COMPUTATIONAL THERMAL MANAGEMENT OF TRANSIENT TURBOCHARGER OPERATION

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INTRODUCTION

With the ever-increasing spotlight on fuel efficiency and emission control, turbochargers are projected to be in increasing demand with more cars adopting this technology for increased power and more miles per gallon of fuel. Initially designed for aircraft engines operating at high altitudes, turbochargers offer an elegant, simple boost to an engine's performance and are being adopted in cars, motorcycles, trucks, trains and marine vessels. Turbochargers convert the waste exhaust gases from the engine into compressed air for the engine, resulting in more air intake which allows the engine to burn more fuel. An engine with turbocharging produces increased power without significantly increasing engine weight due to their simplistic design, resulting in huge benefits in efficiency and performance. Typical turbochargers consist of a turbine and a compressor connected by a shaft, with the engine exhaust air running the turbine, which in turn delivers air to the compressor via an air pump. To keep the weight down, the turbine and compressor are made of ceramic materials and the high rotational rate of the turbines, sometimes as high as 30 times the engine, coupled with high exhaust gas temperatures, makes the thermal management of turbochargers a critical design challenge.

Integrating modern computational methods into the design cycle helps in understanding the thermal behavior of turbochargers by offering insight into component and system performance.

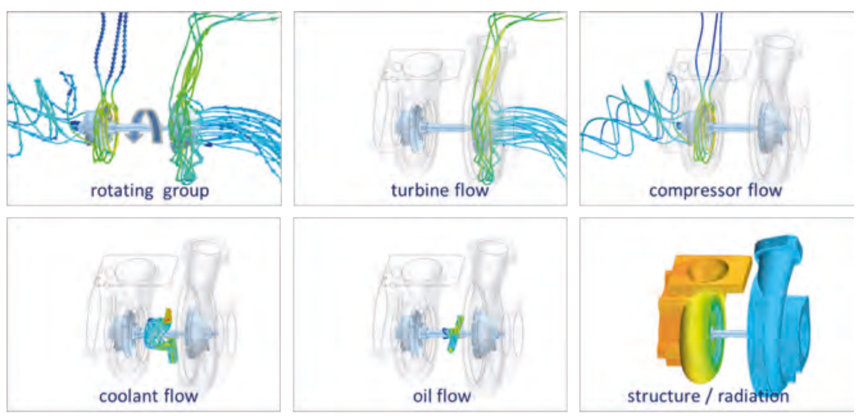

FIGURE 1: Sub-systems for coupled turbocharger simulation

Numerical simulation opens up a whole gamut of possibilities in the understanding of the workings, efficiency and design of rotating components in the turbocharger from a thermal perspective. Recent advances in time-accurate CFD computations, turbulence modeling and processor speed have made transient computational analysis a practical design tool for turbocharger analysis. In this article, InDesA offers a glimpse into their use of computational methods using CD-adapco's STAR-CCM+ for efficient design of turbochargers.

TURBOCHARGER DESIGN – A THERMAL PERSPECTIVE

A turbocharger is thermodynamically coupled to the combustion engine and driven by the exhaust gas which expands through the turbine and powers the compressor which is mechanically linked through a rotating shaft. The hot exhaust gas from gasoline engines can exceed 1000°C at the inlet of the turbine and needs to be insulated from the intake air entering the compressor at ambient temperatures. This temperature difference of up to 1000°C in one component with rotating parts at very high speeds is challenging, not only from a mechanical perspective but also from the flow and thermal side.

Thermal management refers to the balancing of the heat fluxes inside the turbocharger while controlling and limiting temperatures for the structure of the turbocharger housing and rotating assembly as well as for lubrication and coolant fluids. Thermal management must also control heat transfer by radiation, convection and conduction to the ambient and neighboring components. Thermal interaction with the environment can be strong and can lead to damage of the turbocharger, exhaust manifold as well as the neighboring components.

