CHAPTER 14

THERMAL COMFORT

A zero carbon design does not automatically guarantee the achievement of good thermal comfort. Although good design needs to save energy and reduce carbon emissions, buildings are designed for people, and thus thermal comfort is of primary importance.

In this chapter factors that influence thermal comfort will be explained, and assessment of thermal comfort will be introduced. Adaptation of people to internal conditions will also be discussed, and how to carry out adaptation analysis with simulation tools will be explained. It will also be explained how and why thermal comfort results in simulation outputs may be inaccurate, and how to achieve more accurate assessment of comfort through the post-processing of simulation results. It will then be demonstrated in later chapters how dynamic simulation can be used to maximise thermal comfort whilst maintaining zero carbon performance.

DEFINITION OF THERMAL COMFORT

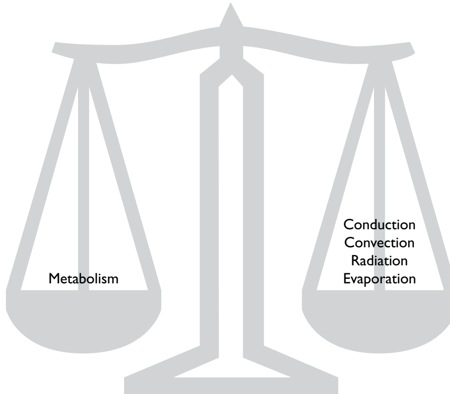
Thermal comfort is defined as a condition of mind that expresses satisfaction with the thermal environment. Although this suggests that thermal comfort is subjective, there are certain measurements that can be used to assess what the majority of people will feel like in an internal environment.

Thermal comfort is based on the equilibrium between heat gains inside the human body and heat losses from the body to the environment. When the heat gain from metabolism is equal to heat loss, then we are in balance with the environment and that makes us feel comfortable.

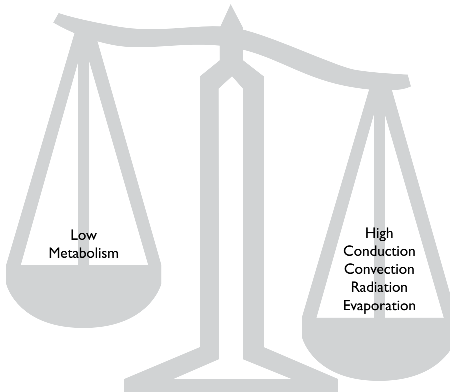
On one side of the scales in Figure 175 is the metabolism, the internal chemical 'engine' that generates heat, and on the other side of the scales is the heat exchange through conduction, convection, radiation and evaporation. If metabolism on the left is in balance with heat transfer mechanisms on the right, we feel comfortable. If metabolism is low or the heat transfer mechanisms are high, we feel cold, and if metabolism is high and heat transfer mechanisms are low, we feel hot.

Measurement of comfort

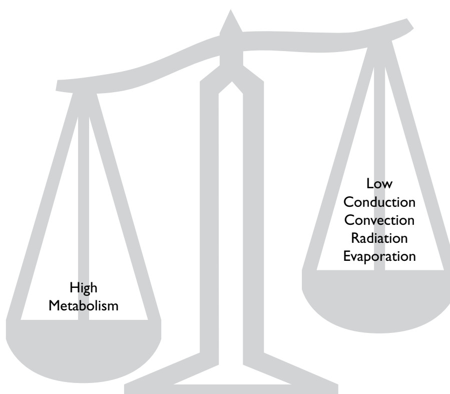
When I ask my students in the class to let me know by a show of hands how they feel: comfortable, slightly warm, hot, slightly cold or very cold, there is always non-uniform distribution of responses. In other words, there are always more hands up in one category and less in other categories. In order to assess thermal comfort of a large number of individuals, Povl Ole Fanger, who was an early pioneer in thermal comfort research, introduced a seven-point scale (Fanger, 1970) as shown in Table 23.



