



EFFICIENT AND ACCURATE MODELING OF HEAT TRANSFER IN AN ENGINE HEAD AND BLOCK

Convergent Science White Paper

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INTRODUCTION

To ensure the longevity of internal combustion engines in the adverse conditions to which they are subjected, engine designers must carefully consider the thermal and structural stresses that affect the critical components of the device. Because of the combustion process that occurs in the engine cylinder, it is critical to study the thermal stresses that exist in the vicinity of the cylinder. Analyzing the temperature distribution in the solid cylinder head is an important part of determining the durability of the engine.

Predicting such a temperature distribution during the design phase helps engineers create a reliable and efficient product. While experimental test devices provide useful results for the temperature distribution in the solid, computational fluid dynamics (CFD) offers the ability to accurately calculate a pointwise temperature distribution in these solid metal components with higher spatial resolution.

Fuel spray, charge ignition, combustion, and turbulence all affect the combustion and heat transfer in the engine. Due to the inherent nature of conductive and convective heat transfer, the time-scale for heat transfer in the solid metal is much greater than the time-scale for solution of the transient fluid dynamics in the engine cylinder. CONVERGE CFD includes several features that address these computational challenges. A detailed chemical kinetics solver accurately models the combustion dynamics in the engine cylinder, yielding accurate near-wall gas temperatures for the surfaces exposed to combustion. Efficient conjugate heat transfer techniques quickly calculate converged solid temperature distributions for combustion simulations. A robust steady-state solver rapidly resolves coolant-solid heat transfer. Surface mapping techniques obviate modeling combustion in all cylinders, accelerating the simulation. Combining these features results in an efficient methodology for predicting accurate solid temperature distributions in just a few engine cycles.

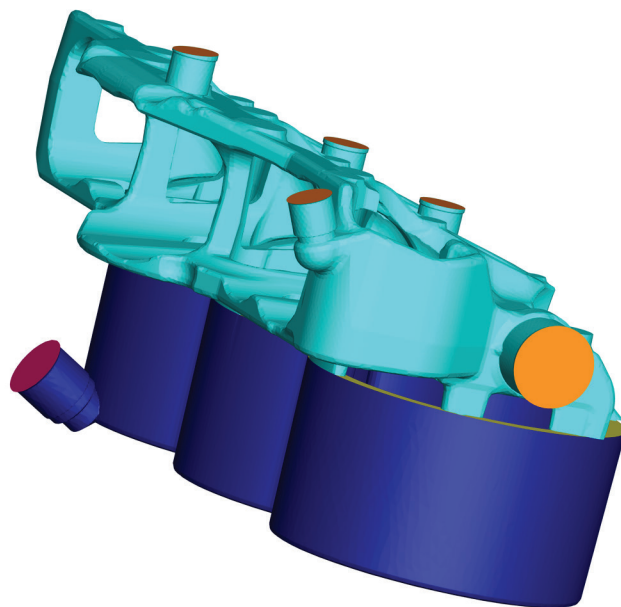


Figure 1: Geometry for the simulation of coolant flow.

OVERVIEW

CASE DESCRIPTION

For this case, the geometry is half of a V6 engine including the engine head and block. The solid components are the liner, head, block, valves, valve seats, and valve guides. We treat the valves as moving solid components. The piston, however, is simply a moving surface with appropriate boundary conditions.

OPTION 1: ENGINE BLOCK AND COMBUSTION GAS – WATER JACKET

In CONVERGE, you can combine several powerful features to accelerate your simulations and obtain accurate results. Because the time-scales of combustion, heat transfer in the solid components of the engine, and heat transfer in the coolant can vary widely, splitting the study into two separate simulations (coolant flow and combustion) allows optimal settings for the coolant and chamber simulations to enhance simulation accuracy and speed.

The CONVERGE methodology involves running two separate simulations and mapping results between the two to obtain converged temperature predictions. The first of the two simulates the coolant flow and the heat transfer between the liquid coolant and the solid materials of the engine head. The second simulation is a conjugate heat transfer simulation that models the combustion process and heat transfer between the combustion chamber and the engine block and head. Since we iterate between these separate simulations, after running the combustion simulation, we obtain spatially varying wall temperatures to use as boundary conditions in the coolant simulation. The coolant simulation provides heat transfer coefficients (HTC) and near-wall fluid temperatures for the appropriate solid boundaries of the combustion simulation.

