CFD Analysis for the Study of Automotive Underhood Aerodynamics and Thermal Management

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1 Introduction

1.1 Automotive Aerodynamics

The subject aerodynamics deals with the study of relative flow of fluid over the vehicle or some other entity of interest like train, buildings, aircraft, etc. A solid body will experience a net force, F, when it is placed in a flowing viscous fluid. This net force, F, is resolved into the drag force, F_D, defined as the force component acting in the flow direction, and the lift force, F_L, which is the component of the force perpendicular to the flow direction. The drag coefficient C_D and the lift coefficient C_L are calculated as

$$C_D = \frac{F_D}{\frac{1}{2}\rho U^2 A}, \tag{1}$$

$$C_L = \frac{F_L}{\frac{1}{2}\rho U^2 A}. \tag{2}$$

Automotive aerodynamics is defined as the study of flow of air, around and through a vehicle during its operating conditions with the main objective of reducing the drag. Because of drag there are added forces which resists the vehicle movement and hence upsurge in consumption of fuel. Due to growing environmental issues and the fuel prices reaching its peak, the primary factor now is cutting down on vehicle fuel use. Optimization of drag and lift specifically emphasizes on the critical zones of the fluid flow for attachment or reattachment after separation from the vehicle body

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[1]. Generally, reduction in drag and lift is done using add on devices, like spoilers, underbody diffusers, air dams, wings, side skirts, etc.

1.2 Underhood Aerodynamics

In their work on aerodynamics of cooling systems, Renn and Gilhaus studied that various underhood components which would act as hindrances such as the fans, engine and its accessories, radiator together called underhood aerodynamics add up to 10% of the total vehicular drag [2].

The interaction between external aerodynamics and the cooling air is termed as interference. Thus additional drag results because of this underhood interference. This drag arises from the cooling air which mainly depends on the car shape and its cooling configuration. Apparently, for cars with low-drag aerodynamics, cooling drag should be kept to a minimum [3].

1.3 Aero-Thermal Research, EVs and Battery Cooling

Aerodynamic thermal (aero-thermal) management is very much reliant on air flow around the components that needs cooling [1], and this traditionally focuses on under hood cooling. The air flow penetrating the underhood is useful for cooling the components but simultaneously it increases drag. In recent years, electric vehicle (EV) and hybrid electric vehicle (HEV) technology is emerging; however, there are still some challenges in battery pack cooling and require innovative solutions. The battery packs in EVs and HEVs have particular cooling requirements, which includes uniform cooling within a preferred range that is still hard to attain. Therefore, there are various research theories which focuses on various cooling methods like using liquid cooling, phase-change material, and air cooling by both natural and forced convection [4–6].

1.4 Boundary Layer Theory

When the fluid flows over a solid surface, due to no-slip condition fluid particles will get stick to the surface. If the surface is stationary, then bottom fluid layer will have zero velocity. Bottom layer will try to retard the movement of adjacent layer. This process continues and a velocity gradient is developed in a fluid. A thin region over a surface in which this velocity gradient is significant is called hydrodynamic boundary layer. If velocity of flow along the direction of flow decreases, then pressure increases and pressure gradient is positive, thus resulting in boundary layer separation. Similarly, if there exists a temperature difference between the fluid flowing over the surface and the surface, bottom layer will reach the thermal equilibrium with the surface and there is a thin zone in which temperature gradient is significant which is called as thermal boundary layer.

2 Literature Review and Objective

2.1 Automotive Aerodynamics

Some previous studies on automotive aerodynamics highlight on enhancing outward appearance of the car body, like advantages of rounded edges or closed openings for drag reduction purpose. [7] Also further studies on extra aerodynamic components like air dams, diffusers, and spoilers as thoroughly studied by Katz [8, 9]. Also there are studies that considered the interaction between underhood and exterior of airflow, such as one that lowers the temperature by 20% and improves cooling flow through the radiator by optimizing the external airflow using ducts and air dams [10]. Also, Saab et al. [11] proposed that decreasing the front grille opening size decreases both cooling and overall drag.

