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Turbocharging small size engine to increase engine output: An assessment of turbocharger study field

H M Herzwan[1] *, **A Azri** [1] , **M Rizalman** [1]

[1] Faculty of Mechanical Engineering, Universiti Malaysia Pahang, Pekan, Pahang, Malaysia

*Corresponding author: herzwan@gmail.com

Abstract. In recent years, engine downsizing becomes popular in modern vehicles since rising demands for less consuming vehicle and more stringent emission regulations. Along with this trend, turbocharging also gains popularity as a method to increase the output of small size engine hence enables it to produce comparable output to bigger displacement engine. In this paper, recent turbocharger studies in three major area that are heat transfer studies, flow studies and mechanical studies are reviewed. In heat transfer studies, the findings from experimental and modelling of heat transfer are presented. For flow studies, the reviews are separated to the different part of the turbocharger and method of study. While for mechanical studies in turbocharger, the mechanical losses in turbocharger was reviewed. At the end of this review, the area of interest for the next study will be concluded.

1. Introduction

The introduction of turbocharger for automotive application starts about year 1905 when a Swiss engineer named Alfred Buechi apply for his pattern of compound motor [1]. In the beginning, it is not identified as turbocharger as well known today but rather an axial flow turbine and compressor that linked by a shaft with the engine that they are fitted to.

The turbocharger unit build consist of three parts that are turbine side, compressor side and bearing housing. At the turbine side, it consist of turbine housing, and turbine wheel assembly. Turbine wheel and shaft assembly are commonly come as one parts. Turbine wheel is commonly made from casting process and the material that used is high nickel content materials [1]. While for turbine housing, it commonly made from cast iron that can withstand high exhaust temperature.

The compressor side consist of two part which are the compressor wheel and the compressor cover [2]. The turbocharger's compressor wheel is classed as a radial compressor since it induce fresh air into turbocharger inducer and accelerate it in radial motion. Most compressor wheel is made from various aluminium alloys through casting process while for compressor cover; it is commonly made from aluminium.

The turbine and compressor wheel are connected through a shaft [3]. The connecting shaft is supported by a bearing system. The bearing system has many considerations that affect its design. It must be able to handle the thrust load that caused by the high boost pressure. It also must be able to withstand the high temperature that caused by the exhaust temperature. Other than that, it must be able to withstand the shaft motion gyrations imparted onto the turbine shaft by the engine pulses. Lastly, the bearing system must be able to support high speed rotations of the shaft that connects between turbine and compressor. The turbine wheel rotates at speed that commonly more than 100,000 rotations per minute (rpm) for automotive applications [4].

Turbocharger unit works with three or four working fluids which are intake air, exhaust gas, lubricating oil and cooling water [5]. At the beginning, the exhaust gas from the combustion process is channelled into the turbine housing thus spinning the wheel. Hereby, the energy from the exhaust gas is converted into work where the turbine wheel is linked to the compressor wheel by a shaft. As the turbine wheel spins, the compressor wheel also spins. The compressor wheel induce fresh air into the compressor cover, compressed the air and discharge the compressed air into the intake manifold. This creates a positive air charge in the intake manifold.

2. Turbocharger applications in vehicles

In the modern ages, the number of motorized vehicles around the world including Malaysia is increased. According to a report by Malaysia Automotive Associations [6], total registered vehicles in Malaysia is increasing every year from year 2010 until 2015 except for year 2011 as shown in Table 1. Since the number of vehicles is rising year by year, the emission level also increase. This will cause negative effect to the peoples and environment such as greenhouse effect, health issues and acid rain [7].

As action taken to overcome the emission problem, many countries have tighten the emission regulations and encourage the automotive maker to produce more efficient engine [8, 9]. One of the solution that gains attention among the carmakers is engine downsizing [10, 11]. The advantages of small size engine are, it produce lower emission and consume less fuel [12]. It also have less mechanical losses, less pumping losses and also lighter [13-15].

