

Micro-Cooling/Heating Strategy for Energy Efficient HVAC System

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Shailendra Kaushik, Kuo-huey Chen, Taeyoung Han and Bahram Khalighi
General Motors Company

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ABSTRACT

Energy efficient HVAC system is becoming increasingly important as higher Corporate Average Fuel Economy (CAFE) standards are required for future vehicle products. The present study is a preliminary attempt at designing energy efficient HVAC system by introducing localized heating/cooling concepts without compromising occupant thermal comfort. In order to achieve this goal of reduced energy consumption while maintaining thermal comfort it is imperative that we use an analytical model capable of predicting thermal comfort with reasonable accuracy in a non-homogenous enclosed thermal environment such as a vehicle's passenger cabin. This study will primarily focus on two aspects: (a) energy efficiency improvements in an HVAC system through micro-cooling/heating strategies and (b) validation of an analytical approach developed in GM that would support the above effort. The paper will discuss the analytical approach adopted in this study, its application in predicting overall comfort and sensation levels for various micro-cooling strategies, and subsequently comparing these predicted results with the real human subject test. The combination of the present CFD work coupled with the thermal comfort simulations will allow for the exploration of different microclimate control strategies as they relate to occupant thermal comfort for an "Energy Efficient HVAC System".

1. INTRODUCTION

A recent comprehensive study of fuel consumption for vehicle air-conditioning (AC) on a state-by-state basis using thermal comfort based approach by NREL's Johnson [1] shows that US uses an estimated 7 billion gallons of gasoline every year for air conditioning vehicles. This is equivalent to 6% of domestic petroleum consumption, or 10% of US

imported crude oil. The study further shows that vehicle air conditioning loads are the most significant auxiliary loads and outweighs even other significant loads such as rolling resistance, aerodynamic drag or driveline losses. The fuel economy of a vehicle drops substantially when the AC compressor load is added to the engine. The AC increases the fuel consumption of a conventional gas-fueled car by approximately 35% and significantly higher for hybrids. This translates to a reduction of fuel economy from approximately 22 mpg and 18 mpg to 17mpg and 15mpg for a typical sedan and a light-duty truck, respectively. Given this backdrop, "Energy Efficient HVAC Systems" is getting significant attention from the automotive industry to improve fuel economy of their vehicles, and to conform to tighter CAFÉ standards. As is widely recognized in the automotive industry, energy efficiency of HVAC systems can be improved using the following three techniques: (a) optimization of the existing conventional HVAC system (b) use of advanced window glazing for reduced passenger cabin soak temperatures [2] and (c) localized (micro) cooling/heating strategies. It is the third proposal in the preceding list - localized cooling/heating, that is of primary focus of this paper. The key idea behind this technique is to provide adequate levels of overall thermal comfort to the vehicle occupants with reduced demand on the HVAC system. It is hypothesized that in a conventional AC system, a significant portion of the AC cooling energy is lost to the ambient. A small fraction of this is used in providing thermal comfort to the occupants. This becomes apparent by noting that both the air velocity and the air temperature diffuse substantially in its travel from the IP mounted AC outlets to the occupant. It is further assumed that by delivering cool AC air directly to the thermally sensitive body parts using spot-cooling nozzles, equivalent thermal comfort levels, as typically provided by a conventional AC system, can be achieved at a fraction of energy cost.

In order to test this theory, we propose a cutting-edge simulation methodology that combines CFD with the state-of-the-art human physiology and comfort model. With this approach one can complement the expensive and time consuming human subject testing required to optimize the two competing requirements - energy efficiency and thermal comfort. In order to arrive at a global optimum (minimum AC energy and maximum thermal comfort) a large number of expensive tests or simulations are typically needed. The paper, therefore, proposes a highly streamlined, largely automated and a validated analytical process involving CFD, human physiology model for thermoregulation and a thermal sensation/comfort perception model to assess the relative merits of various localized or micro cooling strategies on thermal comfort, relatively rapidly and inexpensively. However, before employing this analytical technique to optimize the local cooling strategy in a vehicle, it is vital that the model predicted results correlate reasonably well with the human subject testing for thermal comfort. All of the testing for micro-cooling strategies was carried out in University of California at Berkeley (UCB). Their thermal environment test setup was appropriately modified to simulate a vehicle passenger cabin with steering-wheel, glass windows and a heater to replicate the effect of solar radiation on the human thermal comfort in a vehicle. A number of individual micro-cooling strategies, such as ventilated car seat, an array of three front nozzles just at the steering wheel, a nozzle to cool the neck and face area, and a seatbelt capable of delivering HVAC air close to the body were tested and analyzed. Since the preliminary results from the test data suggest significant thermal comfort gains by using ventilated seats all of the subsequent cooling strategies that were tested and analyzed, and presented in this study, include ventilated seat as a default.

