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Turbochargers and related technologies

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Abstract. Turbochargers are one of the most important inventions to facilitate internal combustion engines. This paper is a thematic review of the technology of the turbocharger with emphasis on its workings, influencing factors, applications, problems, solutions and related or derived technologies for purposes outside the motoring industry. This paper reveals that the turbocharger resembles a modeled heat machine with thermodynamic processes for boosting engine power output with exhaust gas flow. It gives rise to various problems including inefficiencies, lags and conditions to be met, etc. As solutions, various mechanisms have been developed, as well as special modifications such as multiple turbochargers. E-boosting, gas turbines and microturbines have been discussed as related technologies with similarities in principles or origins that are of use in the power generation processes from various points of view, including principles, working conditions and efficiencies.

Keywords: turbochargers, turbines, motorsports, microturbines, energy

1. Introduction

People have innovated to maximize the efficiency of internal combustion engines since their inception, with turbochargers being one of the most notable examples of machinery added. Invented by Büchi in 1905 as an improvement on previous concepts of superchargers, they are still in wide use and under heavy research up to this date. In 2019 the global automotive turbocharger market reached a size of USD 13.81 billion and was projected to grow at a rate of about 9% annually until 2027[1]. This paper is to be focused on the working principles, criteria, determinants and examples of turbochargers in the motoring industry, together with research into the inventions inspired by or related to turbochargers represented by microturbines. The results can be used as a reflection of this piece of engineering judging both from principles and from actual applications, while providing a view into the potential that still lies within so as to give it value for future research concerning greener power generation.

2. Turbochargers

First patented by Swiss engineer Alfred J. Büchi in 1905, turbochargers are improvements based on the previous superchargers invented by Daimler. Büchi's design uses exhaust gases rather than direct engine power to power the compressor, resulting in lower power requirements for driving the system with about 1.5% of engine power used for "self-maintenance of turbocharging"[2].

A simplified explanation of how turbochargers work is as follows: a turbine section is powered by the exhaust gas from the internal combustion engine and begins rotating when the gas reaches a certain

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velocity, usually when sufficient throttle is applied. The rotating motion of the turbine is then converted into shaft work, which is used to power the compressor part of the turbocharger via a physical connection to a shaft. Through this process, energy is extracted and converted from the kinetic energy of the exhaust gas. The compressor in turn pressurizes the inflow air to feed into the cylinders for combustion.

Due to their heat machine nature, thermodynamic processes and corresponding calculations could be done on turbocharger systems. Casey and Fesich took the difference between adiabatic and diabatic processes into account and arrived at an elaborate equation to determine the diabatic efficiency of an ideal isentropic process, as cited below [3]:

$$\mathrm{Efficiency}_{\mathrm{dia,C}} = \frac{T_{2,is} - T_1}{(T_2 - T_1) - \frac{q_{12}}{C_p}} \tag{1}$$

This extra modification proved to be of considerable importance. Adiabatic assumptions only apply when the turbine inlet is less than 100 degrees Celsius as stated by Cormerais et al., which is rarely the case in a real world turbocharger working condition[4]. The error when calculating power that results from this ignorance of heat transfer can reach an alarming 48% as stated by Chesse et al. in 2011[5].

Intercoolers are optional components of turbochargers. Due to the compression process of the compressor, the air itself gets heated and expands to largely offset the density increase from the turbocharger. The process of changing pressure that results in the heating of gas is described quantitatively as follows [6]:

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\gamma-1/\gamma} \tag{2}$$

By using intercoolers and cooling to increase the density, higher pressure and more molecules per unit volume can both be achieved in order to provide better combustion conditions with fuel. The mechanism by which intercoolers work can be classified as air conditioned or not air conditioned. The latter simply cools through fins using natural airflow. This works to its maximum extent when the air is cooled to the ambient temperature, an ideal condition for perfect efficiency. In real world conditions, efficiency is affected by environmental conditions (temperatures) for the hotter the environment, the smaller the temperature difference and the poorer the performance. This effect can be significant in regions with hot summers. Air conditioning systems with coolants as mediums of heat exchange is a solution to this limitation.

An experiment on the effectiveness of an air conditioning system on the intercooler unit has been carried out by Muqeem in 2012 and adapted below are the results [7]:

Table 1. The data for normal air cooled intercooler, ambient temperature 20°C.

Engine RPM	Temperature of inlet air/°C	Temperature of outlet air/°C	Temperature drop across the intercooler/°C
2800	89	45	44
3200	93	55	38
3600	99	68	31
4000	105	77	28
4400	111	86	25
4800	118	99	19

Source: Adapted from Muqeem (2012) [7]

Table 2. The data for refrigerated intercooler, ambient temperature 19℃.

Engine RPM	Temperature of inlet air/°C	Temperature of outlet air/°C	Temperature drop across the intercooler/°C
2800	87	22	65
3200	92	28	64
3600	96	34	62
4000	101	38	63
4400	110	51	59
4800	119	62	57

Source: Adapted from Muqeem (2012) [7]

From the table 1 and table 2, a conclusion can be derived as under similar physical conditions, refrigerated intercooler holds a significant advantage over normal air cooled intercooler over the entire range of engine RPM tested. Muqeem stated that normal air cooled intercooler provides a 1.43 times improvement on the mass of oxygen fed into the engine, compared to that of 2.618 times for refrigerated intercooler[7]. Both of these have considerable influences on the performance of turbochargers.

