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RESEARCH ARTICLE

Thermal Examination of a Simplified Exhaust Tube-Heatshield Model

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Abstract
Exhaust system and its surrounding is a thermally highly critical part of a vehicle: during forced operation, hottest elements can reach 600 °C. The thermal conditions turn to even more critical if the forced flow leaves off – e.g. when the car stops at a highway parking place. In such a case not only the cooling effect of cross-flow disappears, but the natural convection starts to bring heat toward nearby elements – resulting potential overheating of concerned parts. A measurement setup for modelling such case was built, and different parameters were examined, which have influence on the heating of aluminium heatshield above the exhaust tube. Measurements were complemented by CFD simulations and flow visualization technique aiming the better understanding of evolving thermal and flow conditions.

Keywords
exhaust system, thermal examination, CFD

1 Introduction

During the development of vehicle thermal- and energy-management the design and optimization of exhaust system and its surrounding is a challenging task. The importance of this process is emphasized by the fact, that 30 40 % of the total chemical energy fed into an internal combustion engine (ICE) escapes through the exhaust system with the exhaust gases – as thermal energy (Vijay et al., 2016). By an average passenger car it can result in more than 25 kW thermal power beside high operational load, which equals the average heating power of 20 households (EU, annual average – Lapillonne et al., 2015). Such thermal load can lead to temperatures higher than 600 °C in the elements of exhaust system, which generates significant thermal load for the neighbouring elements too. A slim aluminium heatshield is dedicated to protect the modestly heat resistant elements from extreme temperatures. Consequently, the thorough recognition of thermal and flow mechanisms around the exhaust line in a loaded engine state is essential; which gives the opportunity of optimizing the location, size and surface of heat shielding elements as well as improving the thermally critical areas. Furthermore, numerical flow- and thermal simulation of such area is challenging as well – reliable results can be expected only after detailed validation. This work will be supported too by the newly constructed experimental setup.

2 Measurements

2.1 Measurement system setup

In our previous works (Vehovszky et al., 2016; Schuster et al., 2016) a simplified measurement setup was presented, consisting of a tube and a concentric half-tube – corresponding to the exhaust tube and the heatshield, respectively. The same basic layout was used, but the system was significantly improved, and the following modifications were carried out to ensure wider range of applicability:

- Heating with electric heating insert (instead of hot air) resulting lower heating power, better temperature control and constant temperature alongside the tube. (Around 25 kW heating power would be necessary if hot air was used as heating media – modelling the operation of a car

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– as described in the introduction section. Instead, 7.5 kW power is enough for the electric heater to reach the required temperatures easily).

- Exhaust tube surface temperature can be heated up to even 650 °C – enabling us modelling the extreme case, when thermal radiation become significant compared to heat transfer via natural convection.
- Quasi 2D flow field was designed by using parallel endplates – by eliminating longitudinal flows, simulations and measurements become simpler and more reproducible as well.
- Feedback temperature control of the exhaust tube surface ensures constant tube temperature beside different examination conditions – e.g. upside-down position, black tube surface etc. Without feedback control (beside constant heating power) these conditions would have measurable effect on the tube surface temperature, which makes quantitative comparison more difficult.
- Newly designed apparatus makes it possible to visualize flow field with fume and to measure flow directions, velocities and turbulence even optically. Thus, we are able to carry out highly sophisticated flow measurements, as Particle Image Velocimetry (PIV) for example.

The sketch and realization of the new measurement apparatus can be seen in Fig. 1.

The active parts of the measurement setup were made of real exhaust materials: the tube was a ferritic stainless steel welded pipe (AISI 444), while the heatshield was prepared of the base material of heatshields (embossed aluminium plate). Heat resistant fireplace-glass plates were used to delimit the middle measurement area – one of them was painted to black for better visualization.

