A Co-Simulation Approach to Model the Thermal Behavior of Automotive Vehicles During Dynamic Driving Cycles

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1 Introduction

In addition to well-established steady state thermal simulations for full vehicles the prediction of temperature distributions in space and time for dynamic driving cycles (e.g. race track, uphill driving, etc.) comes to the center of attention. An entire transient simulation of these sequences is most accurate but also associated with high computation times. In order to reduce the computational effort several methods have been proposed in literature, most of them applying quasi-transient approaches. In the scope of this work a reduced test model was created and several methods to account for a dynamic driving cycle (race track) were applied and the results are compared with full transient coupled solutions. As simulation software STAR-CCM+ (fluid flow), TAITherm (radiation and solid body heat conduction) and MpCCI (coupling) were applied.

2 Simulation Procedure and Model

Concerning transient thermal problems in vehicle development, a complete transient conjugate heat transfer simulation or a transient coupled approach (Fig.1a) generate certainly the most accurate temperature distributions. Due to the large size of full vehicle models, the computation times are rather high depending on the temporal fluctuations respectively the time step size. There are developments in automotive industry for quasi-transient approaches where the convective heat transfer (fluid flow) is modeled in a stationary way, whereas solid heat conduction and radiation are modeled in a transient manner. Disch [1] proposed a method (referred here as DIQUTRANS) in which stationary fluid flows updated with current wall temperatures are attached to a transient solid body heat conduction and radiation simulation at certain time intervals Δt_{couple} (Fig.1b). The fluid flow is iterated until convergence and the convective boundary conditions (heat coefficient, film temperature) are returned to the solid body model (e.g. in STAR-CCM+ or TAITherm).

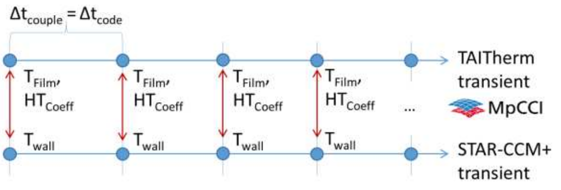

Fig.1a Full transient coupled approach (FUTRANS)

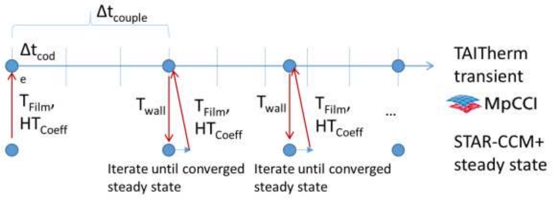

Fig.1b Quasi-transient approach of [1] (DIQUTRANS)

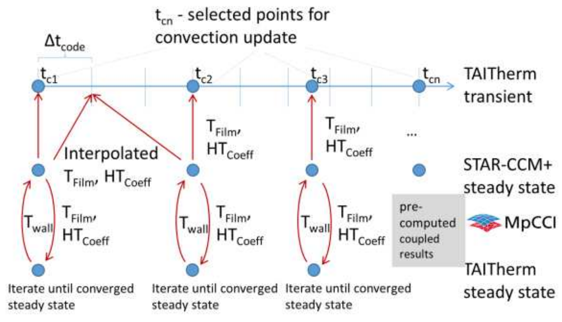

Fig.1c Quasi-transient approach of [2] (HAQUTRANS)

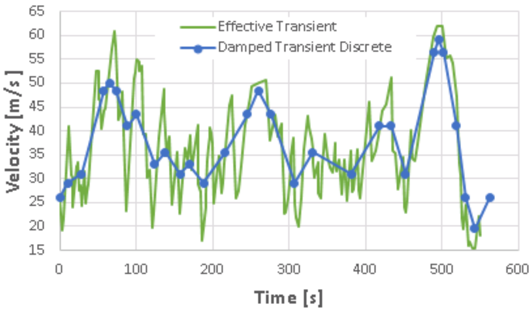

Fig.2 Race-track driving velocity [2]

Haehndel et al. [2] [3] proposed a different approach (here referred as HAQUTRANS) where convective data for certain driving conditions, e.g. certain driving velocities, is determined in pre-coupled stationary solutions. To reduce the computational effort, the driving velocity profile is damped [2] and discrete time points are defined (Fig.2 blue dots), where the convective data is determined. Intermediate convective conditions are interpolated and in case of recurring velocities convective data can be reused.

