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Title: Heat retention analysis with thermal encapsulation of powertrain under natural soak environment

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Highlights:

- Demonstrate 3D CFD modelling of buoyancy-driven convection flow resolved on a full-geometry passenger car with two thermal encapsulation designs under a vehicle static soak environment.
- A coupled transient CFD - heat transfer modelling analysis successfully characterised by the cool-down behaviours of the key engine fluids during the soak condition.
- Additional heat retention benefits characterised by vehicle-mounted-encapsulation design.
- A CAE tool developed enabling cost-effective evaluations of heat retention and encapsulation design to help achieve reduced CO2 emissions and fuel consumption.

Abstract — This paper investigates high fatality modelling of vehicle heat transfer process during natural soak environment and heat retention benefits with powertrain encapsulations. A coupled computer-aided-engineering (CAE) method utilising 3D computational-fluids-dynamics (CFD) and transient thermal modelling was applied to solve buoyancy-driven convection, thermal radiation and conduction heat transfer of vehicle structure and fluids within. Two vehicle models with different encapsulation layouts were studied. One has engine-mounted-encapsulation (EME) and the other has additional vehicle-mounted-encapsulation (VME). Coupled transient heat transfer simulations were carried out for the two vehicle models to simulate their cool-down behaviours of 9 hours static soak. The key fluids temperatures' cool-down trajectories were obtained and correlated well with vehicle test data. Increased end temperatures were seen for both coolant and oils of the VME model. This provides potential benefits towards CO2 emissions reduction and fuel savings. The air paths and thermal leakages with both encapsulations were visualised. Reduced leakage pathways were found in the VME design in comparison with the EME design. This demonstrated the capability of embedded CAE encapsulation heat retention modelling for evaluating encapsulation designs to reduce fuel consumption and emissions in a timely and robust manner, aiding the development of low-carbon transport technologies.

Keywords — ATCT/WLTC driving cycle, buoyancy-driven heat transfer, CAE method, heat retention modelling, vehicle thermal soak, encapsulation.

Declarations of interest: none

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1. INTRODUCTION

Computer aided engineering (CAE) has become a key development tool for modern vehicle designs, aiding the understanding and evaluation on vehicles' aerodynamics behaviours, noises and vibration hazards (NVH), and thermal energy heat protection performances. To reduce the effect on climate changes, modern vehicles are urged to be delivered with reduced CO_2 emissions. Vehicle and powertrain thermal encapsulations have shown potential benefits in improving fuel consumption, noise and emissions in legislated drive tests [1-3]. As engine is not fully efficient until it has warmed up to its operating temperatures, engine consumes the largest amount of fuel due to greater internal friction and high viscosity of the engine oil at cold temperatures. Thermal encapsulation designed to keep the heat within the engine bay when vehicle is placed at static soak conditions helps the engine solids and fluids cool-down slower and reach an elevated temperatures close to their operating temperatures at cold-starts. Engine friction losses can be consequently reduced and thus improves fuel economy. The encapsulation concept has been tested and investigated by several original equipment manufacturers (OEMs) over the past decade. In 2009 green car congress, BMW announced the intelligent heat management outline, in which engine encapsulation was applied and significantly shortened the engine warm-up period. Engine temperatures were cooled-down slowly and reached about 40 °C after 12 hours key-off soak. It was suggested a 0.2% fuel saving for each extra degree of temperature improved by encapsulation [1]. Autoneum tested and reported (2014) the dual benefits of encapsulation concepts in view of current and future CO_2 emissions and exterior noise regulations. It addressed that the engine bay architectures were still in an early development stage with several OEMs in and outside Europe and addressed the need for exploiting sustainable lightweight and multifunctional materials for engine encapsulation [2]. A recently joint effort by Jaguar Land Rover (JLR) and Ricardo on the exploration on different vehicle and powertrain encapsulation layouts and their associated benefits in fuel consumption, CO_2 emissions and NVH, provided a test methodology for assessing varying levels and types of encapsulation with respect to benefits addressed above. A vehicle mounted encapsulation (VME) concept has been found to have over 10 °C temperature rise in the engine fluids at the start of second- cold-starts drive cycle compared with baseline vehicle without the VME encapsulation for the period of 9 hours static soak. A modified VME concept was introduced with low impact on the vehicle weight and over half of the reduction in CO_2 emissions compared with the baseline model [3].

The above research investigations have suggested the potential benefits in CO_2 emissions reduction through heat retention via engine and vehicle thermal encapsulations. To reduce development costs in time and in resources, the development of a robust and reliable CAE heat retention modelling method to evaluate thermal encapsulation design thus becomes an important part of powertrain and vehicle design to help improve fuel consumptions and greenhouse emissions. Currently, the CAE method for heat retention encapsulation design and analysis is missing in the literature.

