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# Turbocharging in Military Industry

## Turbófeltöltés alkalmazása a hadiiparban

*The appearance of the turbochargers provided a great opportunity for the engineers to increase the power of the internal combustion engines. Thanks to the present-day development trends, most of the newly manufactured vehicles are mounted with a turbocharged engine. However, competition of the development during the wars of the 20<sup>th</sup> century largely contributed to the spread of the turbochargers. In this article, the author presents the operation of the turbochargers and the increasing power of the internal combustion engines depending on time, and the effect of the increased performance on the military vehicles.*

**Keywords:** turbocharger, internal combustion engine, power, efficiency, turbocharged engines

*A turbófeltöltők megjelenése lehetőséget biztosított a mérnökök számára a belső égésű motorok teljesítményének növelésére. Napjaink fejlesztési irányzatainak köszönhetően a legtöbb gyártósorról lekerülő gépjármű feltöltött motorral szerelt. A turbófeltöltő elterjedéséhez viszont nagymértékben hozzájárult a 20. század háborúi okozta fejlesztési verseny. A cikkben a szerző bemutatja a turbófeltöltők működését, illetve a belső égésű motorok teljesítményének növekedését az idő függvényében, és ennek hatását a katonai járművek fejlődésére.*

**Kulcsszavak:** turbófeltöltő, belső égésű motor, teljesítmény, hatásfok, feltöltött motorok

## Introduction

Nowadays, the application of turbochargers is widely common in the automotive industry. Most likely, the destiny of the internal combustion engines will depend on the energy politics. In the foreseeable future, crude oil will be the primary energy source for the combustion engines for automotive and other public road uses. Natural gas and, to a limited extent, synthetic fuels, moreover hydrogen could gain popularity, therefore internal combustion engines will

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be the main power source of our vehicles. Looking back at the development competitions of the 20<sup>th</sup> century induced by the wars, the power output of the internal combustion engines highly increased. The aim of developments was to produce the highest achievable power density, so the manufacturers tried to obtain the highest power output from the possibly smallest displacement engines. The increasing power-to-weight ratio of the vehicles was a huge motivation especially in the aircraft design because it had a significant effect on the flight altitude and also the bomb load capacity increased due to the lighter aircraft. It can be noted that the output power of the vehicles had an effect in the combat situation and could lead to an advantage for the soldiers over the enemy. Hence, the engine developments were important processes for the outcome of the wars. The need for increasing the power density of the internal combustion engines led to the spread of the turbocharged engines. The primary aim of the author is to present the operation and structure of the charging systems [1].

## The Steps of Development of the Supercharged Engines

The supercharged internal combustion engine appeared about the same time as did the internal combustion engine itself. The first supercharged engines were used on aircraft to increase their high-altitude performance. Later, the main object was to improve the peak performance of sporty and expensive automobiles. It took almost thirty years until the supercharged engines reached their importance in economic use, in the form of efficient, turbocharged slow- and high-speed diesel engines. It took another thirty years, until the mechanically-driven compressors and the exhaust gas turbochargers appeared in the mass production of the internal combustion engines [1].

The history of supercharging goes back all the way to Gottlieb Daimler. Daimler used supercharging on his first engines too, such as the DRP 34926 engine which he presented in 1885. The reason for Daimler's brave construction was to increase the engine speed and intake of the combustion engines because, at the time, only the production of the small-sized intake and exhaust valves were possible. The problems forced him to give up his idea because of the appearing bigger valves and also the multivalve cylinder head constructions, made by his colleague, Wilhelm Maybach [1] [2].

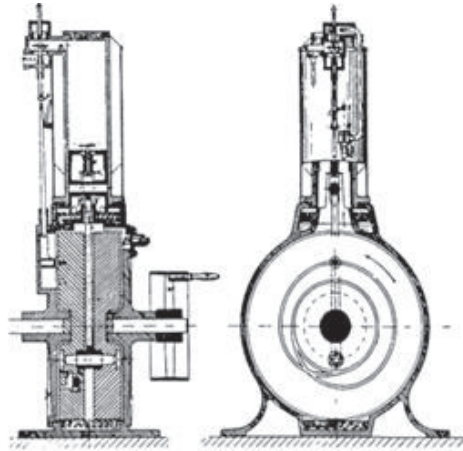


Figure 1. Daimler's DRP 34926 type engine [1]

The first mass produced supercharged engines were used in aircraft. Between 1920 and 1940, the turbo compressors continuously improved with the maximum achievable peripheral speed of the impeller. The first absolute golden age in regard to the power output of supercharged Otto engines, was the end of the Second World War when Curtiss Wright's 18-cylinder dual-radial compound engine with mechanically powered turbo compressor reached 2420 kW takeoff power in mass production [1].