The heating insert – placed inside the tube – was custom made, constructed of a spiral resistance-heating wire (kanthal) coiled around a ceramic core and housed in a quartz-glass tube. Appropriate operation is ensured by a HAGA KD481P type PID controller. Feedback temperature is measured on the surface of the steel tube. Beside the tube surface five more temperatures were measured on the middle section of the heatshield (see Fig. 1) by K-type thermocouples.

2.2 Measurement process

Measuring program was started with switching on the heating, from which point the temperatures were continuously registered by a PC with 2 Hz acquisition frequency. Each investigated tube temperatures were reached in 2 steps: First, the heating was controlled so that the tube surface reaches the pre-set temperature value. Subsequently this temperature was kept constant for a while so as to all transient phenomena could come to pass. After that phase the thermal and flow effects are considered to be stationary, and the temperature values are determined as the average of a short "inspection period".

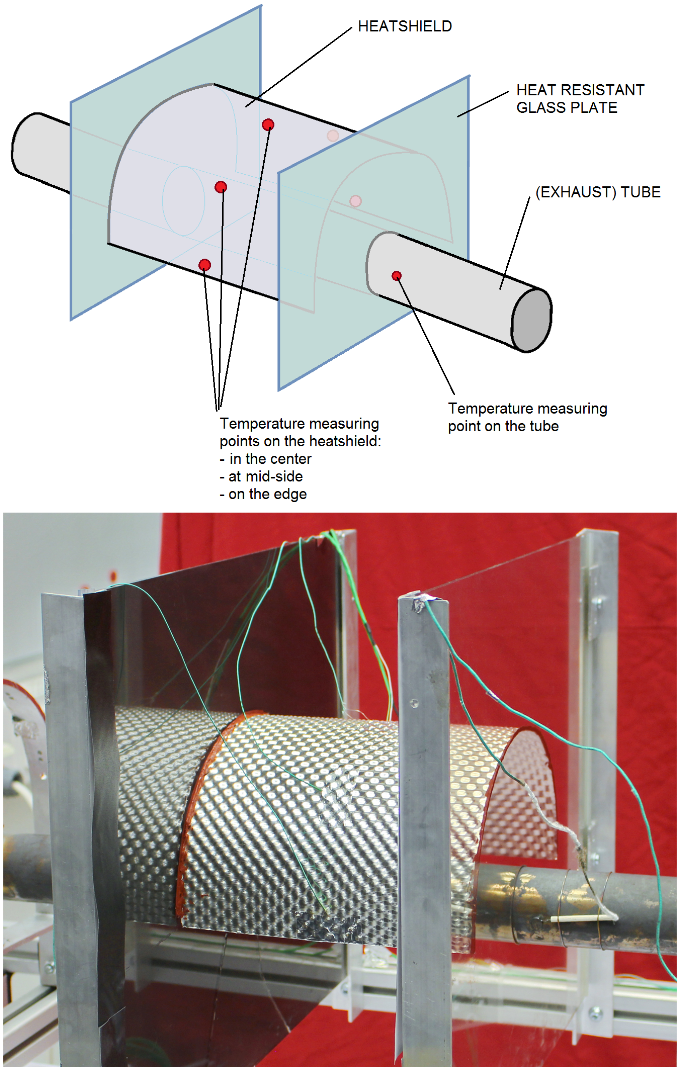


Fig. 1 Sketch of measuring setup (up) and the real apparatus (down)

Different setups were compared based on stabilized heatshield surface temperature aiming the better understanding of different influencing factors on the heating of the heatshield:

- By measuring in normal and upside-down position (see Fig. 3) the effect of thermal radiation can be quantitatively uncoupled from that of free convection.
- Different heatshield surfaces were compared (as-received, black, white and muddy).
- The effect of different ground distances and qualities (heat-reflective, matte white and tarmac-like) were compared.
- The effect of heatshield surface structure was investigated (embossed vs. flat surface).

Each measurement case was investigated at three different tube temperatures, which were reached in three heating cycles as follows:

1. Free heating up to 300 °C and holding.
2. Free heating up to 450 °C and holding.
3. Free heating up to 600 °C and holding.