2.2 Underhood Aerodynamics

The additional drag caused due to interference under the hood should be minimized. Barnard [12] used a modified Ahmed model that consist of internal ducting to undertake numerous unique experimental studies into cooling drag. Kuthada and Wiedemann [13] used numerical and experimental methods to examine the reasons of cooling air drag on a vehicle. As was to be predicted, the front of the car saw the most drag because the hood abruptly redirects airflow there. In a study on the impact of engine bay packaging density and layout on a vehicle's exterior aerodynamics, Christoffersen [14] discovered that directing cooling airflow out of the rearmost area of the front wheel housings could reduce overall drag. According to Baeder, the engine compartment and grill's directed cooling air flow may increase pressure at the grill while reducing the vehicle's aerodynamic drag [3]. A general guide for design for the optimal geometry and dimensions of an automotive underhood diffuser for the purpose of higher downforce and lower drag when taking into account an Ahmed body was mentioned in a study by Jowsey and Passmore [15].

2.3 Electric Vehicle and Battery Cooling

Generally, batteries are subjected to localized temperatures and hence may result in damage. To maintain the uniform temperature is the main objective. For the purpose of guiding the air to the battery at the proper temperature, active cooling works by bringing fresh cooling air from outside the car through a supporting air heating or cooling system first [16]. For the case of liquid cooling, though the heat transfer rate is higher when compared with air cooling but it is associated with more power to pump the cooling liquid thus affecting the mass flow rate. For air cooling forced convection method, using fans is generally used. Also focus is on channelling the air flow using ducts. For a battery pack with multiple cooling passageways, six distinct tapered shape air manifold inlet and outlet designs were numerically evaluated by Park [4]. By externally cooling the battery pack using air flow under the hood, energy required in forced convection can be saved. Khasow, R. and Agelin-Chaab, M. conducted experimental and numerical study to analyse underhood aerodynamics and cooling using underbody diffuser. Chevrolet Aveo5 test vehicle was used at different yaw angles with eddy viscosity-based SST turbulence model [1].

Thus, the overall gap is the linkage between aerodynamics and the thermal aspect specifically in the underhood of a vehicle and how the aerodynamic drag reducing add on device or modification like diffuser can be used for underhood cooling.

2.4 Objectives

- To perform numerical simulation to study automotive aerodynamics with the main aim to reduce overall drag.
- To analyse the velocity and temperature profiles at the underhood of a car affixed with heat source, i.e. a hot plate. This general case of hot plate is further extended to a specific case to study how underhood components like battery pack can be cooled.
- To study the use of diffuser for drag reduction as well as for underhood cooling specifically for battery cooling.

3 Materials and Methods

3.1 Numerical Simulation

The fluid flow is represented in differential form by the Navier–Stokes equations. The steady-state Navier–Stokes equations are as mentioned below.

$$\nabla.V = 0\,[\text{continuity}], \tag{3}$$

$$(V.\nabla)V = -\frac{1}{\rho}\nabla \mathrm{p} + v\nabla^2 \mathrm{V}\,[\text{momentum}], \tag{4}$$

$$0 = -V.\nabla s + \frac{Q}{T}\left[\text{Energy}\right]. \tag{5}$$

The flow in this study is predominantly turbulent. Navier–Stokes equations cannot be solved directly as for turbulent flows there is no exact solution for these equations. Computational Fluid Dynamics (CFD) uses numerical methods to get the approximate solutions of the Navier–Stokes equations. Reynolds-Averaged Navier–Stokes Equations (RANS) are used here as this study involves turbulent flow. The Reynolds-Averaged Energy equation is also solved because the temperature field is also involved. The *k*-*ω* SST model in ANSYS Fluent is used for this study.