One of the challenges with the numerical analysis of the heat retention of vehicle engine bay is to resolve the transient buoyancy-driven convection flow characteristics and the associated convective heat transfer coefficients. During the vehicle key-off, for instance parking for 4-16 hours, the vehicle speed and fan duties are zeros. The air flow around the vehicle and within the under-hood region are driven by the buoyancy effect. The Grashof number is used in the buoyancy flow to correlate heat and mass transfer due to thermally induced natural convection, and to categorise the flow regimes as laminar, transition and turbulent in natural convection. Grashof number Gr is described in (1) by gravitational constant g, thermal expansion coefficient β, the temperature difference ΔT, the characteristic dimension L, and the kinematic viscosity of the fluid ν. The critical Gr defines turbulent flow regime is about 10^9 for vertical plates. From the Grashof number, one can quantify the convective heat transfer coefficient h through (2) with known the fluid thermal conductivity k, and the Prandtle Number Pr.

$$Gr = g\beta\Delta T L^3 \nu^{-2} \tag{1}$$

$$h = (f(\mathrm{Pr}, Gr) \cdot k)/L \tag{2}$$

One of the pioneer works conducted by Chen et al. [4] on a simplified under-hood model [4] with open enclosure simulating the vehicle static soak condition, suggested that the surrounding air flow was in the laminar regime for the engine block and exhaust regions. Similarly, Minovski et al. [5] conducted heat transfer modelling on a detailed full-geometry engine model [5] with additional CFD simulation addressed in the buoyancy-driven flow of oil inside the engine oil sump during the vehicle soak period and identified the laminar flow characteristics of the engine oil indicated by the Grashof number, which was calculated at around 1.35×10^6.

However, from simplified geometries to full designed geometries of the engine bay compartment, to capture the natural convection flow and the convective heat transfer coefficients at around the engine, the computing resources are usually found demanding [4-9]. A 384 ~ 2,720 CPU-hours was used for simulating 1 minute transient flow structure in a simplified engine model [4], and 24,000 CPU-hours was used for a 16 hours simulated drive cycle with intermittent steady-state flow analysis of the full-geometry engine CFD model coupled with transient 1D thermal engine model [5]. A coupled transient flow dynamics 3D CFD and 3D vehicle thermal model for the full-size designed geometries of a passenger vehicle and its under-hood region took 258,000 CPU-hours for 30 minutes soak simulation [7]. The transient numerical approach were found to be essential to accurate predict natural convection flow solutions, the heat transfer in between the surrounding air flow and the engine solids, and the overall heat transfer behaviours of the engine compartments [4, 7-8]. On the other hand, a sensitivity analysis on the internal heat transfer coefficients in between the internal fluids (coolant and oil) and solid components (engine and transmission units) was conducted in a passenger vehicle under-hood region with detailed CFD – heat transfer modelling [8]. It was found that the values of the internal heat transfer coefficients were not critical to the prediction of the end temperatures of the fluids 9 hours cool-down. It suggested that a cost-effective coupled simulation approach could be applied to successfully predict the heat retention effect with account of the detailed encapsulation and powertrain design.

This paper investigated the heat retention modelling of a passenger car powertrain region and the encapsulation effect on engine fluids cool-down behaviours during the 9 hours soak required by the worldwide harmonized light-duty vehicle test procedure (WLTP) and the supplemental ambient temperature correction test (ATCT) [10] legislation to determine the CO_2 emissions. One advantage of the coupled CAE method discussed in this paper was the capability of taking account of the detailed full-scale vehicle geometries embedded with the powertrain encapsulation design. At the same time, it allowed an evaluation of the encapsulation heat retention benefits for the vehicle thermal management during a long-hours' vehicle static cool-down period. The CAE results of the fluids cool-down behaviours compared with the test data and the simulation resources will be discussed.

2. NUMERICAL METHOD

2.1. Coupled 3D heat retention modelling approach

The buoyancy-driven flow behaviour and heat transfer modelling under vehicle soak conditions was developed and detailed previously in Yuan et al. [8]. In the following, a brief description of the methodology is discussed The Lattice-Boltzmann Method (LBM) was used provided by PowerFLOW, SIMULIA [11] to solve the transient flow dynamics [12-13] with detailed vehicle and engine bay geometries. The convective heat transfer coefficients and air mass flow rates were obtained by the CFD and imported into the 3D thermal model in PowerTHERM, SIMULIA [14], to calculate the full heat transfer process taken account of convection, radiation and conduction rates in between the various components at the vehicle under-hood region. The fluids cool-down rates and temperatures were solved by the 3D thermal model. The surface temperatures of the engine bay solids obtained by the 3D thermal model were updated to the 3D CFD as the new boundary conditions to resolve the next period of transient flow simulation. These data exchange in between the flow model and thermal model occurred at a user-defined time interval in the coupled transient modelling stage (in Figure 1), during which, both models ran transiently and simultaneously. To reduce the simulation time with account of the prediction accuracy, a fast transient model with standalone 3D thermal model was run after the first stage of the soak. The details of this approach were discussed in and please refer to ref. [8].

