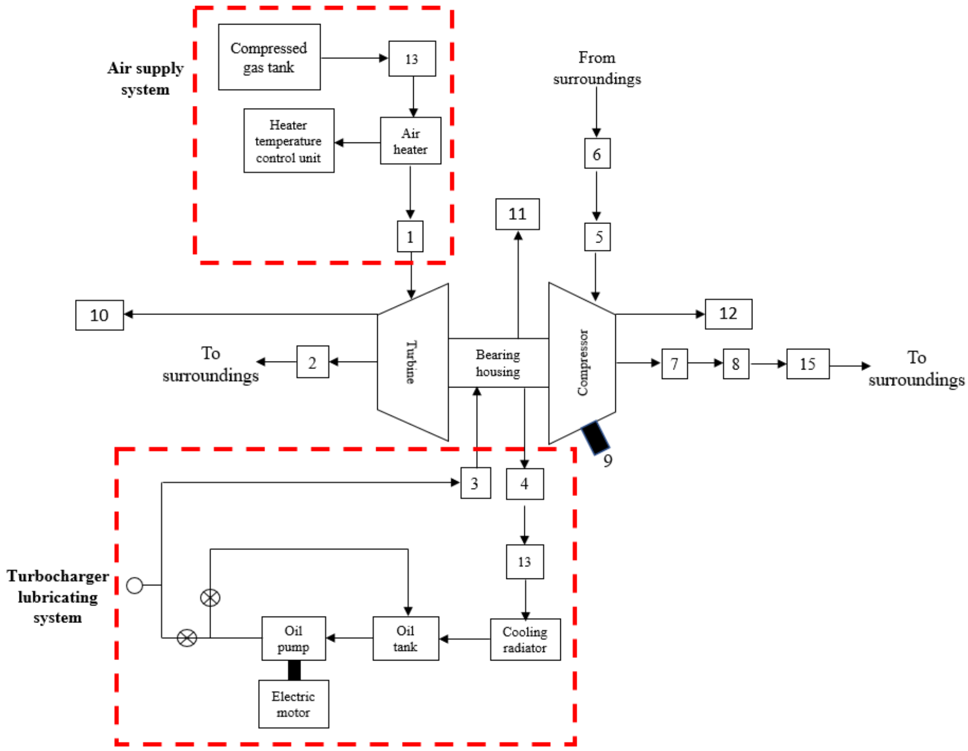

Fig. 1. Turbocharger test rig schematic diagram

Table 1
List of measured parameters

Number	Parameters
1	Turbine inlet temperature
2	Turbine outlet temperature
3	Lubricating oil inlet temperature
4	Lubricating oil outlet temperature
5	Compressor inlet pressure
6	Compressor inlet temperature
7	Compressor outlet temperature
8	Compressor outlet pressure
9	Turbocharger speed
10	Turbine outer casing temperature
11	Bearing housing outer temperature
12	Compressor outer casing temperature
13	Turbine inlet mass flow
14	Lubricating oil flow meter
15	Compressor outlet mass flow
16	Ambient temperature

The experiment was conducted referring to SAE J1826- Turbocharger Gas Stand Test Code and SAE J922- Turbocharger Nomenclature and Terminology as reference. The environment for testing is in the lab environment. The gas that used in the experiment is compressed air. Since the wastegate of this turbocharger is internally built, the wastegate valve is closed during the experiment testing. The oil pressure that used for lubrication is set at constant pressure at 3.5 bar. The turbocharger is tested with no heat applied to the air that enters the turbocharger. The data that was manipulated during the experiment is turbocharger speed while the turbine inlet temperature and compressor inlet temperature remains at room temperature. The speed range of the turbocharger was between 20 000 rpm to 70 000 rpm with 10 000 rpm increment. The measurement data is taken after the temperature and mass flow of the compressor outlet is stabilised after one minute. The testing is repeated for each turbine inlet temperature and turbocharger speed ten times for data consistency. The data is determined by measuring the temperature difference between turbine inlet and outlet, the temperature difference between bearing housing inlet and outlet, and also the temperature difference between compressor housing inlet and outlet.