The paper is organized as follows: in section 2 a detail overview of the current analytical process for human thermal comfort and sensation is laid out; section 3 describes the various micro-cooling strategies that were tested and analyzed for human subject comfort evaluations; in section 4 both the test and the corresponding simulated results are discussed, and finally in section 5 we provide the conclusions of this study and plan for future work.

2. PROPOSED HUMAN THERMAL COMFORT ANALYTICAL PROCESS

The key aspects of the proposed human thermal comfort (HTC) analytical methodology are described in the following subsections:

2.1. PASSENGER COMPARTMENT MODEL

The proposed HTC modeling process begins with identifying and procuring all the interior surfaces comprising the passenger compartment, including seats and appropriately segmented manikins from the CAD system. In this study, we created both the Fluent and the Radtherm models of a cross-over vehicle passenger compartment as shown in [Figure 1](#). The model has all the key design parameters for thermal comfort modeling, such as the A/C outlet location and size, windshield angle, body vent locations, and many other parameters which influence the performance of the HVAC system. The [Figures 1a](#) and [1b](#) show the corresponding CFD model in Fluent [3] with a manikin, representing a 50-percentile male in the driver's seat. ANSA modeling software [4] was used to mesh the vehicle passenger compartment. In this paper, only the driver-side manikin, segmented into 21 body parts was modeled. A separate 2D surface mesh model of the identical passenger cabin for analysis in Radtherm [5] is shown in [Figure 1c](#).

2.2. PASSENGER COMPARTMENT CFD AIR FLOW ANALYSIS IN FLUENT

Prior to predicting human thermal comfort and sensation levels using UCB's HTC model, it is first required to compute both the core and the skin temperatures of all body segments. These are computed in Radtherm through solution of energy balance equations at the surface of these body segments. However, since Radtherm relies on a CFD solution for convective boundary conditions, Fluent was used in this study to provide this information. Around 3,000,000 tetrahedral elements were required to capture the geometric and the flow details of the passenger compartment with Fluent. A converged steady-state flow solution in Fluent was used to provide the convective heat transfer coefficients and film temperatures on the entire model to Radtherm. However,

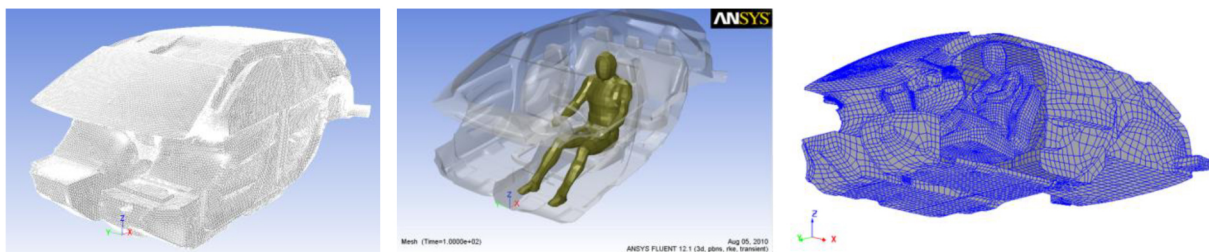


Fig 1a, b & c. Fluent and Radtherm surface mesh representations of the passenger compartment.

for the manikin, velocities close to the surface from Fluent was used to compute heat transfer coefficients based on an empirical formulation available in Radtherm. The entire data transfer process between Fluent and Radtherm has been fully automated.

2.3. PASSENGER COMPARTMENT THERMAL ANALYSIS IN RADTHERM

As mentioned in the above sub-section, the convection heat transfer coefficient and film temperature distribution on the entire passenger compartment including the manikin is imported from Fluent and mapped onto the much coarser Radtherm's surface mesh model. However, Wang's [6] empirical formula relating velocity to heat transfer coefficients on the manikin was chosen instead of the Fluent's convective coefficients. This was done primarily because of the limitation of wall-function based formulation to provide accurate convective coefficients on these relatively low velocity regions on the manikin. One can observe a checkerboard pattern of heat transfer coefficient distribution on the manikin when plotted in Fluent. In this study, standard procedure recommended by Radtherm for HTC was followed.