DETAIL: SIMULATION OF COOLANT FLOW

In this engine coolant system (shown in Figure 1), the coolant is a 50/50 ethylene-glycol and water mixture with a mass flow rate of 24 *gpm*. We model this liquid as single-phase and use the Rohsenow model to account for nucleate boiling.

To account for the effects of combustion, this simulation uses spatially varying wall temperatures mapped from the combustion simulation. The surface geometry consists of only the engine coolant system.

As with any simulation, CONVERGE automatically generates a Cartesian grid at runtime. Patented efficient cut-cell techniques create a body-fitted mesh. To improve accuracy, Automatic Mesh Refinement (AMR) refines the grid during the simulation in regions of high velocity gradients to help capture relevant physics. Also, grid scaling increases the resolution at specific times in the simulation. In the coolant simulation step, this allows some initial unsteadiness in flow quantities to settle before refining the grid.

DETAIL: COMBUSTION CHT SIMULATION

In the combustion simulation, CONVERGE uses the SAGE detailed chemistry solver for the chemical kinetics that occur during combustion. SAGE calculates the reaction rates for elementary reactions (described in a supplied mechanism file) to model combustion of the fuel. Figure 2 shows the combustion simulation domain, which in this case includes the solid.

As is typical in a CONVERGE combustion simulation, the piston, intake valves, and exhaust valves move throughout the simulation. CONVERGE employs the automated cut-cell Cartesian meshing technique to account for this motion without manual mesh generation. Thus, engineers can focus primarily on the physics of flow and heat transfer.

CONVERGE includes conjugate heat transfer capabilities to compute fluid-solid heat transfer. As mentioned above, a typical computational challenge is that the time-scale of conductive heat transfer is generally much greater than that of convective heat transfer and the transient phenomena occurring within the engine cylinder and ports. To address this issue, the super-cycling capability in CONVERGE iterates between fully-coupled transient and steady-state solvers to accelerate the solution of the temperature field in the solid. This helps achieve a steady-state in the solid metal with fewer engine cycles.

During super-cycling, CONVERGE solves the fluid and solid heat transfer together in a fully coupled manner using the transient solver, periodically freezes the fluid solver to solve for an updated steady-state solid temperature, and then continues solving for the fluid and solid using the transient once again. This procedure repeats at user-specified intervals specified to allow the solid temperature to rapidly reach a steady-state condition. At this point, any changes to the solid temperature are due to rapid transient interactions with the localized combustion and flow events instead of from the slower overall warming of the solid.

To reduce the computational effort of combustion modeling in multi-cylinder engine applications, CONVERGE includes a super-cycle mapping capability. The engine case described in this paper is half of a V6 engine—three cylinders. While modeling combustion with SAGE in all three cylinders is highly accurate, it may unnecessarily slow the simulation. Instead, if we are willing to assume that combustion behaves in a similar manner in all cylinders, then super-cycle mapping can be used to map heat transfer coefficients and temperatures from combustion in one cylinder to the other two cylinders.

Configuring super-cycle mapping involves specifying a main cylinder in which SAGE models combustion and the duplicate cylinders onto which CONVERGE maps the heat transfer data. During the super-cycling process, when the fluid solver freezes, CONVERGE maps the cycle-averaged heat transfer coefficient and near-wall fluid temperature of the fluid-solid interface boundaries in the main cylinder to the corresponding boundaries in the duplicate cylinders. This way, the surrounding solid material in these cylinders experiences the appropriate heat load.

In this scenario, an exhaust manifold connects the three full cylinder geometries. Since combustion is not directly simulated with SAGE in the duplicate cylinders, the gases in the duplicate cylinders must be appropriately heated to obtain the appropriate heat load in the exhaust manifold during the exhaust process. To approximate combustion in the duplicate cylinders, we specify a heat release source that mimics the effects of combustion within those cylinders. At exhaust valve opening, the blowdown and exhaust processes occur, where energy is exchanged between the exhaust gases and the surrounding solid of the exhaust manifold. Thus, including all the cylinder geometries helps improve the simulation accuracy by including energy exchange in the exhaust manifold. As the CONVERGE simulation includes moving valves with the appropriate solid temperature distributions, the accuracy of the energy exchange process during the open cycle is substantially improved.

The combustion simulation also employs AMR. In addition to velocity AMR (discussed previously), we activate temperature AMR to refine the grid in areas of high temperature gradients due to combustion.