In order to reduce the computational costs, the here considered simulation model was reduced to an exhaust part with heat shields, floor, drive shaft and a small unconnected part of the rear axle. The latter is only heated or cooled by convection and radiation and not by solid body conduction. In STAR-CCM+ the inlet velocity is determined according to Fig.2. For FUTRANS and DIQUTRANS the effective velocity was used and for HAQUTRANS the velocity sampling points of the damped profile were applied. The inlet temperature was set to 80°C. In TAITherm the exhaust flow was modeled with seven fluid nodes and a transient exhaust temperature and mass flow similar to [3] (Fig.4). The whole simulation time was one race track lap of 550s. The two simulations codes were coupled with the MpCCI CouplingEnvironment.

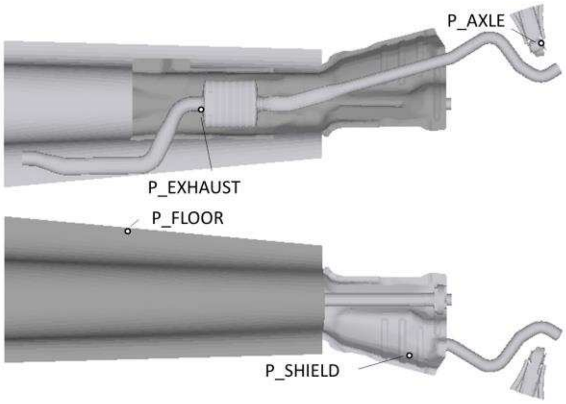

Fig 3 TAITherm model with evaluation points

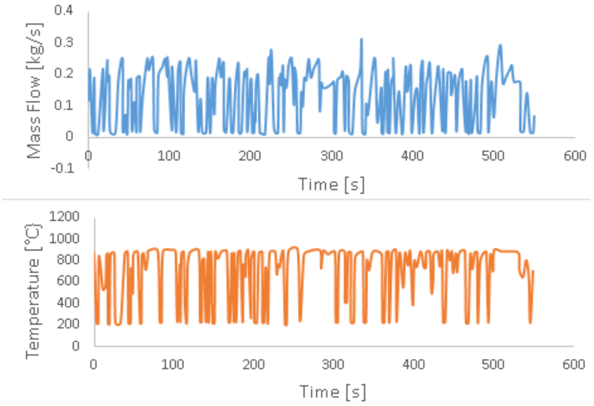

Fig.4 Exhaust mass flow and temperature

3 Simulation Results

First of all, two transient simulations (FUTRANS) using a parallel coupling of transient STAR-CCM+ and transient TAITherm with an identical time and coupling step of 0.5s and 1.0s each were accomplished and compared. A typical footprint of the exhaust system on the heat shields and floor panel is depicted in Fig.5. Looking at the temporal temperature distribution at the four evaluation points in Fig.3, there was no essential difference, only small variations as exemplarily showed for the heat shield in Fig.6.

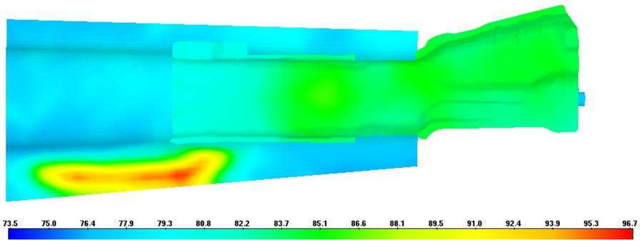

Fig.5 Typical temperature footprint on shields and floor from exhaust pipe (t=20s)

