Optimization of Car Interior Temperature Regulation and Air Infiltration System Using Computational Fluid Dynamics Analysis

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Abstract
This study addresses the pressing issue of regulating automotive cabin temperatures, particularly in scenarios of prolonged sunlight exposure. As parked cars can quickly reach internal temperatures exceeding 70ºC, with even cloudy days seeing highs of 55ºC, there's a critical need for efficient interior climate control. Traditional air conditioning systems struggle to rapidly adjust cabin temperatures upon engine startup, leading to increased engine workload and fuel consumption. Moreover, the prevalence of heat-related illnesses among children left unattended in vehicles underscores the urgency of this challenge. To tackle these issues, our project focuses on implementing a thermal management system to regulate cabin temperatures and ensure continuous fresh air infiltration. Through the integration of an exhaust and blower fan assembly, we conduct comprehensive computational fluid dynamics (CFD) simulations using FLUENT, alongside modeling and meshing in GAMBIT. Our analysis aims to assess the performance of various assembly configurations, identify flow patterns including potential dead zones, and evaluate temperature variations within the car. By determining optimal assembly settings and operational parameters, our research seeks to enhance automotive cabin comfort, safety, and energy efficiency. This study contributes to the development of innovative solutions for mitigating the adverse effects of extreme temperatures within vehicle interiors, ultimately striving towards a safer and more comfortable driving experience for all passengers.
Keywords: CFD, Fluent, mesh, GAMBIT, dead zone

1. Introduction

The interior temperature of a parked car can soar up to 35°C higher than the outside temperature, posing a severe risk to occupants, especially children and pets, particularly during the scorching summer months. This temperature surge is primarily driven by various modes of heat transfer, including conduction, convection, and radiation, with radiation absorption playing a predominant role [1,2]. Our objective is focused on addressing this critical issue by devising methods to regulate the internal temperature of vehicles. The phenomenon of heat accumulation in vehicles is akin to the greenhouse effect observed on a planetary scale [3-5]. The greenhouse effect entails the absorption of thermal radiation by atmospheric greenhouse gases, which is then re-radiated in all directions [6,7]. A portion of this re-radiation is directed back towards the surface and lower atmosphere, leading to an increase in average surface temperatures [8]. Similarly, in cars, solar radiation penetrates through the glass windows, but it becomes trapped inside due to the greenhouse effect, causing a rapid rise in internal temperatures [9-11]. The gravity of the situation is underscored by the alarming statistics of deaths caused by heatstroke in unattended vehicles, particularly among children [12,13]. In 2013 alone, there were fifty-five reported deaths of children due to heatstroke in vehicles, with an additional thirty-three deaths reported in the previous year. These incidents demonstrate that even relatively mild external temperatures (~70°F) can quickly escalate to life-threatening conditions inside vehicles [14-16]. This study aims to shed light on the urgency of addressing vehicle interior temperature regulation and proposes strategies to mitigate the risk of heat-related fatalities. By understanding the underlying mechanisms driving temperature fluctuations inside cars, we can develop effective solutions to ensure the safety and well-being of vehicle occupants, especially vulnerable populations such as children and pets [17,18].

Literature review: In the study carried out in the research paper 'Design of A Smart Automotive Ventilation System For A Parked Car' by Gaurav Kumar Jaiswal, Mohit Gandhi, Sanket Phalgaonkar, Harshal Upadhyay, Ankit Aggrawal, Vasudevan Rajamohan, K.Ganesan, can be seen that the temperature rises significantly in first 15 min and then remains constant at 71ºC after 20 min. The heating process did not slow down and the maximum temperature did not decrease even with the windows leaving slightly opened (McLaren et al., 2006).Akiko et al. (2007) of Honda R&D have studied the effect of cabin environment on the driver fatigue. In this work, three effects were studied, (1) the intensity of direct simulated solar radiation, (2) spectral content of simulated solar radiation and (3) glazing type on human thermal sensation responses. Intelligent solar-powered automobile-ventilation system was studied by David et al., (2005).Mezrhab and Bouzidi (2006) developed a numerical model to study the behavior of thermal comfort inside the passenger car compartment according to climatic conditions and materials that compose the vehicle. Available thin films on the glass window cannot maintain comfortable temperature inside the car compartment. This investigation also found that the existing ventilation is not enough to meet the required comfort. The main objectives of these work is to identify the key point of the vehicle compartment and placed the ventilator system for optimum performance. Hussain H. Al-Kayiem's study on the 'car cabin comfort' had been carried out experimentally and numerically. The experimental results have been obtained by a measurements program conducted on a car prototype.R. Saidur, H. H. Masjuki and M. Hasanuzzaman studied that the reduction of temperature inside the car compartment will reduce the energy consumption of the AC system. Moreover, the reduced temperature will retard the deterioration of the aesthetic look of the interior parts.

