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HUMAN RESPONSE MODELLING FOR THERMAL COMFORT ASSESSMENT: THE CORE-CARE CASE STUDY

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INTRODUCTION

Thermal comfort is defined in the standard ASHRAE 55 - 2017 as *“a condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation”* [1]. The interest in this topic has increased in recent years since people’s lives are conducted mostly in indoor environments, thus thermal comfort and indoor air quality (IAQ) are important to be taken into account in designing new environments.

Thermal comfort models have been developed to describe the correlation between the objective thermal environment and subjective thermal sensations. The first physiological model developed to predict thermal comfort is the Fanger model: he developed the PMV index for predicting steady-state comfort responses. Subsequently, many thermal comfort models have been developed; for example, Gagge developed the two-node model dividing the body into two concentric cylinders, Stolwijk developed the 25-node model of thermoregulation, dividing the body into 25 nodes, Berkeley model was improved and validated for steady-state conditions, transient and non-uniform environments [2].

In this project, three two-node models, the first developed by Gagge and its improvements, are implemented to predict subjective thermal sensations and have been applied to the CORE-CARE laboratory, a test room located in the Industrial Engineering Department at the University of Padova. In the laboratory 32 tests have been carried out for the winter and summer seasons to measure how the environment influences the human thermal sensation when its conditions change. The evaluation of thermal comfort is conducted with the Standard Effective Temperature (SET), established on a two-node model and introduced by ASHRAE. Finally, an analysis of the obtained results with *PMV* and *SET* indexes is carried out.

CHAPTER 1

1. LITERATURE REVIEW

1.1 FANGER MODEL

Thermal comfort is defined by Fanger in agreement with ASHRAE standard 55 as "the condition of mind which express satisfaction with the thermal environment" [4]. The purpose of the study is to find the optimal thermal comfort condition for the highest percentage of people in a group, since it is almost impossible to satisfy every person due to the subjective reaction to the environment characteristics. The goal is to keep the human body in a state of thermal neutrality, which is the condition where a person is in equilibrium with the environment and is satisfied with the surroundings.

Fanger developed a model to calculate the level of thermal comfort of the indoor environment by introducing the Predicted Mean Vote (PMV) index. The model's output (PMV) is obtained known the six variables that influence the thermal comfort:

- *met*: activity level [met];
- i_{cl}: thermal resistance of the clothing [clo];
- t_a: air temperature [°C];
- t_r: mean radiant temperature [°C];
- v_{el}: relative air velocity [m/s];
- *RH*: relative humidity [%].

Four of the six inputs described for the model are related to physical environment, while only two are related to the subject. The comfort equation is based on the heat balance with the environment in steady-state conditions and it explains how the parameters should be combined to obtain the optimal thermal comfort, thus showing that it is not related to subjective sensation of the person. Hence, the PMV index is introduced to understand the level of comfort and it is directly related to the Percentage of People Dissatisfied (PPD), an index that calculates the amount of people that in that group are not in a comfort state and would prefer a colder or warmer environment.

1.1.1 HEAT BALANCE

Fanger developed a steady-state model, which considers the body in equilibrium with the environment; therefore, the heat storage within the body is assumed to be zero. The heat balance is shown in Eq. (1):

$$\mathrm{M} - \mathrm{E_d} - \mathrm{E_{sw}} - \mathrm{E_{re}} - \mathrm{C_{res}} - \mathrm{W} = \mathrm{K} = \mathrm{R} + \mathrm{C} \qquad (1.1)$$

where

- M = metabolic rate [W];
- E_d = heat loss by water vapor diffusion through the skin [W];
- E_{sw} = heat loss by evaporation of sweat from the surface of the skin [W];
- E_{re} = latent respiration heat loss [W];
- C_{res} = dry respiration heat loss [W];
- W = external mechanical [W];
- K = conduction through clothing from the skin surface to the outer environment [W];
- R = heat loss by radiation from the outer surface of the clothed body [W];
- C = heat loss by convection from the outer surface of the clothed body [W].

From these equations the following relation is obtained (Eq. 1.2):

$$\mathrm{M} = \mathrm{E_d} + \mathrm{E_{sw}} + \mathrm{E_{re}} + \mathrm{C_{res}} + \mathrm{W} + \mathrm{K} \qquad (1.2)$$

The comfort equation is based on heat balance, and its satisfaction is a necessary but not sufficient condition for achieving the optimal thermal comfort. This requirement is related to the thermoregulatory system that works to keep the internal core of the body at constant temperature. However, it does not take into account the thermal sensation of people in an ambient where the conditions for an optimal thermal comfort are not satisfied. Therefore, the predicted mean vote was introduced to predict the thermal sensation for any combination of the six inputs, and it is measured with a seven-point scale (Tab. 1.1):

Vote	Perception
+3	hot
+2	warm
+1	slightly warm
0	neutral
-1	slightly cool
-2	cool
-3	cold

Table 1.1. ASHRAE seven-point scale for PMV evaluation.

The magnitude of the PMV is difficult to understand, hence the PPD index has been introduced. It predicts the percentage of people who are not thermally satisfied with the environment. Indeed, each person is different, therefore in the same ambient there could be two people, one could feel in neutral conditions, while the other not. The PPD parameter is evaluated as function of the PMV.

For example, it has been evaluated from the tests carried out, that, when the PMV is equal to zero, up to 5% of the subjects can be unsatisfied with the environment. (Fig. 1.1)

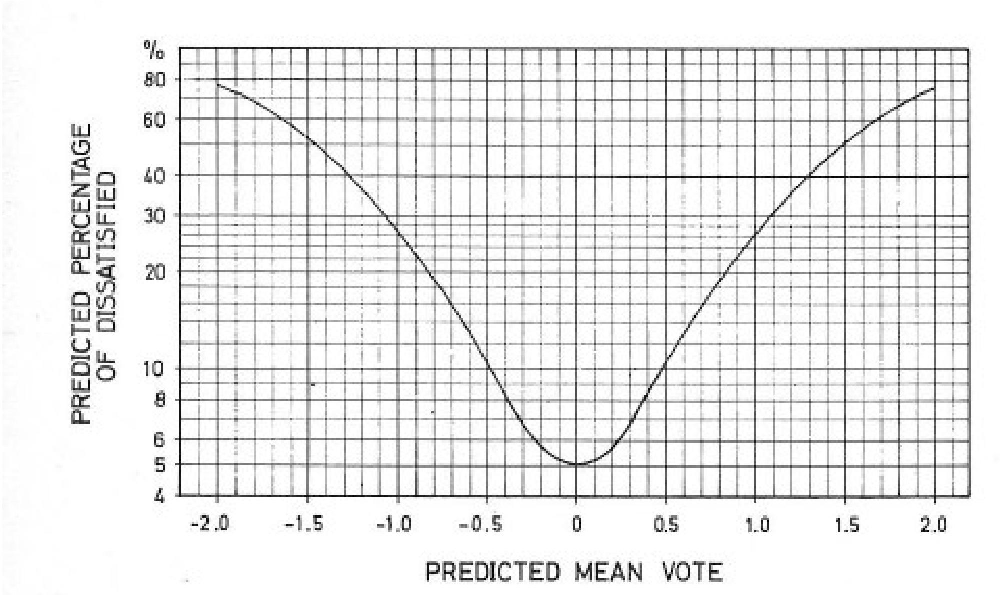


Figure 1.1. Predicted Percentage of Dissatisfied (PPD) as a function of Predicted Mean Vote (PMV) [1]

1.2 TWO NODE MODEL: GENERAL FEATURES

The two-node model was firstly introduced by Gagge in 1971 [5]. Its aim is to predict the physiological response of the human body after one hour exposure to the ambient.

The thermoregulatory system is divided into two parts: the passive and the controlling system (Fig 1.2). The passive system consists of a cylinder that simulate the human body and that is divided into two layers. The internal layer is the core while the external layer is the skin. Instead, the controlling system consists of three elements: the thermo-receptors, which are nerve endings that are sensitive to the temperature, the system that elaborates the signals from the thermo-receptors and the mechanisms that react to these signals.

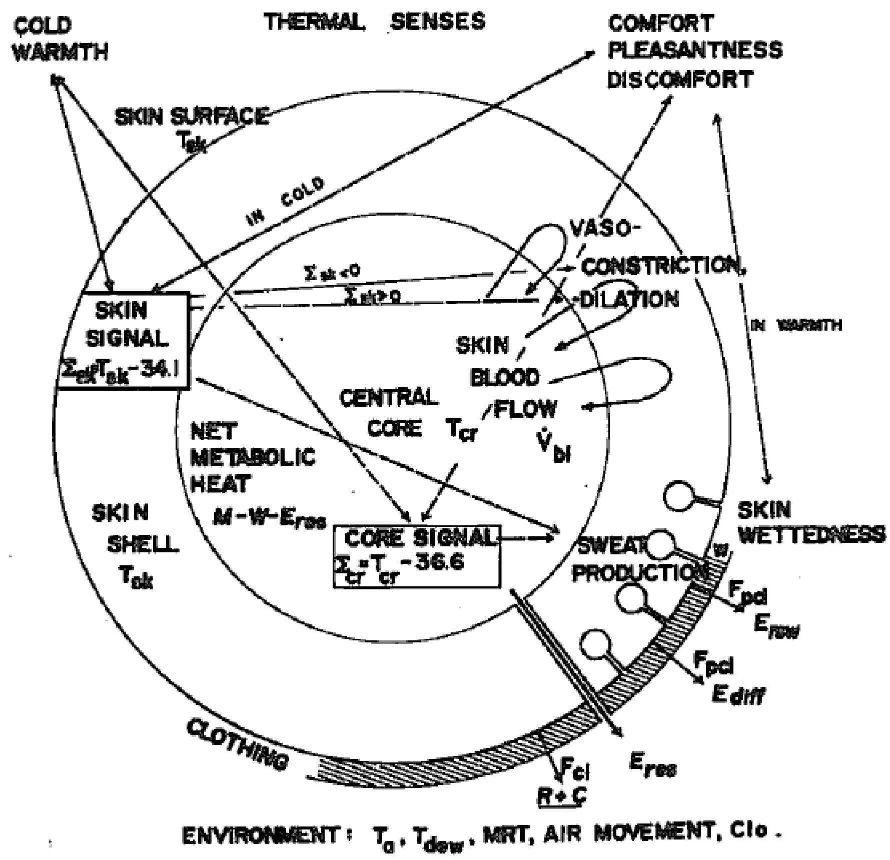


Figure 1.2. A concentric shell model of a man and his environment [2]

1.2.1 THE PASSIVE SYSTEM

The body is divided into two concentric cylinders. The inner cylinder is the core and is at temperature T_{cr}, while the outer cylinder is the skin and is at temperature T_{sk}.

The two-node model assumes that the body is in equilibrium with the environment as long as the parameters of the surrounding environment remain unchanged; when this happens, the inputs change and the outputs after one hour of subject exposure to the environment are recalculated, assuming that after that time the body reaches equilibrium again.

The first step is to calculate the heat gained from and lost by the body with the heat balance equations between the skin layer and the environment and between the core layer and the skin layer.

The total heat balance equation can be written as (Eq. 1.3):

$$S = M - E + R + C - W \qquad [W/m^2] \qquad (1.3)$$

where

- S = rate of heating (+) or cooling (-) by the body;
- M = net rate of metabolic heat production;
- E = total evaporative heat loss;
- R = heat gained (+) or lost (-) by radiation;
- C = heat gained (+) or lost (-) by convection;
- W = work accomplished.
- The total evaporative heat loss is divided into three elements (Eq. 1.4):

$$E = E_{res} + E_{diff} + E_{rsw} \quad [W/m^2] \qquad (1.4)$$

where

- E_{res} = heat of vaporized moisture from the lungs;
- E_{diff} = heat of vaporized water diffusing through the skin layer;
- E_{rsw} = heat of vaporized sweat necessary for the regulation of the body temperature.

E_{rsw} is the sensible heat loss from the body while the sum of $E_{res} + E_{diff}$ is the insensible heat loss.

E_{res} can be calculated with a relation developed by Fanger (Eq. 1.5):

$$E_{res} = 0.0023\, M\, [\, 44 - \Phi_a P_a \,] \qquad [W/m^2] \qquad (1.5)$$

where

- 44 mmHg = is the saturated vapor pressure for an average lung temperature of 35.5 °C;
- φ_a = relative humidity [%];
- P_a = saturated vapor pressure for the dry bulb or air temperature of the environment [mmHg].

The heat of vaporized moisture from the lungs during respiration is directly proportional to the gradient of vapor pressure from the lungs to the ambient air and to the ventilation rate of the lungs.

The maximum evaporative heat loss from the body surface is E_{max} (Eq. 1.6):

$$E_{max} = \kappa h_c [P_{sk} - \Phi_a P_a] F_{pcl} \qquad [W/m^2] \tag{1.6}$$

where

- κ = Lewis relation, equal to 2.2 [°C/mmHg] at sea level;
- h_c = convective heat transfer coefficient [W/(°C m^2)];
- P_{sk} = saturated vapor pressure at mean skin temperature [mmHg];
- F_{pcl} = permeation efficiency factor for water vapor evaporated from the skin surface through clothing to the ambient air.

The total evaporative heat loss from the skin surface is E_{sk} (Eq. 1.7):

$$E_{sk} = E_{diff} + E_{rsw} \qquad [W/m^2] \tag{1.7}$$

The average wettedness of the body skin surface is introduced as (Eq. 1.8):

$$w = \frac{E_{sk}}{E_{max}} \qquad [-] \tag{1.8}$$

When the sensible heat loss is equal to zero, the body doesn't produce any sweat, E_{rsw} is equal to zero and, thus $E_{sk} = E_{diff}$. Therefore, the minimum value of the skin wettedness is obtained, which is equal to $w_{diff} = 0.06$, which corresponds to the normal dampness of the human skin without sweating. At the opposite, when the surface is fully wet the w value reaches its maximum, $(w = 1)$. The parameter w_{rsw} is introduced as the skin wettedness due to the regulatory sweating and is calculated as the ratio of E_{rsw}/E_{max}. When the total surface of the body is wet, $w = w_{rsw} = 1$, on the contrary, when the surface is not wet and $E_{rsw} = 0$, $w = w_{diff} = 0.06$ and $w_{rsw} = 0$. The following equation (Eq. 1.9), which calculates the evaporative loss from the skin surface, describes these two limit conditions and the intermediate ones that occur when only a part of the human body is covered by sweat:

$$E_{sk} = (0.06 + 0.94\, w_{rsw})\, E_{max} \quad [W/m^2] \qquad (1.9)$$

The body is considered as a cylinder with two layers. The core and the skin of the human body are treated as two concentric shells that have their mass. m_{sk} is the mass of the skin layer, while m_{cr} is the mass of the core, the total body mass is $m_b = m_{sk} + m_{cr}$ [kg]. The total body area is the DuBois area A [m^2].

The first step is to do the heat balance at the skin and the core layers. The net heat flow between the skin shell and the environment is given by the relation (Eq. 1.10):

$$S_{sk} = K_{min}(T_{cr} - T_{sk}) + c_{bl}\dot{V}_{bl}(T_{cr} - T_{sk}) - E_{sk} - (R + C) \quad [W/m^2] \qquad (1.10)$$

where,

- S_{sk} = rate of heat storage [W/m^2];
- c_{bl} = specific heat of blood, equal to 1.163 [W hr/(kg °C)];
- $\dot{V}_{bl}$ = rate of skin blood flow [L/(hr m^2)];
- K_{min} = minimum heat conductance of skin tissue, equal to 5.28 [W/(°C m^2)];
- R = heat power lost from the body by convection [W/m^2];
- C = heat power lost from the body by radiation [W/m^2].

The first term represents the heat power gained by conduction between the core layer and the skin layer, while the second term represents the heat power gained by convection between the core and the skin related to the flux of blood. The remaining terms E_{sk}, R and C, are negative because they represent the heat power lost from the skin to the environment.

The net heat flow between the central core and the skin shell is given by the relation (Eq. 1.11):

$$S_{cr} = (M - E_{res} - W) - K_{min}(T_{cr} - T_{sk}) - c_{bl}\dot{V}_{bl}(T_{cr} - T_{sk}) \quad [W/m^2] \qquad (1.11)$$

M is the metabolic effect [W/m^2] generated in the core, E_{res} is lost due to the respiration with the lungs, W is the mechanical work [W/m^2] lost due to mechanical actions and the last two terms represent the heat power lost by conduction and by convection from the core to the skin layer, related to the blood flow.

The total body heat storage is calculated as (Eq. 1.12)

$$S = S_{cr} + S_{sk} \quad [W/m^2] \tag{1.12}$$

The skin temperature and the core temperature vary over time. The core and the skin layers are assumed to be uniformly at T_{cr} and T_{sk} temperatures and that both refer to the same surface area of the body (A). The temperatures rate of change is given by the equations (Eq. 1.12), (Eq. 1.14):

$$\dot{T}_{sk} = \frac{S_{sk}A}{c'_{sk}} \quad [°C/h] \tag{1.13}$$

$$\dot{T}_{cr} = \frac{S_{cr}A}{c'_{cr}} \quad [°C/h] \tag{1.14}$$

- c'_{sk}, c'_{cr} are the total thermal capacities of the skin shell and the central core and are calculated as (Eq. 1.15), (Eq. 1.16):

$$c'_{sk} = c_b m_{sk} \quad [Wh/°C] \tag{1.15}$$

$$c'_{cr} = c_b m_{cr} \quad [Wh/°C] \tag{1.16}$$

where

- c_b is the specific heat of the body, equal to 0.97 [Wh/(kg °C)].