The temperature run of a measuring cycle can be seen in Fig. 2: the controlled tube temperature is followed with some delay by the measured heatshield temperature.

3 Evaluation

A deep, comprehensive evaluation is not feasible here due to some limitations, however, some important and unexpected characteristics will be described and interpreted in the followings.

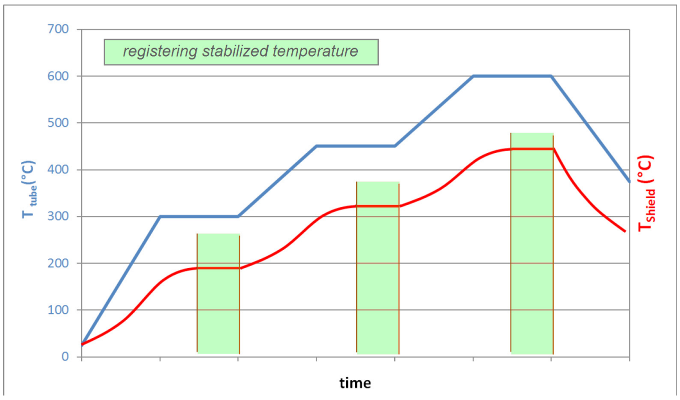


Fig. 2 Temperature run of a measurement cycle

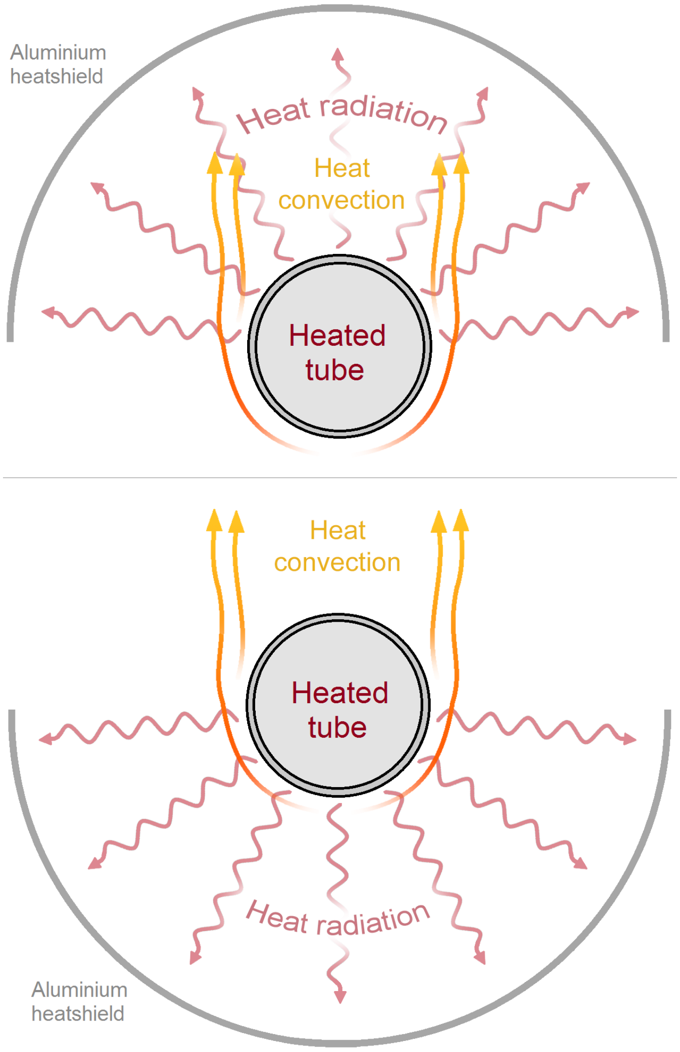


Fig. 3 Normal (up) and upside-down measurement positions (down)

