A Dynamic Convergence Algorithm for Thermal Comfort Modelling

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Abstract. This paper attempts to utilize experimental results in order to correlate clothing insulation and metabolic rate with indoor temperature. Inferring clothing insulation and metabolic rate values from ASHRAE standards is an alternative that totally ignores environmental conditions that actually affect human clothing and activity. In this work, comfort feedback regarding occupants' thermal sensation is utilized by an algorithm that predicts clothing insulation and metabolic rate values. The analysis of those values reveals certain patterns that lead to the formulation of two non-linear equations between clothing – indoor temperature and metabolic rate – indoor temperature.The formulation of the equations is based on the experimental results derived from the thermal comfort feedback provided by actual building occupants. On trial tests are presented and conclusions regarding the method's effectiveness and limitations are drawn.

Keywords: thermal comfort · metabolic rate · clothing insulation · indoor temperature · user feedback.

1 Introduction

The main European objectives require an alternation in energy consumption behaviour by energy saving. The most challenging task, is that the energy saving must be achieved with comfortable approaches for the residents. In order to determine the subjective comfort levels of the occupants there must be a method for the detection of both indoor climate conditions and occupants estimation. This indoor climate data is based on sensor generated inputs and it includes the metering of indoor humidity, indoor temperature and indoor luminance. The occupants' estimation is based on users' feedback about their comfort level which can be provided by a mobile or web application.

Thermal comfort indicates the human satisfactory perception of the indoor environment. Environmental and personal conditions must be estimated for people to feel comfortable. Thermal comfort is provided by the predicted mean vote (PMV) [2]. The Standard ISO 7730 [2] defines that the PMV is affected by four physical variables, which are air temperature, mean radiant temperature, air humidity and relative air velocity and two personal variables, that are metabolic rate and clothing insulation.

The physical variables needed for thermal comfort estimation can be effortlessly given by technological means like indoor air sensors and indoor humidity and temperature sensors. Diversely, the personal factors are laborious to be estimated. The most precise method to calculate clothing insulation is by thermal manikins [1]. Another approach for clothing insulation estimation is by using scientific questionnaires [11].

Metabolic rate is also a difficult factor of the thermal comfort function to be evaluated. Many studies estimating thermal comfort simply compute PMV by utilizing activities having low metabolic rates (like seating, relaxing and standing) [4], [7], [13] when calculating PMV, those activities are ranked based on ASHRAE tables [6]. This kind of approach is inaccurate as it excludes main basic indoor activities. Another way to measure metabolic rate is by wearable or portable metabolic devices. Those devices are expensive and are proven not accurate enough [12],[9]. As a consequence, they are rarely used.

To overcome all the above issues, initially the thermal comfort is calculated using an assumption for clothing insulation and metabolic rate based on the tables provide by ASHRAE [6]. Afterwards, these two factors are predicted based on user's feedback for thermal comfort. Consequently, PMV is calculated using the updated values of clothing insulation and metabolic rate. The assumption is that indoor temperature affects the way we dress and act in indoor spaces. We propose a dynamic convergence algorithm, which in case of lack of user feedback, updates clothing insulation and metabolic rate values progressively according to indoor temperature.

2 Clothing insulation and metabolic rate estimation

There are 7 points at the thermal sensation scale, according to ASHRAE thermal comfort scale (in Table 1) [6].

Table 1. ASHRAE thermal comfort scale

Value	Sensation
+3	Hot
+2	Warm
+1	Slightly warm
0	Neutral
-1	Slightly Cool
-2	Cool
-3	Cold

The most commonly used method for computing thermal comfort has been suggested by Fanger [3]. The final PMV is calculated by a set of equations. All the equations are described below.

Identification of a skin temperature and sweating rate required for comfort conditions [10]:

$$T_{sk,req} = 96.3 - 0.156 q_{met,heat}. \tag{1}$$

$$q_{sweat,req} = 0.42(q_{met,heat} - 18.43). \tag{2}$$

$$q_{met,heat} = M - \dot{w}, \tag{3}$$

where T_{sk} is the avergae skin temperature (^oF), M is the rate metabolic generation per unit DuBois surface area ($Btu/h\ ft^2$), and w is the human work per unit DuBois surface area ($Btu/h\ ft^2$).

