Development of Turbine Components in Turbocharger System for Internal Combustion Engines: A Brief Review

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Abstract - **In the concept of downsizing an internal combustion engine, the turbocharger in one of the key device for reducing emissions while maintaining engine performance. Turbine as one of the main components in a turbocharger has an important role in determining the power generated by an internal combustion engine. This paper presents the development of turbine components in turbocharger and methods of turbine design optimization. In order to maximize the performance of the turbine in the turbocharger, a variable geometry turbine (VGT) is used. VGT has several variations that have been developed such as Active Controlled Turbocharger (ACT), Passive Controlled Turbocharger (PCT), Variable Nozzle Turbine (VNT), and Regenerative Electrically Assisted Turbocharger (REAT). Another thing that can be developed to maximize turbine performance is to use a double-entry turbine. The double entry turbine has the aim of saving exhaust gas energy and facilitating cylinder gas exchange. One way to produce efficient turbine performance is to replace the existing spiral casing on the turbine with a multi-channel casing (MC). The use of this multi-channel turbine reduces the best efficiency points (BEP).**

Keywords: Turbocharger, Internal Combustion Engine, Turbine component, Optimization, Variable Geometry.

I. INTRODUCTION

Turbochargers have been widely used in various types of applications such as cars and airplanes. In the concept of downsizing, the turbocharger is one of the key devices to increase the thermal efficiency and exhaust emissions of an internal combustion engine [1]. The turbocharger is the primary enabler for energy conservation in internal combustion engines[2]. There are two main components in a turbocharger, namely a compressor and a turbine. The compressor serves to provide impetus to the air so that it can enter the engine cylinder. While the turbine converts exhaust gas from the engine into mechanical energy by compressing the air into energy [3]. The use of turbo charging technology in an internal combustion engine can reduce engine size and

reduce exhaust emissions without reducing the power generated [4].

Turbine as one of the main components in a turbocharger has an important role in determining the power generated by an internal combustion engine. Turbine performance in a turbocharger is influenced by the energy carried by the exhaust gases produced by the engine [5]. This energy is in the form of heat transfer. The performance of the turbocharger turbine can be seen through non-adiabatic performance experiments through energy and exergy analysis, taking into account the impact of heat transfer [6].

Modern internal combustion engines in use today must meet several applicable requirements. The engine must be able to reduce pollutant gas emissions and easy engine maintenance. The machine used must be efficient at low and high load conditions. Therefore, VGT or variable turbine geometry is used to provide proper engine acceleration from exhaust gases under low load operating conditions [7]. The use of VGT can increase efficiency and reduce harmful CO_2 emissions by 23% and 30-50% for NOx[8]. The designs used for VGT are usually analyzed by control methods. The control method used is to actively adapt the emission gas pressure to optimize the average power extraction for each engine crank cycle [9].

The radial turbine in the turbocharger works on the principle that the exhaust gases enter perpendicular to the rotor blades radially, and are directed 90° by the rotor before the exhaust gases exit the housing in an axial direction [10]. Turbocharged radial turbines have a strong impact on the fuel consumption and transient response of internal combustion engines [11]. The development of the design used in the radial turbine in the turbocharger is aimed at increasing efficiency and lowering inertia. In the design of radial turbines for turbochargers, VGT is used to improve transient response and reduce torque at low-speed conditions [12]. The use of the engine at low speeds will increase the speed of exhaust gases and the energy used by the turbine. This will lead to low volumetric efficiency and high exhaust back pressure.

Many studies using various turbine operating conditions (temperature, pressure, etc.) have been carried out to accurately evaluate turbocharger efficiency and broaden the range of turbine performance evaluations. In a turbocharger, the internal heat exchange between the compressor, turbine, coolant, lubricating oil and atmosphere occurs simultaneously [13]. The non-uniform distribution of heat in the turbocharger causes a lot of thermal strain on its body. The results show that heat transfer reduces compressor performance and decreases heat transfer effect by increasing the turbocharger rotational speed [14].

Turbine efficiency and moment of inertia are naturally the main focus when designing turbine wheels. Changes in the thickness of the turbine blades cause changes in mass and moment of inertia [15]. In fact, reducing the size of a turbocharged turbine can increase the hysteresis of a turbocharged engine. A small turbine will have a small moment of inertia. Therefore, when the engine is running at low speed, the turbine can reach optimal working speed. Thus, turbine hysteresis can be increased effectively [16].

This review will discuss the development of turbine components in an internal combustion engine turbocharger or ICE. The analysis was carried out to determine the developments that occurred in terms of design, heat transfer, power, and the type of flow that occurred. The analysis carried out in this review is expected to provide an overview of the development of the turbine in the turbocharger up to the time this review was made and be able to identify existing deficiencies and weaknesses and provide possible solutions.

