

# Assessment of thermal comfort near a glazed exterior wall

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**ABSTRACT:** In many highly glazed buildings, the thermal comfort of the occupants will tend to be related to the incoming solar energy and the solar heat gain coefficient of the glazing. Many real buildings tend to be deep relative their height and therefore, areas close to the facade receive a much greater amount of the incoming energy than those farther from it. In turn, this imbalance leads to occupants near the facade experiencing a high dissatisfaction with their thermal environment (near-facade zone).

This study experimentally examines the thermal environment of occupants near the facade of a glazed building wall. It presents results for Fangers' predicted mean vote (PMV) and the predicted percentage dissatisfied (PPD) and explores some options for improving the thermal environment in this near-facade zone.

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## 1. INTRODUCTION

The heat gain or heat loss from a glass façade system, such as that shown in Figure 1, can have a significant impact on people's perceptions of their environment. These gains or losses are all related to the physical properties of glass (conductivity, absorption, reflection, and transmittance) and are a function of the environmental conditions (solar radiation, wind and external/internal air temperatures). It is these parameters that determine the glass' surface temperature and therefore the heat transferred to building occupants by convection and/or radiation.



**Figure 1: Eastern glazed facade of office building**

Previously work had been undertaken into the indoor environmental quality testing of a commercial office building in a refurbished wool-store in Geelong, Victoria (Figure 1). During this investigation it was found that occupants near the single glazed eastern perimeter of the building (circled in Figure 2) experienced greater discomfort than those situated in the interior workplace due to variations in inside air temperature. One of the improvements made was the introduction of an optimized conditioning control system that attempted to balance the temperature throughout the open office space. However, several years later, the management and occupants of this building still remain dissatisfied with the thermal conditioning near the glazed perimeter on extremely hot days.

As such, the building occupants were interested in investigating the existing façade system and possible solutions to the problem using in-situ measurements of the facade performance together with external weather and solar parameters. Therefore, the objective of the study was to investigate possible solutions such that the occupants can

work in a comfortable temperature range, particularly near the eastern perimeter which consists of a three-metre floor-to-ceiling single glazed façade with a selective mirror-faced external coating and a heat absorbing glass.

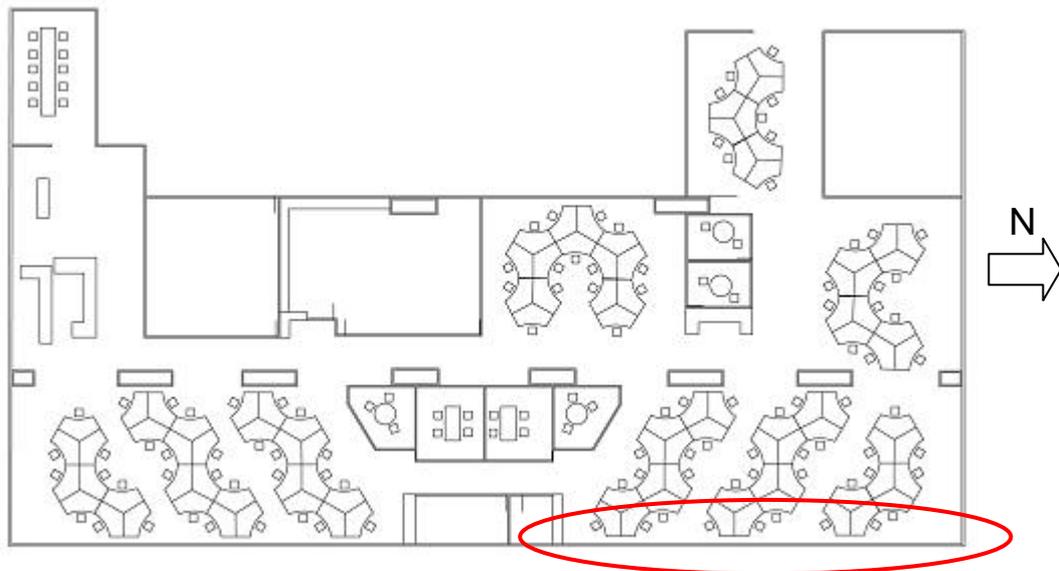


Figure 2: Office floor plan showing area of interest

## 2. THERMAL COMFORT

The idea of human thermal comfort is one that is particularly complex, at its most basic it can be defined as “that condition of mind which expresses satisfaction with the thermal environment” (ISO 7730, 2005). Therefore the idea of someone being “comfortable” relates not just to the air temperature but also to a range of other non-environmental parameters such as health, psychology, sociology and situational factors. As such, comfort is a complex relationship between, parameters such as metabolic rates, the level of clothing being worn, air temperature, relative humidity, mean radiant temperature, local air velocity and radiant asymmetry.

Fanger (1973) developed a quantitative method (the “Comfort Equation”) to describe comfort levels using six parameters as shown in Equation 1.

$$f(M, Clo, v, t_r, t_a, P_w)=0 \quad (1)$$

Where M is the metabolic rate, Clo is a clothing index, v the air velocity (m/s),  $t_r$  is the mean radiant temperature ( $^{\circ}\text{C}$ ),  $t_a$  the ambient air temperature ( $^{\circ}\text{C}$ ) and  $P_w$  is the vapour pressure of water in ambient air (Pa). When any combination of these parameters satisfies the comfort equation the thermal comfort of the majority of occupants will be neutral, i.e. not too hot nor too cold.