2.4. PREDICTION OF OCCUPANT SKIN AND CORE TEMPERATURES

The human physiology model in Radtherm can simulate an arbitrary number of body segments. Each of these segments consists of four body layers (core, muscle, fat, and skin tissues) and a clothing layer. A blood pool node and a series of conductors provide for convective heat transfer between arterial blood and the tissue nodes as well as for the countercurrent heat exchange between the arteries and the veins. The human body thermal regulation is mainly achieved by regulating the blood flow, so a realistic blood flow model is important for any dynamic model of the human thermal comfort. The occupant body uses vasoconstriction and vasodilatation to regulate blood distribution in order to control the skin temperature through an increase or decrease of heat loss to the environment. Veins and arteries are paired, even down to very small vessels, and veins carry heat from the arteries back to the core. The details of this human physiology model are described in [7,8,9,10]. The model is able to predict both core and extremity skin temperatures with a reasonable accuracy under a range of environmental conditions. Detailed validations for transient conditions can be found in [11, 12].

The current model includes clothing nodes to model the heat capacitance and the resistance to the flow of both heat and moisture due to the clothing. Heat capacity of the clothing is important when considering the transient effects [13]. Moisture resistance is important to correctly model the evaporative heat loss from the body through clothing. The

human physiology varies significantly among individuals, and these differences can affect the perceptions of thermal comfort; e.g., higher metabolic rate or increased body fat can cause people to feel warmer. The present model which is a standard 50 percentile physiology model was used for the human physiology with a metabolic rate of 2 MET (1 MET= 1 kcal/kg/hr). Clothing level varies based on the body segment - short sleeve shirt, trousers, socks, shoes, etc. for summer clothing during cool-down simulations.

In almost any environment, the occupant body is in contact with solid surfaces and loses or gains heat via heat conduction. In the passenger compartment, the seat contacts a considerable fraction of the body and must be considered to accurately model the occupant. The current model includes a contact surface for each body segment. The thermal properties of the contact surface are used to simulate its surface temperature. Each body segment includes the fractions of the exposed skin and clothed skin in contact with the surface.

2.5. PREDICTION OF THERMAL SENSATION AND THERMAL COMFORT FROM THE SKIN AND CORE TEMPERATURES

The human sense of thermal comfort is very complex, and involves both the physiological and the psychological states of a person under specific conditions. In uniform environments, sensation and comfort correlate well: a neutral sensation corresponds to the best comfort; warmer or cooler sensations correspond to reduced comfort. In non-uniform or transient environments, however, the relationship between sensation and comfort becomes more complex: for example, the same cool face sensation could be perceived as very pleasant if the whole-body is warm or uncomfortable if the whole-body is cold.

In the past few years, UC Berkeley has been working on studies of local body part thermal comfort. UC Berkeley has carried out human subject tests, developed comfort predictive models, and has gained valuable knowledge regarding human responses to the local cooling/heating. The human subject test results and local comfort predictive models developed from those tests provide unique information for understanding the human responses and the prediction of their responses. In both uniform and non-uniform environments, different parts of the body feel warmth and cool at different levels. The differences obviously depend on many factors, such as how the body's thermoregulatory physiology responds to the body's overall thermal state, asymmetry in clothing insulation and the environment conditions around the body, the rate of change in the body's skin and core temperatures, and on the thermal sensitivity of the different parts involved.

UC Berkeley proposed to develop a local sensation model of the form in Eq. (1). The local sensation model is a function of local skin and mean skin (or core) temperatures and their rates of change. The local- and mean-skin temperatures represent the response to stable conditions, and the derivatives of skin temperature and core temperature represent response to transients. The local skin temperature represents the local skin thermal conditions. Mean skin temperature represents the whole-body thermal status in the static part of the model. There will be a distinct model for each body part, so that together they capture the asymmetrical features of the environments. Based on the local and overall whole body sensation and comfort votes of the human subject tests, UC Berkeley performed regression analyses to arrive at the overall sensation and comfort models as shown in Figure 2. The details of the UC Berkeley thermal sensation and the thermal comfort models can be found in [14,15,16,17,18,19].

$$\text{Local Sensation} = f\left(T_{\text{skin},i}, \frac{dT_{\text{skin},i}}{dt}, \bar{T}_{\text{skin}}, \frac{dT_{\text{core}}}{dt}\right) \quad (1)$$

where:

$T_{\text{skin},i}$ = local skin temperature of one body part
 t = time
 $\bar{T}_{\text{skin}}$ = the mean skin temperature
 $dT_{\text{skin},i}/dt$ = the derivative of local skin temperature
 dT_{core}/dt = the derivative of the core temperature

Term i in the model ranges from 1 to 19, corresponding to the body parts: head, face, neck, breathing zone, chest, back, pelvis, left and right upper arms, left and right lower arms, left and right hands, left and right thighs, left and right lower legs, left and right feet.

