MODELING THERMAL COMFORT IN STRATIFIED ENVIRONMENTS

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ABSTRACT
Some HVAC systems save energy by creating stratified air temperature distributions in which the occupied lower regions are cooler and the upper regions warmer. Comfort standards prescribe a 3°C limit to vertical stratification, independent of where the mean temperature is relative to the comfort zone. This paper evaluates thermal comfort in stratified environments using a model developed to predict local thermal sensation and comfort. The results indicate that near the center of the comfort zone, acceptable stratification is up to 7ºC, considerably larger than the 3°C limit imposed by standards. As the mean temperature moves from the center of the comfort zone, the acceptable stratification becomes smaller. At the lower and upper ends of the comfort zone, even a small amount of stratification causes cool feet or warm head discomfort. We briefly explore the potential of using local air motion to reduce local discomfort in highly stratified conditions.

INDEX TERMS
Thermal stratification, stratified environment, local comfort, local sensation, comfort modeling, perimeter zone, local air motion

INTRODUCTION
ASHRAE Standard 55 (2004) prescribes 3ºC as the limit for the vertical air temperature difference between head and ankle levels (in this paper, we define the amount of stratification as this difference) regardless of the operative temperature of the environment. ISO 7730 (1994) describes the stratification limit using three categories of decreasing quality: A<2ºC, B<3ºC, C<4ºC. These standards are based on a human subject study by Olesen et al. (1979) that was conducted on 16 subjects exposed to four levels of stratification. Other studies have not only found higher stratification acceptable (up to 6ºC), but also demonstrated that the operative temperature is a much stronger cause of discomfort than stratification (McNair 1973, Ilmarinen et al. 1992, Palonen et al. 1992, Kawahara et al. 1999, Tanaka et al. 1986, Wyon and Sandberg 1996). Studies have also shown that discomfort in stratified environments is not due to asymmetry per se, but rather to local discomfort (Wyon 1994) from a warm head or cold feet (Olesen at al. 1979, Tanaka et al. 1986, Wyon 1994). Pellerin et al. (2004) tested 345 subjects under different non-uniform environments and concluded that the number of locally uncomfortable body parts determines thermal comfort in non-uniform environments. The purpose of this paper is to examine acceptable stratification in various operative temperatures by examining local discomfort using a thermal comfort model.

THE CBE COMFORT MODEL
The CBE Comfort Model is a unique model that predicts thermal sensation and comfort for the whole body as well as for 16 local body parts in non-uniform and transient thermal environments. The model simulates skin and core temperature response based on a detailed physiological model of the thermoregulatory system and uses these temperatures to predict

sensation and comfort. The 9-point sensation scale is an extended version of the ASHRAE 7-point scale, adding very cold (-4) and very hot (4). The 9-point comfort scale is defined from very uncomfortable (-4) to very comfortable (4), with 0 representing the transition from discomfort to comfort. For more detailed description of the CBE Comfort Model please see Huizenga et al. (2000) and Zhang et al. (2004).

SIMULATION RESULTS

Model validation

ASHRAE Standard 55 defines a comfort zone using the PMV model based on 80% occupant acceptability (10% dissatisfaction for general whole-body thermal comfort and 10% dissatisfaction for local body parts). We define a comfort zone using the CBE Comfort Model in which the whole body is comfortable and there is no local discomfort. The upper and lower limits of the ASHRAE and CBE model comfort zones are shown in Table 1 for typical summer clothing. The models are in good agreement at the warm end of the zone, but the CBE model extends the range 0.5°C at the cool end.

Table 1. Comfort temperature range for uniform environment (0.59 clo, 50% RH, 0.1 m/s, 1.0 met)

Operative temperature (°C)	Cool side	Warm side
ASHRAE	24.1	27
CBE Comfort Model	23.6	26.8

Kawahara et al. (1999) tested 16 subjects under 24 conditions combining different upper and lower body environment temperatures. A comparison of the comfort votes between the test data and the CBE Comfort Model predictions are presented in Table 2.