3.2 Geometry and Mesh Generation

The three-dimensional car model was developed in Creo 4.0 for the simple Honda car with a heat source, i.e. a hot plate affixed at the under hood of it and then with the diffuser. The computational flow domain's dimensions are obtained in relation to *L*, where *L* is the length of the car. The inlet flow section is located at 2.4 L upstream of the model front, while the outlet flow section is at 6.6 L downstream from the rear of the car model [17] as shown in Fig. 1. In second case, the heat source is further approximated as HEV battery pack. The battery pack is built into the angled surface of a drag and downforce diffuser design as given by Jowsey and Passmore [15], and it is compared with the scenario in which diffuser is not used. The angle for this diffuser was set to 14.5°. The named selections given are inlet, outlet and walls for the enclosure, and the entire car surface and hot plate are termed as "car" and "hotplate", respectively.

Unstructured tetrahedral mesh was generated for the geometry and finer mesh was used near the car surface in critical areas as shown in Fig. 2.

3.3 Grid Independence

The grid independence test was studied as given in Table 1. From Table 1 it can be observed that, after mesh 3 further increase in the mesh size will not have a remarkable effect on the results, so mesh 3 is used for all numerical computations.

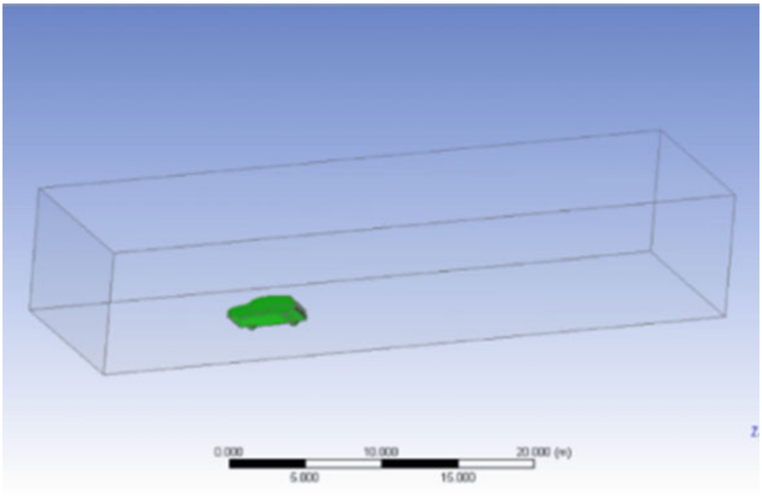


Fig. 1 Vehicle model inside computational domain

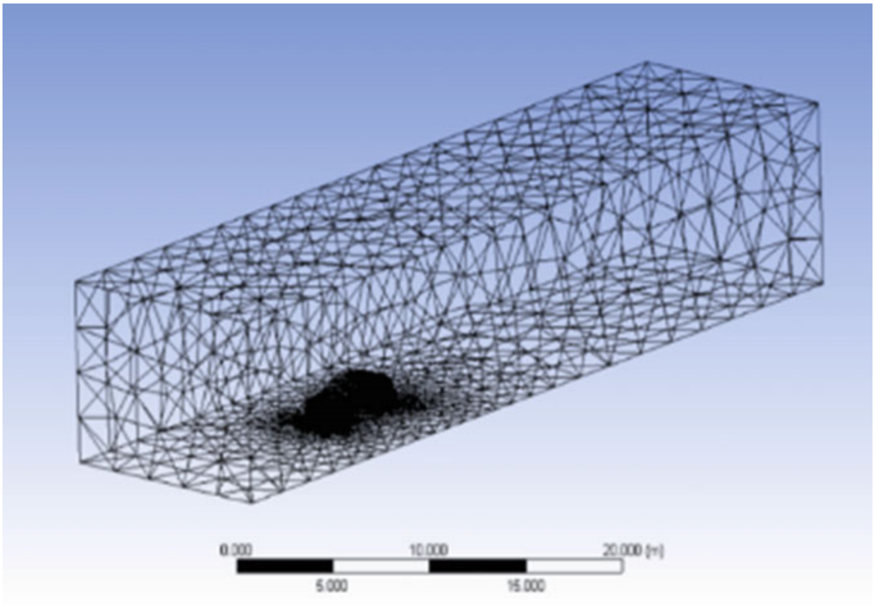


Fig. 2 Entire mesh domain

Table 1 Grid independence results

Mesh size (no. of elements)	C_D
Mesh 1—650,000	0.326
Mesh 2—830,000	0.317
Mesh 3—920,000	0.301
Mesh 4—1,000,000	0.301