Upon those conditions Fanger, corelated PMV as a function to the thermal load L on the body.

$$\begin{aligned} L = {} & q_{met,heat} \\ & -f_{cl} h_c (T_{cl} - T_a) \\ & -f_{cl} h_r (T_{cl} - T_r) \\ & -156(W_{sk,req} - W_a) \\ & -0.42(q_{met,heat} - 18.43) \\ & -0.00077M(93.2 - T_a) \\ & -2.78M(0.0365 - W_a), \end{aligned} \tag{4}$$

where clothing temperature is calculated from the required skin temperature:

$$\frac{T_{sk,req} - T_{cl}}{R_{cl}} = f_{cl} h_c (T_{cl} - T_a) + f_{cl} h_r (T_{cl} - T_r), \tag{5}$$

$$T_{cl} = \frac{T_{sk,req} + R_{cl} f_{cl} (h_c T_a + h_r T_r)}{1 + R_{cl} f_{cl} (h_c + h_r)}, \tag{6}$$

where

$$f_{cl} = \begin{cases} 1.0{+}0.2\mathrm{I}_{cl} & \mathrm{I}_{cl} < 0.5clo \\ 1.05{+}0.1\mathrm{I}_{cl} & \mathrm{I}_{cl} > 0.5clo \end{cases}, \tag{7}$$

$$h_c = \max \begin{cases} 0.361(\mathrm{T}_{cl} - T_a)^{0.25} \\ 0.151\sqrt{V} \end{cases}, \tag{8}$$

$$h_r = 0.7 Btu/h\ ft^{2o}F. \tag{9}$$

The final equation is given by the correlation between PMV and the thermal Load [3] and is given by:

$$PMV = 3.155 \left(0.303 e^{-0.114M} + 0.028\right) L. \tag{10}$$

2.1 Clothing insulation and metabolic rate estimation

Fanger's PMV equation [3] needs four main factors to be computed: temperature (T_a), humidity (RH), clothing insulation (I_{cl}) and metabolic rate (M). Thus, thermal comfort is dependent upon those factors:

$$PMV = (T_a, RH, I_{cl}, M). \tag{11}$$

Temperature and humidity are received by indoor metering sensors. Clothing insulation and metabolic rate are initially assumed based on ASHRAE [6] tables. Consequently, PMV is calculated with two different approaches based on the existence or lack of the users' feedback.

In case a user gives feedback, clothing insulation and metabolic rate values are predicted based on the PMV feedback value. The values of I_{cl}, M are calculated by solving Fanger's equation [3], where indoor temperature and humidity are estimated from the time the user feedback is provided.The new I_{cl}, M are calculated from a pre-trained model that utilizes as inputs the thermal comfort feedback, the temperature and the humidity. This model calculates I_{cl}, M for selected values of T_a and RH and was trained using Fanger's "Comfort Equation"[3]. The formulated problem requires the prediction of multiple continuous variables $y_i = (M, I_{cl})$ from a vector of k input variables $x_i = (PMV_{feedback}, T_a, RH)$. This is a multi-target regression (MTR) problem so extremely randomized trees were selected [5] for I_{cl}, M prediction.

The total observations of clothing insulation and metabolic rate values that are predicted from feedback are correlated to indoor temperature using a non-linear regression model [5]. The outcome of this regression model is two equations for clothing insulation and metabolic rate which are both indoor temperature dependent. The new clothing insulation value is estimated by:

$$I_{cl} = f(T_a) = 89.279(T_a)^{-1.592}. \tag{12}$$

And the new metabolic rate value is given by:

$$M = f(T_a) = 3081.9(T_a)^{-1.173}. \tag{13}$$

Whenever there is a feedback thermal comfort is estimated utilizing the predicted clothing and activity values. On the other hand, thermal comfort is estimated utilizing I_{cl} and M that results from the correlation of indoor temperature to clothing insulation and metabolic rate. The overall flow-chart of the algorithm is presented in Figure 1:

2.2 Indoor building study

The study takes place in 157 households. The number of the active users is in average 157. Users are asked "how they feel" regarding their thermal comfort scale and their feedback is saved along with the exact time it is given. The indoor conditions from the users' room are monitored by humidity and temperature