II. DEVELOPMENT OF TURBINECOMPONENTS IN TURBOCHARGERS

In this era, the use of turbochargers in internal combustion engines has been widely used in the automotive industry, especially for diesel and gasoline vehicles. Turbocharging has become the preferred approach for downsizing internal combustion engines to reduce fuel consumption and CO_2 emissions, without compromising their performance[17]. The existence of highly efficient compressors and turbines supports increased engine power [7]. Turbocharger engines in vehicles, especially cars, were first developed by Swiss engineer Alfred Buchi, head of diesel engine research at Gebruder Sulzer in 1905. He patented a compressor driven by exhaust gases which forced air into the diesel engine to increase power output. in 1925 he succeeded in making the first exhaust gas turbocharging system effectively applied to an engine, obtaining a power increase of more than 40 percent.

For the automotive industry that is currently taking place, it must be able to pay attention to existing environmental factors without reducing the power output [4]. Turbocharger technology that has been developed to date makes it possible to use less fuel but produce more power. This significantly contributes to emission reductions and the development of sustainable low-carbon transportation. Although this engine can reduce exhaust emissions, user experience must remain the main key in the development of turbochargers in automotive internal combustion engines.

2.1 Radial Turbine and Axial Turbine

Radial turbine as one of the important components in the turbocharger system of internal combustion engines is often used to increase the power generated, efficiency, and transient response [11]. In order for the use of radial turbines to run properly and properly, the turbines and compressors used must take into account various design parameters. The form of consideration that is often used is the use of VTG to control the performance of the radial turbine in the turbocharger of an internal combustion engine.

The working principle of the radial turbine is that the exhaust gas enters perpendicular to the rotor blades radially, and is directed 90^0 by the rotor before leaving the housing in the axial direction. On the other hand, the axial turbine works in the opposite way, wherein the exhaust gases enter the rotor axially and exit in the radial direction. In an axial turbine, there is less mechanical stress on the blades due to the fact that the flow enters the turbine at a zero angle [10]. The use of an axial turbine can reduce the turbo-lag phenomenon that occurs by reducing engine inertia [18].

High cycle fatigue (HCF) of turbine blades is the most common form of turbocharger failure, caused by alternating aerodynamic forces exerted on the blades due to rotor-stator interaction. There is also the term turbine-wheel mistuning which is a phenomenon that occurs due to material and geometric deviations from the ideal design cyclic symmetry [19]. Therefore, to overcome these problems without reducing the aerodynamic performance, it is necessary to investigate the excitation mechanism of the radial turbine blades [20].

The simulation results that have been carried out by Pan, et. al [20] for one type of turbine, namely the vaneless radial turbine, show that energy transfer is the key to understanding the blade excitation mechanism. The total energy applied to the entire blade is positively related to the vibration amplitude, which can be thought of as a measure of the vibration amplitude which is the energy at the suction surface resulting in a 'V-shape' correlation between the vibration response and the turbine load. In particular, the energy at the suction surface shows a non-monotonic correlation with the pressure ratio.

In addition, a high forcing work area appears near the trailing edge of the suction surface at a low-pressure ratio, resulting in high energy as well as high vibration response.

Axial turbines have proven to be an alternative to radial turbines because they can handle very high flows and loads while maintaining high efficiency. This can be attributed to the less constrained design of the axial turbine blades compared to the fibrous radial turbine blades. The forward sweep blade of a mixed flow turbine may be an improvement but the most significant efficiency gains can only be achieved with an axial turbine design [21, 22]

Guarda, et al. [23] conducted experiments using a GT1548 turbocharger with three types of turbines, namely radial turbine (baseline model), axial turbine, and optimized axial turbine (new design) by comparing emission, transient response, and moment of inertia.
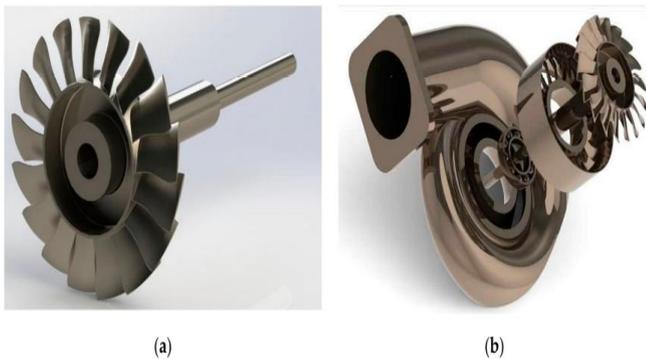
Figure 1: (a) Optimized axial turbine and (b) Axial turbine 3D model [23]

From the simulations carried out by Guarda, et al.[23] where optimized radial turbines, axial turbines, and axial turbines were compared, it was found that the use of axial turbines can reduce the moment of inertia by about 35% without compromising the safety factor. The transient response of the axial turbine also shows an average increase of 11.76% with a maximum of 21.05% compared to the radial turbine [23]