3.4 Boundary Conditions

The floor and all the surfaces of the car model are subjected to the no-slip boundary condition. To consider the highway condition, the inlet velocity is specified as 100 km/h, such that air cooling would be efficient because of higher speed and higher convective rate of heat transfer. The turbulent intensity was set to 1% [17]. A constant average temperature was the applied boundary condition to the hotplate. At the domain outlet, zero relative pressure was stated as the outflow condition. For the underbody battery pack cooling case, 245 W/m^2 heat flux was specified from the battery pack surface as suggested by Park [4]. Both the ambient temperature and the inlet air temperature were assumed to be 300 K.

4 Results and Discussion

4.1 Velocity Results

The air flow strikes the front portion of the car, stops, and then splits to go over and under it. Because of various obstructions in the under hood path, the flow is slower under the vehicle as compared to over it. In the rear part, there is a wake because of air separation. In practical case, the underhood heating sources are radiator, engine, and auxiliary components such as turbo, starter motor and pump and batteries in case of EVs and HEVs. As the cooling of battery packs in EV and HEV vehicles involves many challenges, external air cooling can be used like in hotplate case. Also, the battery capacity is reduced because of the damage caused by overcharging of individual cell due to different charging rate. For prevention of these high temperature zones, it is important to maintain the batteries at a uniform and consistent temperature. Thus instead of using other forced convection cooling methods like fans, diffuser is used. This results in potential energy saving.

This section analyses the local velocity variations via the diffuser and the impact it has on the battery pack surface temperature. The goal is to determine if an increase in velocity and convective heat transfer at the diffuser's inlet can compensate for a decrease in convective heat transfer at the diffuser's exit caused by a decrease in velocity [1].

Figure 3 depicts the velocity contours at the mid-plane of the car for both diffuser and without diffuser scenario. The wake region can be identified in both the cases at the rear of the car with certain differences in both the situation.

Figure 4 depicts the enlarged view of the flow patterns at the vehicle's rear part at the mid-plane, respectively. As the front geometries for both cases are same, the velocity contours in front are same. For rear of the vehicle, variation is seen as the dead air volume, or the region of little or no velocity, is bigger for the diffuser example. Since it is a drag and downforce optimized design of the diffuser, it means that there is a high pressure region at the rear of the car to balance the stagnation point at the front, lowering pressure drag. Again, the flow is not completely detached from the battery pack.

The flow nearer to battery pack is slower, as estimated since the flow continues downstream to the rear part of the vehicle. At the diffuser throat, a larger portion of the air is faster when compared with the case of no diffuser. Another advantage is that the diffuser helps in controlling of vortices formation in the wake in the rear

