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A Thermal Sensation Prediction Tool for Use by the Profession

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ABSTRACT

As part of a recent ASHRAE research project (781-RP), a thermal sensation prediction tool has been developed. This paper introduces the tool, describes the component thermal sensation models, and presents examples of how the tool can be used in practice. Since the main end product of the HVAC industry is the comfort of occupants indoors, tools for predicting occupant thermal response can be an important asset to designers of indoor climate control systems. The software tool presented in this paper incorporates several existing models for predicting occupant comfort.

INTRODUCTION

Many state-of-the-art thermal sensation models have been developed from dozens of research projects conducted during the last 35 years. Out of this enormous body of work, two thermal comfort prediction methods—Fanger's PMV-PPD (Fanger 1970) and Gagge's 2-Node (Gagge et al. 1986)—have been most widely used. These models predict the thermal comfort (including, but not limited to, thermal sensation) of humans. The International Standards Organization (ISO) has adopted the PMV-PPD model in its thermal comfort standard 7730 (ISO 1984), while ASHRAE uses ET* (one of the indices calculated by the 2-Node model) to define the boundaries of the comfort zone in its thermal comfort Standard 55 (ASHRAE 1992).

Both the PMV-PPD and 2-Node models solve heat balance equations for the human body and are generally implemented on a computer. These models are in the public domain and are available to professionals by request from several different sources. However, the lack of user-friendly interfaces, lack of information on how to interpret results, and lack of information on which models to use in different situations ward off many potential users.

ASHRAE recently sponsored a research project (Fountain and Huizenga 1995) to prepare thermal sensation prediction software for possible inclusion in ASHRAE Standard 55 (ASHRAE 1992). ASHRAE's goals included determining which models to incorporate and providing a user-friendly front end, a comparative analysis of the models, and information that allows a professional who is not necessarily involved in thermal comfort research to apply the models successfully. The thermal sensation prediction tool that resulted from the project will be described in this paper.

Eight existing physiologically based thermal comfort models and five existing non-physiologically based thermal comfort models were identified for possible inclusion in the software tool (Table 1). A physiologically based thermal comfort model is an algorithm that produces a predicted physiological state and predicted thermal comfort vote for a human exposed to an indoor environment using certain physical parameters of the environment (and of the human) as input. Non-physiologically based thermal comfort models are statistical fits to data relating comfort indices to the physiological environment. A brief description of the models is presented below; however, a

TABLE 1
Some Physiologically Based Thermal Comfort Models

Date	Author	Description
1964	Wissler	225-node finite element model
1970	Fanger	PMV steady-state model
1970	Stolwijk	25-node basic heat flow model
1986*	Gagge et al.	2-node basic heat flow model
1990	de Dear and Ring	40-layer finite difference skin model
1990	Int-Hout	Modified PMV
1992	Jones and Ogawa	2-node with transient response
1992	Tanabe	Modified Stolwijk model

* Most recent iteration; many have been released.

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complete discussion of the models' structure and their strengths and weaknesses is beyond the scope of this paper and is available elsewhere (Fountain and Huizenga 1995).

In brief, these physiological thermal comfort models have at their core a statement about the heat balance of the human body. Humans gain heat from metabolism and lose heat due to respiration and evapotranspiration. In addition, depending on the physical environment, they either gain or lose heat by conduction, convection, and radiation. The hypothalamus is charged with regulating heat gain and loss mechanisms to maintain the body's core temperature at 37°C (98.6°F). All the physiological models listed in Table 1 (except for Fanger's PMV-PPD and PMV-IH) use initial values for physiological constants and physiological variables and then iterate for a user-specified time period. Each iteration consists of establishing thermoreceptor signals to the brain, determining physiological responses, calculating heat flows, calculating new core and skin temperatures, and, finally, calculating the resulting thermoreceptor signals again, usually on a minute-by-minute basis.