The temperature of the skin and of the core at any time are obtained by integration over time τ of the temperatures change rate equations (Eq 1.17), (Eq 1.18):

$$T_{sk} = T_{sk0} + \int_0^t \dot{T}_{sk} d\tau \tag{1.17}$$

$$T_{cr} = T_{cr0} + \int_0^t \dot{T}_{cr} d\tau \tag{1.18}$$

T_{sk0} and T_{cr0} are the skin shell temperature and the central core temperature at the initial exposure of the body to the environment characterized by the air temperature t_a and the relative humidity φ_a.

1.2.2 THE CONTROLLING SYSTEM

The controlling system processes the hot and cold signals and transform them into a variation of the blood flow or the production of the metabolic energy. It consists of three elements: the first are the thermo-receptors that measure the feeling of warmth and of cold; the signals from the thermo-receptors are processed by the elaboration system that determine their entity and identify their nature; finally, the signals are transformed into variations of blood flow or of the metabolic energy production.

The temperature signals that come from the core layer and the skin layer are compared respectively with their reference temperature T_{sk0} and T_{cr0} to obtain the error signals (Eq. 1.19), (Eq. 1.20):

$$\Sigma_{sk} = T_{sk} - T_{sk0} \tag{1.19}$$

$$\Sigma_{cr} = T_{cr} - T_{cr0} \tag{1.20}$$

Then the following consequences occur (Tab. 1.2):

$\boldsymbol{\Sigma_{sk} < 0}$	COLD SIGNAL
$\boldsymbol{\Sigma_{sk} > 0}$	WARMTH SIGNAL
$\boldsymbol{\Sigma_{cr} < 0}$	COLD SIGNAL
$\boldsymbol{\Sigma_{cr} > 0}$	WARMTH SIGNAL

Table 1.2. Cold and warmth signals.

The signals from the core and the skin govern the variation of the blood flow. The cold signal induces vasoconstriction, while the warm signal induces vasodilation. If the thermal sensation of the body is cold, the blood flow decreases to the periphery because of the valve closure, so the heat exchanged with the external environment decreases and the body temperature decreases. While if the thermal sensation is hot the blood flow increases to the periphery because of the opening of valves, the heat exchanged with the external environment increases and the temperature of the body increases. If the warm signal comes from both the skin layer and the core layer, the body is subjected to sweating to act against the heat, while the shivering is caused by both the cold signal from the skin and the core and helps the body in cold conditions because shivering generates metabolic energy.

The blood flow at initial condition is $V_{bl0} = 6.3$ [L/(h m^2)], the blood flow at any time is (Eq. 1.21):

$$\dot{V}_{bl} = \frac{V_{bl0} + DILAT\,\Sigma_{cr}}{1 + STRICT\ \Sigma_{sk}} \quad [L/(h\ m^2)] \tag{1.21}$$

- DILAT = coefficient related to the opening of the valves,
- STRICT = coefficient related to the closure of the valves, in general equal to 0.5.

In this relation the DILAT coefficient depends on the version of the model that is considered and on the type of activity that the subject is doing. When the signals of cold from the central core Σ_{cr} or the ones of warmth from the skin shell Σ_{sk} are sent, they are put equal to zero in this equation, because the vasodilation depends only on the warmth signals from the core and the vasoconstriction depends only on the cold signals from the skin.

When the warmth signals come from both the skin shell and the central core, the glands are activated and start to produce the regulatory sweating $\dot{m}_{rsw}$ at the skin surface. It regulates the temperature by evaporation and is calculated with the equation (Eq. 1.22):

$$\dot{m}_{rsw} = 250\,\Sigma_{cr} + 100\,\Sigma_{cr}\,\Sigma_{sk} \qquad [g/(h\ m^2)] \qquad (1.22)$$

The first term is related to the production of regulatory sweating during exercise, while the second term is associated with the production of sweat during rest and is regulated by the product of the core and skin warmth signals *(Σ_{cr}) (Σ_{sk}).*

The sensible heat loss, which is the heat of vaporized sweat necessary for the regulation of body temperature, is calculated according to (Eq. 1.23):

$$E_{rsw} = 0.7\dot{m}_{rsw}\left[2^{(T_{sk}-T_{sk0})/3}\right] \qquad [W/m^2] \qquad (1.23)$$

Where 0.7 is the latent heat of sweat [Wh/g].

1.2.3 1971 TWO NODE MODEL

In 1971 the first version of the two-node [6] model was developed assuming simplifications for the calculation of some parameters. This model has seven independent variables which are the input of the model:

- t_a: air temperature [°C];
- φ_a: relative humidity of the environment [%];
- h_c: convective heat transfer coefficient [W/(°C m²)];
- h_r: radiative heat transfer coefficient [W/(°C m²)];
- *met*: metabolic rate [met];
- i_{cl}: insulation of clothing [clo];
- w_e: work accomplished [W/m²].

From these inputs the model calculates the outputs after one hour of exposure of the human body in the environment. The most relevant outputs are the skin temperature, the core temperature, the blood flow, the heat lost due to the evaporation of the sweat from the skin and the corresponding skin wettedness.

The model is valid for moderate activity conditions air temperatures between 5 and 45 °C and for relative humidities down to 10%. The thermal environment is described by the operative temperature T_o and the dew point temperature, that are related to the heat transfer coefficient and the mass transfer coefficient. Thanks to this information it's possible to understand the energy exchange between the environment and the skin surface.

To calculate the saturated vapor pressure, it has been used the following empirical relation (Eq. 1.24):

$$\mathrm{SVP(T)} = e^{(16{,}6536-4030{,}183/(T+235))} \quad \text{[kPa]} \tag{1.24}$$

The following values are assumed as predefined values for the calculation of the outputs (Tab. 1.3).

Parameter	**Value**	**U.M.**
T_{sk0}	34.1	°C
T_{cr0}	36.6	°C
m_{sk}	3.4	kg
m_{cr}	78.3	kg
A_d	2	m^2
DILAT	75	$L/(m^2hK)$
STRIC	0.5	[-]

Table 1.3. Predefined parameters in 1971 model.

1.2.4 1976 TWO NODE MODEL

The two-node model published in 1976 [7] was improved from the original model of 1971. It presents some differences and some improvements with respect to the previous model. As for the first version, the inputs of the model are seven. In the Tab. 1.4 the differences between the models are shown:

INPUT	1971 model	1976 model
t_a: air temperature [°C]	YES	YES
φ_a: relative humidity of the environment [%]	YES	YES
***met*: metabolic rate [met]**	YES	YES
i_{cl}: insulation of clothing [clo]	YES	YES
w_e: work accomplished [W/m^2]	YES	YES
h_c: convective heat transfer coefficient [W/(°C m^2)]	YES	NO
h_r: radiative heat transfer coefficient [W/(°C m^2)]	YES	NO
v_{el}: room air movement [m/s]	NO	YES
t_r: mean radiant temperature [°C]	NO	YES

Table 1.4. Differences between the inputs of 1971 and 1976 model.

The mean radiant temperature was not included in the 1971 model, while the effect of the air movement was considered in the convective and combined heat transfer coefficients.

The model assumes the following values as predefined values for the calculation of the outputs (Tab. 1.5).

Parameter	Value	U.M
T_{sk0}	34.0	°C
T_{cr0}	36.6	°C
m_b	70	kg
A_d	1.8	m^2
DILAT	150	$L/(m^2\ h\ K)$
STRIC	0.5	[-]

Table 1.5. Predefined parameters in 1976 model.

In this model the empirical equation used to calculate the saturated vapor pressure is slightly different to the one used in the 1971 model (Eq. 1.25):

$$\mathrm{SVP(T)} = \mathrm{e}^{(18.6686-4030.183/(\mathrm{T}+235)} \quad \text{[Torr]} \qquad (1.25)$$

Furthermore, in the 1976 model some improvements have been implemented:

1. The fraction alpha *(α)* is used to calculate the fraction of the body that corresponds to the skin and core with respect to the total body and it is assumed to be equal to 0.1 for the first iteration. The alpha parameter in helpful to calculate the total body temperature from the skin and core temperature and the mass of the skin shell and the central core from the total body mass. It has been introduced in the newly developed model because it takes into account the variation of the fraction of skin and core mass due to the variation of the blood flow when the controlling system receives cold signals or warmth signals. For example, when the core sends a warmth signal, the blood flow increases due to vasodilation, hence the mass of the skin shell will be higher. The new values of skin, core mass and body temperatures are calculated at each iteration, thus the

alpha parameter is recalculated according to the Eq. 1.26, as function of the blood flow that depends on the signals from the thermo-receptors:

$$a = 0.04415 + 0.351/(V_{bl} - 0.014) \quad [\%] \tag{1.26}$$

2. Another difference with the 1971 model is related to the convective and radiative heat transfer coefficients h_c, h_r, that were assumed as inputs of the previous model. In the '76 version of the model, the convective heat transfer coefficient due to the air movement (h_{cm}) (Eq. 1.27) and the one due to activity in still air (h_{cv}) (Eq. 1.28) are calculated, and the highest value of the two is used in the calculations, while 3 [W/(°C m^2)] is used if the highest heat transfer coefficient is lower than this value.

$$h_{cm} = 5.66\,(met - 0.85)^{0.39} \qquad [W/(°C\ m^2)] \tag{1.27}$$

$$h_{cv} = 8.6\,{v_{el}}^{0.53} \qquad [W/(°C\ m^2)] \tag{1.28}$$

Furthermore, the new value of the radiative heat transfer coefficient (Eq. 1.29) is calculated at each iteration as function of the mean radiant temperature, which is an input, and the clothing temperature *(t_{cl})*:

$$h_r = 4(5.67 \cdot 10^{-8})\left(\left(\frac{t_{cl}+t_r}{2}\right) + 273.2\right)^3 \cdot 0.725 \qquad [W/(°C\ m^2)] \tag{1.29}$$

The clothing temperature depends on the operative temperature (*t_o)*, the skin temperature at each iteration and on the clothing thermal efficiency factor (F_{cl}) (Eq. 1.30):

$$t_{cl} = t_o + F_{cl}\,(T_{sk} - t_o) \qquad [°C] \tag{1.30}$$

3. The model of 1976 calculates the mass of regulatory sweating and the sensible heat loss due to the evaporation of the sweat with different equation with respect to the 1971 model. Indeed, firstly the total body control signal for

sweating is defined, and then the rate of sweat secretion can be obtained (Eq. 1.31):

$$m_{rsw} = 200\Sigma_b e^{(\Sigma_{sk}/10{,}7)} \quad [g/\,(h\,m^2)] \qquad (1.31)$$

where Σ_b is the warmth signal from the total body and CSW=200 g/(m^2h).

The heat loss by evaporation of the mass of sweat produced *(E_{rsw})*, necessary for the regulation of the body temperature, is calculated (Eq. 1.32):

$$E_{rsw} = 0{,}68\ m_{rsw} \quad [W/m^2] \qquad (1.32)$$

4. The most important improvement present in this model is the introduction of the SET index [8, 9, 10]. It is the ASHRAE's Standard Effective Temperature index defined as the equivalent dry bulb temperature of a hypothetical isothermal environment at 50% of relative humidity in which a human subject, while wearing a clothing standardized for activity concerned, would have the same heat exchange at skin surface (H_{sk}) and skin wettedness *(w)* as in the actual test environment.
   The heat exchange between the skin surface and the thermal environment *(H_{sk})* consists of two components:

- the sensible heat *(DRY)* exchanged by convection, radiation and conduction through clothing, driven by the temperature difference between the thermal environment and the skin surface *($T_{sk} – T_o$)* and governed by the combined heat transfer coefficient (*A*) (Eqs. 1.35, 1.36);
- the insensible heat *(E_{sk})* exchanged by evaporation of sweat on the skin surface, controlled by the product of *wB* and driven by the gradient of pressure *(P_{ssk} – P_{sdp})*.

- P_{ssk} = saturation vapor pressure at skin temperature;
- P_{sdp} = saturation vapor pressure at ambient dew point temperature (Eq. 1.33);

- P_{sa}= saturation pressure at air temperature T_a;
- P_a = ambient vapor pressure.

$$P_{sdp} = RH \cdot P_{sa} = P_a \quad (1.33)$$

Body heat balance equation (Eq. 1.34), it describes the external heat exchanged at the skin surface:

$$H_{sk} = A \cdot (T_{sk} - T_o) + w \cdot B \cdot \left(P_{ssk} - P_{sdp}\right) \quad [W/m^2] \quad (1.34)$$

- A: sensible heat transfer coefficient [W/(m²K)] (Eqs. 1.35 or 1.36),

$$A = \frac{1}{I_a + I_{cl}} \quad [W/(m^2\,K)] \quad (1.35)$$

$$A = \frac{f_{cl} \cdot h}{1 + 0.155 \cdot f_{cl} \cdot h \cdot I_{clo}} \quad [W/(m^2\,K)] \quad (1.36)$$

- I_a: insulation of air layer (Eq. 1.37)

$$I_a = \frac{1}{f_{cl} \cdot (h_r + h_c)} \quad [m^2K/W] \quad (1.37)$$

- I_{cl}: intrinsic insulation of clothing layer (Eq. 1.38)

$$I_{cl} = 0.155 \cdot I_{clo} \quad [m^2K/W] \quad (1.38)$$

- f_{cl}: ratio of the clothed body surface area to the body skin surface (Eq. 1.39)

$$f_{cl} = 1 + 0.25 \cdot I_{clo} \quad [-] \quad (1.39)$$

- B: insensible heat transfer coefficient [W/(m²kPa)] (Eq. 1.40 or 1.41)

$$B = \frac{1}{R_{ea}+R_{ecl}} \qquad [W/(m^2\ kPa)] \tag{1.40}$$

$$B = \frac{f_{cl} \cdot h_c L_a}{1+\frac{0.155 \cdot f_{cl} \cdot h \cdot I_{clo}}{i_{cl}}} \qquad [W/(m^2\ kPa)] \tag{1.41}$$

- R_{ea}: evaporative resistance of air layer [m^2kPa/W] (Eq. 1.42);
- R_{ecl}: evaporative resistance of clothing layer [m^2kPa/W] (Eq. 1.43).

The model assumes that the heat loss of evaporation occurs on skin surface and the permeation of water vapor to the outside environment is a function of the vapor resistance of air and clothing layers.

$$R_{ea} = \frac{1}{L_a \cdot f_{cl} \cdot h_c} \qquad [m^2kPa/W] \tag{1.42}$$

$$R_{ecl} = \frac{I_{cl}}{L_a \cdot i_{cl}} \qquad [m^2kPa/W] \tag{1.43}$$

- i_{cl}: permeation coefficient.

A and *B* are function of the relative atmospheric pressure, the ambient air movement, the effective insulation *(I_{cl})* of clothing worn [m^2K/W] and of vapor resistance of clothing *(I_{cl}/i_{cl})* to evaporative heat loss [m^2kPa/W], where i_{cl} is a measure of vapor permeability efficiency of the clothing layer (Eq. 1.44)

$$H_{sk} = M - W - (E_{res} + C_{res}) - (\pm S) \qquad [W/m^2] \tag{1.44}$$

- *M*: metabolism [W/m^2];
- *W*: work accomplished [W/m^2];
- $E_{res} + C_{res}$: total heat lost from the evaporation and convection from the respiration of the lungs [W/m^2];
- *S*: heat storage, positive if it rises the temperature and negative if it decreases the temperature of the body [W/m^2].

To evaluate the SET index is important to calculate the standard operative temperature T_{so} and the standard operative vapor pressure P_{so}.

T_{so} is the operative temperature at standard conditions, so it is the temperature of a uniform enclosure in which an occupant in sedentary conditions, 1.25 [met], in still air, v_{el}=0.2 [m/s], while wearing 0.6 [clo] of clothing, would lose the same sensible heat as in the actual environment described by the operative temperature T_o.

Similarly, P_{so} is defined as the vapor pressure of a uniform environment in which the occupant would lose the same insensible heat from his skin surface at vapor pressure P_{ssk} as he would in the actual environment described by an ambient vapor pressure P_a and coefficient B.

For the environment (Eq. 1.45):

$$\mathrm{H_{sk} = A_s(T_{sk} - T_{so}) + wB_s(P_{ssk} - P_{so})} \qquad [\mathrm{W/m^2}] \qquad (1.45)$$

For standard (Eq. 1.46):

$$\mathrm{H_{sk} = A_s(T_{sk} - SET) + wB_s(P_{ssk} - 0{,}5 \cdot P_{SET})} \qquad [\mathrm{W/(m^2\,K)}] \qquad (1.46)$$

Finally, SET index is the solution of the Eq. 1.47:

$$\mathrm{(T_{so} - SET) + \frac{wB_s}{A_s}(P_{so} - 0{,}5 \cdot P_{SET}) = 0.} \qquad [°\mathrm{C}] \qquad (1.47)$$

1.2.5 1986 TWO NODE MODEL

The two-node model developed in 1986 [11] is very similar to the 1976 model, presenting some differences in the input parameters (Tab. 1.6).

Parameter	Value	U.M.
T_{sk0}	33.7	°C
T_{cr0}	36.8	°C
m_b	70	kg
A_d	1.8	m^2
DILAT	200	$L/(m^2hK)$
STRIC	0.1	[-]
CSW	170	$g/(m^2h)$

Table 1.6. Predefined parameters in 1986 model.