Now in reality, it is not always possible to satisfy this criterion and so have “optimal” thermal comfort. As such it is necessary to describe the relative level of discomfort. This can be achieved by two quantitative means: the Predicted Mean Vote (PMV) Index and the Predicted Percentage Dissatisfied (PPD) Index (Fanger, 1973). The PMV index predicts the mean response of a large group of people according to the ASHRAE thermal sensation scale and results in a rating from +3 (hot) to -3 (cold) and is a function of the metabolic rate (M) and thermal load (Equation 2), where the thermal load (L) is defined as: the difference between the internal heat production and the heat loss to the actual environment for a person kept at comfortable values of skin temperature and evaporative heat loss by sweating at their actual activity level.

$$PMV = (0.303e^{-0.036M} + 0.028) L \quad (2)$$

The second criterion, PPD, is a quantitative measure of the thermal comfort of a group of people in a particular thermal environment and is a more meaningful indicator of thermal comfort. Fanger (1973) related the PPD to the PMV using Equation 3.

$$PPD = 100 - 95 e^{-(0.03353PMV^4 + 0.2179PMV^2)} \quad (3)$$

What Fanger (1973) found from the PPD, was that irrespective of how perfect a thermal environment is, it is not possible to achieve a PPD of less than 5% for similarly clothed people undertaking the same activity.

### 3. GLASS PERFORMANCE INDICATORS

Given that occupants of the office near the glazed facade of the building complained of greater discomfort than those situated in the interior workplace it is important to understand the mechanisms of heat transfer that are occurring to (and from) the glass, how they are defined and the impact they can have on thermal comfort. The 'instantaneous' transfer of heat to and from a glazing system is represented by three components as illustrated in Figure 3 (Luther, 1995).

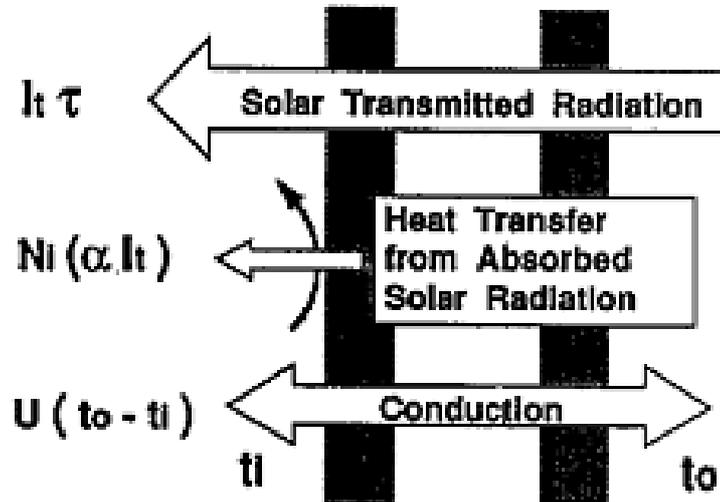


Figure 3: Heat transfer in a double glazed window (Luther, 1995)

The overall transfer of heat can then be described by Equation 2:

$$q_A = I_t \tau + N_i (\alpha I_t) + U (t_o - t_i) \quad (2)$$

where:

- $q_A$  = the total inward heat gain through the glass
- $I_t$  = incident solar radiation available on the exterior glass
- $\tau$  = the fraction of  $I$  that is directly transmitted through the glass
- $N_i$  = inward-flowing fraction of absorbed solar radiation
- $\alpha$  = fraction of  $I_t$  which is absorbed within the glass
- $U$  = total thermal conductance of the glazing unit
- $t_o$  = the exterior (ambient) air temperature
- $t_i$  = the interior air temperature

The coefficients of the first and second terms on the right hand side of equation 1, ( $N_i \alpha I_t \tau + N_i (\alpha I_t)$ ), represent the Solar Heat Gain Coefficient (SHGC) of the glass. This is the transfer of heat from solar irradiated glass. The last term on the right hand side  $U (t_o - t_i)$  represents conductive heat transfer through the glass considering air temperature differences between the interior and exterior, only. Therefore if the interior and exterior air temperatures are equal the conductive term reduces to zero allowing only the heat gains due to radiation to occur.

The U-value is the overall heat transfer coefficient ( $W/m^2K$ ) of the glazing unit and includes the conduction resistance the internal and external convection resistance. For insulated glass units this includes the layers of glass and the cavities' (air or gases) thermal resistance.

Finally, the Shading Coefficient is a ratio of the Solar Heat Gain Coefficient (SHGC) of a specific glazing unit to that of a standard DSA glass (a clear architectural glass 3mm thick). Usually all other glazing systems are less than unity when compared to a DSA glass. Therefore, low SC's are an indication of the glazing systems capability to reduce incident solar heat gain transfer into a building

In summary, U-Value, Solar Heat Gain Co-Efficient (SHGC) and Shading Co-Efficient (SC) loosely describe the thermal comfort that may be encountered near glazing systems, as these coefficients relate to heat transfer through a window system.

In light of this, it was decided to explore three alternatives to help remedy the issue of poor thermal comfort near the glazed facade:

- A shading screen fabricated from a protruded 3-D micro-screen, situated on an external frame 50mm from the existing glass facade.

