Development of an Improved Turbocharger Dynamic Seal

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Abstract: Emissions regulation continually drives the automotive industry to innovate and develop. The industry must push the limits of engine/ turbocharger interaction to meet this changing regulation. Changes to the way a turbocharger is used, to help meet emission regulation, can impact the pressure balance over the compressor and turbine end seals. Seal capability can place constraints on the acceptable operating conditions.
Market trends indicate that, in the near future, turbocharger operating conditions will be challenging for today's compressor side seal systems. The need for improved compressor end sealing is greater than ever. This market intelligence drove Cummins Turbo Technologies to develop a robust seal system that meets the future demands of our customers. There are many benefits to the slinger/ collector seals systems used today and cutting-edge analysis has helped us generate the next level of understanding required to unleash further performance. This report gives insight to the market requirements and the approach to developing a seal to meet this need.

Key Words: Turbocharger Seal, Multiphase Computational Fluid Dynamics, CFD, Compressor Oil Leakage

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1 Introduction

The majority of the turbocharger market uses a similar approach to sealing with piston rings to control gas leakage and a slinger/collector seal system to handle oil. The slinger/collector seal system is used to keep oil away from these piston rings. In normal operation the pressure in the end housings is higher than the bearing housing and gas flows into the bearing housing, through the oil drain to the crankcase. With a good oil drain design, the bearing housing pressure will track the crankcase pressure. Under certain conditions, such as low idle and thermal management, this pressure difference can be reversed with a higher bearing housing pressure than the pressure behind the compressor wheel. Under this condition gas will flow out of the bearing housing to the recess behind the compressor wheel. The oil slinger/collector must keep oil away from the piston rings or oil will be carried out with the gas flow.

These current technology, noncontact oil seal systems do not degrade over time, is low cost and suited to high volume manufacture. The compressor oil seal systems themselves don’t fail, however it’s not uncommon that the operating conditions go beyond the seal oil leakage capability.

Historically the oil seal systems have been developed based on literature, experience and a lot of testing. Today, cutting edge multiphase computational fluid dynamics (CFD) can simulate the interaction of oil and gas in the seal cavity giving a leap forward in our understanding of the physics in play. CFD has allowed us to understand and predict the flow structures in a way not possible by experimental observation alone. The new level of understanding has allowed us to develop this technology to give levels of seal performance beyond what was previously thought possible with this seal type.

2 Market Requirements

There is a continual drive for improved reliability in the market. Oil leakage is a failure mode that can lead to reduced performance, oil consumption and emission non-compliance. It is essential our systems help deliver emission compliance and enable customer requirements.

Drivers include:

- Regulation change
- Engine down speeding
- Engine downsizing
- Exhaust throttle valves
- Exhaust brakes
- High exhaust bypass

- Robustness to lack of maintenance in certain markets

Thermal management of aftertreatment, for example, has driven a number of strategies to increase exhaust temperatures. Most of these strategies have made the pressure difference over the compressor end seal more severe.

3 Emission Regulation and Market Trends

Next generation engines will require:

- Better Fuel Economy
- Lower NOx Emissions

The pathways to achieve this are shown and implications for sealing discussed

3.1 Fuel Economy Pathway

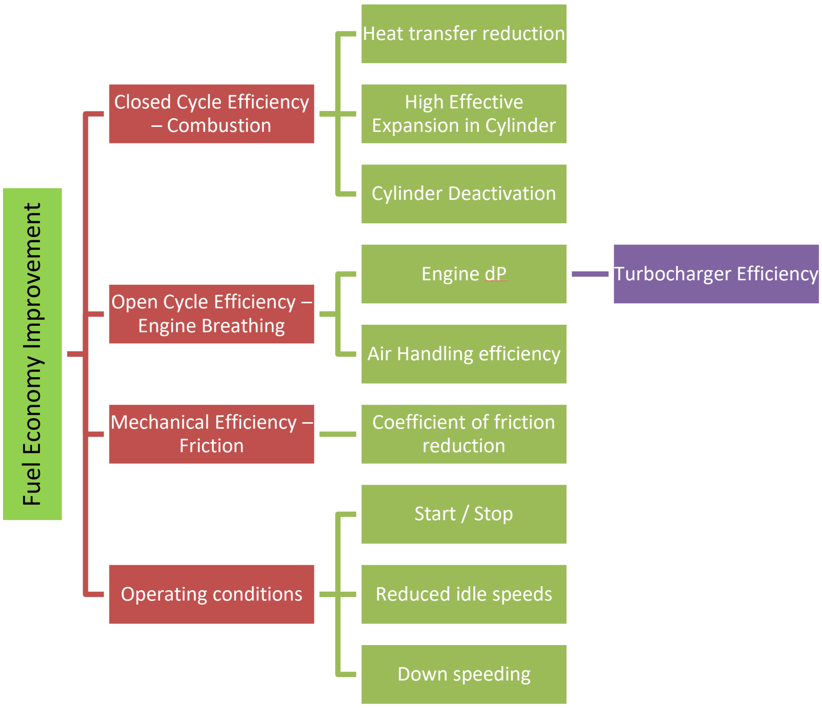

Figure 1: Fuel Economy Improvement Pathway

The seal system enables fuel economy improvements by being robust to operating conditions from the necessary engine system changes. Engine developments that impact on seal requirements are discussed below.

