

Thermal Comfort Modeling of Cooled Automotive Seats

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ABSTRACT

Seat cooling systems are becoming more common as luxury features offered by original equipment manufacturers. Despite the extensive research & application of these systems, a thermal model and comfort requirements of the occupant/seat system have not been established. Without a model or thermal criteria for comfort, the seat temperature & humidity conditions required for optimal comfort can not be defined.

A synopsis of the thermal comfort conditions required to achieve an occupant's subjective comfort as well as their comfort transition points are explained. In this context a model is designed specifically from a heat and mass transfer perspective between an occupant and a seat cooling system. Focus is given to the local conduction, convection, and evaporative cooling that takes place at the body to seat surface interface. The goal of this model is to examine the occupant's physiological response to the seat cooling system in order to identify what thermal conditions & energy quantities are required to achieve an occupant's local neutrality point. The model is then verified using a pre-defined 50th Percentile American Male (AM50).

With a defined AM50 occupant under varying thermal conditions the quantities of energy transfer required to achieve thermal equilibrium (comfort) have been defined. In conjunction the ratios of the necessary heat transfer to mass transfer (moisture removal) were defined in order to give total comfort to an occupant at the same conditions.

The benefits from the investigation findings will allow for seat cooling system designs to be optimized or improved for next generation seat cooling systems. Using this component level model in conjunction with the total HVAC system would allow for future studies in regards to a total occupant

comfort system with reduced power consumption & maximized occupant comfort.

INTRODUCTION

The goal of a vehicle air conditioning system is to create a thermally comfortable environment for the occupant. This is done by providing the interior cabin of the vehicle with cooled/warmed. The applied airflow to the vehicle cabin is the main source of occupant thermal regulation. Developments in alternative methods for creating comfort under warm environments have become a focus within the automotive industry for the potential reduction in fuel consumption while the AC system is engaged. These methods include reducing the thermal load of the vehicle, enhancing AC system efficiency, & indirect/direct delivery of comfort. For this study the direct occupant cooling devices, also known as seat cooling systems, will be considered with respect to the total vehicle thermal management.

Seat cooling systems have been considered for use within the automotive industry over the past 88 years. The first automotive seat cooling system was proposed in 1922 by Lu Alkire & Wiley Carter [1] showing how to pass air through a seat and thereby cool the occupant during a warm day. The technology & construction of the seat cooling systems have greatly increased over the years with independent seat ventilation systems to the inclusion of thermoelectric cooling devices (seebeck effect devices). In the end, the final goal of these systems is the same; achieving thermal comfort.

Within this document several methods for cooling a seat will be discussed and therefore any mechanism that utilizes an external component to provide comfort to an occupant via airflow/other mechanism to the seat will be labeled as a seat cooling system or cooled seat.

Despite the extensive research & application of seat cooling systems within the automotive industry, a thermal model & basic comfort requirements of the occupant on the seat have not been established. Without a model for the occupant seat interface the critical components related to thermal comfort based on energy transference cannot be identified. With the creation of a model and energy values quantified it is then possible to understand what steps are required to optimize/maximize the benefit from a seat cooling system within a vehicle during warmer environmental conditions. Inherently the final goal of any product is the optimization based on performance to other factors (e.g. cost, mass, etc.). This study will support the realization of this performance output.

The key to this papers output is the creation of the seat cooling model that incorporates all pertinent forms of energy transfer within the seat occupant interface being, conduction, convection, & evaporation. In conjunction with energy transfer the focus on local discomfort instead of the total discomfort allows the study to be completed with microclimates of interest which can then be utilized to achieve different types of desired comfort at respective locations. Also, taking a step back from the typical thermal rating scale, it's been realized that an additional subjective measure is required to call out the relative wetness feeling due to perspiration within given microclimates.

