Thermal and System Management Approach for Exhaust Systems

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Abstract: The automotive and heavy-duty industry (off- and on-highway) requirements for emission, noise and fuel reduction and control have become more stringent. Based on the complexity of the system with its involved components and operating environment a new approach needed to be developed to meet the new demands. Today it is almost given that CAE plays the central role in engineering development, not only does it offer the potential for shorter development cycles and reduced costs but it also offers the potential to optimise complex systems and demonstrate component and system limitations.

A comprehensive approach as described in the present paper requires a detailed understanding of the components, their functions and interaction as well as their future development trend. For its implementation a complex testing infrastructure is needed to serve as a basis for component and system validation and correlation. The testing infrastructure is a critical part of the process for developing the material properties needed for CAE input

A modern exhaust system is dealing with extreme temperature environments, which can be briefly characterized with key words like heat soak, transient conditions, aging, creep, distortion, fluid and air flow, heat flux, radiation, convection, reflection, time, plasticity, etc. This collection of terms alone gives an enormous feeling of the complexity we are dealing with. From a simulation perspective it involves disciplines such as FEA, CFD, NVH and FSI.

Bringing this together under one umbrella is the objective of the presented paper. It ranges from newly developed experimental and simulation techniques to data handling and management through SLM.

Keywords: CAE, CFD, FSI, Fluid Structure Interaction, NVH, Thermal Management, System Management, Creep, Aging, Transient, reflection, radiation, convection, plasticity, flow, flow rate, heat soak, thermal imaging

1. Introduction

1.1 Exhaust systems in the automotive / heavy duty industry

It is well known that regulative requirements for emission, noise and fuel reduction and control in the areas of automotive and heavy-duty industries (off- and on-highway) are becoming more stringent. Historically the exhaust system was a basic arrangement of components to channel and guide waste combustion gas from the engine. With the renewed focus on emissions, NVH and fuel efficiency more emphasis is being placed on the exhaust system as a critical component to achieve these goals.

Hardware components like catalysts (CAT), turbo chargers, exhaust gas recirculation (EGR), active diesel particulate filters (aDPF) and Selective Catalytic Reduction (SCR) technology have emerged through rapid development to meet the legislative requirements (reduced emission regarding NO_x, CO and diesel particulates) placed on some markets and regions. In addition to the legislative requirement the exhaust system must also meet the market expectations for cost, NVH and fuel efficiency.

As new technology was added to the exhaust system, the control, management, functionality and robustness were continually refined and improved. Today's exhaust and after treatment systems have their own computer control unit and often designed in the form of a cascade system, like sequential turbo charging, flexible EGR and active catalytic converters. The ultimate goal is to have a real-time, closed loop control system based on combustion measurements and exhaust system readings. This fully integrated system approach would also utilise a certain level of intelligence for continuous control and management.

Besides those developments, the exhaust system integration is being applied from passenger car applications, to on-highway heavy duty truck applications and also to off-highway applications. There is meanwhile tight regulation in place (and will be even stronger in the future) for construction equipment especially when operating in residential environments.

1.2 Role of sealing application for exhaust systems

As mentioned it is very clear that the exhaust system has become more complicated not just from a management perspective but also based on the sheer number of additional components. The challenge then is to connect and join these components providing adequate sealing, robustness and durability in a very hostile environment. The additional types of joint and connections include

- Pipe flanges
- Manifold flanges
- Slip joints
- V-clamps

- Welds
- Etc.

All but the welded joint require some kind of a sealing element. Since the exhaust system has developed from a simple pathway for the exhaust gas, so too have the demands placed on the sealing elements. These additional demands include:

- Thermal management (Insulating / Conducting)
- Damping function to reduce, eliminate or avoid noise and excitation
- Thermal expansion control.

The sealing function itself became more rigorous with clear sealability targets being demanded for each application. Quite common today is to have a maximum limit of 2l/min pre and post operation. Even though this is already a tough requirement the future will demand even further improvements for sealing.

1.3 Operating environment

Since we are talking about the exhaust system, naturally we are dealing with a higher temperature environment. Besides a harsher thermal environment there are also additional consideration for higher back pressures and vibration issues. In general we expect to see the following conditions:

- Maximum exhaust gas temperature:
    - 1050ºC for gasoline applications
    - 850ºC for diesel applications.

Based on the driving conditions, the engine packaging environment and the shielding of specific areas, the skin and flange temperature of the components are continuously changing. With good air flow management around the engine compartment and exhaust system, the flange temperatures are normally lower than the exhaust gas temperature. However, once air flow becomes stagnated (heat soak), like idle conditions, in an encapsulated environment or aftertreatment operation, temperatures may actually rise beyond the maximum gas temperature. A good maximum temperature assumption is 1100ºC.

Exhaust back pressures have continued to increase with the addition of exhaust gas aftertreatment. Design considerations for back pressures in excess of 5Bar are common depending on the application and system design.

Besides increased temperature and system back pressure, the additional components (such as multiple turbo chargers) in general create a much higher probability for vibration and, thus noise and fatigue. Especially critical is the correct placement of components for their support and surrounding environment. A wrongly positioned and supported turbo can create excitation in excess of 25g that will ultimately fail surrounding components in a very short time period. The system and component resonance is also a key consideration.

Considering the joint or connection for each component of the exhaust system is not just a simple question of sealability. The thermal, vibration and system interaction is critical to achieve a cost effective and robust exhaust gas after treatment system. To ensure that these goals are met a system approach is needed for design. This is not just from a geometrical point of view, as done too often in the past making sure that all components just fit together, but from a functional and operational perspective. This is why we started with the Thermal and System Approach for Exhaust Systems.