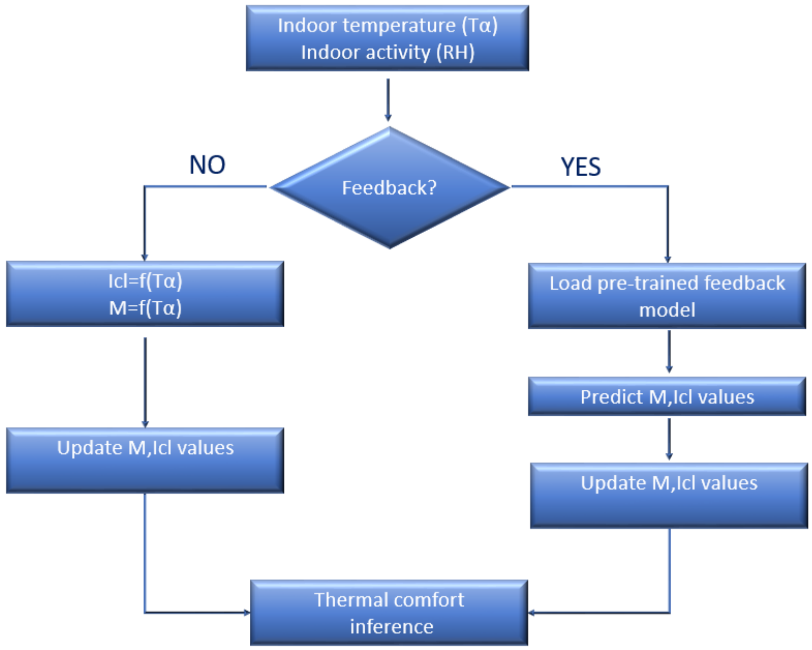

Fig. 1. Thermal comfort flow chart

sensors and saved every 15 minutes. As soon as the feedback is given, along with the indoor environmental values, the values of clothing insulation and metabolic rate that are predicted are updated for each user.

Table 2. Number of users and feedbacks.

Month	Number of users	Number of feedbacks
September 2018	12	58
October 2018	22	101
November 2018	29	201
December 2018	24	218
January 2019	30	191
February 2019	19	207
March 2019	13	263

Average indoor temperature is depicted in Figure 2 and outdoor average temperature is shown in Figure 3. Indoor temperature is not affected by the outdoor temperature as it has less fluctuations and smaller range of values.

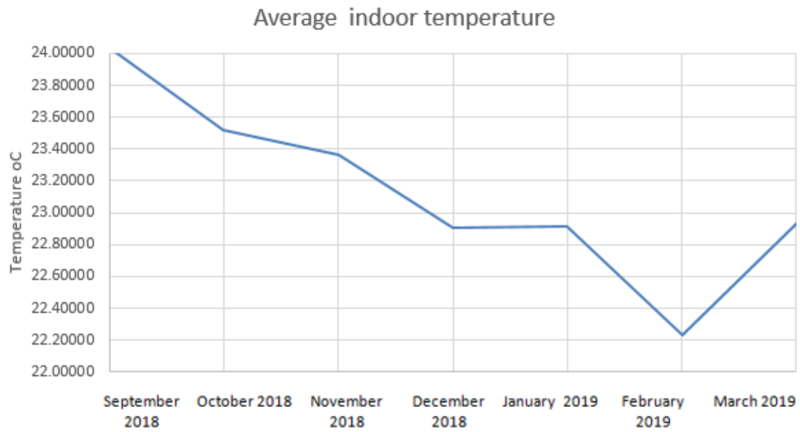

Fig. 2. Average indoor temperature in oC.

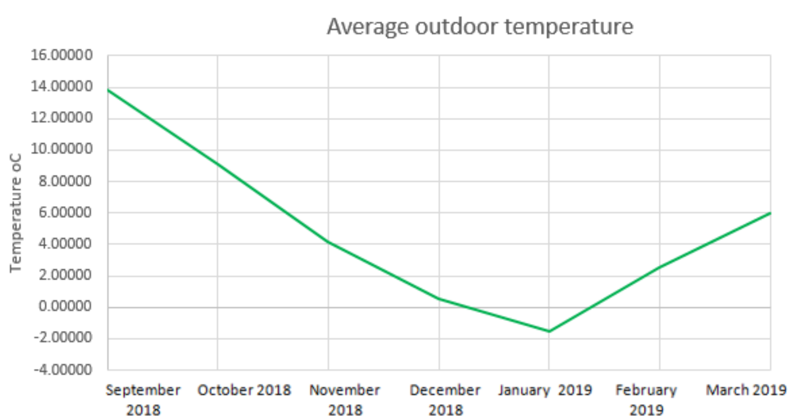

Fig. 3. Average outdoor temperature

3 Results

The relationship between temperature and clothing insulation has been thoroughly examined by Morgan [8], but the indoor environment examined was not domestic. Moreover, the indoor environment tested (shopping mall, offices) is an indoor environment that has a dress-code (casual, formal) and clothes worn are chosen based on the fact that people have to go outside before arriving to the destination the experiment is done. Our sample refers to indoor clothing insulation and metabolic rate in households. The results from the calculation of clothing insulation compared to indoor temperature monitored, are depicted in Figure 4.