One of the turbocharger designs being developed are the use of a two-stage turbocharger system consisting of a radial turbine connected in series to an axial turbine. This type of two-stage turbocharger is intended for vehicles that use diesel engines. In particular, the two-stage turbocharging technology can not only increase the intake airflow and reduce emissions, but also improve the dynamic response of the engine and achieve high EGR levels, which are widely applied to engines [24].
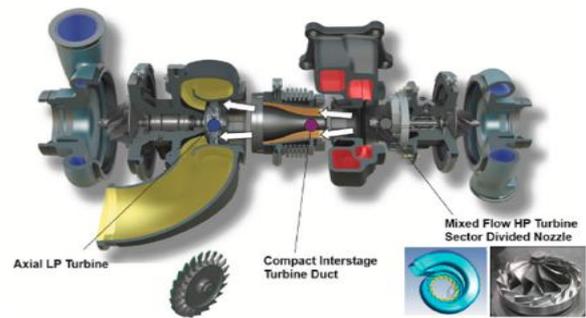
Figure 2: Honeywell twin turbo system [10]

From the simulation results that have been carried out by Panayides, et al. [10], where a comparison is made between a single radial turbine and a radial/axial two-stage turbine. It was found that the results for the radial and axial turbines showed efficiency of 83.4% and 81.74%, respectively [10]. However, the two-stage system, as shown in the results section, did not operate as expected. Therefore, a number of changes need to be introduced into the system to increase the accuracy of the engine model with a two-stage turbo system. Another turbocharger model used is a turbocharger model with a twin-turbine concept using an axial turbine.

2.2 Turbine Optimization

Two key aspects for this development were the optimization of the aerodynamics of the main turbocharger components and improved matching between the turbocharger and engine. In the literature, many studies have focused on optimizing the efficiency of turbine and compressor design points, while reducing the moment of inertia to improve transient performance. In a general approach to turbine optimization, turbine geometry is parameterized and optimized with regard to adiabatic efficiency and rotor inertia, while limiting mass flow parameters and considering structural integrity through evaluation of mechanical stresses [4].

One of the main problems associated with turbochargers is turbocharger lag at low exhaust gas flow rates as the turbine receives insufficient gas flow resulting in a slow response to engine acceleration commands. During this period the efficiency and performance of the engine decreases and emissions increase. This brings the need to increase the efficiency of the turbocharger at low exhaust gas mass flow rates [25]. Existing approaches to improve turbine performance at low speeds typically include wastegate bypass, two-stage turbocharging, and Variable Geometry Turbocharger (VGT) [26].

2.3 Variable Geometry Turbocharger

The existence of strict pollutant emission laws and low emission vehicles has brought the automotive industry to an

efficient engine [27]. Reducing fuel consumption and exhaust emissions is currently a fundamental target for automotive engines, due to rising fuel costs and the need to control CO_2 emissions [29]. The internal combustion engine in today's cars must pay attention to the exhaust emissions produced to reduce air pollution but still maintain its performance. One technology that can be used is the Variable Geometry Turbocharger (VGT). The use of VGT can increase efficiency and reduce CO_2 emissions by up to 23% and 30 - 50% for NOx[8].

Most modern engines now use a fixed geometry turbocharger which functions to drive exhaust gases at high load conditions. At high load conditions, the exhaust gas has a high speed so as to produce a large torque on the turbine wheel. [7]. However, when the vehicle gets a low load, the exhaust gas speed slows down and causes the torque produced to tend to be small. To overcome this, VGT is used to make its performance stable at low loads.

When compared to the use of a waste-gate on a turbocharger, VGT has advantages in conditions of low torque (1250-1500 rpm) and high speed (from 4000rpm). From the results of research conducted by Serrano, et al [27], it was found that at low speeds, these advantages come from higher boosting abilities. The VGT provides a further advantage also in medium engine speeds at 1300 m above sea level. This is because the waste-gate is operating close to its maximum capacity (fully closed position), while the VGT still shows some additional margin to compensate for the higher compressor pressure ratio.

The initial design of the turbine wheel is based on parameters such as: total inlet temperature T_0, total inlet pressure p_0, isentropic nozzle vane outlet temperature $T_1 iz$, relative angle at rotor outlet β_2, average diameter of turbine wheel inlet and outlet D_1, D_2, and speed, turbine rotation n.

3D simulation to simulate a two-stage turbine system with VTG vanes positioned before the 2nd stage rotor using a K44 Turbine Wheel on a 6 cylinder, 2 stroke diesel engine. The vane angles used are 30^0, 20^0, and 11^0 at turbine speeds of 40.000rpm, 50.000 rpm, and 60.000 rpm [7]. Simulations that have been carried out show that increasing turbine speed makes the temperature of the rotor stage 1 increase, while the rotor stage 2 decreases. This makes the efficiency of rotor 1 reduced by 5%. On the other hand, rotor 2 has an efficiency increase of 10%. The maximum efficiency of a two-stage turbine system with VTG is 60% for 60.000rpm and a VTG position of 11^0.