3.1 Effect of radiation and free convection

Measuring beside normal (shield above tube) and upside-down position (tube above shield) enables us to estimate the influence of different processes on heatshield warming: the effect of radiation + convection compared to the effect of radiation only, respectively. As thermal radiation is proportional to the 4th power of temperature – resulting more than 5 times higher power output at 600 °C than at 300 °C, a more pronounced effect of radiation is expected at the higher temperature range. Radiation has even higher dominancy, when highly absorbent (black or muddy) surface is present on the heatshield. Both effects appear clearly on the results shown by Fig. 4: while at 300 °C beside original aluminium surface the thermal radiation causes only around one-fifth of the total warming of the heatshield, this ratio approaches the four-fifth value when tube temperature is raised to 600 °C and black surface was prepared onto the inner side of the heatshield.

3.2 Effect of heatshield surface

As radiation get more and more importance with increasing temperature, it can be expected, that the absorption properties

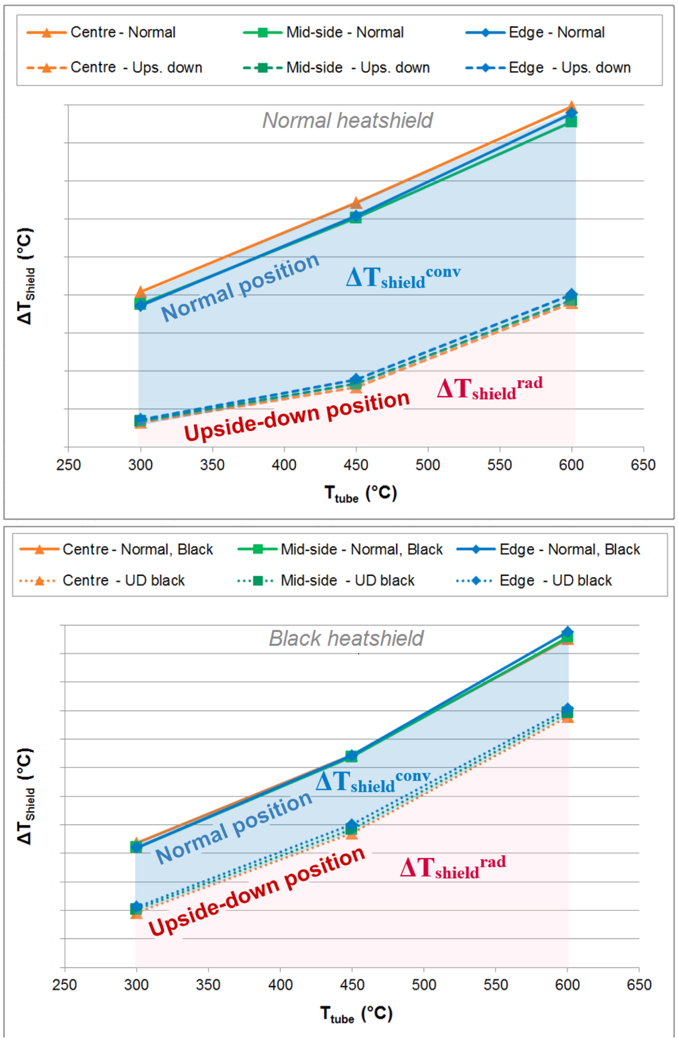


Fig. 4 Temperature increase of heatshield with as-received (up) and black coated inner surface (down) beside different exhaust tube temperatures

of the heatshield has great influence on the warming – especially beside high tube temperatures.

Three different surfaces were compared between 300 and 600 °C: the clear, shiny aluminium surface, a black-coated (graphite) surface and a muddy surface – intended to model the case, when the heatshield get extremely dirty (see Fig. 5). Results of these measurements at 300 and 600 °C tube temperatures are shown in Fig. 6. In these cases there were no ground and the setup was in normal position – thus free convection and radiation took place in the heat transfer process as well.