(a) *Feeling comfortable*



(b) *Feeling cold*



(c) *Feeling hot*

Figure 175 Relationship between heat gains and heat losses in the human body

TABLE 23 SEVEN-POINT SCALE	
−3	cold
−2	cool
−1	slightly cool
0	neutral
+1	slightly warm
+2	warm
+3	hot

This table was used as the basis of voting by a large number of volunteers who were asked to express how they felt under different activity levels, clothing levels and internal environmental conditions. Through the analysis of experimental results it was found that these votes can be predicted. A concept of *predicted mean vote* (PMV; Fanger, 1970) was established as a function of six parameters that influence thermal comfort as follows:

$$PMV = f\,(M, Rc, Ta, Tmrt, v, rh) \tag{49}$$

where:

M – metabolic rate due to activity
Rc – resistance of clothing
Ta – air temperature
Tmrt – mean radiant temperature
v – air velocity
rh – air relative humidity.

Details of PMV calculations in Equation (49) consist of four extensive equations (British Standards Institution, 1995); however, there are a number of external sources that automate these equations within standard spreadsheet software.

Furthermore, the predicted percentage of dissatisfied people (PPD) was found to correlate to PMV (British Standards Institution, 1995) as follows:

$$PPD = 100 - 95 \times e^{-(0.03353\,PMV^4 + 0.2179\,PMV^2)} \tag{50}$$

Graphical representation of this equation is shown in Figure 176. A striking feature of this equation is that it has a minimum of PPD = 5% for a thermally neutral vote. This means that there will always be at least 5% of dissatisfied people in every building. If we get our design slightly wrong resulting in predicted mean vote deviating further from the neutral vote, the PPD will increase exponentially.

In the second half of this chapter it will be shown how PMV and PPD are used in dynamic simulations, and how thermal comfort can be improved by making changes in the design and using these parameters to assess alternative designs. But first the parameters that influence thermal comfort, as shown in the PMV Equation (49) above, will be discussed.

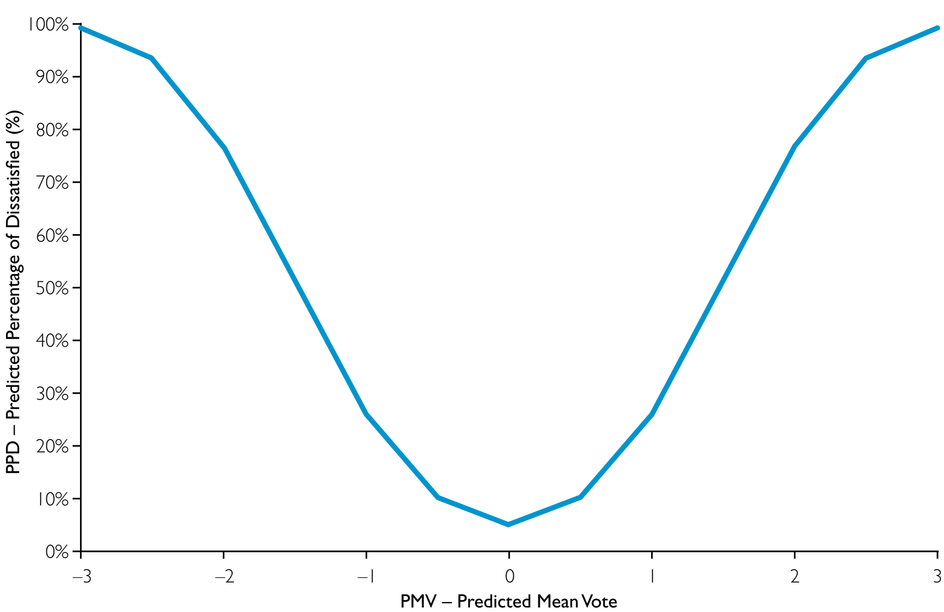


Figure 176 Predicted percentage of dissatisfied as function of predicted mean vote

Comfort parameters and how to influence them

Metabolic rate

Metabolic rate is internal heat production in the human body. Fanger (1988) introduced a unit of metabolic rate called the 'met' and established a simplified list of activities and corresponding metabolic rates as shown in Table 24.