2. Objectives

The research aims to evaluate how well a recently developed ventilation system works to control the interior temperature of a parked automobile, especially in direct sunshine when the ignition is off. With the use of blowers, exhaust fans, temperature sensors, and electronic control circuitry, the system attempts to automatically regulate cabin temperature in order to lessen passenger discomfort and cut down on fuel usage related to extended use of the air conditioner. The study also aims to address safety issues associated with overheating, such as the possibility of damaging important car parts and the danger of heat-related deaths. Specifically, the objectives include:

a)Investigating temperature differences between the interior and outside of a parked car that has been exposed to direct sunshine.

b)Using SOLIDWORKS, Gambit, and Fluent software, do a flow study of air circulation within the automobile cabin.

c)Evaluating the effects of intake and exhaust port placements on air circulation efficiency and temperature reduction.

d)Identifying parts of the automobile cabin that may not be adequately cooled and analyzing flow paths to improve ventilation.

e)Addressing security concerns with the design and location of intake and exhaust holes.

By addressing these objectives, our study hopes to provide light on the efficiency of the ventilation system in mitigating heat-related difficulties in parked automobiles. Finally, this study helps to increasing occupant comfort, lowering fuel consumption, and minimizing safety.

3. Methods

The methodology of this study involves the utilization of an exhaust fan, a blower fan, a dedicated battery, and a microcontroller-based circuit to regulate the temperature inside a parked car cabin. The microcontroller circuit, equipped with temperature sensors, monitors the temperature differential between the interior and exterior of the car. Based on this temperature difference, the circuit controls the activation of the exhaust and blower fans to facilitate air circulation and temperature regulation. To determine the optimal specifications and placement of the fans, as well as to understand temperature variations within the car cabin, a SOLIDWORKS model of the vehicle is utilized for analysis. The following scenarios are considered:

Two ducts positioned directly opposite each other on either side of the car.

Two ducts positioned adjacent to each other on the same side of the car.

Two ducts positioned diagonally opposite each other within the car.

Flow distribution and temperature variations are assessed for each scenario to evaluate their effectiveness in facilitating air exchange and reducing cabin temperature. This comprehensive analysis allows for the identification of the most efficient fan configuration and duct placement to optimize interior temperature regulation. Furthermore, the study also investigates potential security threats associated with the placement of inlet and exhaust openings, ensuring that the proposed ventilation system does not compromise vehicle security. Overall, this methodology enables a systematic evaluation of the ventilation system's performance in mitigating heat-related issues in parked vehicles, providing valuable insights for enhancing occupant comfort and safety.

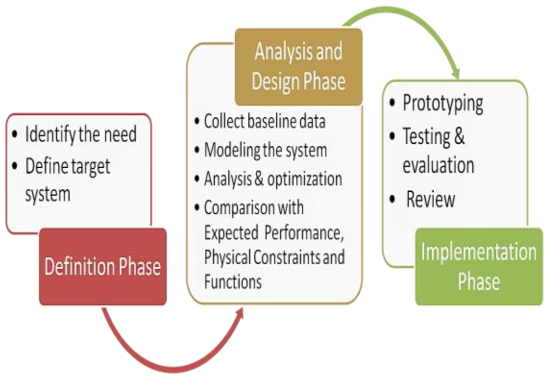

Fig1.Methodology

4. CFD modelling of air circulation in automobile cabin

The formulation of a computational fluid dynamics (CFD) model to study the air circulation in the automobile cabin has been done in this section. The finite element method known as FLUENT is used to simulate air flow in the cabin, provided the boundary conditions. This is accomplished by solving numerous variants of the Navier Stokes equations. FLUENT's algorithm for addressing CFD issues consists of numerous consecutive phases, each of which contributes to an accurate simulation of fluid dynamics. Grid creation, governing equation discretization, solution initialization, iterative solution techniques, convergence evaluation, and post-processing are all phases in the process. The flowchart (Fig.2) summarizes these processes, indicating the logical path taken by FLUENT during the simulation process. Structured mesh with triangular elements was used for meshing the geometry. 100 X100 X10 nodes were created with element size of 0.0005 in all the three dimensional coordinates. The solution based on the governing equations and discretized mesh took 1000 iterations to converge. CFD analysis predicted the air circulation and related phenomena by solving simultaneous set of following governing numerical equations (1-4) which include continuity, momentum and energy equations for fluid and solid.

