

Experimental and Numerical Investigation of Vehicle Drive and Thermal Soak Conditions in a Simplified Engine Bay

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ABSTRACT

Driven by the demand to continuously reduce the development time of new vehicles, it is of critical importance to robustly develop design and packaging concepts early within a new vehicle program using CAE methods. As the underhood and underbody package is constantly getting tighter and the engine power increases, the development of a sophisticated heat protection concept requires much more attention. For many years, heat protection CAE is an integral part of the vehicle development at Ford. However, due to challenges related to transient analysis, e.g. high numerical effort, simulation of transient buoyancy driven airflow (thermal soak), and dependency on high quality thermal material properties, heat protection CAE was primarily focused on steady state vehicle operating conditions. Due to the constantly raising expectations towards CAE as a driver of vehicle design, an investigation has been carried out which aims to better understand the most influential factors impacting transient analysis, and in particular, thermal soak behavior. This investigation is expected to enable the development of an efficient numerical method to simulate this highly transient phenomenon. The present paper describes the design of a Soak Test Rig (STR) which mimics a vehicle front end but at the same time, provides a simplified and controlled environment for CAE method development. The tests carried out delivered a detailed view of the interior air and component temperature distribution for the steady-state preconditioning phase as well as throughout the transient thermal soak phase. Initial CAE analyses have been carried out and compared to test data. This overall investigation has led to an improved understanding of the underlying physics of thermal soak and led to the early phase development of a CAE process to predict thermal soak. The preliminary CAE method accurately predicts the trends in the measured data for three geometric configurations that were tested.

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INTRODUCTION

Today numerical simulation plays a very important role in the development of new vehicles. In particular, in the early phase of the development process, CAE methods are intensively used to improve the overall quality and robustness of design and packaging concepts. Due to the increased usage of CAE, a reduction in physical prototype testing and overall development time has been achieved. To enable further time and cost reduction, a growth in CAE capability and quality remains a key priority.

Thermal management has become an increasingly important aspect of the vehicle concept and packaging development, as the underhood and underbody package is constantly getting tighter while the engine power increases. For many years CAE heat protection models have been used to identify potential overhear issues under steady-state vehicle operating conditions. However, it is well known that some of the most severe operating conditions are transient—in particular,

thermal soak. The thermal soak condition occurs when shutting down the engine after a vehicle has gone through a high load test. An example would be towing a heavy trailer uphill at constant speed, which is known to create a very high heat load on underhood and underbody components.

For more than a decade the automotive industry has sought to progress the development of a reliable and efficient thermal soak CAE method. Due to the geometric complexity of the underhood of a real vehicle and the lack of knowledge regarding the real world boundary conditions, simplified rig models have been used to carry out thermal soak related investigations. In 2005 Weidmann et al. proposed a simplified test rig to study the stabilized natural convection in a fully encapsulated environment and to validate a coupled STAR-CD – RadTherm based CAE method [1]. In the same year, Franchetta et al. developed another simplified half-scale underhood compartment to study buoyancy driven flows using PIV

and thermocouple measurements [2, 3]. Data from this study has been used to develop and validate a VECTIS based thermal soak CAE method. Chen et al. designed in 2006 a simplified underhood rig which enables an even more detailed investigation of buoyancy driven flows [4]. Since Chen et al. introduced their model, it has been used to study the prediction capabilities of several commercial CFD software packages [5, 6, 7]. By focusing on buoyancy driven flows most of the formerly mentioned papers covered only one, certainly very important, aspect of the thermal soak process. In 2010 Mukutmoni et al. presented a test bench set up which attempts to replicate the essence of an automotive thermal soak scenario. Using a coupled PowerFLOW – PowerTHERM simulation process, Mukutmoni et al. reported a very good overall prediction of the transient temperature development for the very simplistic rig during the soak phase [1]. Using a similar coupled CAE process Mukutmoni in 2011 simulated the thermal behavior of a detailed production vehicle during “idle” [2]. The idle vehicle test condition differs from the thermal soak condition in so far that the fan continues to run when the engine shuts down. With that, the idle condition does not include the very unstable and difficult to predict purely buoyancy driven flow scenario. Overall Mukutmoni showed a very good correlation between test and CAE for the steady state phase of simulated test condition whereas some difference between test and CAE have been reported for the transient idle phase.

