Powerful Turbocharging System for Passenger Car Diesel Engines

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Driven to satisfy escalating demand for increased fuel economy and more performance, BorgWarner engineered a regulated three-turbocharger system (R3S), consisting of two small parallel high-pressure variable turbine geometry turbochargers integrated with one larger low-pressure stage turbocharger. Developed in collaboration with BMW, the system combines the benefits of two-stage turbocharging for a high specific power output and parallel sequential turbocharging for maximum drivability.

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Multi-stage Charging Prevail

High levels of driving dynamics in combination with low fuel consumption have become features of a wide range of engine models. With the introduction of two-stage turbocharging for passenger car diesel engines in 2004 [1], BorgWarner was able to develop a turbocharging system which significantly enhances the diesel engine power density. Today's turbo diesel engines achieve a rated power of up to 170 kW in the 2.0-l four-cylinder engine and 230 kW in the 3.0-l six-cylinder engine which has been in series production since 2009 equipped with a BorgWarner R2S (regulated two-stage) turbocharging system. Two-stage turbocharger systems have now become the state of the art.

The R2S turbocharger system uses two turbochargers: a large one in the low-pressure stage and a small one in the high-pressure (HP) stage [2]. Figure 1 shows a schematic diagram of two-stage turbocharging as used in commercial diesel engines. Compared to classical regulated two-stage turbocharging, the passenger car R2S system has an additional bypass valve in the low-pressure stage turbocharger and a compressor bypass for the high-pressure stage compressor. The aim of regulated two-stage turbocharging is primarily to achieve higher low-speed torque while at the same time increasing nominal engine power output. Even in the medium speed range, however, a considerable increase in medium pressure is possible.

Only the low-pressure stage turbocharger provides the boost pressure and the full pressure ratio at the rated power. For this reason, the rated power is limited by the maximum pressure ratio, which the compressor of the low-pressure stage can achieve. The compressor of the low-pressure stage was developed for high-pressure ratios and good efficiencies. Typically for R2S, a specific power of up to 85 kW/l can be realised.

For a higher specific power, single-stage turbochargers such as those used at high engine

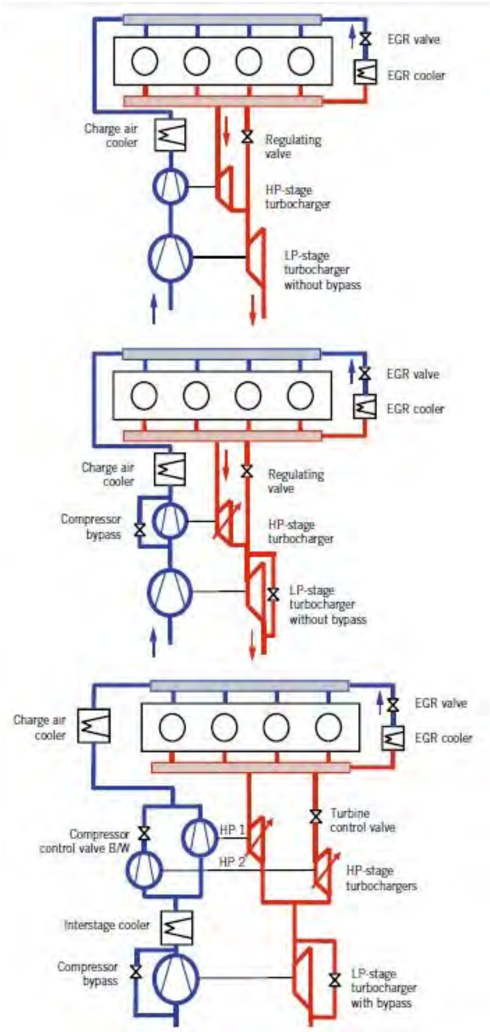

Figure 1. System layout for R2S charging systems for commercial diesel engines (permanent two-stage, top), R2S for passenger cars (middle) and R3S (bottom)