Fanger's PMV-PPD model is also physiologically based, but, instead of iterating changing heat flows for a specific period of exposure, the iteration determines clothing surface temperature, and the convective heat transfer coefficient is based in fixed heat flows. The equation uses a steady-state heat balance for the human body and postulates a link between deviation from the minimum load on heat balance effector mechanisms—e.g., sweating, vasoconstriction, and vasodilation—and thermal comfort vote. The greater the load, the more the comfort vote deviates from zero or "neutral" sensation. A modified form of PMV was also considered for inclusion in the software tool. PMV-IH (Int-Hout 1990) is the Fanger PMV calculation with a modification in the way heat is transferred through the skin-clothing system that accounts for the vapor resistance of clothing.

Five non-physiologically based models were also considered for inclusion in the software: three empirical models and two adaptive models. The three empirical models are PD (Fanger et al. 1988), or "predicted percent dissatisfied due to draft," which is a fit to data of persons expressing thermal discomfort due to drafts; PS (Fountain et al. 1994), which is a fit to data of comfortable persons choosing air velocity levels; and TS (Rohles and Nevins 1971), which is a fit to data of thermal sensation as a linear function of air temperature and partial vapor pressure. The two adaptive models include variations in outdoor climate for determining thermal preferences indoors. Auliciems' (Auliciems 1983) neutral temperature model fits sensation data based on field investigations of thermal comfort in Australia spanning several climates. Humphreys' (Humphreys 1978) neutral temperature equation is a fit to more than 100,000 observations of sensation in climate-controlled and non-climate-controlled buildings. Equations for PD, PS, and TS are as follows:

$$PD = 3.413(34 - Ta)(v - 0.05)^{0.622} + 0.369vTu(34 - Ta)(v - 0.05)^{0.622} \quad (1)$$

$$PS = 1.13\sqrt{Top} - 0.24Top + 2.7\sqrt{v} - 0.99v \quad (2)$$

and

$$TS = 0.245Ta + 0.248p - 6.475 \quad (3)$$

The PD equation arises from two studies in which 100 people were exposed to various combinations of air temperature, air velocity, and turbulence intensity. For each combination of conditions, the people were asked if they felt a draft. The PS equation arises from a study in which 50 people were asked to adjust an air velocity source as they pleased when exposed to a specific air temperature. PS represents the cumulative percent of people choosing a particular air velocity at the temperatures tested. TS is an equation that predicts thermal sensation vote using a linear function of air temperature and partial vapor pressure.

The adaptive models include in some way the variations in outdoor climate for determining thermal preferences indoors. The equations for the adaptive models included in the software are

$$Tn = 9.22 + 0.48Ta + 0.14Tmmo \quad (4)$$

and

$$Tn = 23.9 + \frac{0.295(Tmmo - 22)}{e - \left[\frac{(Tmmo - 22)}{24\sqrt{2}}\right]^2} \quad (5)$$

METHOD

The first task was to identify the location and status of the thermal comfort models discussed above. Specifically, does a computer code exist for the model, where is it, and what language is it in? A survey was then distributed to HVAC professionals via facsimile. The survey questioned professionals about basic thermal comfort analysis needs. Based on the survey responses and available computer code, decisions were made about the subset of models to include in the software.

It was decided that several, but not all, of the eight existing physiologically based thermal sensation models (listed in Table 1) should be incorporated in the software package. It was also decided that the "model selection," or method for choosing among these models, should be presented in the documentation via instructions for using the software. The widespread availability of very fast microprocessors lends itself readily to the task of including several models. A 60-minute iteration of the Gagge 2-Node model that once took minutes (or longer) of real time to process now takes less than one-tenth of a second on a fast computer.

A survey was distributed via facsimile to 60 professional HVAC engineers in the San Francisco Bay area to assess interest in and experience with thermal sensation models. Based on the survey results, it was decided that to incorporate heat balance models beyond PMV-PPD and 2-Node at this time would provide diminishing returns for most users of the software, adding additional complexity and possibility for error in application without providing any truly unique information useful to a professional. In addition, it was decided that all five of the empirical and adaptive models should be implemented due to their simplicity. A complete list of the models included is given in Table 2 and a complete list of the indices computed is given in Table 3.

USING THE SOFTWARE

Utilizing a point-and-click interface (Figure 1), users adjust the input values and the outputs are updated in real time. The right-hand side of the screen controls the input variables, while the left-hand side presents the output from the models. Values can either be entered directly or the up/down arrows can be used to scroll to the desired number. When the program is loaded, default values for all inputs are loaded and all the models are cycled. When any input value is changed, all the models are run again. With today's fast processor speeds, there is no time delay between clicking on an arrow to adjust an input and having all of the output values change in response.