Building on the success of using simplified rigs to advance the development and validation of a thermal soak CAE method, in the present work a new Soak Test Rig (STR) is proposed which targets a more realistic representation of the nature and physical complexity of the real world thermal soak test. By integrating a fan and an exhaust pipe, which operates at a temperature level comparable to a real world vehicle, the complete thermal soak test can be mimicked via the STR, including the high load, forced convection dominated, steady state preconditioning phase followed by an engine off, buoyancy driven, transient soak phase. To further increase the relevance of the rig several heat receiving parts made of materials with very different thermal properties have been integrated in the STR. Via a variable ventilation concept which strongly influences the flow and temperature field inside the rig, different design variants of the STR were investigated. These variants were also analyzed via CAE to better quantify the sensitivity of the CAE process to geometric changes in the model. Analogous to a real world vehicle test, all three heat transfer mechanisms, i.e., convection, conduction and radiation have a significant impact on the component temperatures distribution inside the rig during the thermal soak test.

The current paper describes the design of the STR and the experimental setup, followed by a detailed review of preconditioning and thermal soak test results. Finally the test data has been used for an in-depth validation of a numerical method using ANSYS Fluent [3].

SETUP OF THE SOAK TEST RIG

Soak Test Rig Design

To accelerate the development and validation of a CAE method to predict thermal soak, Ford has developed a Soak Test Rig (STR). While the rig is significantly less complex than a real world vehicle

engine bay, it includes a simplified representation of all those components which are expected to influence the thermal soak behavior of a real world vehicle. As shown in [Figure 1A](#), the STR represents a partially enclosed engine compartment which includes an exhaust system, a cooling fan, and several simplified engine bay components. The main structure of the STR is made of steel and measures 1.8 x 0.85 x 1.55m (L x W x H). The interior and exterior of the STR chassis is covered with heat shield material (not shown) to better insulate the rig. The simplified engine bay components are shown in [Figure 1B](#). [Table 1](#) provides an overview of the different components including the component name (TC Name), the component dimension, mass, material type, and emissivity. Materials chosen for the study included CPVC (chlorinated polyvinyl chloride), polypropylene, Al 6061, and 3003 H14 Al.

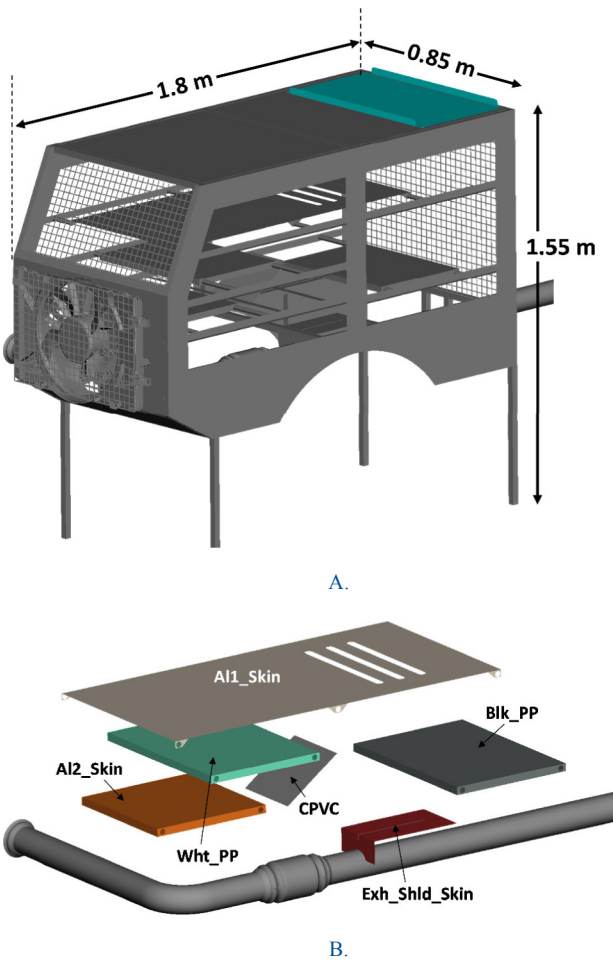


Figure 1. (A) CAD representation of the STR. The side panels (left, right, front and back) of the rig are hidden in order to reveal the interior. (B) TC Names of interior components.