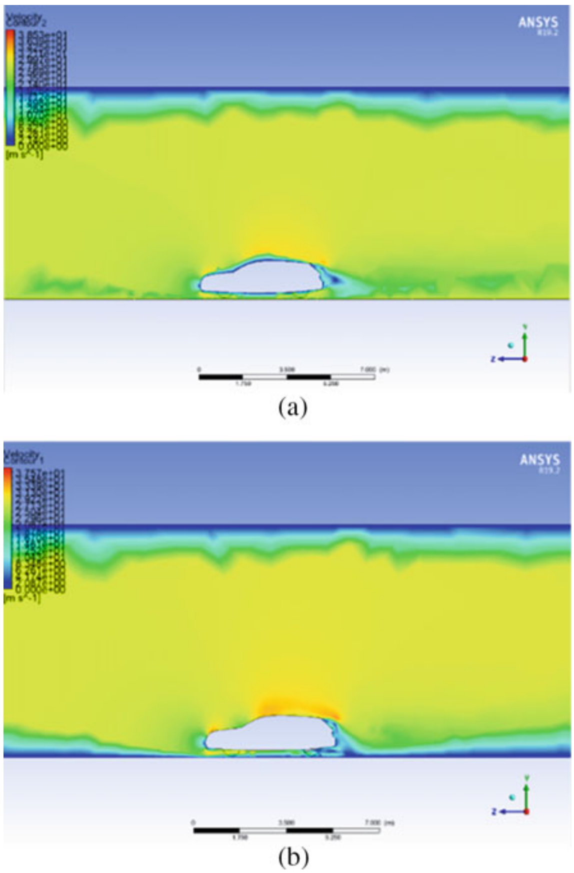


Fig. 3 Contours of velocity at car mid-plane **(a)** without diffuser **(b)** with diffuser

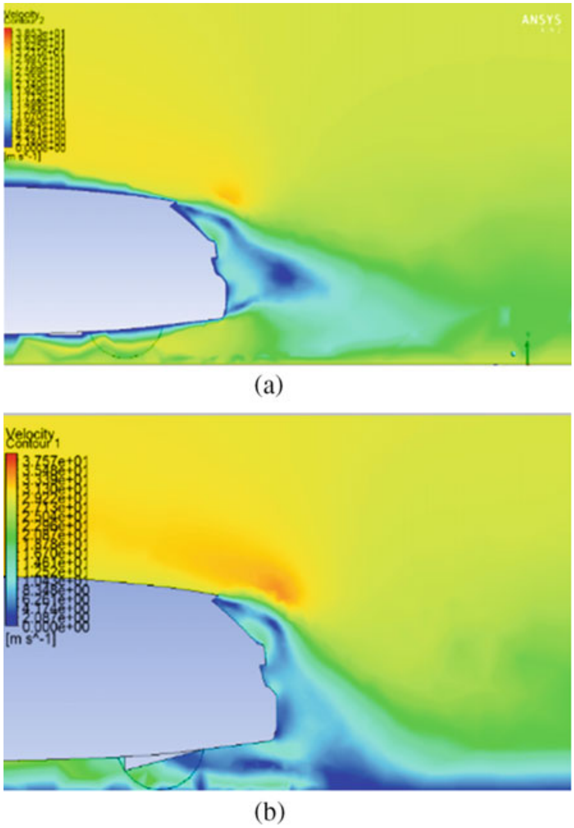


Fig. 4 Contours of velocity at mid-plane at the rear of the car **(a)** without diffuser **(b)** with diffuser

bumper section. The decrease in vortices raises the pressure behind the car in the diffuser scenario and reduces drag as predicted from the drag-optimized design of diffuser.

4.2 Thermal Results

Figure 5 shows zoomed in view of the contours of temperature from the side profile of the car for a generalized hotplate case. Figure 5 depicts the way the heat convection takes place away in the direction perpendicular (vertically in Fig. 5) to the surface of the hotplate. As the air moves downstream down the hotplate, the temperature differential is reduced as the heat convects away in a boundary layer under the influence of air velocity and air heating.

To illustrate the heat convection away from the hotplate, Fig. 6a–c shows the temperature isosurfaces for three different temperatures of 300.125, 301, 303 K [18]. The heat that is convected away moves in the same direction of the flow. From