The model considers the same value of the alpha parameter equal to 0.1 as initial value, but the empirical relation (Eq. 1.48) used to calculate its variation as function of the blood flow is slightly different:

$$a = 0.0417737 + 0.7451832/(V_{bl} - 0.585417) \quad [\%] \tag{1.48}$$

As said before, it influences the variation of the mass of the skin and the mass of the core with respect to the total body mass related to the variation of the blood flow induced by the signals sent by the controlling system. But the blood flow is limited to the range of 0.5 [$L/(m^2h)$] as minimum value, and 90 [$L/(m^2h)$] as maximum value.

In this model, the metabolic heat is adjusted in case of shivering (Eq. 1.49):

$$M = \text{met} + 19.4\, \Sigma_{sk}\, \Sigma_{cr} \tag{1.49}$$

which means that the body produces metabolic energy due to shivering if the controlling system sends cold signals both from the skin shell and from the central core.

Another difference with the 1976 model is related to the Lewis Ratio, in the previous model it was considered constant and equal to 2.2 [°C/mmHg], while in this version it varies with the skin temperature and is evaluated with the relation (Eq. 1.50):

$$LR = \frac{15.1512(T_{sk}+273.15)}{273.15} \quad [kPa/K] \tag{1.50}$$

1.2.6 ASHRAE 55-2013 STANDARD

The Standard ASHRAE 55-2013 [12] is the last two-node model that has been considered and it is strongly based on the 1986 model. Its structure is similar to the one of the 1976 and 1986 models, but it presents some differences in the calculation of some parameters (Tab. 1.7).

Parameter	Value	U.M.
T_{sk0}	33.7	°C
T_{cr0}	36.49	°C
m_b	69.9	kg
A_d	1.8258	m^2
DILAT	120	$L/(m^2hK)$
STRIC	0.5	[-]
CSW	170	$g/(m^2h)$

Table 1.7. Predefined parameters in ASHRAE 55 model.

In this model the skin wettedness is limited w_{crit}. Indeed, when i_{cl} is equal to zero the value of w_{crit} is obtained with (Eq. 1.51) and thus $I_{cl} = 1$, while in the general case w_{crit} is calculated with (Eq. 1.52) and $I_{cl} = 0.45$.

$$w_{crit} = 0.38\, v_{el}^{-0.29} \tag{1.51}$$

$$w_{crit} = 0.59 v_{el}^{-0.08} \tag{1.52}$$

The temperature of the clothing and the radiative heat transfer coefficient are calculated by iteration using the equation (Eq. 1.53):

$$H(T_{sk} - T_o) = h_c(t_{cl} - T_o) \tag{1.53}$$

where

- $H = \frac{1}{R_{ea}+R_{ecl}}$, $R_{ea} = \frac{1}{F_{acl}+h}$
- R_{ea} is the resistance of air layer to dry heat transfer [m^2kPa/W] (1.42),
- R_{ecl} is the clothing resistance [m^2kPa/W] (1.43).

The alpha parameter is calculated in the same way as in the 1986 model.

A more important difference is in the calculation of the SET index with respect to the 1976 and 1986 models. First, the standard conditions of the environment are set, then a first value of SET is calculated with the equation (Eq. 1.54). Then the iteration starts.

$$SET = T_{sk} - \frac{H_{sk}}{H_{ds}} \qquad [°C] \tag{1.54}$$

Where H_{ds} is equal to H but in standard conditions.

In Figure 1.3 the timeline of the models is presented, with their main differences and improvements.

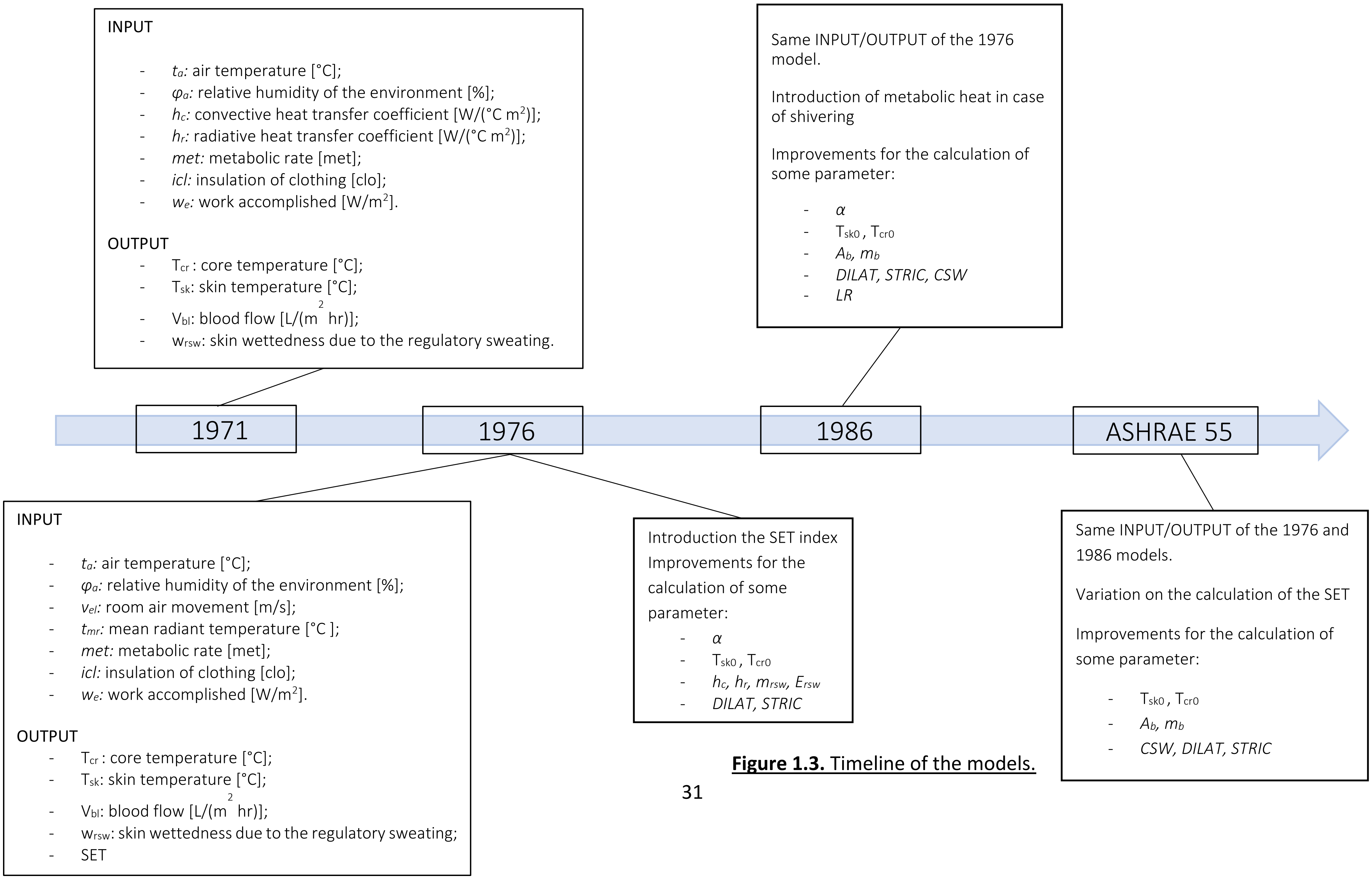


Figure 1.3. Timeline of the models.

CHAPTER 2

2. IMPLEMENTATION OF THE MODELS

2.1 FANGER MODEL

The Fanger model has been implemented using Python. The implementation follows the ISO 7730-2005 standard [13]. In Figure 2.1 the flow chart of the calculation of the *PMV* and *PPD* is shown.

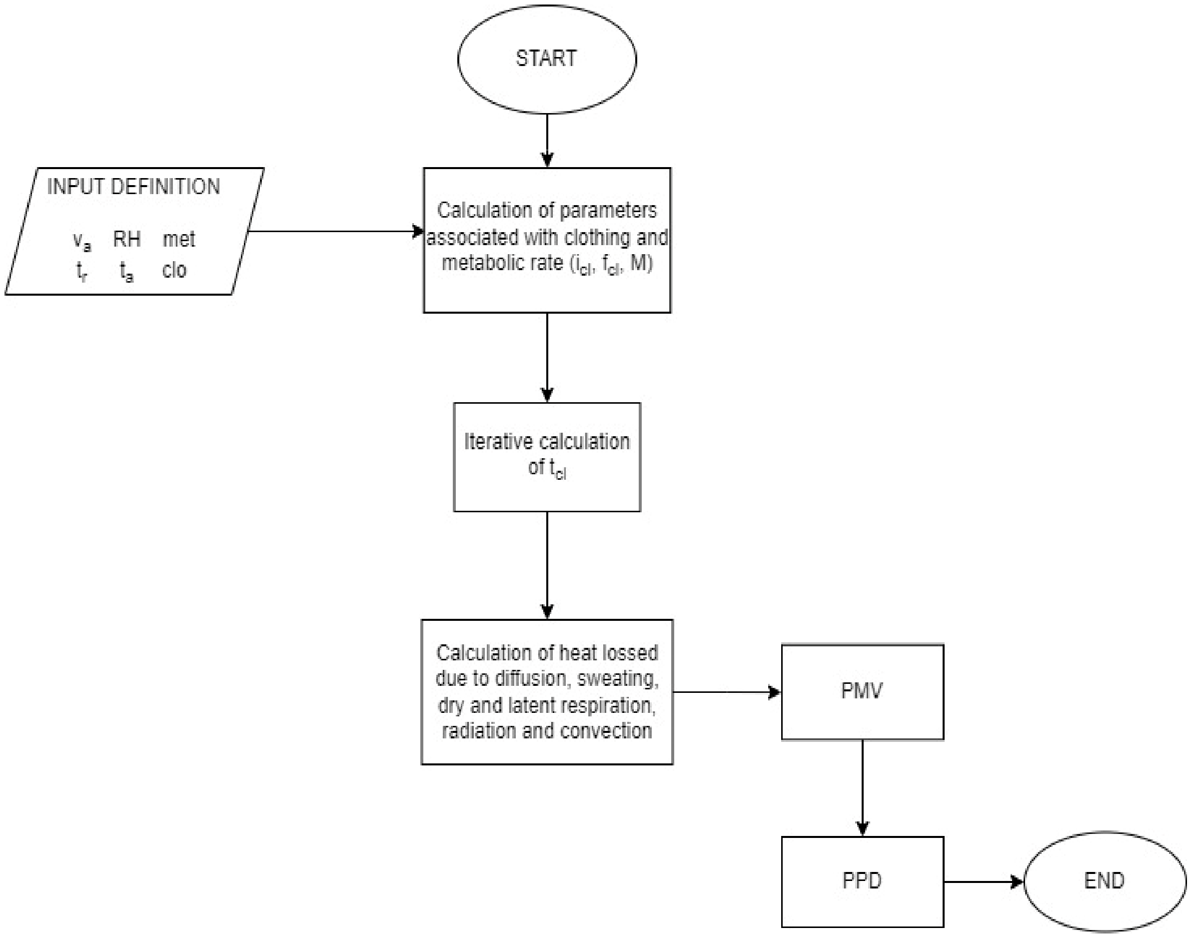


Figure 2.1. Block diagram of the Fanger model.

2.2 TWO- NODE MODEL STRUCTURE

The two-node models that have been implemented are the first version of 1971, the improved version of 1976 and the ASHRAE Standard 55. These three models have been implemented using Python and present the same structure [6, 11, 12].

The calculation has been divided into two steps: firstly, the two-node model function is defined, it is the `twonode_model1971` for 1971 model, `twonode_modelSET` for 1976 model and `twonode_ASHRAE` for ASHRAE 55 model. Subsequently, the second step is implemented, indeed the calculation of SET is obtained with the `SETmodel1971` for 1971 model, the `SETmodel` for 1976 model and `SETmodel_ASHRAE` for ASHRAE 55 model functions. The SET function calculates the

SET index taking as inputs the values of the outputs of the two-node model function. Finally, the functions are called in a new file. With this method it is possible to apply easily the models to the applications, indeed it allows to change easily the inputs and the predefined values of the models according to the requirements.

2.2.1. TWO-NODE MODEL FUNCTION

This function takes as inputs the actual inputs of the models, that, as it was shown in Chapter 1, differ between the 1971 model and the 1976 and ASHRAE 55 models for the convective and radiative heat transfer coefficients and for the introduction of the mean radiant temperature and the room air movement in the most recent models.

In the following table the inputs of the three functions are defined (Tab. 2.1)

INPUTS AND PREDEFINED VALUES		
1971 model	**1976 model**	**ASHRAE 55**
t_a	t_a	t_a
RH	RH	RH
i_{cl}	i_{cl}	i_{cl}
met	met	met
$w_e = 0$	$w_e = 0$	$w_e = 0$
h_r	v_{el}	v_{el}
h_c	t_r	t_r
$A_d = 2$ [m^2]	$A_d = 1.8$ [m^2]	$A_d = 1.8258$ [m^2]
$T_{sk0} = 34.1$ [°C]	$T_{sk0} = 34.0$ [°C]	$T_{sk0} = 33.7$ [°C]
$T_{cr0} = 36.6$ [°C]	$T_{cr0} = 36.6$ [°C]	$T_{cr0} = 36.49$ [°C]
$m_{cr} = 78.3$ [kg]	$m_b = 70$ [kg]	$m_b = 69.9$ [kg]
$m_{sk} = 3.4$ [kg]	-	$P_{atm} = 101.325$ [kPa]

Table 2.1. Definition of the inputs and predefined values of the three functions.

The first seven inputs present in Table 2.1 are set as general values that will be filled in with real data when the function is called. The other inputs regard the standard values assumed by the models. In the table, it is shown the different values for the body area, the reference skin and core temperatures and the body mass. These are as predefined values to run the model, but can be changed when the functions are called.

In the first part of the implementation the variables are defined and the initial values of iteration are set. For instance, the clothing thermal efficiency factor (*Fcl)* and the permeation efficiency factor for clothing (*Fpcl)* are calculated in the 1971 and 1976 models. While regarding the 1976 model and the ASHRAE 55, the values of the convective heat transfer coefficients due to activity in still air (h_{cm}) and due to air movement (h_{cv}) are evaluated and the maximum values of the two is taken for the following calculations. If the highest of the two is lower than 3 [W/(m^2 K)], this value is assumed.

In the second part of the code, the iteration starts. Since the function calculates the output after one hour of exposure of the body to the environment, at the beginning the time is set at zero. A "while" loop is set: the loop starts and continues its iteration until the time reaches one hour.

The 1976 and ASHRAE 55 models calculate iteratively the value of the radiative heat transfer coefficient, therefore its value is continuously recalculated at each timestep. Similarly, the temperature of clothing and the operative temperature are iterated in the loop. Especially, in the ASHRAE 55 model, t_{cl} and t_o are solved iteratively in a nested while loop and then their value at the last timestep is taken for the following calculations.

The timestep that has been considered is:

$$\Delta = \frac{1}{500} \text{ [h]}$$

The timestep considered is lower than the one suggested in the models because it provides more precise results. For example, the timestep application has been applied to the calculation of the skin temperature and the core temperature, as shown by Eq. 1.17 and 1.18. According to this calculation it is possible to integrate them over the time and to obtain their value after one hour.

Furthermore, the controlling system is implemented. The warmth and cold signals from the skin and the core are defined and at that point the blood flow is calculated according to the equation of the model taken into account (Eq.1.21). Therefore, the mass of sweat produced due to the regulatory sweating and the related heat of vaporized loss, in case of warmth signal from both the skin and core layers, are obtained.

Finally, the following parameters are evaluated:

- E_v: total non sensible heat loss from the body;

- E_{diff}: heat of vaporized water diffusing through the skin layer;
- E_{sk}: total evaporative loss from skin;
- E_{max}: maximum evaporative heat loss from the body surface.

These parameters are calculated for all the possible cases:

1. The regulatory sweating is not present, so the skin is not wet, the skin wettedness reaches its lowest value because it is equal to the skin wettedness due to the normal dampness of the skin;
2. The skin is entirely covered by sweat, the skin wettedness due to regulatory sweating is maximum and the heat of vaporized sweat equals the maximum evaporative heat loss;
3. The intermediate conditions are evaluated.

In conclusion, when the sum of the timesteps is one hour, the regulatory loop ends and the outputs are obtained.

Finally, the "return" values of the function are set and represent the output of the first function. The most relevant are the skin temperature, the core temperature, the total skin wettendess, the skin wettedness due to regulatory sweating, the blood flow, the total skin heat loss, the maximum evaporative heat loss and the heat of vaporized sweat.

2.2.2 SET FUNCTION

Subsequently, the second function is defined. The definition is analogous to the one of the two-node model function, but it gets the return from `twonode_model1971`, `twonode_modelSET` and `twonode_ASHRAE` functions as inputs to start the calculation of SET.

The first step is the definition of the standard environment according to ASHRAE. Thus, the definition of the standard values of the parameters involved in the calculation of SET, such as: the convective heat transfer coefficient, the resistance of clothing, the resistance of air layer, the permeation efficiency factor and the thermal clothing efficiency factor.

The initial value of SET index is evaluated and the iteration starts, indeed the SET is the solution of the heat balance equation (Eq. 1.47).

The return is SET, which is the final output of the model.