In the past, thermal comfort models have been established to determine appropriate working conditions for all types of activities by ASHRAE [2]. These guidelines are followed across the industry to show the physical limits of working throughout all types of environmental conditions. The acceptable working conditions were originally studied by P.O. Fanger [3]. Fanger is most notably known as the founder of general human thermal comfort model. Several key points that come from the following technical body were based on his findings. Fanger's studies focus on the environmental conditions in an open space and the respective energy transference that takes place. This energy transference is then related to the occupant's thermal comfort and how the energy generated is required to be dissipated otherwise there would be a side effect to thermal comfort (cool/warm feeling). This study was helpful to understand the total environment; however when focus is given to a medium/ microclimate, the interaction cannot be modeled as previously given.

In conjunction with theoretical models of comfort passed studies by NREL [4] have shown great benefit from seat cooling systems to improve total occupant comfort. These studies have shown potential to reduce up to 0.5% fuel usage when the AC system is on. While these fuel savings are small on an individual vehicle scale, considering the national level of fuel usage & potential green house gas reduction, the summation is significant. The potential benefits from their study show how direct cooling systems can be utilized for improved time to comfort and thereby reduce AC usage;

however our study will try to focus on the minimum/ optimized amount of cooling that is necessary to achieve comfort at steady state within actual vehicle.

Understanding past works difference and key points to this documents this body of work will set out to create the detailed model of the occupant seat interface from the standpoint of energy transference. By taking this model it will be shown that a team of panelists' subjective ratings of thermal and wetness feeling can be linked to the quantities of energy transferring between the two bodies. The neutral/ comfortable subjective rating correlation to the energy transference model will then allow for the quantities of energy required to be captured. Additional discussion points for the effects to the occupants overall comfort with a relationship to wetness feeling will be given in regards to this study preceding the final energy conditions required to achieve comfort locally.

NUMERICAL MODEL

To capture a body's energy balance relationship with its environment it was necessary to review Fangers full body model demonstrated in Fig 1. The focus of this model was related to the thermal comfort & energy transference of the occupant. This model was given for a person within an open room and was created to show the relationship between how H the body's heat generation was dissipated to its environment. The forms and order of transference were from K the conduction through the body, then from the body to the actual surroundings are R radiation, C convection, Ed diffused sweat, Esw evaporated sweat, Ere respiratory moisture transference loss, and L latent heat.

<figure 1 here>

From the thermal circuit given in Fig 1, it is possible to represent this energy transference by Eqn. (1)

$$H = K = R + C + E_d + E_{sw} + E_{re} + L$$

Eqn. (1)

One of the key terms to Fanger's model is related to body heat generation (H). H is based on the body's activity level. Table 1 shows a list of real world activities and the corresponding energy production (metabolic rates). These values give a general understanding of the amount of energy the body is producing. It should be noted that even with no mechanical/physical output, it's possible to quantify the relative magnitudes of the outgoing, discharged energy forms.

