THERMAL COMFORT SENSOR FOR HVAC SYSTEMS CONTROL

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Abstract. *HVAC control systems based on thermal comfort, in contrast with strategies that consider only temperature and humidity, provide advantages such as the improvement of the thermal quality of the built environment. Among different thermal comfort indices, the Fanger's model (PMV) is the widest used. However the attainment of this index in real equipment is considerably difficult. The first reason is the difficulty of measuring the mean radiant temperature. The second one is the difficulty on the determination of individual parameters such as human metabolic rate and the thermal resistance of clothing which have inexact and uncertain character and both are strictly related to the occupants' thermal sensation. Due to those difficulties, adjustments and adaptations must be carried out in order to develop a PMV-based sensor coupled to a HVAC system. In this way, this paper presents the development of a PMV-based thermal comfort sensor easily installable in HVAC systems, considering how sensitive Fanger´s model is to the mean radiant temperature, to the other environmental variables and to those two individual parameters. First, the hardware is presented according to a careful sensitivity analysis that has been carried out and its use is analyzed. Results obtained by using a genetic algorithm are used for better choosing standard values of metabolic rate and clothing thermal resistance that should be available to the built hardware. An uncertainty analysis for the six Fanger's model parameters are also shown. To conclude, results are presented in terms of thermal comfort control, showing the viability of the developed sensor.*

Keywords: *thermal comfort, sensor, PMV index, HVAC systems, error analysis.*

1 INTRODUCTION

Mankind has always tried to create a thermally comfortable environment. This is reflected in building traditions around the world - from ancient history to nowadays. Today, creating a thermally comfortable environment is still an important issue to be considered by building designers. For instance, if the working environment thermal comfort is not satisfactory, the working performance will inevitably suffer (Innova AirTech Instruments, 2005). The establishment of thermal comfort in buildings is the main goal of the HVAC systems control.

Thermal comfort is a concept of difficult definition and, over the four last decades, a great number of thermal comfort indices has been established for the analysis and design of HVAC systems (ASHRAE, 1993). One of those indices is the PMV (Predicted Mean Vote), which was proposed by Fanger (Fanger, 1970). Such index considers environmental variables and individual factors and, the closer to zero the PMV, the better the occupants' thermal sensation. The thermal comfort equation developed by Fanger is complex and tends to reproduce, with a good reliability, the comfort sensation for most of the people in a given environment. Therefore, an equipment that uses somehow the PMV index in its control strategy tends to obtain better results in the sense of providing thermal comfort.

In order to use PMV data in HVAC equipment, the PMV signal should be available to the controller. Unlike most common sensing procedures in this context, such as temperature and humidity sensors, PMV cannot be directly measured but, instead of that, it is necessary to measure four environmental variables (air temperature, mean radiant temperature, relative humidity, and air velocity) and to evaluate two individual parameters (the occupants level of physical activity and thermal resistance of clothing) by feeding these six parameters into the Fanger's mathematical model in order to get the PMV signal. Such procedure requires an evaluation of the PMV formulae, therefore it is necessary the use of a digital processor in the sensor hardware. However, the attainment of this PMV index in real equipment is considerably difficult since some of the PMV parameters are difficult to be obtained. Due to the importance of using Fanger's model for thermal comfort estimation and to the complexity of its attainment, this paper presents results related to the development of a PMV hardware, for closed loop control purposes. Approaches of thermal comfort control are also presented in (Hamdi and Lachiver, 1998), (Freire, 2006), (Freire *et al.*, 2005), and (Gouda *et al.*, 2001).

The topics discussed in the present paper are the architecture of the hardware and the influence of each single input parameter on the final PMV computation, in terms of error and sensitivity analysis. Related works such as (Kon, 1994) usually present only overview of the hardware and no discussion about the final results and the related uncertainties.

The present article is structured in the following way. In section 2, some issues related to PMV estimation for control purposes are reviewed. In section 3, the PMV sensor hardware is proposed and its functional description is presented.

An analysis of each PMV input parameter accuracy, and the measurement uncertainty for the thermal comfort index due to the combination of all parameter measurement uncertainties, is discussed in Section 4. In section 5, it is shown not only an alternative way to use the PMV sensor but also the uncertainty analysis for this case. Finally, in section 6, the conclusions are addressed.