Table 2. Comparison of measured comfort data by Kawahara et al. (1999) with predictions of the CBE Comfort Model

Temperature (°C)		Kawahara - Tested	CBE model - Predicted
Upper body	Lower body		
17	20	uncomfortable	uncomfortable
	23	uncomfortable	uncomfortable
	26	uncomfortable	uncomfortable
20	20	neutral	uncomfortable
	23	neutral	uncomfortable
	26	neutral	comfortable
23	20	neutral	uncomfortable
	23	comfortable	comfortable
	26	comfortable	comfortable
26	20	comfortable	uncomfortable
	23	comfortable	comfortable
	26	comfortable	comfortable

The CBE Comfort Model predicts either comfort (positive value) or discomfort (negative value) and therefore cannot match the "neutral" votes of Kawara. Aside from this difference, the comparison shows that the predictions are the same as the tested data in all but one condition where the upper body was exposed to 26ºC and the lower body to 20ºC. In this case our model predicts discomfort due to cool feet.

Tanaka et al. (1986) tested 6 subjects under conditions where the lower body air temperature was fixed at 25ºC while the upper body air temperature was changed to five different temperatures. Table 3 show that the only difference between our model predictions and the measured responses appears when the upper body air temperature was 20ºC. Our model predicts discomfort due to cool hands in this environment.

Table 3. Comparison of measured comfort data by Tanaka et al. (1986) with predictions of the CBE Comfort Model

Upper body air temperature (ºC)	Tanaka - Tested	CBE model - Predicted
15	uncomfortable	uncomfortable
20	comfortable	uncomfortable
25	comfortable	comfortable
30	uncomfortable	uncomfortable
35	uncomfortable	uncomfortable

Predicted stratification limits

We performed a series of simulations to predict the maximum acceptable stratification (defined as the absence of any local or whole-body discomfort) based on linear vertical temperature profiles at different points in the comfort zone (Figure 1). Our simulations show that the acceptable stratification depends very much on operative temperature. When the average operative temperature is near the center of the comfort zone (25.3 - 25.8ºC), up to 7ºC stratification is acceptable. As the operative temperature moves away from the center, the acceptable stratification becomes smaller. At the cool (23.6ºC) and warm (26.8ºC) ends of the comfort zone, no stratification is acceptable because the stratification causes cool feet or a warm head, respectively. The ASHRAE 3ºC limit is indicated in Figure 1 for comparison. In the simulations, the walls of the room (4.5m wide, 6m deep, 3m high) were divided into three sections vertically to model surface temperature stratification. Floor temperature was assumed to be the same as the foot-level air temperature, and the ceiling temperature was assumed to be the same as the head level air temperature (no further stratification above head level).

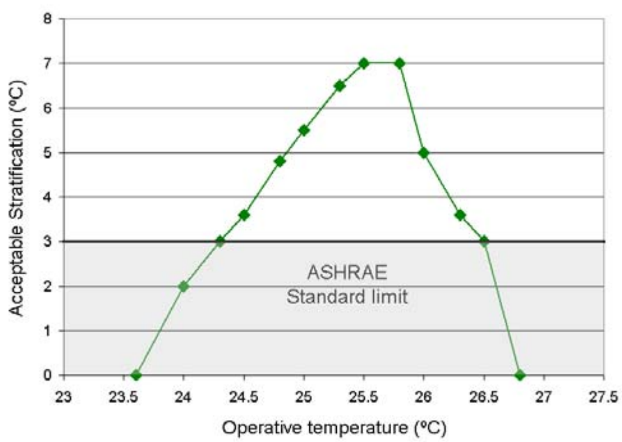


Figure 1. Acceptable stratification as a function of operative temperature. (clo 0.59, met 1.0, RH 50%)

Perimeter zone stratification
In perimeter zones of buildings, radiant heat transfer to warm and cool window and wall surfaces can contribute to local discomfort. Short-wave solar radiation transmitted by glass can also cause local discomfort, but we excluded that obvious problem from our analysis. We simulated the effects of a 3m wide x 2m high window with a 1m sill height on the thermal comfort of a person standing 1m from the window.