Start/Stop: Automatic engine shutdown saves fuel over a vehicle that is left to idle. This transient condition can result in pressure decaying behind the compressor wheel more rapidly than crankcase pressure decays, particularly if this follows a rapid deceleration event. If a high volume of oil is present in the system while the pressure behind the wheel decreases, there is a risk of oil leakage.

Reduced idle speed: Reducing engine idle speeds will typically reduce the turbocharger idle speed. Pressure behind the wheel is a function of the turbocharger speed therefore increases the risk of negative pressure difference over the seal (PDOS) and puts a greater reliance on seal system to prevent oil leakage.

Turbocharger Efficiency: The non-contact seal system design allows for good transient response by not introducing additional friction to the rotor system. Additional capability from the seal system has opened up opportunities to optimise the compressor stage diffuser and wheel line up for efficiency. Traditionally there were constraints to maintain pressure behind the wheel to help prevent leakage.

Cylinder Deactivation: Additional heat can be generated by deactivating cylinders, making the active cylinders work harder. This can avoid the need to add additional fuel to maintain exhaust temperature under low load conditions. Turbo speed can drop for the same power if air to fuel ratio (AFR) is lowered to generate temperature.

3.2 NOx Reduction Pathway

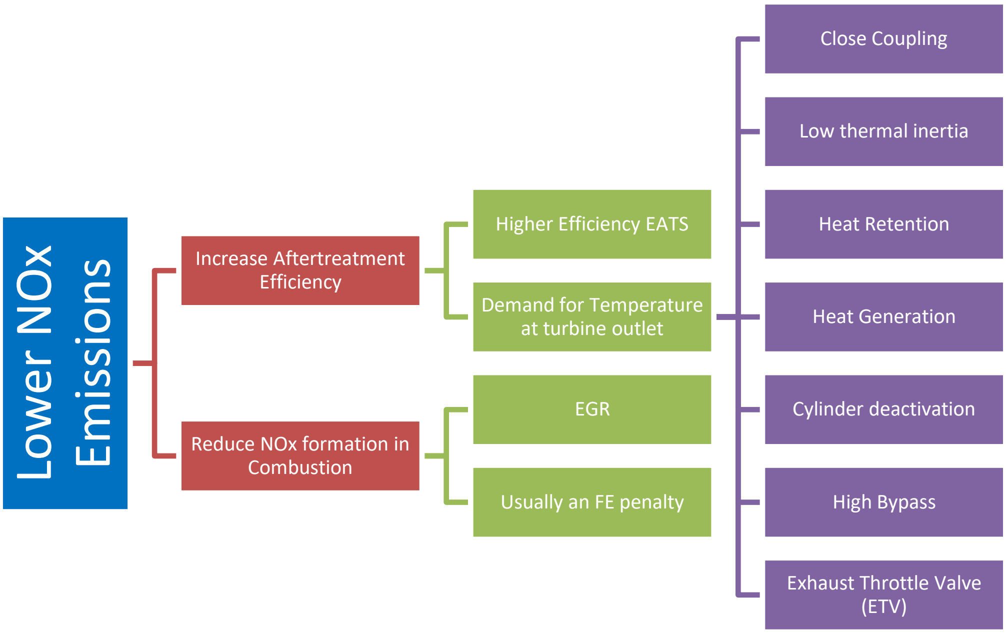

Figure 2: NOx Reduction Pathway

3.2.1 Demand for Temperature at Turbine Outlet

High Bypass: One option to deliver high temperature, to get aftertreatment up to temperature, is high bypass. This may be achieved using a high bypass wastegate or a rotary turbine control valve (RTC). One impact is less energy to drive the turbine resulting in reduced turbo speed and less pressure behind the compressor wheel. The seal system must be able retain the oil to enable this strategy.