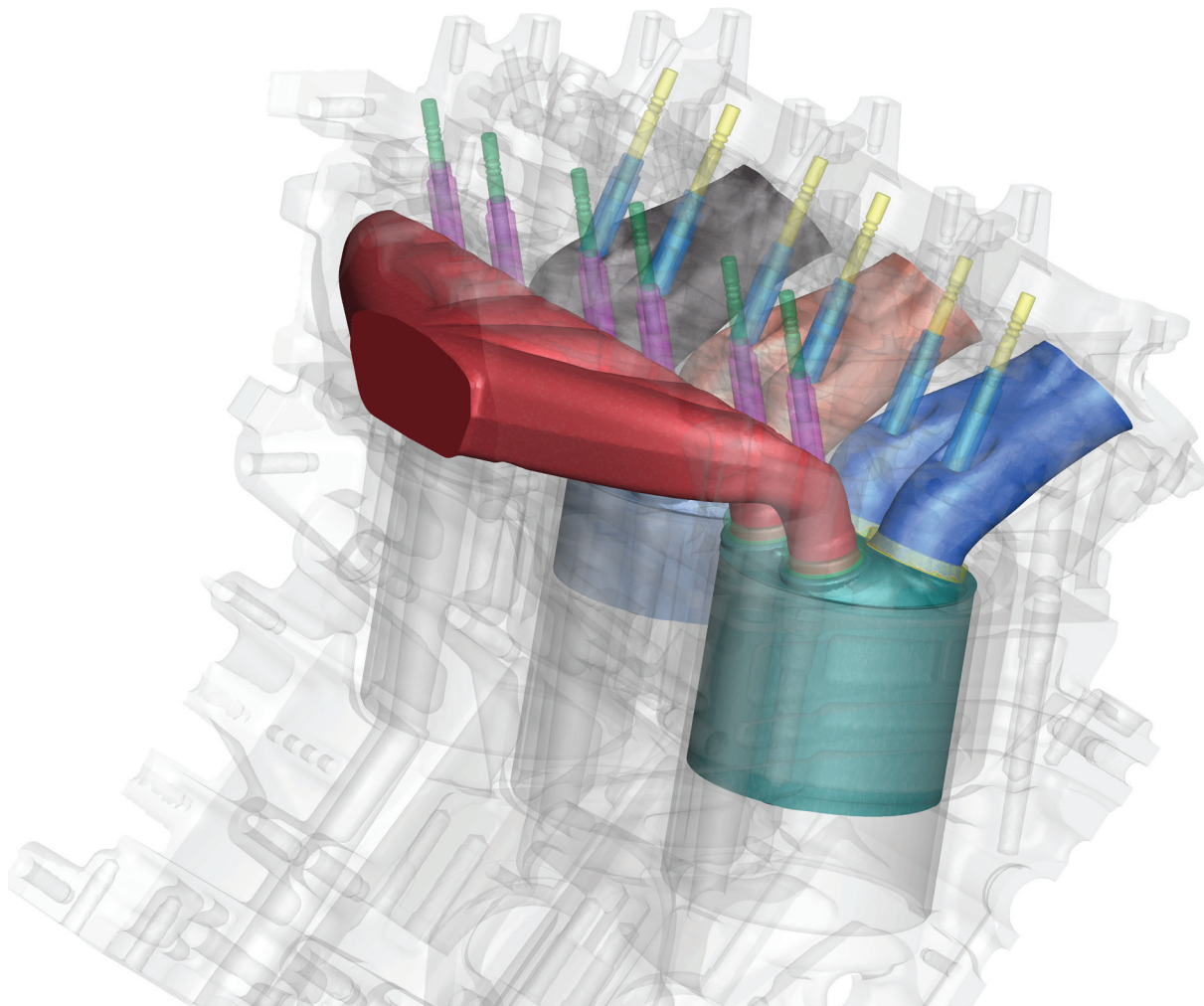


Figure 2: Geometry for the combustion simulation.

OPTION 2: ENGINE BLOCK AND WATER JACKET—COMBUSTION

A second approach commonly employed in the automotive industry also involves iterating between two simulations. To efficiently determine the requisite solid temperature field, engineers first perform simulations modeling combustion (which may take longer to run) in the engine cylinder and then perform a CHT simulation modeling heat transfer between the coolant and the solid material. This approach couples the engine cylinder and coolant simulations via the heat flux at the combustion chamber wall. The work of Iqbal et al. presents a detailed discussion of this approach¹.