Figure 2 shows the acceptable stratification limits for a cool window (15°C) and a warm window (35°C). The presence of the window has two noticeable effects: it shifts the comfort zone and changes the acceptable level of stratification. The cool window shifts the unstratified comfort zone about by approximately 0.5°C and the warm window shifts the comfort zone by approximately -0.4°C. In the stratified environments, the cool window reduces warm discomfort at the head and increases cool discomfort at the feet. However, the radiation exchange between the head and the window is more significant than the exchange between the feet and the window, due to the view factor geometry and the fact that the head is unclothed. As a result, the cool window increases acceptable stratification because the reduction of the warm discomfort at the head is more significant than the increase in cool discomfort at the feet. Similarly, the warm window reduces the maximum acceptable stratification because the increase in warm head discomfort is more significant than the reduction in cool feet discomfort. The influence of the cold or warm window becomes insignificant when the person is more than 3m away from the window.

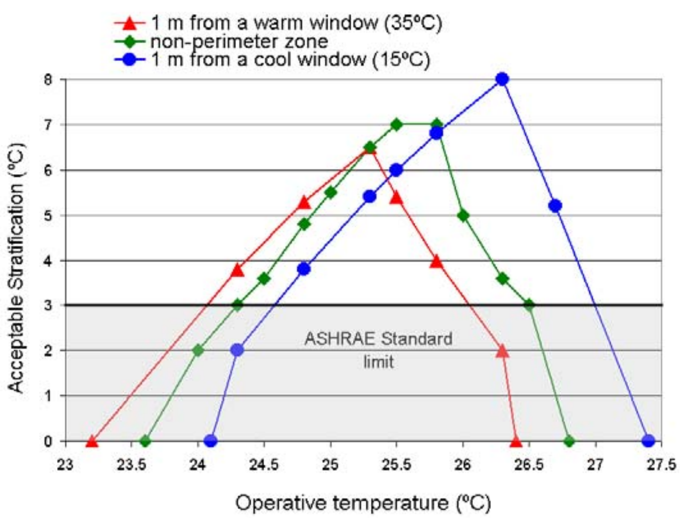
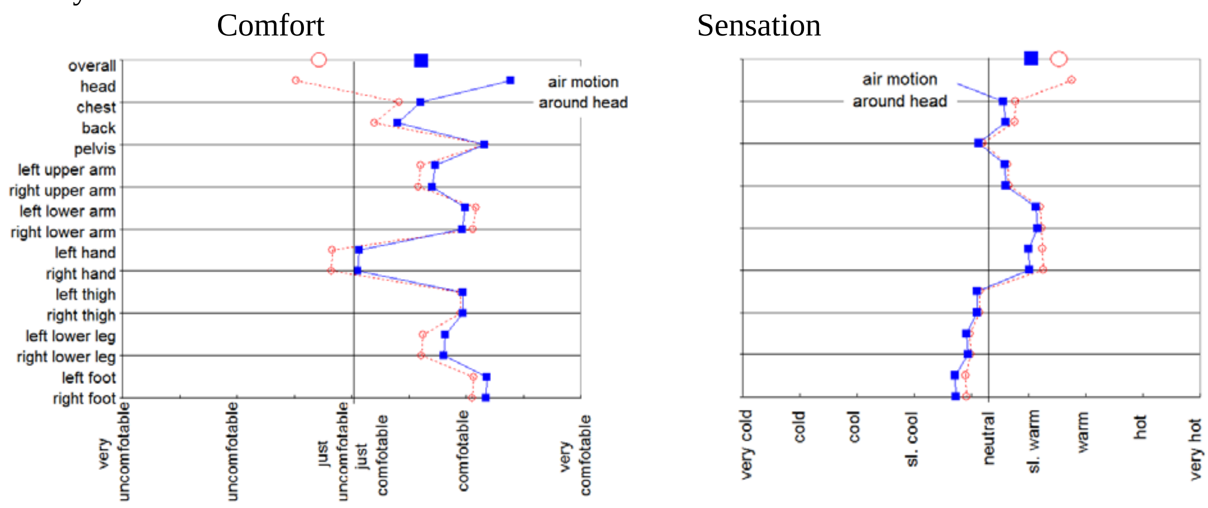