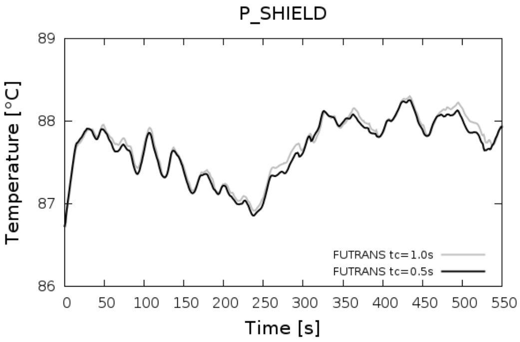

Fig.6 Comparison of two full transient simulations with different time-steps (FUTRANS)

That followed simulations of type DIQUTRANS (Fig.1b) with a coupling interval Δt_{couple} of 10s and 15s. Both simulations resulted in a fair approximation of the temperature distributions. Expectedly a shorter coupling interval of 10s revealed a higher accuracy. Concerning the HAQUTRANS simulation procedure, it is not quite clear from literature how to handle exhaust boundary conditions for repeated use of convective data for same velocities but different time points. E.g. one can find 48.5m/s at 57s, 73s and 260s (Fig.2), but looking at different velocity recurrences it is noticeable, that the exhaust values for mass flow and temperature are not compulsorily identical. It the scope of this work the values were varied. Average exhaust temperature and mass flow values for all velocities showed the most reasonable results compared to the full transient simulation. In Fig.7 the results of the DIQUTRANS, HAQUTRANS and FUTRANS simulations are depicted. The temperature course on the exhaust pipe (P_EXHAUST) is quite well approximated concerning the different convective approaches, although the amplitudes of the HAQUTRANS procedure are rather excessive. Looking at the floor temperature (P_FLOOR) both procedures show the approximation to the course progression of the full transient simulation, again a better estimation of the DIQUTRANS method. Concerning the heat shield (P_SHIELD) and the axle part (P_AXLE) HAQUTRANS cannot really satisfy the temperature trend, whereas DIQUTRANS appears to be able to fit reasonably the FUTRANS course progression. It should be noted, that the temperature for P_AXLE and P_SHIELD does vary merely in a small range at all, so that errors are more recognizable. The improper wall temperatures due to the pre-computed stationary coupled simulations not considering the thermal history, might be a reason for these discrepancies.

As already mentioned the reason for applying the quasi-transient methods originated from avoiding high computational times, therefore one has to be careful when choosing a quasi-transient approach not to exceed the full transient simulation costs by defining too many stationary convective hooks. For example had DIQUTRANS with Δt_{couple}=10s and FUTRANS with a time-step of dt=1.0s approximately the same computational time. Due to the reuse of pre-computed simulation results for repeated driving velocities the simulation run-time using HAQUTRANS could be reduced by 50% compared to DIQUTRANS.