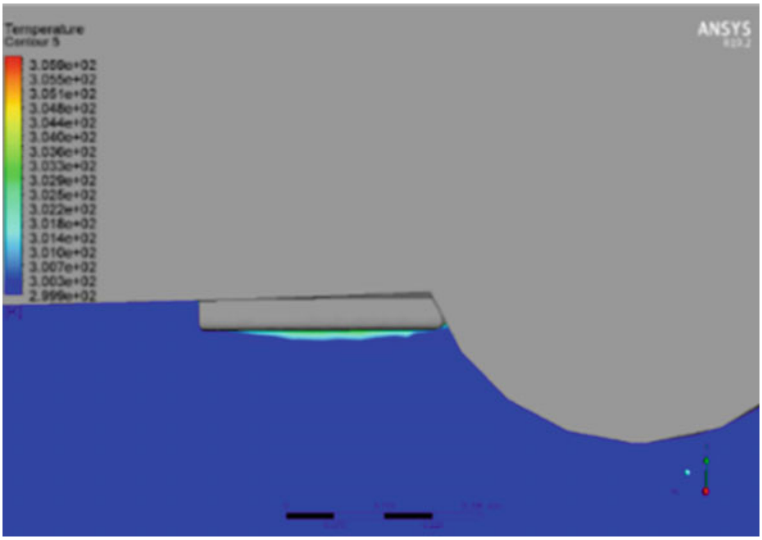


Fig. 5 Zoomed in view of the temperature profile around the hot plate from the vehicle side profile

the contours it can be understood that as the temperature increases heat flow gets trapped. Also for a particular case, the more temperature would be near the heat source and cold air diffuses further.

Figure 7 depicts the temperature contours for the battery pack. In both the cases hot spots are present, mainly because of the asymmetrical underbody which affects the flow. For the first case, i.e. the no diffuser one, there is the presence of hot spots mainly in two areas near the leading edge and in the middle of trailing edge. However, for the second case, the one which includes diffuser, the hot spots exist roughly in the middle of the rear trailing edge. Another observation is that due to diffuser there is a delay in the appearance of hotspot and there is shift further downstream. Though there is minor increase in the maximum value of the temperature in the battery pack, the leading edge of the pack is cooled by the increase in velocity at the diffuser throat.

Figures 8, 9 and 10 indicate isosurface plot at temperatures values of 300.125 K, 301 K and 303 K, respectively [18]. Figure 8(a) indicates how recirculation directly off the trailing edge cause the heat to somewhat become trapped behind the battery pack; on the other hand in the diffuser case of Fig. 8b, there is faster heat dissipation because of build in design of the battery pack with the diffuser which removes the zone of recirculation. Also it shows the relatively quick movement of heat from the diffuser inlet.

Figure 9 indicates isosurfaces at temperature of 301 K. In the diffuser scenario, more air at this given temperature is found near the battery, particularly downstream and close to the battery pack's back, where there appear to be greater pockets of 301 K air. As a result, hot air is rapidly removed from the diffuser's leading edge, as indicated by the isosurface further downstream in the diffuser one compared to the