- An argon filled IG unit consisting of a clear glass and a low-e glass mounted on the interior of the existing facade. This solution provides a triple glazed façade with the low-e surface on the cavity side of the interior glass.
- An argon filled IG unit with the middle glass replaced by a heat absorbing grey glass and again forming a triple glazed system.

The reason for the three alternatives was to explore options that would lead, primarily, to a reduction of the mean radiant temperature (a factor in Fanger's comfort equation). In the first instance a shading device would block out large percentages of radiation reaching the glass, yielding a lower surface temperature and resulting in a cooler building air temperature, through reduced radiant and convective gains. As the shading device was not expected to lower the U-Value of the glass it was anticipated that the building might still be too cold during winter periods. However shading offered to at least minimize temperature variation in periods of extreme heat (Tzempelikos et al, 2010).

Secondly, triple glazed units with a gas fill such as argon, could provide an effective solution as such insulating glazing units have lower U-Values. Further, the introduction of a low-e coating can reduce radiant heat transfer from the window due to the higher infrared (long wave) reflectance of the coated surface. Triple glazed units have been found to minimize the overall inside air temperature variance of a building due to lower values of solar heat gain as well as loss (Fang et al, 2010). As such these units could help improve thermal comfort under high radiation and also during cold periods.

#### 4. EXPERIMENTAL SETUP

Now in order to assess the impact of the three alternative solutions on thermal comfort near the glazed facade it was decided to conduct an in-situ experimental assessment in conjunction with the original system. Therefore, a weather station was assembled on the roof of a building adjacent to the office. This station consisted of a pyranometer measuring global radiation on a horizontal plane and a HMP35C Temperature/Relative Humidity Probe to measure air temperatures and relative humidity. This data was logged at 15-minute intervals using a CR10X Campbell Scientific data logger.

Additionally a pyranometer was mounted on the facade of the building to measure the solar radiation incident on the windows. An array of T-type thermocouples were used to measure the temperature at various locations within the glazing systems. Further radiant asymmetry sensors were placed approximately 500mm from the inside glazing to measure the radiant heat gain or loss from the windows.

To assess the comfort level of the occupants a 1221 Bruel & Kjaer Comfort Meter was used to measure the interior glass surface temperature, dry and wet bulb temperature, mean radiant temperature, absolute humidity, air velocity and the radiant asymmetry. The outputs were from these was used in determining thermal comfort parameters set out in ISO-7730 (Fanger Model of comfort).

##### 4.1. Original Glazing System

The original glazing system consisted of a single layer of tinted glass, the properties of which are summarised in Table 1. It is interesting to note that the original glazing system has a high emissivity value on its inner surface, this suggests that a significant portion of the incident radiation absorbed by the glass (over 60%) could be radiatively transferred to office. Furthermore, it can be seen that approximately 20% of the incident radiation is transmitted into the building and therefore heat gains by the building will be high during high radiation times. Finally, during colder periods the building will suffer heat losses due to the high emissivity and poor insulating properties of a single layer of glazing.

**Table 1: Optical properties of single glazed system**

Glazing System	Visible		Solar		Longwave Reflectance	
	$\tau$ %	$\rho$ %	$\tau$ %	$\rho$ %	Out %	In %
Original Heat Absorbing Tinted Glass	29	17	21	16	16	35

##### 4.2. Shaded Glazing System

The first solution explored was the use of a metallic mesh shade screen. For the shaded glazing system the glass optical properties are the same as for the original glazing system, as the screen was added to the exterior of this. However, for the simulations, it was assumed that the screen would block a significant portion of the radiation from reaching the glazing such that the glass temperature would be substantially reduced from that of the original glazing system. In turn, the total heat gain would significantly less than the original glass and the inside glass surface temperature cooler leading to lower radiant and convective gains from the glass. The net result of the screen being that the shading screen should lead to improvements in the SHGC and SC. However, the U-Value of the system would still be relatively high, as the screen offers no real thermal resistance.

##### 4.3. Clear Triple Glazed System

The second solution that was explored was a retrofit triple glazing unit. In this system, the original glazing was maintained and a double glazed unit, with a clear glass pane forming the middle pane of the triple glazed unit, was fitted behind this on the interior of the building. As such, this new system had varying glass properties between the three layers with the new middle and interior layers having high values of visible and solar transmittance and low values of visible and solar reflectance as shown in Table 2.

The inclusion of a low-e coating on the outside of the interior layer of glass means the surface has a high long-wave reflection compared to the rest of the high emissivity surfaces. Therefore a high amount of the incident radiation is absorbed in the outside layer of the glass but the interior surfaces absorb very little radiation and hence the inside glass temperature should be lower than the original system. In this system about 10% of the incident radiation is still transmitted, but overall the, heat gain by convection and radiation from the facade into the room should be significantly less. On this basis the overall system should perform better than the original system.

**Table 2: Optical properties of clear glass triple glazed system**

Glazing System Grey Triple Glazed	Visible		Solar		Longwave Reflectance	
	$\tau$ %	$\rho$ %	$\tau$ %	$\rho$ %	Out %	In %
Tinted Glass:	29	17	21	16	16	35
Grey Glass:	32	10	29	8	16	16
Low-E Glass:	82	10	66	22/10	84	16

#### 4.4. Grey Triple Glazed System

The third solution that was explored was another retrofit triple glazing unit. Again, in this system a double-glazed unit, with a grey glass pane forming the middle pane of the triple glazed unit was fitted behind the original glazing on the interior of the building. Table 4 shows the glass properties for the three layers, where the grey middle layer has low visible and solar transmittance compared to the clear glass in the previous system. The interior glass however was a clear low-e glass, meaning high long-wave reflectance on the outside of the interior glass.