speeds in passenger car R2S applications will not be sufficient. Even at the rated power, therefore, a two-stage charging system is required. The result is a permanent two-stage charging system. However, the rated power can only be achieved successfully if one turbocharger for the low-pressure stage and one turbocharger for the high-pressure stage run in series at all times with a valve to regulate the boost pressure – rather like the R2S system used in many commercial diesel applications. For superior low-end torque and maximum transient response, a smaller turbocharger is required in the high-pressure stage. Figure 1 and Figure 2 show a comparison of the different turbochrager systems. At the rated power, the high-pressure stage turbocharger still has to work and contribute to the boost pressure. A good solution for the high-pressure stage is a parallel sequential charging system. At low engine speeds, a small turbocharger works to provide good low-end torque and transient behaviour, whereas at high engine speeds, the exhaust gas mass flow is separated and fed to two turbochargers running in parallel, thus providing the energy required to run two compressors in parallel in the high-pressure stage. The result is a regulated three-turbocharger system as a combination of R2S and a parallel sequential charging system. Figure 2 shows the brake mean effective charging systems. The all-new R3S system sets a new benchmark with regard to the bmep curve and poses a challenge for the development of new turbocharger components.

Regulated Three Turbocharger System

The major objectives for downsized diesel engines with the new R3S turbocharging system, see Figure 3, are to match the range of power output, torque and comfort provided by an engine with more displacement or a higher number of cylinders while equalling the lower fuel consumption and power/weight ratio typical for existing diesel engines. The new R3S turbocharging system contains one large turbocharger in the low-pressure stage and two turbochargers running in parallel in the high-pressure stage. The operating principle of the turbochargers and the additional core components of the R3S turbocharging system ae shown in Figure 4 for different operating modes of the R3S turbocharging system. The intake air enters the low-pressure stage compressor. Optionally, the compressor of the low-pressure stage can be bypassed as the intake

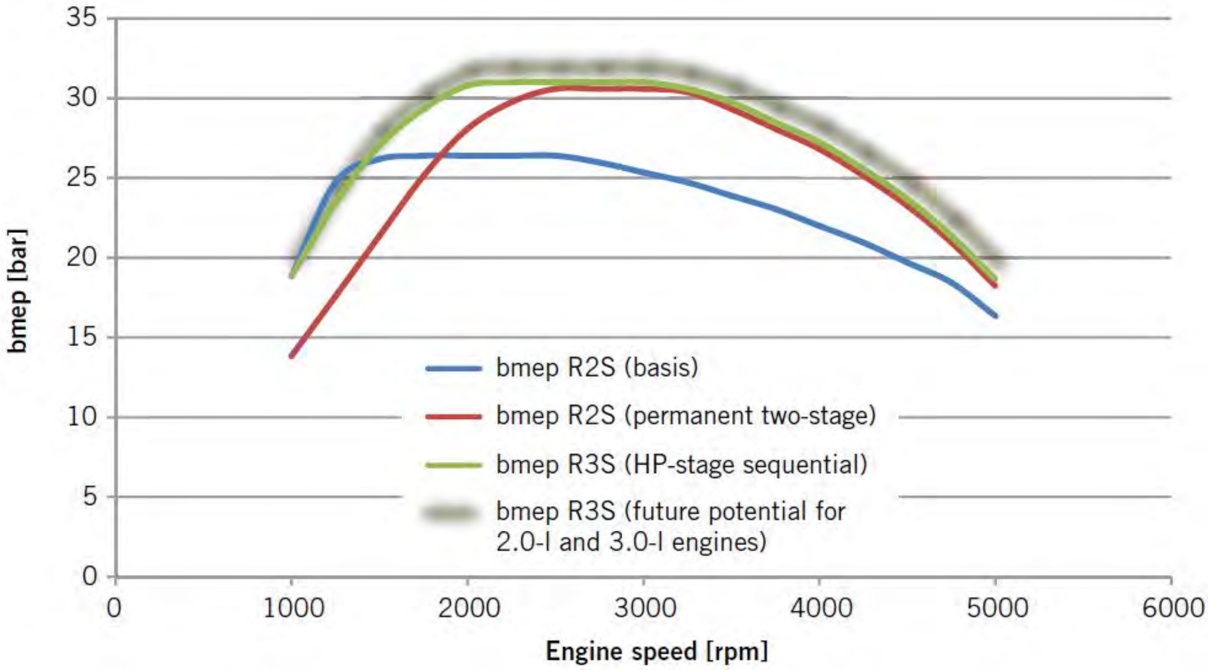

Figure 2. Brake mean effective pressure characteristics of R2S and R3S charging systems