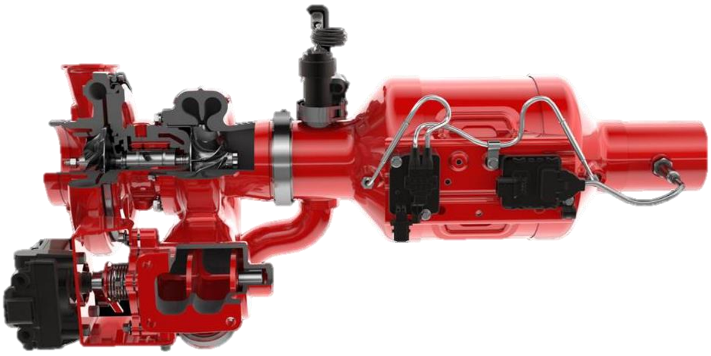

Figure 3: Close coupled aftertreatment with RTC valve for high volume bypass.

Exhaust Throttle Valve (ETV): During engine idle or part load operating conditions, fuel injected into the combustion cycle may not be sufficient to maintain gas temperatures. Generating engine back pressure is a method for increasing engine out temperature. Back pressure can be achieved by utilising a valve after the turbocharger. Partially obstructing the flow creates load on the engine, increasing the exhaust temperature [3]. Reducing the expansion ratio over the Turbine wheel reduces turbocharger speed. Oil pressure is related to engine speed, while higher oil pressure combined with lower rotor speed increases the compressor side oil leakage risk. Both exhaust brakes and ETV can push the compressor operating point towards the choke side of the compressor map. This results in a reduced pressure behind the wheel for a given speed when compared with engine idle conditions.

3.3 Engine Development Pathway

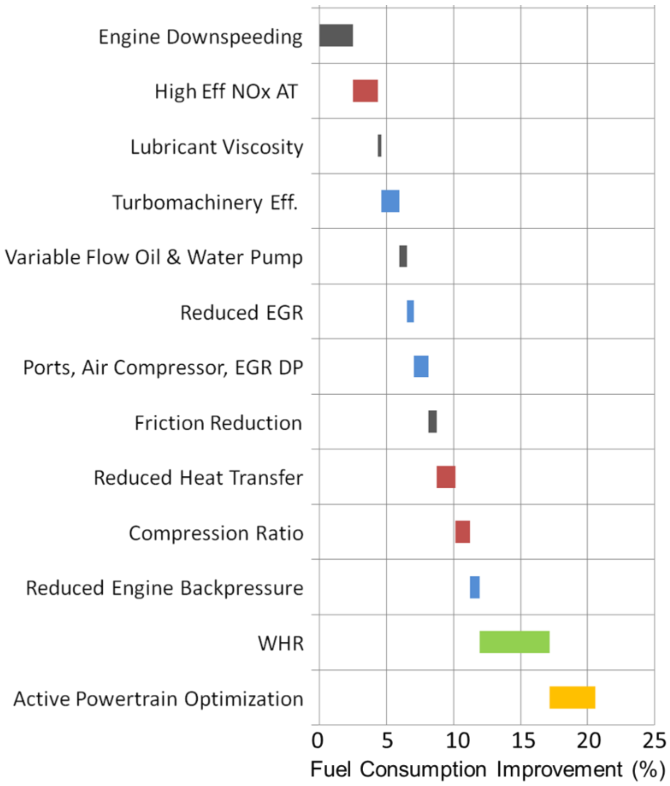

Figure 4. Key enabling technologies to meet fuel efficiency improvements and GHG regulations [1]

3.4 Turbocharging & Air Handling Solutions to Fuel Economy Demands

There is currently no clear favoured turbo architecture by OEMs. Architectures include Two Stage, High Efficiency VGT, High Efficiency WG, Turbocompound, E Machines, Miller Cycle and Cylinder Deactivation. Strategies with implications for the seal system are discussed below.

3.4.1 Two Stage Architecture

Two stage is an enabler for Miller Cycle engines as it can provide the extra boost pressure necessary to compensate for the volumetric efficiency drop. With two stage architecture, the conditions created in the lower pressure (LP) stage can be challenging for the turbocharger seal. The high pressure (HP) stage receives exhaust gas ahead of the LP. This combined with higher LP inertia gives a lower transient response of LP stage. The HP breaths through the LP further reducing pressure behind the compressor wheel. The engine breather system must also manage blowby from two turbochargers.

Risks include:

- High oil pressure at low turbo speed
- Low pressure behind the wheel

Figure 5: Two Stage Architecture

3.4.2 High Efficiency Variable Geometry (VGT) & Wastegate (WG)

The new generation of seal system is helping release further efficiency and map width from the compressor stage. Historically the line up between the compressor wheel blade passage and the annular vaneless diffuser was key to oil leakage prevention. Recessing the wheel deck below the diffuser face would generate pressure behind the wheel to maintain a positive pressure difference across the seal system. The new level of seal performance enables a relaxation of this requirement and further efficiency gains.