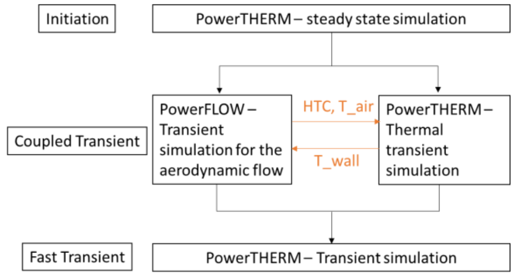
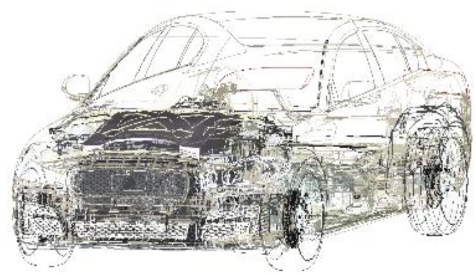


Fig. 1 Diagram of the thermal transient simulation process [8]

(a)

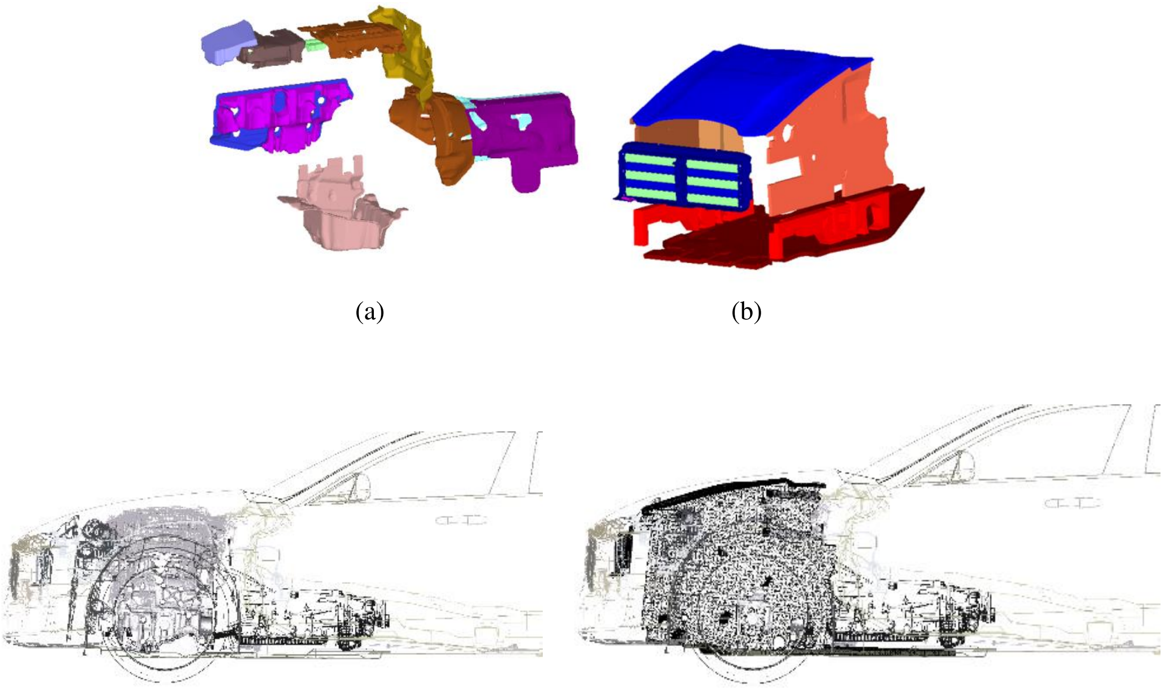


(b)

Fig. 2 Full-size geometry models for the CFD simulation and thermal modelling, (a) external geometries and (b) internal compartments of the under-hood engine bay region

2.2. Full-vehicle models and encapsulation layouts

Vehicle and engine mounted thermal encapsulations could potentially help retain the heat within the engine bay during the long-hours vehicle soak and increase the end fluids temperatures beneficial to the second cold-start WLTP cycle under 14°C ambient condition. The CAE heat retention modelling method with the encapsulation layout build within would be a cost-effective tool for the development of low-emission powertrain and the analysis of thermal management and optimisations. In the current work, two layouts of the encapsulations were analysed. One is an engine mounted encapsulation (EME) with insulation panels added onto the engine and transmission unit directly. The other one is a vehicle mounted encapsulation (VME), in which additional insulation panels were introduced mounted on the vehicle around the engine block and vehicle undertray underneath the engine oil sump and transmission oil sump. The full-vehicle model and two encapsulation layouts were shown in Figures 2-3. A full-size Jaguar XE with diesel four-cylinder engine was built in CAE as the vehicle models in both 3D CFD modelling and 3D thermal modelling. The external and internal model geometries were shown Figures 2a-b. The designed two encapsulation models were shown in Figure 3a-d.



(a) (b)

(c) (d)

Fig. 3 Layouts of the encapsulations of the CAE vehicle model: (a) EME layout, (b) VME layout, (c) baseline model with EME and (d) comparison model with VME.