Pull-down menus allow file handling, access to additional model parameters, adjustment of units, and interactive program help. A toolbar is "wired" to frequently used menu options for quick access. The model is written in C++ in a way that will allow integration of additional models at a later date if desired.

In addition to numerical outputs, the program utilizes icons and text that change color (or appear and disappear) to indicate when the outputs are within certain ranges. For example, the "ASHRAE 55" icon in the upper right corner turns blue, green, or red when conditions are below, within, or above the ASHRAE 55-92 comfort zone, respectively. When one of the input variables does not coincide with one of the ASHRAE 55-92 assumptions, the icon turns a lighter shade to indicate that ASHRAE 55-92 does not apply. Similarly, when the calculated value of PD is above 15% (ASHRAE 55-92 limit), the words "draft risk" appear next to the PD calculation. It should be noted here that it is not sufficient to run this program to show ASHRAE Standard 55 compliance as it does not incorporate all of the requirements of ASHRAE 55-92.

Three pull-down menus are available at the top of the screen—"File," "Options," and "Help." "File" accesses file input and output functions; "Options" allows control of various control constants, the unit system, and calculation utilities; and "Help" runs the on-line help. Frequently used commands from the pull-down menus are linked to icons in the toolbar (Figure 2).

TABLE 2
Models Included in Software

Model Name	Author	Year First Introduced	Type
PMV-PPD	P.O. Fanger	1970	Heat balance
2-Node	Gagge et al.	1970	Heat balance
Revised PMV	D. Int-Hout	1990	Heat balance
PD	Fanger et al.	1988	Empirical
PS	Fountain et al.	1994	Empirical
TS	Rohles and Nevins	1971	Empirical
Tn	M.A. Humphreys	1978	Adaptive
Tn	A. Auliciems	1983	Adaptive

TABLE 3
Indices Computed by the Software

Index	Reference
PMV (Predicted mean vote)	Fanger (1970)
PPD (Predicted percent dissatisfied)	ISO (1984)
ET* (New effective temperature)	Gagge et al. (1986) as modified by Doherty and Arens (1988)
SET* (Standard effective temperature)	Gagge et al. (1986) as modified by Doherty and Arens (1988)
TSENS (Predicted thermal sensation)	Gagge et al. (1986) as modified by Doherty and Arens (1988)
DISC (Predicted thermal discomfort)	Gagge et al. (1986) as modified by Doherty (1988)
PD (Predicted percent dissatisfied due to draft)	Fanger et al. (1988)
PS (Predicted percent satisfied with the level of air movement)	Fountain (1994)
Tn (Neutral temperature based on mean monthly outdoor temperature)	Humphreys (1978)
Tn (Neutral temperature based on long-term indoor and outdoor temperature)	Auliciems (1983); de Dear and Ring (1984)
TS (Predicted thermal sensation)	Rohles and Nevins (1971)
PPD (Calculated by Int-Hout model)	Int-Hout (1990)
PMV-IH (Calculated by Int-Hout model)	Int-Hout (1990)