air is only throttled and not pre-compressed in this operating mode. To reduce the charge air temperature, the intake air passes through an intercooler integrated into the low-pressure stage compressor housing and is subsequently, depending on the operating mode, compressed further in one high-pressure compressor stage (operating mode 2 in Figure 4) or both high-pressure compressor stages (operating mode 3 in Figure 4). After cooling in the main intercooler, the charge air is fed into the combustion chamber via the intake system.

On the exhaust side, at low speeds and loads, the gas only flows through one of the high-pressure stage turbines. This ensures spontaneous charge air pressure build-up and excellent dynamic response characteristics (operating mode 1 in figure 4). At medium engine speed there is enough exhaust gas mass flow to provide significant boost pressure in the larger low-pressure stage compressor in addition to the high-pressure stage (operating mode 2 in figure 4). And at high exhaust gas through-put rates, a parallel route passing via the exhaust gas control flap is opened to reduce the exhaust gas backpressure (operating mode 3 in Figure 4). Subsequently, the exhaust gas is further relaxed in the low-pressure stage before it enters the exhaust aftertreatment system located close to the engine. To optimise charge air pressure control, the waste-gate on the low-pressure stage turbine is activated in the switchover range from two to three turbochargers and in the rated power range.

Figure 3. R3S turbocharging system with three exhaust gas turbochargers

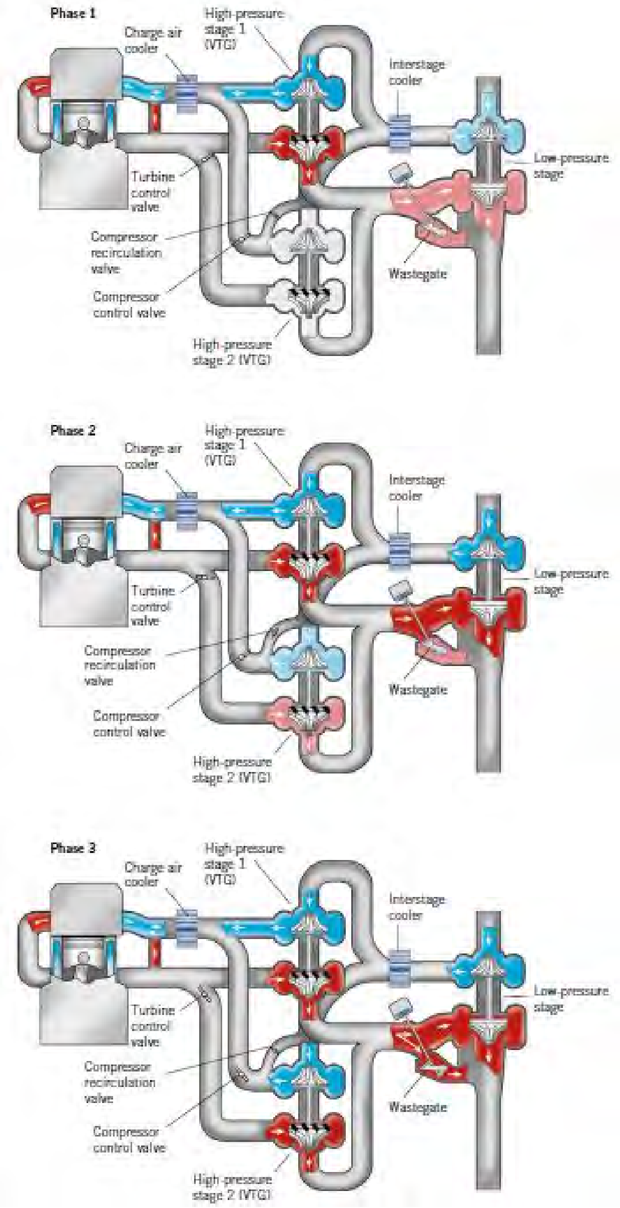

Figure 4. Operating modes of the R3S turbocharging system

New Turbocharger Components

Applying a R3S to diesel engines requires some modifications to the engine. A new injection system for increased injection mass and a new cylinder head for increased cylinder pressure are just a few of these [3, 4]. On the turbocharger side, some very important improvements and developments have to be considered for R3S. The control systems are very important for providing maximum performance. For this reason, a new regulation valve with maximum sealing behaviour is used. For improved transient behaviour, turbochargers with Variable Turbine Geometry (VTG) technology are used in the high-pressure stage. As one VTG turbocharger in the high-pressure stage does not rotate permanently, a special sealing system is introduced.

Another critical aspect is the compressor outlet temperature. A high compressor outlet temperature may lead to coking of blow-by gases in the compressor volute. To reduce the temperature downstream of the low-pressure stage turbocharger, a compressor with water cooling is used. In addition, a charge air cooler is required between the compressor of the low-pressure stage and that of the high-pressure stage.

Regulation Valve

The great relevance of the regulation valve for engine dynamics causes much attention to be paid to ensuring that the exhaust gas control flap has a tight seal. The new so-called spherical design, see Figure 5, consisting of a spherical part in the flap and a cone in the lever leads to a more flexible connection in the valve