Table 1. Number of Vehicles in Malaysia [6]

Year	Number of Registered Vehicles
2010	605,156
2011	600,123
2012	627,753
2013	655,793
2014	666,487
2015	666,677

However, small size engine produce lower output compared to big size engine. Hence, modern trends among automobile makers tends to equip the small engine with turbochargers. The purpose of turbocharging is to increase the degree of intake air boosting thus producing higher system efficiency [15]. Turbocharger also forces higher air flow into the engine and therefore increase the engine power [5, 16]. Turbochargers also offers the benefit of improved fuel economy and also emission reductions [17-20]. The advantages of turbocharger usage are, it enables small size engine to produce comparable output compared to bigger natural aspirated (NA) engine. It also utilizes waste energy from the engine which is exhaust gas to spin the turbine thus pumping fresh air to the intake manifold [21]. Hence, it cause smaller parasitic load to the engine compared to supercharger system. Moreover, when the engine usages involves changes in altitude, non-turbo engine output decreases by 5 to 10% as the altitude rises by every 2 km. Therefore, turbocharging is one of the main methods for engine power recovery at high altitudes [22].

Nowadays, the technology involving the turbochargers has evolved. The advancements like variable geometry turbocharger (VGT) [23], electrical assist turbocharger [24], electric turbocharger [25], twin entry turbocharger [26] and many more makes turbocharger performs more efficient in the modern applications. Aside from that, usage of advance material like ceramic [27] also contribute to high efficient turbocharger.

Since the turbocharger usage becomes more common, many studies have been conducted to gain more understanding about turbocharger performance characteristics when operating in various conditions. It is stated by Bontempo et al [13] that the turbocharger performance research area can be divided into two research area which are flow analysis and heat transfer effects. The methods that commonly used in turbocharger studies includes 1D modelling, 3D modelling, gas stand testing and turbocharger engine testing.

3. Heat transfer in turbocharger

3.1 Experimental study

Bontempo et al. [13] experimenting on the steady and unsteady conditions of a small size turbocharger for automotive applications. In the study, the experiment is done using turbocharger gas stand where diesel engine is used as hot gas generator. Furthermore, the whole turbocharger unit is analysed using the first law analysis to estimate the heat transfer effect on the evaluation of efficiency through the classical adiabatic assumption. At the end of the study, it is concluded that the thermal power transferred to the lubricating oil as well as to the environment has a relevant impact on the performance of turbocharger. It is also stated that the algebraic sum of the two thermal power is estimated about 20 to 30% of the compressor enthalpy change per unit time. Baines et al [28] also analyses the heat transfer in automotive turbochargers. Experimental testing have been conducted on the commercial turbocharger and 1D heat transfer model has been developed based on the experimental results. From the experiment, a set of heat transfer coefficient have been obtained where it were largely independent on the turbocharger model.

Chesse et al. [29] studied the impact of heat transfer on the performance calculations of automotive turbocharger compressor. In the study, the author also proposed an experimental method to determine the compressor internal heat transfer in a turbocharger. At the end of the study, it is claimed that automotive turbocharger compressors are not operating in adiabatic conditions. Moreover, the compressor maps depends on the turbine inlet temperature. Other than that, the use of adiabatic model in the engine simulators generates error for the compressor power and compressor outlet temperatures. In the other research, Tanda et al [30] also measure the impact of internal heat transfer to the turbocharger efficiency. To perform the study, an innovative experimental approach that determine the spatial distributions of the surface temperature was done. By doing the analysis, general understanding of heat transfer mechanism occur during turbocharger operation and the relationship for heat transfer rate can be used to derive the real adiabatic efficiency. The study was done under diabatic and quasi-adiabatic conditions and was integrated by surface temperature measurement of the turbocharger using digital infrared camera. It is also concluded that the evaluation of internal heat transfer based on the thermographic inspections and the related correction of measured efficiency shows the importance of heat flux effect when the turbocharger running at low blade speed.

Turbine side of a turbocharger unit is the principle heat source for turbocharger heat transfer as stated by Burke et al. [14]. Hence, the authors do the analysis on the heat transfer at this part. The author also assess the applicability of gas stand derived heat transfer model to on engine conditions where the flow are hotter, pulsating and highly transient. Finally, it is concluded that the heat transfer always represents at least 20% of enthalpy change in the turbine. Furthermore, heat transfer correlations determined on engine and gas stand can be significantly different due to the different instrumentation layout. Additionally, the use of heat transfer correlations from gas stand to simulate on engine conditions will provide a significant improvement in prediction accuracy using either averaged or pulsating flow Re number.