Exhaust gas flowing in the engine changes in magnitude very quickly. So to be able to control the turbocharger, an Actively Controlled Turbocharger (ACT) is used [29]. ACT is able to adapt to the amount of exhaust gas pressure actively so as to optimize the average power extraction in each engine crank cycle. However, ACT still has many shortcomings where the tool to control VGT must use highly reactive and precise sensors and actuators. To overcome this problem, a Passive Controlled Turbocharger (PCT) is used. PCT is a VGT equipped with a passive actuator that moves due to exhaust gas pressure and functions to manipulate the turbine inlet area [8]. PCT uses exhaust gases to drive the vane with a spring-damper mechanism.

The simulation results that have been carried out show that the use of PCT in VGT produces the actual power and isentropic power values which are relatively the same as experiments using fixed-vane angle in VGT [8]. The error that existed during experimental testing for fixed-vane angle was calculated with the mean absolute percentage error and resulted in an error of 3.6% for the average actual power and 6.7% for the pulsating frequencies of 40 and 60 Hz. The results of this simulation prove that the use of PCT on VGT can improve the performance of the internal combustion engine because the vane angle can vary according to the existing exhaust gas pressure.

In Variable Geometry Turbine (VGT) there is one type of VGT called VNT or Variable Nozzle Turbine. The VNT nozzle area used is adjusted to the opening of the turbine inlet guide vane (IGT) setting, this can change the operating conditions of the turbine according to the needs of the engine used. In VNTs used in internal combustion engines, the nozzle vane is located upstream of the turbine wheel, adjusting the nozzle channel where the fluid is accelerated and changing the direction of flow [30]. The position of the vanes of the VNT is controlled by means of an electric actuator connected by a rack and crankshaft pinion. The new VNT model used uses elastically restrained guide vanes to adjust the turbine inlet mass flow rate. The rotation of the guide vanes is driven by the pressure difference between the suction surface and the pressure surface then the elastic force acting on the guide vanes balances the pressure difference [31].
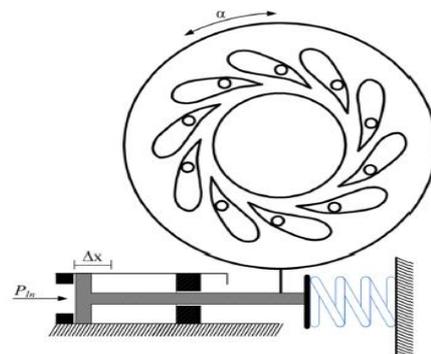

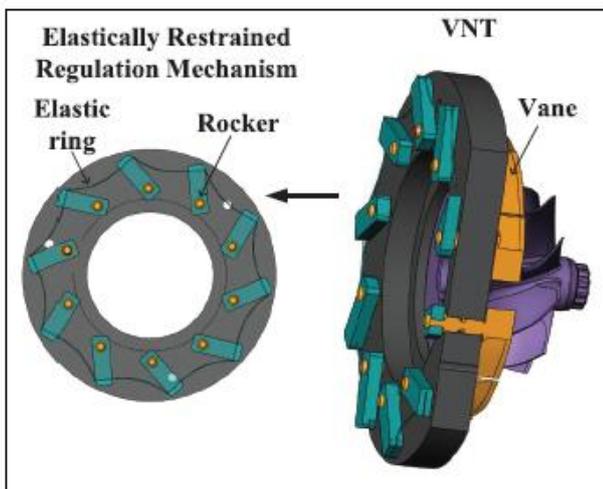**Figure 3: Schematic diagram of PCT tools [8]**

Figure 4: Elastically restraint nozzle ring system on VNT [31]

The Elastically Restrained Guide Vane or ERGV is a system that aims to increase the pressure level at the turbine inlet and optimize the match between the turbocharger and the engine. In contrast to conventional VGT operation, the ERGV tuning is capable of continuously following each incoming pulsed pressure wave. When the turbine rotates, elastic deformation occurs in the elastic ring of the ERGV system. Sequentially, the elastic forces due to the deformation resist the rotating motion of the propellers to balance the aerodynamic forces on the propellers generated by the gas flow. Thus, the guide vane rotates in response to the pulsating flow, that is, the elastic force changes in response to the aerodynamic force [31].

From the simulation process that has been carried out by Z Wang, et al., it was found that the use of the latest VNT model at medium to high engine speed conditions can increase engine efficiency, and produce higher power and torque. The power generated increases by up to 7.3% when compared to conventional VNT.

When the engine accelerates, the crankshaft loads much faster than the turbocharger because the engine burns additional fuel quickly without exceeding the smoke limit. This rapid increase in torque is called "snap torque". The coupling between the engine and the turbocharger is fluid dynamic, and therefore there is a delay in turbocharger spooling known as "turbo lag" [32]. To be able to overcome the turbo lag that may occur when the engine is running, VGT can prevent it by narrowing the propeller opening during a tip-in situation. But this will make efficiency decrease and cause pumping loss to increase [33]. To prevent this, a regenerative electrically assisted turbocharger (REAT) can be used. The significant impact of using REAT is through reducing the use of electrical energy to achieve performance equivalence with the base turbine design. Especially for FTP-75 drive cycle

simulation with W (assist TEMG) / W(Emg) 2%, only 0.1% gain in BSFC and 7.7% decrease in E-energy is obtained with 5% increase in VGT efficiency. At high relief rates, the added benefit of an improved turbine design disappears as the assistance is equivalent to an increase in turbine efficiency [34].