1.4 The role of CAE

Since we are in a fast-moving environment where time-to-market, cost, "first-time-right", design and quality are major driving factors in developing new designs, there is a definite need to look into new tools in development. Computer Aided Engineering (CAE) started here to play the major role. It has long proven its reliability for the different applications regarding accuracy, however to achieve this level of accuracy requires a detailed understanding of the materials and their properties, which is especially challenging in the exhaust environment.

How CAE as an overall development tool is implemented plays a major role for its effectiveness regarding cost minimization and reduction in time-to-market. Factors influencing here, are:

- Hardware architecture
- Software performance and interaction with hardware
- Sweet spot identification for the specific model / product simulation environment
- Simulation process flow.

Leaders in the market implemented the so-called "analysis-led-design" philosophy in development, this made it possible for them to deliver huge potential for cost savings and avoidance.

2. Thermal and System Management Approach for Exhaust Systems

2.1 Thermal and System Management Approach

The complexity of the exhaust system as described above and in light of the mentioned stricter regulations requires a new approach away from just a joint evaluation. It is a must that all the components are linked into a whole: a system. This system does not have to be, at the initial stage, the complete exhaust / aftertreatment system but a sub-system. Examples for such a sub-system are:

- Cylinder head / exhaust manifold / turbo charger / catalytic converter / shielding components when evaluating just the exhaust manifold gasket
- Exhaust manifold / turbo charger / EGR / SCR / shielding components
- Exhaust manifold / catalytic converter / down pipes / DPF / shielding components
- EGR / intake system / shielding components.

Just those few examples provide a good overview of the challenges related to linking the exhaust system components together. This alone explains the need for such an approach when talking about developing the system while optimizing the noise level at the same time.

The most challenging factor though is the thermal factor. In the past when developing / designing the individual joints separately from each other the evaluation criteria were different as well. By saying this it becomes clear that just joining the components is not the solution. The evaluation criteria need to be adjusted as well. This means that the system has to be “tested” under the same conditions. Only this guarantees that the thermal interaction between the different components is on the same level and offers potential correlation. It is like testing all the components of the system / sub-system together on the dynamometer or the hot-gas-test bench.

The first factor which needs to be considered for the system is “thermal interaction”, not so much the mechanical interaction. Thermal interaction means:

- Thermal stress induced into the structural components
- Thermal balance in the system.

Thermal balance is the consideration and understanding of:

- Conduction
- Convection
- Radiation between the interacting components.

In CAE terms we are talking about a complex multi-physics environment of fluid-structure-interaction (FSI).

This leads into the “Thermal Management / System” approach for exhaust systems (Figure 1):

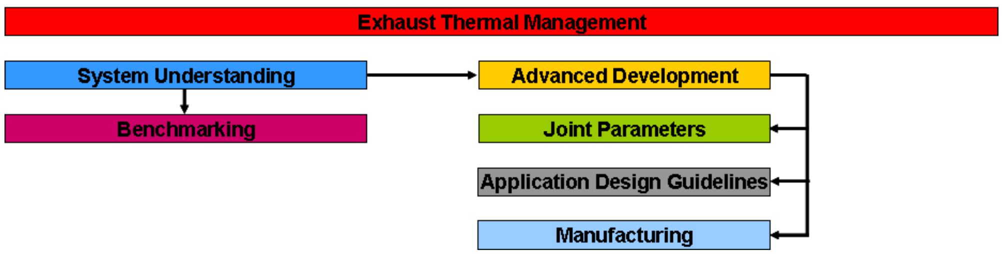

Figure 1: Thermal Management / System Approach

- System understanding: understanding of the overall system layout, function, and, especially the thermal flow between the components
- Benchmarking:
  - Understanding of the system components and their development trends
  - Evaluation of the market trends for sealing products and their competitive strategy
- Advanced development: Basic development and study of the basic features / mechanism / components and designs for sealing products in exhaust applications, like:
  - Friction and it’s influence on fretting and fatigue
  - Material development
  - Coating development
  - Sealing feature development, like bead or stopper types for metal gaskets
  - Test method development
  - CAE technique development.
- Joint parameters: design recommendations and standards for the overall joint comprising of:
  - Structural components
  - Sealing component.

- Application guidelines: specific design recommendation for sealing products for the different exhaust applications
- Manufacturing: manufacturing guidelines for the recommended sealing products.

The objective of all this is to understand the complex interaction of the exhaust / aftertreatment system (including intake system) in order to design, simulate and test (precisely and efficiently) Dana Sealing Products applications, along with coordination with other suppliers and the final customer.

The main drivers for the exhaust / after treatment system are, as mentioned:

- Emission control
- Fuel consumption
- NVH control.

Understanding those drivers and their influence in the context of the exhaust / aftertreatment system for sealing products, one can derive the main influencing factors for those applications:

- Thermal influence
- Structural influence
- Calibration of the system.

Thermal influence:

The trend in the system is towards higher exhaust gas temperatures. Emission and fuel consumption requirements also define limitations on the upper spectrum of the temperatures range for certain exhaust components, like the DPF or catalytic converter. The most critical condition is usually the cold start. The faster the system can reach the lower temperature limit of the optimal range for the mentioned components the less emission will be emitted. Basically thermal influence can be characterized with the following factors:

- Maximum temperature will increase
- The system will be subjected to steeper thermal gradients.