In Figure 2.2 and 2.3 are represented the block diagrams for the 1971 model and for the 1976 and ASHRAE 55 models. In the 1971 model was included the calculation of SET even if it was not introduced yet, thus it was added the calculation of the 1976 model.

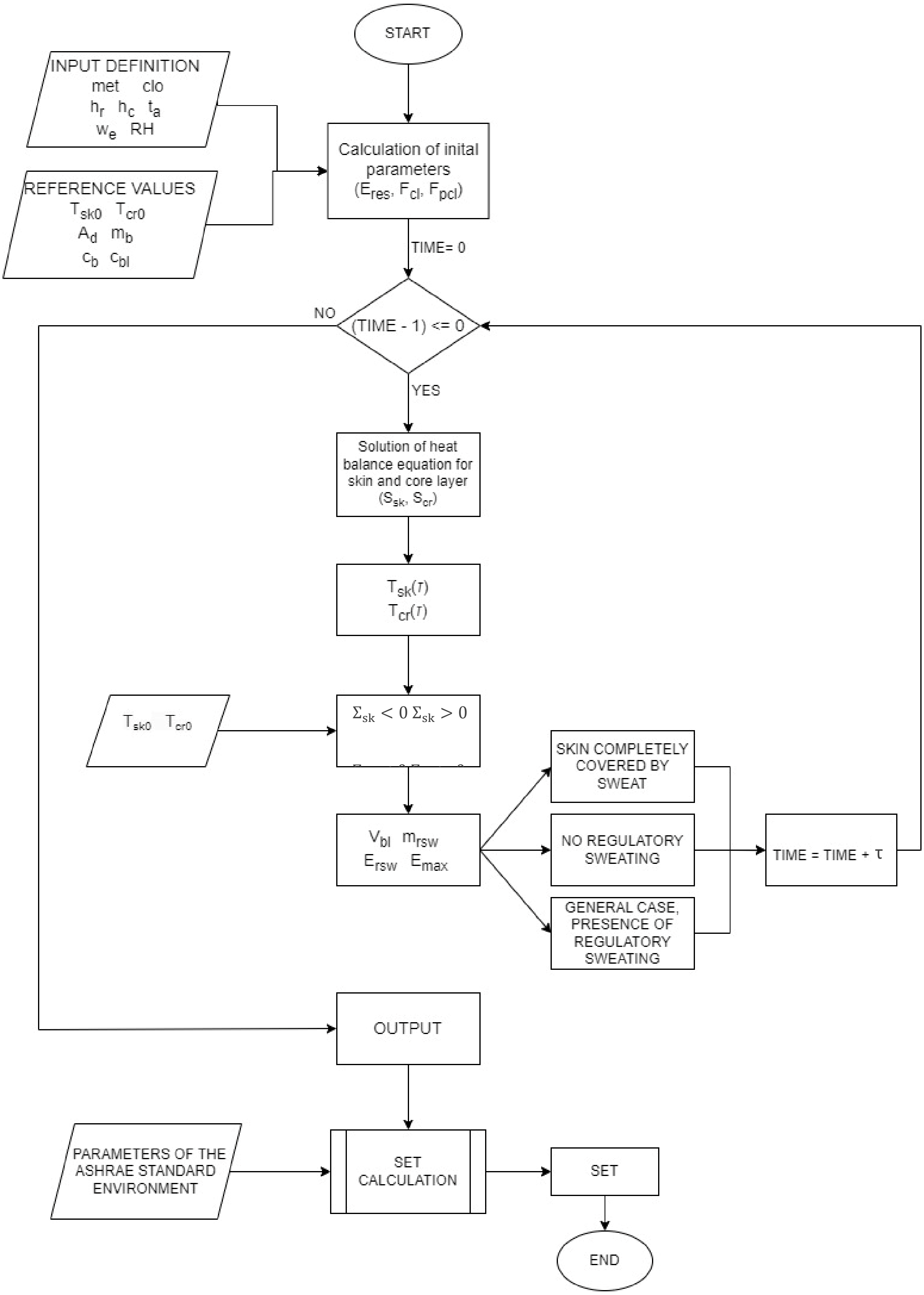


Figure 2.2. Block diagram of 1971 model.

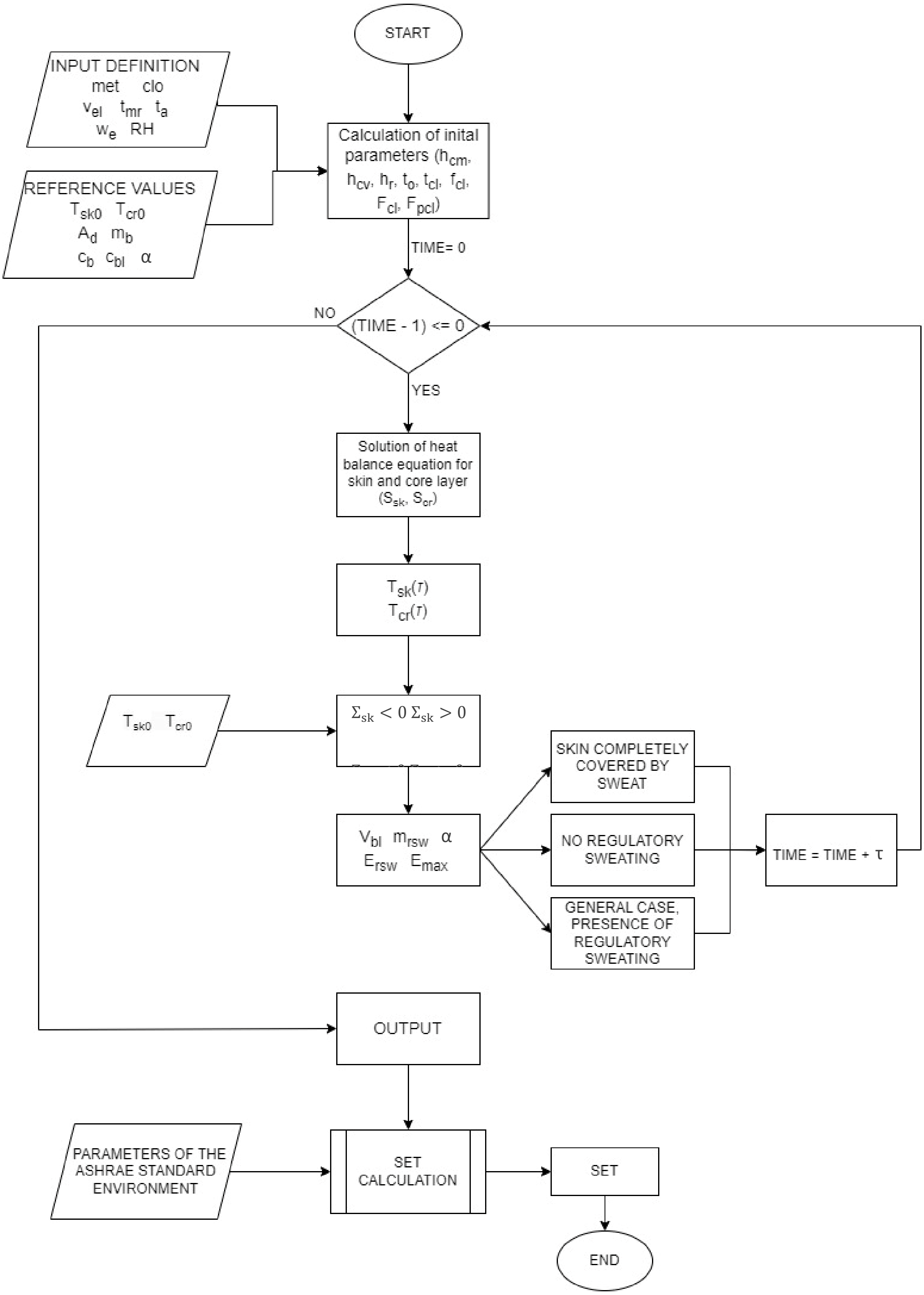


Figure 2.3. Block diagram of 1976 and ASHRAE 55 models

2.3 VALIDATION OF THE MODELS

The models implemented in Python were found in the literature [4,5,6]. Thus, the obtained results have been compared with the original results to validate the implementation and to test its accuracy for further implementations to other case studies.

2.3.1 VALIDATION OF 1971 MODEL

The results obtained with the 1971 model have been compared with the graphics present in literature [5] and are shown in Fig. 2.4, Fig. 2.4, Fig. 2.5, Fig. 2.6. To validate the model, the output of the first function have been taken into account, because, as explained in the previous chapters, the SET index was not introduced yet.

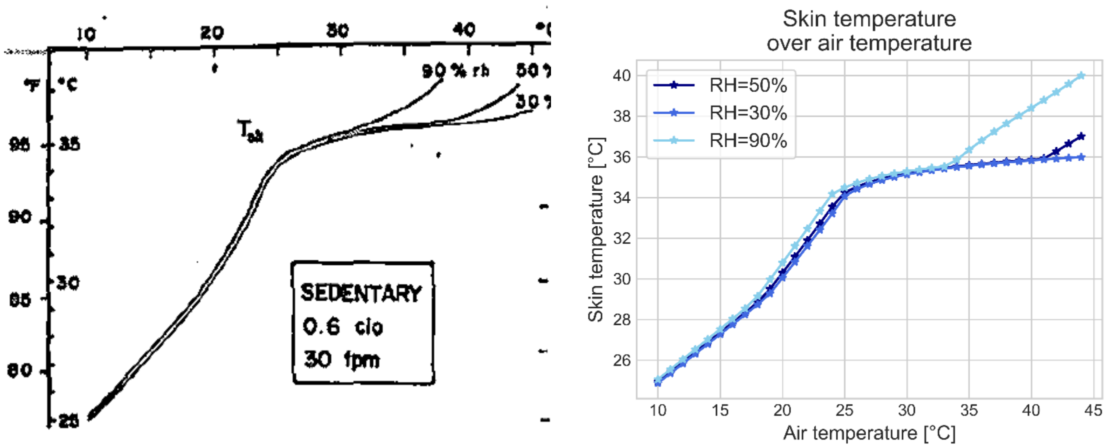


Figure 2.4. Skin temperature over air temperature

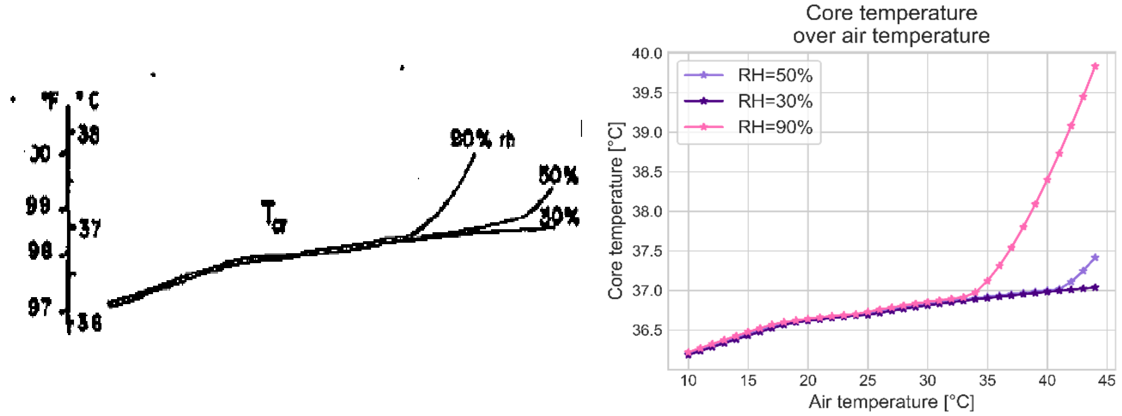


Figure 2.5. Core temperature over air temperature.

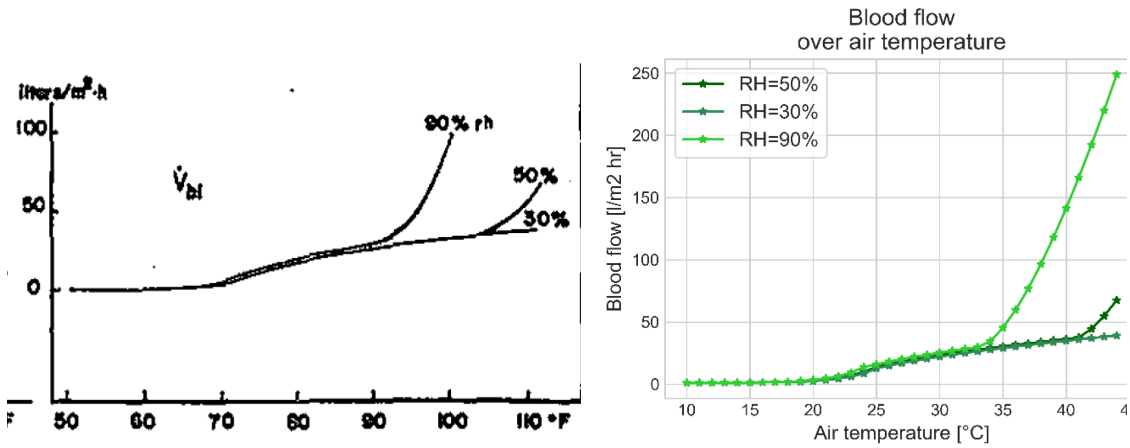


Figure 2.6. Blood flow over air temperature.

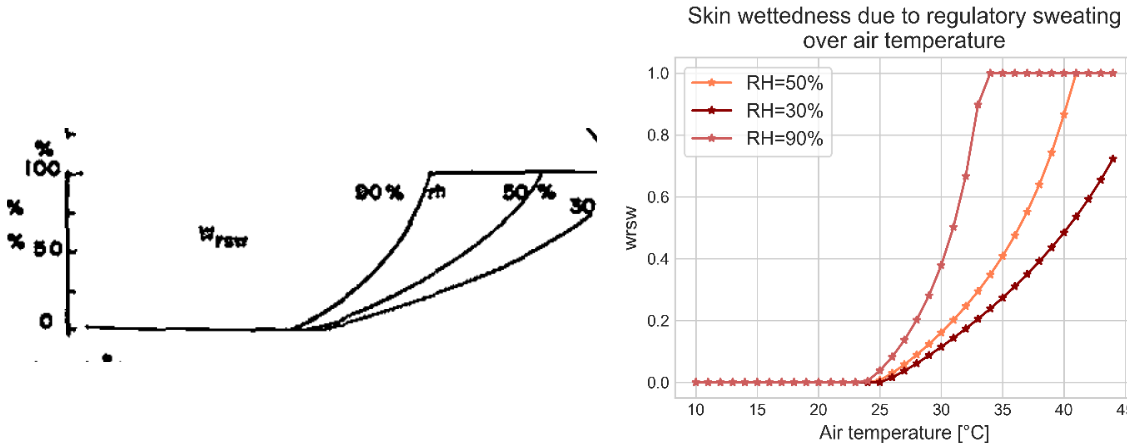
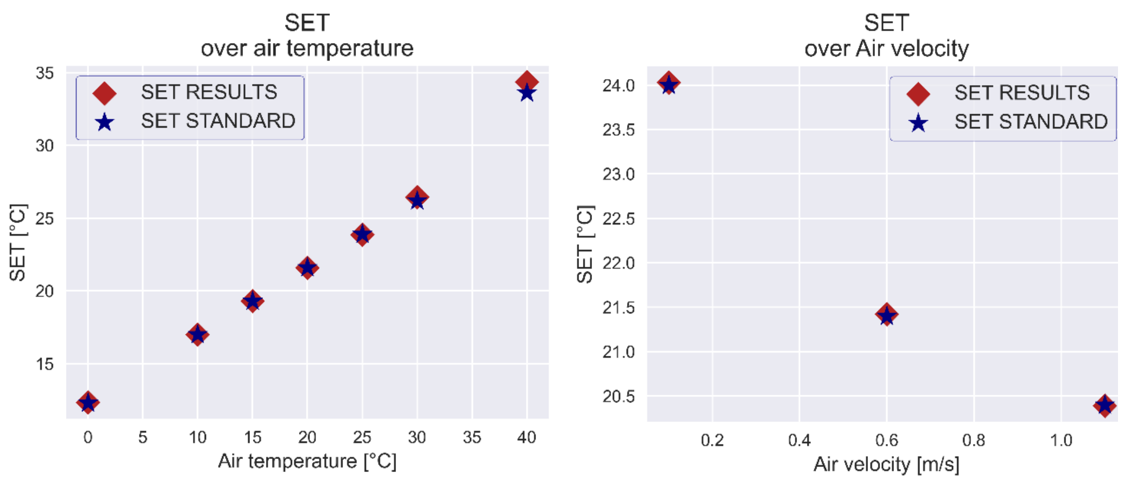


Figure 2.7. Skin wettedness due to regulatory sweating over air temperature

The figures show the skin and core temperature, the blood flow and the skin wettedness due to regulatory sweating over air temperature for three values of relative humidity (*RH=30%, RH=50%, RH=90%).* As it can be observed, the obtained results are coherent with the literature, their shape match very precisely the shape of the reference curves for all the three values of relative humidity. Moreover, in the reference plots, the curves of core temperature and blood flow at *RH = 90%* are cut at *38 °C* concerning T_{sk} and *100* $L/(m^2\ h)$ regarding the blood flow.