4 Turbocharger Seal Development

4.1 Why Develop Current Technology?

The majority of the turbocharger market today uses a similar approach to sealing. The non-contact oil seal systems do not degrade over time, there is no wear out. The system is low cost and suited to high volume manufacture. The oil seal systems themselves don't fail however it's not uncommon that the operating conditions go beyond the seal capability. Challenging operating conditions driven by market trends demand better seals. Maintenance of filters and increasing engine blowby over time can make the operating conditions challenging for historic product.

Emissions legislation is continually moving forward bringing new challenges for the seal system. If using today's technology can meet these new requirements then a non-contacting seal system that will not wear out is still the best solution.

4.1.1 Performance Enhancement of Existing Technology

To make a significant improvement in the performance of an existing technology you first need a much deeper understanding.
Cummins Turbo Technologies used Computational Fluid Dynamics (CFD) to model the flow of oil through the thrust bearing into the seal system. Advances have been made by studying how the oil interacts with the air and how the seal system geometry can influence both oil and air movement within the seal cavities. This multiphase analysis allowed detailed understanding of the oil radial and circumferential velocity, how we use its momentum to our advantage and ultimately how to design a better seal.

4.1.2 CFD Approach

Computational Fluid Dynamics (CFD) has been used to model the flow structures within the seal, understand the interaction of the gas and oil then analyse the impact of changes in response to these learnings.

Seal System structure:

- Pressurised oil enters the bearing housing and flows through the bearing housing oil rifle to the thrust bearing
- Oil travels through a radial drilling in the thrust bearing to the inside diameter of the bearing
- The oil contacts the rotating slinger and is driven through the narrow-thrust bearing / slinger interface (TSI)
- The flow emerges from the TSI into the seal cavity 1
- Under circumstances where the pressure behind the wheel is lower than the bearing housing pressure, gas will escape from the bearing housing
- If the oil reaches the piston ring seal it will be carried out with the gas flow (Figure 6).

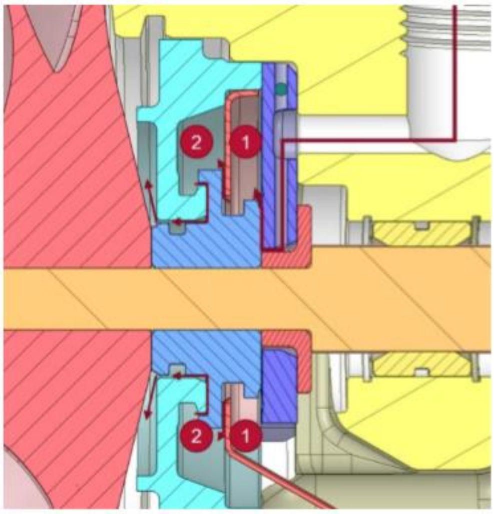

Figure 6: Existing Seal: Compressor side leakage oil flow path

A structured approach was taken to progressively understand the flow mechanisms within the cavities and the key parameters affecting the oil flow

1. Sector model – to understand the flow through the thrust bearing and slinger interface
2. Full air model – to understand bulk flow structures
3. Full multiphase flow model – to understand how the flow of oil is impacted by the bulk air structures and visualise the likely oil structures during operation

4.1.3 Sector Model

The Sector model is used to understand the flow dynamics within the TSI (highlighted in Figure 7). The flow in this area is governed by the rotation of the walls on this narrow passage and the geometry in this area.

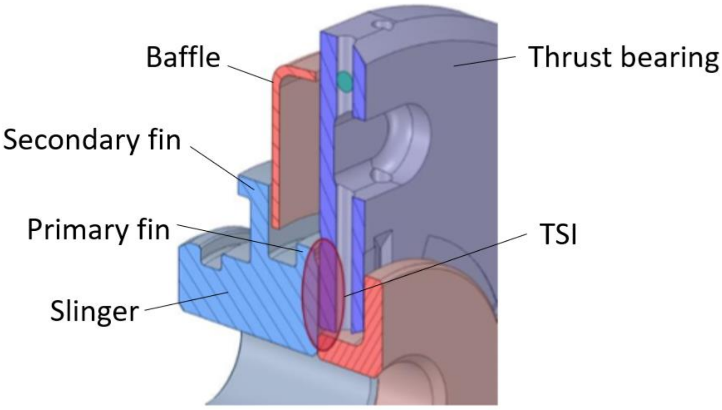

Figure 7: Thrust Bearing / Slinger Interface (TSI)

Flow reaching the inner radius of the thrust bearing must travel up the narrow interface between the thrust bearing and rotating slinger before it is able to enter the cavities. Since the motion of the oil flow, through the narrow interface, is heavily influenced by the wall shear occurring on the slinger surface, it is important to capture the near wall flow structures accurately. This requires a dense near-surface mesh, making a full 360° simulation of this interface prohibitively computationally expensive.