Table 1. Soak Test Rig interior components

TC Name	L x W [cm]	Thickness [mm]	Mass [kg]	Material Type	Emissivity [W/m ²]
Al1_Skin	120 x 60.3	2.4	4.45	3003 H14 Al	0.9
Wht_PP	40 x 55	25.4	4.96	Polypropylene	0.9
Al2_Skin	40 x 40	25.4	11.64	Al 6061	0.9
CPVC	22.8 x 22.7	3.1	0.25	CPVC	0.9
Blk_PP	40 x 55	25.4	4.96	Polypropylene	0.9
Exh_Shld_Skin	30.4 x 17.7	2.0	1.10	Stainless steel	0.25

One major unknown in full vehicle heat protection modeling is the emissivity values of the components (both receiving and exhaust components). Taking this into consideration, each of the STR components' emissivities were measured using two different methods—an Emissometer (Model AE, Devices & Services Co.) and an infrared (IR) camera (ThermaCAM SC640, FLIR Systems, Inc.). The Emissometer is calibrated such that the emissivity of the sample is linear with the measured voltage output from the detector. (Technical notes regarding the Emissometer's operation can be found on the company's website) [4]. To obtain emissivity values from the IR camera, the exhaust system was heated, and at locations where there was a thermocouple (TC), the skin temperature was monitored. The emissivity value (which is input on the IR camera) was adjusted until the temperature reading on the camera matched the TC measured value at a given exhaust location. For some locations along the exhaust network, there was excellent agreement in the emissivity values between the two methods. For locations where the measurement differed, an average value was used. Initial emissivities along the exhaust network were in the range between 0.3 and 0.48. Emissivity rose slightly with subsequent tests as the exhaust surface began to oxidize over time at elevated temperatures. To eliminate uncertainty in the component emissivities, all components (with the exception of the white polypropylene slab) were painted with a black spray paint that had an emissivity of 0.9. Hence, even the aluminum components in the STR have an emissivity of 0.9.

Heat capacity, thermal conductivity, and surface properties of the components in the STR span a wide range and were chosen to represent typical vehicle underhood components.

Mounted to the front of the STR is an engine cooling fan. Since the rig tests were conducted in a laboratory environment which lacks the infrastructure provided by a full-scale wind tunnel, the fan provides the forced convection needed to represent the air entering the underhood compartment during a high load vehicle condition. The fan characteristic is shown in Figure 2. In real vehicles, the engine block and various other underhood components block fan air flow from directly impacting components packaged rearward within the engine compartment. To simulate the blockage effect, an aluminum circular plate with a diameter of 23.3 cm was mounted 11.1 cm behind the fan. A photo of the actual fan used during testing and an image of the splitter plate are included in Figure 2.

To generate heat during the precondition test phase, an exhaust network was mounted to the STR. The network includes an inert exhaust catalyst with high thermal mass. The exhaust pipe was made of stainless steel with 1.65 mm thickness and 8.9 cm outer diameter. Emissivity of the exhaust pipe in several regions was measured and found to be within the range of 0.3 to 0.5. The inlet to the rig exhaust network was attached several meters downstream of a natural gas burner capable of generating exhaust gas temperatures of up to 1000 °C and mass flow rates of up to 750 kg/hr. However, it was observed that a high gas flow rate combined with high exhaust gas temperature caused large fluctuations in both parameters during testing. Thus the exhaust gas flow was limited to about 900 °C and 400 kg/hr. The exhaust outlet of the STR was connected to the exhaust venting system of the testing laboratory.