3. Results and Discussions

Figure 2 shows the trend of turbine temperature difference when the turbocharger speed increase. The value is measured by calculating the temperature difference between the turbine outlet and the turbine inlet. The turbine temperature difference value ranges from -3.5°C until -13.7°C while the turbocharger speed range begins from 20 000 rpm until 70 000 rpm. For the turbine case, the heat is released from the turbine since the pressure inside the turbine housing is drop hence causing the temperature also drop [28]. Due to this, the temperature at the turbine outlet will be lower compared to the temperature at the turbine inlet. From the graph, it can be observed that the turbine temperature difference is increase when the turbocharger speed is increased. The temperature difference at 30 000 rpm is higher compared to 20 000 rpm by 25.71%, while the temperature difference at 40 000 rpm is increased by 52.27% compared to 30 000 rpm. While the turbocharger speed continues to increase until 50 000 rpm, the temperature difference also continues to increase by 22.39%. Furthermore, as turbocharger speed reaches 60 000 rpm and 70 000 rpm, the temperature difference increases by 27.44% and 24.4% respectively. Referring to the graph, it can be observed that the amount of heat released inside the turbine is increased as the turbocharger speed is increased. This is because higher turbocharger speed requires more energy extracted from the exhaust gas to spin the turbine wheel. However, since no heat is applied to the turbine inlet, the compressed air that passes through the turbine housing will cool the turbine housing. This causes water droplets to form outside and also inside the turbine housing due to the condensation process. This proves the significance of the procedures highlighted by Yang, Martinez-Botas *et al.,* [31] where the air needs to be heated to prevent condensation. The water condensation inside the turbine housing needs to be avoided since it can affect the turbine efficiency and power output [32].

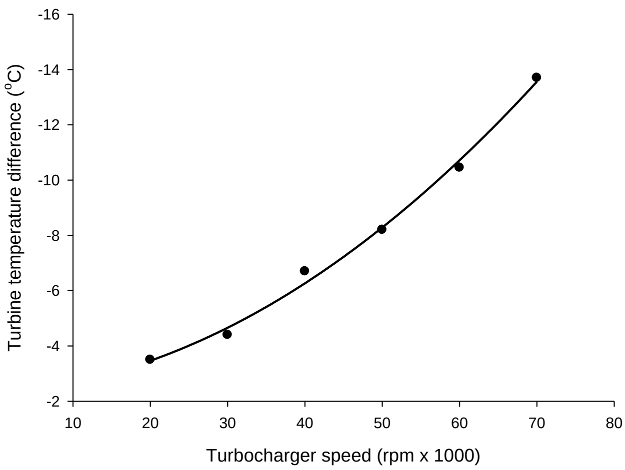

Fig. 2. Graph turbine temperature difference vs turbocharger speed

Figure 3 shows the trend of compressor temperature difference versus turbocharger speed. It can be observed from the graph that the trend of the graph shows a non-positive, increasing trend. The compressor temperature difference ranged from 3℃ until 20.5℃ while the turbocharger speed ranged from 20 000 rpm until 70 000 rpm. The graph shows increasing trends of compressor temperature difference where the temperature difference at 30 000 rpm is higher compared to 20 000 rpm by 47%. When turbocharger speed is increasing to 40 000 rpm, the temperature difference is increase by 59%. Next, while turbocharger speed increases to 50 000 rpm, the temperature difference also increases by 57%. Finally, when the turbocharger passed 60 000 rpm and reached 70 000 rpm, the temperature difference also increases by 37% and 39%.

Figure 4 presents the relations between the oil temperature differences versus turbocharger speed. It is shown by the graph that the temperature difference is increase when the turbocharger speed increase. The oil temperature difference is ranged from 5.2℃ to 18.9℃ for turbocharger speed between 20 000 rpm to 70 000 rpm. The oil temperature difference at 30 000 rpm is 45% higher compared to 20 000 rpm. When turbocharger speed is increased to 40 000 rpm, the oil temperature difference is increased by 38%. Then, the temperature difference increased by 30% when the turbocharger speed reach 50 000 rpm. When the turbocharger speed reaches 60 000, the temperature difference is increasing by 21% and at the speed of 70 000 rpm, the temperature difference increases by 15%.