A single-phase oil sector model has therefore been used to approximate the geometry of the TSI and assumes the TSI is completely flooded with oil, and with no entrainment of air.

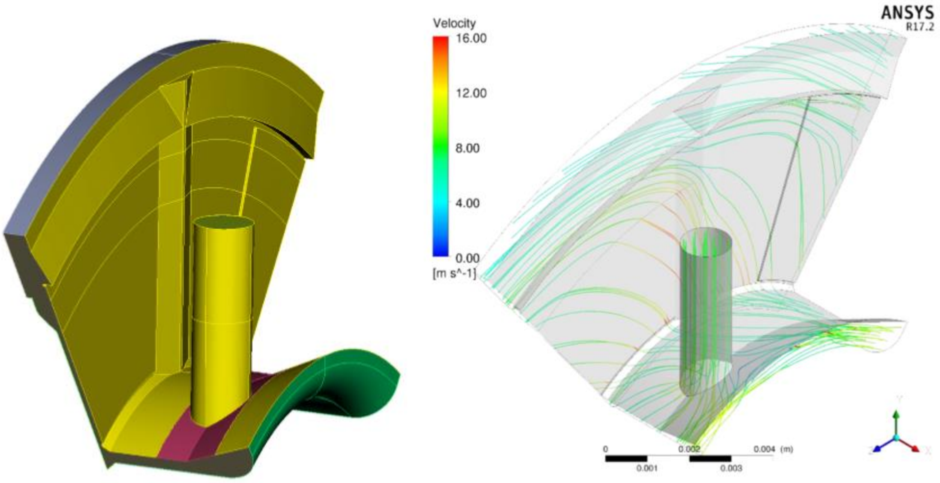

Figure 8: Sector Model Geometry and Streamlines

4.1.4 Air Model

The single-phase air model aims to determine the flow structures that develop in the cavities due to the geometry and rotation of the components only. It does not include inlets or outlets and there is therefore no driving pressure difference over the cavities.

Whilst in practice the flow of oil in the two dynamic sealing cavities will depend on the multiphase interaction with the air, qualitative indications of the flow of oil can be obtained by a single-phase air model. It can be expected that oil entering the cavities from the TSI, is entrained in the bulk air flow structures already present in the cavities. Whilst a multiphase transient simulation of the flow within the cavities is possible, the use of a single-phase steady state model is significantly less computationally expensive. The air model therefore provides a mechanism to cost effectively simulate a number of parameters (e.g. rotational speeds, geometries).

4.1.5 Multiphase Model

The transient multi-phase oil and air model provides a qualitative evaluation of a particular sealing geometry. By outputting transient results throughout the simulation, it is possible to animate the solution and provide a visual comparison of the flow behaviour with in-house oil leakage/ visualisation tests.

During steady operation of the dynamic sealing system, the air/ oil distribution and flow field is complex. Therefore, for the purpose of providing some insight into the behaviour of the individual phases, how they develop and to give a visual comparison with leakage tests, a dam burst scenario was used. A dam burst scenario refers to instantaneously adding a fixed oil mass at t=0 and then tracking, over time, how the flow develops. The model is initialised with developed bulk air flow structures, before oil is added to the system at the TSI. The resulting flow behaviour is interrogated through time from this point onwards.

A snapshot of the multiphase simulation is shown below for an existing seal system. Oil flow was visualised at key operating points and compared with CFD predictions. Correlation is observed with key behaviour replicated. Once satisfied that the analysis was reflecting what we observe in real life we could start to study the influence of key features within the seal system.

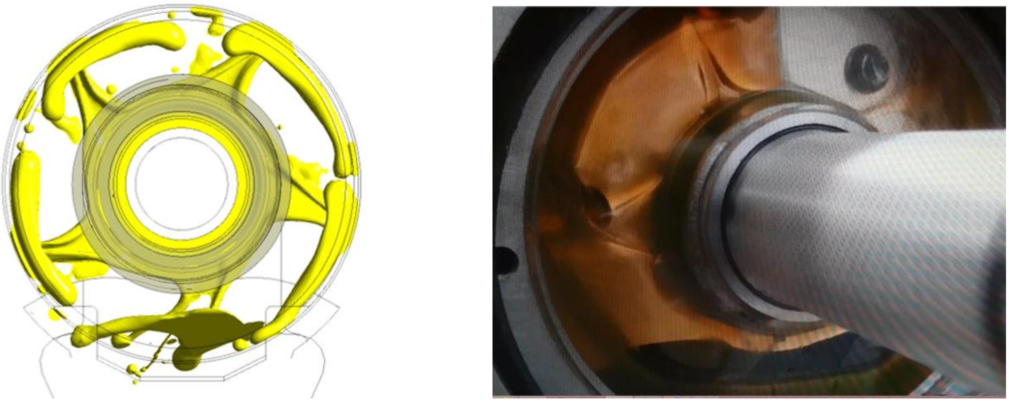

Figure 9: CFD prediction of initial oil flow & Visualisation on test cell

Initially an existing seal system was modelled in CFD. This allowed us to run the correlation work and also start to understand the limitations of our current product. The snap shots of CFD work included are from this analysis of the existing seal system.