TABLE 24 ACTIVITIES AND METABOLIC RATES

Activity	Metabolic rate (1 met = 58 W/m^2)
Lying at rest	0.8
Sitting	1.0
Standing	1.4
Walking 3 km/h	2.0
Walking 5 km/h	3.0
Running 10 km/h	8.0

Higher metabolic rates require a higher intensity of heat transfer with the environment in order to maintain constant body temperature and feeling of thermal comfort (Figure 175). Designers can influence metabolic rates of building occupants only to some extent. For instance, it is possible to make the use of stairs more inviting than the use of lifts by making flights of stairs short. However, metabolic rates in buildings are primarily influenced by the building use type, such as office, school, home, etc. A more detailed list of activities and corresponding metabolic rates is available in CIBSE (2015).

Resistance of clothing

Resistance of clothing is categorised in a similar way as metabolic rates, by introducing the unit of thermal resistance named 'clo'. Fanger (1998) defines the thermal resistance of typical clothing arrangements as shown in Table 25.

TABLE 25 RESISTANCE OF CLOTHING

Description of clothing	Resistance of clothing (1 clo = 0.155 m^{2}K/W)
Underpants	0.1
Shorts, short sleeve shirt, sandals	0.5
Lightweight trousers, short sleeve shirt, shoes	0.5
Boiler suit	0.8
Suit and tie	1.0
Padded overall	1.5
Winter coat, boots, gloves, scarf, fur hat	3.0

Resistance of clothing can be influenced by designers only to an extent. For instance, well-insulated buildings will make people more comfortable in less clothing. A more detailed list of clothing resistances is available in CIBSE (2015).

Air temperature

This temperature controls the conduction and convection heat transfer mechanisms between the human body and its environment (Figure 175). If it reaches the body temperature of 37°C, the corresponding heat transfer mechanisms will stop functioning and thermal comfort will be affected considerably. The maintenance of thermal comfort will in that case need to be taken over by the remaining two heat transfer mechanisms: radiation and evaporation.

In the summer months we can influence internal air temperature by providing sufficient thermal mass to stabilise temperature fluctuations and by providing adequate natural ventilation to prevent overheating, combined with adequate solar shading. In the winter months we can influence internal air temperature by providing adequate space heating, thermal mass and thermal insulation.

Mean radiant temperature

This temperature controls the radiation heat transfer mechanism between the human body and the environment (Figure 175). It is an area-weighted average temperature of all internal surfaces in an internal space. To get a mean radiant temperature, the surface temperatures of all internal surfaces are multiplied with corresponding surface areas, added together, and divided by the sum of all internal surfaces:

$$T_{mrt} = \frac{\sum_i^N T_i \times A_i}{\sum_i^N A_i} \quad (51)$$

where:

T_i – temperature of i-th surface
A_i – area of i-th surface
N – total number of surfaces in internal space.

If mean radiant temperature approaches 37°C, the radiation heat transfer mechanism for maintaining heat balance in the human body (Figure 175) will stop functioning, and will need to be taken over by the other three mechanisms. If the other two temperature-based mechanisms (conduction and convection) have also stopped functioning because of high air temperature, the only remaining mechanism will be evaporation.

A large amount of standard glazing will have low surface temperature in cold weather, and this will reduce the mean radiant temperature. We can influence this temperature by reducing the amount of glazing or improving the specification of glazing to a higher U-value. We can also influence it by increasing the amount of thermal insulation in opaque surfaces.

Dry resultant or operative temperature

This is a combination of air temperature and mean radiant temperature. For air velocities below 0.1 m/s this temperature is defined as:

$$T_r = \frac{(T_a + T_{mrt})}{2} \quad (52)$$

Dry resultant temperature is measured at the centre of a blackened globe of a diameter of 40 mm. The globe exchanges heat with air and with all surfaces in an internal space and is a simplified representation of the human body. This is why this temperature is referred to as comfort temperature and it is the basis of temperature recommendations for internal spaces.

We can see from Equation (52) that we can increase dry resultant temperature T_r by either increasing air temperature or mean radiant temperature. We can also keep the dry resultant temperature unchanged by reducing air temperature and increasing mean radiant temperature by the same amount, or the other way round. Most of these changes can be achieved by making changes in the building fabric or in the ventilation strategy, and all of that can be tested using dynamic simulation.