2.4 Double Entry Turbine

Turbine has 3 main components, namely volute, stator (consisting of vanes or spans), and rotor. The flow passing through the volute is distributed among the stator blades, and finally circulates to the rotor. Viscous flow at the volute and stator at the volute and stator can reduce the overall efficiency of the turbine, turbocharger and the entire system. Therefore, volute design and fluid behavior relationship are very important aspects in optimizing turbine performance [35].

The turbine housing has a significant effect on the overall working output of the turbocharger [36]. Double entry turbines are usually used to save exhaust pulses in the exhaust pipe of the engine. This is because the turbines in turbocharged multi-cylinder engines often operate under off-design conditions. The turbocharger turbine is constantly experiencing unstable exhaust flow even under a steady engine load. This is because of the gust of the engine cylinder generated by the exhaust valve opening [37]. The double entry turbine has the aim of saving exhaust gas energy and facilitating cylinder gas exchange. There are two types of double entry turbines, namely Double Entry Volute Asymmetrical Turbine and Twin Entry Symmetrical Turbine.

Double entry volute asymmetrical turbine is a volute that is divided in such a way that each turbine scroll receives exhaust gases in a separate rotor section [27]. The turbine scroll which has a longer volute is called the outer limb and the shorter one is called the inner limb [38].

Ahmed Ketata and Zied Driss [38] conducted tests on single entry turbines and double entry volute turbines, and compared the flow swallowing abilities of the inner and outer limbs. In his research, in the first step, a single-entry turbine model based on a commercial turbocharger turbine was tested. In the second step, the double entry volute asymmetrical turbine design is obtained by dividing the coil casing of the single-entry turbine under test into two parts, namely the inner scroll and the outer scroll. The cross-sectional area of the inner and outer channel inlet is 480 mm^2. The equivalent lengths of the inner and outer channels are 60 mm and 115 mm, respectively. The flow coming out of these two windings is then collected into the boundary of the T junction and driven to the rotor.
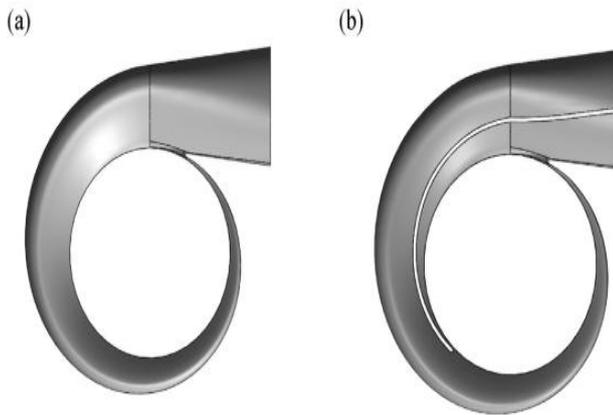
Figure 5: (a) Single entry turbine and (b) Double entry volute turbine [38]

The results show that the outer limb of the double entry volute asymmetrical turbine has the ability to flow swallowing from the engine exhaust manifold compared to the inner limb in the out-phase admission mode. In this condition, the efficiency of the total-to-static turbine has increased by 10% compared to the in-phase admission mode. In this study, an increase in the hysteresis loop area of the mass flow rate was also found when switching between in-phase admission mode to out-phase admission [38].

In contrast to the asymmetric volute double entry turbine, the scroll turbine in the symmetrical twin entry turbine has a single wall around the turbine housing so that each entry receives exhaust gases throughout the circumference of the turbine wheel. The entry closer to the turbine outlet is called Shroud (Sh) and the entry closer to the bearing housing side is called Hub (H) [27].

For a twin entry symmetrical turbine, performance (efficiency) is parameterized in terms of two angles of incidence relative to the blades of the turbine wheel. The first angle is the conventional angle of incidence relative to the turbine wheel blades in the turbine wheel rotation direction. The second angle is the angle from the volute plane to the rotational axis of the turbine wheel [39].