The temperature difference between the exhaust gas and the intake air is an engineering challenge, in addition to the temperature change caused by a sudden load change, for example, from accelerating at full load to zero and back to full load. Those incidences can cause temperature changes of several hundred degrees within seconds on the turbocharger exhaust side leading to high thermal stresses and eventually fatigue. This is why transient thermal analysis is essential for structural analysis and the layout of turbocharger designs.

Thermal reliability is certainly the main goal of thermal management. However, it should be mentioned that heat transfer from the exhaust side to the compressor can lower the efficiency of the compressor and thus directly influences engine performance. Besides, unstable compressor operation can be triggered if the compressor is operating close at its pump or surge line.

Thermal analysis of turbochargers is based on thorough gas dynamics analysis. Pressure and shear stresses from the gas flow through turbine and compressor are balanced with frictional losses from the rotating shaft and with mass inertia from the rotating assembly, allowing for steady state as well as for transient operation of the turbocharger. InDesA has gained expertise and confidence in flow simulation of compressors and turbines with STAR-CCM+. Even local supersonic flow areas with interacting shock waves can be captured in the diffuser of a compressor near surge operation. Thus, entire performance maps for compressors from pump to surge line can be simulated which is one precondition to deal with transient flow and thermal phenomena.

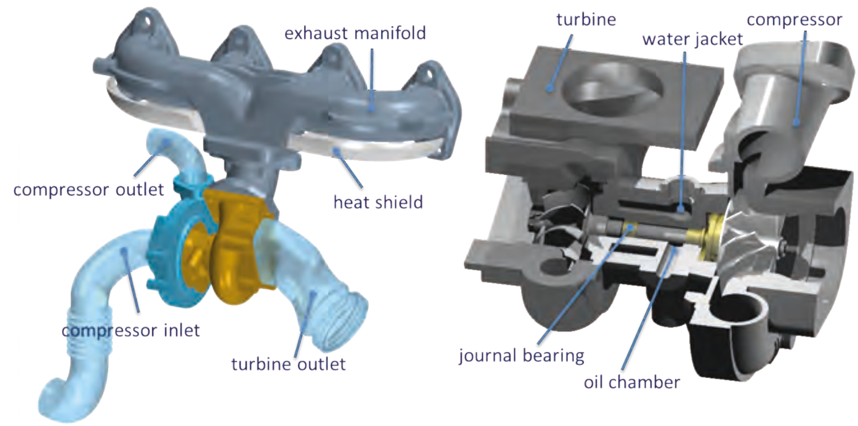

FIGURE 2: Simulation model of a turbocharger

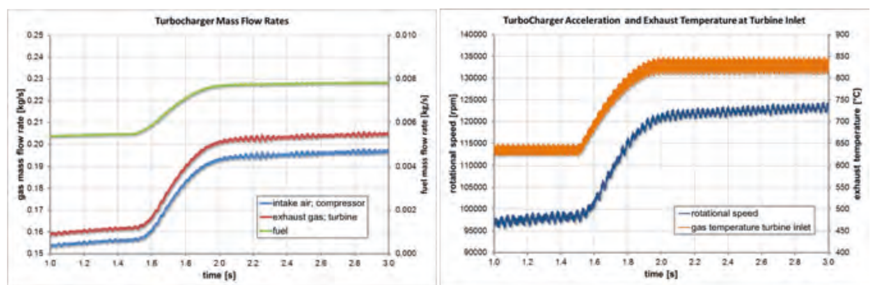

FIGURE 3: Dynamic response of turbocharger

SIMULATION METHODOLOGY

A simulation approach with direct thermal-fluid-structure coupling (CFD/CHT) was chosen for the turbocharger and its closer environment. This includes the exhaust gas, the intake air, coolant and engine oil as well as different materials for the rotating assembly, compressor and turbine housing, bearings and seals as well as for heat shields (Figure 1). The rotating assembly is coupled to the flow through compressor and turbine by fluid-body-interaction where the resulting moments from the flow on the compressor and turbine wheel are used to compute the angular acceleration of the assembly. Friction torque for the bearings and seals were estimated with the angular velocity and oil temperature as dependent variables. The rotation of the assembly is coupled to the non-rotating regions by sliding interfaces.