Structural influence:

The factors in this category are clearly interlinked with each other and cannot be evaluated independently:

- Joint and component rigidity

- Weight
- Material
- Assembly between components.

Fuel consumption drives towards lower weight. This pushes the development and use of alternative light weight materials. Weight also can be reduced by optimizing the geometry of the structure. Thus, it's influencing the joint and component rigidity.

The thermal influence / trend as mentioned above requires new strategies regarding materials used to withstand those thermal conditions and being creative in implementing new structural designs. An example here is the trend from cast exhaust manifolds to fabricated single or even dual-walled exhaust manifolds.

The complexity of components in the exhaust system requires a special approach in the assembly of those components. The engine packaging space, at best, has remained constant and in some applications has reduced due to vehicle crash zone requirements. To add to the challenge, this limited space availability is required to package a greater number and complexity of components. This requires an innovative assembly strategy for relative ease of assembly during manufacturing as well as under service conditions in the field. This usually results in fewer or somewhat simplified bolting / fastening layouts and procedures. This of-course has a dramatic influence on sealing capability / performance of a joint and vibration behavior under operating conditions.

In order to understand how those drivers, factors and operating conditions may influence the sealing technology and, thus, exhaust system behavior we need to let's have a look what Dana Sealing Products are involved in for exhaust applications.

When talking about Dana Sealing Products applications for powertrain and exhaust systems one first needs to know what is understood under sealing products. Those products include flat gaskets and ring seals, rubber-molded gaskets and seals, covers and pans (thermo-plastic and thermo-set), shielding components.

- Flat gaskets and ring seals, like:
    - Cylinder head gasket
    - Rocker cover gasket
    - Cylinder block hand hole gaskets
    - Exhaust manifold gasket
    - Turbo charger gasket
    - Exhaust gas recirculation (EGR) gasket
    - Slip joint gasket
    - V-band gasket, …..

- Rubber-molded gaskets and seals, like:
    - Valve cover gasket
    - Cam cover gasket
    - Front cover gasket
    - Window gasket
    - Intake gasket
    - Valve stem seal
    - Rubber inserts, …..
- Covers and pans, like:
    - Valve cover
    - Cam cover
    - Front cover
    - Oil pan, ….
- Shielding components, like:
    - Exhaust manifold shields
    - Down pipe shields
    - CAT aDPF
    - Sensor shields, …..

Figure 2 gives a visual powertrain example of what’s typically involved for Dana Sealing Products.

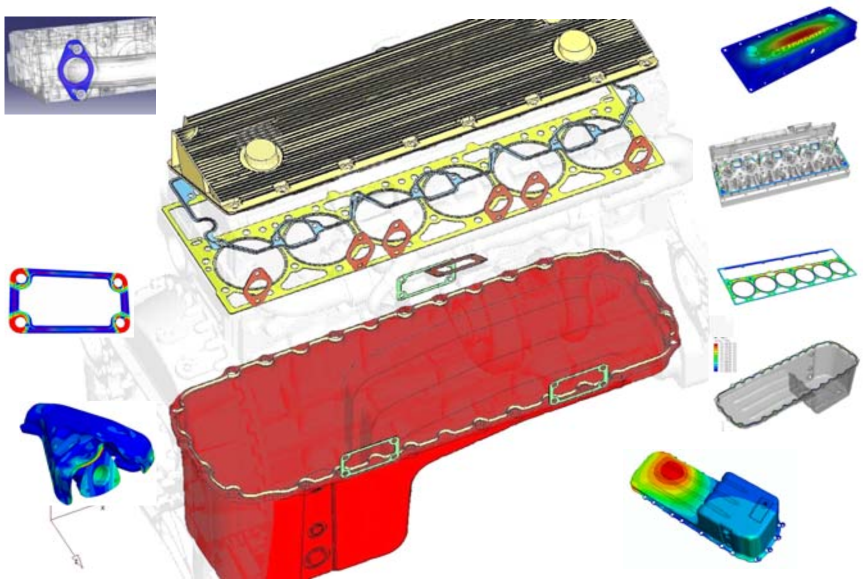

Figure 2: Sealing System

Those applications range from:

- Low temperature (below 400ºC) to high temperature (above 1000ºC)
- Quasi-static to dynamic
- Combustion gas to fluid seals
- Thermal to noise shielding
- Thermal reflection to thermal insulation
- Friction withstanding to friction reducing
- Sealing to controlled metering of fluids, ….

2.2 The new role of CAE

The approach for analyzing the different sealing joints and thereby the sealing system for a powertrain as a whole is accomplished by following step-by-step process outlined below in Figure 3. Since there are several different components and different materials involved in the exhaust system, it is all the more important to have a database with a collection of material properties at different thermal conditions. The approach can be slightly modified for the different parts of the exhaust system. The main driving factor here is the gas temperature, which dictates the different material types and the design direction that is chosen. Since several companies are involved designing and manufacturing these different components, it is all the more important to bring all the components together, to analyze them together and to look at the interaction between each other.