For this system the middle grey glass layer absorbs a significant fraction of the radiation transmitted through the outside layer, this results in a low absorption on the inside layer as a result of the low amount of transmitted radiation (Under 5%). However, the absorption by the grey glass may lead it to having a higher inside temperature than the clear triple glazed system and so a high rate of radiant heat transfer to the low-e pane. This could lead to the inner pane having a higher temperature thereby resulting in a higher convective and radiant heat gain from the inside pane to the office space. Therefore, this type of triple glazing should have lower values of SHGC and SC than the clear unit described previously but will have a higher U-Value due to the radiant properties of the grey layer of glass allowing more outward heat loss.

**Table 3: Optical properties of grey glass triple glazed system**

Glazing System Clear Triple Glazed	Visible		Solar		Longwave Reflectance	
	$\tau$ %	$\rho$ %	$\tau$ %	$\rho$ %	Out %	In %
Tinted Glass:	29	17	21	16	16	35
Clear Glass:	87	7	77	7	16	16
Low-E Glass:	82	10	66	22/10	84	16

## 5. RESULTS

Now to quantify the indoor comfort, a PMV and PPD calculation was made for each of the glazing options. This could be utilized to determine when the occupants were the least satisfied and if the occupants were dissatisfied was it because the building was too cold or too hot. As the PPD is calculated from the measured values from the comfort meter including dry bulb temperature and air velocity, the instrument was placed adjacent to the east facing facade.

Before exploring the potential solutions, a benchmark assessment of the predicted percentage dissatisfied was performed on the existing glazed facade assuming a clothing index of 0.8 and a metabolic rate of 1, typical values for Australian office workers (Rowe, 2001), though perhaps conservative for summer conditions. Figure 4 illustrates a period of warm weather with high incident radiation where the office becomes very hot and the air temperature near the facade reaching nearly 30°C. This causes occupants to be dissatisfied with around 30% not happy with the level of thermal comfort in the building. This illustrates that the original glazing system is not blocking out enough heat and so during hot summer conditions the inside air temperatures would cause a very large percentage of the employees to be dissatisfied. More importantly, before midday tends to be the worst time of day, as this is when the eastern face of the building is under high levels of incident solar radiation. However, once the building has been heated in the morning it stays warm all day, leaving occupants dissatisfied all day long. Finally if the weather cools down it can be seen that the office can also be too cold even during the late spring testing period.

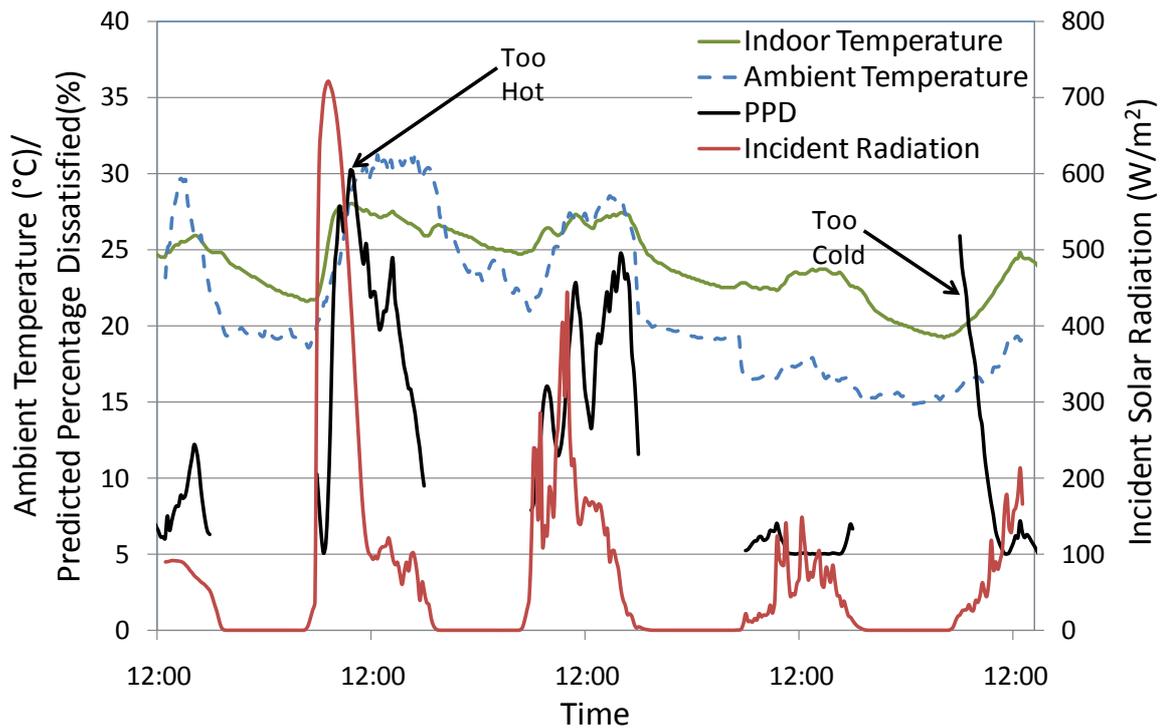


Figure 4: Predicted Percentage Dissatisfied (original glazing)