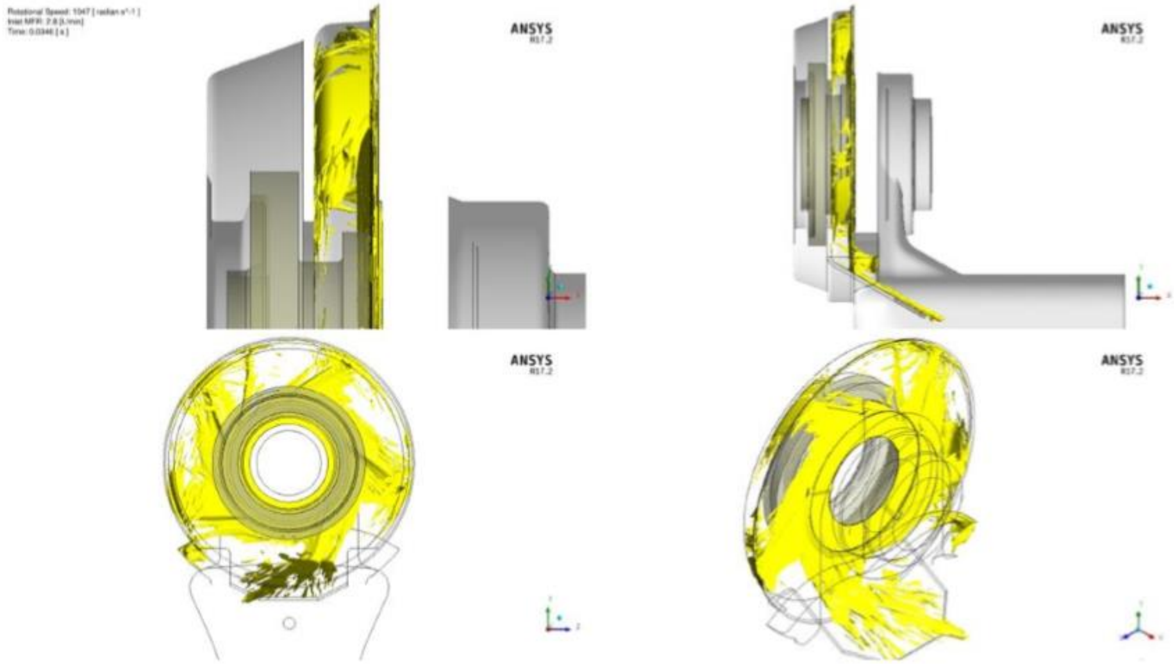

Figure 10: CFD analysis of existing seal system

CFD captured the rotation in the oil. This helps us understand how we can influence the oil rotation and the impact of doing so.