Romagnoli and Martinez-Botas [31] conducted a study to provide an insight into the heat transfer process that occur within a turbocharger unit. In the study, a turbocharger unit is fitted to a diesel engine where the engine is tested under different load and engine speed. From the study, it is concluded that the engine has large impact on the surface temperature of the turbine and compressor casing. The surface temperature of both turbine and compressors also vary linearly with the exhaust gas temperature.

Serrano et al [32] also studied the internal convection in turbocharger by measuring heat fluxes between the turbocharger parts. The study is done through gas stand test rig where the testing conditions are hot flow and cold flow. From the experiment, it is concluded that the heat losses in turbine side grow with turbine enthalpy drop. However, this condition gives high impact only at low loads. Moreover, heat transfer will be concentrated at the compressor inlet since no heat should arrive to the compressor inlet.

3.2 Heat transfer modelling

The heat transfer in turbocharger also can be analysed through heat transfer model as considered by Serrano et al [33]. In the study, a heat transfer model consist of five metal nodes is proposed to analyse the heat transfer in the turbocharger. The heat flows between the metal nodes are calculated using Fourier's Law. Next, the lump model is validated through experimental testing. Results from the study shows that the heat flows from the turbocharger gives significant impact at low engine load for turbine and compressor efficiencies calculation. Moreover, the differences between turbine and compressor efficiencies are also stated. For turbine, the differences are important from medium to high turbocharger speed while for compressor, the differences only appear at low speed. Same analysis method are done by Olmeda et al [34] and Serrano et al [35]

There is also study that analyses both modelling and experimental on the heat transfer as done by Payri et al [36]. From the study, it is concluded that the most important external heat fluxes comes from the turbine external surfaces due to its higher temperature and big areas. While for central housing, the external heat fluxes are negligible and for compressor side, the external heat flow can be reversed. Marelli et al [37] also studied both modelling and experiment where from the study, a simplified correction model is developed where it not requires geometrical information to be provided. The proposed correction model is claimed to pre-process compressor maps generally available thus improving the engine-turbocharger matching calculations. Same study also have been performed by Burke et al [38] where a lumped capacity heat transfer model has been developed and compared with experimental results of a 2200cc diesel engine that operating under steady and transient conditions. From the study, a sensitivity study shows that the parameters of the heat transfer gives effect to the gas temperature by only ±4˚C but housing temperature up to 80˚C. Moreover, transient simulations shows that errors in thermal capacitance also lead to errors. Mrosek, M. and R. Isermann [39] presented a semi-physical turbocharger power and heat transfer model. The model quality and proportion of heat transfer in the measured temperatures is demonstrated with measured data obtained from the experiment. It was concluded that especially at low turbocharger power, the heat transfer has a large impact on the measured enthalpy difference.

Turbocharger heat transfer modelling also have been done under steady and transient conditions by Cormerais et al [40]. In the study, the author proposed a method to calculate the heat transfer occurring in the turbocharger from geometric data. Findings from the study shows that the heat transfer influence the turbocharger performance especially at low and partial loads. Furthermore, it is also stated that the heat transfer modelling must be based on an experimental study. Same flow conditions have been studied by Serrano et al [41] where findings from the study concludes that the heat fluxes become more important for the overall turbocharger prediction when the turbocharger reduces. It is also stated that in certain cases, the heat transferred from the exhaust gas to the rest of the turbocharger via turbine case can achieve up to 50% of the total turbine enthalpy drop.

Olmeda et al [34] proposed a mathematical 1D model that improves the efficiency determination at the turbine side. The author concludes that the application of 1D lumped model into real turbocharger application has shown the importance of internal heat fluxes when the turbocharger running at lower rotational speed.

3.3 Heat transfer theoretical analysis

The heat transfer analysis also have been done using theoretical analysis where it leads to the equations for work input and efficiency corrections as described by Sirakov and Casey [42]. In the study, the analysis are done using calculations, alongside with series of testing where the amount of heat transfer is varied. From the study, it is concluded that the aerodynamic and thermodynamic effect of heat transfer gives small effect to the overall turbocharger performance as it leads to no changes in the pressure ratio characteristics of either components.