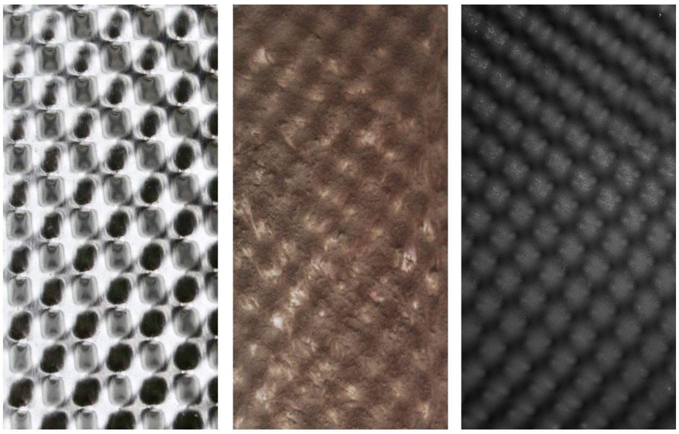


Fig. 5 Examined heatshield surfaces: as-received, muddy and black coated

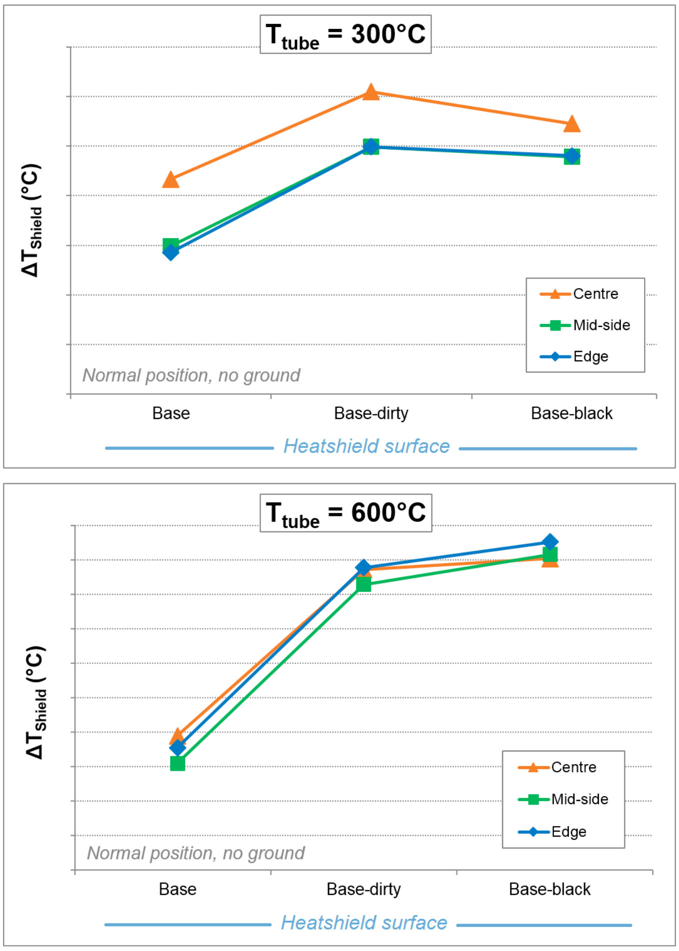


Fig. 6 Effect of heatshield surface quality on its warming

As expected, the clear aluminium surface resulted in the lowest temperatures due to its high reflectivity. The effects of the other two surfaces are not so evident: at 300 °C the dirty surface led to the highest heatshield temperature while at 600 °C the black one. The interpretation of this phenomenon can be understood considering Fig. 4: the most important difference between the two temperatures is that beside 300 °C tube the free convection plays at least as big role in the heatshield warming as thermal radiation. At 600 °C, however, radiation become dominant. Based on the higher temperature, it is clear, that the black surface absorbs heat radiation most efficiently. The still greater warming of muddy heatshield at lower temperature should be caused by the buoyancy-driven free convection, which is thus the most efficient beside the muddy surface. Indeed, it is comprehensible due to the more structured surface topology.