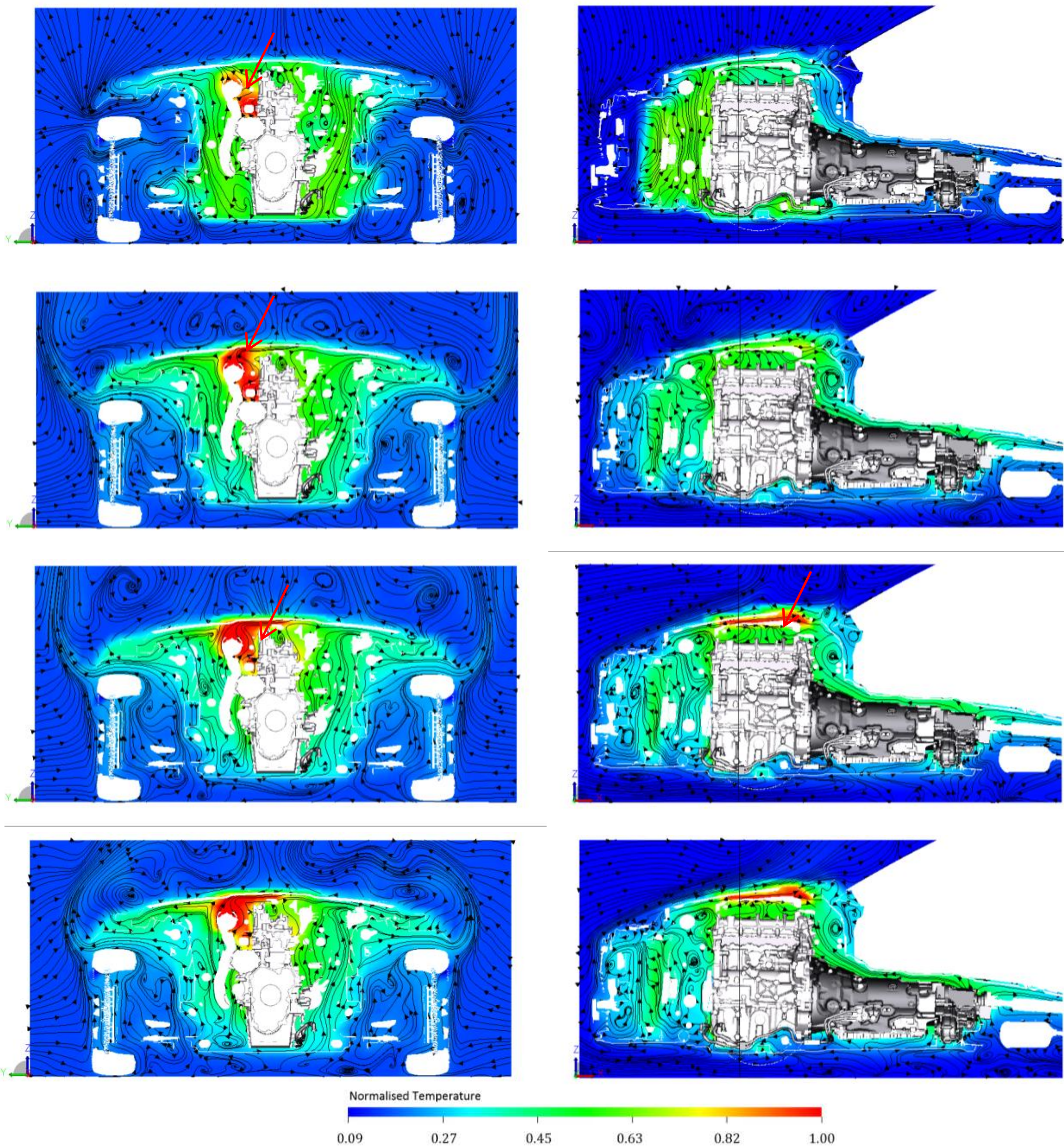
2.3. Data Correlation and Analysis

The coupled 3D heat retention modelling were carried out on a baseline vehicle model with EME feature and on a comparison model with VME feature respectively. A 9 hours soak period were simulated. The fluids cooldown behaviours were plotted and compared in between the two models. The temperatures were compared with the test data obtained with similar encapsulation features tested in [15].

3. RESULTS AND DISCUSSIONS

3.1. Flow field visualisation at beginning of the soak of the baseline vehicle model

At the beginning of the soak, the transient buoyancy flow dynamic was solved by the 3D CFD with the solids temperature simultaneously solved from the coupled 3D thermal models. The air flow around the engine bay and the paths of air and thermal leakages from the under-hood region were visualised in Figs 4-5 of the baseline vehicle model. After key-off event, the vehicle was static during the soak and the air inside was driven by the buoyancy effect. Figures 4a-d shows the air temperature distribution at around the engine bay in a vertical transverse (x) plane (Fig. 4 left) and a vertical longitudinal (y) plane (Fig. 4 right) of the vehicle front. Heat from the engine compartments (cylinder head, engine block and engine oil sump) and exhaust units (turbine unit, exhaust manifold and pipelines) was conducted to the surrounding air inside the under-hood region around the engine bay (Figs. 4a-d). Also shown in Figs. 4a-d that underneath the bonnet cover, air temperatures increases at the beginning of the soak (0-10 min, Figs. 4a-c, arrows), whiles less changes were observed on air temperatures in between 10 – 30 min (Figs. 4c-d) of the soak, so as the temperature distribution of the under-hood region around the engine bay.