2 ISSUES RELATED TO PMV MEASUREMENTS

Unlike temperature and humidity sensors, mean radiant temperature sensors are difficult of being obtained or are not-viable of being incorporated in HVAC control systems. In addition, the mean radiant temperature has an important weight (Trebien *et al.*, 2007b) on the thermal comfort balance - in some cases the heat losses by radiation may account for 45% of the total sensible heat loss - so that it should be considered. Therefore, a mean radiant temperature input will exist on the PMV sensor proposed by the present work, but it will consider, whenever it is possible, the mean radiant temperature equal to the measured air temperature. Trebien et al. (2006) showed that if the actual difference between these two temperatures is within the band + or -3,9^{o}C, the PMV index value will consequently be within the acceptable band for comfort + or -0.5 (Fanger, 1970). In section 4, an uncertainty analysis has been carried out to check the impact of this hypothesis considering the combination of the six parameter errors.

In real systems, thermal resistance of clothing is a parameter which is assumed constant. However, it is difficult to know the value to be attributed to this parameter. Despite the fact that the user knows his clothing, he never knows its thermal resistance value (Trebien *et al.*, 2006). A solution is elaborating the sensor hardware with an interface containing a group of clothing options. The system considers for the CLO (see Tab. 1) parameter, the value in agreement with the options selected by the user. Then, if CLO parameter is measured in a real equipment, the system will have an inexact and uncertain character because a finite number of options is available for an user that can be dressing an infinite number of garment types. Errors may also occur because built environment occupants will be dressing different clothing. The measurement of physical activity presents problems similar to those described for the CLO parameter, with an additional difficulty. Besides the problem related to the user does not know his activity value and that occupants could be accomplishing different activities, occupants have different metabolism levels. Then, uncertainties in obtaining MET (see Tab. 1) are larger in case it exists more than one occupant in the controlled environment. Therefore, uncertainties will always be present on the PMV prediction.

Table 1. List of Symbols

$Symbol$	Parameter	Unit
ϕ	Relative humidity	(-)
CLO	Thermal resistance of clothing	(clo)
MET	Human metabolic rate	(met)
PMV	Predicted mean vote	(-)
T_{ar}	Air temperature	(^{o}C)
T_{rm}	Mean radiant temperature	(^{o}C)
V_{ar}	Air velocity	(m/s)

The analysis of the impact caused on the PMV index due to the adaptations and adjustments for obtaining these individual parameters is accomplished in (Trebien *et al.*, 2006). In this work, it was verified that the partial derivatives of PMV with respect to individual parameters have a moderate variation in case of modifications on the values of air temperature, and a little for modifications on values of humidity and the air velocity. However, the great variation is verified for different values of clothing and metabolism.

These results are relevant for designing PMV-based thermal comfort sensors, specially those designed to work coupled to HVAC control systems, because a commitment between results reliability and sensor assembly complexity should be observed. The reason is that it is impossible to incorporate many options for these individual parameters to avoid the increase of both equipment cost and complexity. However, it was verified through the results that a correct choice of the parameters values is important for obtaining the PMV index in a more reliable way. Based on the explanation, it is important to use an optimization method in the search of the values for these parameters, that it is accomplished in (Trebien *et al.*, 2007a). Then, the individual parameters measurement uncertainty can be reduced without the increment of new switches. Due to the nonlinear character of the PMV equation, some classic methods, as Simplex, could not be used. Methods denominated as genetic algorithms are totally appropriate in these situations, where besides the nonlinear character, a great complexity is verified in the mathematical model. The reason is that the evolution for the individual parameters values is obtained, through the generations, despite being complex the mathematical model.

Due to the exposed above an uncertainty analysis of the PMV sensor parameters was carried out in this work. In (Trebien *et al.*, 2006), the impacts that the adjustments cause on the PMV were analyzed, for each parameter. However, if a real equipment is being designed, the PMV uncertainty will be influenced by the six parameters measurement uncertainty.

3 HARDWARE FOR PMV SENSOR

The PMV Sensor hardware is based on modules shown in Fig. 1.