Turbo lag is one of the main disadvantages of turbochargers that is inherent in their mechanism. After applying throttle, the engine must first increase RPM without using the turbocharger before enough exhaust gas can start the compressor and provide increased performance. This is a phenomena that makes the car unpredictable and unresponsive. As a result, top-level motorsports aim to minimize this inefficiency when using turbochargers. The World Rally Championship, the fastest race on unpaved surfaces, saw the first use of turbochargers in 1978 on the SAAB 99 with a T03 turbocharger, giving it 270 horsepower in total[8]. This technology is now standard in WRC and various solutions have been proposed in order to minimize the effects of the turbo lag problem, making WRC a representative application of turbochargers.

Various Anti-lag Systems (ALS) have been derived from motorsport events and made their way into commercial modification markets. They function by delaying the combustions and allowing fuel-air mixtures to reach early exhaust states before combusted there. The combustion forces air through even when not enough throttle has been applied, keeping the turbocharger spinning and responsive whenever more power is demanded. This exceeds the originally designed working conditions for the power unit and puts additional pressure on the system, which has huge damaging effects and greatly reduces the lifespan. This technology is most commonly used in rally events with specially designed rally cars, such as the WRC, but its high performance and fire-spitting effect have made it very popular in the market for modifications on commercial vehicles.

A modification of the conventional concept of turbocharging is the use of multiple turbochargers, ranging from two to four. Usually a smaller turbo with lower rotational inertia is used at low RPM to fill the gap in which the bigger one would not be able to operate, before enough pressure has been built up for the bigger one to spin, i.e. exceeding the threshold exhaust. This technology has evolved since the Maserati Biturbo, the first commercial vehicle with two turbos, and has resulted in a variety of designs. The most representative modern example is the quad-turbo design found in Bugattis.

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3. Derived & Related Technologies

According to Hu, Akehurst and Brace, downsizing the engine with a turbocharger is an important way of improving fuel efficiency[9]. If no other changes are made, this will come at the expense of power and responsiveness. E-boosting is one of the solutions that does not sacrifice too much performance. It mainly takes control at low rpm ranges to compensate for the lag of the turbo, as mentioned above in the turbo lag section. A statement from King et al. mentioned "in a 1.0T EcoBoost three cylinder Ford engine, the 3.3kW electric device improves the response time of the transient torque at 1500 rpm from 3.0s to 0.7s, a significant performance boost that has an immediate and perceived effect"[10]. Together with other developments in turbochargers and engines, this device can be of help in cutting emissions from the operation of internal combustion engines to minimize pollution.

Gas turbines are devices that use gaseous substances to pass through a series of turbines, extracting kinetic energy from them to usually generate electricity. The turbine part, where fluid energy is converted into the rotation of blades, is similar to that of turbochargers or hydroelectric plants. One of the main emphasises for this facility is the design of the turbine blades, which varies according to the purpose, size, and other parameters of the generator as stated by Omosanya et al[11].

The method of treatment for the used gas is another section that has huge potential to increase efficiency. A recuperating approach means the exhaust heat is reused by sending it back into the generator in some other form, an example of which includes chemical recuperation, where the exhaust heat is used to generate hydrogen rich fuel to operate the system. The bottoming cycles refer to the heat being used for the power generation of another device, which Heppenstall concluded as "gas turbine and secondary power generation systems are, in general, 'thermodynamically' independent but they may be linked mechanically" [12].

Microturbines are said to have drawn inspiration from vehicle turbochargers and airplanes' auxiliary power units. They are gas turbines with a power output in the 5-200kW range, with miniturbines producing more than the upper bound [13]. Their recuperators, like gas turbines, are optional. But in microturbines the effectiveness of recuperators is of much greater importance. At a pressure ratio of about 3-4, a recuperator effectiveness of 87% increases the efficiency of the microturbine from about 20% to about 30% [14]. According to Rodgers, the microturbines demand a much higher rotational speed than ordinary turbines, roughly 100,000 rpm below 10kW and 93,500 rpm at 10kW [15]. By 2001, manufacturers including Capstone, Elliot, Ingersoll-Rand, Bowman, Nissan and Turbec had already been producing microturbines with varied ratings ranging from 2.6kW to 250kW [14]. McDonald, Muley and Sundén concluded the preferred or aimed performance criteria for microturbines [16,17]. These objectives guide the research in the area and microturbines are projected to have a substantial influence on the conversion of energy generation processes towards greener energy.

4. Conclusion

This paper used a thematic approach to investigate and present information related to turbochargers and turbines. Turbochargers are internal combustion engine boost devices that consist of the following main components: turbine, compressor, shaft and shaft housing, as well as optional efficiency improvement solutions such as intercoolers. The system itself resembles a heat engine; therefore, various thermodynamic processes are included and efficiency calculations can be carried out at each stage. The effectiveness and efficiency of the system are affected by parameters such as friction and inlet temperatures. Its working principle of a turbine-driven compressor inherits problems, chief of which is turbo lag. Various solutions have been proposed and implemented, while others are under heavy research for potential future applications. Better packaging and downsizing of engines can be achieved with the help of turbochargers and this leads to the main way of cutting carbon emissions in the transportation sector. Turbines for power generation are closely related concepts. The power conversion through gas turbines provides a green and sustainable energy generation plan with adequate efficiency and relative ease to set up and operate. At varying sizes, turbines fit into varied situations and requirements. Rapid development from manufacturers across the globe pushes the technology closer to large scale operation to revolutionize power generation.

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