(a) 0 s

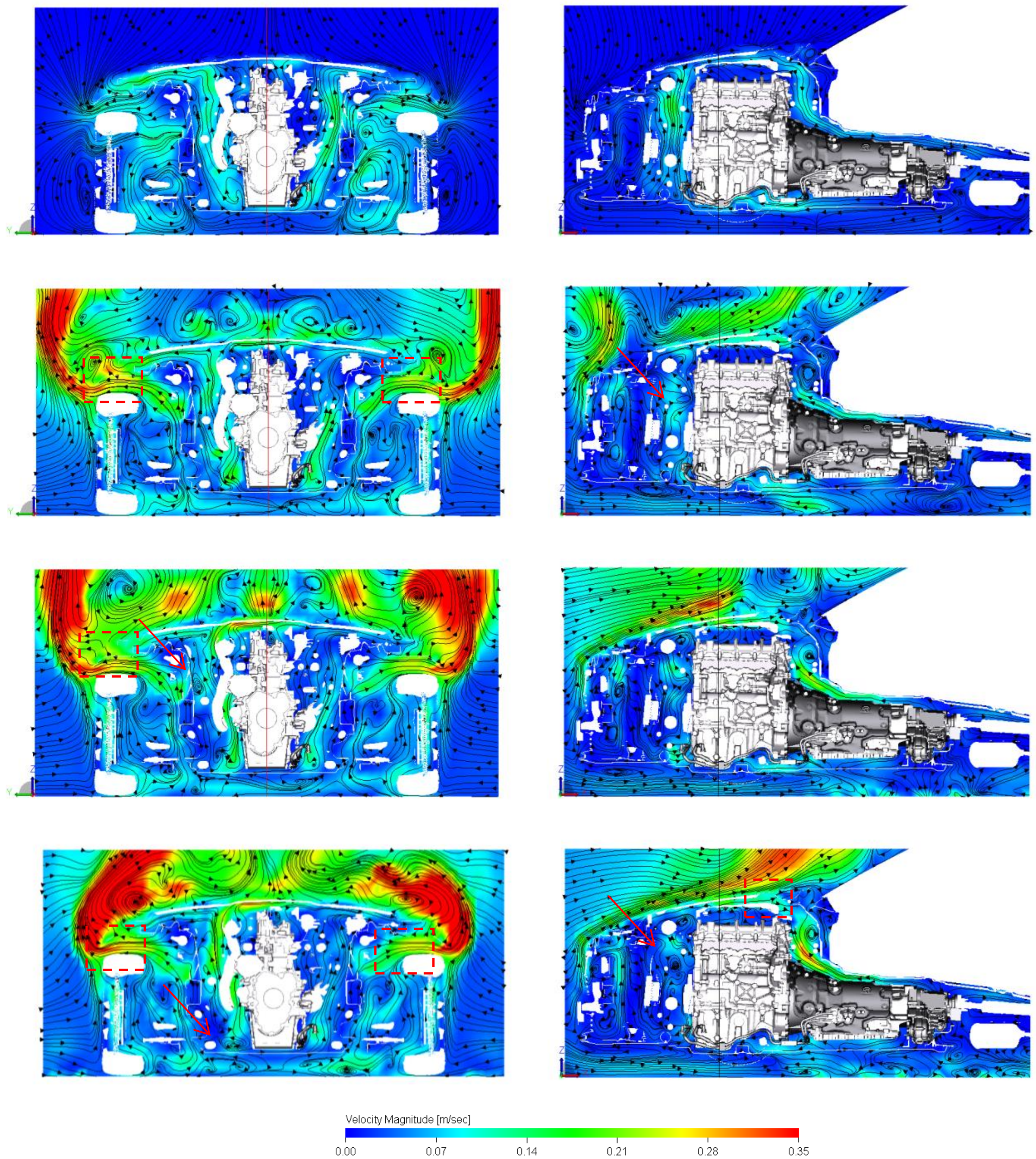
(b) 5 min

(c) 10 min

(d) 30 min

Fig. 4 Streamlines of the internal and external flow around the engine bay superimposed on the flow temperature contour (normalised by the maximum temperature) at (a) 0 s, (b) 5 min, (c) 10 min and (d) 30 min of the vehicle soak from the baseline vehicle model with EME layout. Left: vertical transverse (x) plane cross-section, and right: vertical longitudinal (y) plane cross-section.

Figures 5a-d compares the velocity magnitude distribution around and within the vehicle under-hood region at early stage of the natural soak event (0 - 30 min) at the vertical transverse and vertical longitudinal planes. It shows that due to buoyancy effect, upwards air movements were observed at around the engine compartments at beginning (0 – 5 min), whose magnitudes gradually reduced as vortices formed (Figs. 5b-d arrows). Apparent air paths are seen through the gaps (Fig. 5 rectangular) from the front wheels arches and from the bonnet cover edges. Velocity magnitudes were in the range of 0 - 0.35 m/s obtained from the simulation.



(a)

(b)

(c)

(d)

Fig. 5 Streamlines of the internal and external flow around the engine bay superimposed on flow velocity magnitudes contour at (a) 0 s, (b) 5 min, (c) 10 min and (d) 30 min of the vehicle soak from the baseline vehicle model with EME layout. Left: vertical transverse (x) plane cross-section, and right: vertical longitudinal (y) plane cross-section.