2.3.2 VALIDATION OF ASHRAE 55 MODEL

The validation of ASHRAE 55 model has been done by comparing the results of the SET index. The Standard includes a validation table [12] where the values of SET are calculated varying the air temperature, the mean radiant temperature, the relative humidity, the resistance of clothing, the activity of the subject and the room air movement. Figure 2.8 shows the values of SET obtained, compared with the values present in the standard. It is observed that the obtained results are overlapped with the standard values in all cases, only the SET evaluated at 90% of relative humidity is slightly higher than the SET value present in the standard.



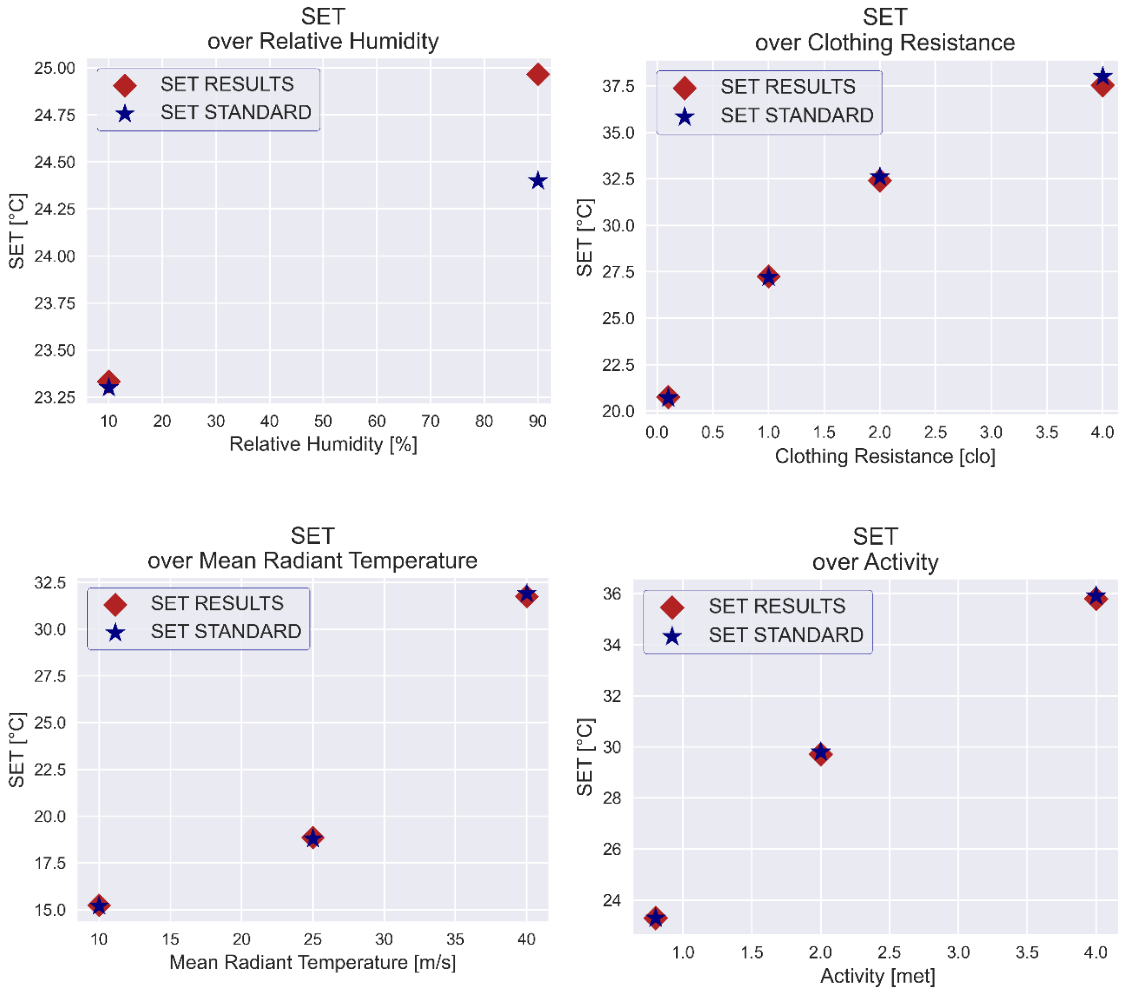


Figure 2.8. Validation of ASHRAE 55 model

CHAPTER 3

3. APPLICATION OF THE MODEL TO THE CORE-CARE LABORATORY

The three models have been applied to a dataset collected in the CORE-CARE laboratory during some tests on thermal comfort and productivity carried out between December 2021 and September 2022. The tests were planned to evaluate the matching between various PMV settings and participants votes, in a test room where steady-state conditions were created.

3.1 DESCRIPTION OF THE LABORATORY

The CORE-CARE laboratory (COntrolled room for building Environmental Comfort Assessment and subjective human Response Evaluation) is located at the third floor of the Department of Industrial Engineering of the University of Padova (Italy). It is a test room where it is possible to study thermal comfort, indoor air quality (IAQ), acoustics and lighting by controlling different parameters independently and thus testing many environmental conditions and investigating other aspects of human life, such as productivity in working places.

The CORE-CARE laboratory was built in an existing building, it was a meeting room that has been completely renovated, therefore it creates a realistic work environment. The laboratory consists in a test room and a control room. In the test room the tests are performed and the data are obtained. The control room is adjacent to the test room, where the parameters that characterize the environment of the test room are controlled and studied in real time.

The test room has a surface of *18.5 m^2* and its height is *2.8 m^2*. It is equipped with independent radiant systems on the floor, ceiling and the four walls of the room, a mechanical ventilation system and different sensors to acquire the data and measure the parameters of the environment. Finally, the test room has two windows installed on the external wall of the building, while the other walls and the floor are adjacent to heated environments and the ceiling is directly under the roof. The laboratory layout is shown in Fig. 3.1. The radiant system operates both in heating and cooling conditions, thus it is supplied with hot or cold water according to the requirement. The water is heated or cooled in the control room, where the HVAC systems are installed. Furthermore, the ventilation unit operates with external air, it can work in cooling or heating integration, dehumidification or free-cooling modes.

The test room was furnished with four desks provided with computers, as to create a workstation per each subject. (Fig. 3.2).

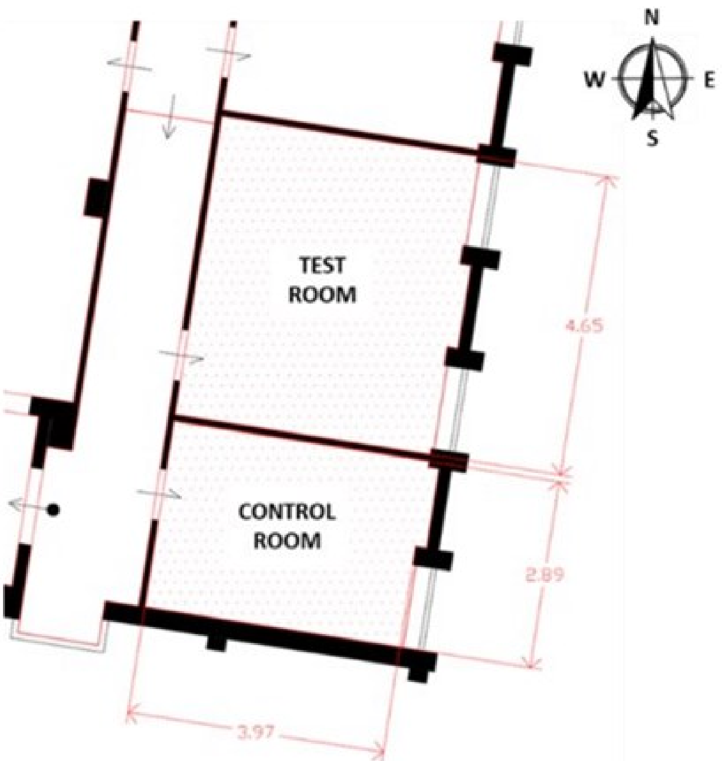


Figure 3.1. CORE-CARE laboratory layout.

Figure 3.2. Office test example.

3.2 DESCRIPTION OF THE STUDY

The tests were performed at the CORE-CARE laboratory and were carried out for the winter and the summer seasons, in order to evaluate the thermal comfort for both seasons. Overall, 32 tests have been conducted divided in 16 tests performed during the winter season (December 1^{st}, 2021 and March 22^{nd}, 2022), and 16 tests during the summer season (May 19^{th}, 2022 and September 30^{th}, 2022).

The participants to the test were 117, 58 for the winter tests and 59 for the summer tests. Most of the tests have been performed with four subjects, while some of them with three or two subjects, due to the impossibility of the people to be present to the tests.

3.3 SETUP CONDITIONS OF THE TESTS

The tests have been set up for five values of *PMV* for both seasons: *-0.7, -0.5, 0, +0.5, +0.7*. These values were chosen to test different conditions of comfort, indeed the *PMV = 0* is the condition for thermal neutrality, the *PMV = -0.5* and *PMV = +0.5* are still acceptable conditions for the comfort and the *PMV = -0.7* and *PMV = +0.7* are more extreme conditions. The tests have been carried out for two values of air flow rate for each value of *PMV: 80* m^3/h and *250* m^3/h.

The tests differ between each other according to a variation of the PMV, the air flow rate and the air and mean radiant temperatures, while the other parameters have been set at constant values. Within the same test, some of the parameters may slightly vary to keep the PMV constant. The air temperature was controlled with the ventilation system, while the mean radiant temperature with the radiant panels; their values were adjusted to obtained uniform conditions in the environment and thus to calculate the operative temperature. The subjects had to perform office activities; thus, the *met* value was set at *1.2 met.* Moreover, the room air movement value was set at *0.05 m/s.* Finally, the resistance of clothing was imposed to the participants, that couldn't change their clothing during the experiments; for the winter season it was set at *0.75 clo,* differently for the summer season it was set at *0.47 clo.* The clothing imposed consisted of shoes, socks, long trousers and a t-shirt for summer season, with the addition of a sweatshirt for winter season. It was asked to the subject to not modify their clothing or to change the hairstyle during the experimental session in order obtain a constant clothing thermal resistance. From the combinations of these input values, the PMV was set in real time in the test room, thanks to the application of the Fanger's thermal comfort equation.

In Table 3.1 and 3.2 are reported the setup conditions of the 32 tests performed in winter and summer seasons.

Date	Expected PMV	Air flow rate [m^3/h]	Participants
01/12/2021	0	250	4
02/12/2021	0	80	4
03/12/2021	-0.5	250	4
07/12/2021	-0.5	80	4
15/12/2021	+0.5	250	4
21/12/2021	+0.5	80	4
21/01/2022	+0.7	250	4
03/02/2022	-0.7	80	4
04/02/2022	-0.7	250	3
11/02/2022	+0.7	80	3
24/02/2022	0	250	4
25/02/2022	+0.5	250	4
03/03/2022	-0.5	250	3
10/03/2022	+0.7	250	2
18/03/2022	-0.7	250	4
22/03/2022	+0.7	250	3

Table 3.1. Setup conditions for winter season

Date	Expected PMV	Air flow rate [m^3/h]	Participants
19/05/2022	-0.5	80	4
31/05/2022	0	80	4
01/06/2022	-0.5	250	4
06/06/2022	+0.5	80	4
07/06/2022	0	250	4
16/06/2022	+0.5	250	4
20/06/2022	+0.5	250	4
23/06/2022	0	80	3
29/06/2022	-0.5	80	4
07/07/2022	-0.5	250	3
18/07/2022	+0.5	80	4
21/07/2022	0	250	4
08/09/2022	+0.7	80	4
19/09/2022	-0.7	80	4
22/09/2022	-0.7	250	3
30/09/2022	+0.7	250	2

Table 3.2. Setup conditions for summer season

3.4 STRUCTURE OF THE TESTS

The structure of the tests is reported in Figure 3.3. The participants didn't have any knowledge about the investigated aspects. The first part regards the acclimatization, it occurs before the actual tests and it lasts for 30 minutes, 15 in a separate room and 15 in the test room. During acclimatization, the subjects adapted to the thermal environment and could move inside of the test room; they were given general instruction concerning the working activity that they had to perform: two participants had to work individually, they were asked to translate a text from English to Italian (ID2, ID3), while the other two participants had to work as a team and could interact with each other, in order to create working conditions as similar as real working environments and they were asked to organize and event and to prepare a presentation with the PC. During the second part of the acclimatization, the participants received a survey regarding general information such as gender, age, weight, height, study title and personal background, as well as information on personal well-being, if they had eaten and if they had performed activity in the two hours before the test. After the acclimatization part, the actual test could start. During the test the subjects couldn't move inside the test room and couldn't interact with the external environment, moreover they had to wear a face mask to comply with Covid-19 containment measures.

The test was divided into two phases that lasted for one hour each. After the first hour the subjects were given the intermediate survey and at the end of the second hour received the second survey. At the end of the test, the participants could exit the test room, get their personal belongings back and ask some curiosities about the tests.

During the tests, the participants were given the surveys according to ISO 10551. The surveys had the aim to investigate the thermal perception of the subjects, which is the Thermal Sensation Vote *(TSV)* or Actual Mean Vote *(AMV)* and the evaluation of the environment.

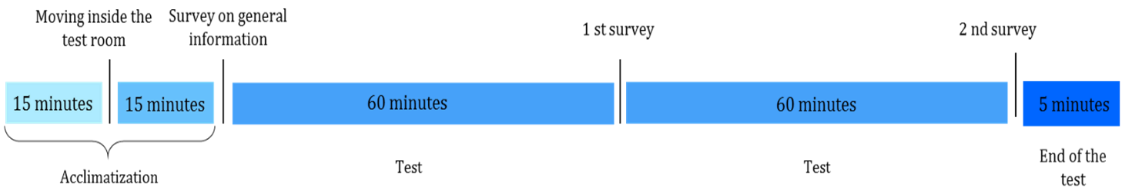


Figure 3.3. Timeline of the test.

3.5 APPLICATION OF THE MODELS TO THE LABORATORY

The results of *AMV* obtained with the tests have been compared to the actual values of *PMV* of the test room. Furthermore, the three two-node models implemented have been applied to the 32 tests. The *SET* index was calculated with the 1971, 1976 and ASHRAE 55 models and the results have been compared one to each other and to the values of *PMV* and *AMV* to observe which model fits better the *AMV* results.

CHAPTER 4

4. RESULTS

4.1 COMPARISON OF THE MODELS

In this chapter, the models' outputs are compared: considering skin and core temperatures, blood flow and skin wettedness due to regulatory sweating.

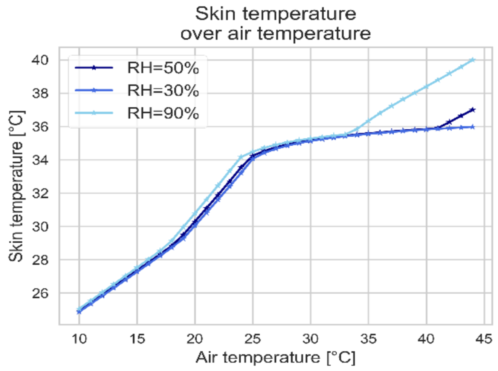
In Figure 4.1 skin and core temperatures are presented over air temperature at three values of relative humidity (*RH = 30%, 50%, 90%*). The shape of the curves is similar for the three models. Considering the skin temperature, the knee of the curve of the 1971 model is at *25 °C* air temperature, while it is at *24 °C* with the 1976 and ASHRAE 55 models. Moreover, after the knee, the curve of the 1971 model is flatter with respect to the other curves that increase more with the increase of air temperature. The difference in the skin temperature due to the variation of relative humidity is relevant when air temperature is higher than *30°C* for 90% *RH* and is between *37°C* and *42°C* for 30% of *RH;* it increases with the increase of air temperature, in particular the curves start to separate earlier with the ASHRAE 55 model. Finally, the maximum skin temperature evaluated by the ASHRAE 55 model at 30% and 50% of relative humidity is higher with respect to the other models.

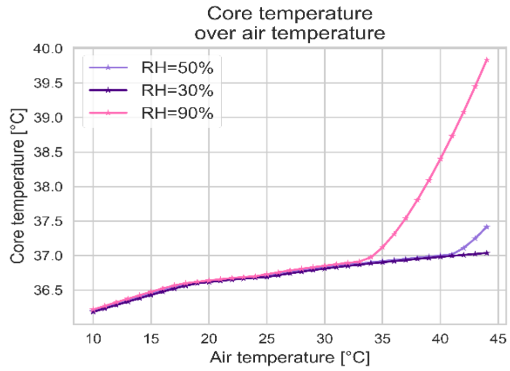
As well as the skin temperature curves, the shape of the core temperature curves is similar for the three models. Analogously to the skin temperature curves, the difference in the core temperature due to the change in the relative humidity becomes relevant over *30°C* of the air temperature for RH = 90% and at air temperature between *37°C* and *42°C* for *RH = 30%* and it increases with the increase of air temperature; with ASHRAE

55 model the separation of the curves starts at lower air temperature with respect to the other curves. At *50% RH* the maximum value of core temperature is reached at *44°C* with ASHRAE 55 model, moreover the 1976 model and ASHRAE 55 model curves are flatter with the increase of air temperature between 10°C and *30°C*.