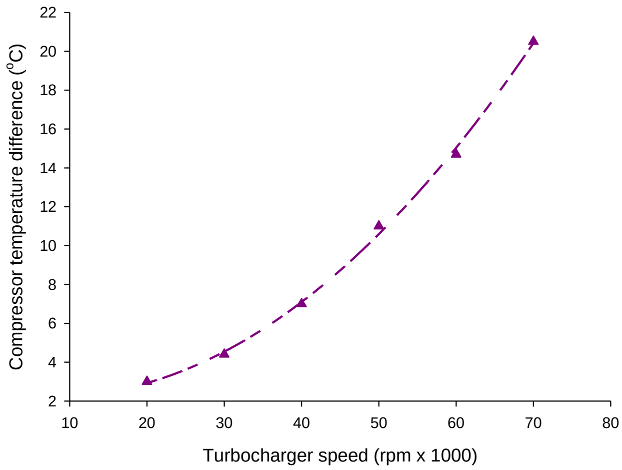

Fig. 3. Graph compressor temperature difference vs turbocharger speed

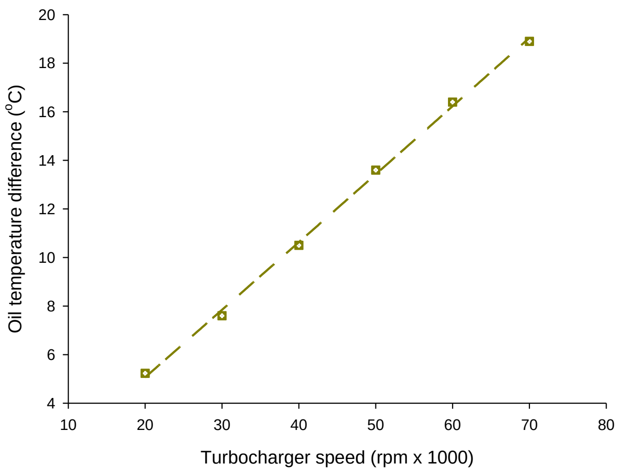

Fig. 4. Graph of oil temperature difference versus turbocharger speed

Figure 5 shows the compressor, turbine and oil temperature differences in a single graph. From the graph, it can be seen that oil temperature difference is the highest compared to turbine temperature difference and compressor temperature difference. This is because, inside the bearing housing, there is a three-piece thrust bearing that supports the shaft that connects between the turbine wheel and compressor wheel. When the turbocharger speed increase, the friction between the shaft and the bearing increases hence causing higher temperature generated. Heat transfer will occur between the bearing surface, the shaft and lubricating oil that flows through the parts. The temperature of the oil that exits from the bearing housing is greater compared to the temperature of the oil before it enters the bearing housing. This makes the bearing housing is the highest part the generates heat when there is no external heat exerted to the turbocharger unit. Additionally, the compressor housing produces the second-highest temperature difference referring to Figure 4. This is because when the air is compressed, the air molecules collide with each other in high frequency. This frequent collision between the air molecules produces heat that causes the temperature of air that leaves the compressor is higher compared to the temperature of the air before it enters the compressor. When the turbocharger speed increased, the air molecules collide with each other more frequent thus causing a higher temperature difference between the compressor outlet and inlet. Moreover, observing the temperature difference for the turbine side, it can be observed that the temperature difference is the lowest compared to the other parts. This can be related to the temperature of air that enters the turbine inlet, which is only at room temperature. Since the turbine is an energy extracting device, the amount of energy contained inside the air will be extracted to rotate the turbine wheel. This will cause the temperature of the air that exits the turbine will be lower compared to the temperature at the turbine inlet. It can be observed at the turbine outlet where water droplets started to form when the turbocharger speed is increased due to the condensation process that happens when the energy contained inside the air that passing through the turbine casing is extracted.