3.2. Flow fields at beginning of the soak of the VME vehicle model

The simulation results on the air flow and air temperatures of the vehicle under-hood region around the engine bar of the vehicle model with VME layouts insulations were plotted in Figures 6a-d. Compared with the baseline vehicle model (Figs. 4-5), with VME insulation panels, heat from the engine bay was retained within the VME encapsulations and the air adjacent to the engine compartments was at a higher temperatures at early soak conditions (Fig. 6b, red arrows, vs. Fig. 4b). At the same time, heat leakage from the front wheel arches (Fig. 6b green arrow) was less (air flow was of lower temperatures). Figures 6c-d shows the flow velocity magnitude distribution at the beginning of the soak, where less air flow was found leaking from the wheel arches (Fig. 6d red box) in comparison with the leakages without the VME encapsulations (Fig. 5b). Also, less air movements were found within the VME at close to the engine solids in comparison with the baseline models' results. These results suggest that the VME design helped retain the heat within the engine compartments' nearby region and helped reduced the air and heat leakages from the engine bay to the outside at the beginning of the soak period.

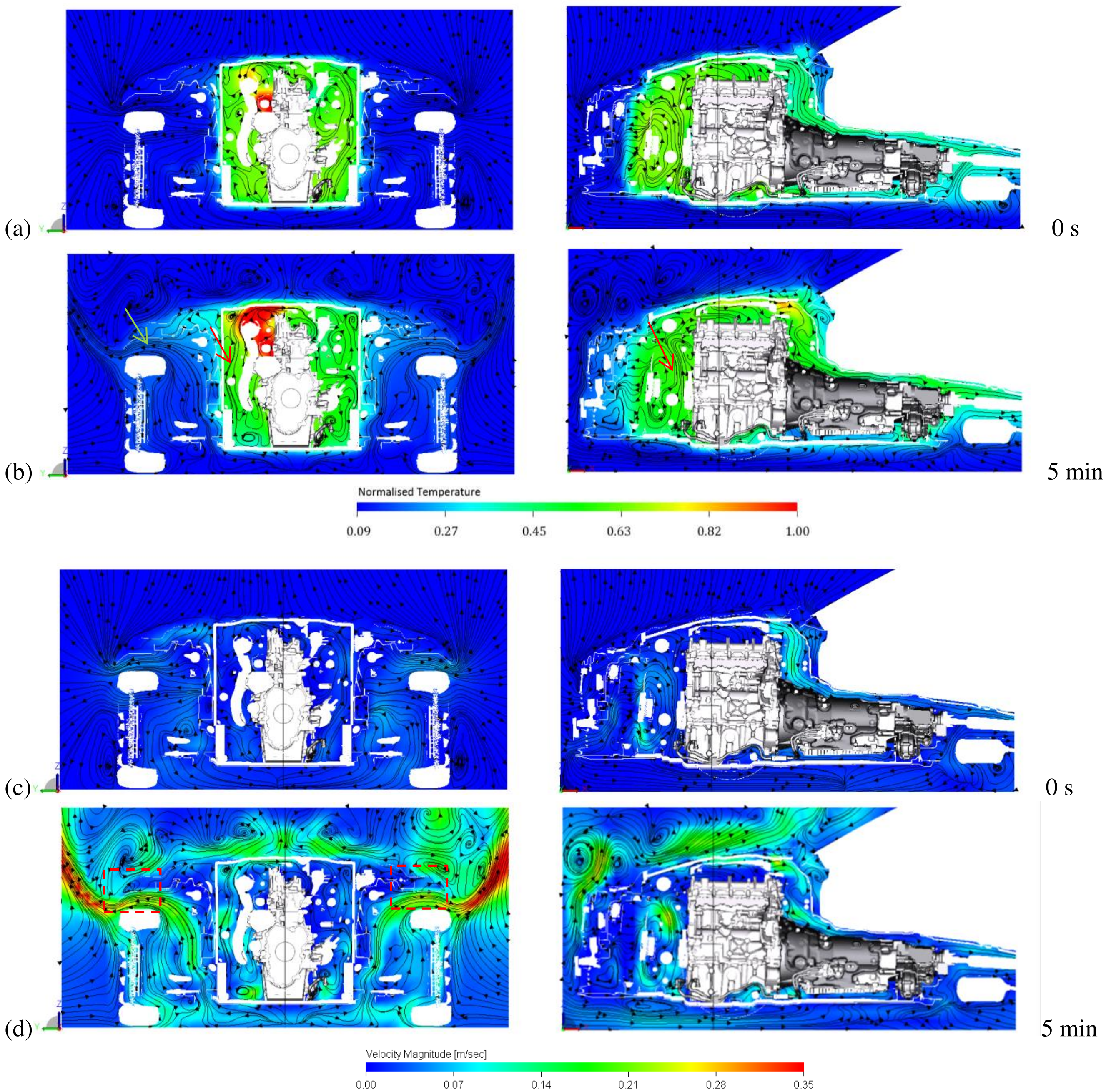


Fig. 6 Streamlines of the internal and external flow around the engine bay superimposed on flow temperature contour (normalised by the maximum temperature) (a, b) or on flow velocity magnitudes contour (c, d) at 0 s (a , c) and 5 min (b, d) of the vehicle soak from the comparison vehicle model with VME layout. Left: vertical transverse (x) plane cross-section, and right: vertical longitudinal (y) plane cross-section.