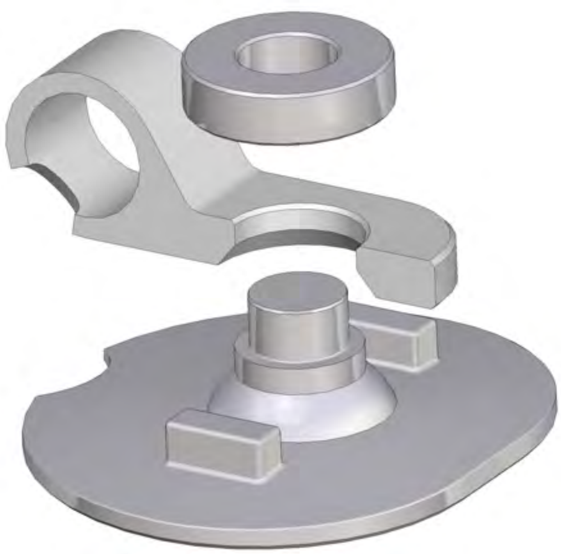

Figure 5. New regulation valve with improved sealing characteristics

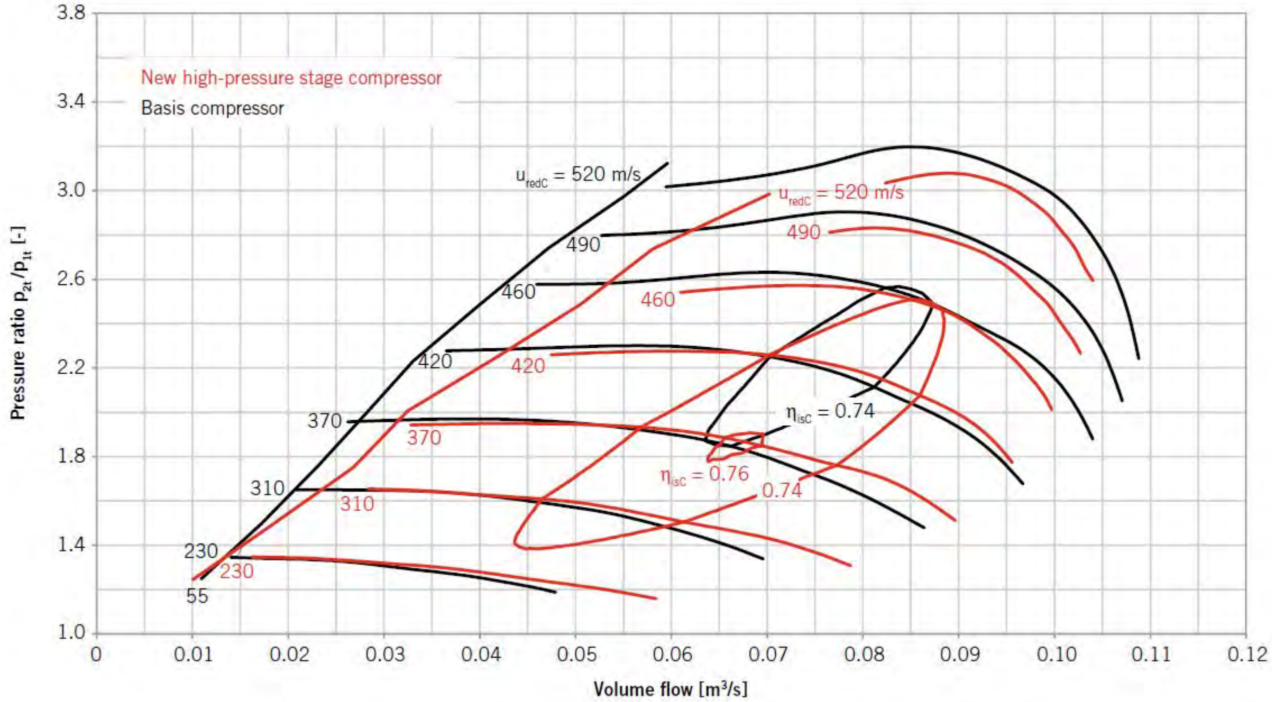

Figure 6. Compressor for new high-pressure stage turbocharger versus standard compressor

seat. The materials used for the components were also optimised.

Compressor Applications

The requirements for the high-pressure stage turbocharger differ completely from the demands made on a single-stage application. For this reason, a completely new compressor design is required. In the stationary state, the full load curve and the part load operating points require a low-pressure ratio for the compressor. The efficiency level therefore has to be optimised in the relevant area. Figure 6 shows an efficiency increase for the new compressor (red lines) at low-pressure ratios. Nevertheless, during transient response, the compressor has to cover the full speed range up to the maximum turbocharger speed because, under transient conditions, the high-pressure stage turbocharger has to provide the largest portion of the deliverable boost pressure until the low-pressure stage turbocharger with its much higher mass inertia and higher swallowing capacity is able to take over the delivery of the boost pressure.

The compressor for the low-pressure stage turbocharger is designed for high-pressure ratios. A high efficiency level at a high-pressure ratio is very important for a minimum compressor outlet temperature because the fresh air is compressed for a second time in the high-pressure stage.

Gas Lubricated Face Sealing

The R3S turbocharging system consists of one low-pressure stage turbocharger and two high-pressure stage turbochargers arranged in parallel. In some operating points, only one turbocharger in the high-pressure stage rotates while the other one does not. This is a major challenge for the sealing concept.

The turbocharger has an oil inlet and an oil outlet. Oil is required to lubricate the shaft and wheel assembly of the bearing system. Howe-