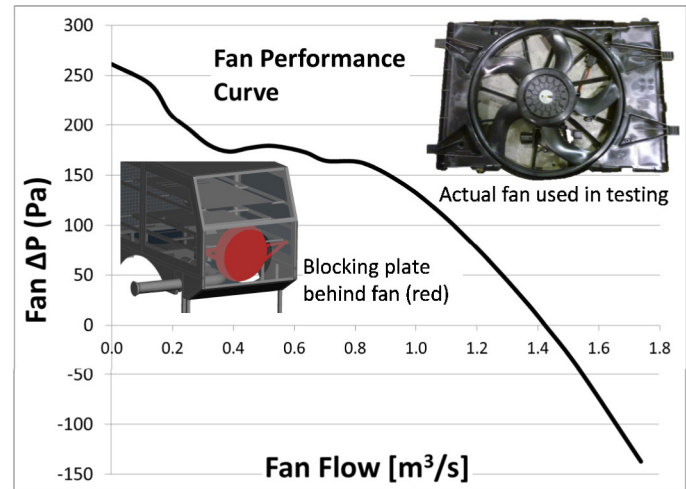


Figure 2. Flow versus pressure curve for STR cooling fan. Photo of actual fan used and fan splitter plate situated behind fan are also shown.

During engine-off soak in a real vehicle, the air inside the engine bay heated up by hot underhood components becomes buoyant and rises towards the top of the engine compartment. Depending on the level of sealing, the rising hot air might escape the engine bay through various leaks. To mimic this effect, which has a significant impact on the buoyancy driven flow field and the temperature distribution in the engine bay, a variable venting mechanism has been included in the STR. Figure 1A shows a blue colored panel at the top rear of the STR housing, which moved rearwards to partially or even completely open up a ventilation opening.

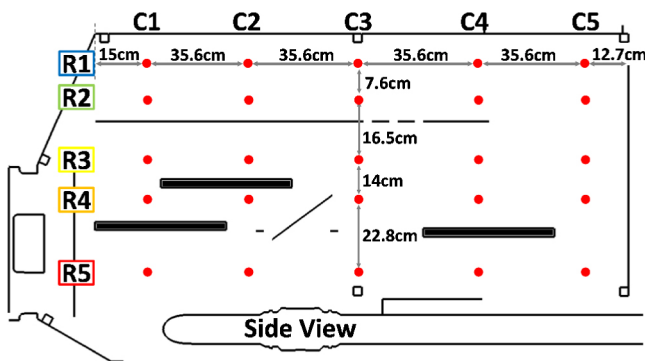
With this initial setup, it was possible to run physical tests with varying test conditions for exhaust gas temperature, exhaust flow rate, fan speed and vent opening position.

Soak Test Rig Instrumentation

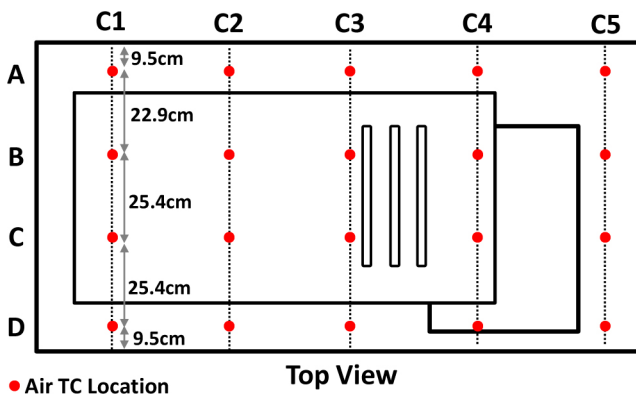
The STR was instrumented to record air temperatures, exhaust and component skin temperatures, fan speed, exhaust flow rate, and exhaust gas temperature. All temperature sensors were Type-K thermocouples which have a small range of uncertainty, on the order of ± 2 °C from the actual temperature. Frames A and B of Figure 3 show the locations of 100 TCs measuring air temperatures within the rig. The TCs were positioned in a grid-like pattern within the STR, made up of five rows top to bottom (R1-5), five columns front to back (C1-5), and four columns side to side (A-D). Four TCs were placed directly behind the fan and then averaged to measure fan inlet temperature. Eight additional air temperature TCs were positioned outside of the rig to capture the ambient temperature.