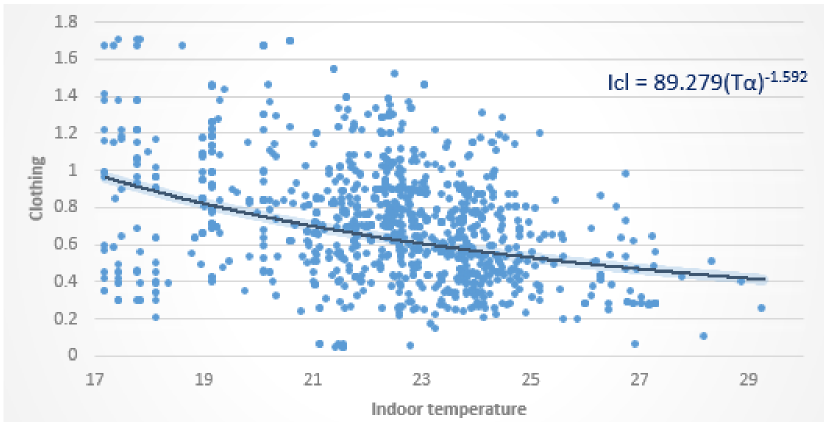

Fig. 4. Clothing related to indoor monitored temperature.

The relationship between clothing insulation and Indoor temperature is as expected, inversely proportional. The colder it gets the more clothes someone is wearing. Statistical analysis of the correlation clothing – indoor Temperature is given in Table 3. Adjusted R-Square (Table 3), is a statistical measure of how close the data are to the fitted regression line and the p-value tests the null hypothesis, that the coefficient is equal to zero. When p-value is below the confidence interval it suggests strong evidence against the null hypothesis.

As seen in Table 3, adjusted R-square's value is relatively low (0.14) but this is justified by the fact that clothing is subjective and may differ from person to person. Morgan's study [8] adjusted R-square value is 0.24 which is also low but reveals the same pattern observed in this study, as viewed in Figure 5. The inclusion of more variables in the model could probably improve R-square but this is beyond the scope of the current study which attempts a more precise clothing inference utilizing only temperature measurements.

Table 3. Non-linear regression statistics for clothing insulation.

Nonlinear Regression Statistics Clothing-Indoor Temperature	**value**
Adjusted R Square	0.137879952
P-value	≤ 0.01
Observations 2018	1288

The equation that came as a result for the relationship between clothing worn inside buildings [8] by Morgan compared to the equation in Figure 4, is depicted in Figure 5 . It is observed that there is a small deviation between the two lines. This is a remarkable outcome considering the fact that Morgan's study was situated in a different continent, type of indoor environment, number of observations, season and year. The main assumption is that there is a significant relationship between indoor temperature and clothing insulation.

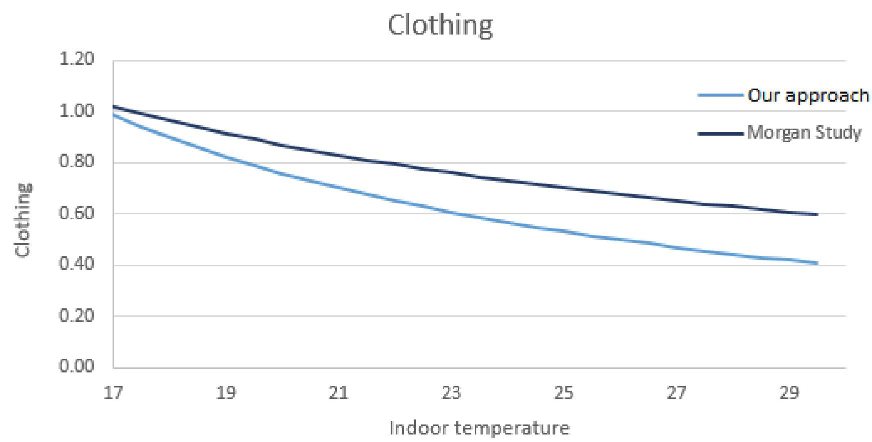

Fig. 5. Comparison of our approach and Morgan's study

Likewise, the relationship between indoor temperature and metabolic rate is examined in Figure 7. The statistical results are better than the clothing insulation as the R-square is almost 30 percent (Table 4).