$$\nabla.(\rho u)=0 \quad \text{(Eq.1)}$$

$$(u.\nabla)u=\nabla.[-pI+\mu(\nabla u+(\nabla u)^{T}-2/3\mu(\nabla.u)I)+F] \quad \text{(Eq.2)}$$

$$\frac{\partial\rho}{\partial t}+\nabla.(\rho V)=0$$

$$\rho C_p u.\nabla T=\nabla.(k\nabla T)+Q+Q_{vh}+W_p \quad \text{(Eq.3)}$$

$$\rho C_p u.\nabla T=\nabla.(K\nabla t)+Q \quad \text{(Eq.4)}$$

Table 1 Initial Conditions

Thermodynamic parameters	Static Pressure: 117325.00 Pa Temperature: 340.00 K
Environment temperature	308.00 K

Table 2. Boundary Conditions

Inlet Flow Condition	Volume Flow Rate - 0.02 m^3/s Temperature – 308 K
Outlet Flow Condition	Ambient Pressure
Body Wall Temperature	340 K

Table 3. Properties of mild steel(cabin)

Density	7850 kg/m^3
Thermal Conductivity	173 W/mK
Specific heat capacity	1765 J/kgK
Heat transfer coefficient	7.9 W/m^2K

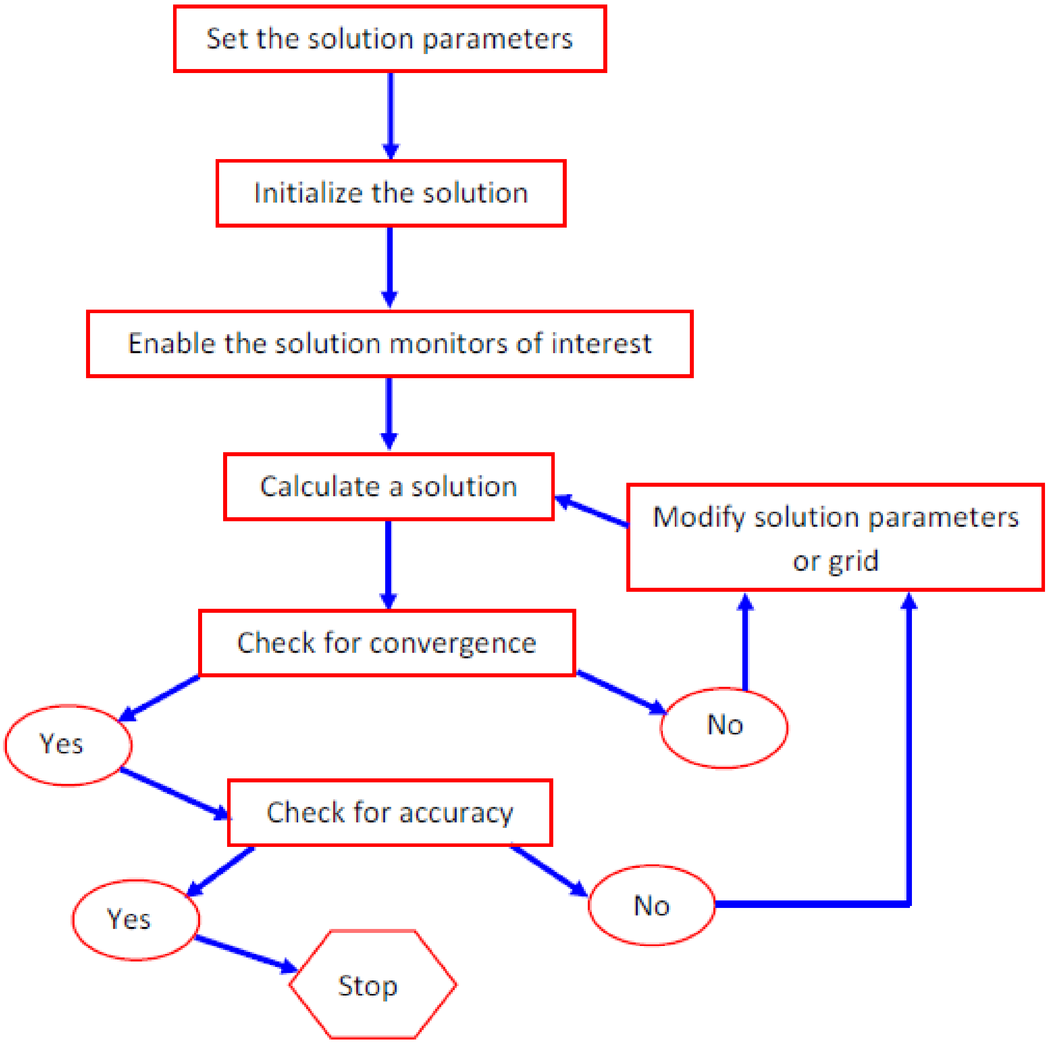

Fig. 2 Algorithm of fluent software.

5. Results and Discussion

The results of the simulation performed using fluent on air circulation in the cabin i) when fans are placed on opposite faces ,ii when fans are placed on same side and iii) when fans are placed diagonally opposite are shown in Fig. 3,Fig.4 and Fig.5 respectively.The temperature variation plots for the three