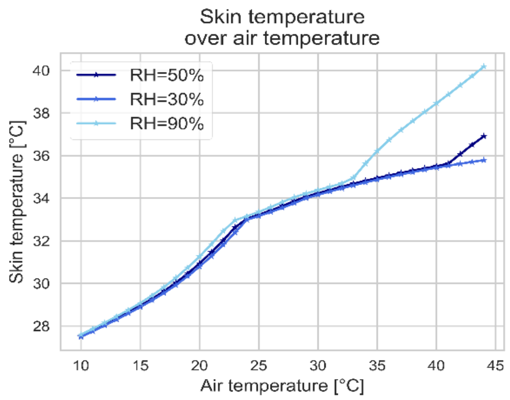
SKIN TEMPERATURE OVER AIR TEMPERATURE	CORE TEMPERATURE OVER AIR TEMPERATURE

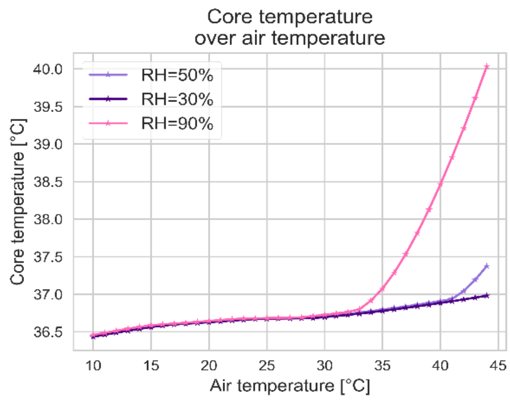
1971 MODEL



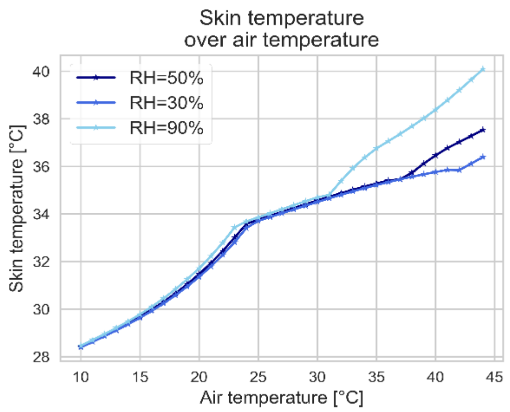


1976 MODEL





ASHRAE 55



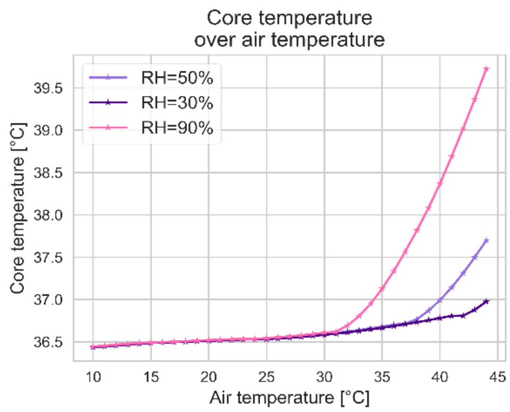


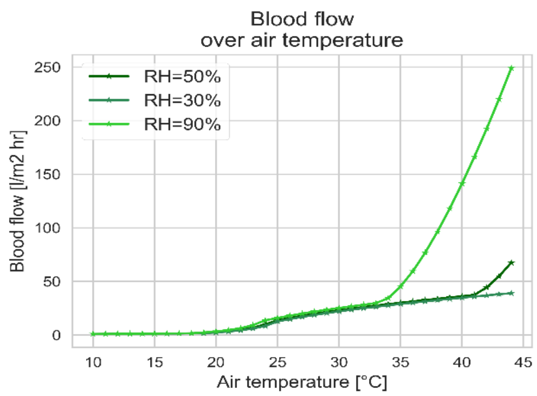
Figure 4.1. Comparison of skin and core temperatures calculated with 1971, 1976 and ASHRAE 55 models.

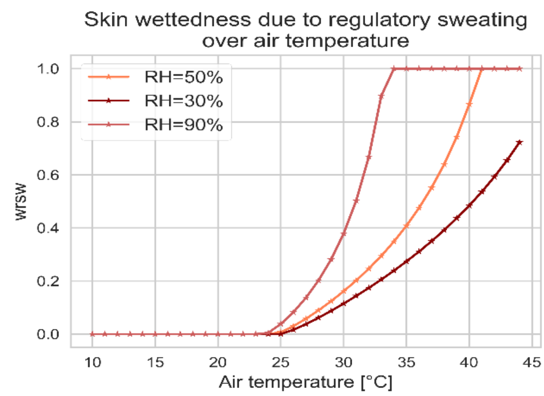
In Figure 4.2 is presented a comparison of the blood flow and the skin wettedness over air temperatures at three values of relative humidity (*RH = 30%, 50%, 90%*). The shape of the blood flow curves is similar for the 1971 and 1976 models. It can be observed that the blood flow calculated with ASHRAE 55 model is limited to the maximum value of *90* $L/(m^2\ hr)$, on the contrary in the other models it not limited, thus for *RH = 50%* the value of *250* $L/(m^2\ hr)$ is reached. Moreover, higher values of blood flow are evaluated with ASHRAE 55 model also at *RH = 30%* and *RH = 50%* with respect to the other models. The blood flow is equal to *6.3* $L/(m^2\ hr)$ at low air temperatures, then it increases with air temperature and relative humidity.

Similarly, the skin wettedness curves of the 1971 and 1976 models have a good correspondence. The regulatory sweating is not present at low air temperatures, around *23-25 °C* skin wettedness starts to increase for all the values of relative humidity. It can be observed that the maximum w_{rsw} is *1* with 1971 and 1976 models, while is equal to *0.75* with ASHRAE 55 model due to the assumption done in the model. The higher skin wettedness occurs for the highest value of relative humidity.

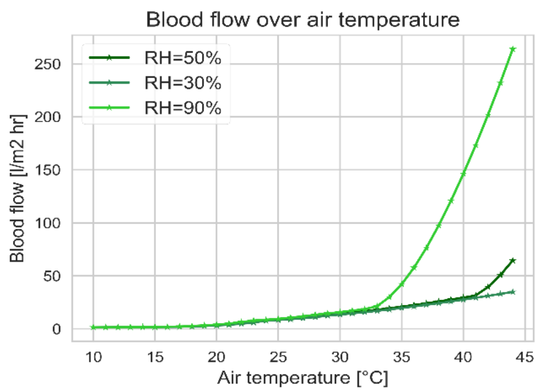
BLOOD FLOW OVER AIR TEMPERATURE	SKIN WETTEDNESS OVER AIR TEMPERATURE

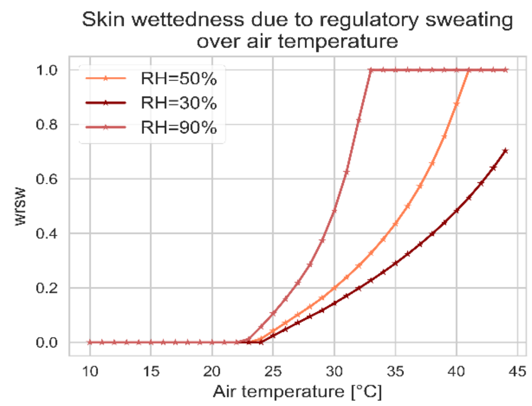
1971 MODEL



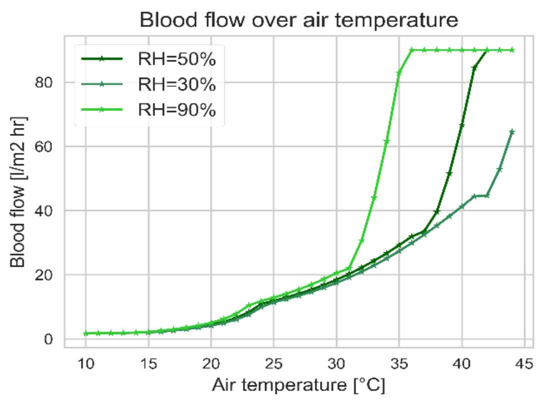


1976 MODEL





ASHRAE 55



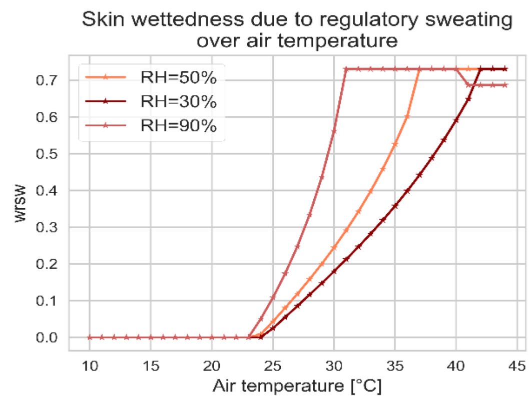
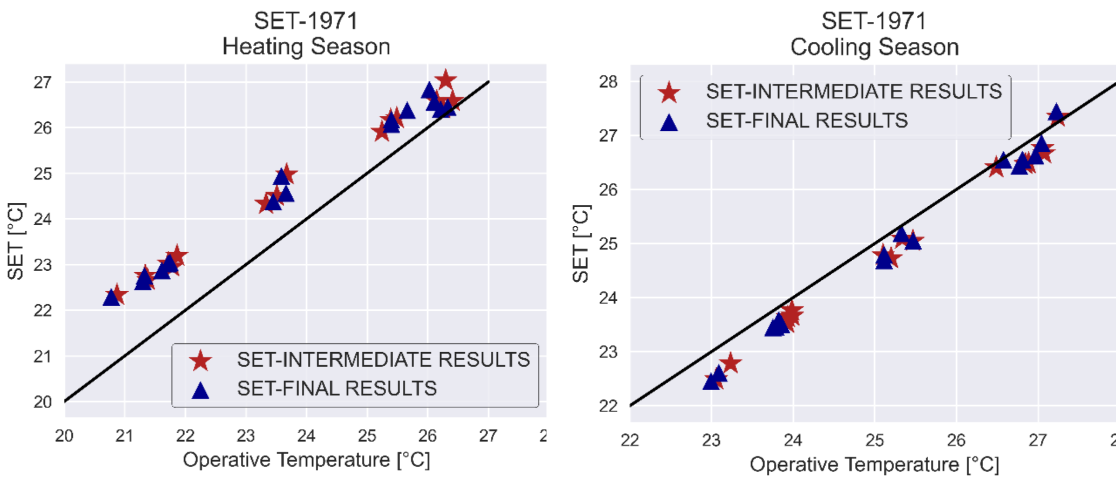


Figure 4.2. Comparison of skin and core temperatures calculated with 1971, 1976 and ASHRAE 55 models.

4.2. RESULTS OF THE APPLICATION OF THE MODEL TO THE CORE-CARE LABORATORY

The models were applied to evaluate the *SET* index for the heating and cooling seasons tests, after the first hour and at the end of the test; the obtained results have been compared with the intermediate and final *AMV* and *PMV* values.

In Figures 4.3, 4.4 and 4.5 the *SET* index is plot over the operative temperature at air velocity equal to *0.05 m/s*, activity of *1.2 met* and clothing resistance of *0.75 clo* for winter season and *0.47 clo* for summer season. The results of the three models are presented after the first hour and at the end of the test. It is observed how the intermediate *SET* is not coincident to the final *SET* for all models.



<u>**Figure 4.3**. SET index over operative temperature – 1971 model.</u>

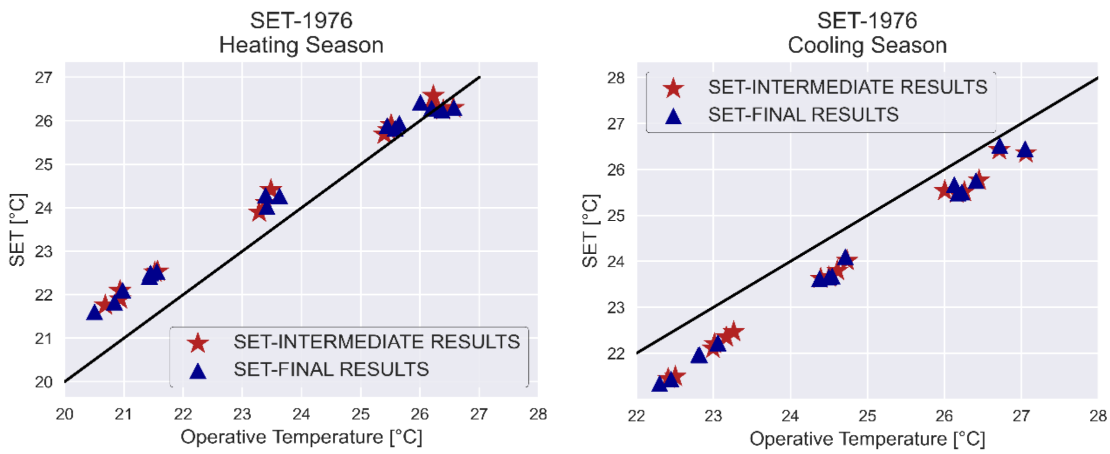


Figure 4.4. SET index over operative temperature – 1976 model.

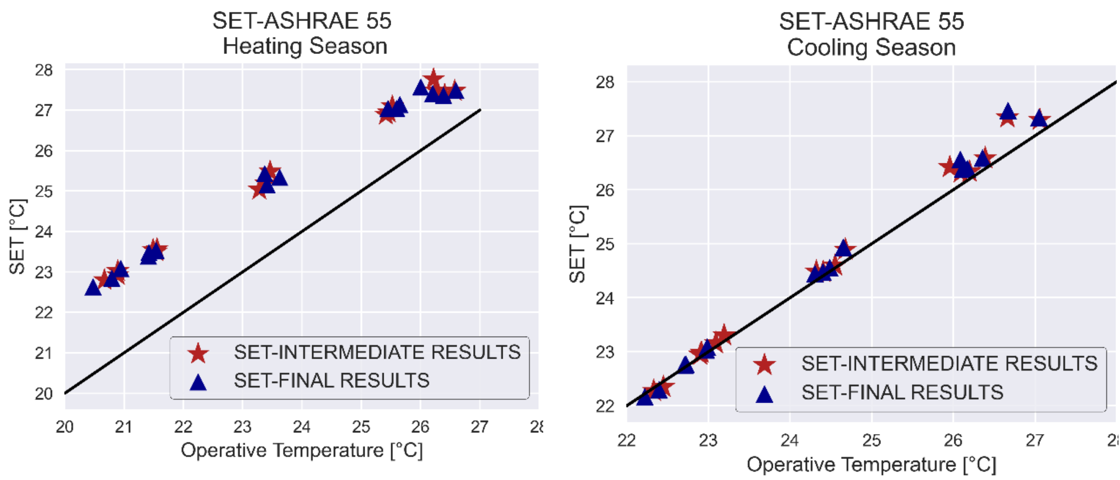


Figure 4.5. SET index over operative temperature – ASHRAE 55 model.

Figure 4.6 is obtained with ASHRAE 55 model and is representative of the behaviour of *SET* when operative temperature varies *SET* is coincident with the operative temperature when the relative humidity is *50%*, while it is higher when *RH* is higher than *50%* and lower when *RH* is lower than *50%*, moreover the difference increases when the operative temperature increases. In Figure 4.3, 4.4, 4.5 the *SET* index results to be higher that the operative temperature in heating season and in all models, even if, most of the time, the relative humidity of the test room is lower than *50%*. While with 1971 and 1976 models the SET is lower than operative temperature and with ASHRAE 55 the SET values coincides better with the operative temperature. This is because also the resistance of clothing, the activity and the air velocity influence the value of *SET*.

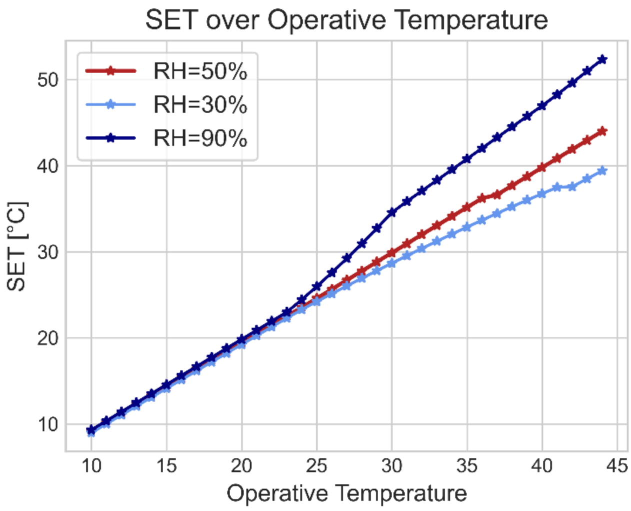


Figure 4.6. SET index over operative temperature – ASHRAE 55 model.

In Figure 4.7 and 4.8 the *SET* index evaluated with the three different models have been compared in the case of winter and summer seasons. The results of the intermediate test are on the left, while on the right the final test results are presented. Regarding the heating season, it can be observed that the *SET* values obtained with ASHRAE 55 are shifted up with respect to the *SET* obtained with the 1976 model, while the values of 1971 model are between them. Concerning Figure 4.8, as well as heating season, the highest values of *SET* are obtained with ASHRAE 55 model and the lowest with 1976 model. *SET* evaluated with 1971 model is not at the same operative temperature of *SET* of other models, that is because 1971 model assumes that the environment is uniform (i.e., air temperature is equal to the operative temperature) and thus only the air temperature of the test room was involved in the calculation of the index.