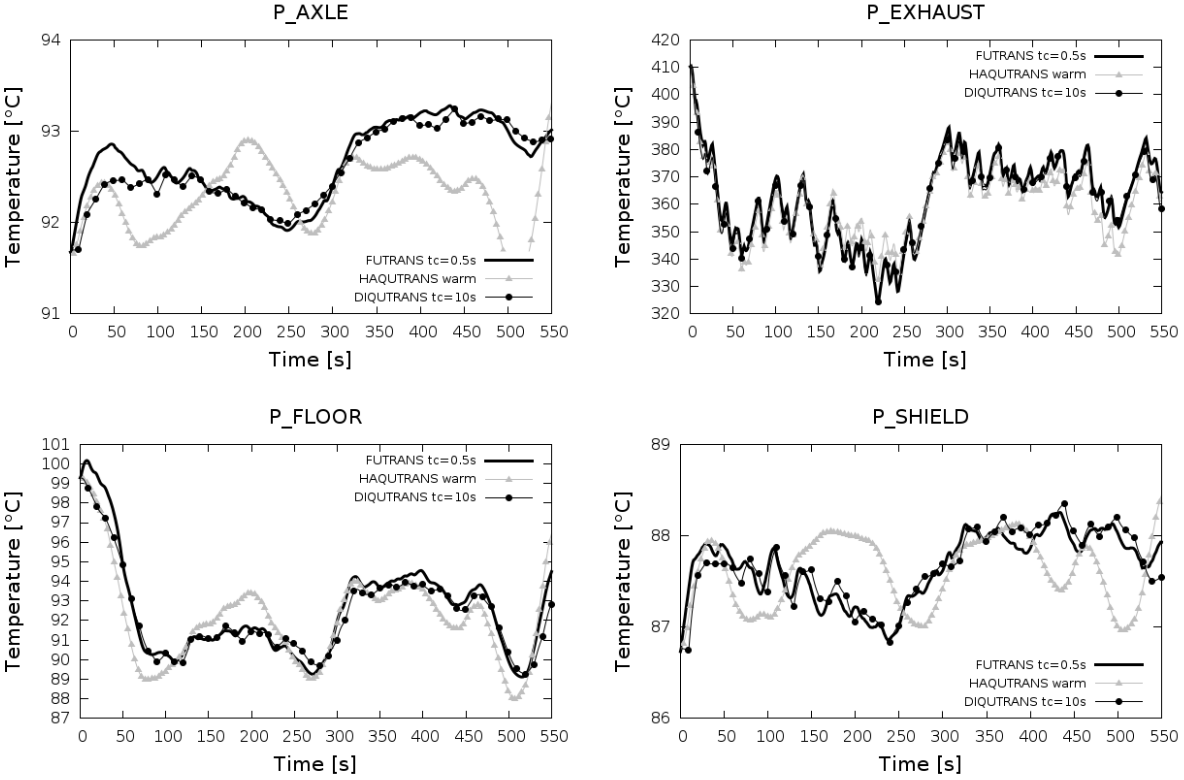

Fig. 7 Temperature distributions at evaluation points comparing simulations of type FUTRANS, DIQUTRANS and HAQUTRANS

4 Conclusions and Outlook

In the present work two quasi-transient methods for transient thermal simulations regarding motor vehicles were applied to a test model and compared with a coupled simulation where both codes run in a transient manner. In the DIQUTRANS approach following [1] after certain time intervals stationary flow simulations (STAR-CCM+) with a present driving velocity were provided with present wall temperatures of the solid parts (TAITherm). The iterated flow data was then used in TAITherm as convective boundary condition for this interval. This procedure showed a good agreement of the temperature distribution for the selected evaluation positions but with shorter convection update intervals the simulation time was still high. Regarding the HAQUTRANS approach following [3] stationary coupled solutions with STAR-CCM+ and TAITherm were pre-computed for distinct driving velocities. For recurring velocity conditions during the driving cycle the generated data was reused to reduce the computational costs. The convective data was then hooked to a transient standalone TAITherm simulation. The HAQUTRANS results showed less accuracy compared to DIQUTRANS, however revealed a significant reduction of the computational time.

Continuative, the described procedures should be applied to further test models. In addition, the obtained experience in handling the quasi-transient methods will be integrated in enhancements for the MpCCI CouplingEnvironment to enable users to accomplish suchlike simulations in a more straightforward, automatic and efficient way.

5 References

[1] Disch, M., „Numerische und experimentelle Analyse von instationären Lastfällen im Rahmen der thermischen Absicherung im Gesamtfahrzeug“, Wissenschaftliche Reihe Fahrzeugtechnik Universität Stuttgart, Springer Fachmedien Wiesbaden, 2016

[2] Haehndel, K., Pere, A., Frank, T., Christel, F. et al., „A Numerical Investigation of Dampening Dynamic Profiles for the Application in Transient Vehicle Thermal Management Simulations", SAE Technical Paper 2014-01-0642, 2014

[3] Haehndel, K., Frank, T., Christel, F., and Abanteriba, S., „An Innovative Approach to Race Track Simulations for Vehicle Thermal Management," SAE Int. J. Passeng. Cars - Mech. Syst. 6(3):2013