cases are shown in Fig.6 ,Fig.7 and Fig.8 respectively.The flow does not circulate throughout the cabin and is confined to a limited space when fans re placed on opposite faces and this configuration does not provides effective cooling as the temperature in most of the part is still high. The flow circulates throughout the cabin but dead zone formed have a significant size and therefore effective cooling occurs in limited space when fans are placed on the same side.Fig.9 shows that the minimum temperature that can be achieved after running the fan assembly for 100sec is 328K (55^0C) & from interpolation we can conclude that after 200 sec the temperature achieved is 320K. The flow circulates effectively throughout the cabin,so a very small dead zone is formed and therefore effective cooling occurs in complete space when fans are placed diagonally opposite to each other. Fig. 10 shows that the minimum temperature that can be achieved after running the fan assembly for 100sec is 324K (51^0C) & from interpolation we can conclude that after 200 sec the temperature achieved is 316K.

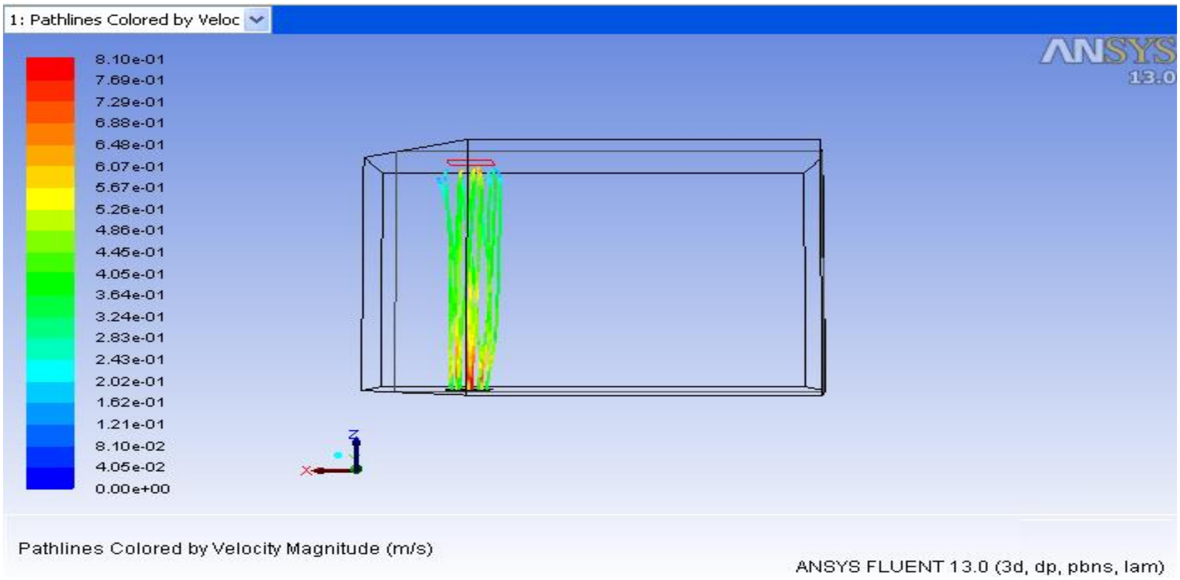

Fig. 3 Simulation results of air circulation when fans are placed opposite to each other