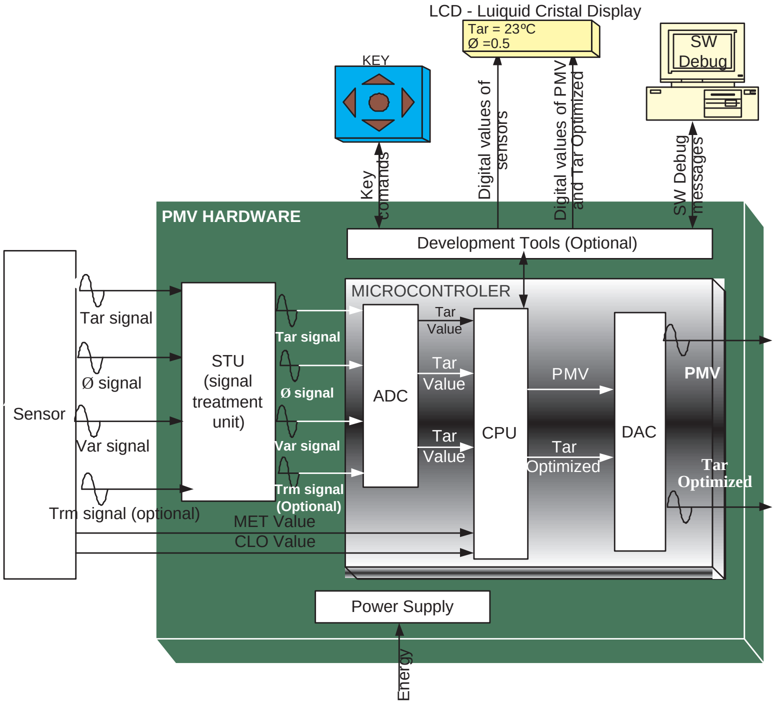

Figure 1. Block Diagram for PMV Sensor hardware

The PMV Sensor, presented in Fig. 1, is appropriate not only to evaluate the thermal comfort in a built environment but also to be the source of PMV index in HVAC control system. For this reason, there are two analogic outputs in its hardware. The first one, is used to return the PMV index, while the another output can be used by any other related application.

Fanger's model considers six parameters, on the other hand, a PMV control system could be limited to modify only one of this parameter, for instance T_{ar} (see Tab. 1). Therefore, in a controller strategy point of view, instead of PMV index, T_{ar} could be the controlled parameter. Summing up, the PMV index can be controlled indirectly by the HVAC control system because the controller can modify the parameter T_{ar}, targeting a set point value that turns the PMV index into zero. For this use, PMV sensor must not only evaluate the PMV index but also find, using an optimization method, the air temperature that leads PMV index to zero (T_{ar}optimized). In this case, T_{ar} must be applied in the first analogical output and T_{ar}optimized must be applied in the second one. The necessity of two analogical output was considered to choose MSP430 as the processor.

3.1 Module "Sensor"

In the "Sensor" module there are the environmental parameters sensors as shown in Tab. 2, where the models have been already defined. Therefore, it is possible to carry out an uncertainty analysis, as shown in Sec. 4. In this table is also shown the signal characteristics and its limits. As can be seen, the same equipment sources both $T_{\rm ar}$ signal and ϕ signal (see Tab. 1).

Table 2. List of Sensors

Parameter	Model	Signal characteristics	Lower limit	Full scale value
T_{ar}	RHT-WM-TM	Voltage (V)	0	10
$T_{rm}(optional)$	LM35 coupled with a black globe	Voltage (V)	0	0.5
V_{ar}	EE66-VC3-K500	Voltage (V)	0	10
ϕ	RHT-WM-TM	Voltage (V)	0	10

Not only these analogical signal parameters but also two individual parameters, to know MET and CLO, must be considered for the PMV computation as user-defined inputs. The strategy to get the individual parameters is that proposed in (Trebien *et al.*, 2007a), where ten discrete options for MET are provided (see Tab. 3). There are also ten discrete options for CLO parameters, where each one is related to one garment (see Tab. 4).

Table 3. Values for MET parameter obtained by using a genetic algorithm.

Activity	MET **Value**	**Switch number**
Reclining\sleeping	0.8000	1
Reclining	0.8932	2
Seated Relaxed	1.0000	3
Clock and watch repair	1.1000	4
Standing Relaxed\Sedentary activity (office,dwelling,school,laboratory)	1.2000	5
Car Driving\playing electronic games	1.4000	6
Standing, light activity (Teacher\presentation\shopping\laboratory\light industry)	1.6000	7
Standing, medium activity (shop assistant\domestic work)	2.000	8
Washing dishes standing	2.5000	9
Domestic work (washing by hand\ironing)	2.9000	10

Table 4. Garment description and CLO Values for each switch.

Garment description	CLO **value**	**Key number to add each garment**
Shoes	0.03	1
Walking shorts \ Thin strap, short gown	0.15	2
Normal trousers\Heavy skirt(knee-length)	0.25	3
Turtleneck Panties	0.03	4
Short sleeve shirts \ T-shirt	0.09	5
Long sleeves shirts \ Thin sweater(long sleeves, turtleneck) \ Light dress (sleeveless)	0.25	6
Sweater	0.28	7
Jacket	0.35	8
Coveralls (either daily wear, belted or work) \ Coats and over-jackets \ Winter dress long sleeves \ Sleepwear (long sleeve, long pyjamas) \ Robes (long sleeve, wrap, long)	0.50	9
Highly-insulating coveralls	1.13	10