This assumption is also confirmed by the measured temperature-distribution alongside the heatshield: at lower temperature the centre (top-middle point) of the heatshield got significantly warmer compared to the other measured points, while beside 600°C tube temperature the differences between the measured heatshield temperatures are much smaller. The first case can be explained by the strong influence of free convection – which is the most effective in the middle region. Beside 600°C tube, however, the dominating thermal radiation warms the heatshield uniformly along its surface.

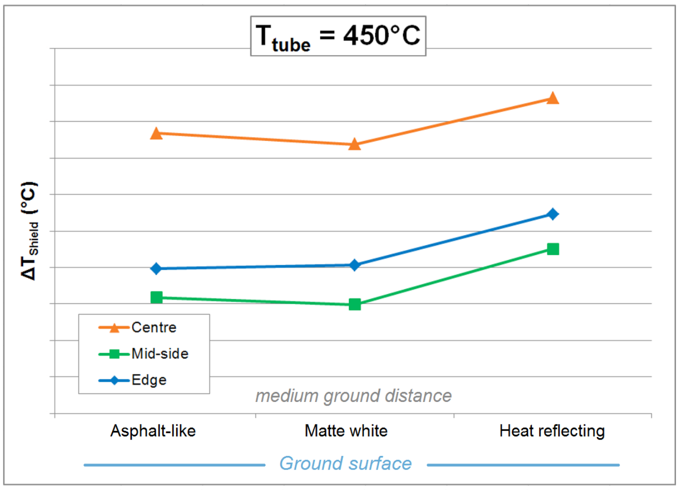
3.3 Effect of ground

The presence of ground affects the warming of the heatshield in more ways: on the one hand it modifies the evolving flow field, on the other hand, it absorbs/reflects heat radiation. The overall effect of ground quality and distance on the warming of heatshield edge, centre and mid-side region can be seen in Fig. 7 for the intermediate tube temperature.

We can conclude, that ground surface quality has obvious but slight influence via radiation absorption/reflection: measuring above heat-reflecting surface result in the highest heatshield temperature at each investigated point, while matte white surface absorbs marginally better the thermal radiation than the investigated asphalt-like surface – resulting nearly the same heatshield temperatures. On the other hand, closer ground results in definitely lower heatshield temperatures – measured above asphalt-like surface. At first glance it can be surprising – one could expect that a more compact setup owns poorer self-cooling ability, thus, closer ground leads to higher temperatures. In fact, however, the smaller ground distance hinders the evolution of free convection stream resulting weaker heat transport towards the heatshield and, eventually, lower heatshield temperatures.

3.4 Effect of heatshield surface topology

The influence of heatshield surface macro topology on warming was investigated too: beside the original, embossed heatshield material an aluminium sheet with flat surface was measured.



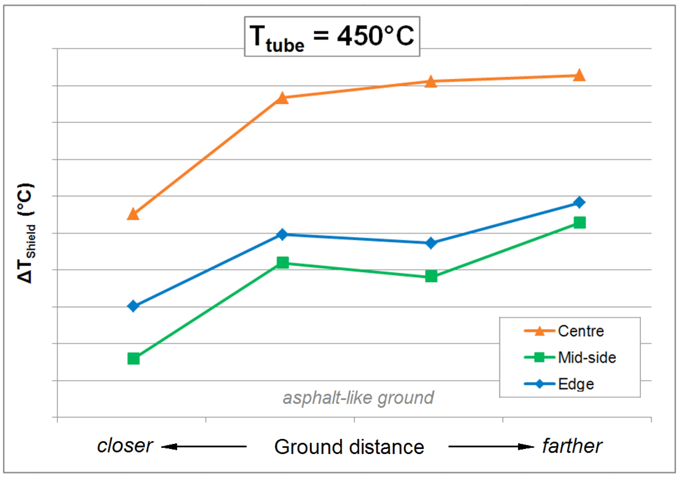


Fig. 7 Effect of ground quality (up) and ground distance (down) on the warming of the heatshield

These examinations were carried out in upside-down position so as to emphasize the effect of radiation as the embossed surface is suspected to scatter more effectively the incident radiation resulting less reflections, and thus, lower temperatures.