The development of the turbocharger is related to a Swiss engineer, named Alfred Büchi. In 1905, Büchi designed the operation of the turbocharged diesel engines, but he had to wait for the first application until 1925. His first products were used on MAN's stationery diesel engines and the Maschinenfabrik Winterthur's passenger ships. In the MAN marine engine, the mean effective pressure was increased by 40%. Büchi's charging system is still the base for all today's turbocharged engines [1].

It is important to mention the main design equation of an internal combustion engine, which says the following of the effective power ( $P_e$ ):

$$P_e = \frac{V_{H1} \cdot z \cdot n \cdot p_{eff}}{30 \cdot i}$$

Where:

- $V_{H1}$  – displacement of one cylinder
- $z$  – number of cylinders
- $n$  – rotational speed of the crankshaft
- $p_{eff}$  – effective mean pressure
- $i$  – number of strokes

Based on the equation, if the effective mean pressure increases, the performance of the engine will be higher too. This means that the displacement volume can be decreased under unchanged power output. Thanks to the smaller stroke volume, the efficiency of the engine can be improved, because of the better fuel consumption, therefore the pollutant emission is decreasing. On the other hand, until the 1990s the turbochargers and mechanically driven compressors of the passenger vehicles were used to achieve increased performance in almost every case [1] [2].

## The Aim of Supercharging

The aim of the application of turbochargers is to increase the performance of the internal combustion engines with the pre-compression of the intake air. The main advantage of the construction is that it utilizes the energy of the exhaust gas, which would be lost after the combustion cycle, due to the geometrical and constructional capabilities of the crank-train. The boundary conditions of the combustion and the power stroke can be improved at the same time, so the emission of the engine is corrigible. Therefore, the main application area of the turbochargers are the engines with the aim of high power density combined with reduced harmful emissions and low fuel consumption.

To understand the aim of the application of the turbochargers, the gas law needs to be presented in the following:

$$\rho = \frac{p}{RT}$$

Where:

- $p$  – intake air pressure
- $R$  – gas constant
- $T$  – the temperature of the charging air
- $\rho$  – the density of the charging air

To increase an internal combustion engine's performance, a larger amount of fuel should burn inside the cylinders when it is needed, therefore choosing the appropriate air-fuel ratio is also important during the design process.

Figure 2 shows the effect of the changing air-fuel ratio to the power of an Otto engine. Even the engine is optimised for higher power output or best fuel consumption, a significantly larger mass of air has to be in the combustion chamber before the power-stroke than petrol.

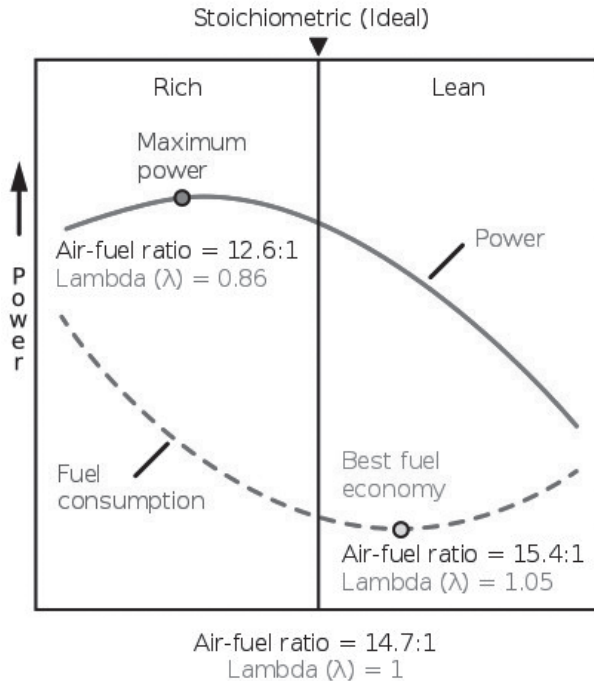


Figure 2. The effect of the air-fuel ratio on performance [3]