3.2 "STU" (Signal Treatment Unit) Module

The impedance of the sensored signal inputs should be high. Otherwise, the specified values for measured signals (For instance 10V) will not be present at the inputs. In this case, a lower value may be present because the current sourced by the sensor is increased when the input impedance is lower. Therefore impedance of both own sensor and wire decrease the signal voltage. If the impedance of the input pins are low, either hardware compensations or calibrations over the digital signal could be done. However, in this case, if sensors, wires and connectors were changed, errors may been caused. The signals may be sensible even by the modifications in temperature, that influence material resistivity. Summing up, the signal inputs must have high impedance to reduce the sensibility with respect to sensors impedance. On the other hand, the source for signals applied to "ADC" module (see sec. 3.3) must have a lower impedance due to the fact that analogical to digital converter needs a minimum current on voltage to a digital code process. Based on the explanation, the adequacy of the sensors and ADC impedance is one of the "STU" module purposes. This task is possible by the use of an operational amplifier for each sensored signal. These components have a hight impedance in its input (resistor should be around $k\Omega$) and a low impedance in its output. For this project, it was proposed the use of LM6484, which has four operational amplifiers in chip, being fitted to this project that needs four operational amplifiers (one for each parameter signal).

Signal limits for T_{ar}, V_{ar}, and ϕ sensors are from 0 to 10V (see Tab. 2). However ADC peripheral operates from 0 to

3V. Then "STU" module has also the purpose of applying a gain in the sensor signal, using specific resistors value together with the operation amplifier. "STU" must reduce the signals level. For instance, in this project "STU" was configured to has $\frac{3}{10}$ as the gain.

3.3 "ADC" Module

In order to be possible the evaluation of the PMV index, the PMV sensor must include a digital processor. "ADC" module is responsible for the conversion of measured analogical signals (from "STU") to digital codes. For the processor chosen, there is a peripheral, to know ADC12, that plays the role of "ADC" Module. (see Fig. 1). The advantages in a microprocessor which contains an ADC peripheral, as size, costs and consumption of the board, were considered when a MSP430 was chosen as the processor. These advantages are important to enable the use os this sensor in HVAC control systems.

There are twelve input pins in analogical to digital convertor present in MSP430. Then the number of digital codes to digital signal representation, its resolution, and digits, are shown in Eq. 1, 2, and 3 respectively.

$$\text{number of combinations} = 2^{\text{number of inputs}} = 2^{12} = 4096 \tag{1}$$

$$\text{resolution} = \frac{\text{Full scale value}}{\text{number of combinations}} = \frac{\text{10V}}{\text{4096}} = 2.441 * 10^{-3} V \tag{2}$$

$$\text{digits} = \log 2^{\text{number of inputs}-1} = log 2^{12-1} = 3^{\frac{1}{2}} \tag{3}$$

3.4 "CPU" (Central Processor Unit) Module

Digital signal processing targeting the evaluations of the PMV index equation is the purpose of the "CPU" module. As seen in Fig. 1, "CPU" is present in MSP430 microprocessor. The CPU architecture is RISC, with seventeen bits and a 8MHz clock. The performance demanded to a real time digital signal processor are aided by some MSP430 resources like timers, RAM size of 5kB, and hardware multipliers. To be possible the use of this sensor in equipments which controls the parameter T_{ar}, the "CPU" has to process an optimization method targeting to find the air temperature that leads to the PMV index to zero. Based on Fanger's model, this method must be non-linear. In spite of being complex and non-linear, Fanger's model optimization should not use high computation efforts methods like genetic algorithm. These methods do not fit to a real time application.

3.5 "DAC" Module

As it has just been mentioned, the PMV index obtained in the "CPU" module is digital. However, this project aims to obtain an equipment for general use in HVAC applications. Then, the evaluated values (either PMV and PMV set point or T_{ar} and T_{ar}optimized) should be converted into analogical signal. If the PMV sensor had digital interfaces, the HVAC equipment, which uses the PMV sensor, would have an interface, with the same communication protocol. Therefore, digital signals from "CPU" module must be converted into analogical signals in the "DAC" module.

The "DAC" module plan is done by two MSP430 peripherals (DAC0 and DAC1), one for each output signal, which are electronic devices denominated as digital to analogical converter. The presence of two DAC peripherals was considered to choose MSP430 as the PMV sensor processor.

3.6 "Development Tools" Module

For a development of a complex system, like PMV Sensor, where four analogical environmental parameters are measured, two individual parameters are selected by user, a digital signal processor and an optimization method must be evaluated, and two analogical output signals must be present, the software development, tests, validation, and presentation will be difficult if the two analogical signals are the only analyzed results. For instance, if the output signal is incorrect, the user can not know, which module or part of module is not working well. The problem might be on the digitalization process ("ADC" module), in the Fanger's model evaluation ("CPU" module), or in the reconstruction process ("DAC" module). As a conclusion, digitally processed systems, specially those which make a real time digital signal processing, like the PMV Sensor, should have some resources that becomes easier the development phase. Then, PMV Sensor hardware was designed to include the "Development Tools" module, as seen in Fig.1.

