Thermal Comfort Assessment in Vehicle: A Review

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Abstract *— Mengukur kenyamanan termal dalam kendaraan akan berbeda dari bangunan. Pengaruh radiasi matahari, insulasi interior yang buruk, ketidakseragaman rata-rata temperatur radian, keterbatasan waktu dalam memastikan parameter nyaman adalah beberapa karakteristik dari lingkungan kendaraan. Dari studi yang sudah pernah dilakukan, menunjukkan bahwa sampai saat ini belum ada standar internasional dalam menentukan kenyamanan termal dalam kendaraan. Metodologi yang dilakukan tidak konsisten, ini disebabkan karena banyaknya perbedaan yang krusial dalam pendekatan teori. Para peneliti dalam bidang kenyamanan termal dalam kendaraan rata-rata mengadopsi konsep dan prosedur metodologi dari penelitian sebelumnya yang sebagian besar ditujukan untuk bangunan. Paper ini ditujukan untuk mengulas beberapa studi dalam bidang kenyamanan termal dalam kendaraan sekaligus memberi ringkasan tentang model-model pendekatan yang ditujukan untuk keadaan transien dan lingkungan yang tidak seragam, sekaligus sebagai bahan rujukan bagi peneliti selanjutnya dalam memilih metodolgi yang sesuai dengan kebutuhan penelitian.*

Keyword: Thermal comfort, vehicle, thermophysiology

INTRODUCTION

Thermal comfort is studied in many areas, built environment, open space area and vehicles. Thermal comfort is one of the important parameter for engineers in designing HVAC (heating, cooling and air conditioning) system.

According to ASHRAE (American Society of Heating Refrigeration and Air Conditioning Engineers), thermal comfort is defined as condition of mind in which satisfaction is expressed with the thermal environment (ASHRAE, 1993). The reason for creating thermal comfort is to satisfy man's desire to feel thermally comfortable (Fanger, 1972).

Comfort is related with the heat balance. Heat balance means the rate of heat generation of the body is equal to the rate of heat loss from it. To maintain the functionality of vital organs like liver, spleen and heart yet ensure comfort condition, the heat generation of the human body must be transmitted to the environment. Thus the body has its control system that is responsible for balancing this thermal inputs and thermal losses named thermoregulatory.

There are three main effector mechanism involved in thermoregulation (Encyclopedia of Nursing & Allied Health, 2007). The first is the vasomotor system, which consist of the nerves that act on vascular smooth muscle to control blood vessel diameter, it is responsible for two physiological responses called vasodilatation and vasoconstriction. The first increases blood flow in the tissue and the second decreases it. The second is provided by metabolic effectors, which are substances produced by the body to increase its activity. The third main effector mechanism is provided by the sweat glands.

According to Atmaca and Yigit (2005), "in warmer conditions or with increased activity, the vasomotor system and sweat glands occur in order to dissipate the metabolic heat generate and maintain the heat balance between the body and its surrounding. In hot

conditions, the most important thermoregulatory control process is active perspiration. If the relative humidity is high, the latent heat dissipation ability of the body reduces depending on the increase in vapor pressure and the sweat rate increases over the body. In these case human feels discomfort due to increase in skin temperature and residual skin wettedness. Skin temperature affects thermal comfort. The deviation of skin temperature from its respective neutral set point occur from not maintaining thermal balance". If the environment is maintained at conditions where the body can easily maintain a thermal balance with the surrounding, then a person can be considered to feel comfortable.
Assessing thermal comfort in any areas, we surely need methods. According to O'Callaghan (1978), there are three basic models used that define thermal comfort criteria; the physical, physiological and sociological approaches. The physical model considers the body as a thermal system in which heat is exchanged between the body tissues and the environment through the skin and clothing. The physiological model examines subjective responses to imposed thermal environments (thermal sensation) and produces data for comfortable conditions. The sociological approach concerns on the behavioral response of an individual to any particular stimulus. Sakoi et al. (2006) added there are at least six factors that influence the thermal state of human. They classified into two classes: environment factors and personal factors. Four of them are environment factors which include air temperature, thermal radiation, air velocity and relative humidity. The other two is come from personal factors which covered clothing insulation and activity (metabolic rate).

The very first model of thermal comfort was developed by P.O Fanger back in 1970s. He defined thermal comfort with two indexes, PMV and PPD.
PMV (Predicted Man Vote) number:

$$PMV = 0.303e^{-0.036M} + 0.028L \quad (1)$$

Where M is metabolic rate and W is external work. L is thermal load on the human body, defined as below:

$$L = (M-W) - 3.05x10^{-3}[5773 - 6.99(M-W) - p_a] - 0.42[(M-W) - 58.15] - 1.7x10^{-5}.M(5867 - p_a) - 0.0014M(34 - t_a) - 3.96x10^{-8}f_{cl}[(t_{cl}+273)^4 - (\bar{t}_r + 273)^4] - f_{cl}.h_c(t_{cl} - t_a) \quad (2)$$

and,

$$t_{cl} = 35.7 - o.028(M-W) - I_{cl}\{3.96x10^{-8}.f_{cl}[(t_{cl}+273)^4 - (\bar{t}_r + 273)^4] + f_{cl}.h_c(t_{cl} - t_a)\} \quad (3)$$