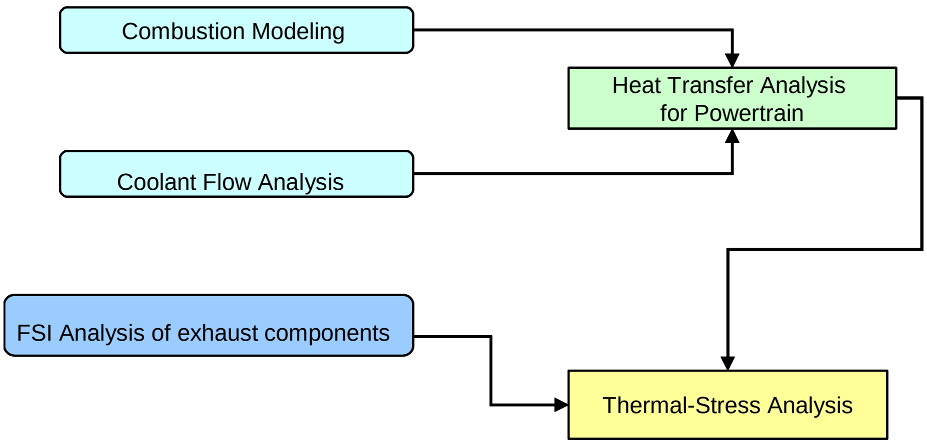

Figure 3: Analysis Flow Process

The starting point of CAE analysis is the combustion modeling using a 1D CFD code like GT-Power. This process involves the modeling of the intake system, exhaust system and also other sub components like turbo chargers and EGR. This data or analysis may be done in-house or received from a Powertrain OE. A typical model for a 4 cylinder gasoline engine is shown in Figure 4.

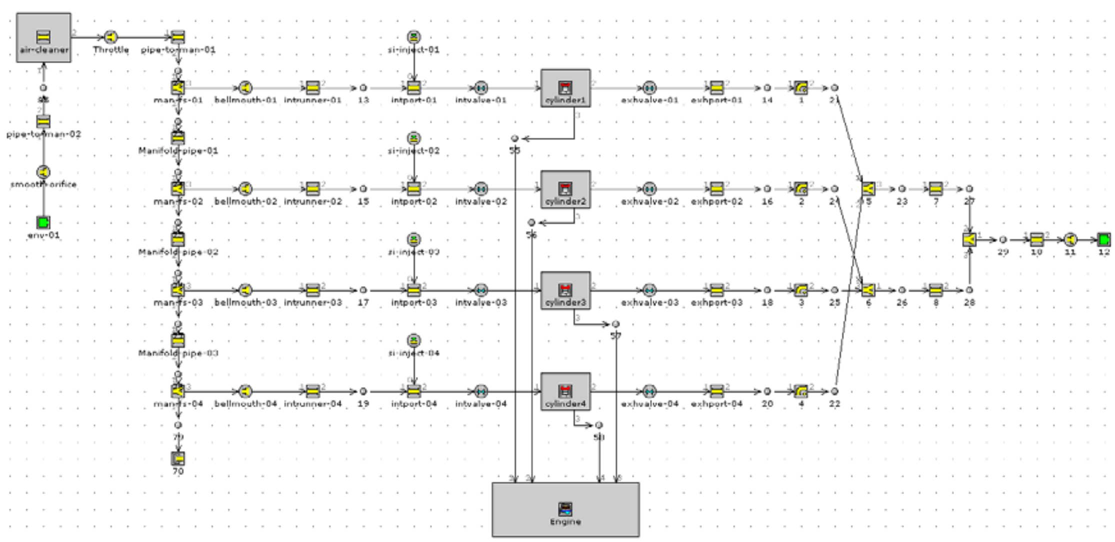

Figure 4: GT-Power Model Example

The results from the GT power models such as heat transfer coefficients and the skin temperature provide the inputs for a heat transfer analysis of the powertrain. The outputs from GT-Power are also used as inputs for the flow rates and temperature of the exhaust gases for the CFD calculation.

The initial flow through the exhaust systems can be optimized by using a 1D CFD software such as GT-Power. This analysis can be used as an input for more detailed sub-system simulation. GT-Power is a 1D code that is widely used to simulate powertrain systems, representing all system components with 1D models. However, certain components, like intake and exhaust manifolds, exhibit a high degree of three dimensional behavior and cannot be accurately represented by a 1D model. To more accurately represent these components in the powertrain system model, a CFD simulation can be coupled to a GT-Power simulation. By coupling the two techniques, 3D components can be simulated with CFD code while simulating the rest of the system using the 1D model available in GT-Power. Throughout the simulation, information is continually passed back and forth between the codes, resulting in more accurate results from component level as well as on system level.

The next step for the study of the exhaust system is the CFD analysis of the exhaust gas flow path. CFD analysis gives gas velocity distribution within the hot exhaust gas region. In CFD analysis, the hot flow region of the gases (see Figure 5); starting from the exhaust ports all the way to the down-pipe is considered. This may include exhaust manifold, EGR, turbo charger, catalytic converter and other exhaust system components. The analysis can be separated for different components depending on the components included or the complexity of the results that need to be obtained from the analysis. Once the fluid flow distribution is achieved along with the temperature profile in the fluid domain, the fluid domain is coupled with the structural domain using a coupling program such as MpCCi to run a heat transfer analysis to obtain the temperature distribution on the structural components. The temperature distribution can be a steady state distribution which represents continues operating conditions of the components or it can be a transient condition, which represents the initial start up conditions, cool down or in general thermal swing conditions.

This heat transfer analysis results in the thermal distribution on the structural components which are further used in the sequentially coupled thermal-stress analysis for the structural domain. Analysis of the assembly conditions plus the operating conditions is carried out as well as the durability analysis of the joint by subjecting the hardware to heating and cooling cycles (thermal cycle).