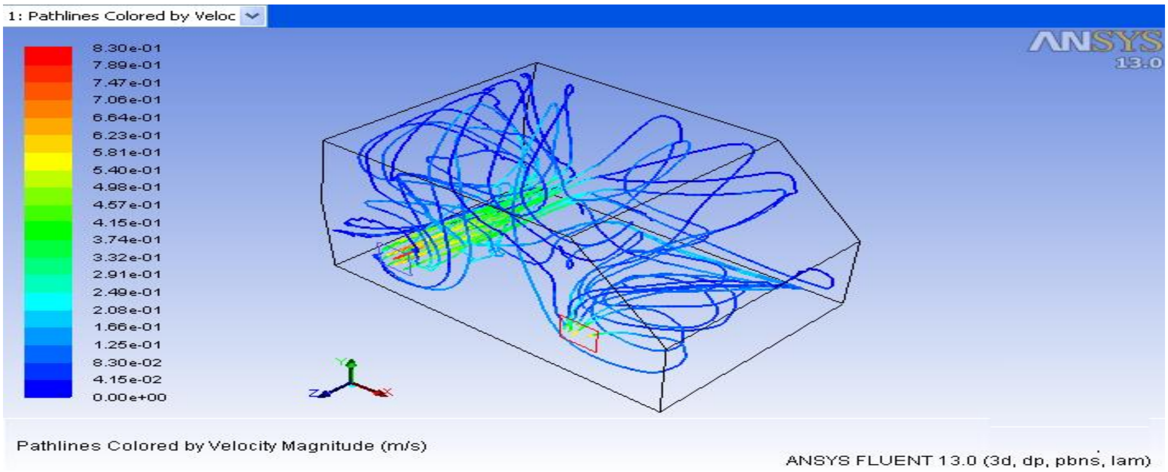

Fig. 4 Simulation results of air circulation when fans are placed on same side

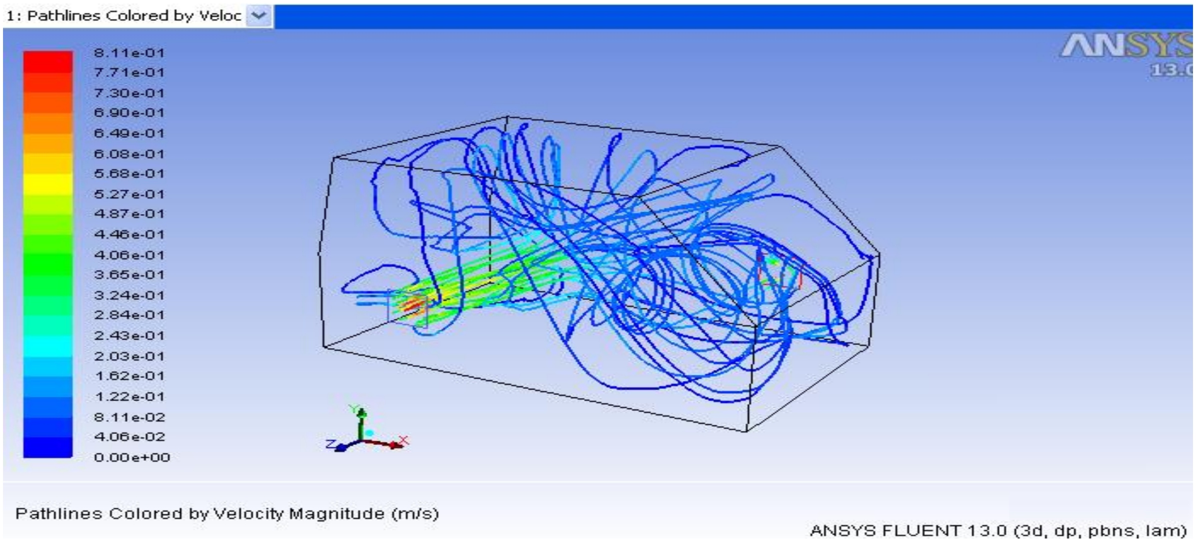

Fig. 5 Simulation results of air circulation when fans are placed diagonally opposite to each other