The combustion simulations yield detailed temporally and spatially resolved convective boundary conditions, which consist of the heat transfer coefficient and gas temperature adjacent to the wall. The coolant-solid CHT simulations use the convective boundary conditions from the combustion simulation to apply the heat load to the solid walls of the combustion chamber. In the same manner as the methodology for Option I, we repeat the pair of simulations with information exchange between them: the coolant-solid CHT simulation takes HTC and near-wall fluid temperatures from the combustion simulation and the combustion simulation takes boundary temperature from the coolant-solid CHT simulation.

As described for Option I, this approach employs the SAGE detailed chemistry solver for the combustion simulation. At the first outer iteration, the combustion simulation begins with uniform temperatures on the solid walls and produces cycle-averaged spatially varying convective boundary conditions as described above.

In the second step of the iterative process, the solid geometry is entirely stationary. The intake and exhaust valves are included in the model but are held fixed in the closed position to account for conductive heat transfer to the cylinder head with a fixed contact resistance. Solid surfaces that are exposed to the combustion gases have convective boundary conditions as calculated in the combustion simulation. Again, as with Option I, the conjugate heat transfer functionality in CONVERGE couples the fluid-solid heat transfer, this time between the coolant and the solid.

One additional complexity of the Option 2 methodology is that the combustion simulation does not include the gas exchange between all three cylinders and the exhaust manifold (a phenomenon that Option I accounts for). In the work of Iqbal et al., researchers performed a separate simulation to obtain the cycle-averaged spatially varying convective boundary conditions in the exhaust manifold for use in the conjugate heat transfer simulation. For Option 2, we use data from the Option I simulation to provide these boundary conditions.

RESULTS

CONVERGE produces output that includes a set of results describing the temperature distribution in the solid material of the engine as well as the velocity and temperature fields in the coolant and combustion gases. After a suitable number of iterations (typically three outer iterations are required) of either of the above approaches (*i.e.*, when temperatures and the associated heat transfer rates reach a steady-state), we can analyze the results and compare with experimental data.

Figures 3 and 4 show normalized metal surface temperature distributions on the coolant passage surface and the combustion side surfaces, respectively.

Figures 5 and 6 compare normalized metal temperatures on the intake side and exhaust side, respectively, between experimental thermocouple data, Option 1, and Option 2. In general, the CONVERGE results from both options shows good agreement with the experimental data.