When the air-fuel mixture is stoichiometric,  $\lambda = 1$  (air-fuel ratio;  $\lambda$  [kg]) [in case of Otto engines (14.7:1)] the fuel consumption is relatively low, while the engine performance is acceptably high and also the pollutant emission is fairly low. Thanks to the advanced injection technologies, the delivery of the fuel into the combustion chamber can be done with a large pressure difference. Even in the 1940s, Bosch's injection systems specially developed to fighter aircraft could reach up to 90 bar injection pressure, while the difference at the moment of the intake valve opening between the pressure inside the cylinder and the environmental pressure is low. Therefore, the main barrier of the increased performance is the delivery of the right amount of air mass to the combustion chamber [4].

Since the stroke volume of a traditional engine is not variable, the delivery of the larger amount of air mass into the cylinders can be solved only by increasing the density of the intake air. Based on the ideal gas law, the density of the intake air can be increased by higher intake air pressure or by decreasing its temperature, so larger air mass can be delivered to the cylinders. With the help of superchargers, the intake pressure can reach higher values, therefore it creates an opportunity to burn more fuel in the combustion chamber making the engine more powerful, while the displacement is unchanged. A further option to increase the intake air pressure is to achieve lower temperatures and the solution in most of the time is the use of intake air cooling systems or so-called intercoolers. There are several cooling system structures, such as air-to-air coolers, but in case of high power output engines, even water-to-air coolers are

commonly combined with turbochargers, because the compression of the intake air in the compressor side increase the temperature and this temperature growth is solved by inter-coolers [5].

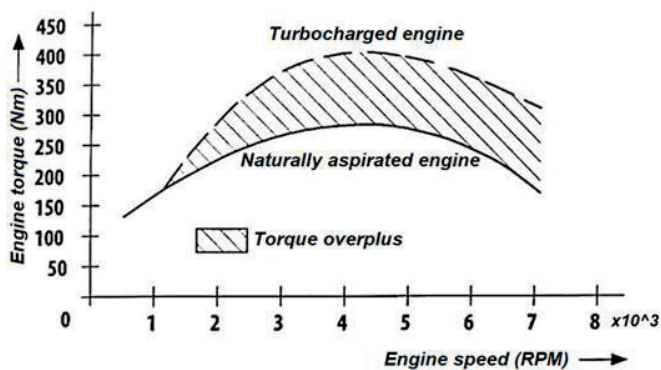


Figure 3. The effect of the turbocharger to engine torque [6]

The spread of the turbochargers took the development competition to a new level. Nowadays, the aim of the developments is to reduce the harmful emissions while the engine displacement is relatively small. On the other hand, in the middle of the 20<sup>th</sup> century, the continuous pursuit for power increase justified the use of turbochargers.

### The Operation of Charging Systems

One of the most common supercharging systems is turbocharging. The turbochargers can be separated into three main components based on the operation: turbine side, compressor side and bearing housing (or center housing). The exhaust gases get to turbine housing from the downpipe. With the help of the turbine wheel, the energy of the exhaust gas (heat energy, kinetic energy) can be transferred into mechanical energy [2].

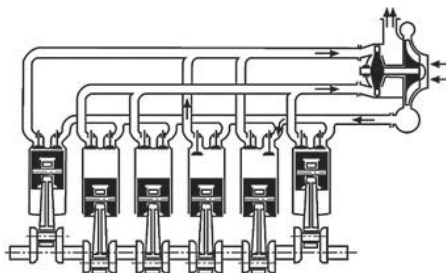


Figure 4. Alfred Büchi's charging system [1]

During operation, the turbine wheel has to be mechanically connected with the compressor wheel so the proper amount of intake air can be delivered into the cylinders of the internal combustion engine. This connection is solved by the shaft of the turbocharger. After the mounting of the turbine wheel to the shaft, they become one part, named turbine shaft, because they are friction welded together. With the purpose of positioning and minimalizing the wear of the shaft, thrust and radial bearings are used. There are turbochargers with plain or roller radial bearings too, but the plain bearings are more common due to the lower production costs. The bearings are located in the center housing.