I_{cl} = clothing insulation
f_{cl} = ratio of clothed to nude body area
h_c = convective heat transfer coefficient
p_a = water vapor partial pressure in the ambient air

where convective heat transfer coefficient, h_c is defined as follows:

$$h_c = \begin{cases} 2,38(t_{cl}-t_a)^{0.25}, \; if \; 2,38(t_{cl}-t_a)^{0.25} > 12,1\sqrt{V} \\ 12,1\sqrt{V}, \; if \; 2,38(t_{cl}-t_a)^{0.25} < 12,1\sqrt{V} \end{cases} \quad (4)$$

The PMV scale is range from -3 to 3

Scale	Thermal Sensation
+3	Hot
+2	Warm
+1	Slightly warm
0	Neutral
-1	Slightly cool

-2	Cool
-3	Cold

Table 1 The PMV Scale

The acceptable comfort level is range between -0.5 until +0.5.
Predicted Percentage of Dissatisfied (PPD) is expressed by the equation below:

PPD = 100 - 95 exp(- 0,03353PMV e4 - 0,179PMVe2) (5)

This Fanger model with the PMV and PPD indexes are adapted by ASHRAE and become a guideline for a long time in assessing thermal comfort. ASHRAE defines thermal comfort in its ASHRAE 55 Standard as *a subjective concept characterized by a sum of sensations, which produce a person's physical and mental wellbeing, condition for which a person would not prefer a different environment* (Danca et al, 2016).
Not only by ASHRAE this Fanger model was adapted by European as standard guidelines to assess thermal in car cabin and buildings through its EN ISO 14505 (ISO, 2006) and EN ISO 7730 (ISO, 2005) respectively.
In other hand, this Fanger Model has some limitations; valid only for steady state condition and near thermos neutrality, based only on the physics heat transfer and valid for standard population (NUTRIM, 2009). And assessing thermal comfort in vehicles might be differ from building. The effect of solar radiation, poor interior insulation, the non-uniformity of the average radiant temperature, a very short time to ensure the comfort parameter are some of the characteristics of an automotive environment (Danca et. al, 2015). Kaynakli and Kilic in 2005 already stated that cars have their own HVAC, this device system can cause a complicated three dimensionals unsteady turbulent flow and temperature variation in the vehicle interior. Non uniform air and temperature distribution may cause localized discomfort.

Danca et al (2015) also reviewed that up until 2015 there are no international standards which allow to easily assess thermal comfort specific to the vehicular environment space. They said that the current state of the art has been inconsistent in methodology, there are often crucial differences in the theoretical approaches for existing studies and important differences in the experimental methods which assess thermal comfort. The research also found that the researchers who have studied thermal comfort in vehicles have adopted concepts and methodological procedures from the only previously existing thermal comfort literature which was mainly intended for building.

This paper is aimed to review some studies in vehicles' thermal comfort and also sum up the latest existing model approach which proposed for assessing thermal comfort in transient and non-uniform environment. This might be help researchers to choose methodology which suit their study.

METHODE

A number of experiments have been carried out related with the thermal comfort in vehicles. If it is classified, there are roughly two types of studies.
A. Studies which focused on improving comfort level

As performed by Jaksic and Salahifar (2003), they proposed to change standard window glass material with the electrochromic one (EC). By performing optical properties (transmission, absorption and reflection) comparison using VSOLE model, it is proved that by controlling EC windows the car cabin cooler and fuel usage is more economical.
Beside on window material, Madsen (1993) designed a ventilated car seat to increase thermal comfort in hot summer day. The 21

m/s airflow in that ventilating system gave a significant influence on the dry heat loss and mainly on the latent heat loss.

Another car seat experiment was performed by Cengiz and Babalik in 2005, they experiment with the seat cover material; velvet, jacquard and micro fiber. The 10 participants gave similar respond. They felt the same thermal sensation (warmer) around the waist than any other body areas.

The most recent study is performed by Socaciu et al (2016). To maintain thermal comfort in vehicle, they suggest to substitute the air conditioning with PCM (Phase Change Materials) thermal energy storage. Using the AHP (Analytic Hierarchy Process) method, they select one of ten commercials samples PCM.

B. Studies which focused on developing new methods

Mezrhab and Bouzini (2005) predicted the thermal comfort inside a passenger car compartment using computation approach. They only concerned with the behavior of thermal comfort inside the compartemen according to climatic conditions and materials that compose the vehicle. The paper describes 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. A numerical method which based on nodal method and the finite difference were developed. They also investigated the effects of solar radiation, types of glazing, car color and radiative properties of materials composed. They found that a considerable reduction of the temperature inside the cabin is caused by the use of reflecting glazing and a white color of the bodywork of the car

Another study by Kaynakli and Kilic (2004) combined theoretical and experimental measurements. They measured temperature, relative humidity and air velocity at a number of points inside the car. The human body was also divided into 16 sedentary segments. During transient conditions of the heating period, heat and mass transfer between the human body and the interior environment were simulated by computational model. Their results were considered effective for the designer to test and to make some optimizations in air conditioning system in order to meet comfort requirements.