### 5.1. Thermal Comfort near Shaded System

As mentioned previously, a PMV and PPD calculation was made for each alternative system explored during this study. When examining, the predicted mean vote for the fixed shaded glazing system (Figure 5), it can be seen that the occupants are likely to be satisfied with their environment. It is interesting to note that during early office hours (c. 8:30) there is a period where occupants may feel slightly warm. This is also illustrated in the PPD assessment, Figure 6, where a brief period of increased dissatisfaction is predicted. However, it can be seen that as the indoor air temperature decreases, the PMV and PPD also decrease suggesting the thermal comfort for the occupants with this glazing arrangement will be dominated by the mean radiant and indoor air temperature.

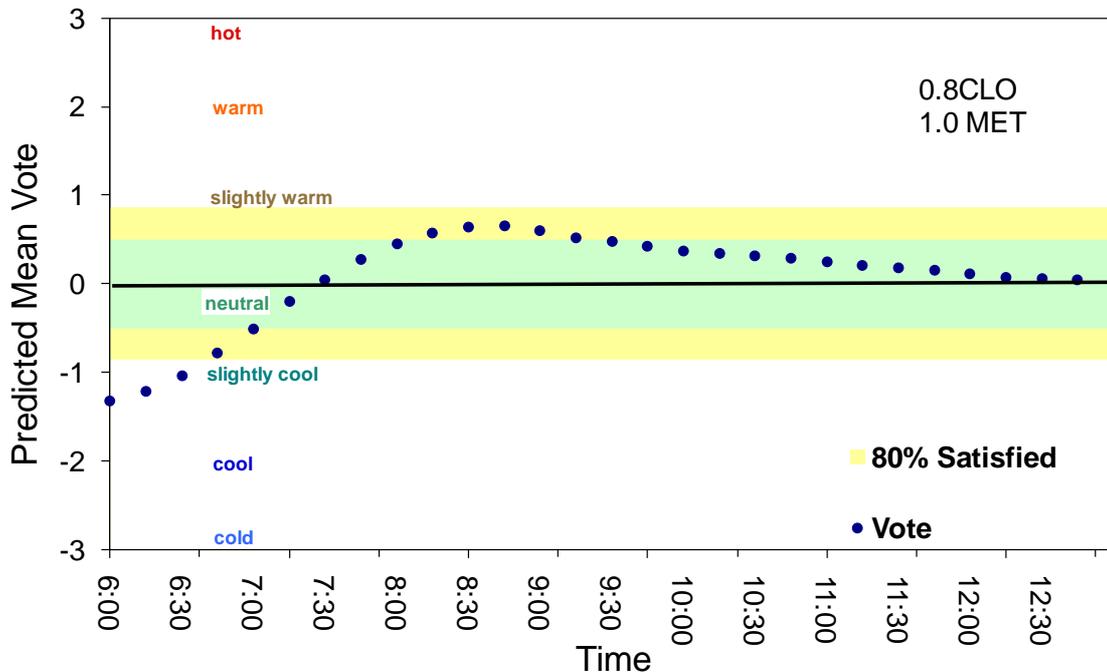


Figure 5: Predicted Mean Vote (shaded glazing)