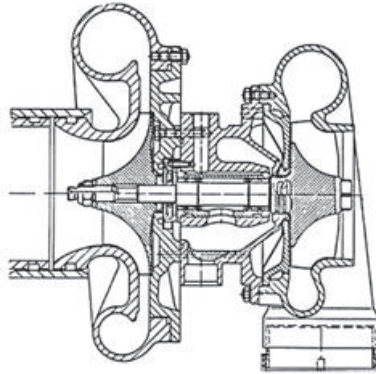


Figure 5. The section of a turbocharger [2]

Moving forward, the compressor wheel is located on the compressor side with the compressor housing, which is also often called the “cold side” of the turbocharger. The turbochargers are centrifugal compressors containing three main units: the compressor wheel, the diffuser and the compressor housing. The intake air enters the compressor in an axial direction, then its speed increases and leaves in a radial direction. The air slows down in the diffuser and so its static pressure and temperature increase. The diffuser is located inside the compressor housing between the backing and the volute. The speed of the intake air increases in the volute before leaving the housing.

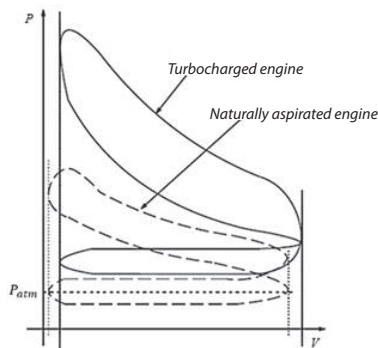


Figure 6. The effect of pressure charging to the P-V diagram of an Otto engine [7]

Figure 6 shows the effect of turbocharging to an Otto engine's pressure-volume diagram. In case of the naturally aspirated engine, the compressing takes part in environmental pressure. On the other hand, due to the pre-compression of the turbocharger, the compression stroke always starts with a higher pressure in the turbocharged engines. After the compression, the amount of heat from the combustion is also larger, because of the more injectable fuel, so the peak pressure will also increase. By comparing the diagrams of the naturally aspirated and the turbocharged engine, it is obvious that the mean effective pressure can be significantly higher in a turbocharged engine, than a naturally aspirated one with the same stroke volume. The mechanical parts of the engine are not always capable of sustaining the increased peak pressure, moreover (in case of Otto engines) knocking can occur, which is an abnormal combustion result in an inappropriate fast combustion outside of the envelope of the original combustion front. This phenomenon has a huge effect on the lifetime of the engine. To avoid knocking, the compression ratio should be decreased, but the performance of turbocharged engines is still higher than the naturally aspirated ones. Different, but also very common supercharging types are the mechanically driven compressors, which have a similar effect on the power, but this charging system is driven by the crankshaft via a belt or gear drive, despite the energy of the exhaust gases. Therefore, the efficiency of the engines with mechanically driven compressors is lower than the turbocharged engines, because the compressor is driven by the produced effective energy of the crankshaft, unlike the turbocharger where the energy of the exhaust gas will be lost in the naturally aspirated operation. On the other hand, the throttle response will be more instant, due to the direct connection between the crankshaft and the supercharger. The mechanically driven superchargers were commonly used already in the Second World War.

## Outstanding Constructions of the Second World War

One of the famous constructions of the Second World War's fighter aircraft is the 12 cylinder, V layout engine developed in 1936 by Rolls-Royce, named Merlin. It was the power source of some well-known aircraft, such as the Supermarine Spitfire or the Hawker Hurricane. The 27 liters displacement, liquid cooled engine had a two-step charging system, which served by mechanically driven centrifugal compressors. The weight of the construction reached 600 kg [8].

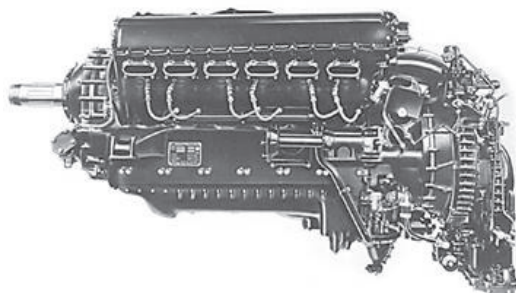


Figure 7. Rolls-Royce Merlin [8]



In the beginning, the performance of the engine was 1036 horsepower, which reached over 1520 horsepower by 1943, thanks to the continuous development. One of the main disadvantages of the Merlin was that the mixture was created by a carburettor, so during hard manoeuvring, the huge lateral forces caused engine misfire. On the other hand, the German Daimler-Benz DB 600 series engines had a Bosch direct fuel injection system, which was capable of creating proper mixture even during large accelerations, so the aircraft could carry out more sudden manoeuvres [7] [8].