The internal STR components and exhaust network were also instrumented. Figure 3C (Side View) shows the component surface TC locations. Wht_PP, Al2_Skin, and Blk_PP had one TC on the top and bottom surfaces, placed in their geometric center. Al1_Skin and CPVC had three TCs evenly spaced on each side. To ensure TCs properly adhered to the plastic components, the tips of the TCs were heated and then inserted about 2mm below the component surface. The TCs were then secured with plastic adhesive. This method ensured that the TC measurement was that of the component skin

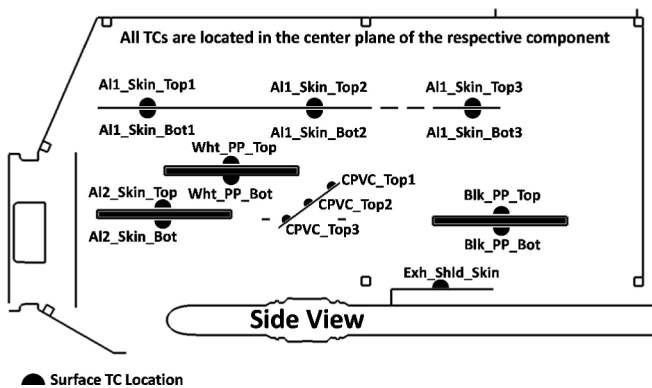
temperature (not a near wall air temperature), and also shielded the TC from radiation via the exhaust pipe surface. TCs were welded to the exhaust network at 11 locations along its length. At most locations along the exhaust network, TCs were placed at the 12, 3, 6, and 9 o'clock positions around the pipe outer surface.



A.



B.



C.

Figure 3. (A, B) Locations of air temperature TCs. (C) Location of component skin temperature TCs.

General Test Procedure

After instrumentation and verification of the data acquisition process, the STR was positioned in the test laboratory. The laboratory measured 12.2 x 9.6 x 6m [L x W x H]. It was equipped with a high

capacity HVAC system, which was required to keep the ambient temperature in the laboratory constant during the test, and a large furnace with blower designed for natural gas combustion. Each test consisted of two phases: a long duration preconditioning phase (fan and furnace on) and a 20 minute soak phase (fan and furnace off). To ensure that all components reached a steady-state condition the preconditioning phase was typically run for 45-90 minutes, depending on the operating condition used. For the exact same boundary conditions, less than one degree variability in component skin temperatures was observed during the precondition and soak phase in all tests.

Tests were performed at various operating conditions. This paper however focuses on the following operating conditions: $m_{\text{Exh}} = 400\text{kg/hr}$, $T_{\text{Exh}} = 900^\circ\text{C}$, $N_{\text{Fan}} = 1220\text{ RPM}$. Beside the baseline rig configuration (VC) with a completely closed ventilation opening two alternative test configurations, one with a 8cm open (VO8) and one with a fully open (VFO) ventilation opening will be considered in this paper.

TEST RESULTS

In this section some key findings from the rig tests will be discussed starting with the precondition phase and followed by the soak phase.

Precondition Results

Figure 4A shows the exhaust and component skin temperature distributions during the precondition phase for the vent closed (VC) case. It can be clearly seen that in general the component skin temperatures decrease with an increasing distance to the exhaust system. A significant temperature difference between the upper and lower side TCs for the low conductivity components (Blk_PP, Wht_PP, and CPVC) is visible while the top and bottom temperatures of the highly conductive aluminum components (Al1_Skin, Al2_Skin) are very similar. Figure 4B and Figure 4C show the changes in surface temperatures, ΔT , when opening the top vent by 8 cm (VO8) or completely (VFO). While one might expect that by opening the vent the temperature in the generic engine bay would decrease, the opposite trend was observed and confirmed in a repeat test.

The presumable reason for the temperature increase of all components inside the STR is the significant increase of the exhaust system skin temperature. At this stage it is not fully understood why the exhaust system temperature increases by up to 29°C in the VO8 case and up to 41°C in the VFO case. A potential explanation could be a change in the convective cooling of the exhaust system due to the alteration of the flow field in the vicinity of the exhaust pipe when opening the vent (Figure 5A - C). But also an undesirable variation in upstream exhaust gas temperature (at the burner outlet) might be a potential root cause of the observed exhaust pipe temperature change. In the future a more detailed investigation will be conducted to research this behavior. For the purpose of this paper this topic is less relevant, as the measured exhaust system surface temperatures are used as a boundary condition for the CAE analysis.