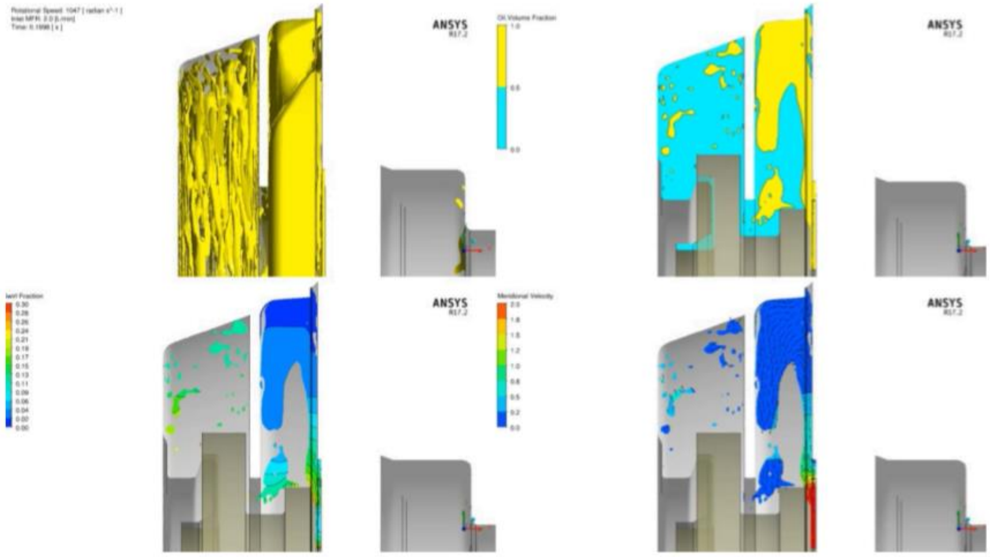

Figure 11: Oil carryover into second cavity in existing seal system

The CFD investigation was able to find the limitations of the existing seal system giving us the first insight into how the system could be improved. The study included looking at the impact of varying clearances, baffle geometry, slinger fin geometry and height. Understanding how the oil flow was influenced by changes in the TSI led to further insight as to how the internal geometry could be modified to take advantage of this new understanding.

5 Performance Validation

Design of Experiments work was completed to validate the findings from CFD

5.1 Gas Stand Performance Mapping

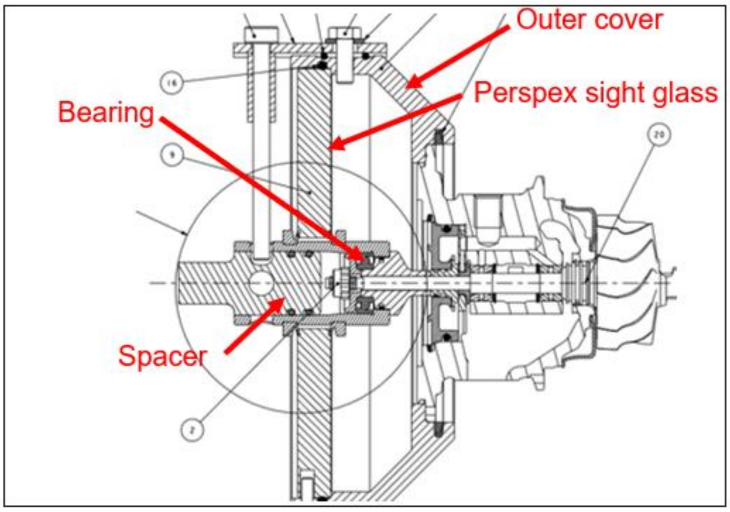

Figure 12: Gas stand test configuration

Testing on gas stand has the advantage of also allowing visualisation of the oil flow as the operating conditions are changed. Oil flow trends from CFD can be observed in real time. The gas stand test allows changes in oil temperature/viscosity, oil pressure, rotor speed and pressure difference over the seal. Another advantage of gas stand testing is the ability to accurately control key oil parameters independently of turbocharger speed.

Scenarios investigated in CFD were repeated on the gas stand test to build up confidence in the analysis. Detailed changes were investigated with CFD and the optimised assembly mapped on gas stand.

Gas stand testing demonstrated a big leap in performance over the current product seals. The proposed concept from gas stand testing was taken forward for engine testing.

5.2 Engine Performance Mapping

Gas stand test work was demonstrating such a leap in performance that it was prudent to also evaluate the results on an engine. Seal performance mapping was completed on two separate engines at two oil temperatures across the speed range of interest. Engine testing confirmed the gas stand results. Project targets were surpassed by a significant margin.