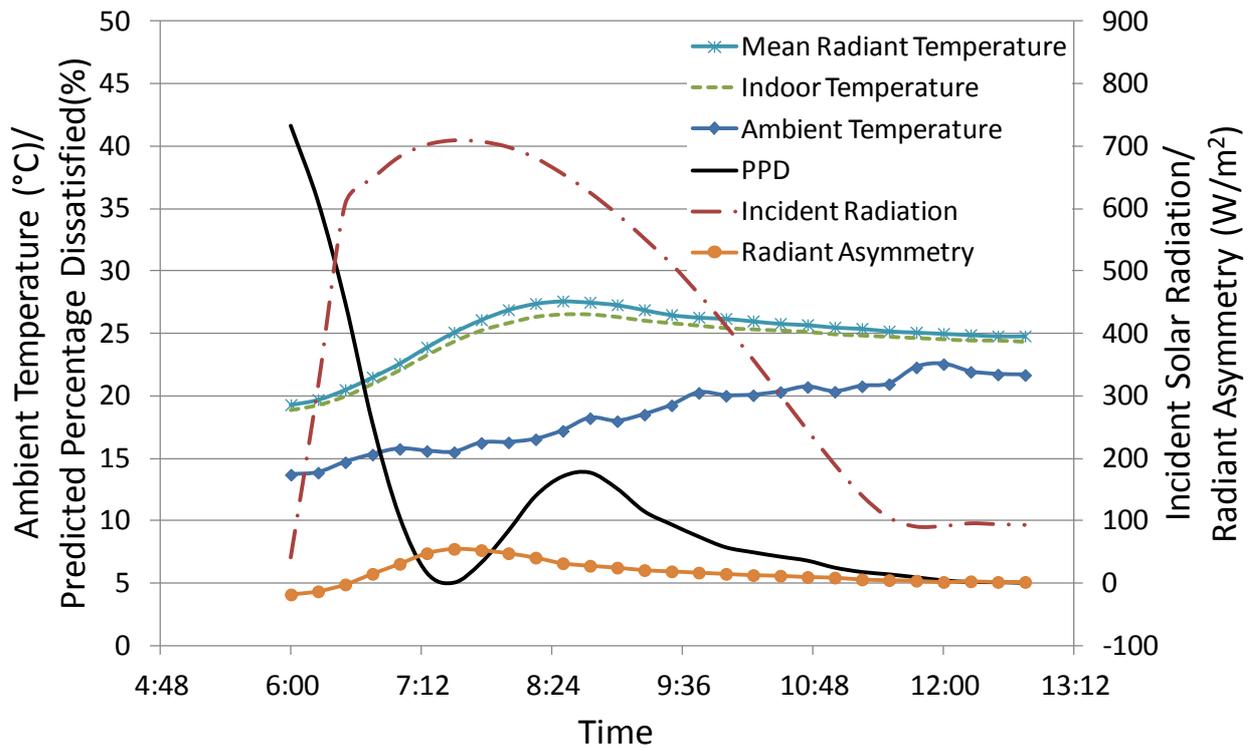


Figure 6: Predicted Percentage Dissatisfied (shaded glazing)

### 5.2. Thermal Comfort near Clear Triple Glazing

When examining, the predicted mean vote for the clear triple glazing system (Figure 7), it can be seen that the occupants are likely to feel slightly warm in their environment. Again in Figure 8 it can be seen that as the indoor air temperature decreases, the PMV and PPD also decrease, however it is interesting to observe that at approximately 9:00, there is a sharp increase in the predicted dissatisfaction, with only a slight change in the mean radiant and indoor air temperature. This suggests that for this instance, the air temperature becomes less significant than other factors, such as radiant heat transfer from the glass. On the whole however, the relatively high temperature in the office suggests that air temperature is still a relatively significant factor, and that perhaps the cooling system was not functioning appropriately.

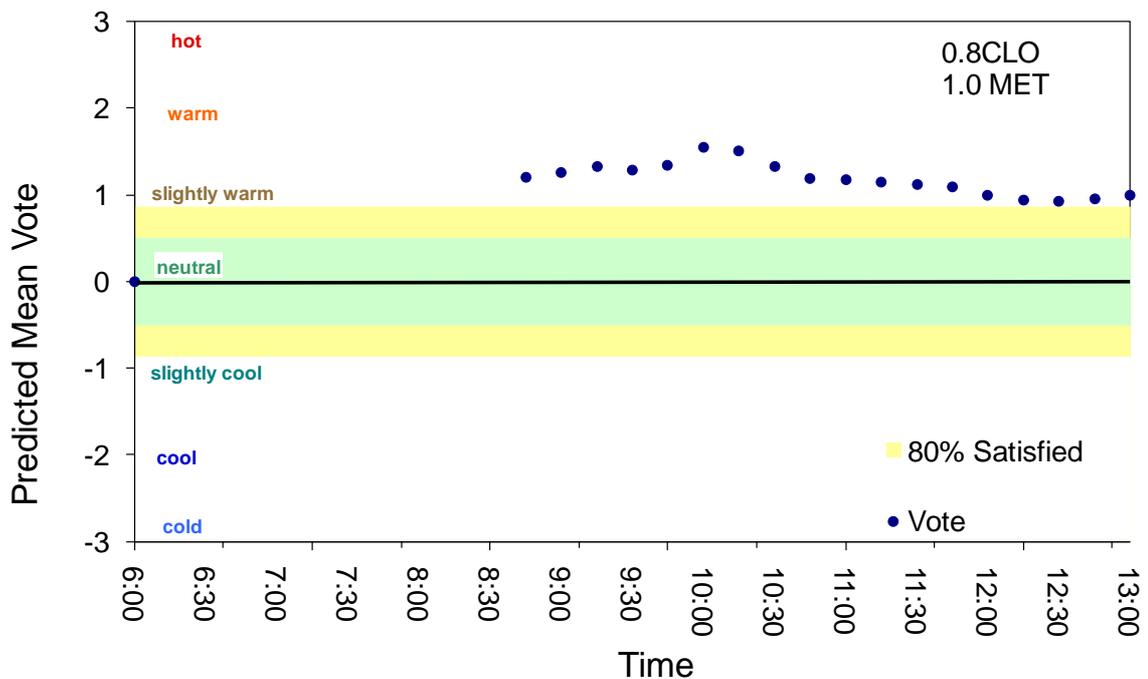


Figure 7: Predicted Mean Vote (clear triple glazing)