In a commercial product, a compromise between quality and both complexity and cost should be observed. Therefore, the main purpose of the PMV Sensor, to know, the signals to be correctly evaluated and after applied in two analogical outputs, will occur, if "Development Tools" module components are not present in the hardware. Then, at tests, validation and software development phases, the board should be assembled with the "Development Tools" module components. PMV Sensors constructed to be incorporated in HVAC control systems should be assembled without this components. If the PMV Sensor is used to evaluate the built environment thermal comfort (it is not included in a HVAC system), some items of "Development Tools" module, like a LCD display and a key, would be useful. Users may see the equipment information and calculated values on the display and change menus by the key.

Software debug is the main purpose of "Development Tools" module, through the JTAG interface, which becomes possible the communication between microcomputer (through either USB or parallel interfaces) and PMV Sensor processor (MSP430). Then, the execution software steps can be viewed in the environment programming. The need of a JTAG interface was considered to choose MSP430. Software debug feature is very useful for code development and test phase because it permits the verification of any digital values, like the values resulted in the parameter signal digitalization. Problems in the "ADC" module are discovered independently of other modules. It is possible also to see not only the PMV index but also intermediate values during the Fanger's model evaluation. If the PMV index is correct and the related analogical signal is wrong in the output pin, user will know that the problem is in the "DAC" module.

4 Uncertainty Analysis

Adjustments and adaptations on T_{rm}, MET and CLO parameters must be done in order to develop a PMV Sensor (Trebien *et al.*, 2006). For this reason, after the PMV Sensor has been just proposed (sec. 3), including the determination of parameter sensors and the determination os the great values for both MET and CLO options, it is important to carry out an uncertainty analysis.

An uncertainty analysis of a measurement system includes the information about each measurement parameter accuracy, uncertainty of the Fanger's model with respect to each parameter and, finally the uncertainty of the PMV index considering the combinations of the uncertainty of all parameters. This strategy is adopted in case of knowledge of measurement uncertainty for all the parameters of the mathematical model. However, for the proposed sensor, the analysis is inverse because it was adopted the strategy that T_{ar} is the same as T_{rm} and then the the measurement accuracy for T_{rm} is not known due to the fact that is not possible knowing the difference between the two temperatures. However, it is known that the maximum absolute error possible on the PMV index, is 0.5. Therefore, considering the accuracy of the other five parameters and treat the difference between T_{ar} and T_{rm} as an unknown, it is possible to determine the maximum value for the difference between the temperatures that leads to the uncertainty on the PMV index up to 0.5.

However, in this case the uncertainty analysis is complex because the PMV equation is not only complex but also non-linear with respect to its parameters. Furthermore, the partial derivation of PMV with respect to its parameters is also non-linear and dependent not only of the own parameter but also on the other Fanger's model parameters (Trebien *et al.*, 2006). Therefore, it is impossible to do the uncertainty analysis through the derivative function analytical solution. Even the numerical method to solve the partial derivative presents some problems due to the difficult to determine the values that lead the partial derivative to its maximum values. A best strategy is to find each parameter accuracy, the PMV uncertainty to each parameter, and finally the PMV uncertainly due to the combination of PMV uncertainty for each parameter, considering all possible combinations of the six model parameters. Despite the fact that to obtain all combinations is impossible, good results are obtained in case of using the Monte Carlo statistic method (Duarte, 1994) to generate a lot of parameters combinations (1500 for this research) according to a random distribution.

4.1 Accuracy for the Fanger's Model Parameters

T_{ar} parameter is gotten through an analogical sensor (see Tab. 2), which accuracy can be seen in Fig. 2. Therefore, the accuracy for any T_{ar} value, that is necessary for the analysis, can be found in Fig. 2. Due the strategy adopted, T_{rm} accuracy is function of both T_{ar} sensor accuracy and the difference between T_{rm} and T_{ar}, at the analyzed built environment. Due the fact that both positive and negative errors can occur in the two T_{rm} source uncertainty, the expected T_{rm} accuracy, which is used in this analysis, can be evaluated through Eq.4, where T_{rm}-T_{ar} is a variable to be gotten through the analysis.

$$IM_{T_{rm}} = \sqrt{(\mathrm{IM}_{T_{ar}})^2 + (T_{rm} - T_{ar})^2}. \tag{4}$$

The ϕ and V_{ar} parameters are obtained through an analogical sensor (see Tab. 2), which accuracy values can be found in Fig. 3 and Eq. 5 respectively.