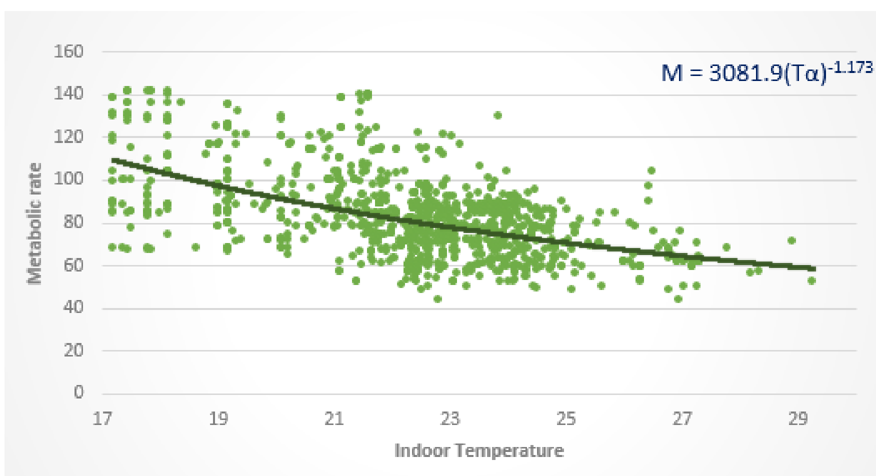

Fig. 6. Metabolic rate related to indoor monitored temperature

Table 4. Non-linear regression statistics for metabolic rate.

Nonlinear Regression Statistics Metabolic rate-Indoor Temperature	**value**
Adjusted R Square	0.288332
P-value	$\leq$ 0.01
Observations 2018	1288

The proposed equations are tested for their performance for calculating thermal comfort using real time indoor measurements. Two months were selected. One with "high" Indoor temperatures and one with "low" indoor temperature. Afterwards, a random day was selected for both of them. Thermal comfort was calculated at 15 minute frequency, and the results are depicted in Figure 7. As both clothing insulation and metabolic rate factors are correlated to indoor temperature the results of thermal comfort are the ideal. For this exact reason PMV values for high indoor temperatures are close to positive 0 and PMV values for low temperatures are close to negative 0.

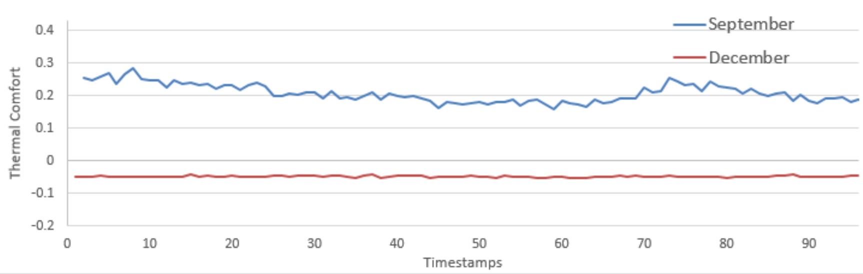

Fig. 7. Thermal comfort

4 Conclusions

This paper emphasizes on a dynamic algorithm that estimates thermal comfort in indoor environments. Based on the fact that thermal comfort is not only affected by indoor micro climatic parameters but also by personal psychological estimation the model concentrates more on the personal factors needed for the PMV computation. Both clothing insulation and metabolic rate values are proven a thorny task for thermal comfort evaluation, so a flexible but still feasible solution is tested.

Based on the feedback observations the non-linear regression relationship between clothing insulation and indoor temperatures advocates that indoor temperature is an essential factor of clothing worn inside buildings. Moreover, the variability in clothing insulation values in the sample may be explained by the fact that what we wear is affected by many factors except temperature like gender, age, and cold and heat tolerance. Furthermore, the non-linear regression relationship between metabolic rate and indoor temperatures also reveals that temperature is a dominant component of metabolic rate.

It is strongly believed that if the non-linear regression model is fitted individually and distinctly for every user the relationship between indoor temperature and personal factors will grow stronger and R-square will be better. After creating a user profile for even a small range of temperature values, clothing insulation and metabolic rate would be fitted to the ideal thermal comfort for each user.

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