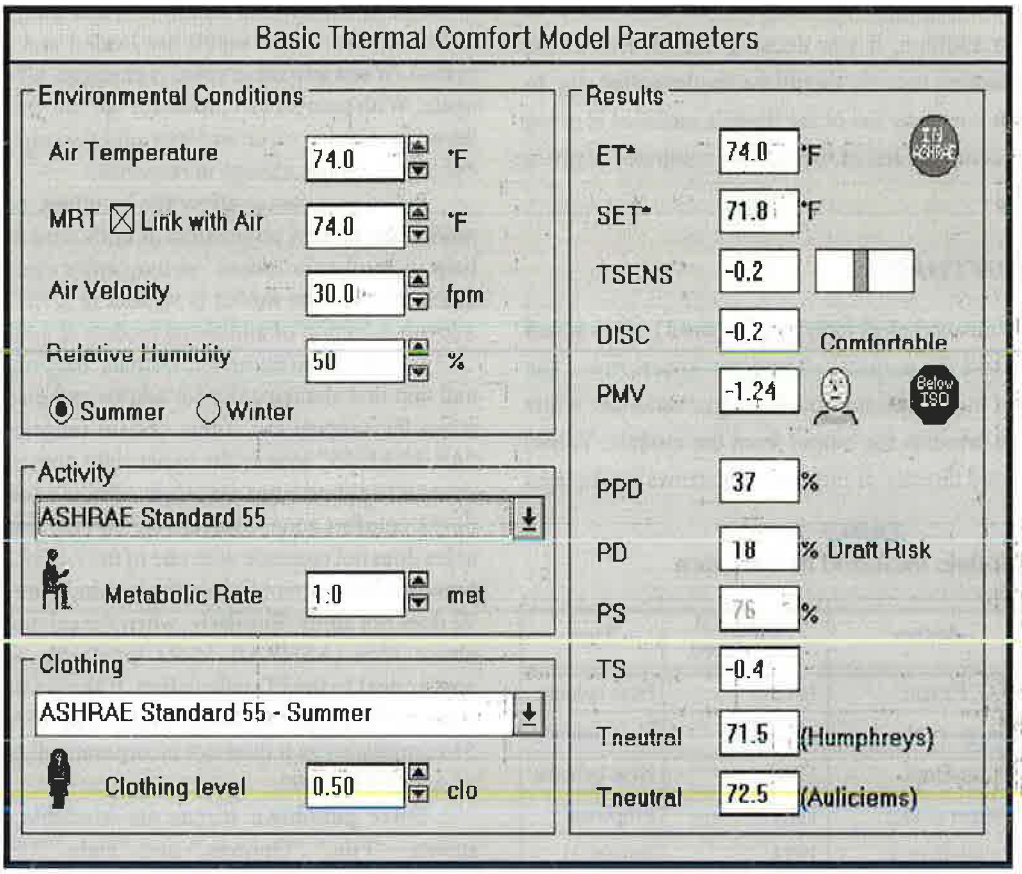

Figure 1 *Thermal comfort model user interface.*

Figure 2 *Toolbar.*

From left to right, the icons perform the following functions: (1) select an input file, (2) select an output file, (3) read a set of input data from the input file, (4) write the current run to the output file, (5) toggle all inputs and outputs between Fahrenheit and Celsius, (6) select type of humidity input, (7) invoke the clo calculator, (8) access the physiological variables, and (9) use the on-line help facility.

The humidity input window (Figure 3) shows the types of humidity input. Users can select from relative humidity, partial vapor pressure, dew point, wet bulb, or humidity ratio by clicking on the appropriate radio button. This feature allows easy comparison of design scenarios that have different control parameters.

The "clo calculator" (Figure 4) and the "globe calculator" are modules that pop up for specific computations. Clothing insulation is input to the heat balance models as a single number (clo) that combines all of the different articles of clothing on the body weighted by insulation value and area of skin surface covered. The clo calculator allows the user to compute a clo value for an ensemble of individual articles by selecting the articles individually. When all of the desired clothing items are selected, the user can give that specific ensemble a name and save it to the clothing library. Ensembles in the clothing library are available in the clo selection box on the main screen (Figure 1). The globe calculator allows determination of MRT based on a measurement of "globe temperature" for a globe thermometer of any size. Globe thermometers are a common method for determining MRT indoors, and the globe calculator simplifies the conversion of measured globe temperatures to MRT for field survey data.

Figure 3 *Humidity specification selection box.*

ENGINEERING APPLICATIONS

Engineering applications for the model are numerous. The model can be used to examine the relative trade-offs between