A different approach in assessing thermal comfort was carried out by Alahmer et al. (2011). They investigate the analysis and modelling of vehicular thermal comfort parameters using set of designed experiments aided by thermography measurements.

RESULT

Since Fanger model has limitations and there is no standard international for assessing thermal comfort in vehicles yet, many studies develop a new model. The existing recognized thermal models are Fiala, Berkeley Comfort model, Tanabe and ThermoSEM (Katic et al., 2016).

Thermophysiological models is developed based on body segment. The body can present as single segment or multi segment. Single segment means the body is consider as one thermodynamic machine. When the body is divided into parts it considers as multi segments. Next the segments are classified into one node, two nodes and multi nodes and multi element models.

One node models simulate a human body as one unit and no thermoregulatory system is involved. Two and multi nodes means the body is divided into two (core and skin) or multi concentric layers (core, muscle and fat).

Below are summaries of thermophysiological models through the years as adapted from Katic et al. (2016):

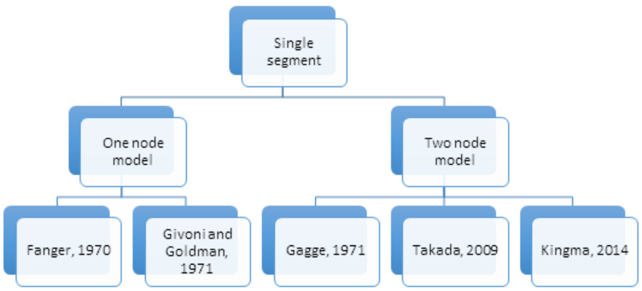

Fig. 1 Schematic diagram for single segment

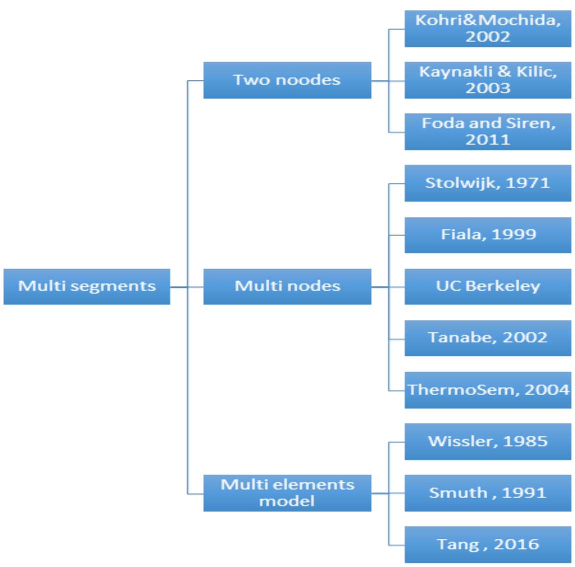

Fig 2. Schematic diagram for multi segments

Below are summaries of characteristic recognized developed thermophysiologycal models:

Tanabe, 2002	
Description	• 16 Segments • 65 nodes • 4 layers: core, muscle, fat and s
Body characteristi	Average man, physical paramete changed
Enviroment	Transient and non-uniform

conditions	
Active system	Based on Stolwijk model
Fiala, 1999	
Description	• 15 segments • 187 nodes • 3 sectors; anterior, posterior, inf • 7 tissues: brain, lung, bone, mus and viscera
Body characteristi	Average person
Enviroment conditions	Steady state and transient conditi
Active system	Regression based
UC Berkeley, 2001	
Description	• Multi node (arbitrary number of • 5 layers: core, muscle, fat and (s thing layer)
Body characteristi	Body builder
Enviroment conditions	Non uniform and transient
Active system	Based on Stolwijk model
ThermoSEM, 2004	
Description	• Multi node • 19 segments • Spatial sub division: anterior, p inferior
Body characteristi	Individual differences (height, w fat percentage)
Enviroment conditions	Non uniform and transient
(Continue)	
(Continue)	
Active system	Incorporates neurophysiology of Reception in the skin blood flow

Table 2 Thermophysiological models characteristic (modified from Katic et al., 2016)

CONCLUSION

Defining thermal comfort in vehicles is significantly different from the buildings. The most influenced the comfort is the air temperature, because this air temperature is correlated to a greater extent with relative air humidity which will influence the thermal comfort of passenger (Simion et al., 2015)

Since it differs from the building, there were a lot of studies regarding thermal comfort in vehicle. A lot of new approach methodology are developed. The newest model developed by Technical University Eindhoven/Maastricht University (ThermoSEM) in 2004. This model is based on physiology and valid for personalized characteristic (special attention to ageing and obesity). ThermoSEM is also valid for a non-uniform conditions. This model seems to be promising as a standard guideline for assessing thermal comfort in vehicle.

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