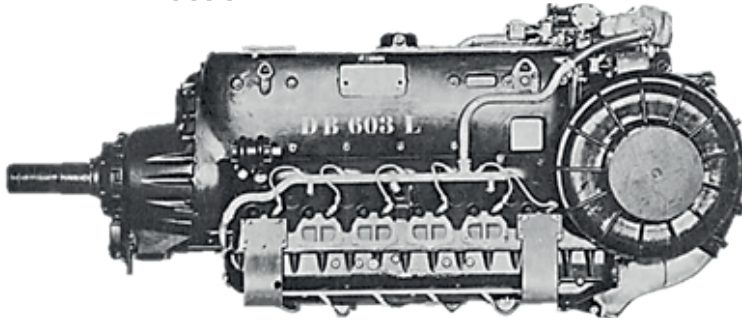


Figure 8. Daimler-Benz 603 [9]

The development of the type 605A of the Daimler-Benz DB 600 series was finished in the last months of 1940, which was also a 12 cylinder V layout power source, used in the Messerschmitt bomber aircraft. The 35 liters displacement internal combustion engine's performance reached up to 1400 horsepower and thanks to the state-of-the-art engineering solutions, it was one of the most successful constructions of the Luftwaffe. The success can be seen in the manufactured number of pieces as more than 42,000 units were produced in the DB 600 series [9].

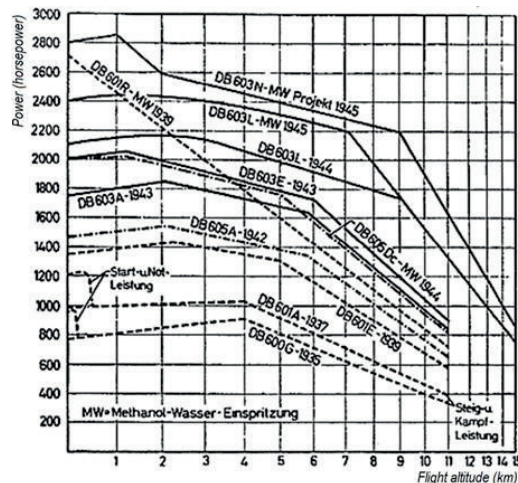


Figure 9. The performance of Daimler-Benz 600 series type engines depending on flight altitude [10]

A hydraulic coupling makes the drive of a centrifugal compressor possible from the crankshaft, the speciality of which is that an automatic actuator could vary the rotational speed of the compressor wheel depending on flight altitude by changing the drive ratio of the hydraulic coupling. The speed of the compressor wheel increased with the flight altitude up to 5700 meters, where it reached its maximum. Moreover, the engine performance could increase by even 20% for a short period of time, thanks to a special additional mixture injection system, which consisted 50% water, 49.5% methanol and 0.5% special anti-corrosive additive [9].

Figure 8 shows the power output depending on flight altitude of the different constructions of the DB 600 series. Thanks to the supercharging, the engines can operate with a slight power loss up to 4000 meters of flight altitude. The development is significant, comparing the 1935 construction with the 1945 one: the peak performance of the latest models was twice as much as that of the old ones and they were capable of reaching 15,000 meters in flight altitude instead of 11,000 [9].

## Vehicles with Turbocharged Engines

The higher power output and better fuel consumption of the supercharged engines make a significant advantage in military use since the travelling speed and the range also increase. Firstly, the requirements of the aircraft industry made the supercharged engines deployment necessary. Later, they were also used as power sources for ships and ground vehicles. By comparing a naturally aspirated construction and a turbocharged one, it is clearly visible how much potential of the supercharging has. Figure 10 shows the effect of a well-matched turbocharger to the performance of 3 liters displacement, 6 cylinder, V layout engine [11].