Serrano, et al.[28] compared the efficiency of a double-entry asymmetric volute turbine and a double-entry symmetrical turbine under steady flow conditions. Efficiency depends on several parameters, namely mass flow reduction, turbine speed reduction, expansion ratio, adiabatic efficiency and blade to jet velocity ratio. In his research, Serrano, et al. [28] presents a model for extrapolating the performance maps of a double-entry volute asymmetric turbine and a double-entry symmetrical turbine in terms of different flow inlet conditions, rotational speed, and blade-to-jet velocity ratio.
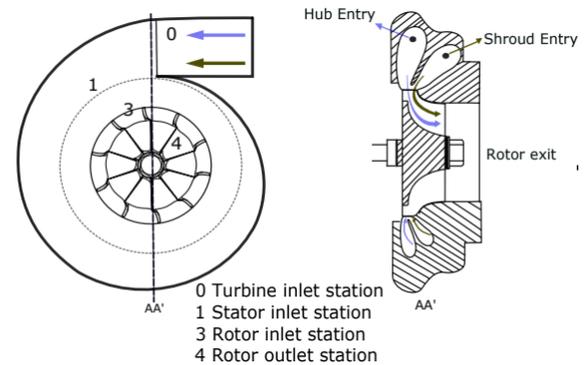

Figure 6: Twin entry symmetrical turbine [27]

The results showed reduced mass flow and apparent efficiency for twin entry symmetrical turbine and double entry volute asymmetrical turbine. For twin entry symmetrical turbine, reduced mass flow and apparent efficiency on Shroud are 0.9963 and 0.9333. Meanwhile in the Hub, the reduced mass flow and apparent efficiency are 0.9964 and 0.9287, respectively. For the double entry volume asymmetrical turbine, in the Outer limb, the reduced mass flow and apparent efficiency are 0.9952 and 0.9572, respectively. For the Inner limb, the reduced mass flow and apparent efficiency are 0.9984 and 0.9319 [28].

III. TURBINE DESIGN

Currently the turbocharger design is more advanced. Nowadays, there are various types of turbocharger designs such as variable geometry turbocharger, variable propeller turbocharger, waste-gate turbocharger, and power assist turbocharger, variable nozzle turbocharger but research on turbine design optimization has received a lot of attention recently. Turbine is a combination of turbine wheel and turbine housing. The turbine wheel is an impeller that absorbs kinetic energy from the exhaust gases entering the combustion chamber. Energy extraction from exhaust gases lowers its pressure and temperature [40].

The impeller inlet diameter (Din) is an important parameter that directly affects the turbine flow capacity which affects the turbine work. Decreasing Din increases the angle of incidence and flow loss, so turbine efficiency decreases significantly. When Din increases, turbine efficiency increases resulting in higher engine performance, but an excessive increase in Din will make the impeller line too long which increases line losses and causes a decrease in expansion ratio under the same flow conditions. This can cause performance degradation, especially at lower engine speeds [41].

The rotor inlet blade height (Hin) determines the flow area from the impeller inlet, which affects the turbine flow characteristics. Increasing the Hin reduces the relative inlet

velocity, while increasing the flow angle at the inlet leading to higher incident losses. However, the reduced relative speed reduces the incidence and loss of the track. Since relative speed has a more significant role in determining turbine efficiency, engine performance increases as the intake blade height increases. However, too large a Hin can limit engine performance by lowering the turbine expansion ratio [41].

Turbine volute throat area (At) is a critical parameter that affects turbine performance. The volute converts the exhaust energy into kinetic energy and directs the flue gas flow to the rotor inlet at a suitable flow angle. The volute throat area determines the minimum volute flow area which consequently determines the maximum exhaust flow through the turbine. Reduction of At can be useful when the engine is running at low speed conditions, but excessive reduction of At will make the turbine flow capacity too small and reduce turbine efficiency. Increasing At will improve engine performance by reducing flow losses. However, increasing Atbeyond a certain limit can also reduce engine performance.

Baturin, *et al.*[42] conducted research on the rotor blades of a TK-32 turbocharger turbine, manufactured by LLC "Penzadieselmash". In his research, it was found that the rotor of the TK-32 turbocharger turbine could not be in optimal condition if forced to n = 28000 rpm. This is due to design issues in the blade bode and blade attachments.Factors that cause a decrease in optimal turbine conditions are bending stress and bending stress. Several attempts have beento overcome this problem. To reduce bending stresses, the blade periphery can be removed. To reduce the buckling stress, the edges of the rotor blades are shifted in a circular direction towards the suction side. When the peripheral part is shifted 0.05 h towards the suction side, the maximum voltage value is reduced by 18% to 506.8 MPa. This can increase turbine efficiency by 0.4%.Reducing the number of blades on the TK-32 turbocharger turbine was also carried out by Baturin, *et al.*[42]. By reducing the number of blades from 49 to 43 by maintaining the number of nozzle vanes can increase turbine efficiency by more than 1%.

Padzillah, *et al.*[43] conducted research on turbines with a predetermined design with the aim of analyzing the relationship between the angle of entry and turbine efficiency. It was found that the maximum efficiency can be achieved in the angle of incidence between -40° to -50° for the vaned volute and also for the vaneless volute.

Leonard, *et al.*[44] conducted experiments on two rotors (30-β30 and 60-β10) with different blade angles and cone angles. The study was conducted with three stator vane (SV) conditions, namely Max. SV, 25% SV, and Min. SV. This study discusses the effect of the inlet design of a mixed flow

turbine (inlet blade angle and blade cone angle) on its aerodynamic performance.