Air velocity

Air velocity influences thermal comfort in combination with air temperature and turbulence intensity. The influence on PPD can be expressed as:

$$PPD = f\,(t_a, v_a^c, tu) \tag{53}$$

where:

t_a – air temperature
v_a – air velocity
tu – air turbulence
c – constant.

This means that PPD changes linearly with air temperature and air turbulence, and exponentially with air velocity. If turbulence is kept constant, then an increase of air temperature will require an exponential increase of air velocity to maintain the PPD unchanged. Further details of how air velocity influences thermal comfort can be found in Fanger (1988) and CIBSE (2015). Designers can respond to the need to increase air velocity exponentially by making adequate provisions for natural ventilation, which can be tested using dynamic simulation.

Air relative humidity

A high level of relative air humidity will progressively reduce and ultimately eliminate the evaporation heat transfer mechanism from the human body (Figure 175), and can cause serious problems to individuals if the other three temperature-based mechanisms (conduction, convection and radiation) have already been eliminated due to high temperatures. We can control this parameter by adequate ventilation in summer months, assuming that outside air humidity is not very high, and in winter months by adequate heating and ventilation.

ADAPTIVE THERMAL COMFORT DUE TO PHYSIOLOGICAL ADAPTATION

The pioneering work by Fanger (1970, 1988) and subsequent related work provided input into several standards and other technical documents that are used by simulation tools as the basis for thermal comfort assessment (ISO, 2005; ASHRAE, 2013; European Standards, 2007). The importance of physiological adaptation of people to internal conditions has also been recognised in recent years (ASHRAE, 2013; European Standards, 2007). Based on the guidance from these standards and subsequent work, CIBSE (2013) established three criteria for defining overheating in free-running buildings. Using a temperature difference between the operative temperature T_{op} and a maximum acceptable temperature T_{max}, rounded to the nearest integer and referred to as $\Delta T = T_{op} - T_{max}$ below, the CIBSE TM52 criteria are as follows:

1. hours of exceedance – the number of hours during which ΔT is greater than or equal to 1 Kelvin shall not exceed more than 3% of occupied hours; the maximum acceptable temperature T_{max} is defined using the running mean of the outdoor temperature T_{rm} as $T_{max} = 0.33\, T_{rm} + 21.8$;
2. daily weighted exceedance – a daily sum of a product of ΔT and the corresponding hours of occurrence shall not exceed 6;
3. upper limit temperature – the absolute maximum of the operative temperature for which ΔT shall not exceed 4 Kelvin.

See CIBSE (2013) for a detailed explanation and guidance on these criteria for adaptive thermal comfort. A comprehensive overview of the subject can be found in Nicol *et al.* (2012).

Simulation tools now provide options for physiological adaptive thermal comfort analysis. In DesignBuilder, ASHRAE 55, CSN EN 15251 and CIBSE TM52 and others can be included in the analysis (Figure 177), and in IES VE, CIBSE TM52 adaptive thermal comfort can be specified (Figure 178). As will be seen from the remainder of this chapter, this analysis of physiological adaptation is not matched by the analysis of behavioural adaptation and can lead to erroneous assessment of thermal comfort.

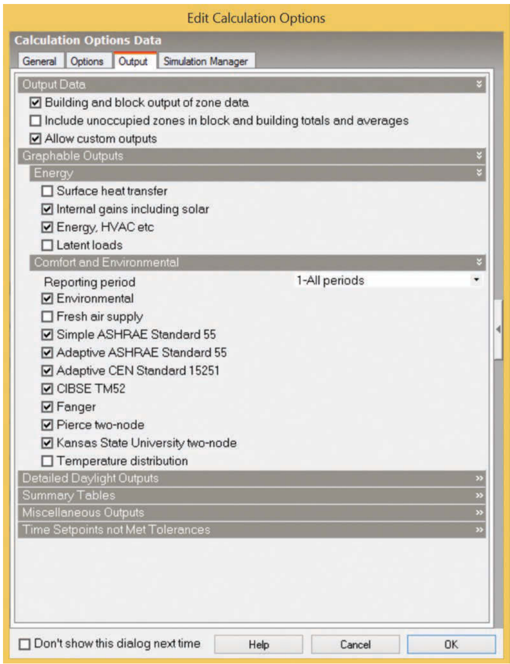


Figure 177   Calculation options dialogue box in DesignBuilder showing adaptive thermal comfort output options