4. Flow Studies in Turbocharger

4.1 Flow study in compressor side (experimental)

Abdelmadjid et al [12] analyses the effect of volute geometry on the turbulent air flow in the turbocharger compressor side. In the study, three different volute design in the compressor are studied. Simulations also have been done to analyse the flow characteristics and performance level of the compressor. From the study, it is concluded that the modifications of the volute cross section shape affect the operating range more than the peak efficiency while modifications on the volute inlet location affect the peak efficiency more than the operating range. Furthermore, higher peak efficiency is observed in the case of tangential inlet and wider operating range is observed in the case of modified circular case.

Torregrosa, A. J., et al [10] performs a study to characterize flow instability in turbocharger compressor especially the distributions of the high temperature compressed backflow that appears upstream of the impeller at marginal surge conditions. In the study, the compressor inlet was fitted with linear and circumferential thermocouple arrays in order to measure the temperature distribution caused by the backflow. Miniaturized pressure probes at the inducer and diffuser shows that the pressure spectra varied during the different operating conditions. Analysis from the results obtained shows that inlet whoosh noise being boosted by the reversed flow but not caused by it. The source of noise probably being located at or downstream of the compressor impeller.

4.2 Flow study in compressor side (simulation and modelling)

Flow inside the turbocharger compressor also can be simulated using 1D modelling approach as done by Bozza and Gimelli [43]. In the study, the flow inside the rotating pipe inside a centrifugal compressor is simulated using 1D modelling. From the study, it is stated that the 1D modelling method is able to simulate the steady performance map of the compressor of a turbocharger unit at all operating region. The proposed modelling method is also proven to solve some of the limitations related to the employment of the steady performance map and to calculate the turbocharger-engine matching conditions.

Some modern turbochargers are designed with dual volute design at the compressor side. Hence, the performance are analysed using computational fluid dynamics (CFD) method as done by Jiao, K., et al [44]. The numerical simulations are focused on the air flow from the compressor impeller inlet to volute exit. Other than that, the overall performance level and range are predicted. From the analysis, is was revealed that the dual volute design could separate the compressor into two operating regions which are “high efficiency” and “low efficiency” regions with different air flow characteristics. Treating the two regions separately with dual diffuser design showed extended stable operating range and improved efficiency by comparing with conventional single volute design.

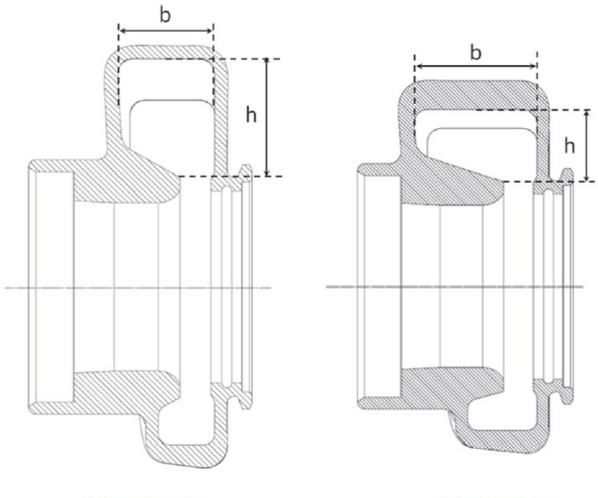
Abdelmadjid, C., et al. [12] presents a numerical solutions of the volute geometry effect on the turbulent air flow through the turbocharger compressor. In the study, three different shaped volutes with the same impeller were investigated using the computational fluid dynamics. Due to analysis complexity, the flow conditions that only considered is the steady flow. From the analysis, it is concluded that the modification of the volute cross section shape affects the operating range more than the peak efficiency. The modification of the volute inlet location affects the operating range more than the operating range.

4.3 Flow study in turbine side (experimental)

Serrano et al [45] studied an unsteady approach to determine the performance of a small radial inflow turbine where the turbine is operating under cold pulsating flow. In the study, the results from cold flow test are compared with the results from 1D modelling. From the results obtained, it is concluded that the mechanical efficiency model and turbine isentropic efficiency model can be used in a 1D gas dynamic code to reproduce the turbocharger behaviour with acceptable accuracy. Moreover, the biggest factor that affect the unsteady flow on the turbine efficiency is through the influence of blade jet to speed ratio.