3.3. Natural convective heat transfer coefficients

The buoyancy-driven convective heat transfer coefficients (HTCs) were calculated from the CFD modelling and plotted in Figures 7a-b of the baseline vehicle model with EME encapsulation (Fig. 7a) and of the comparison model with

VME encapsulation (Fig. 7b) at beginning of the soak. The convective HTCs distribution near the engine compartment and the transmission unit were similar in between the two models, from which a smaller values were obtained with the VME model around the engine block and engine oil sump region. The overall HTCs were around 5 ~ 15 W/(m^2K) as shown in Figure 7, although a higher value of around 40 W/(m^2K) was found at several scattered places around the engine block region in the baseline model (Fig. 7a).

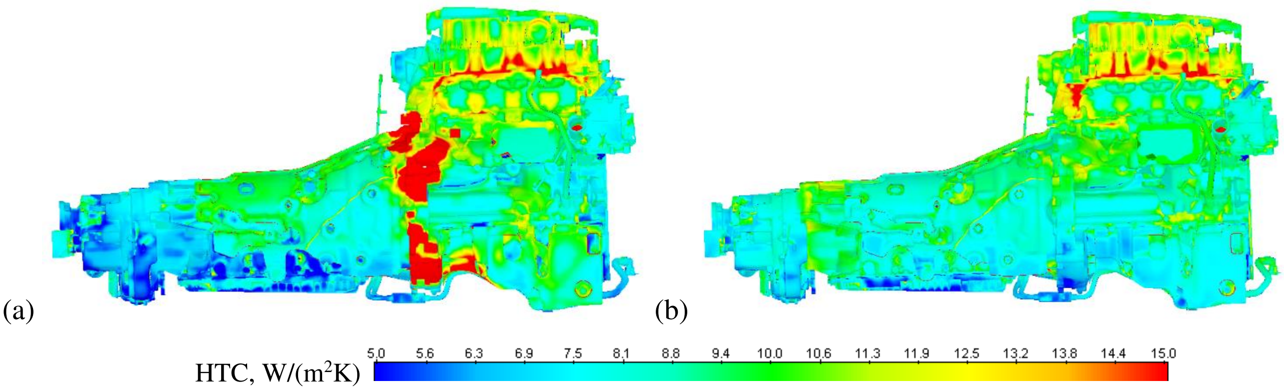


Figure 7. External HTCs (colour map unit: W/(m^2K)) around the engine and transmission unit computed from CFD at the 5 min of the soak of the baseline vehicle model with EME encapsulation (a) vs vehicle model with VME encapsulation (b).

3.4 Comparison of the cool-down trajectories of the key fluids between the baseline model and with VME model

The simulated 9 hours cool-down behaviours of engine solids and internal fluids parts (coolant and oils) were obtained for the baseline vehicle model with EME encapsulation and the comparison vehicle model with VME encapsulation. Figure 8 shows the simulated cool-down curves of the coolant temperatures of the engine head, block (Fig. 8a), and of oil temperatures at the engine and transmission oil sumps (Fig. 8b) from the baseline vehicle model (black) and plotted against the curves obtained from the VME model (red). With VME encapsulation, all four fluids (coolants at engine block and cylinder head, oil in engine oil sump and in transmission oil sump) were found of slower cool-down behaviours throughout the soak and with a higher temperatures at the end of the soak period. Compared with the baseline model results, around 10 °C temperature rises were found at the end of the 9 hours soak of the coolant and engine oil and about 6 °C temperature rises were found for the transmission oil obtained from the VME model CAE results. These predictions agree well with the testing results [15] obtained from a similar encapsulation design, with which also indicated a 3g CO_2/km benefit compared with the baseline data [15] for the 14°C ATCT WLTP cycle. The CAE calculated surface temperatures of the engine solid and transmission unit at the end of the 9 hours soak were plotted in Figs. 9a-b for comparison between the baseline model and VME model. Increased block surfaces temperatures (average in about 10 °C) were obtained with the VME introduced. This results and the fluids cool-down results discussed earlier (Fig. 8) suggest that with the VME encapsulation, there were evident heat retention benefits on the fluids and solids temperatures during the soak period, which led to increased temperatures effect at the end of the soak to better coup with the following engine cold-start process.