Figure 2. Acceptable stratifications in perimeter zone (1 m from a 15ºC or 35ºC window)

Increasing acceptable stratification with air motion around the head
When a task-ambient system is available (e.g. personal ventilation systems for head, local heaters for feet or hands), the local discomfort caused by the stratification can be reduced and the acceptable stratification can be higher. Figure 3(a) shows the effectiveness of providing air motion around the head in a 26.8°C environment with 6°C stratification. Without the air motion, no stratification is acceptable (Figure 1). By applying 0.8 m/s air motion around the head, the acceptable stratification goes up to 6ºC. Head comfort is increased from –1 (clearly uncomfortable) to 2.8 (clearly comfortable). Overall comfort increases from –0.5 to 1.2. The added air motion to the head also improved comfort levels for other body parts (e.g. hands, feet, chest and back) because head cooling is an effective way to remove heat from the body. Figure 3(b) shows that while the head thermal sensation is clearly lowered by the air motion,

other body parts are also perceived as cooler due to the overall increase in heat loss from the body.



(a) (b)

Figure 3. Comfort (a) and sensation (b) with and without air motion (0.8 m/s) around the head in a warm environment (26.8°C) with 6°C stratification

DISCUSSION

Our comfort model is based on the hypothesis that thermal sensation and comfort are dependent on input from thermoreceptors that sense skin and core temperatures. Although this approach differs from Fanger's PMV model (Fanger 1972), which is based on an overall heat balance between the body and the environment, we have shown that the two models predict similar comfort zones for non-stratified conditions. Although the cool end of the comfort zone defined by the CBE model is lower than that predicted by the PMV model, it is highly sensitive to the insulation levels of the socks and shoes used in the model. Using a thinner sock is sufficient to bring the models into very close agreement.

The CBE model shows very good agreement with human subject tests performed by Kawahara and Tanaka. Our analysis suggests that the amount of acceptable stratification is dependent on the operative temperature- near the center of the comfort zone more stratification is acceptable. This is in agreement with several studies which emphasize the importance of operative temperature in non-uniform environments (Olesen et al. 1979, Fanger et al. 1985, Ilmarinen et al. 1992, Palonen et al. 1992, Wyon and Sandberg 1996). However, our model predicts that more stratification is acceptable than suggested by Olesen, which is the study that provides the basis for the ASHRAE and ISO comfort standards. Using the same environmental conditions for which Olesen found a 3°C stratification limit, the CBE model predicts a 5ºC limit. We do not offer an explanation for this discrepancy, other than to point out that a small number of subjects were used in Olesen's study.

By reducing local discomfort, stratification levels can be increased even further. Our analysis suggests that by providing air motion around the head, acceptable stratification increases from 0 to 6°C in a warm 26.8°C environment. Similarly, we have found that feet warming with 30ºC air in a cool environment (23.6ºC) increases acceptable stratification from 0 to 7ºC.

The acceptable stratifications in Figure 1 are for a sedentary activity (1 met). With higher activity, the acceptable stratifications are increased for both cool and warm conditions.

Higher blood circulation reduces discomfort from cold feet in cool conditions, and the cooler comfort zone that applies for higher activity reduces warm-head discomfort through increased skin- and breathing heat exchange to the surroundings.

CONCLUSION AND IMPLICATIONS

Innovative HVAC systems offer opportunities for energy savings by creating non-uniform thermal environments. Existing standards place restrictions on vertical air stratification based on limited research. Several previous studies have suggested that existing stratification limits may be overly restrictive and our present analysis supports this position. Even more studies have suggested that local discomfort rather than asymmetry per se is what drives overall thermal comfort. Traditional heat balance analysis may be inadequate to assess comfort in buildings with complex thermal environments and for occupants wearing a wide variety of clothing. Models such as ours that predict local discomfort offer an opportunity to explore a wider set of solutions for more efficiently maintaining thermal comfort in buildings.

ACKNOWLEDGEMENT

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