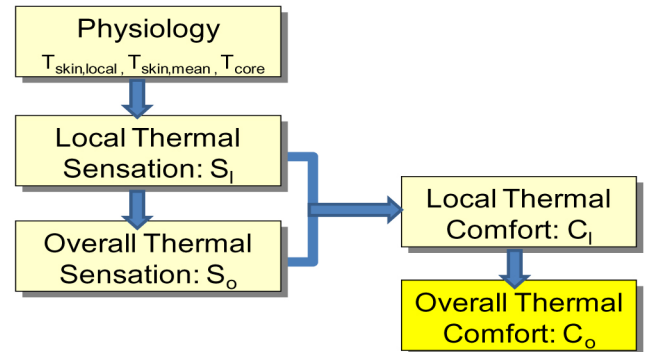


Fig 2. A flow chart to show models developed and their relationships

3. LOCAL/MICRO COOLING STRATEGIES FOR ENERGY EFFICIENCY

One of the key objectives of this study, besides validating the newly proposed analytical approach, is to explore various micro-cooling/heating strategies and to subsequently implement a subset of these in a real vehicle. The idea is to pick the optimal combination of the various individual micro-

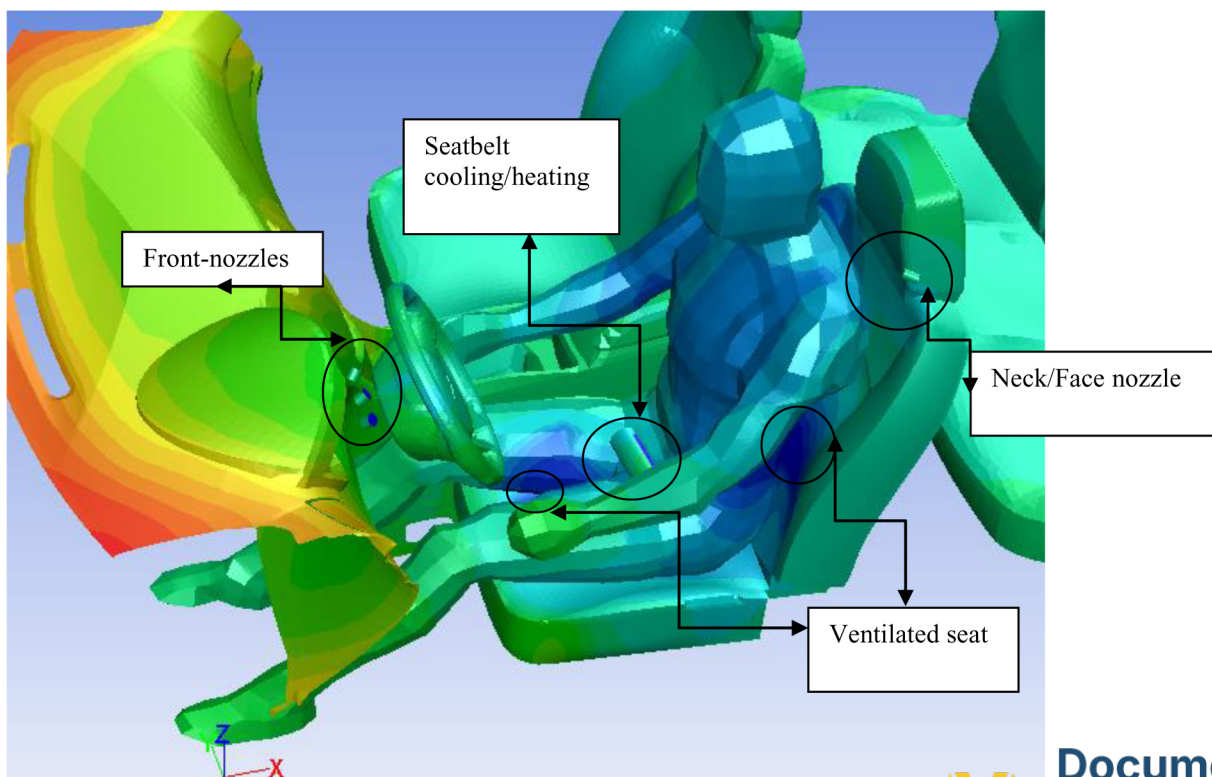


Fig 3. An overall pictorial depiction of various micro-cooling strategies discussed in this paper