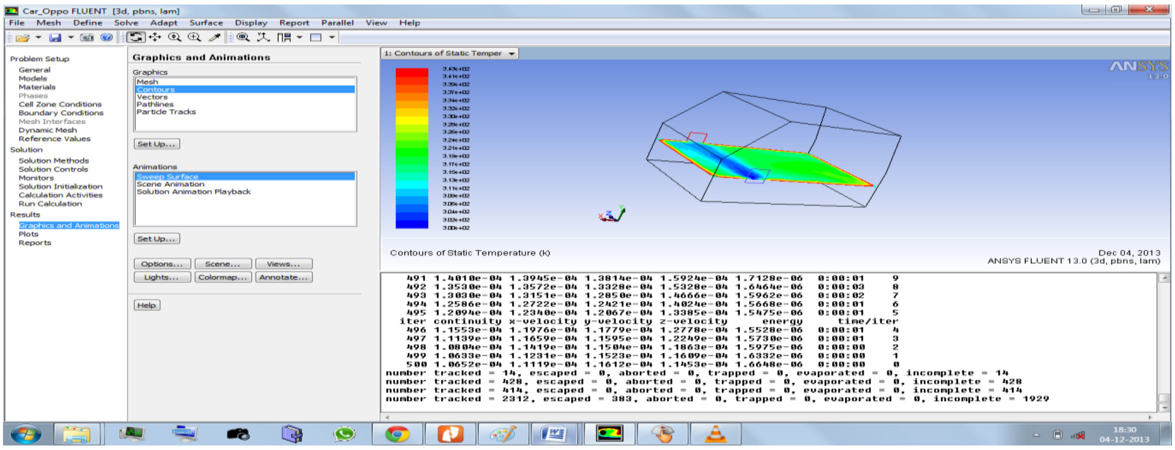

Fig. 6 Temperature plots of air circulation when fans are placed opposite to each other