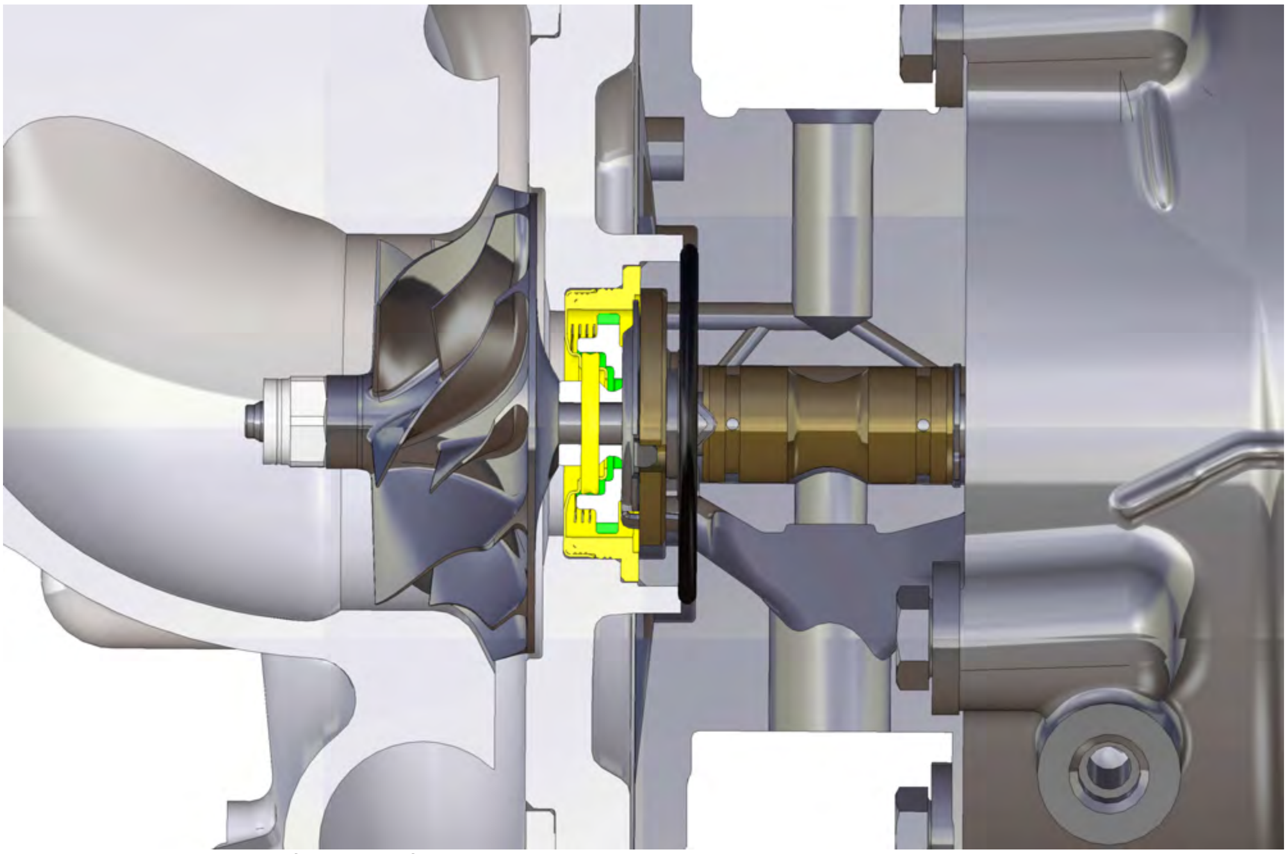

Figure 7. Face sealing (in yellow) on the compressor side

ver, when the turbocharger is not rotating, the dynamic sealing function of the turbocharger is not enabled. Because the standard sealing system is not dynamic, oil will flow out of the centre section and into the compressor, causing a high level of oil consumption that cannot be managed by the engine oil circuit. A mixture of fresh air and oil will lead to an increase in engine emissions, which is not acceptable either. To prevent oil from entering the air system from the bearing housing of the stationary exhaust turbocharger, a gas lubricated face sealing for the compressor of the turbocharger was developed [5].

As shown in Figure 7, gas-lubricated face sealing is used for the compressor side. This dynamic sealing concept was specifically developed for use in turbochargers and was first-to-market in the R3S turbocharging system application. It provides perfect sealing capability for non-rotating rotors and rotors, which are in operation. At certain low rotor speeds, the sealing switches from a static sealing function to a dynamic one.

State-of-the-art technology for turbochargers is one or two piston rings on the compressor and turbine side. With state-of-the-art piston rings, blow-by achieves problematic high values at in creasing boost pressures. Vacuum pressure at the intake side of the compressor, reinforced by throttle losses in the intake section and the pump effect on the backside of the compressor wheel, causes an oil leakage from the bearing housing to the intake air. Piston rings are dynamic gap seals, which cannot be flooded with oil. Therefore the use of piston rings in a non-rotating turbocharger is not applicable.