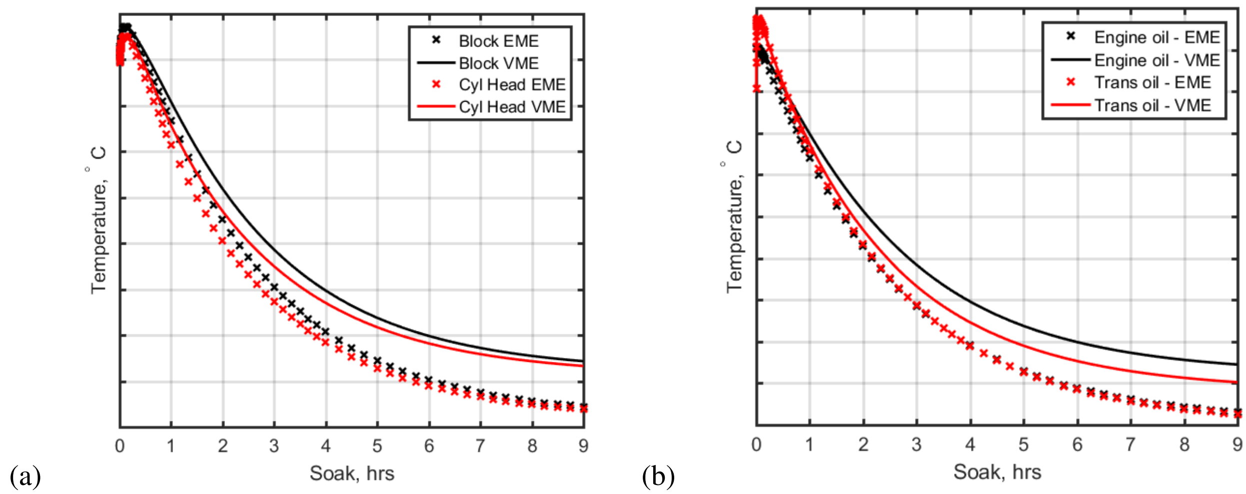


Figure 8. Comparison of the fluids cool-down curves between EME baseline model and the VME comparison model for the coolants in engine block and cylinder head (a) and oil in the engine oil sump and transmission oil sump (b) throughout the 9 hours vehicle soak, obtained from the CAE simulations.

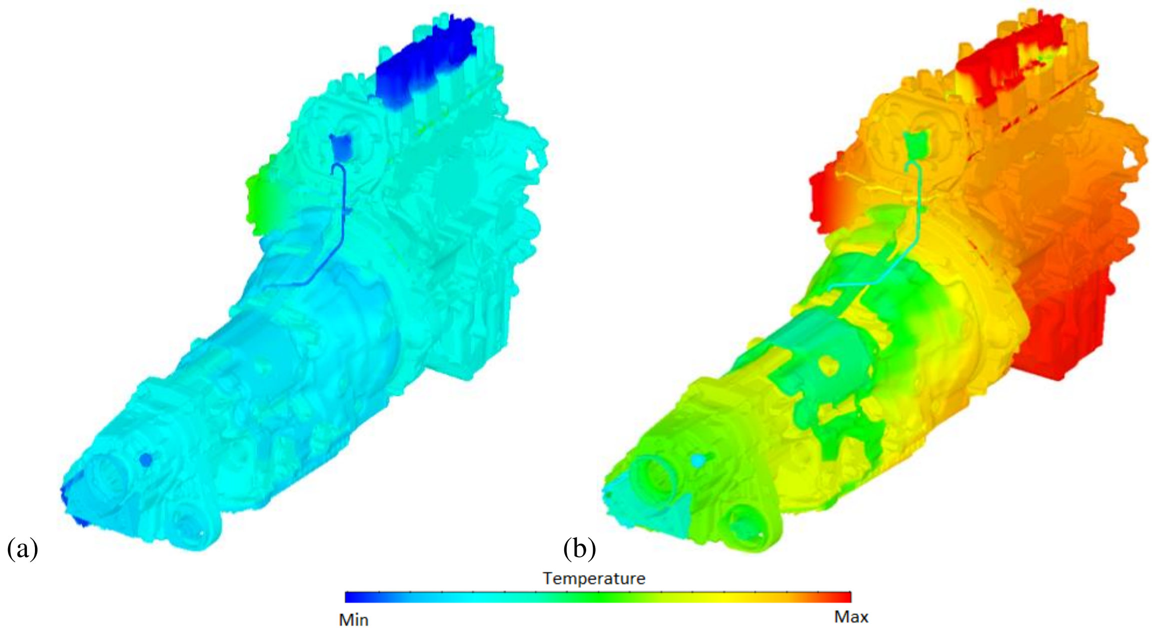


Figure 9. Comparison of the engine and transmission unit surface temperatures between (a) EME baseline model and (b) the VME model at the end of the 9 hours vehicle soak, obtained from the CAE simulations.

4. SUMMARY

Heat retained within the engine bay compartments and the internal fluids coolant and oil in engine and transmission oil sump, throughout the vehicle soak period is beneficial to the powertrain cold-start in reducing friction loss, CO_2 emissions and fuel consumptions. Engine and vehicle encapsulation show potential heat retention benefits of powertrain.

To provide a cost-effective development tool for encapsulation design and evaluations on the heat retention, a CAE tool was developed and examined with two encapsulation designs for a full-vehicle CFD and thermal modelling study. It was found that with the introduction of the VME encapsulations, heat was retained better within the engine bay nearby the engine components. Air and thermal leakages were found through the front wheel arches and through the bonnet cover edges, which were reduced for the VME model. The engine fluids (coolant and oil) were cool-down slower of the VME model than the baseline model, leading to an increased fluid temperature for all the four fluids interested at the end of the 9 hours soak. The engine surface temperatures were found to increase as well at the end of the soak for the VME model. These provide potential benefits in CO2 emissions for the subsequently cold-start drive cycle. The CFD - thermal coupled simulations for the complete 9 hours soak transient simulation took 41 hours (× 384 CPUs) for each of the vehicle model. This will enable an embed development tool for the encapsulation design and heat retention analysis in the early stage of the automotive industry vehicle design process with a fast turn-over time and reduced cost in comparison with experimental investigations. It can be further linked to the powertrain warm-up model and cooling network models to study the thermal and energy management and optimisation strategies, helping deliver low-emission solutions and vehicle technologies.

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