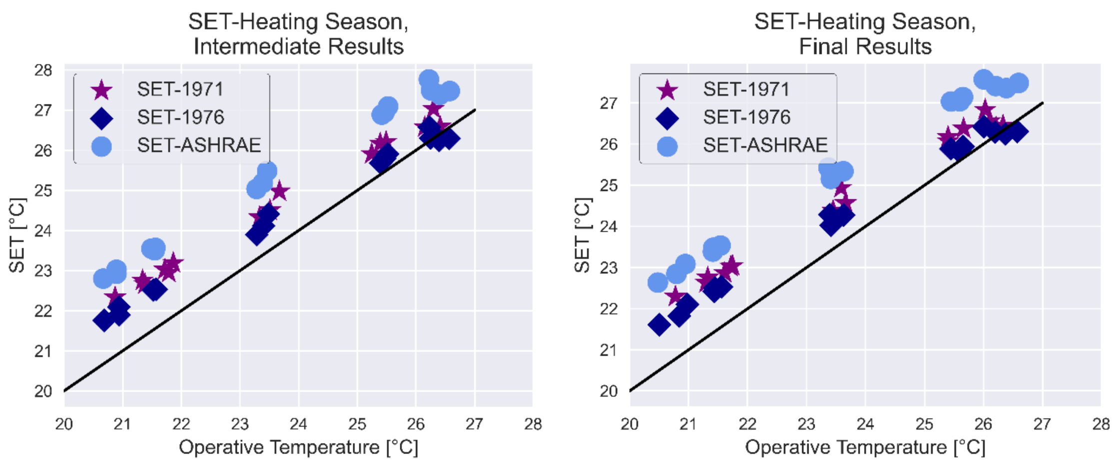


Figure 4.7 Comparison of SET index obtained with the models – Heating season.

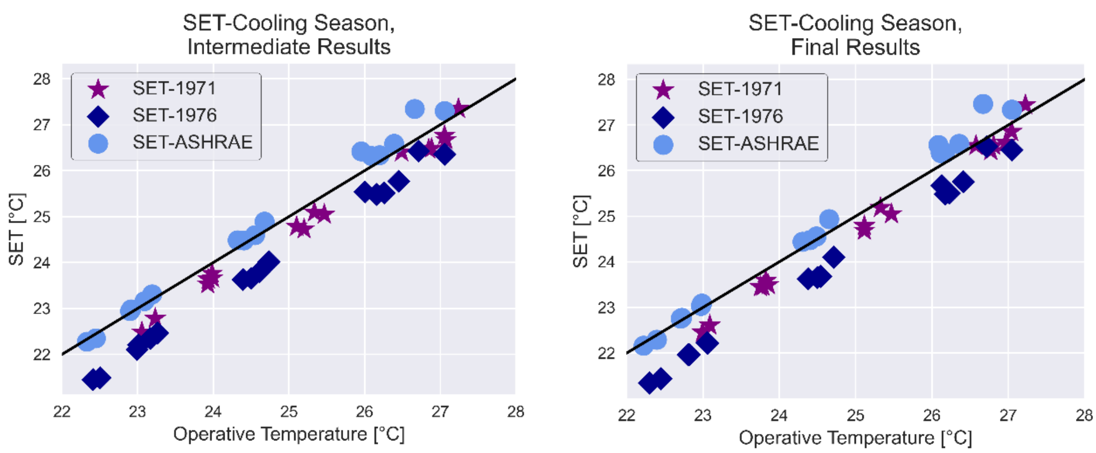


Figure 4.8. Comparison of SET index obtained with the models – Cooling season.

In Figure 4.9, 4.10, 4.11, 4.12 the *AMV* and *PMV* are compared in winter and summer seasons and after the first hour and at the final test. The heating and cooling results are coherent one to the other, because the *AMV* obtained with the intermediate surveys have always higher values with respect to the *AMV* of the final surveys. This result is influenced by the acclimatization process, indeed at the end of the test the subjects' thermal sensation is more in accordance with its prediction with Fanger's PMV model.

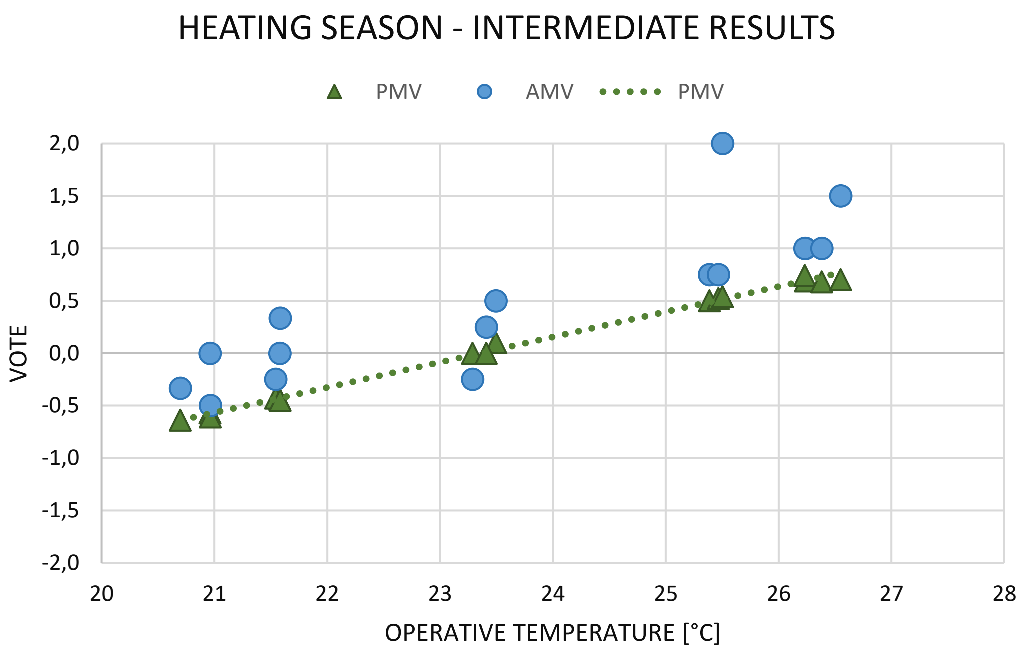


Figure 4.9. AMV and PMV comparison – Heating season – Intermediate results.

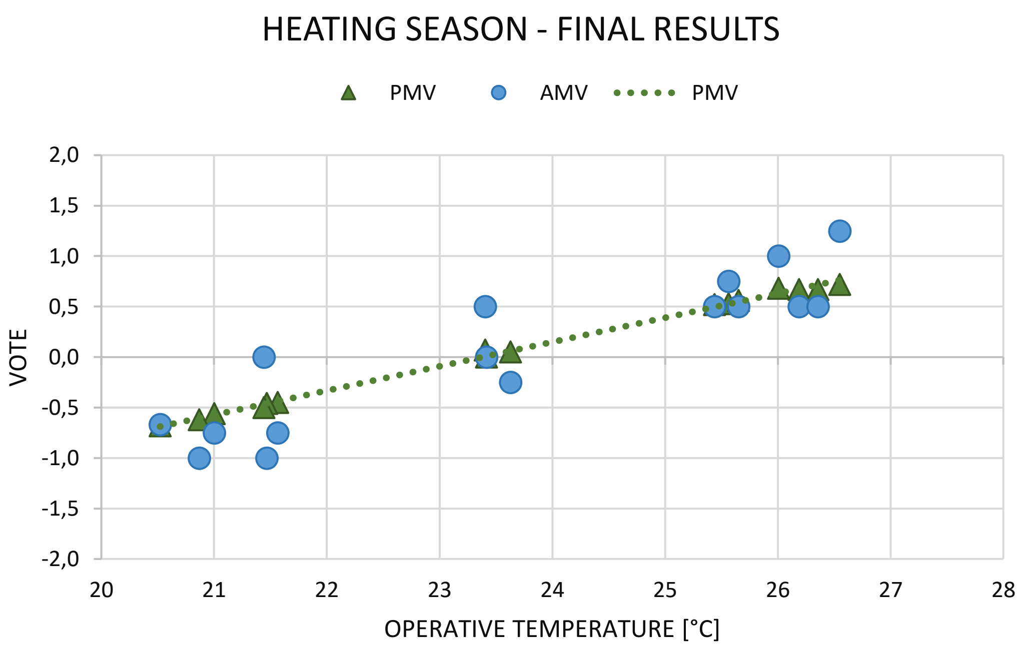


Figure 4.10. AMV and PMV comparison – Heating season – Final results.

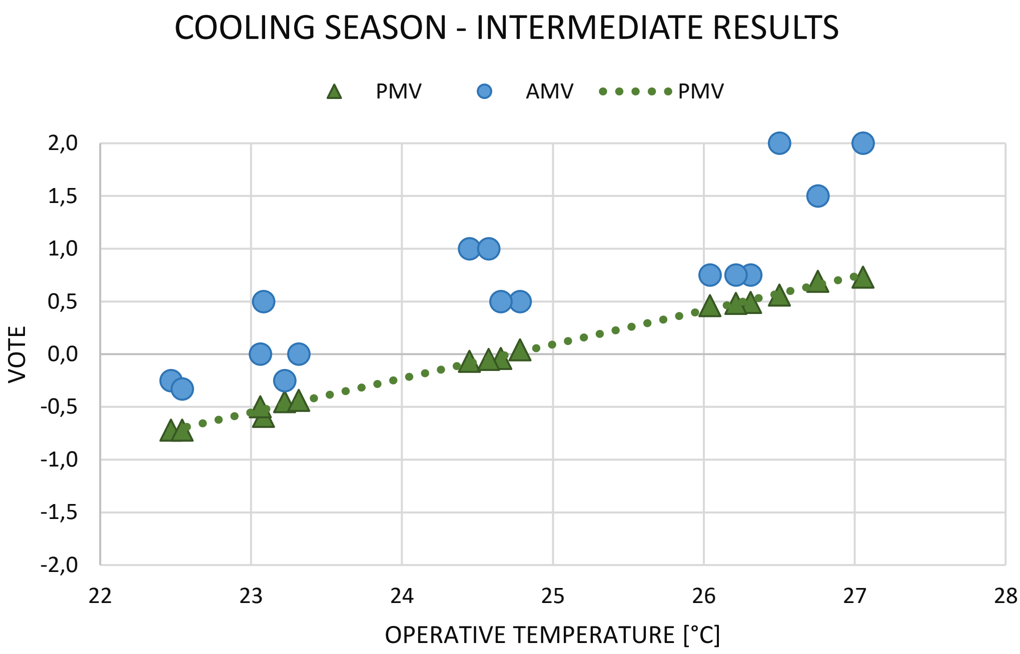


Figure 4.11. AMV and PMV comparison – Cooling season – Intermediate results.

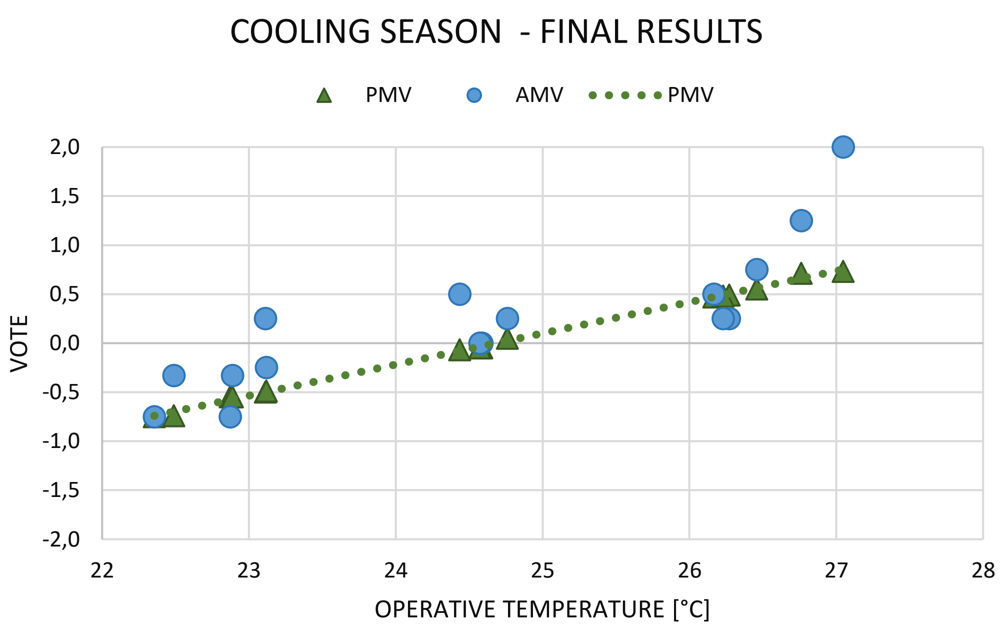


Figure 4.12. AMV and PMV comparison – Cooling season – Final results.

In Figures 4.13, 4.14, 4.15, 4.16 *SET* index obtained with the ASHRAE 55 model is plotted over operative temperature and is compared with *AMV* for both seasons and at the intermediate and final tests. The results are coherent with the *PMV* results: the intermediate votes result to be higher with respect to the prediction, while at the end of the test, due to acclimatization, they coincide better with the prediction, for heating and cooling seasons. In cooling season, at high operative temperatures, at the end of the test the SET tends to overestimate the votes. It is important to underline that the comparison of the *AMV* results with the *SET* results is difficult because the *AMV* parameter is measured in votes, while *SET* represents an equivalent temperature, and it is measured in °C.

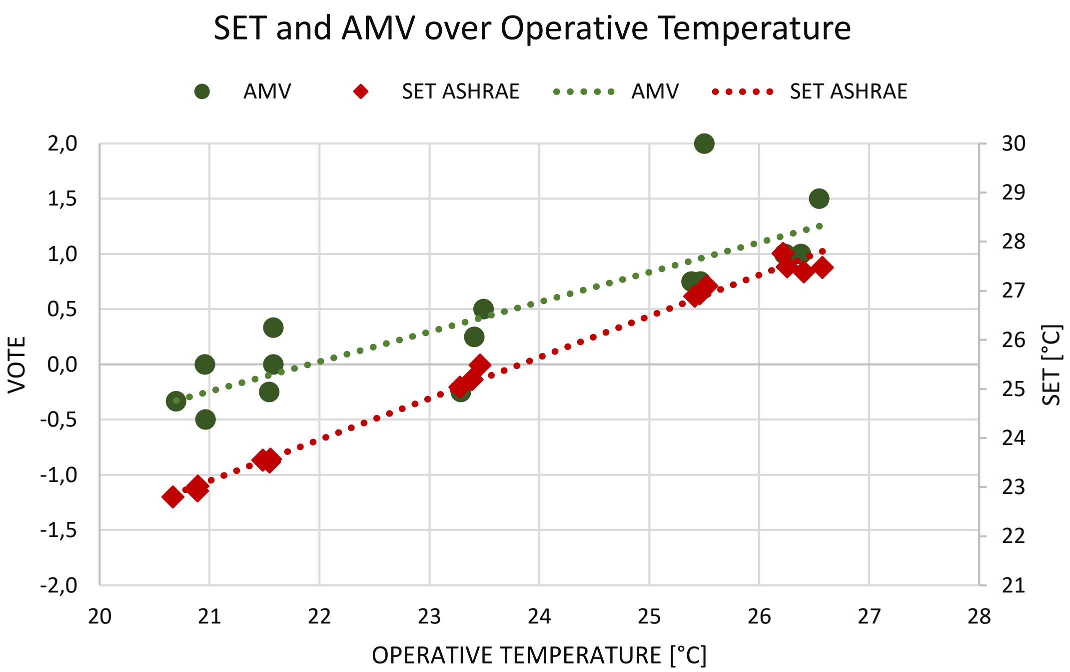


Figure 4.13. AMV and SET comparison – Heating season – Intermediate results.

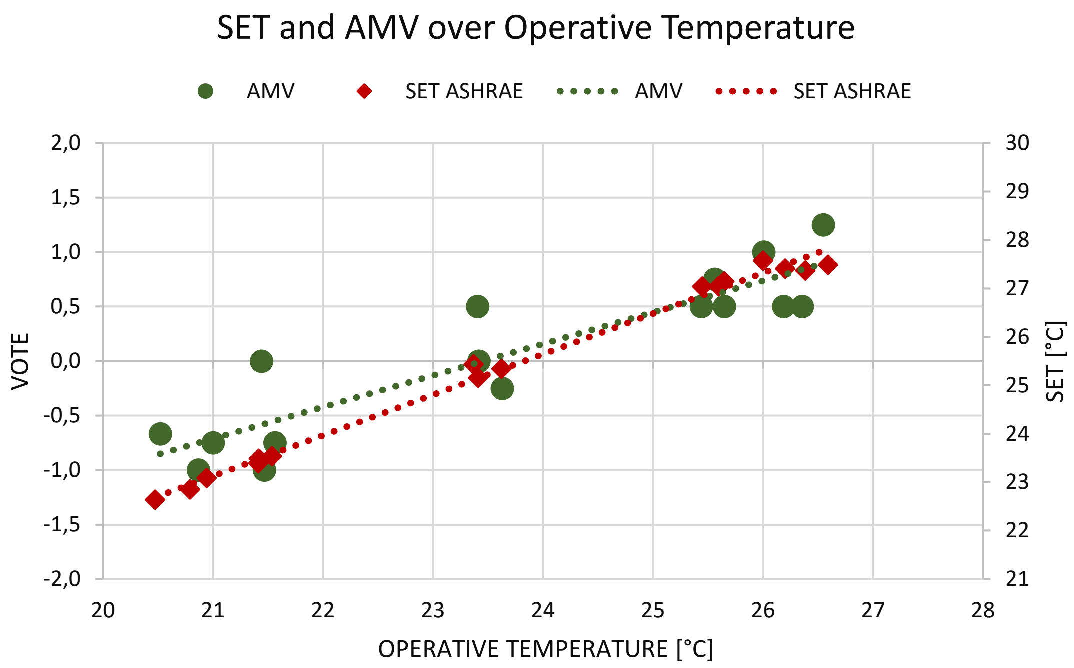


Figure 4.14. AMV and SET comparison – Heating season – Final results.