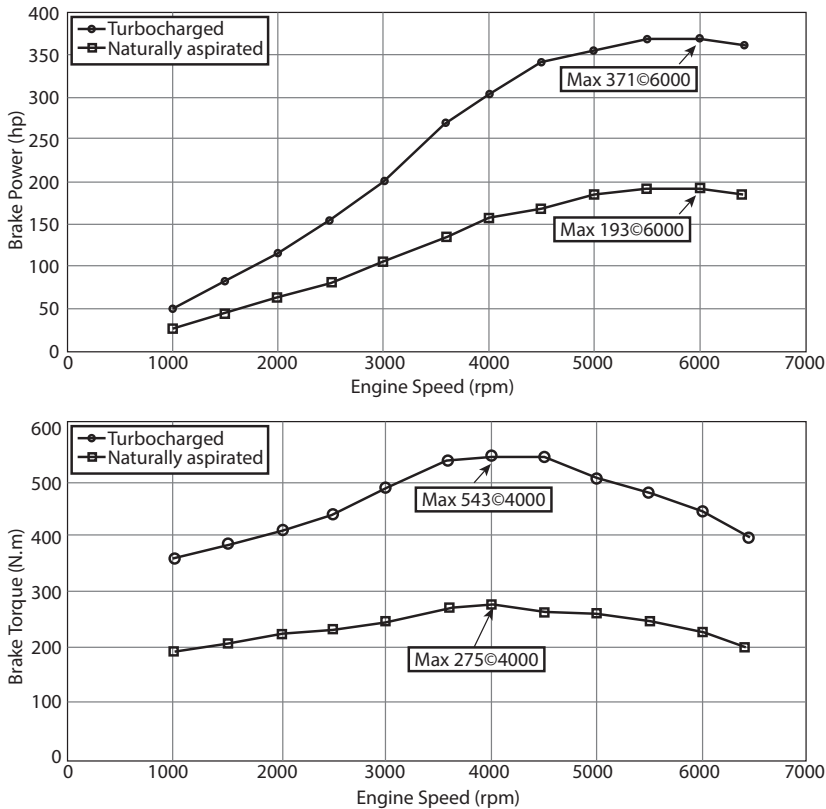


Figure 10. The effect of turbocharging on performance and torque [11]

Thanks to the potentials of the supercharged engines, the turbochargers can be found on engines in military use even in case of transport vehicles and warships since the 1950s. The turbocharged engines appeared early also in the vehicles used by the Hungarian Defence Forces, such as the BTR-80 armored personnel carrier, which was manufactured since 1986 and some of them are still in use. The BTR-80 can reach up to 80 km/h travelling speed on a driveway, with a range of 800 km thanks to the KamAZ-7403 V8 turbocharged diesel engine. Moreover, the Hungarian Defence Forces still own KrAZ 255 type heavy trucks mounted with 14.9 liters displacement JaMZ-238 V8 internal combustion engines, the production of which started already in 1967. The production of the 2S1 Gvozdika self-propelled howitzer started in 1972 in the Soviet Union, which was driven by turbocharged diesel engines producing 177 kW power and with a range up to 500 km. All member states of the Warsaw Pact put it into service, the Hungarian Defence Forces used 144 of them [12].



Figure 11. 2S1 Gvozdika military vehicle [12]

The turbochargers also take an important role in the warship industry. The Hungarian Explosive Ordnance Disposal and the River Flotilla Regiment still use AN-2 warships, which was produced from 1952 and fitted with two Csepel D-613 naturally aspirated engines, but due to the present requirements, the Csepel power sources were changed to Volvo Penta engines using turbocharging systems.

## Summary

The power density of internal combustion engines increased significantly over the past hundred years. The supercharging had a huge effect on the improving performance, which offered new opportunities for the engineers. Because of the higher efficiency, by 2020, 70% of the personal vehicles sold worldwide will be mounted with a turbocharged engine. In Europe, this rate was 75% in 2014. The turbocharged engines started to spread around 1990 in case of automotive use in the direct injection diesel engines; however, in military use, the supercharged engines became common as early as the late 1930s. The wars of the 20<sup>th</sup> century sped up the development since the opposing participants were not only in combat on the battlefield but behind the designer tables too. Even on land, in water or in the air, the military vehicles are really important in a strategic point of view. Moreover, depending on the power output of the internal combustion engines, the soldiers can gain an advantage during battle and even can decide about the fate of lives. Therefore, it is not fortuitous that the increasing performance of the engines reached its highest level during the Second World War. As the improving power

output of the Messerschmitt aircraft shows, in only 10 years, an engine could double the performance with the same stroke volume, and therefore, the enemy should adopt the technology, since the use of charging systems became almost a requirement, and the ones using naturally aspirated engines would be disadvantaged. Among others, the turbocharged engines became an essential tool of the modern engine technology thanks to military developments and thanks to the turbocharger, the pollutant emission can be decreased while the power density is improving.

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