Rajoo, S et al [26] presents the details of unsteady experiment and analysis on a twin-entry variable geometry turbine of automobile turbocharger. The twin entry turbine was designed in progression from single-entry nozzle-less and nozzled turbines while maintaining the main geometrical features in all cases. The turbocharger operates under pulsating flow conditions. From the experiment, it was concluded that for the optimum vane angle setting (60˚) and in-phase flow conditions, the overall flow capacity is larger than the equivalent quasi-steady. Furthermore, the quasi-steady assumption for the turbine efficiency under in-phase flow condition found to be only partially true. Next, the quasi-steady assumption for the turbine efficiency under out-of-phase flow condition was found to be unsatisfied.

Exhaust flow from the engine is unsteady, pulsating flow. Hence, the flow condition need to be taken into account whether the flow will affect the turbine efficiency as done by Marelli. S and M. Capobianco [46]. In the study, the efficiency of the turbine was evaluated, especially under unsteady flow condition that typically occur in internal combustion engine. The turbine efficiency was measured under pulsating flow and steady flow conditions are compared where a quasi-steady flow approach was also considered. The effect of waste gate opening was also analysed. From the study, the steady flow analysis shows that if the efficiency was evaluated directly by measuring the thermodynamic parameters at the inlet and outlet planes, a large deviations can be found from the levels estimated by using an external loading device to access turbine power. This is mainly due to the inaccuracy in gas temperature evaluation at the radial flow turbine exit. In pulsating flow study, the pulsating flow causes a reduction of turbine efficiency where this confirms that the steady flow characteristics curves are not correctly represents the real turbine behaviour.



(a) *Volute A* (b) *Volute B*

Figure 1. Different cross sectional shape where baseline volute (denoted as Volute B) was optimized (Volute A) with the same A/R ratio [47]

There were also an attempt to study the effect of volute cross sectional-shape on turbocharger turbine as done by Yang, M., et al [47]. The study was carried under pulsating conditions using cold-flow turbocharger test rig. Two different volute design as shown in Figure 1. From the study, it is shown that the turbine with optimized Volute A has averaged efficiency under pulsating flow condition, for different loadings and frequencies. Next, Volute B produce higher total pressure loss during a pulse cycle. Flow field in the cross-sectional shape with the baseline volute (Volute B) is more sensitive to the pulsating flow in terms of distorted span-wise flow distortion referring to the corresponding steady conditions.

4.4 Flow study in turbine side (simulation and modelling)

Chiong et al [15] uses 1D modelling method to study the geometrical effect to the flow inside the twin entry turbine. In the study, five different models with different complexity are studied. From the study, it is concluded that the flow pressure experienced stronger fluctuations in volute models with varying cross sectional area especially at the turbine entry. Furthermore, the usage of variable area ducts was found to magnify the secondary fluctuations in mass flow rate predictions. Furthermore, Chiong., et al [48] also integrate between the meanline model and 1D model to predict the pulsating performance of the turbine. The purpose of the integration is to predict the instantaneous turbine power and swallowing capacity of a turbine.

The flow studies in turbine side also analysis the mass flow characteristics where the mass flow is modelled and extrapolated as done by Zhu, S., et al [49]. In the study, a new mass flow model was proposed based on the physical model of a radial turbine simplified as two nozzles in series. Ideal nozzle flow equation was applied on the turbine stator thus the mass flow rate through the turbine can be expressed with three fitted coefficient which have clear physical meaning. From the results obtained, is was shown that considering the number of fitted coefficient and the modelling accuracy, the deduced model performs well in regression analyses conducted with experimental data tested from three radial turbines of different sizes.

Galindo, J., et al [50] presents a numerical study that analyses the effect of pulsating flow in a variable geometry radial inflow turbine. The main objective of the study aims to evaluate the non-steady effects in the volute, nozzles and impeller separately. The analysis of the pulsating results shows that the most of the time-shift in the mass flow occurs in the volute. Furthermore, the shift varies slightly with pulse amplitude and frequency. For the nozzle part, the flow in the nozzle section presents a limited hysteretic behaviour in its pulsating flow capacity and lastly, the behaviour of the impeller is even less affected by wave action and accumulation effects than the stator due to its smaller size. From the CFD analysis that are done, the author proposed simplified model that includes a one-dimensional or quasi-two-dimensional element to represent the volute, a nozzle to represent the vaned stator, a small zero-dimensional element to represent hysteresis in the stator and a rotating channel in which rothalpy is conserved to represent the flow in the rotor.