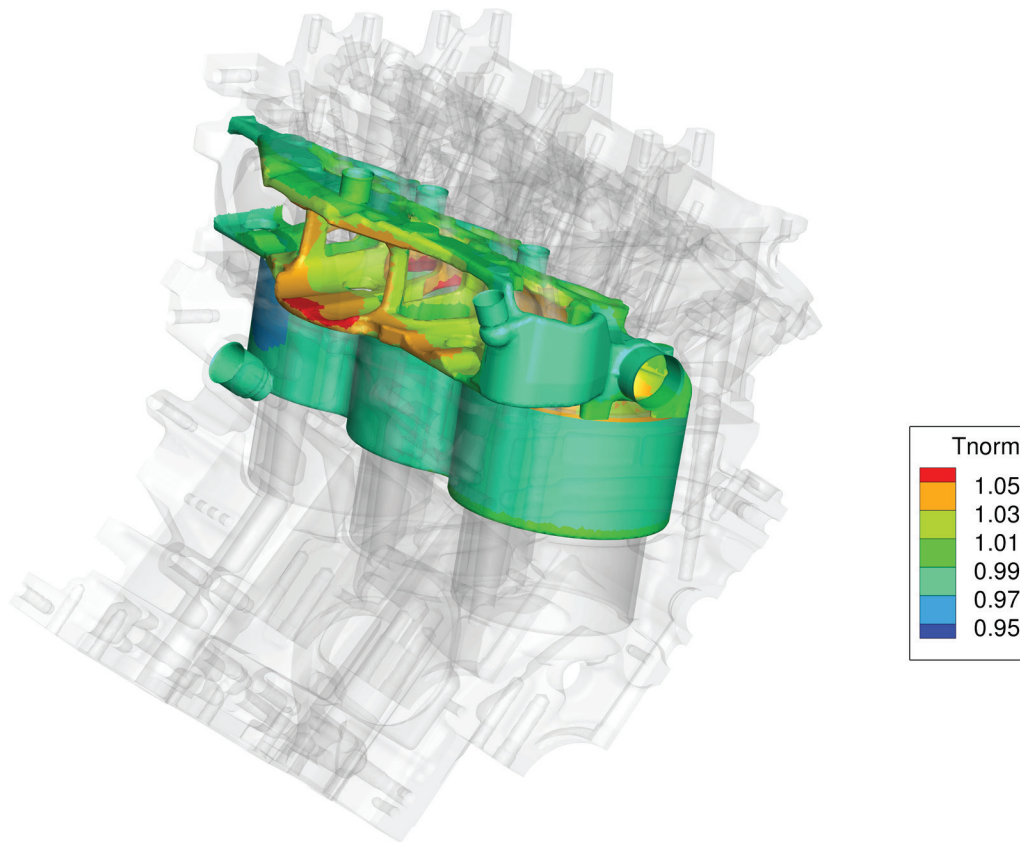


Figure 3: Normalized surface temperature distribution (coolant passages).

For temperatures on the intake side, Option I and Option 2 had mean absolute error of 8 K and 7 K, respectively. The RMS error was approximately 6 K for both Option I and Option 2. For temperatures on the exhaust side, Option I and Option 2 had mean absolute error of 4 K and 3 K, respectively. The RMS error was around 3 K for both Option I and Option 2.

The data clearly show that the three-dimensional calculations performed in CONVERGE provide accurate spatially resolved temperature distributions in critical solid components of the engine.

For approximate runtimes (per outer iteration), Option I required about 2400 core-hours for the engine block and combustion gas simulation and almost 400 core-hours for the coolant flow simulation. Option 2 required 150 core-hours for the engine block and coolant simulation and almost 750 core-hours for the combustion simulation.

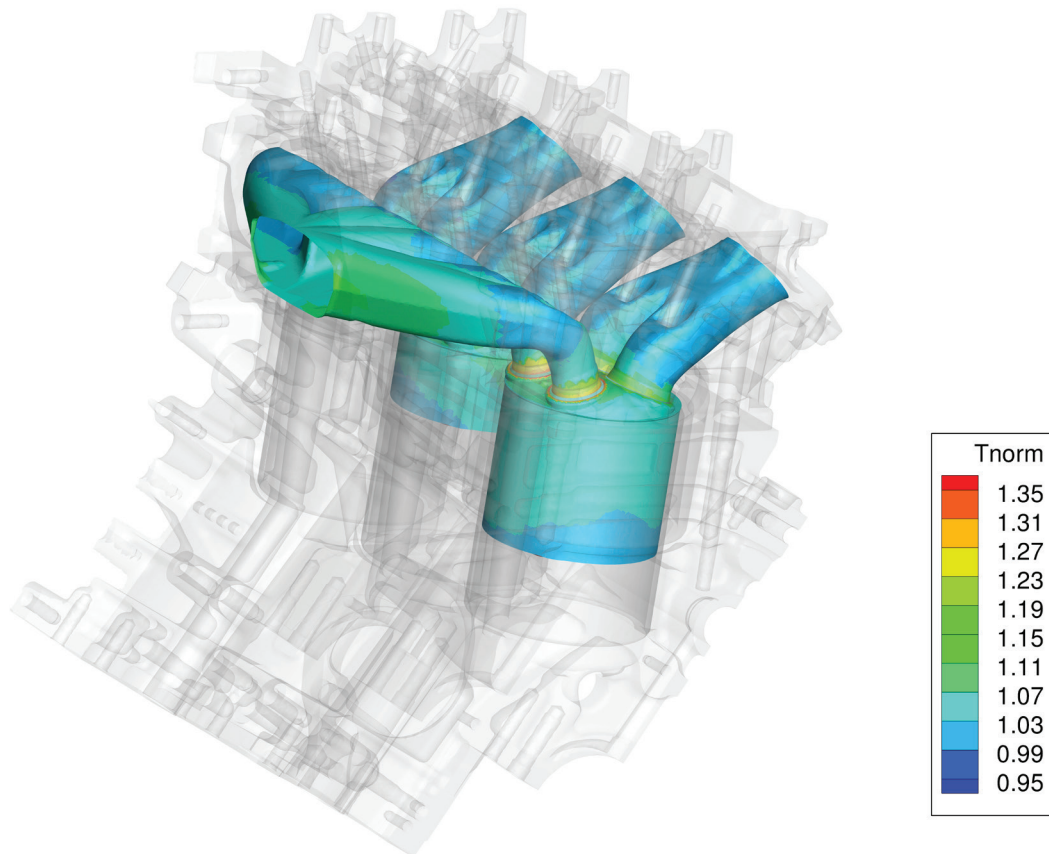


Figure 4: Normalized surface temperature distribution (combustion side).