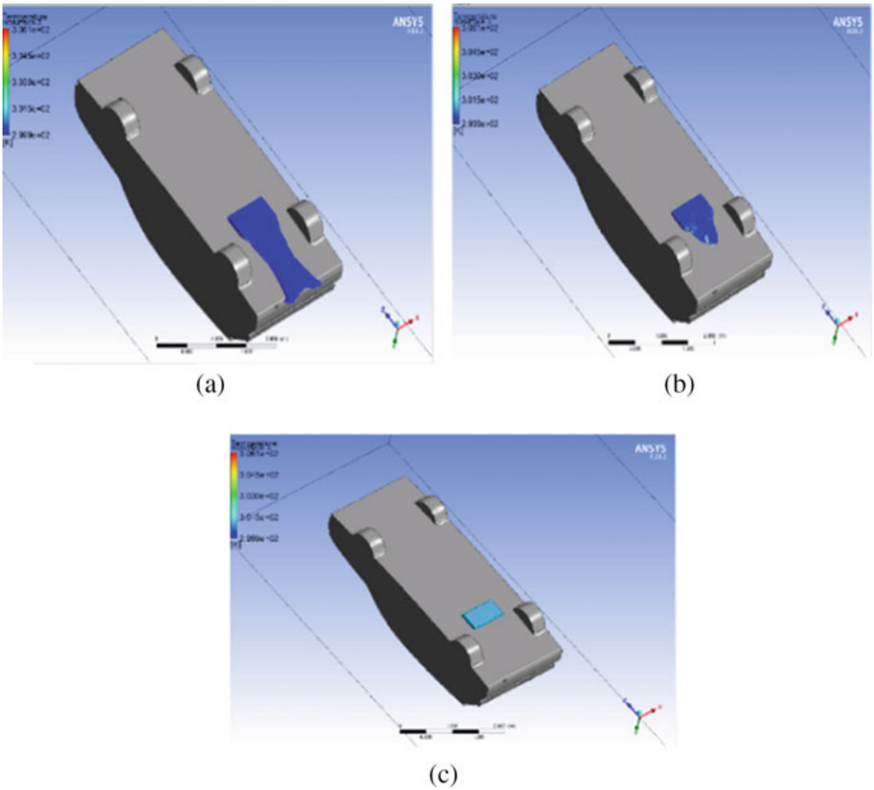


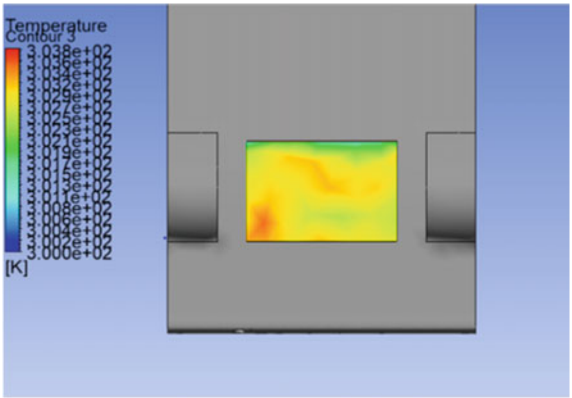
Fig. 6 Temperature isosurface **(a)** 300.125, **(b)** 301 **(c)** 303 K

without diffuser scenario. Figure 10 shows temperature isosurfaces at 303 K with a comparatively smaller isosurface.

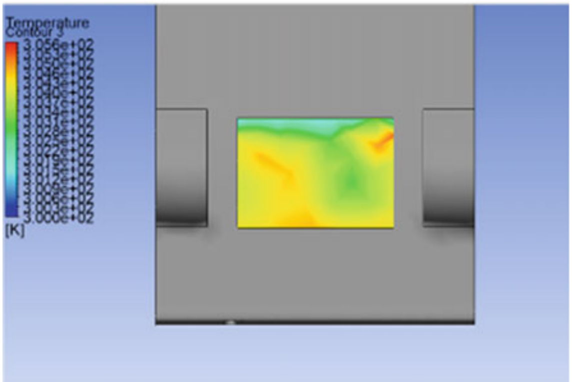
4.3 Validation

Table 2 depicts the C_D values from the numerical simulation carried out in the previous studies with comparative analysis of with and without diffuser. The results from the present work including velocity and temperature contours and temperature isosurfaces are in good agreement with the literature. Also for the battery pack simulation, the maximum surface temperature obtained is 305.6 K which is close to 306 K from the study by Khasow and Agelin-Chaab [18].

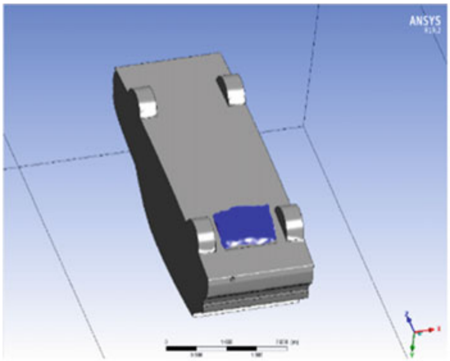
Fig. 7 Contours of temperature for the battery pack surface **(a)** without diffuser **(b)** with diffuser