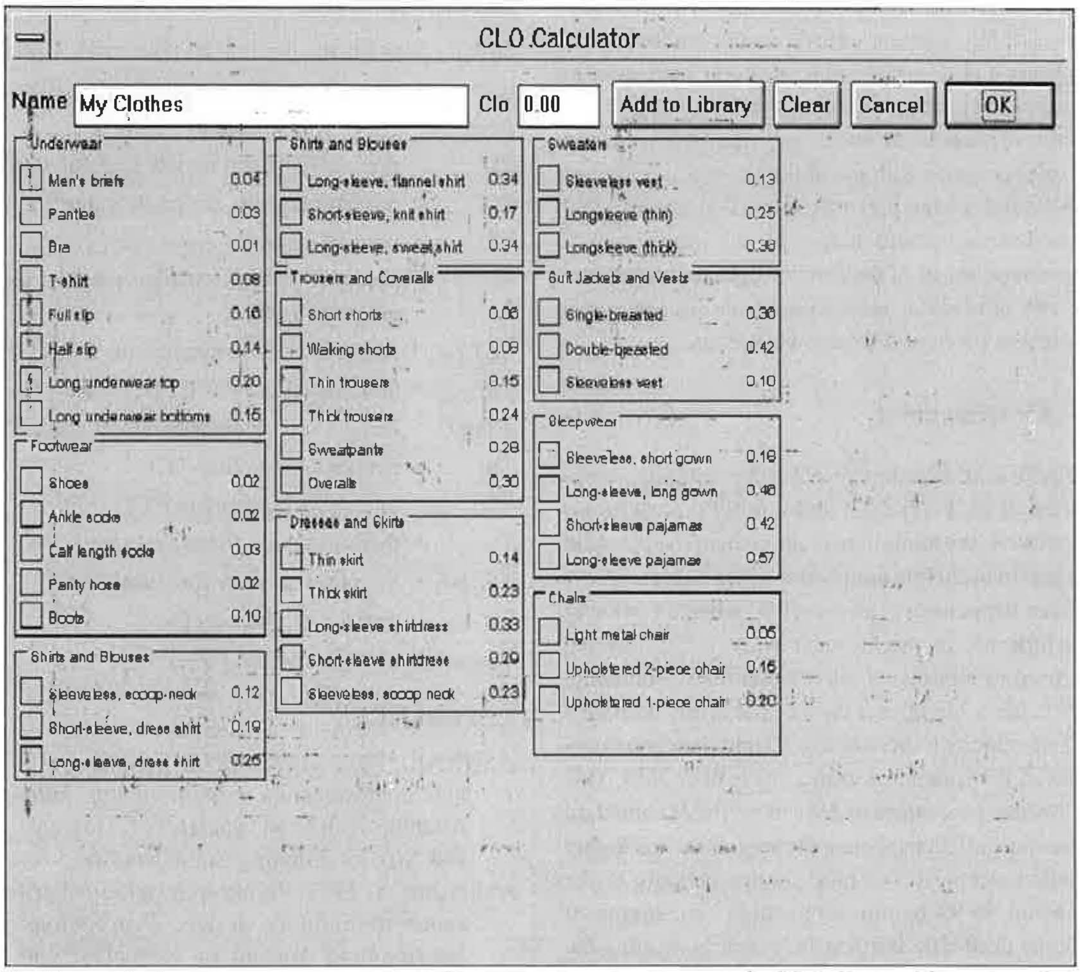

Figure 4 *Clothing calculator.*

various physical parameters; for example, an increase in relative humidity of 10% is predicted to be offset by a drop in air temperature of 0.5°F (0.28°C) using PMV-IH as a measure. This effect changes only slightly between 50% to 90% RH. Similarly, an increase in temperature of one degree is predicted to be offset by an increase in air movement of 12 fpm between 77°F (25°C) and 78°F (25.5°C), but this effect is extremely nonlinear—it takes more air movement (+20 fpm) to provide the equivalent cooling effect between 78°F (25.5°C) and 79°F (26.1°C). The model can also be used to determine the design deadband required to maintain comfort for groups of people performing certain activities. For example, with ASHRAE Standard 55 summer clothing (0.5) and office activity that includes walking about between workstations with little or no sitting (1.7 met), the temperature at which the most people will feel comfortable is predicted to be 70.5°F (21.3°C), the lower limit is 66.3°F (19.0°C), and the recommended upper limit (using PMV) is 74.7°F (23.7°C). But would that temperature range be suitable for people seated quietly at desks? For seated, quiet persons, the temperatures shift up to 75.0°F (23.8°C), 77.7 (25.3°C), and 80.4°F (26.8°C), respectively. Clearly, since the temperature ranges do not overlap, people performing these different activities cannot be comfortable in the same zone. By far the most interesting application is to use the program to model various scenarios that come up during design. We'll look at two common situations and see how the model can help inform design decisions.