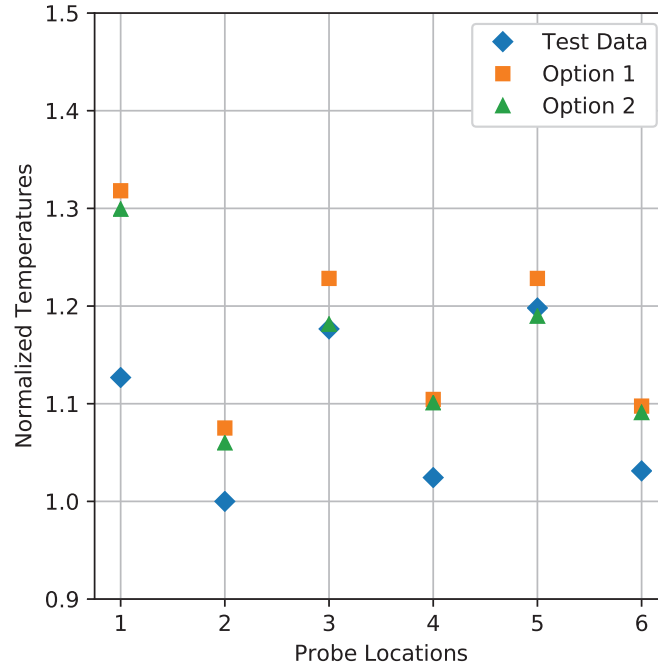


Figure 5: Non-dimensionalized results comparing CONVERGE results with experimental data for intake side temperatures.

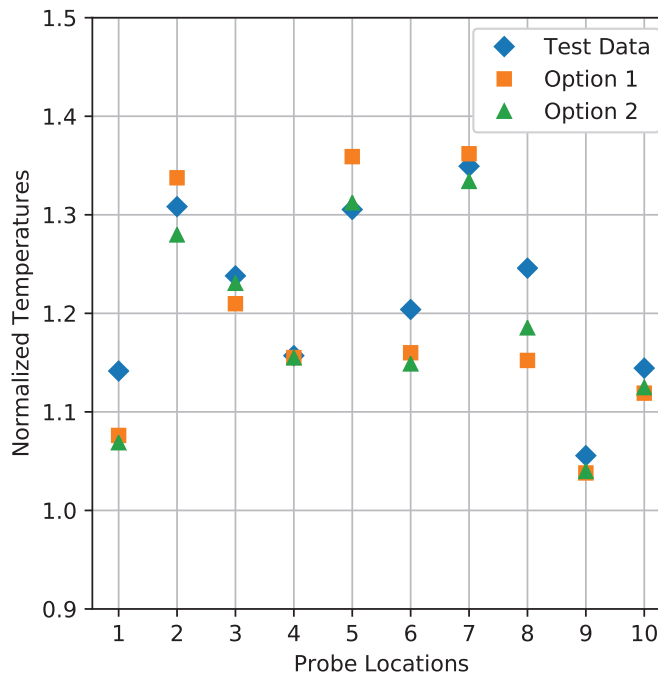


Figure 6: Non-dimensionalized results comparing CONVERGE results with experimental data for exhaust side temperatures.

CONCLUSION

For a more comprehensive prediction of heat transfer in solid portions of the engine, CFD engineers must be able to accurately capture the heat transfer between combustion gases in the cylinder and ports, the solid metal of the engine head and block, and the liquid coolant flowing through the engine head and block. Additionally, for this type of prediction to be viable in an industrial scenario, the computational tools must easily integrate with existing workflow and produce results in a reasonable amount of time.

The two iterative approaches in CONVERGE as described above combine the accurate and detailed simulation of combustion kinetics with conjugate heat transfer to develop a realistic temperature distribution in the solid components of an engine. With CONVERGE, engineers can now more efficiently include the details of gas flow, combustion, and coolant flow to predict the temperature field for optimal design of solid engine components without the additional complexity of building a mesh.

REFERENCES

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Founded in Madison, Wisconsin, Convergent Science is a world leader in computational fluid dynamics (CFD) software. Its flagship product, CONVERGE, includes groundbreaking technology that eliminates the user-defined mesh, fully couples the automated mesh and the solver at runtime, and automatically refines the mesh when and where it is needed. CONVERGE is revolutionizing the CFD industry and shifting the paradigm toward predictive CFD.

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