From the research conducted by Leonard, *et al.* [44], it can be concluded that a larger cone angle causes an increase in the variation in incidence from Shroud to Hub, with Hub incidence being more positive. This is advantageous for peak efficiency performance where the rotor with the greatest blade cone angle achieves a 3% point increase over the radial rotor. However, the large blade cone angle reduces off-design performance by 5% efficiency points at low U/C conditions compared to basic radial rotors. The blade entry angle of 30° (30-β30) achieves a 2.1% point increase in measured efficiency at U/C=0.35, but incurs a 2% point penalty on design point operation. The inertia of the rotor mix flow decreases significantly as the blade cone angle increases. For a blade inlet angle of 30° (30-β30), the inertia of the mixed flow is 30% below the radial baseline. In the case of a 60° (60-β10) blade cone angle rotor, the mixed flow inertia is 50% below the radial baseline.

Syed, *et al.*[41] developed a turbine design on a turbocharger to achieve the best engine performance. This study compares the optimized turbine with the original (baseline) turbine. Where the original turbine has a volute throat area (A$_t$) of 225 mm^2, a high inlet blade (H$_{in}$) of 4 mm, an inlet diameter (D$_{in}$) of 39 mm, an outlet diameter (D$_{out}$) of 34 mm, and a rotor exit blade angle (B$_{b2}$) of -28°. The optimized turbine has a volute throat area (A$_t$) of 250 mm^2, an inlet blade height (H$_{in}$) of 6 mm, an inlet diameter (D$_{in}$) of 41 mm, an outlet diameter (D$_{out}$) of 34 mm, and a rotor blade exit angle (B$_{b2}$) of -35°.

The maximum efficiency of the original turbine (baseline) is 71.42%. With the use of optimized turbines, the maximum efficiency increases to 76.94%. Torque and air flowrate also increased to 5.26% and 8.31%, respectively. Meanwhile, brake-specific fuel consumption (BSFC) decreased by 5%, followed by a decrease in peak temperature of 4.31% [41].

Berchiolli, *et al.*[45] conducted a study comparing turbines with the initial design and turbines with a modified design. In the modified turbine, the leading edge (LE) and trailing edge (TE) thickness are reduced by 4.44% and 13.64%, respectively. The LE wedge and TE wedge were increased by 12.5% and 79% respectively. And the axial chord, stagger angle, and chord were reduced by 15.3%, 7.46%, and 23.52%, respectively. In his research, it was found that a modified turbine design could increase efficiency by 2.55%, but decrease power by 7.44%.

One way to produce efficient turbine performance is to replace the existing spiral casing on the turbine with a multi-

channel casing (MC). The use of MC in this radial turbine can divide the turbine inlet circularly into a certain number of channels. The existing turbine performance is influenced by the opening and closing of the channel which controls the channel area to the turbine [46].

The use of this multi-channel turbine reduces the best efficiency points (BEP). At full and 75% reception, the efficiency at BEP decreases with increasing rotational speed, while for 50% and 25% BEP increases. The change in turbine efficiency due to the geometric optimization process is small compared to the efficiency reduction due to different partial acceptance percentages.

IV. PERFORMANCE ON TURBINETURBOCHARGER

One way to predict the transient performance of the turbine in the early stages of the development process is the application of a 1-dimensional (1D) engine simulation software, but in the simulation, the emptying and filling volute behavior of the turbine caused by the pulsating inflow is not considered. In the development of turbomachinery, the application of computational fluid dynamics (CFD) is used to investigate the flow in the engine. With CFD simulation, the performance of the turbocharger turbine in the pulsating inflow can be predicted with sufficient accuracy [47].

Performance measurements of the turbocharger in the hot gas test are based on SAE J922 and SAE 1826 standards, assuming adiabatic [6]. The use of the adiabatic assumption excludes the effects of aerothermodynamics on heat transfer. The non-adiabatic treatment and heat transfer inside the turbocharger are significant, especially at low operating speeds. This is due to the effect of heat transfer dominating the aerodynamic turbine expansion work, leading to overestimation of turbine power and isentropic efficiency.

The heat transfer that occurs for the turbine inlet temperature was investigated by Bakhshmand, *et al.*[7] The turbine inlet temperatures used are 400^0C, 600^0C, and 800^0C. From the simulation results, it is found that the heat loss in the turbine increases because the steep temperature gradient causes heat transfer. The estimated turbine heat flow for different turbine inlet temperatures is $T_3 = 400^0$C, $T_3 = 600^0$C, $T_3 = 800^0$C is $\dot{Q}_{T,400} = 2.6$ kW, $\dot{Q}_{T,600} = 4.9$ kW, $\dot{Q}_{T,800} = 8.1$ kW.