INTERPRETATION OF THERMAL COMFORT RESULTS IN SIMULATION OUTPUTS

In order to demonstrate the issues associated with the interpretation of thermal comfort results in simulation outputs, a simulation of the simple box as in Figure 106 was carried out using IES Virtual Environment.

In IES Virtual Environment thermal comfort is evaluated as a post-simulation process, after the dynamic simulation is completed. This post-processing occurs within Vista/VistaPro of the IES VE suite, based on the settings in the dialogue box shown in Figure 178. As can be seen from this figure, the activity and clothing levels are adjustable, but once they are set they will remain constant over the entire simulation period. Although the same figure shows that CIBSE TM52 Adaptive Comfort is evaluated, keeping the activity level and clothing level constant throughout the simulation year will inevitably produce a high percentage of dissatisfied people at some point during the year. Other simulation tools, such as DesignBuilder for instance, specify winter and summer clothing and a single activity level, leading to similar thermal comfort assessment issues.

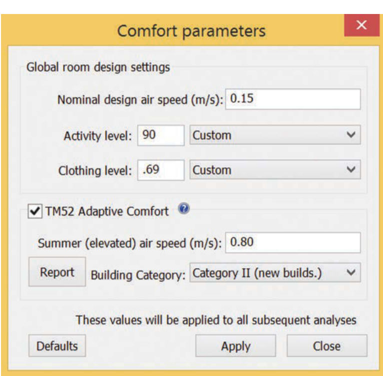


Figure 178   Comfort parameters dialogue box in IES Virtual Environment

This is illustrated in the IES VE simulation outputs in Figure 179. The model from which these results are obtained is heated to 19°C and is free-running in summer, with free cooling operating at five air changes per hour from 25°C and above.

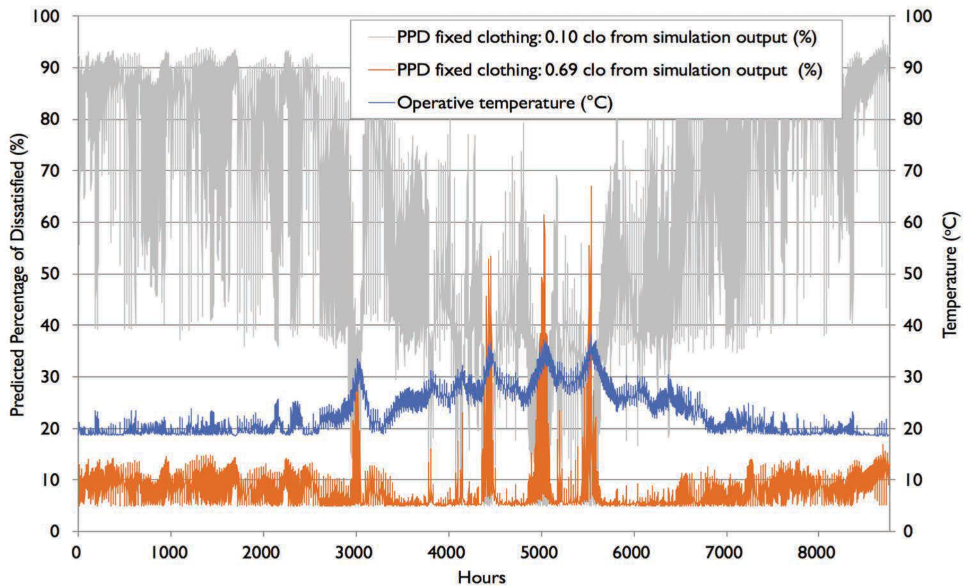


Figure 179 Assessment of thermal comfort based on two different levels of fixed clothing