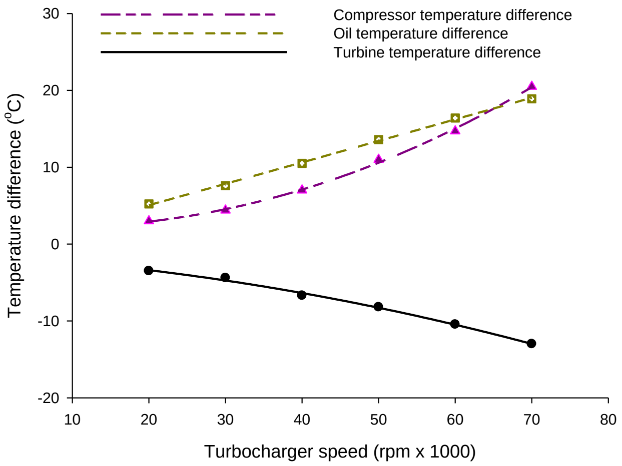

Fig. 5. Graph of turbine, compressor and oil temperature difference

Figure 6 shows the graph of turbine heat loss versus turbocharger speed. The turbine heat loss is ranged from -0.0703 kJ/s until -0.7423 kJ/s. It can be seen from the graph that the heat loss inside the turbine side shows negative quadratic pattern where the heat loss is increasing when the turbocharger speed is increasing. When the turbocharger speed increase to 30 000 rpm from 20 000 rpm, the heat loss increases about 53%. Later when the turbocharger speed increase to 40 000 rpm, the heat loss increases by 84%. When the turbocharger speed increase until 50 000 rpm, the heat loss keeps increasing by another 44%. Later, while the turbocharger speed increasing to 60 000 rpm and 70 000 rpm, the heat loss is increasing by 53% and 71% respectively. With correlations with Figure 2, Figure 6 shows the amount of heat that is lost inside the turbine casing as the energy contained inside the air being extracted to rotate the turbine wheel, and also lost as waste energy. It can be seen from the figure; the amount of energy loss will increase as the turbocharger speed increase. The energy extracted from the air that passes through the turbine will be converted into mechanical energy that rotates the turbine wheel and also waste energy where it will be released to the environment.

Figure 7 shows the amount of heat generated by the compressor versus turbocharger speed while no external heat exerted to the turbocharger. This condition can be related to Figure 3, where the temperature of compressed air that leaves the compressor is higher compared to the compressor inlet temperature. While the temperature of the air is increasing inside the compressor housing, the amount of energy contained inside the air also increased. It can be seen from the graph that the amount of heat generated by the compressor shows increasing trends. The heat generated by the compressor ranged between 0.0263 kJ/s until 0.4891 kJ/s. The line of the graph shows quadratic trends, which is suited to the characteristics of the compressor where the compressor is classified as a non-positive displacement pump or radial pump. When the turbocharger speed is increased from

20 000 rpm to 30 000 rpm, the heat generated is increased by 137%. Later, when the turbocharger speed is increased to 40 000 rpm, the heat generated is increased to 114%. When the turbocharger speed keeps increasing until 50 000 rpm, the heat generated is 93% higher compared to the amount of heat generated at 40 000 rpm. As the turbocharger speed reaches 60 000 rpm and 70 000, the amount of heat generated is 58 % higher and 20% higher for each turbocharger speed.