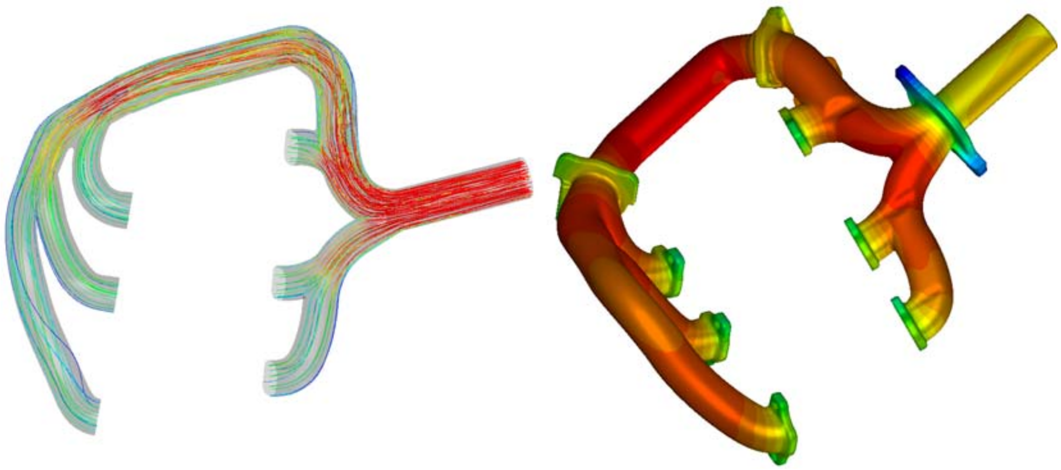

Figure 5: Velocity and static contours of exhaust gas flow in the manifold

The joint behavior such as between head and exhaust manifold in this case, is a strong function of the maximum temperature and rate of temperature change. Hence, the temperature data obtained from the CFD analysis is significant in this case. This demands a rational set of boundary conditions (BC's) for the CFD analysis. For steady state case, a generic set of rational BC's is "Mass Flow Inlet" and "Pressure Outlet". It includes the gas temperature at the inlet and also natural convective heat transfer coefficients on all the other outer surfaces. In case of a transient CFD analysis, a profile file involving flow rates at different crank positions is read in as an input for CFD analysis.

The FSI here involves the transfer of temperatures and surface heat transfer coefficients (HTC's) from the CFD solver (Fluent) to structural solver (Abaqus). The coupling program used to couple the fluid and solid region, transfers the temperatures, HTC's; and Abaqus calculates the temperature distribution within the solid as steady state is reached. Any intermediate temperature profile gives the rate of heat diffusion within the solid. The structural model should have all the contact data with three main material properties:

- Thermal conductivity
- Density
- Specific heat.

By using instantaneous temperature profiles at any step, transient effects can be simulated within the Abaqus model.

The temperature gradient plays a dominant role in the structural soundness of the different components of the exhaust system. It also defines how different component interact with each other. For every joint in the system, there is, usually a gasket or other sealing element that takes care of the sealing. The gasket plays a significant role in the design of not only the joint, but also the system as a whole.

Until recently most of the structural analysis was done on a component or joint-by-joint basis due the cost of computation power and the software limitations. But now with the multi-core computer technology and the distributed memory processing technology available in Abaqus, larger and more detailed models can be created and analyzed within a much shorter time frame. The faster turnaround time also helps in incorporating design-of-experiments (DOE) which in turn fine tunes design aspects not only for the gasket but also for components and material selection. One of the primary joints where this was implemented was the joint between the head and the exhaust manifold. Usually the exhaust gasket was analyzed alone with the head & the manifold as the mating surface only, but how this joint impacted the cylinder head gasket functionality was rarely studied. Including the exhaust gasket and the intake gasket along with their respective manifolds, for the cylinder head gasket analysis shows how the different bolted joints behave together and how the thermal stress in the cylinder head affects the intake joint and exhaust joints or vice versa. The different components bolted on the cylinder head also influence the deformation of the cylinder head during the assembly to block and, thus the thermal balance of the whole system.

The exhaust system usually involves some sort of shielding whose functions are two-fold. Thermal Acoustical Protective Shields (TAPS) (Figure 6) help in protecting the electronic components from getting damaged due to heat as well as trapping the heat between the component and heat shield. It can also provide as a noise absorber for the vibrations in the exhaust system. Due to the presence of the heat shield, the components such as exhaust manifold can be hotter due to the radiated heat that is reflected back to the manifold. This in turn increases the temperature in the manifold and the down pipes, which needs to be controlled for optimal performance of the catalytic converter. This has to be considered when running a heat transfer analysis and a subsequent thermal stress analysis.

Figure 6: Thermal Acoustical Protective Shield with Integrated Exhaust Manifold Gasket

The impact of airflow around the components may also need to be studied, as the heat shield can be used to deflect hot air from thermally sensitive components. In some cases, the air domain is modeled along with the structural components to study how the hot air from, as example the turbo charger environment and other hot pipe areas, can rise and affect different temperature sensitive areas (Plastics, sensors, wires etc).

The material selection of the gasket plays an important role in the thermal distribution between the joint as well as the structural behavior. The gasket can act as an insulator or a conductor and this has to be considered when running the heat transfer analysis of the system. The structural response of the gasket plays a role in the selection of the flange thickness, amount of bolt load required and also the material for the flanges and bolts. The different sealing features, such as stopper heights and topography etc, along with the thermal conductivity of the gasket can help with reducing flange distortion, creep, and a reduction of bolt load loss and thereby increasing the life of the assembly.