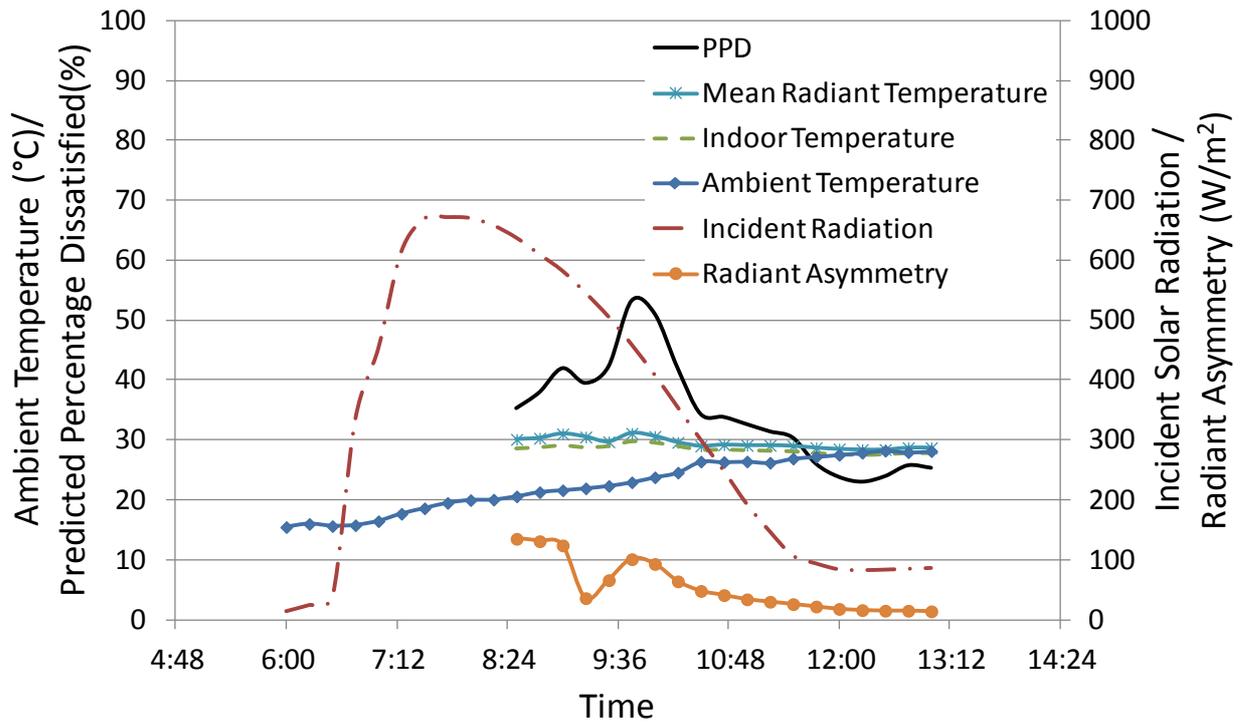


Figure 8: Predicted Percentage Dissatisfied (clear triple glazing)

### 5.3. Thermal Comfort near Grey Triple Glazing

When examining the predicted mean vote for the grey triple glazing system (Figure 9), it can be seen that the occupants are likely to feel slightly warm in their environment. In Figure 9 it can be seen that as the mean radiant and indoor air temperature increase, the PMV and PPD also increase, as would be expected. However beyond 25°C the air temperature becomes less significant than other factors. This is most clearly observed in Figure 10, when at approximately 9:00, the indoor air temperature is constant, but the radiation level is still relatively high and the outside temperature is increasing. Such conditions lead to a reduction of heat loss to the surroundings, which in turn leads to an increase of heat gain by occupants for a short period of time. However, it is perhaps more important to note that the largest predicted increase in dissatisfaction occurs for the period where the mean radiant and indoor temperature increases above 25°C to its maximum (7:12 to 8:24).

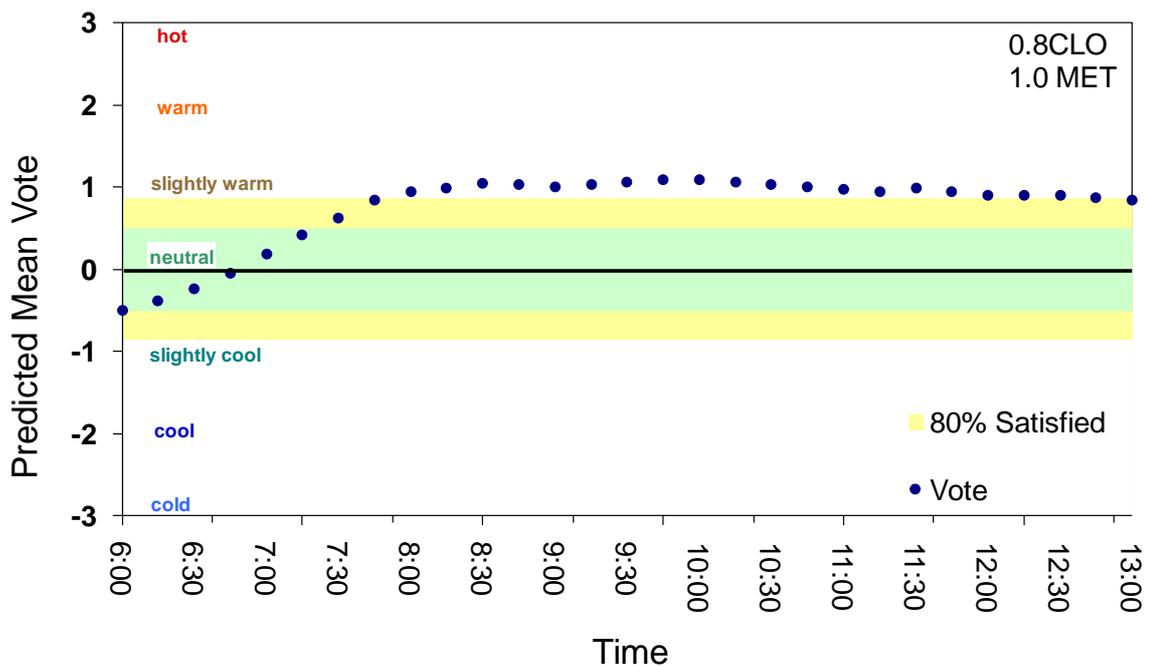


Figure 9: Predicted Mean Vote (grey triple glazing)