The accuracy for any V_{ar} value, that can be seen in Eq. 5, shows that the expected errors are low. Furthermore, this parameter has a low weight on Fanger's model results (Trebien *et al.*, 2007b), so that the final PMV error, influenced by the six parameter uncertainty, may not have much influence due to the V_{ar} accuracy.

$$IM_{V_{ar}} \;=\; 0.04 + 2\% \; of \; V_{ar}\text{measured value} \tag{5}$$

The MET parameter is provided via ten switches. Its measurement uncertainty is evaluated from the difference between the real built environment MET value and the MET value related to the option selected by the user.

The CLO parameter can be provided by ten switches. In (Trebien *et al.*, 2007a) is shown that the determination of the exact CLO accuracy is practically impossible in a real system. With the adopted strategy, 1024 combinations can

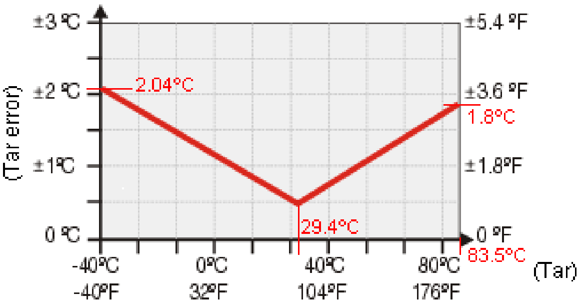

Figure 2. Air temperature sensor accuracy

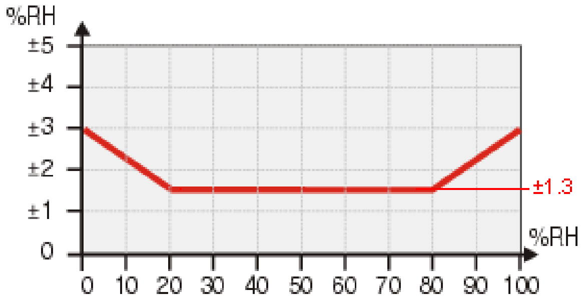

Figure 3. Relative humidity sensor accuracy

be used to determine CLO. Therefore, the measurement uncertainty for CLO can be considered close to zero. However, despite the fact that a lot of combinations can be made, the real CLO value for each user's garment and the CLO value for this garment in the system might be slightly different. Therefore, based on a previous work (Trebien *et al.*, 2007a), a measurement uncertainty constant for PMV regarding to CLO is considered to be equal to 0.048, within a large safe band.

4.2 Uncertainty analysis methodology

First, a file with the 1500 PMV parameters combinations was considered, representing a random value matrix, where the lines (1500) represent the parameters combinations and the columns (6) represent the PMV parameters.

Next, the PMV index for each combination is calculated by the PMV equation (Fanger, 1970). The third step is to obtain a matrix of derivatives of PMV with respect to each parameter, for each combination. Therefore, as a result a 1500x6 matrix is obtained, where each position ij contains the derivative of PMV to the parameter j, for the combination i.

In the fourth step, shown in Sec. 4.1, it is composed a 1500x6 matrix for parameter's accuracy evaluation. In the fifth step, the uncertainty of PMV to each parameter for each of the 1500 combinations is calculated. These values are provided by Eq. 6, where each ij position is the measurement uncertainty of PMV with respect to the parameter j, when the values of the $i-th$ combination are considered.

$$IM(PMV)_{Parameter\ j} = \frac{\partial PMV}{\partial Parameter\ j} \times IM_{Parameter\ j} \tag{6}$$

Finally, in the sixth step, the final PMV error is evaluated for all the 1500 PMV parameters combinations. If the parameter uncertainties are not related among themselves, Eq. 7 should be used. Otherwise, Eq. 8 should be used. ϕ, V_{ar}, MET and CLO are examples of parameters whose uncertainty are not related to themselves. T_{ar} and T_{rm} are examples of parameter whose uncertainty is related to themselves because they are provided through the same sensor. Therefore, mixing these two equations, the PMV uncertainty due to its six parameters is provided by Eq. 9. This step results in a 1500x1 matrix where each line means the PMV uncertainty when the parameters of $i-th$ line is evaluated.

$$IM = \sqrt{\sum_{j=1}^{nParameters} ((IM_{Parameter\ j})^2)} \tag{7}$$

$$IM = \sqrt{(\sum_{j=1}^{nParameters} IM_{Parameter\ j})^2} \tag{8}$$

$$\begin{aligned} IM(PMV) = (\ &((IM(PMV)_{T_{ar}}) + (IM(PMV)_{T_{rm}}))^2 + (IM(PMV)_{\phi})^2 \\ &+ (IM(PMV)_{V_{ar}})^2 + (IM(PMV)_{MET})^2 + (IM(PMV)_{CLO})^2\ )^{0.5} \end{aligned} \tag{9}$$