To close the system, a simplified approach was taken to link the compressor outlet flow to the turbine inlet flow by implementing basic thermodynamic models for the charge air cooler and for combustion yielding intake and outlet valve timing through field functions. To accelerate the turbocharger, the fuel mass flow rate is simply increased which basically simulates diesel engine operation. The increase of fuel rate is controlled by use of a PI-controller with a fuel-air-ratio target. This approach serves to demonstrate the capabilities of the overall approach. For more realistic engine operation, whether diesel or gasoline, it is recommended to use a GT-POWER 1D simulation model that can be directly coupled to the STAR-CCM+ model, allowing for more control of throttle, fuel injection, ignition, valve timing, waste gate or VTG positions and EGR rates.

SIMULATION MODEL AND BOUNDARY CONDITIONS

The turbocharger used for this investigation is shown in figure 2. It is connected to a simple cast exhaust manifold with a heat shield underneath and to an exhaust pipe. Inlet and outlet hoses are attached to the compressor. Using the Conjugate Heat Transfer (CHT) approach, all fluid and structural continua were meshed with polyhedral cells. For all fluid regions close to solid walls with boundary-layer-like-flow, prism layers were integrated with a minimum of four layers. For accuracy reasons, all interfaces were node-to-node connected and conformal. The resulting mesh contained 14 million cells with 24 regions and seven physics continua. No volume mesh was used outside the turbocharger as the heat shields are only thermally connected to the system by radiation. Heat transfer coefficients and ambient temperature were defined on the outer surfaces of the turbocharger and the heat shields to account for thermal convection. Volume flow rates and inlet temperatures were