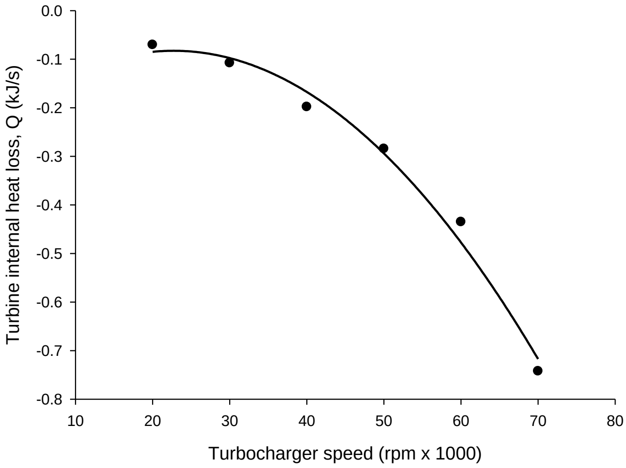

Fig. 6. Graph of turbine heat loss versus turbocharger speed

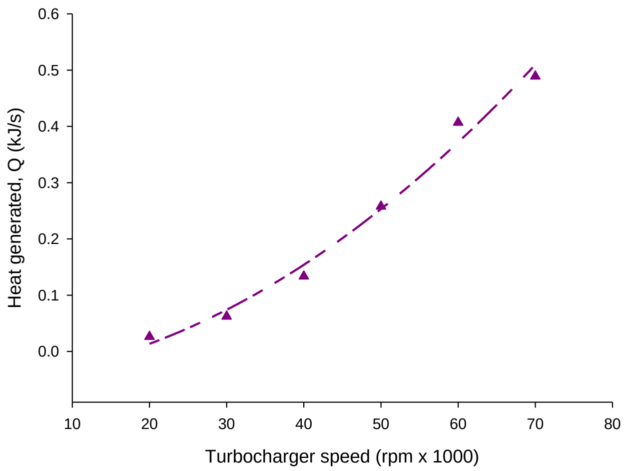

Fig. 7. Graph of compressor heat generated versus turbocharger speed

Figure 8 shows the amount of heat generated inside the bearing housing while the turbocharger speed is increased while no external heat is applied to the turbine inlet. It can be observed from the graph that the amount of heat generated is increased when the turbocharger speed. The heat generated inside the bearing housing is directly proportional to the turbocharger speed. The amount of heat generated inside the bearing housing is between 0.3576 kJ/s to 1.3325 kJ/s. It can be observed from the graph that when the turbocharger speed is increased from 30 000 rpm from 20 000 rpm, the heat generated at 30 000 rpm turbocharger speed is 46% higher. Then, when the turbocharger speed is increased to 40 000 rpm, the heat generated also increase by 39%. Later, when the turbocharger speed reaches 50 000 rpm, 30% additional heat is generated inside the bearing housing. Additionally, when the turbocharger speed is increased to 60 000 rpm, 21% additional heat is generated compared to the heat generated at 50 000 rpm. Finally, when the turbocharger speed reaches 70 000 rpm, the amount of heat generated is 16% higher. Most of the heat generated inside the bearing housing is caused by the frictional force that exists between the surface of the shaft and also sleeves bearing. Since the surface between these two components is only separated between a thin layer of oil film, a higher amount of heat will be generated when the turbocharger speed is increased. This is due to the increment of the frictional forces between the components. According to Tanda *et al.,* [27], most of the heat generated by the friction between the shaft and bearing will be removed by the lubricating oil that flows continuously through the bearing housing.

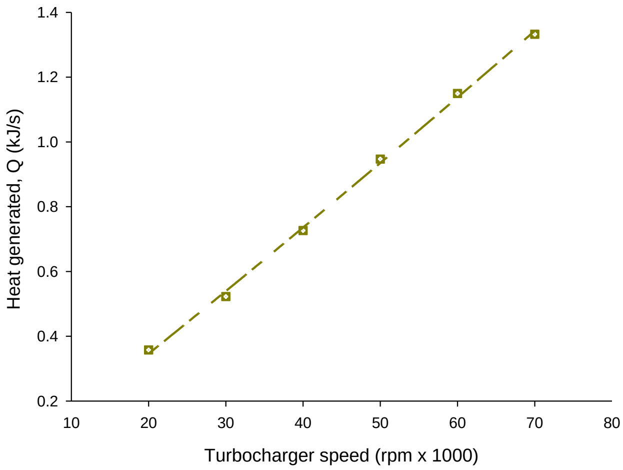

Fig. 8. Graph of heat generated inside bearing housing versus turbocharger speed

Figure 9 shows the comparison of heat loss at the turbine side and the heat generated inside the bearing housing and compressor side without any external heat source. From the graph, it can be observed that bearing housing produce the highest amount of heat compared to the turbine side by 128% and the compressor side by 279%. This condition can be related to the components inside the bearing housing, where there are three-piece sleeve bearing that supports the shaft. As the shaft rotates faster, the amount of heat generated due to the friction between the surface of the shaft and bearing will be increased. It also can be observed from the figure that the amount of heat loss at the turbine side is higher compared to the amount of heat generated by the compressor side. This condition can be seen from the gradient of the graph for the turbine side which is higher compared to the compressor side.

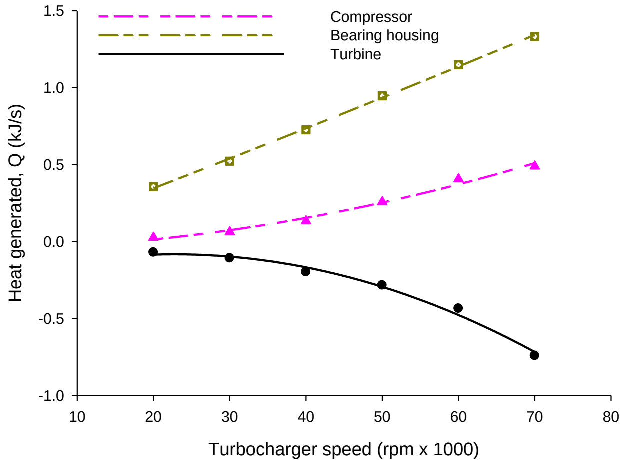

Fig. 9. Graph of heat loss at turbine side and heat generated at the compressor and bearing housing

4. Conclusion

In this paper, the study about heat generation inside turbochargers without any external heat source was investigated. From the experiment, six different speed was used, and the temperature difference at each measurement point was determined. From the results obtained, several conclusions were made.

i. Bearing housing produces highest level of heat compared to the compressor housing,
ii. Turbine housing will extract the energy contained inside the compressed air, causing the temperature at the turbine outlet will be lower compared to the turbine inlet. In this experiment, the temperature is low until water droplets formed at the turbine outlet due to the condensation process, and
iii. The compressor side will also generate heat due to the compression process of air inside the compressor casing. However, the amount of heat will be lower compared to the heat generated by the bearing housing.

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