5. Mechanical Studies in Turbocharger

Serrano, J. R., et al. [51] presents the work to show an approximation through an experimental and theoretical study in order to quantify the mechanical losses in a turbochargers. The losses are mainly due to dynamics in the turbocharger bearing shaft. The experimental consist of measurement of the turbocharger in quasi-adiabatic flow conditions. While for theoretical part, a mathematical model was developed where it considers the radial and the axial bearings. From the results obtained, for quasi adiabatic conditions, the mechanical efficiency could be assumed as a constant value close to unity while the turbocharger operates in high speed. Furthermore, the mechanical losses need to be computed for both journal and thrust bearing to get the best results. The proposed model also shows a good agreement with the experimental data.

There are also a study the investigates the bearing clearance effects to the dynamics of the turbocharger which have been done by Smolík, L., et al. [19]. The turbocharger analysis in the experiment is modelled by means of flexible multibody dynamics approaches. Bearings behaviour is described using Reynolds equations where it was solved numerically. From the results obtained, it was suggested that the changes of radial clearances caused by the operational temperature should be respected when analysis of turbocharger dynamical response is performed. Bearing clearance also can generate sub-synchronous components of the rotor’s response.

6. Conclusions

Turbocharger can increase the engine performance output and at the same time reduce the emission level by increasing the engines combustion efficiency. This paper has reviewed the previous researches that have been done in three different field of studies that are heat transfer study, flow study and mechanical study. From the reviews, the turbocharger studies can be summarised as below:

1) Heat transfer studies in turbocharger commonly covers the impact of the heat transfer to the overall turbocharger performances. Many of the studies combines the experimental and modelling method to analyse the heat transfer impact to the turbocharger performance.

2) Flow study in turbocharger can be separated into two major parts that are turbines and compressor. Flow conditions and the turbocharger design parameters gives significant impact to the result of the study

3) The mechanical study usually covers the bearing parts of the turbochargers. This is because this part involves high-speed rotations and high loads to the connecting shafts.

The area of research that are going to be done by the main author is heat transfer studies on the turbocharger. The studies is about analysing the impact of heat transfer to the turbocharger performance. The study will covers the experimental and simulations study, where it will analyses on how the heat travels from the turbine to the bearing housing and next to the compressor thus influencing the overall turbocharger performance. The study will also investigate on how the heat transfer will cause changes in the turbocharger mapping compared to the standard mapping that provided by the turbocharger manufacturer.

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References

[1] Miller J K 2008 *Turbo: Real World High-Performance Turbocharger Systems* (U.S.A: CarTech, Inc)
[2] Bell C 1997 *Maximum Boost; Designing, Testing and Installing Turbocharger Systems* (Massachusetts, USA: Bentley Publishers)
[3] Holmbom R, Liang B and Eriksson L 2017 Implications of Using Turbocharger Speed Sensor for Boost Pressure Control *IFAC-PapersOnLine* **50** 11040-5
[4] Chen W J 2012 Rotordynamics and bearing design of turbochargers *Mechanical Systems and Signal Processing* **29** 77-89
[5] Burke R, Copeland C and Duda T 2014 Investigation into the Assumptions for Lumped Capacitance Modelling of Turbocharger Heat Transfer. In: *6th International Conference On Simulation And Testing,* (Germany: University of Bath Online Publication Store)
[6] Ahmad A 2017 Market Review for 2016 and Outlook for 2017. Malaysia Automotive Association)
[7] Amaechi J O and Godstime T C 2015 Automotive Exhausts Emissions And Its Implications For Environmental Sustainability *International Journal of Advanced Academic Research* **1**
[8] Chiavola O, Palmieri F and Recco E 2017 Turbocharger Speed Estimation via Vibration Measurements for Combustion Sensing. In: *72nd Conference of the Italian Thermal MAchines Engineering Association,* (Lecce, Italy pp 842-9
[9] Bahiuddin I, Mazlan S A, Imaduddin F and Ubaidillah 2017 A new control-oriented transient model of variable geometry turbocharger *Energy* **125** 297-312

[10] Torregrosa A J, Broatch A, Margot X, García-Tíscar J, Narvekar Y and Cheung R 2017 Local flow measurements in a turbocharger compressor inlet *Experimental Thermal and Fluid Science* **88** 542–53

[11] Kabral R and Åbom M 2018 Investigation of turbocharger compressor surge inception by means of an acoustic two-port model *Journal of Sound and Vibration* **412** 270-86