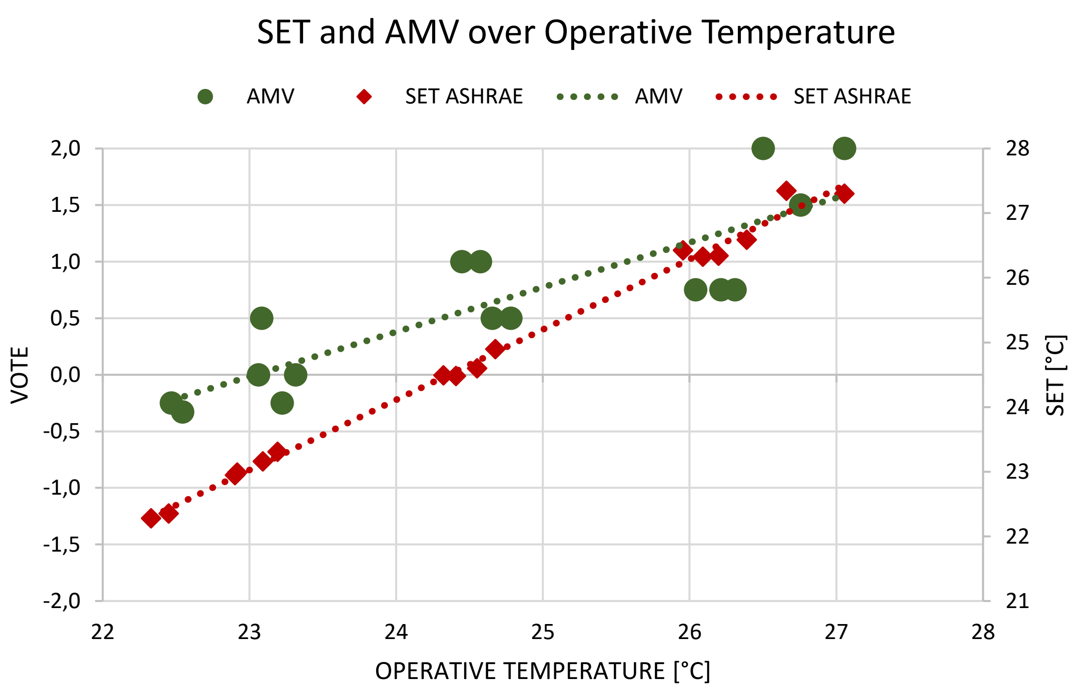


Figure 4.15. AMV and SET comparison – Cooling season – Intermediate results.

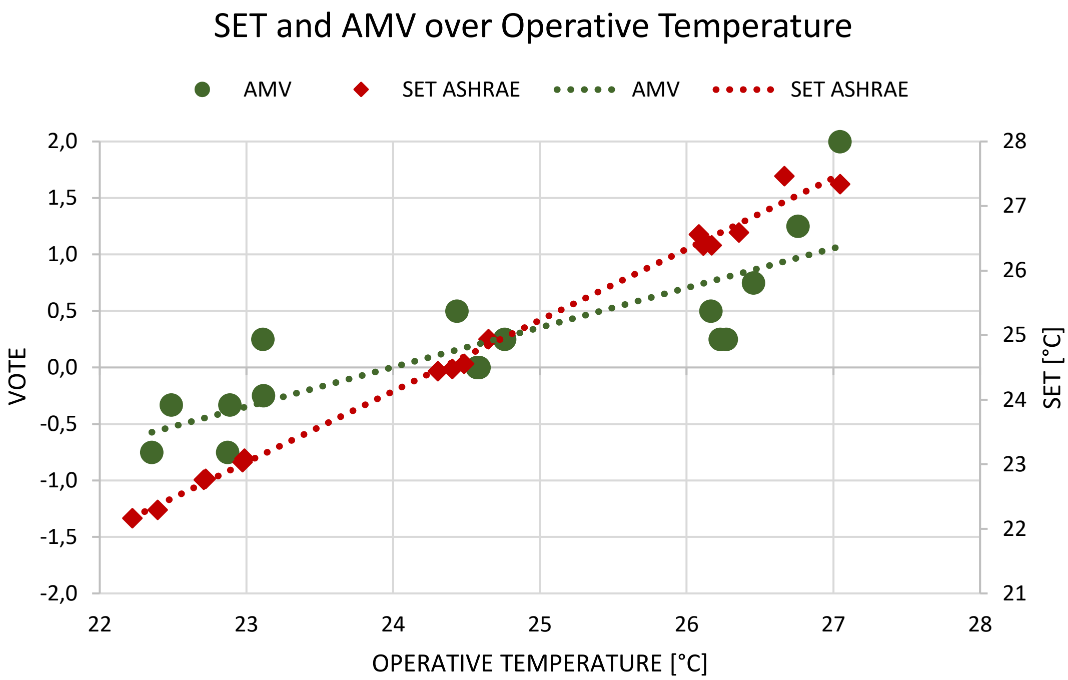


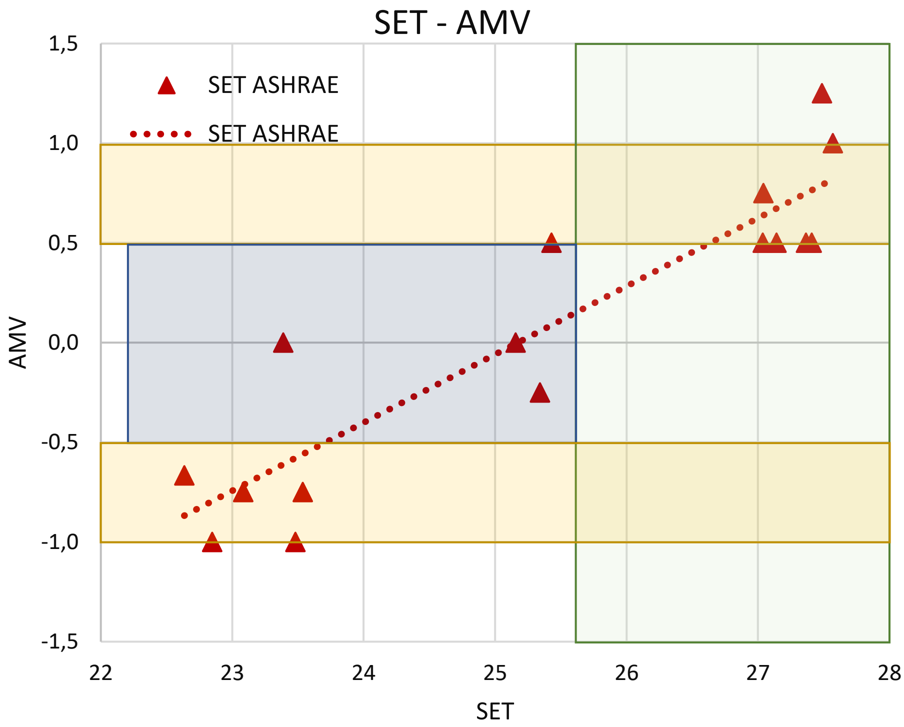
Figure 4.16. AMV and SET comparison – Cooling season – Final results.

Table 4.1 presents the thermal sensation and the physiological reaction of *SET* [14].

SET [°C]	Thermal sensation	Thermal comfort	Physiological reactions of people sitting
>37.5	Very hot	Very uncomfortable	Body temperature regulation failure
34.5-37.5	Hot	Very dissatisfied	Sweating heavily
30-34.5	Warm	Uncomfortable	Sweating
25.6-30	Slightly warm	Slightly dissatisfied	Mild sweating and vasodilation
22.2-25.6	Neutral	Acceptable	Thermal neutral
17.5-22.2	Slightly cool	Slightly dissatisfied	Vasoconstriction
14.5-17.5	Cool	Uncomfortable	Slow body temperature
10-14.5	Cold	Very dissatisfied	Chill

Table 4.1. Thermal sensation and physiological reaction of SET.

In Figure 4.17 and 4.18 the *AMV* is plotted over *SET* for both seasons at the end of the test and *SET* is evaluated with ASHRAE 55 model. The blue area represents the neutral conditions for both *AMV* and *PMV*, the yellow area represents not acceptable conditions for *AMV* and the green areas represent the slightly warm condition for *SET*. In Figure 3.18 is observed that for the same value of *AMV = 0* the value of *SET* is between *23 °C* and *25.5 °C*, thus the neutral condition coincides. At *AMV = +0.5* the value of *SET* is *25.5 °C*, thus the environment is in acceptable conditions according to *AMV* and the subjects in neutral conditions and according to *SET*, this entails that there is a correlation between the votes and the *SET*. Moreover, on the upper-left part of the figure, *SET* values are in the range of slightly warm conditions as the Actual Mean Votes of the subject. On the contrary, in the bottom-left of the figure, *SET* index is in the range of neutral conditions and the correspondent *AMV* is between *-0.5* and *-1,* thus in the area of not acceptability.



<u>**Figure 4.17**. SET – AMV - Heating season - Final votes.</u>

In Figure 4.18 is observed that at *AMV = 0* two values of *SET* at neutral thermal sensation correspond. Many *SET* values are in the range of neutral conditions for *AMV* still in the range of acceptability *+- 0.5*, but not at *0*. In the bottom part of the figure SET is acceptable but the correspondent *AMV* is *-0.7*, thus not acceptable. At the opposite, at *AMV = +-5* correspond values of *SET* that belong to the slightly warm range. Moreover, the *SET* index never exceeds the slightly warm range, while the corresponding *AMV* values result to be higher than *0.5*, reaching *2*, thus the environment is perceived as unacceptable. Hence, the correspondence between *SET* and *AMV* in winter season at neutral conditions becomes weaker during summer season.

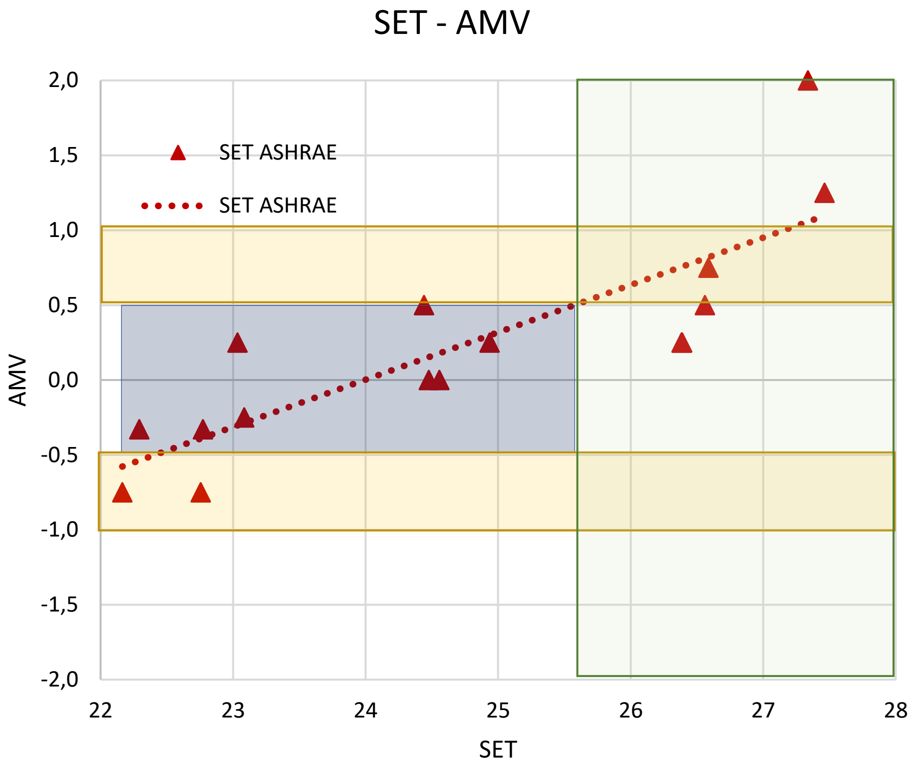


Figure 4.18. SET – AMV - Cooling season - Final votes.

In Figure 4.19 the *PMV* and *AMV* are plot for both winter and summer seasons. The light-blue area represents the acceptable condition for thermal comfort. There is some correspondence for *PMV* and *AMV* around *0* and *+-0.5* in both seasons and for *PMV* between *-1* and *-0.5* in heating season. When *PMV* is between *+0.5* and *+1*, the correspondent *AMV* is mostly higher in both seasons, moreover in cooling season, at *PMV = -0.5* and *-0.7*, *AMV* reaches *-1.*

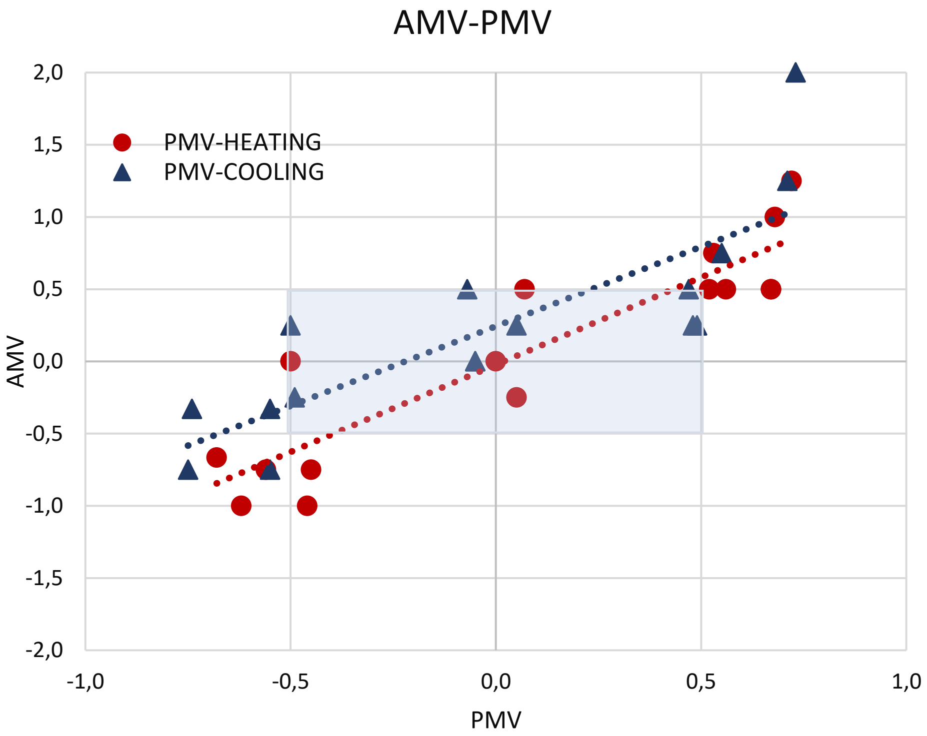


Figure 4.19. PMV – AMV - Final votes.

The correspondence between *AMV-PMV* is stronger with respect to *AMV-SET* in the area of acceptable conditions, but *SET* index is relevant for the following reasons [14]: *PMV* is an index developed for a steady state environment, while *SET* is suitable for dynamic conditions, furthermore, *PMV* doesn't predict the body's physiological response, on the contrary, *SET* predicts the body's skin and core temperature, the blood flow and the skin moisture.

CONCLUSION

The three two-node models of 1971, 1976 and ASHRAE 55 have been implemented in Python to evaluate the physiological response of the human body to different thermal environments. The models have been applied to the CORE-CARE laboratory, located in the Industrial Engineering Department at the University of Padova. The obtained results of SET have been compared with the Actual Mean Votes of the participants to the tests conducted in the test room for heating and cooling conditions.

The most relevant results are:

- the three models provide similar results regarding the skin and core temperatures, the blood flow and the skin wettedness due to regulatory sweating over air temperature at three values of relative humidity *(RH = 30%, 50%, 90%)*: the shape of the curves is similar but presents some differences related to the different inputs and reference values implemented in the models. All the parameters increase with the increase of air temperature and of relative humidity. After the start of regulatory sweating, the blood flow and core and skin temperatures increase, while the growth of core temperature and of blood flow is exponential when the body is not able to regulate anymore and the skin wettedness reaches the maximum value.
- SET results from the application of the models to the tests carried out at CORE-CARE laboratory are always higher than the operative temperature even for relative humidity lower than *50%.* This results because other parameters are involved in the calculation: resistance of clothing, activity and air velocity.
- the prediction of thermal comfort coincides better with the *AMV* at the end of the test with respect to the intermediate votes for both *PMV* and *SET*, it happens because of the acclimatization of the subjects in the environment after two hours.

- a correlation between *SET* and *AMV* is present in both winter and summer seasons for acceptable conditions of comfort, while when the environment is not acceptable the relation between *SET* and *AMV* becomes weaker.

This study was carried out to evaluate thermal comfort in a work environment, but the models can be applied also to other types of thermal environments, for example, varying the air velocity, resistance of clothing and activity performed by the subjects.

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