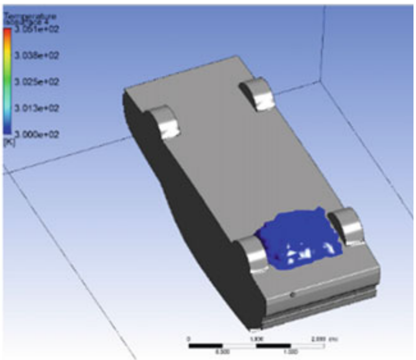
(a)



(b)

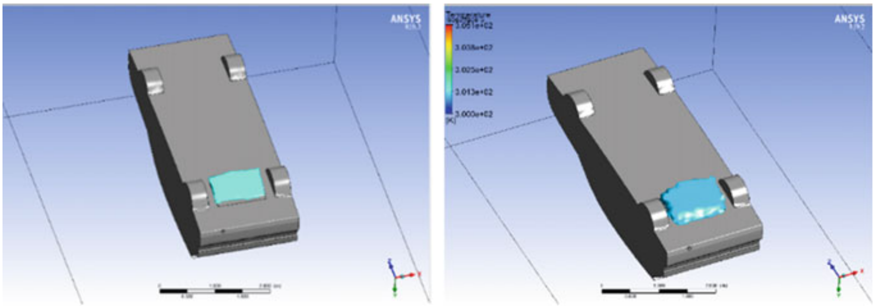


(a)



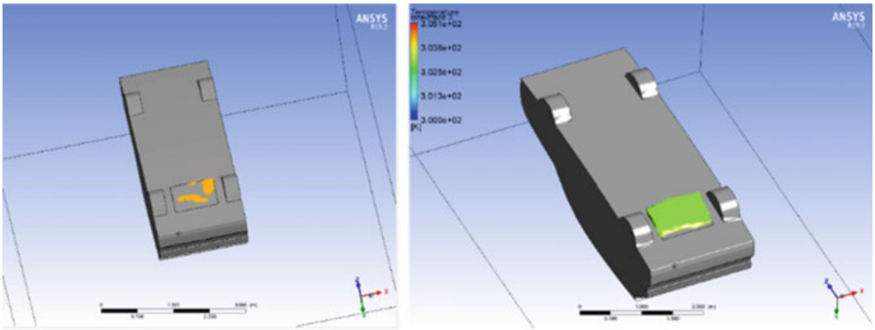
(b)

Fig. 8 Temperature isosurface for the battery pack at 300.125 K **(a)** without diffuser **(b)** with diffuser



(a) (b)

Fig. 9 Temperature isosurface for the battery pack at 301 K **(a)** without diffuser **(b)** with diffuser



(a) (b)

Fig. 10 Temperature isosurface for the battery pack at 303 K **(a)** without diffuser **(b)** with diffuser

Table 2 Comparison of drag coefficient with literature data

Literature review	C_D (No diffuser)	C_D (diffuser)
Kang [20]	0.2838	0.2721
Ajith Balaa [19]	0.3015	0.2895
Present work	0.3012	0.2887

5 Conclusion

To summarize, the results shows that the underhood rear diffuser has significant impact on the velocity and temperature distribution of the underhood geometry specifically the inbuilt battery surface. Due to diffuser, there is more consistent temperature distribution and thus smaller hotspots than without it. Thus, the battery damage can be avoided that may occur because of number of cells getting affected by temperature localization. Also when compared with the no diffuser situation, the temperature upstream of the battery pack surface is decreased and that of downstream increased. This can further be improved by working on the modification in the diffuser design. Thus this can be considered as one of the method for underhood cooling without using source like fan and thus saving energy as well.

Nomenclature

A	Frontal area of rotor [m^2]
U	Free stream velocity [m/s]
C_D	Drag coefficient
C_L	Lift coefficient
ρ	Density of air [kg/m^3]
F_D	Drag force [N]
F_L	Lift force [N]
ν	Kinematic viscosity [m^2/s]
p	Pressure [Pa]
V	Velocity vector
Q	Heat transferred [W]
T	Temperature [K]

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