[12] Abdelmadjid C, Mohamed S-A and Boussad B 2013 CFD Analysis of the Volute Geometry Effect on the Turbulent Air Flow through the Turbocharger Compressor *Energy Procedia* **36** 746-55

[13] Bontempo R, Cardone M, Manna M and Vorraro G 2015 Steady and unsteady experimental analysis of a turbocharger for automotive applications *Energy Conversion and Management* **99** 72-80

[14] Burke R D, Vagg C R M, Chalet D and Chesse P 2015 Heat transfer in turbocharger turbines under steady, pulsating and transient conditions *International Journal of Heat and Fluid Flow* **52** 185-97

[15] Chiong M S, Rajoo S, Martinez-Botas R F and Costall A W 2012 Engine turbocharger performance prediction: One-dimensional modeling of a twin entry turbine *Energy Conversion and Management* **57** 68-78

[16] Gancedo M, Guillou E and Gutmark E 2018 Effect of bleed slots on turbocharger centrifugal compressor stability *International Journal of Heat and Fluid Flow* **70** 206-15

[17] Romagnoli A, Manivannan A, Rajoo S, Chiong M S, Feneleyc A, A. Pesiridisc and Martinez-Botas R F 2017 A review of heat transfer in turbochargers *Renewable and Sustainable Energy Reviews* **79** 1442–60

[18] Ravaglioli V, Cavina N, Cerofolini A, Corti E, Moro D and Ponti F 2015 Automotive Turbochargers Power Estimation Based on Speed Fluctuation Analysis *Energy Procedia* **82** 103-10

[19] Smolík L, Hajžman M and Byrtus M 2017 Investigation of bearing clearance effects in dynamics of turbochargers *International Journal of Mechanical Sciences* **127** 62-72

[20] Ding Z, Zhuge W, Zhang Y, Chen H, Martinez-Botas R and Yang M 2017 A one-dimensional unsteady performance model for turbocharger turbines *Energy* **132** 341-55

[21] Zhao B, Sun H, Wang L and Song M 2017 Impact of inlet distortion on turbocharger compressor stage performance *Applied Thermal Engineering* **124** 393-402

[22] Yang M, Gu Y, Deng K, Yang Z and Zhang Y 2018 Analysis on altitude adaptability of turbocharging systems for a heavy-duty diesel engine *Applied Thermal Engineering* **128** 1196-207

[23] Feneley A J, Pesiridis A and Andwari A M 2017 Variable Geometry Turbocharger Technologies for Exhaust Energy Recovery and Boosting-A Review *Renewable and Sustainable Energy Reviews* **71** 959-75

[24] Grönman A, Sallinen P, Honkatukia J, Backman J and Uusitalo A 2016 Design and experiments of two-stage intercooled electrically assisted turbocharger *Energy Conversion and Management* **111** 115-24

[25] Ekberg K and Eriksson L 2017 Improving Fuel Economy and Acceleration by Electric Turbocharger Control for Heavy Duty Long Haulage *IFAC PapersOnLine* **50** 11052-7

[26] Rajoo S, Romagnoli A and Martinez-Botas R F 2012 Unsteady performance analysis of a twin-entry variable geometry turbocharger turbine *Energy* **38** 176-89

[27] Noor A M, Abbas M R, Rajoo S, Sah M H M and Ahmad N 2014 Review on Ceramic Application in Automotive Turbocharged Engines *Applied Mechanics and Materials* **660** 219-28

[28] Baines N, Wygant K D and Dris A 2010 The Analysis of Heat Transfer in Automotive Turbochargers *Journal of Engineering for Gas Turbines and Power* **132**