If any absolute value of the six-step matrix is greater than 0.5, it means that PMV index uncertainty will be greater than the limit established by ASHRAE, even if T_{ar} is equal to T_{rm}. This situation may not occur because the strategy - which was chosen for providing the individual parameters values - was developed targeting the increase of the accuracy of measurement of individual parameters that represent two of the three parameters more subjected to adjustments and adaptations. Otherwise (all values below 0.5), the difference between the temperatures can be increased interactively till all values of the six-step matrix remains within |0.5|.

4.3 Results

If T_{rm} is equal to T_{ar}, the greater errors in PMV will occur for the parameters combination shown in Tab. 5, where the derivative of PMV with respect to its parameters and the accuracy of each parameter for the analyzed combination is presented. As it can be seen, in this combination, MET, followed by T_{ar}, has the greatest impact on the PMV uncertainty.

Table 5. Uncertainty analysis results, considering $T_{rm} = T_{ar}$.

Parameter	Combination of values	$\frac{\partial PMV}{\partial Parameter\ j}$	Accuracy to Pj	$IM(PMV)_{Pj}$
T_{ar}	23.42	0.27	0.63	0.171
T_{rm}	19.71	0.19	0.63	0.120
ϕ	0.68	0.80	0.01	0.010
V_{ar}	0.03	0.00	0.04	0.000
MET	0.95	7.46	0.05	0.384
CLO	0.35	4.50	-	0.048

The PMV measurement uncertainty due to the combination of the six parameters is 0.485, which is less than 0.5. Therefore the difference between T_{rm} and T_{ar} was increased interactively. The value of 0.4 is the maximum difference between the two temperatures, that leads to the PMV uncertainty of 0.5, for all combinations of parameters. The combination that cause the maximum uncertainty on PMV can be seen in Tab. 6. As it can seen, the values are the same of those presented in Tab. 5, except for the line related to the T_{rm} parameter.

Table 6. Uncertainty analysis results, considering $T_{rm} - T_{ar} = 0.4$.

Parameter	Combination of values	$\frac{\partial PMV}{\partial Parameter\ j}$	Accuracy to Pj	$IM(PMV)_{Pj}$
T_{ar}	23.42	0.27	0.63	0.171
T_{rm}	19.71	0.19	0.75	1.443
ϕ	0.68	0.80	0.01	0.010
V_{ar}	0.03	0.00	0.04	0.000
MET	0.95	7.46	0.05	0.384
CLO	0.35	4.50	-	0.048

The limit between the temperatures is strict. However, this value was obtained considering that all of the 1500 values of PMV uncertainty are up to 0.5, that is, a very severe rule. However, analyzing the data, if the difference between T_{rm} and T_{ar} is 0.63°C, only one of the 1500 combinations will lead to a PMV error greater than 0.5 and 1473 combinations (98.2%) will lead to a PMV error up to 0.4. These results show that the rules adopted are severe because few specific parameter combinations lead to greater PMV errors. Therefore, the difference between the two temperatures was increased and verified that if the difference between T_{rm} and T_{ar} is 2°C, 95% of the combinations will lead to an error on the PMV index up to 0.5.

5 ALTERNATIVE WAY TO USE THE PMV SENSOR

It has already been mentioned that the mean radiant temperature is difficult to be measured for practical HVAC applications. However, if the measurement uncertainty of PMV, shown in sec. 4, is greater than the limit established for the comfort conditions, due to the difference between T_{rm} and T_{ar}, where the sensor is used, T_{rm} sensor can be used to reduce the measurement uncertainty of PMV, as the PMV sensor contains an input for this signal, as shown in Fig. 1. If the sensor is not present, it should be considered T_{rm} equal to T_{ar}. Otherwise, it should be considered the signal from T_{rm} sensor as the correct T_{rm} value.

Therefore, the uncertainty analysis for the PMV sensor, in case of this use, is done targeting to obtain the measurement uncertainty of PMV, for all combinations of its parameters, without the known value of the difference $T_{rm} - T_{ar}$. The accuracy of the T_{rm} sensor can be seen in the Fig. 4.

In this use of the PMV Sensor, the six parameter uncertainty are not related themselves. Therefore, Eq. 7 should be used.