Whilst there are reasonable levels of satisfaction with thermal comfort in winter based on an activity level of 90 and clothing level of 0.69 clo (light office wear), the results are almost completely reversed with the clo level of 0.1 (underwear), where there are high levels of dissatisfaction in winter and much less so in summer, except during the highest temperatures (Figure 179). Although this method of personal adaptation to internal conditions would not be acceptable in an office environment, it illustrates the point that keeping the comfort parameters set to the same clothing throughout the year will produce high levels of dissatisfaction during certain periods. This makes a case for the analysis of adaptive clothing behaviour, which will be introduced in the next section.

IMPROVING THERMAL COMFORT ASSESSMENT THROUGH SIMULATED ADAPTIVE CLOTHING BEHAVIOUR

In real life people can adjust their activity and clothing levels according to internal conditions, and can also move between rooms thus following the most appropriate conditions. This 'comfort tracking' is especially practised in hot and humid climates, and it should not be confused with adaptive thermal comfort due to physiological adaptation discussed earlier in this chapter.

Therefore, the interpretation of thermal comfort results in simulation outputs requires special attention and further post-processing, in order to take into account expected human behaviour, rather than to rely on constant activity and one or two constant clothing levels throughout the year.

In order to simulate the behavioural adaptation, the following steps were taken:

1. hourly air temperature, mean radiant temperature, and relative humidity from the simulation were exported into a spreadsheet, adding fixed air velocity and activity level to this dataset;
2. an initial clothing level was used, as set in the simulation model;
3. the clothing level was subsequently modified on an hourly basis using the formulae in Table 26; essentially the clothing level was increasing as PPD was reducing, and it was reducing as PPD was increasing;
4. the PMV and PPD were recalculated using Equations (49) and (50).

TABLE 26 CLOTHING ADJUSTMENT IN RESPONSE TO PMV	
Predicted mean vote (PMV)	**Adjusted clothing (clo)**
PMV < −1 (Cold)	$clo_{(t)} = clo_{(t-1)} + 0.25$
−1 <= PMV < 0 (slightly cold)	$clo_{(t)} = clo_{(t-1)} + 0.15$
PMV = 0 (neutral)	$clo_{(t)} = clo_{(t-1)}$
1 >= PMV > 0 (slightly warm)	$clo_{(t)} = clo_{(t-1)} - 0.15$
PMV > 1 (warm)	$clo_{(t)} = clo_{(t-1)} - 0.25$

This is a further development of a method initially reported by Huws and Jankovic (2013), where fixed clothing levels were used in the interval boundaries corresponding to the rows of Table 26. That method, however, resulted in significant step changes of PPD when PMV crossed the interval boundaries and did not provide sufficient adaptation. A further development of the method reported here results in smoother changes of the PPD due to the cumulative and therefore progressive changes of the clothing levels.

The resultant PPD taking into account adaptive clothing behaviour represents dynamic and more accurate assessment of thermal comfort. The comparison between fixed clothing and adaptive clothing behaviour form Table 26, and based on the IES model from the previous section, is shown in Figure 180.

As can be seen from Figure 180, adaptive clothing behaviour corresponds to a considerably reduced predicted percentage of dissatisfied people, and therefore this kind of analysis should be conducted routinely through post-processing of simulation results.

A similar method can be used for the simulation of adaptive activity behaviour through post-processing of simulation results, by increasing the activity level when PMV is decreasing and decreasing the activity level when PMV is increasing.