[29] Chesse P, Chalet D and Tauzia X 2011 Impact of the Heat Transfer on the Performance Calculations of Automotive Turbocharger Compressor *Oil & Gas Science and Technology – Revue d'IFP Energies nouvelles* **66** 791-800
[30] Tanda G, Marelli S, Marmorato G and Capobianco M 2017 An experimental investigation of internal heat transfer in an automotive turbocharger compressor *Applied Energy* **193** 531–9
[31] Romagnoli A and Martinez-Botas R 2012 Heat transfer analysis in a turbocharger turbine: An experimental and computational evaluation *Applied Thermal Engineering* **38** 58-77
[32] Serrano J R, Olmeda P, Arnau F J, Reyes-Belmonte M A and Tartoussi H 2015 A study on the internal convection in small turbochargers. Proposal of heat transfer convective coefficients *Applied Thermal Engineering* **89** 587-99
[33] Serrano J R, Olmeda P, Arnau F J, Dombrovsky A and Smith L 2015 Analysis and Methodology to Characterize Heat Transfer Phenomena in Automotive Turbochargers *Journal of Engineering for Gas Turbines and Power* **137** 021901
[34] Olmeda P, Dolz V, Arnau F J and Reyes-Belmonte M A 2013 Determination of heat flows inside turbochargers by means of a one dimensional lumped model *Mathematical and Computer Modelling* **57** 1847-52
[35] Serrano J R, Olmeda P, Arnau F J, Dombrovsky A and Smith L 2015 Turbocharger heat transfer and mechanical losses influence in predicting engines performance by using one-dimensional simulation codes *Energy* **86** 204-18
[36] Payri F, Olmeda P, Arnau F J, Dombrovsky A and Smith L 2014 External heat losses in small turbochargers: Model and experiments *Energy* **71** 534-46
[37] Marelli S, Marmorato G and Capobianco M 2016 Evaluation of heat transfer effects in small turbochargers by theoretical model and its experimental validation *Energy* **112** 264-72
[38] R.D.Burke, Olmeda P, Arnau F J and Reyes-Belmonte M 2014 *11th International Conference on Turbochargers and Turbocharging*: Woodhead Publishing) pp 103-12
[39] Mrosek M and Isermann R 2010 On the Parametrisation of Turbocharger Power and Heat Transfer Models *IFAC Proceedings Volumes* **43** 210-5
[40] Cormerais M, Chesse P and Hetet J-F 2009 Turbocharger Heat Transfer Modeling Under Steady and Transient Conditions *International Journal of Thermodynamics* **12** 193-202
[41] Serrano J, Olmeda P, Arnau F, Reyes-Belmonte M and Lefebvre A 2013 Importance of Heat Transfer Phenomena in Small Turbochargers for Passenger Car Applications *SAE International Journal of Engines* **6** 716-28
[42] Sirakov B and Casey M 2012 Evaluation of Heat Transfer Effects on Turbocharger Performance *Journal of Turbomachinery* **135** 021011
[43] Bozza F and Gimelli A 2009 Unsteady 1D Simulation of a Turbocharger Compressor *SAE International Journal of Engines* **2**
[44] Jiao K, Sun H, Li X, Wu H, Krivitzky E, Schram T and Larosiliere L M 2009 Numerical simulation of air flow through turbocharger compressors with dual volute design *Applied Energy* **86** 2494-506
[45] Serrano J R, Arnau F J, Fajardo P, Reyes Belmonte M A and Vidal F 2012 Contribution to the Modeling and Understanding of Cold Pulsating Flow Influence in the Efficiency of Small Radial Turbines for Turbochargers *Journal of Engineering for Gas Turbines and Power* **134** 102701
[46] Marelli S and Capobianco M 2011 Steady and pulsating flow efficiency of a waste-gated turbocharger radial flow turbine for automotive application *Energy* **36** 459-65
[47] Yang M, Martinez-Botas R, Rajoo S, Yokoyama T and Ibaraki S 2015 An investigation of volute cross-sectional shape on turbocharger turbine under pulsating conditions in internal combustion engine *Energy Conversion and Management* **105** 167-77
[48] Chiong M S, Rajoo S, Romagnoli A, Costall A W and Martinez-Botas R F 2014 Integration of meanline and one-dimensional methods for prediction of pulsating performance of a turbocharger turbine *Energy Conversion and Management* **81** 270-81

[49] Zhu S, Deng K and Liu S 2015 Modeling and extrapolating mass flow characteristics of a radial turbocharger turbine *Energy* **87** 628-37
[50] Galindo J, Fajardo P, Navarro R and García-Cuevas L M 2013 Characterization of a radial turbocharger turbine in pulsating flow by means of CFD and its application to engine modeling *Applied Energy* **103** 116-27
[51] Serrano J R, Olmeda P, Tiseira A, García-Cuevas L M and Lefebvre A 2013 Theoretical and experimental study of mechanical losses in automotive turbochargers *Energy* **55** 888-98