The basic material properties such as mechanical properties along with the thermal conductivity, specific heat and density of the different materials used in the analysis need to studied as a function of temperature and time for an exhaust application. In order to understand the dynamics of the system, the dependency of material properties on time and temperature must be studied. The thermodynamic changes in material properties are accelerated at higher temperatures. It is necessary to determine the relationship between time and temperature in order to optimize testing procedures. The test methods must allow for accelerated development while maintaining a realistic comparison to actual operating conditions.

The temperature dependent material behavior for a gasket design as shown below is studied at different load conditions (Figure 7). This type of data is documented for various gasket designs and different materials using SLM (Simulation Lifecycle Management) software, which helps the analyst to quickly search for the relevant data. In case new data is added to the database the analyst is prompted to rerun the analysis with the new data to update the results.

Correlation is an essential part of the CAE analyst's job. As a design project progresses, more and more data is collected, and this helps in reevaluating the analysis parameters that were previously used during the design phase and also in correlating the different results that were obtained from the analysis work. The typical types of correlation work include the comparison of bead heights and load deflection data of samples at end-of-test (EOT) against the original analysis results. Also the remaining bolt load data can be compared to the analysis prediction. In the case of heat transfer simulation, the thermal map that was obtained from a couple analysis or just CFD analysis can be compared to thermo graphic camera images as shown in Figure 12.

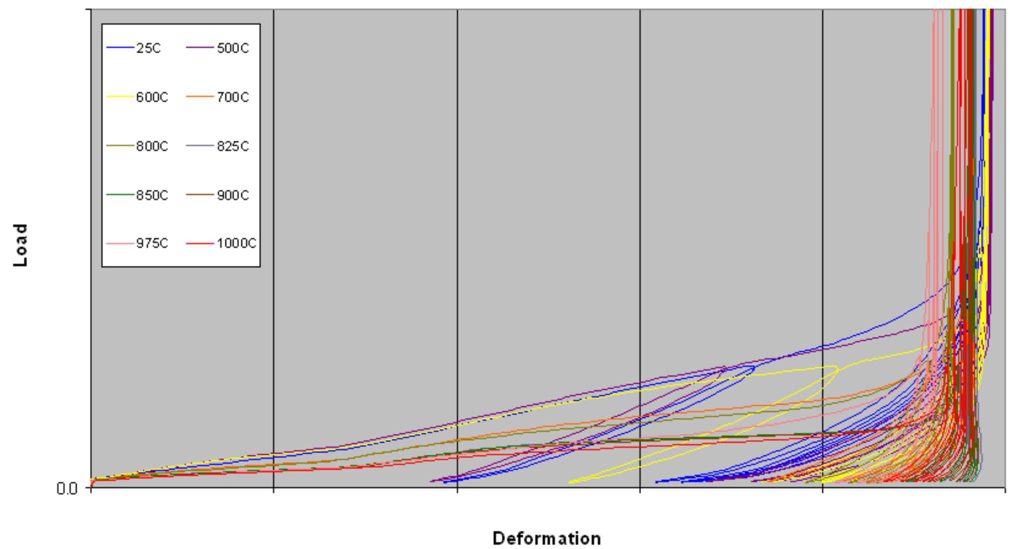

Figure 7: Load / Deformation behavior of a sealing bead at different temperatures

2.3 Testing for exhaust sealing systems

Testing for exhaust sealing systems plays an essential role in optimizing and correlating simulation results. The proper inputs must be provided to guarantee the best results. High temperature systems introduce additional testing requirements that are not generally considered for other applications. The challenges of evaluating material properties and component interaction at extreme temperatures require development of advanced testing techniques. In order to understand interactions and overall behavior of a thermal system, testing needs to be applied to all levels of the thermal system. Testing procedures can be divided into three main levels:

- Material
- Components
- Full systems.

Those levels need to cover the following techniques:

- Establish material properties
- Provide validation
- Correlation support.

Fretting and friction play a central role in the development of high temperature sealing solutions. The extreme changes in operating temperature can generally cause potentially damaging friction forces. These forces are introduced by thermal expansion and contraction and are magnified by the dissimilar nature of the joint and gasket materials. Most commercially available friction analysis procedures provide a low-temperature short-term result. A technique has been developed that involves evaluating the hysteresis of the friction forces and introduce a wear component to the testing. This is a requirement for understanding the wear behavior seen in exhaust sealing systems. It is necessary to understand how the friction coefficients behave over thousands of thermal cycles as surface conditions are altered due to mechanical wear. A thermal cycle is a relatively slow phenomenon. The best option for accelerating the cycle is to approximate the motion using mechanical methods. The entire fixture can be heated and cooled as required to induce the thermal changes in the materials. Figure 8 shows an image of the friction testing fixture. The friction forces must be sampled at a high rate to ensure a distinct output can be assembled that completely describes the friction curve hysteresis.

Figure 8: Friction Test Fixture

Temperature logging and control is an integral part of any high temperature testing system. In order to generate thermal maps a large array of thermocouples can be employed. An alternate method involves the use of thermal imaging. New imaging equipment and software allows for nearly infinite reference points compared to the relatively low limits of conventional data logging hardware. The thermal imaging system can record all visible areas of the hardware and gather transient thermal data. When this surface temperature data is combined with material properties and thermocouple measurements from within the hardware and exhaust stream, a highly accurate thermal map can be constructed. This helps to understand and predict thermal influences such as flange distortion and thermal-mechanical thresholds. The information is also used to identify the critical design areas for specific applications. Figure 9 illustrates the use of a thermal imaging system to measure surface temperatures of an exhaust system.