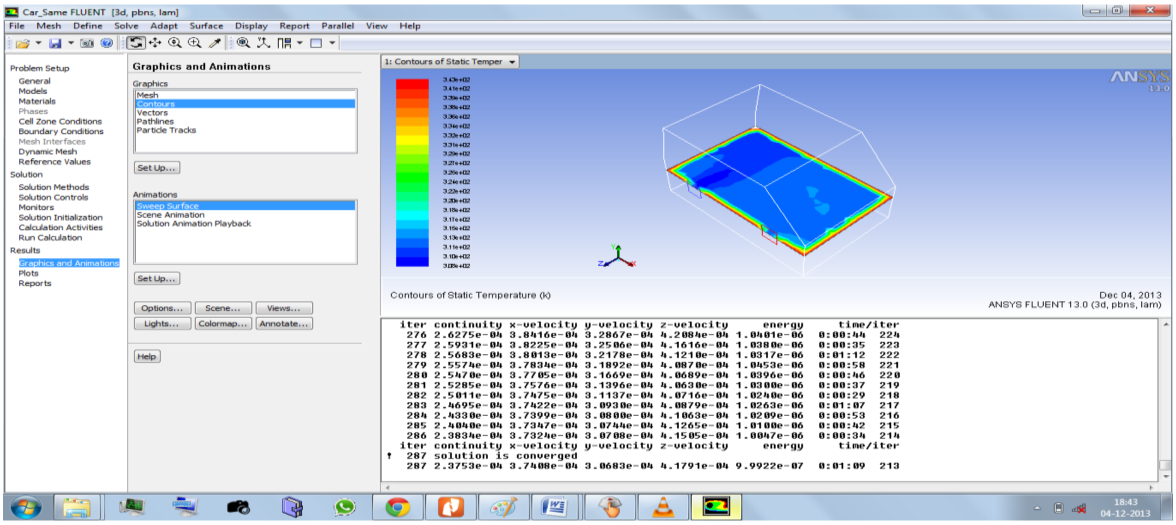

Fig. 7 Temperature plots of air circulation when fans are placed on same side

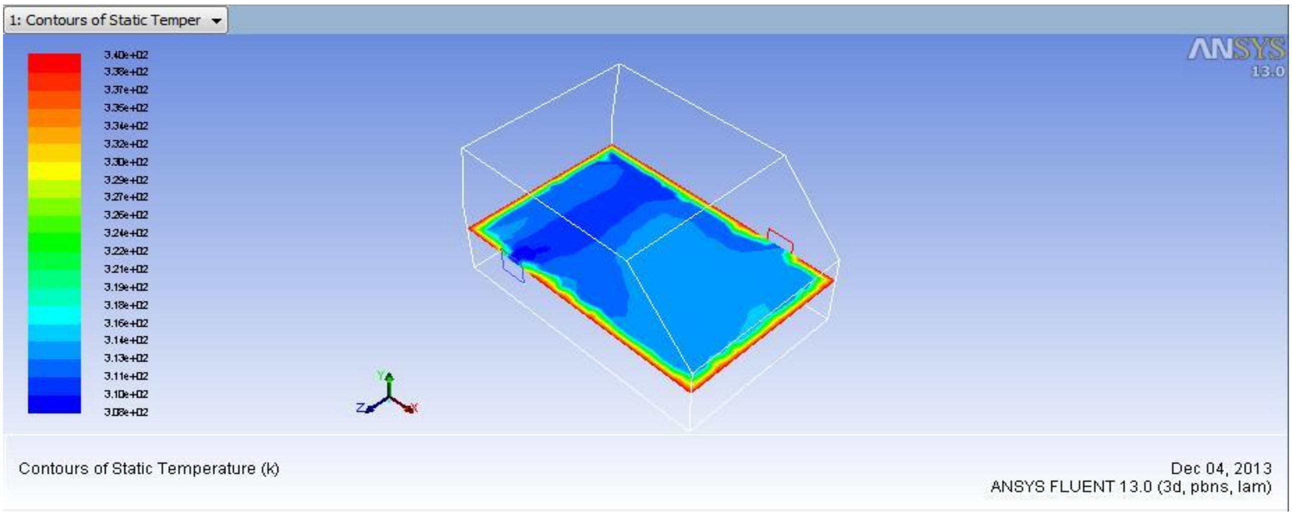

Fig. 8 Temperature plots of air circulation when fans are placed on diagonally opposite side