Measurement results – can be seen in Fig. 8 – proved that the embossed surface has practically no effect on the reached heatshield temperature. The only difference between the two investigated aluminium shields is the more uniform temperature distribution in case of the one with flat surface. However, it could be dedicated to the greater thickness (1 mm vs. 0.4 mm) rather than to any other surface property.

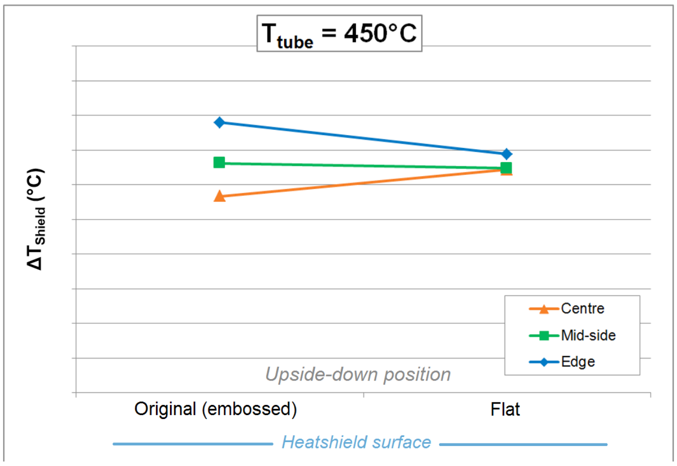


Fig. 8 Effect of heatshield surface topology on warming

3.5 Flow field

The construction of measuring apparatus enables us to visualize (and even measure) the flow field around the exhaust tube and heatshield. Fume was introduced underneath the tube-shield assembly and a line-laser lighting was applied from below to practically generate a cross-section of the flow field. (Quantitative evaluation could also be realized with *particle image velocimetry* or *hot wire anemometry*, but it has not been carried out yet.)

Computational simulations (CFD) were also executed in Star CCM+ software, however, it is quite difficult to execute CFD simulation for the given case due to 2 reasons: On the one hand, the simulation of buoyancy-driven flow is difficult because of the low driving forces – low Reynolds-number. Numerical errors can easily fade out the real physical processes if inappropriate settings are used. On the other hand, the high reflectivity of the heatshield surface makes the calculation of radiation difficult too – more accurate methods consume extreme computational power; even with a smooth (not embossed) heatshield surface model.

Due to the above mentioned reasons, the exact quantitative comparison of simulation and experimental flow fields is not possible yet, however, the qualitative comparison already gives some important base points (see Fig. 9):

- The basic flow structure is quite similar in both cases: the great majority of the upward stream flows around the heatshield area without entering it, resulting very modest flow velocities between the tube and the heatshield.
- The evolving flow pattern beneath the heatshield consist of two vortex-pairs with opposite rotation directions and a moderate upstream just above the tube center.
- The highest flow velocities are developed at the edges of the heatshield.

A more detailed CFD simulation is in progress now, which is expected to confirm all the above mentioned findings – which were established based on the experimental results, and give the possibility to a more detailed theoretical parametric examination.

4 Conclusion

Present paper gave a brief insight to a detailed experimental investigation of thermal phenomena around a hot exhaust tube and a concentrically positioned aluminium heatshield. The newly built apparatus is based on a first demo setup, however, several parameters were changed aiming the wider range of applicability and more accurate operation and validation possibilities.