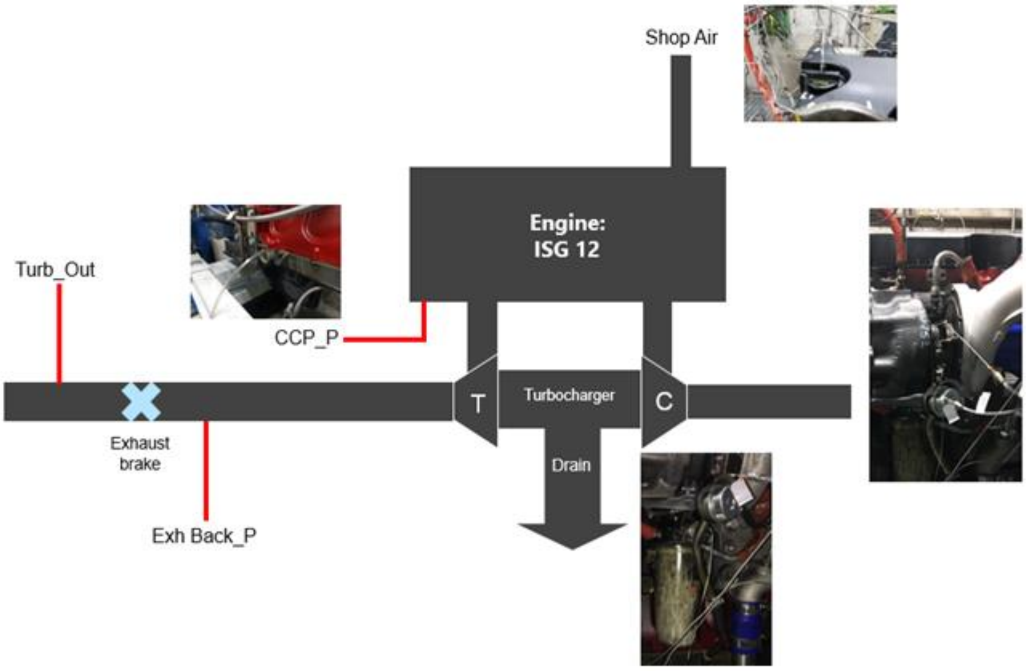

Figure 13: Engine test setup

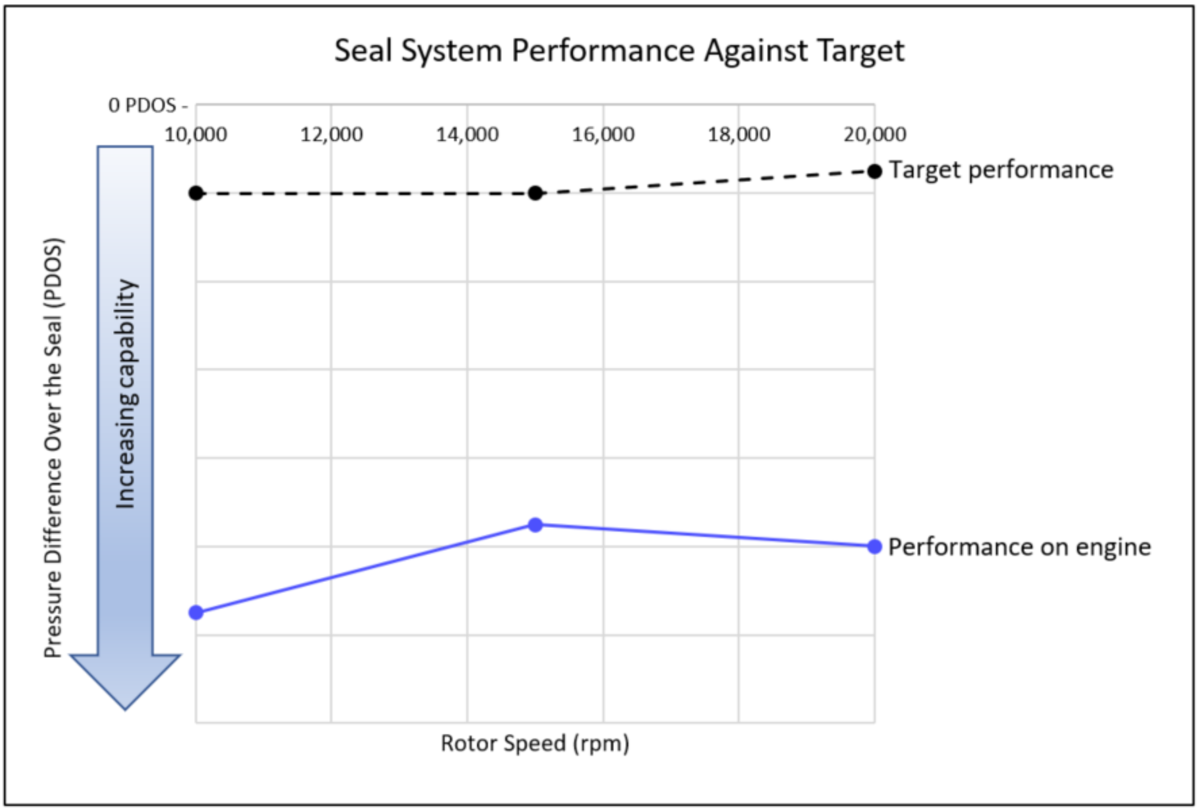

Figure 14: Seal system performance on engine vs project target

The project targets were set based on the market trends and prediction work to translate these into a Pressure Difference Over the Seal targets. The actual performance achieved was many times better than the project targets. This reduces restrictions on the way our customers want to run and provides design margin where packaging constraints drive sub-optimal installations.

6 Summary and Outlook

Cummins Turbo Technologies made a big leap forward in its understanding of the physics of turbocharger oil seal systems. This step change in seal performance is an enabler for all known turbocharger application strategies. The new seal has redefined what is possible from conventional dynamic sealing technology.

Acknowledgements
Thanks to Frazer-Nash Consultancy for their help in developing our Multiphase analysis technique [2].

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