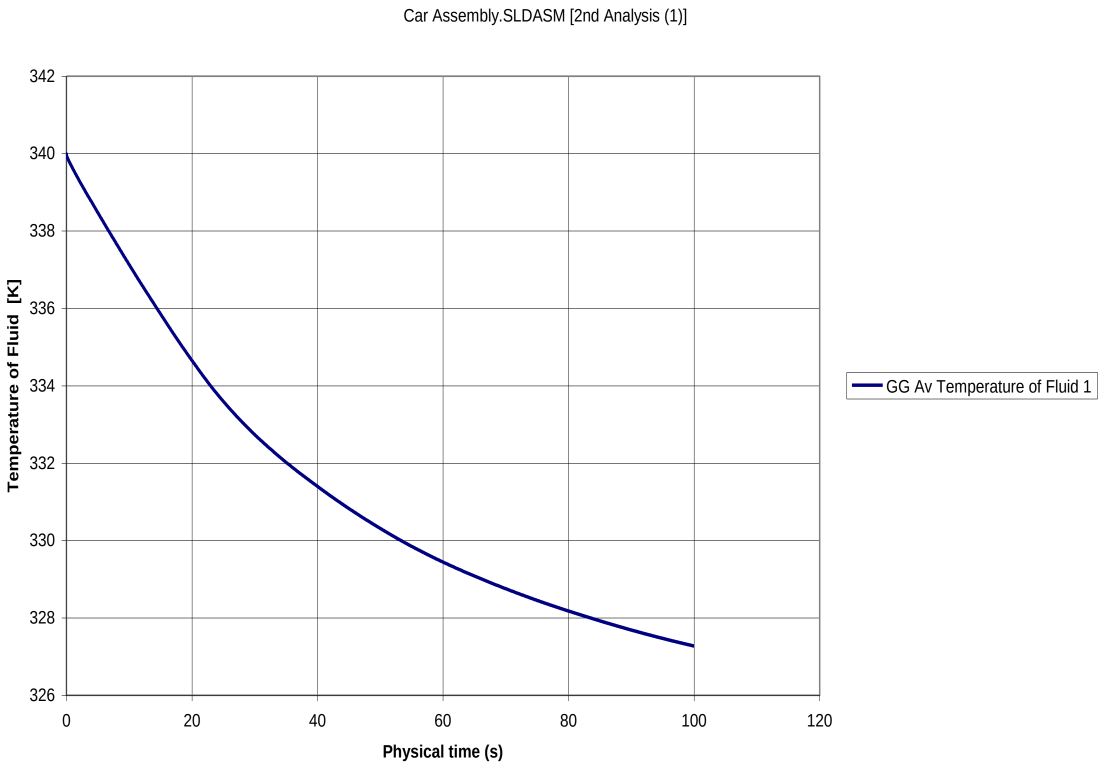

Fig. 9 Temperature vs time plot of cabin when fans are placed on same side

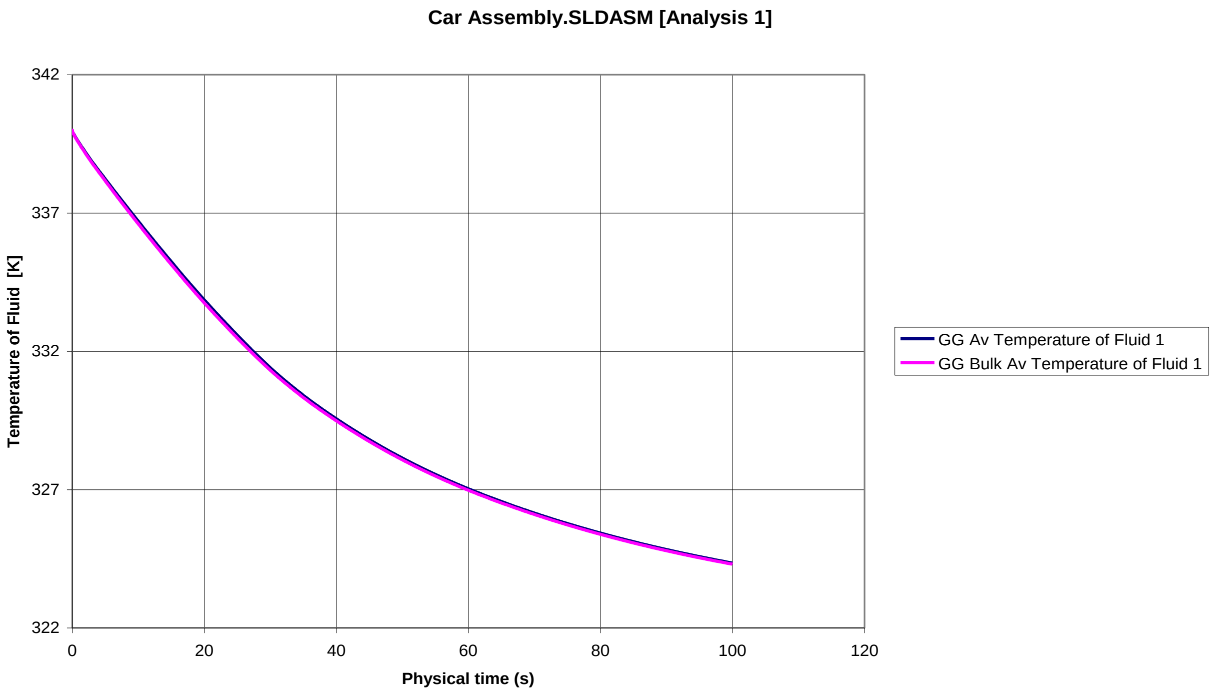

Fig. 9 Temperature vs time plot of cabin when fans are placed diagonally opposite

6. Conclusions and future scope

i)In Ducts Placed opposite to each other:

- Flow does not circulate throughout the cabin
- There are large dead zones
- There is no significant temperature drop inside the cabin

ii) In Ducts placed on same face

- Flow circulation is better as compared to previous case
- There is significant size of dead zones
- Temperature inside the cabin drops to 328K after 100 sec

iii)In Ducts placed diagonally opposite

- Flow circulates throughout the cabin & is best compared to above case
- There are very small dead zones
- Temperature drops to 323K after 100 sec

Advanced insulation materials, predictive algorithm-driven smart HVAC systems, integration of renewable energy sources such as solar panels, active thermal management technologies, user-friendly interfaces for temperature control, safety sensors for occupant monitoring, V2I communication for real-time environmental data, establishment of regulatory standards, extensive field testing, and cost-saving strategies are some of the future developments in automotive cabin temperature control. These programs aim to solve the pressing demand for efficient cabin temperature control while also enhancing comfort, safety, and energy economy. These technologies seek to minimize environmental impact and operating costs while delivering a safer and more comfortable driving experience for passengers through improved thermal comfort and reduced energy usage.

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