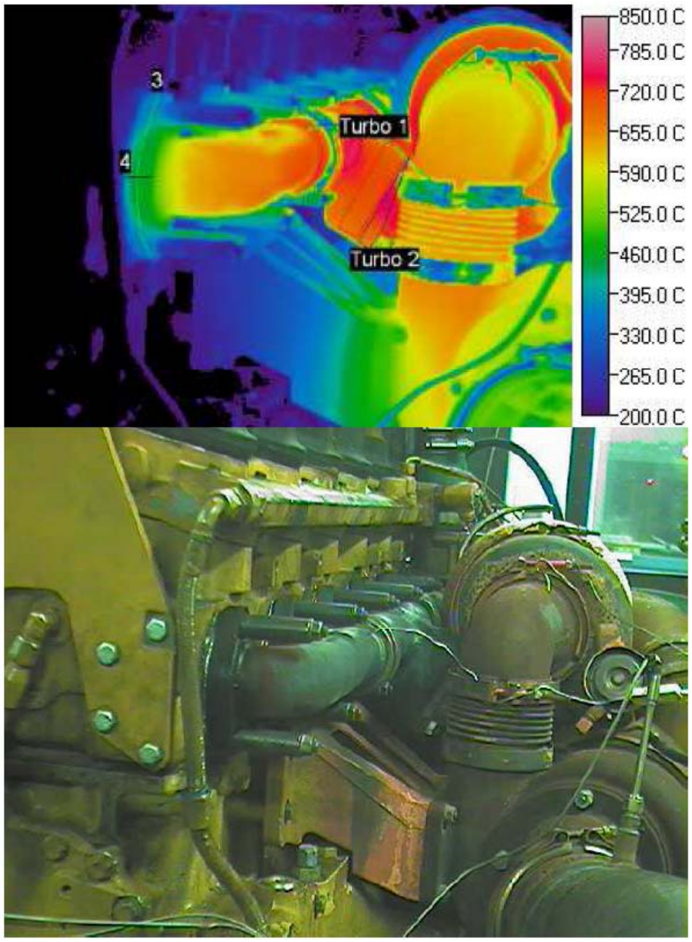

Figure 9: Thermal Imaging of an Exhaust System

Static lab testing allows for some of the most basic material input for simulation analysis. The challenge for exhaust systems is taking the industry standard test procedures and evolving them to be compatible with high-temperature equipment. A variety of thermal chambers are adapted to work inline with existing test equipment to make test setups more modular and adaptable for the needs of the specific operation. Special attention must be paid to the selection of materials used in the construction of fixtures and supporting equipment. Almost all test equipment used for evaluating exhaust systems must be customized since commercially available testing solutions are rarely compatible with the high temperatures dictated by the end-use applications. Additionally, most available systems are designed for tension testing, while gasket testing needs to be conducted under compression. This requires additional robustness of the test equipment materials, especially regarding creep initiation due to higher induced stress. Figure 10 shows an example of a high temperature furnace adapted for load frame compatibility and design for compression testing.

Figure 10: High Temperature Compression Testing Furnace

It is also necessary to perform dynamic evaluations in order to tie the material and component layers of testing into the overall system level. An engine test is the most common method used to evaluate the performance of exhaust gaskets. This type of test is very expensive and has low availability. It also has the disadvantage of narrow operational ranges and interdependency on other systems. The ultimate goal in high temperature exhaust testing is to have a test stand that can completely cover the most extreme ranges of engine operating conditions and to increase flexibility in terms of parameter setup. A dedicated exhaust test stand that can heat a stream of gas to temperatures higher than 1000ºC is employed to give the best results. Figure 11 shows a hot gas test stand setup and the test stand in operation to demonstrate the extreme temperatures produced during this test.

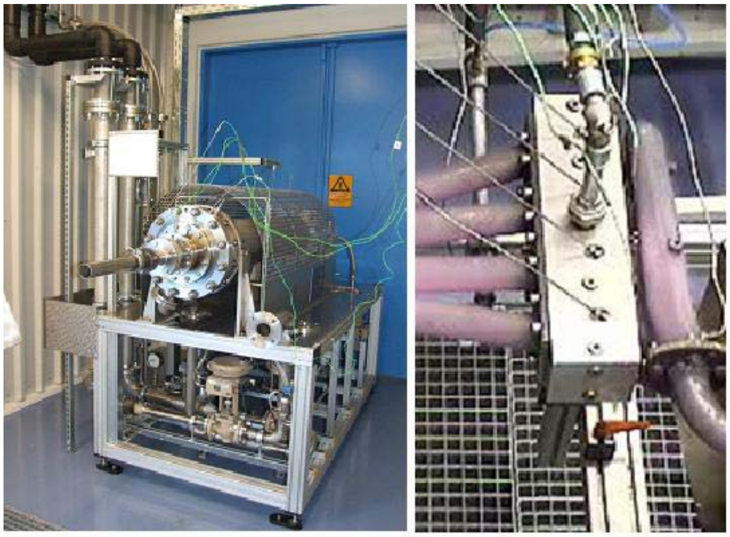

Figure 11: Hot Gas Test Stand and setup with glowing hardware

The stand is able to produce downstream pressures comparable to modern turbocharged exhaust backpressures. Mass flow rates greater than 1000kg/h are generated. This setup enables customization of test conditions well beyond that available in any single engine. This equipment is used to generate simulation input and also to verify results of the analysis. Figure 12 illustrates the use of hot gas testing and thermal imaging to verify FEA simulation results.