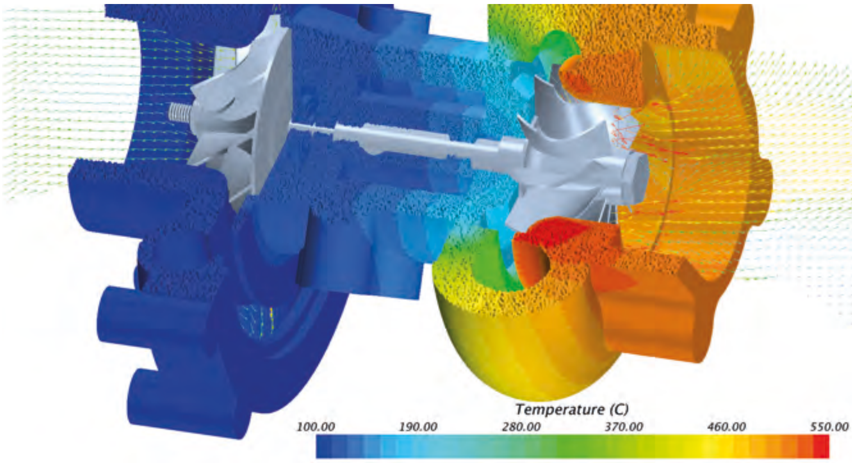

FIGURE 5: Temperature contours in turbocharger structure

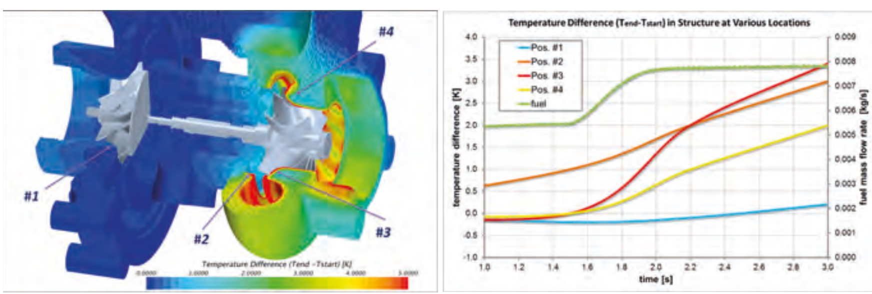

FIGURE 4: Thermal response due to turbocharger acceleration

prescribed at the inlet boundary for coolant and oil, whereas for the intake air, stagnation pressure and temperature were set as inlet boundary conditions. A back pressure was defined at the compressor outlet. Finally, transient response of the system was controlled by the fuel rate with the assumption that the engine speed does not change due to the change of load.

Figure 3 shows the transient profile for the exhaust gas and intake air mass flow rates as they respond to the increase of fuel mass flow rate. This test case consists of three intervals: a steady state period with respect to engine operation and thermal state followed by an interval where the fuel rate is ramped up to its target value. The last interval resumes constant engine operation where thermal conditions start to adjust to the new operating point with the turbocharger running at a higher speed. The oscillations in the fuel mass flow rate are caused by the fuel-air-ratio controller and hence can be observed for the gas mass flow rates as well.

DISCUSSION OF RESULTS

For simplicity, it is assumed that the exhaust gas pressure at the inlet of the exhaust manifold is equal to the boost pressure. The engine and drive train inertia are neglected. As a consequence, a rapid response of the exhaust gas and the rotating assembly is observed (Figure 3).

Thermal response is lagging behind mechanical response of a turbocharger. In fact, the temperatures at different locations show different response times (Figure 4). At the end of the simulation, after three seconds, temperatures have not reached a constant state. At that point, the flow field is stable and the simulation can be continued with moving reference frames for the rotating assembly to reach the final thermal state if that is desired.

The temperature profiles can give some indication on whether transient operation can be critical for the turbocharger structure. In the end, a transient stress analysis must be performed to detect critical thermal stresses where the thermal analysis with STAR-CCM+ delivers the temperature field as input at discrete time steps. A sample temperature contour plot is given in figure 5 for a discrete time step.

The temperature of the turbine wheel and housing is influenced in the first place by the exhaust gas temperature and the compressor wheel and housing by air compression. The instantaneous temperature field results from the balance of all heat fluxes from the turbocharger structure to the coolant and engine oil, as well as to the ambient environment through convection and radiation. Also, thermal interaction of different parts of the turbocharger and the heat shield is significant to determine correct structural temperatures.

In principal, there are three options if critical stresses are detected from a structural analysis. In general, the problem can be cured by either bringing down temperatures, adapting the geometry so that thermal stresses decrease, or by changing to a more robust material for the turbocharger. Exhaust gas temperatures can be controlled by reducing boost, retarding ignition timing, and by enrichment of air/fuel mixture. However, a further option is provided by a thorough analysis of thermal heat fluxes within the turbo charger. Once we gain an understanding of the interaction of the heat fluxes between the different media, they can be eventually redirected by small changes of the water jacket or of thermal bridges within the structure. This is often a more elegant way to cure thermal problems than to adjust combustion parameters.

CONCLUSION

Thermal analysis has become an elementary and reliable technique within the virtual product creation process of turbochargers. It creates an essential input for structural stress analysis to detect thermal stresses which can lead to structural fatigue. For simplicity, thermal stress analysis is often done for hot/cold states only. However, with the capabilities of transient thermal analysis, transient thermal stress can be detected which may be more critical in comparison to steady state analysis. On the other hand, transient thermal effects can also relieve sudden temperature changes as thermal inertia from the masses involved can damp thermal shocks as well. Short but sudden turbocharger acceleration will not immediately lead to critical temperatures. This is why transient thermal analysis will result in higher fidelity of thermal stress prediction.

The presented methodology is a manageable approach using CD-adapco's STAR-CCM+ to couple transient flow phenomena in the turbine and compressor with the rotating group and at the same time predict thermal response.