First, the two major heat transfer phenomena: the buoyancy-driven free convection and the thermal radiation were evaluated: their quantitative role in heatshield warming was

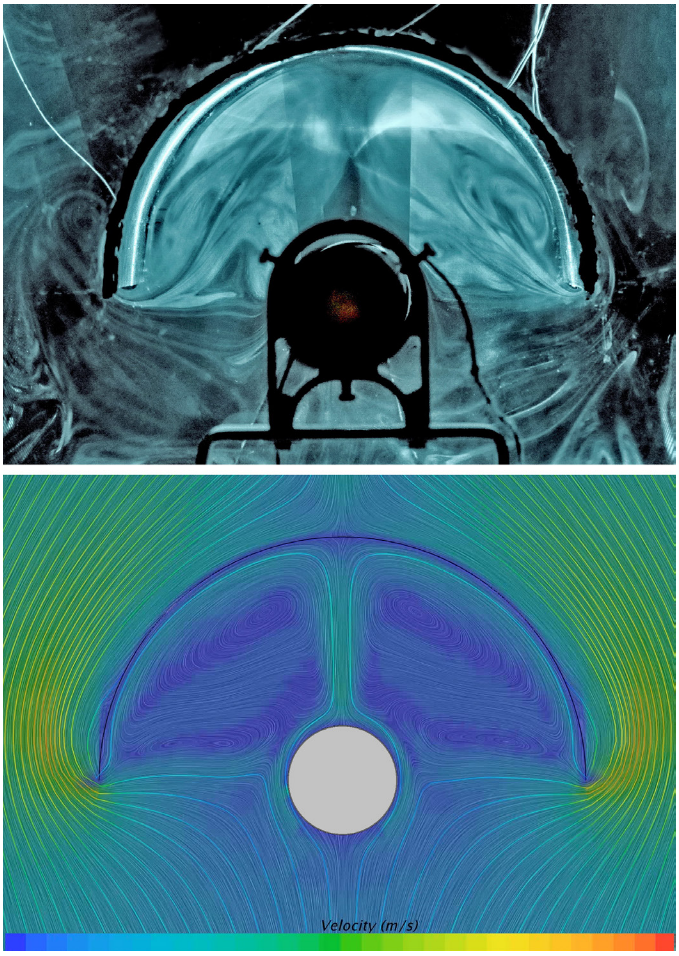


Fig. 9 Visualized flow field (up) and streamline-composite plot calculated by CFD software (down)

presented beside different tube temperatures. It was found that even the free convection or the thermal radiation can be dominant in the heat transfer process depending on the temperature and the absorbing surface.

Further investigated parameter was the inner surface quality of the heatshield: beside the original (extremely reflective) surface, an extremely absorbent (graphite-covered) surface and a muddy surface (representing highly dirty condition) was tested. Results proved that different surfaces promote different heat transfer methods resulting a temperature dependency of the "worst" surface condition: at lower temperatures a dirty heatshield surface – subserves more efficient heat transfer via convection – resulted in the highest temperatures even compared to a highly reflective black surface – the highest absorption of which manifests itself significantly only at higher temperatures.

The presence of ground was expected to have effect on the thermal characteristics – even though this effect was a bit different: the closer the ground was, the cooler the heatshield became. Our interpretation was that despite the more compact arrangement, the close ground hinders the evolving of free convection stream resulting weaker warming. The effect of ground surface, however, led to less significant but clear results: the more reflective ground eventuated higher heatshield temperature.

The last investigated parameter was the heatshield surface: the embossed topology of real heatshields was expected to result in lower temperatures due to more efficient scattering. This assumption could not be verified, only the small heatshield thickness was proved to result in more uneven temperature distribution as a consequence of poorer heat conduction.

In the last section the visualized flow field was presented and compared to the results of numerical (CFD) simulation. Good qualitative agreement was found between them, however, the quantitative evaluation will be a future task.

Overall so we get closer to the fundamental understanding of thermal and flow phenomena taking place around the exhaust line. This knowledge enables us optimizing its structure and the used materials as well as executing more accurate simulations, which subserves the fast and cost-effective vehicle development.

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