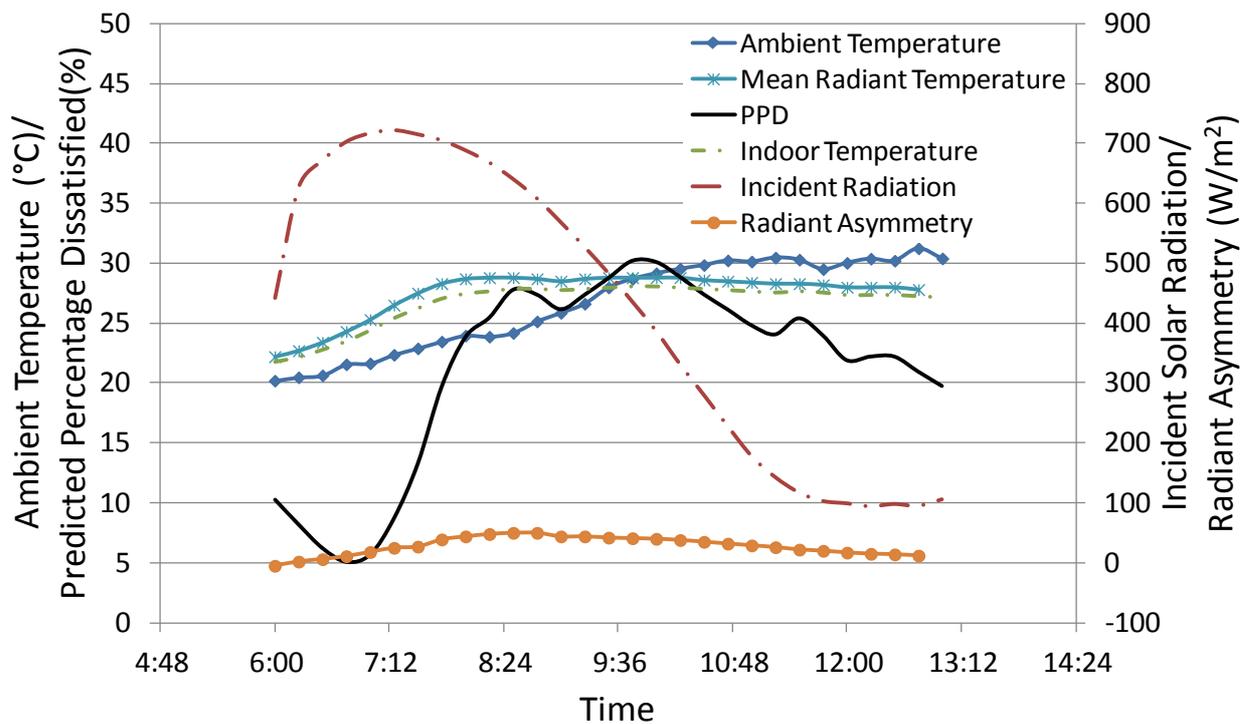


Figure 10: Predicted Percentage Dissatisfied (grey triple glazing)

## 6. DISCUSSION

Now, from examining the alternative solutions to improving thermal comfort in the office building, there are a number of clear findings. Firstly, the indoor air temperature appears to be the determining parameter of thermal comfort for all glazing systems up to 25°C. Beyond this level, the incident radiation and outside temperature show some effect on thermal comfort but this appears to be less significant. For example, in the prediction of dissatisfaction behind the grey triple glazed facade, it was seen that with the indoor air temperature increasing from 25°C to approximately 27°C, the PPD increased by over 20%. However, for the same glazing with the indoor air temperature constant at approximately 27°C, a reduction in incident radiation from 450W/m<sup>2</sup> to 100W/m<sup>2</sup> improved satisfaction by 10%.

Similarly, for the shaded system, with the indoor air temperature being almost constant at 25°C, there was a high degree of satisfaction predicted, whereas, in the case of the clear triple glazing, the high indoor temperature would suggest a high degree of thermal discomfort. As such control of the indoor temperature is paramount; however, there are also advantages to being able to reduce the incoming radiation, as this reduces the load that must be met by building services. Therefore, a system such as the shading screen could lead to improvements in thermal comfort (and energy efficiency) during summer periods. Conversely, the use of triple glazed systems may be less effective in controlling solar gains, however they offer better insulating characteristics, which when coupled with cooling in summer and heating in winter may lead to greater stability in the thermal environment and perhaps in turn to increased satisfaction from the occupants.

## CONCLUSION

In many highly glazed buildings the thermal comfort of the occupants will be related to the incoming solar energy and the solar heat gain coefficient of the glazing. As real buildings tend to be deep relative their height, areas close to the facade receive a much greater amount of the incoming energy. This imbalance leads to occupants near the facade experiencing a high dissatisfaction with their thermal environment (near-facade zone).

This study examined the thermal environment using Fangers' predicted mean vote (PMV) and the predicted percentage dissatisfied (PPD) and explored some options for improving the thermal environment in this near-facade zone. It was found that control of the indoor temperature was paramount; however, it also showed that there are advantages to being able to reduce the incoming radiation through the use of static shading systems and advanced glazing systems.

## ACKNOWLEDGEMENT

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