Among other components, the face sealing consists of a slide and a counter-ring. Immediately after rotation starts, the sliding surface floats on a gas (air) film between the slide and the counter-ring. This gas film is produced by crescent-shaped three-dimensional grooves in the counter-ring, which build up the sealing gap between slide and counter ring. The face sealing operates without contact. As a result, it is free from measurable wear and generates very low friction losses of only a few watts. In non-operating conditions, the sealing gap is closed by the force of the spring, enabling the slide and counter ring to seal statically.

Water-cooled Compressor Housing

Unlike the R2S turbocharging systems, in which only the low-pressure stage turbocharger is used at high engine speeds, there are always two turbochargers running in series in the R3S turbocharging system, even at the rated power. The permanent series mode is required to achieve the targeted specific power with the choosen downsizing grade. For high specific power outputs, an extreme boost pressure and pressure ratio are needed. However, a high-pressure ratio also leads to a high compressor outlet temperature. Oil, which is typically in the fresh air mass flow due to engine and turbocharger blow-by, tends to coke at high temperatures. The coking layer in the compressor leads to a reduced power output. To cope with the high boost pressures, a cooling system, shown in Figure 8, has to be integrated into the low-pressure stage compressor housing to reduce the compressor outlet temperature and ultimately to prevent the coking of oil in the compressor volute and the charge air cooler. Figure 8 shows cooling in the contour area of the compressor housing, can even be combined with a ported shroud compressor. Alternatively, the compressor can be cooled in the back wall of the compressor with very similar results. A combination of cooling in the back-wall and cooling in the contour area even increases the cooling effects and leads to the minimum compressor outlet temperature.

Water-cooled compressor housings were developed and first-to-market in some diesel R2S applications. As a result of the good results achieved in lowering the compressor outlet temperature, this technology was adapted to the R3S turbocharging system at the same time.

Compressor cooling is possible at a standard engine coolant temperature. The reduction of the compressor outlet temperature can be significantly increased via a lower coolant tem-

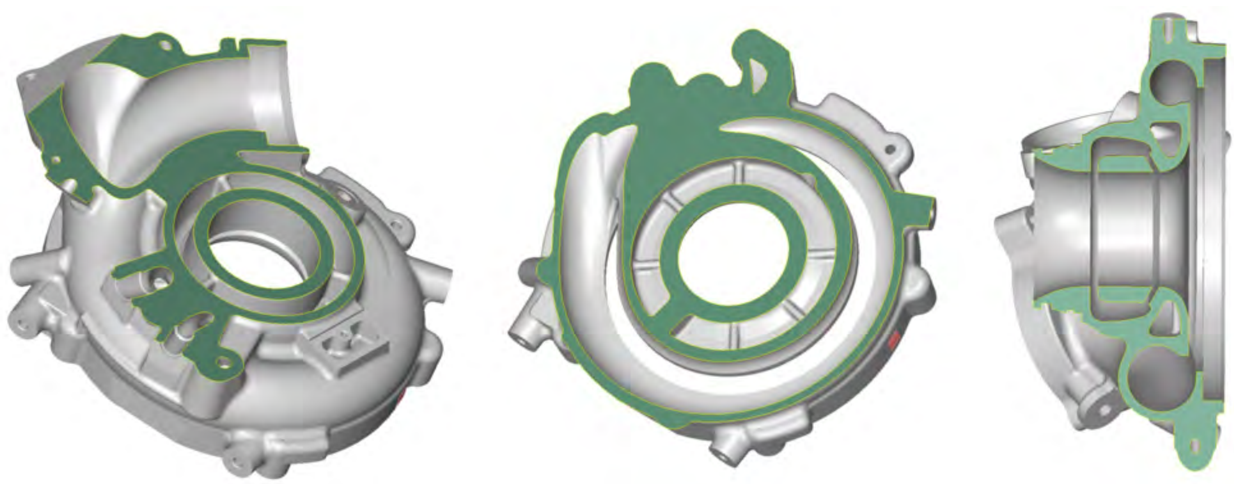

Figure 8. Water-cooled compressor housing

perature. The typical temperature reduction in the case of water-cooled compressor housing is shown in Figure 9. The reduction of the compressor outlet temperature can be significantly increased via a lower coolant temperature. However, much lower coolant temperatures will require a second water-circuit. The integration of a water-cooled compressor housing and an interstage cooler into the compressor housing, see Figure 10, was first-to-market in a BorgWarner application designed to meet extreme package restrictions.