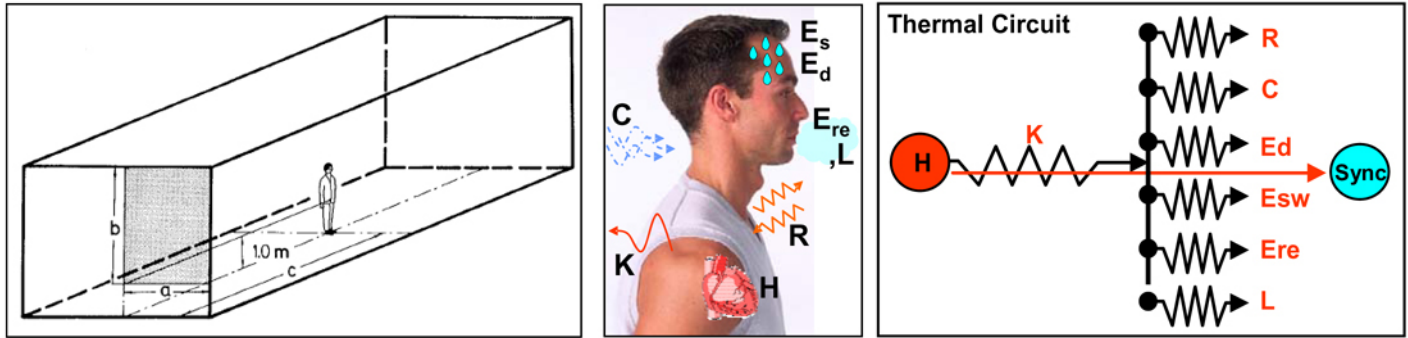


Fig. 1. P.O. Fanger's energy model for body within a room

Table 1. Energy production for body during typical activity

Activity	Internal Energy Production Rate (kcal/hr*m ²)
Sleeping (laying flat)	35
Standing	60
Walking - 5.6 km/hr	160
Carpentry – saw by hand	200- 240

The reason the H term is critical to the understanding of thermal comfort, is because the amount of energy generated & not dissipated will be stored. General understanding of heat capacities will tell you an increase in energy storage will result in a temperature increase or other physiological reactions. Thereby an understanding of these energy quantities and their relationships to one another can be related to the general feeling of warmth/cooling effect found on the body itself. By quantifying the relative values of energy dissipation & how it may be removed from the body it's possible to relate the Fanger full body model to a micro-climate model solely on an occupant sitting on a cooling seat system.

Utilizing the basic concepts of Fangers model and including assumptions based on the physical interface it is possible to create a separate micro-climate model with the given assumptions.

- 1). Localized area of interested disregards respiratory heat loss terms (E_{re} , L)
- 2). Heat transference is through "thin" clothing thereby having energy transfer via the other forms simultaneously with conduction (K moves to other side of equation and redefined as K')
- 3). All sweat released from the body is finally evaporated. Therefore the quantity of E_{sw} can be pulled from past studies of constant sweat evaporation and its relationship to evaporative cooling. E_d term will be quantified by vapor pressure differences.

- 4). Energy generation is evening distributed per unit area
- In the new physical model several features of the interface are shown. This model highlights the fact that there are contact & non-contact points between the occupant and the seat. At the points of contact energy terms related to the circulating air velocity go to zero, where as on the non-contact portions of the model these are highlighted. The interaction of these two types of areas is what has been defined as the energy transference boundary. Considering this occupant seat interface it's possible to get the simplified version of the energy transference model scene in Fig. 2.

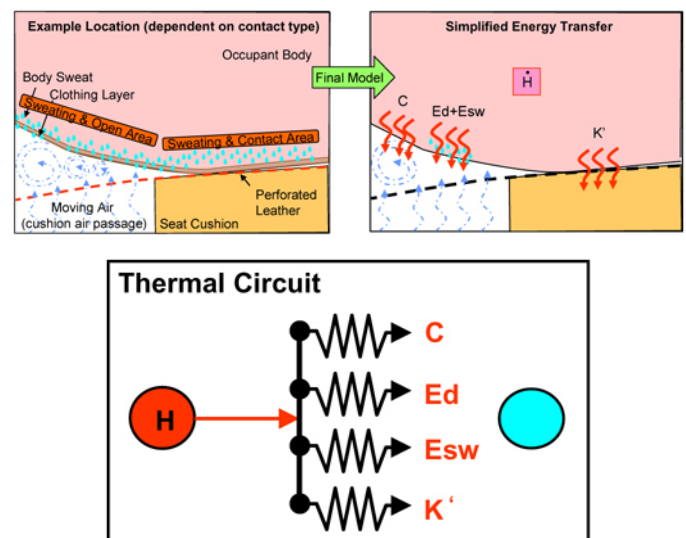


Fig. 2. Occupant seat interface micro-climate model

From the thermal circuit given within Fig 2. it is possible to represent this new models energy transference by Eqn. (2)