5.1 Results

If T_{rm} is monitored, the greater errors on PMV will be 0.4239 and they may occur for the parameters combination shown in Tab. 7, where, also is shown the derivative of PMV with respect to its parameters and the accuracy of parameters for this combination. As it can be seen, in this combination, MET, followed by T_{ar}, has the greatest impact on the PMV uncertainty.

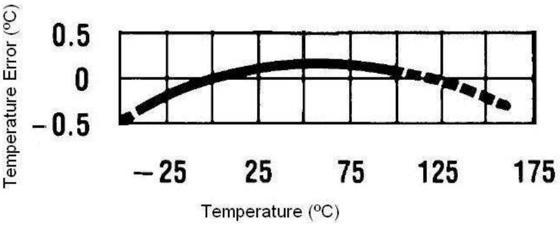

Figure 4. Mean radiant temperature sensor accuracy

Table 7. Uncertainty analysis results when T_{rm} is monitored.

Parameter	Combination of values	$\frac{\partial PMV}{\partial Parameter\ j}$	Accuracy to Pj	$IM(PMV)_{Pj}$
T_{ar}	23.42	0.27	0.63	0.17
T_{rm}	19.71	0.19	0.12	0.02
ϕ	0.68	0.80	0.01	0.01
V_{ar}	0.03	0.00	0.04	0.00
MET	0.95	7.46	0.05	0.38
CLO	0.35	4.50	-	0.05

6 CONCLUSIONS

The attainment of PMV index in real equipment is considerably problematic due to the difficulty of measuring the mean radiant temperature and the difficulty on the determination of individual parameters. Due to those difficulties, adjustments and adaptations must be carried out in order to develop a PMV-based sensor coupled to a HVAC system. In this way, this paper has presented the conception of a PMV-based thermal comfort sensor, considering how sensitive Fanger´s model is to the T_{rm}, MET and CLO parameters. First, the PMV sensor proposed considers T_{rm} equal to the measured value of T_{ar}. Results obtained by using a genetic algorithm have then been used for better choosing standard values of the individual parameters. An uncertainty analysis for the six Fanger's model parameters has also been shown. The results of this analysis show when the proposed PMV sensor, which considers $T_{rm} = T_{ar}$, is viable. If it is not the case, not only an alternative way to use the PMV sensor, which works with a T_{rm} sensor, but also the uncertainty analysis for this case has been presented.

The PMV Sensor hardware, which has just been proposed, has the "Development Tools" module, which contains some items as the connector to a LCD display and key, which helps software development. However, if its components are not present, the PMV Sensor will work perfectly. This is important because in this case the equipment becomes fitted to cost and size requirements.

When adjustments and adaptations must be carried out in order to measure a certain parameter, an individual analysis of this parameter should be done, such as the determinations of the derivative of PMV to this particular parameter (Trebien *et al.*, 2006). On the other hand, if the parameter is measured without those adjustments and adaptations, like T_{ar}, ϕ and V_{ar}, the uncertainty will be lower and an individual analysis is not necessary. However, due to the combination of uncertainty of the parameters, shown in Sec. 4, despite being small the parameter measurement uncertainty, it can be decisive on the total PMV error, due to the six parameters accuracy influence. Great importance should be carried out to T_{ar} measurement process, as it will double influence the PMV computation once it provides the value for both T_{ar} itself and T_{rm}, which have a great weight on the PMV uncertainty.

In the uncertainty analysis, it could be seen that if the difference between the temperatures is up to 2°C, the hypothesis that $T_{ar} = T_{rm}$ would be viable because 95% of possible combinations of the Fanger's model will lead to errors on the PMV index up to 0.5. If is not possible to ensure that the difference between T_{ar} and T_{rm} is up to 2°C, the T_{rm} sensor should be used coupled with the PMV sensor. In this case, the PMV uncertainty will be up to 0.42.

The PMV sensor proposed can be used in a thermal comfort control system, as a source of PMV index. If the control strategy uses a switching device to modify the state of the HVAC system control actuator and then it is capable to maintain the PMV index around zero, the T_{rm} sensor must be used. Then, the unavoidable error due to the switching device should be limited by the difference between the maximum error on PMV calculated value (0.42) and the maximum value around zero for PMV to the neutrality sensation range (from -0.5 to 0.5). However, assuming a built environment where the difference between the temperatures is within 2°C, if the control strategy modify continuously the capacity of the actuator, and then, it is capable to maintain the PMV index on the zero target, the use of T_{rm} sensor will not be necessary. In this case, if the controller leads the PMV index to zero, the real PMV index of the built environmental will be between -0.5 and 0.5, considering all the uncertainties on the PMV value.

For further work, we intend to implement this sensor into a split-type air conditioning system and control PMV in a real-time basis, focusing on the improvement of both thermal comfort and energy savings

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8 Responsibility notice

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