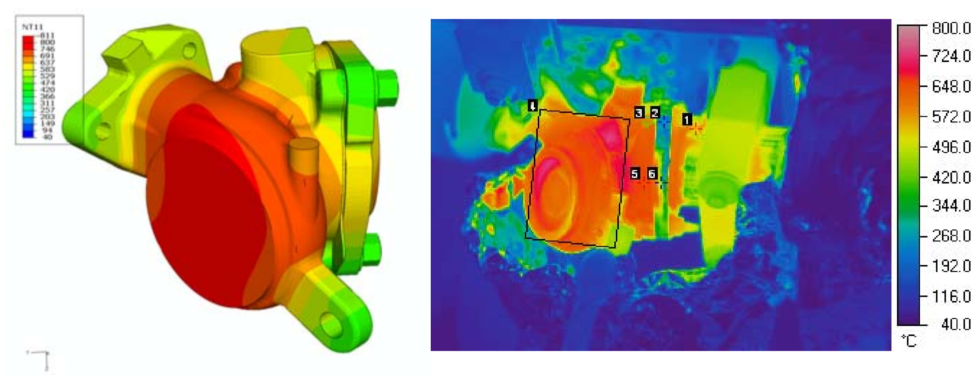

Figure 12: Thermal imaging test result with correlation to CAE

2.4 Data management

Management of the large amount of material data and analysis data is another area which needs to be addressed.

While simulation technology is constantly evolving to meet the demands of designers and engineers, there remains a wide disparity in the effectiveness of simulations to impact product/process design decisions. This disparity exists at multiple levels: across industry segments, across companies within an industry segment, across simulation disciplines (structural, fluid, chemical, etc.), within a company, and even across individual methodologies within a simulation discipline. The quest to markedly improve the efficiency and effectiveness of simulation remains a challenging but fundamental goal for many companies. [1]

The efficiency and effectiveness of simulation within a workgroup or enterprise is driven by several factors, including:

- Competency of the simulation technology and the people utilizing it
- Integration, adoption, and acceptance within standard business processes
- Capture, management and reuse of the resulting intellectual property.

A well-known data management tool in the industry is Product Lifecycle Management (PLM). PLM systems have evolved rapidly in recent years and now provide collaborative Virtual PLM of complex product, process, and resource information - from marketing and design to manufacturing and maintenance. The requirements of simulation technology, methods, data and processes are in many ways more demanding than those associated with PLM, including:

- Data Model
- Performance
- Context.

The emerging attention focused on improving simulation effectiveness within PLM and scientific environments, is referred to as Simulation Lifecycle Management (SLM) [1]. This covers the different disciplines involved in the thermal management / system approach.

The data, for example generated through simulation can be divided into 3 main categories [2]:

- Data directly supporting product / process IP (intellectual property)
- Data supporting simulation IP
- Un-retained data.

The degree of integration across the simulation and product/process worlds will vary with organizational type and structure and is driven by a number of factors, but there are several critical principles that must be adhered to achieve the full benefits SLM can deliver. At its core, an SLM solution must have been designed from the outset to possess the appropriate architecture to satisfy the integration, deployment and maintenance demands of a broad and constantly changing set of information technology (IT) environments. Four functional elements that an effective solution must provide are [2]:

- Built-in Collaboration
- Simulation Data Management
- Process Automation, Integration and Optimization
- Decision Support.

The aspects described in this paper regarding a thermal management approach and its detailed complexity epitomizes the need for an SLM system. By collaborating with SIMULIA on developing and implementing SLM and developing specific features for our business needs will provide us with the necessary tools to guarantee a functional system approach for the future. This is not just from a simulation but also from a management perspective. By studying the SLM architecture and the needs of our approach we can ensure, from the outset that all our structural, data and documentation requirements are met and future proofed.

2.5 Conclusion

A comprehensive "Thermal Management / System Approach" has been developed to better reflect the complexity of an exhaust / after treatment system for automotive and heavy duty applications. This approach covers all the different stages during development from design concept over optimisation and validation to correlation of simulation results. It provides an improved understanding of why simulation cannot exist in isolation but needs to be combined with a basic understanding of the exhaust system, the generation of material properties and the evolving experimental testing techniques. None of these elements can exist in isolation they must complement and interact with each other to make sure that the final proposed design can meet the highest functional and quality standards, as well as providing the best tools to meet the "first-time-right" goal.

It was also shown that because of the complexity of this approach on all levels there is a need for a new data management approach. This can be realized by implementing SLM technology. It provides more than just a "classical" data management approach by offering greater efficiency and smarter simulation IP with its different layers of engagement, it helps to use the data based on the need of response. Not only has the analyst benefited from its structure but also the entire engineering team and management where the data can be used for decision making.

We are aware that there are still a lot of tasks to be accomplished for the fine-tuning of this approach and implementing some of the features. The success achieved so far and from customer feedback for this approach it is clear that this is the future for continued development and a route for competitive advantage.

References

1. SIMULIA: The Case for Simulation Life Cycle Management; report 1 of 3; White Paper
2. SIMULIA: The Case for Simulation Life Cycle Management; report 2 of 3; White Paper