Example 1

It's a cool winter day in the perimeter zone of a large office building. The setpoint of the zone is 71.5°F (21.9°C) and there is some radiant cooling occurring due to cold windows nearby (MRT = 68°F [20°C]). Air movement is low and relative humidity is 50%. A person sitting at a desk, occasionally getting up to walk around (1.1 met), dressed in a business suit (0.9 clo) feels slightly cool but comfortable according to PMV. If we decrease the clothing to underwear, long pants, and a long-sleeved shirt (about 0.65), or a full slip, a blouse, and a thick skirt (about 0.75), the person becomes very cold using both ASHRAE and ISO criteria. How much warmer would the temperature have to be in order to bring these more lightly clothed people into a state of thermal comfort? It turns out that we have to adjust the temperature upward nearly 5°F (2.8°C) to bring these people up to the lower boundary of the comfort zone and 7.5°F (4.2°C) to bring them to a state of thermal neutrality (neither hot nor cold).

This example shows the importance of clothing in determining thermal comfort and reveals how some dress codes can cause widespread discomfort. If the zone occupancy will encompass significant clothing variation, as in the example above, there are several options: (1) design a single-setpoint zone control system and assume that people will fight over the thermostat and use fans or heaters to make themselves comfortable, (2) separate the zone into smaller zones with the ability to produce at least five-degree (in the above example) differences between adjacent zones, (3) consider a task-conditioning approach where individuals control the environment of their own work area and design a system that can produce at least five-degree (in the above example) differences between adjacent work areas.

Example 2—Air Movement

Using the ASHRAE Standard 55-92 winter optimum operative temperature of 71°F (21.6°C) and a fairly typical turbulence intensity of 40%, the minimum air movement over the skin surface is assumed to be 20 fpm simply due to the thermal plume of the body. What happens to draft risk (PD) when air velocity is increased a little bit, as might occur when a fan-powered mixing box is used to improve air circulation rates? Naturally, diffuser selection has a big impact on whether drafts become a problem, but if air velocity is increased to 30 fpm (barely perceptible), the value of PD (predicted draft risk) is over 20%. This exceeds the allowable percentage of 15% in ASHRAE Standard 55-92. Does the same effect happen in the summer when higher space temperatures occur? If we raise the temperature to the ASHRAE Standard 55-92 optimum operative temperature of 76°F (24.4°C), the draft risk drops to 16%, nearly meeting the standard's percentage but not quite. If we assume that the increased air movement has a 20% turbulence intensity, we could raise the air velocity to 35 fpm but no higher without raising the air temperature.

On the other hand, in many parts of the U.S., summer temperatures indoors routinely exceed the ASHRAE Standard 55-92 optimum operative temperature of 76°F (24.4°C). For a space temperature of 78°F (25.5°C), the PS model predicts that air movement up to 65 fpm may be desired by 80% of the occupants for cooling.

CONCLUSIONS

ASHRAE recently sponsored a research project (RP-781) to select and prepare a thermal sensation model for use by the profession. A thermal sensation prediction tool has been developed as part of this project. This paper introduced the tool, described the tool's features, and presented examples of how HVAC engineers can use the tool in practice. The next step in the development of a design engineering tool is to graft comfort models onto a building energy simulation model (such as BLAST) that produces interior surface and space temperature. Establishing this linkage will allow greater feedback between system design and predicted environmental effects.

NOMENCLATURE

DISC = predicted discomfort vote (scale value)
ET* = new effective temperature (°C [°F])
p = vapor pressure (kPa)
PD = predicted percent dissatisfied due to draft (%)
PMV = predicted mean vote (scale value)
PPD = predicted percent dissatisfied (%)
PS = predicted percent satisfied with the level of air movement (%)
SET* = standard effective temperature (°C [°F])
Ta = air temperature (°C [°F])
Tmmo = mean monthly outdoor temperature (°C)
Tn = neutral temperature (°C)
Top = operative temperature (°C)
TS = thermal sensation vote (scale value)
TSENS = thermal sensation vote (scale value)
Tu = turbulence intensity (%)
v = air velocity (m/s)

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