Figure 10. Compressor housing with water cooling and interstage cooler

Summary and Outlook

BorgWarner developed the new regulated three-turbocharger system (R3S) for ultimate downsizing to achieve a maximum level of specific power and a maximum transient response with large improvements for fuel consumption. The first R3S turbocharger technology debuted with M Performance diesel engine from BMW, the most powerful six-cylinder passenger car diesel engine in the world [3, 4]. The 3.0-l engine has a maximum output of 280 kW and a maximum torque of 740 Nm. Compared with the 3.0-l diesel engine boosted by a BorgWarner R2S turbocharging system, the 3.0-l diesel engine with BorgWarner's R3S turbocharging technology increases power output by nearly 25 % and improves fuel economy by 8 % while meeting Euro 6 emissions standards. The diesel engine with the R3S also improves the transient behaviour, even at a better fuel consumption which is at least 18 % below its eight-cylinder-competitors [4].

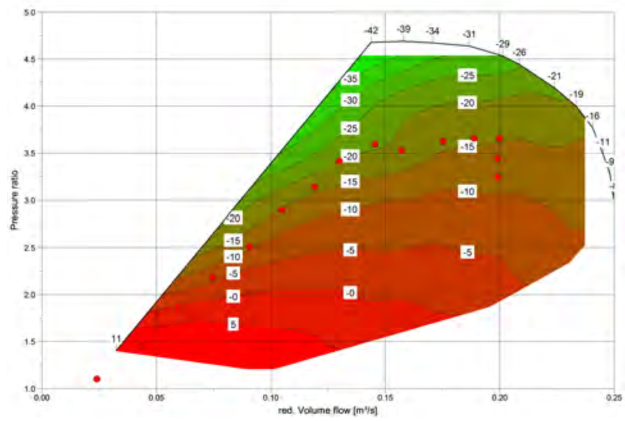

Figure 9. Compressor map showing the temperature reduction with a cooled compressor housing and a typical engine lug line (red dots)

For the high engine power and torque output which can be achieved with the R3S turbocharger system, some modifications of the engine are necessary, for example the optimisation of the injection system and improvements of the durability to withstand higher cylinder pressures. For the regulated three-turbocharger system, new developments such as a water-cooled compressor housing, the integration of water cooling and charge air cooler into the compressor housing, a new regulation valve, a new compressor for the high-pressure stage and a new sealing technology were successfully introduced first-to-market.

Due to lower inertia and VTG technology in the high-pressure stage, especially when used in a parallel sequential charging system, the R3S provides a rapid boost pressure in transient conditions. The low-pressure stage turbocharger is designed for the complete mass flow of fresh air on the compressor side and the full exhaust gas mass flow on the turbine side. This requires large rotors with a high mass inertia; even the rotor includes a high-flow compressor and turbine wheels. During transient response, the high-pressure stage turbocharger accelerates much more rapidly than the low-pressure stage turbocharger does.

A first approach to the further improve ment of the transient response of the R3S turbocharger system is to use a VTG turbocharger in the low-pressure stage. The VTG characteristics allow a better transient response by reducing the swallowing capacity when closing the VTG vanes. A measure to reduce the mass inertia for better transient behaviour of the low-pressure stage is to split the mass flow through one single low-pressure stage turbocharger and send it into two parallel smaller turbochargers. This would approximately half the mass inertia. Using a different turbine wheel material for a single low-pressure stage turbocharger, for example titanium aluminide, would allow the rotor mass inertia to be reduced by approximately 35 %.

R2S turbocharging system from BorgWarner began as a high-performance technology a few years ago and its market share is increasing constantly. Similarly, BorgWarner expects to see growth potential for the R3S technology in the long term. In-line four-cylinder engines with R3S will be able to replace six-cylinder engines with standard charging systems and make a positive impact on fuel economy, emissions and costs.

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