The impact of exergy loss due to heat transfer will affect exergy efficiency. At a temperature of 800^0C and a speed of 37k RPM, the exergy loss obtained through heat transfer reaches 81.9%, and at a temperature of 400^0C, the exergy loss reaches 41%. The increased speed will also make the exergy destruction value increase. This happens because the higher speed of the turbocharger makes the mass flow of gas also

increases. This is the main cause of frictional flow losses at higher velocities, and consequently leads to irreversibility and higher exergy crushing rates [7].
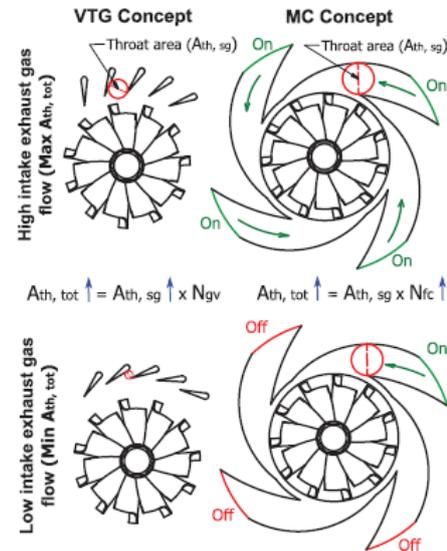

Figure 7: Comparison between VTG (left) and MC (right) in a radial turbine [46]

Measurement of transient response for vehicles is usually done by road test or roller test using a dynamometer. In radial flow turbines, the rotor mass present is high and hence high inertia results. This leads to a reduction in the transient response. Meanwhile, in a mixed flow turbine, the inertia of the rotor tends to be low and causes an increase in the transient response [48]. From the simulation it was found that the transient response times for radial and mixed flows were 0.858 seconds and 0.770 seconds, respectively. The transient response time for mixed flow is faster than for radial flow, this makes mixed flow turbines better for use in turbochargers.

Experiments were carried out by Ketata *et al.*[38] on a vaneless radial turbine flow with different pulse frequencies (100, 133.33, 166.66, and 200 Hz). The experimental results show that the Total to Static (TS) Efficiency increases significantly when the pulse frequency decreases, namely by 33% when the pulse frequency is 200 Hz and then increases to close to 48% when the pulse frequency is 100 Hz. Thus, the turbocharger turbine is more efficient at the lowest pulse frequency than at higher frequencies.

Simulations were also carried out by Udayakumar, Yasho [40] on a mixed turbine flow, it was found that the TS efficiency increased up to 80% and the efficiency obtained was 75%. The efficiency of the mixed flow turbine is higher than that of the radial flow turbine which has an efficiency of 60%. The resulting velocity ratio of 0.61 indicates that this mixed-flow turbine is capable of producing high turbocharger efficiency and is suitable for use on city streets.

V. CONCLUSION

Modern internal combustion engines used today must meet several applicable requirements. The engine must be able to reduce pollutant gas emissions and easy engine maintenance. The machine used must be efficient in low and high load conditions. One thing that can be done is the use of a turbocharger. Turbine as one of the main components in a turbocharger has an important role in determining the power generated by an internal combustion engine. There are two types of turbines commonly used, namely radial turbines and axial turbines. In order to maximize the performance of the turbine in the turbocharger, a variable geometry turbine (VGT) is used. The use of VGT can increase efficiency and reduce CO_2 emissions by up to 23% and 30 - 50% for NO_x VGT has several variations that have been developed such as Active Controlled Turbocharger (ACT), Passive Controlled Turbocharger (PCT), Variable Nozzle Turbine (VNT), and Regenerative Electrically Assisted Turbocharger (REAT).

Another thing that can be developed to maximize turbine performance is to use a double-entry turbine. The double entry turbine has the aim of saving exhaust gas energy and facilitating cylinder gas exchange. There are two types of double entry turbines, namely Double Entry Volute Asymmetrical Turbine and Twin Entry Symmetrical Turbine. One way to produce efficient turbine performance is to replace the existing spiral casing on the turbine with a multi-channel casing (MC). The use of MC in this radial turbine can divide the turbine inlet circularly into a certain number of channels.

Performance measurements of the turbocharger in the hot gas test are based on SAE J922 and SAE 1826 standards, assuming adiabatic. The use of the adiabatic assumption excludes the effects of aerothermodynamics on heat transfer. The non-adiabatic treatment and heat transfer inside the turbocharger are significant, especially at low operating speeds. In radial flow turbines, the rotor mass present is high and hence high inertia results. This leads to a reduction in the transient response. Meanwhile, in a mixed flow turbine, the inertia of the rotor tends to be low and causes an increase in the transient response.

Based on the discussion about the best turbine design that can be used to produce maximum performance. Taking into account the high efficiency of fuel use, the authors suggest further research on the design and development of turbocharger manifolds. The development of a turbine system with PCT can be done by combining an existing turbine system with a VGT compressor that has good workability. Internal combustion engine parameters such as injection time and combustion time can be included in future research to obtain more optimal turbine system performance simulation results.

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