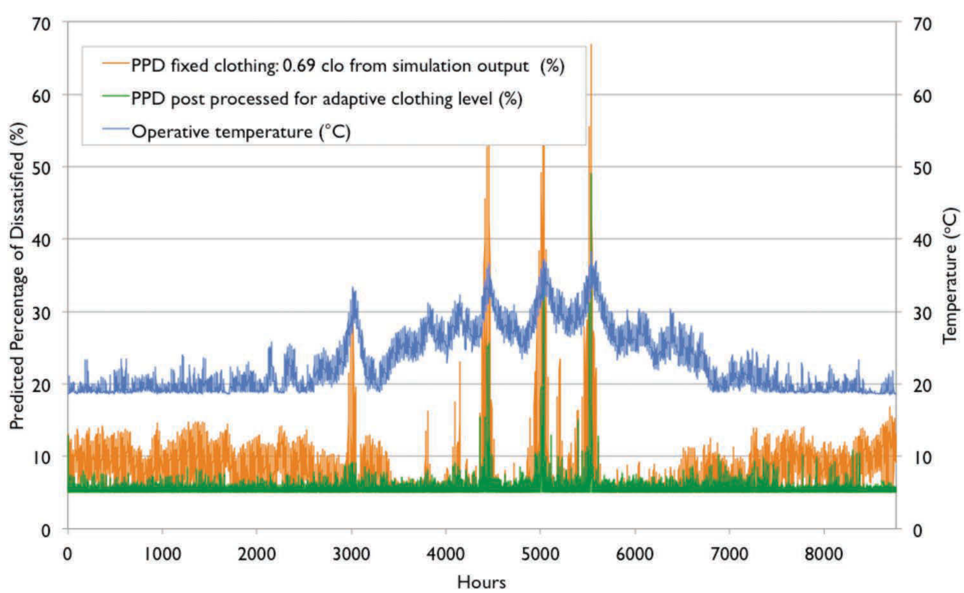


Figure 180 Assessment of thermal comfort based on adaptive clothing behaviour

Whilst preparing the material for this chapter, I attempted to apply this method to this example before the introduction of free cooling and with much higher overheating than in Figure 180. However, in that instance it did not make much difference. It only started making a noticeable difference after summer temperatures were brought down by free cooling. We can therefore say that this method can be useful after the threshold for its application has been lowered by design interventions.

TASKS FOR SIMPLE SIMULATION EXPERIMENTS

1. Carry out the analysis of thermal comfort using the adaptive clothing method introduced in this chapter. First conduct an annual simulation of a building and export hourly values of air temperature, mean radiant temperature, relative humidity and predicted percentage of dissatisfied for a selected room into a spreadsheet. Implement the clothing adaptation in the spreadsheet on the basis of the example in Table 26, and calculate PPD resulting from this adaptation. Compare the calculated PPD with the PPD exported from the simulation model. Experiment by changing the constants from Table 26 that adjust the clothing level and introduce upper and lower limits to clothing levels. Investigate the effect of these changes on the calculated PPD.
2. As (1), but instead of adjusting the clothing level, use the same method to adjust the activity level / metabolic rate as a post-simulation process in a spreadsheet. Compare the calculated PPD with the PPD obtained from the simulation model and reflect on the accuracy of this approach in comparison with the fixed activity level PPD.
3. Develop a post-processing spreadsheet that combines the clothing level adjustment and activity level adjustment simultaneously. Compare the calculated PPD with the PPD obtained from the simulation model and compare the two.
4. Discuss the results with colleagues.

SUMMARY OF DESIGN PRINCIPLES

In summary, we looked at what thermal comfort is, what influences it, and what designers can do about it. We also looked at how thermal comfort can be assessed and how simulation outputs can be interpreted and post-processed to overcome limitations of simulation models, thus achieving higher accuracy. The summary of design principles is as follows.

Simulation software:

- select activity level and clothing level in the simulation tool settings, having checked the units used for these two parameters (they are not always expressed in terms of 'met' and 'clo' in different simulation tools)
- if the values for activity level and clothing level are fixed for the majority of (or for the entire) simulation period, carry out post-processing of simulation outputs using spreadsheet software.

Post-processing using spreadsheet software:

- calculate PMV on an hourly basis using Equation (49) or an equivalent ready-made macro script
- using spreadsheet formulae, increase clothing level when PMV is decreasing and decrease clothing level when PMV is increasing
- following the same approach, increase activity level when PMV is decreasing and decrease activity level when PMV is increasing
- balance the activity and clothing levels as may be appropriate for the corresponding climate and type of space
- calculate PPD on an hourly basis using Equation (50) and PMV from the previous three steps
- use the result of this calculation for dynamic and more accurate assessment of thermal comfort.