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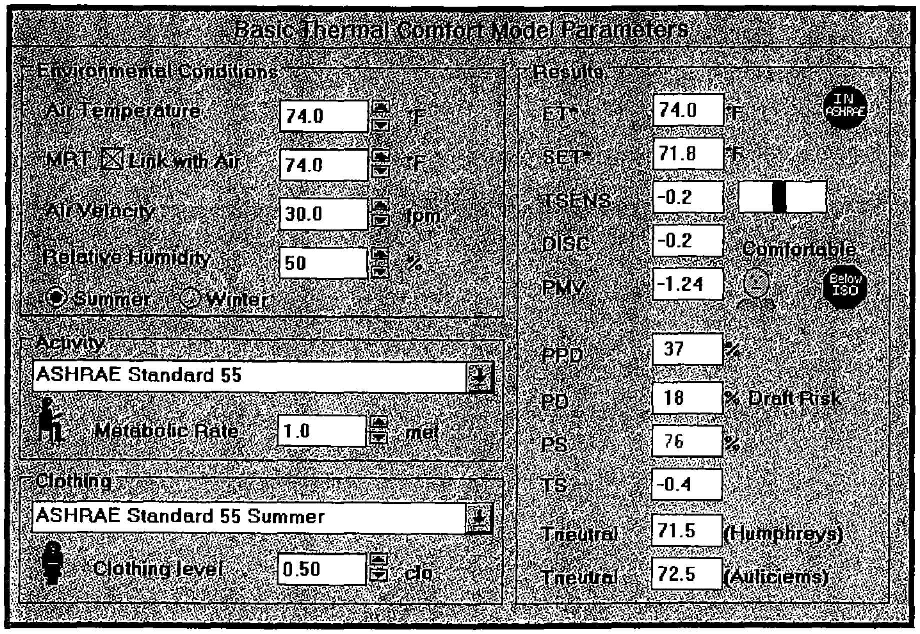

Figure 1: Users enter values on the main screen. When one value is changed, all other values are automatically adjusted. In addition to numerical outputs, the program uses icons that change color to indicate when the outputs are within certain ranges. For example, the ASHRAE 55 icon in the upper right corner turns blue, green or red when conditions are below, within, or above the comfort zone.

A Thermal Comfort Prediction Tool

By *Marc E. Fountain, Ph.D.; Charlie Huizenga*
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As part of a recent ASHRAE research project (RP-781), a thermal comfort prediction tool has been developed. This paper introduces the tool, describes the tool's features, and presents examples of how HVAC engineers can use the tool in practice.

Several computer models have been used over the past twenty years to predict thermal comfort and thermal sensation. Two of the most frequently applied models are: "2-Node"[2] and "PMV-PPD"[1]. In addition to these two models, there are over a dozen others that predict various aspects of thermal comfort including: draft risk, air movement preference, and thermal sensation as a function of outdoor temperature and/or climate.

> *Additional Information*
>
> The software described in the article is currently under review by ASHRAE for future release. To be put on the mailing list to receive information when this software becomes available, please circle #466 on the reader service card.

However, despite the availability and public-domain status of these models, they have received infrequent use outside the narrow scope of thermal comfort research. The reasons include 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.

ASHRAE recently sponsored a research project[3] to prepare thermal sensation prediction software for possible inclusion in *ASHRAE Standard 55, Thermal Environmental Conditions for Human Occupancy*[4]. 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 comfort prediction tool that resulted from the project is presented in this paper.

Brief Description of Models

There are eight models included in the tool, three heat-balance models,

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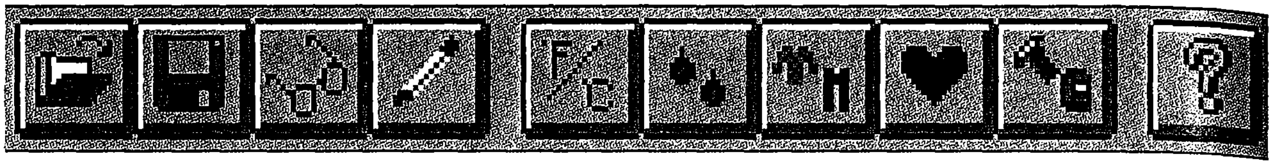

Figure 2: Frequently used commands from the pull-down menus are linked to icons in the toolbar.

three empirical models and two adaptive models. As defined here, heat balance models simulate the heat transfer process, empirical models provide a fit to data of sensation using physical parameters of the environment, and adaptive models are empirical models that account for outdoor climate.

2-Node, PMV-PPD, and a modified PMV (PMV-IH)[5] are considered heat-balance models, PD[6], PS[7], and TS[8] are empirical models, and Tn (Auliciems)[9] and Tn (Humphreys)[10] are adaptive models. The 2-Node model is the basis for the ET* boundaries on the ASHRAE 55-92 comfort zone while the PMV-PPD model is the basis for the recommended limits on thermal environments in the ISO thermal comfort standard, ISO 7730.

The 2-Node model produces a minute-by-minute simulation of the human thermoregulatory system for a user-specified time period. It represents the human body as two concentric cylinders, a core cylinder and a thin skin cylinder surrounding it with clothing evenly distributed over the skin surface. At time "zero," the cylinder is exposed to a uniform environment and the simulation begins allowing heat transfer between the core, skin, and environment.

For environments within the ASHRAE comfort zone with typical clothing and activity, the model generally reaches a steady-state heat balance within 60 minutes of exposure (60 iterations). The steady-state surface skin temperature and surface skin wettedness of the cylinder are used to calculate SET*, ET*, TSENS, DISC and other thermal indices.

PMV represents the "predicted mean vote" (on the thermal sensation scale) of a large population of people exposed to a certain environment. PMV is derived from the physics of heat transfer combined with an empirical fit to sensation. PMV establishes a thermal strain based on steady-state heat transfer between the body and the environment and assigns a comfort vote to that amount of strain. PPD is the "predicted percent of dissatisfied" people at each PMV. A modification to the way PMV treats the effect of humidity (PMV-IH) is also included in the tool as an optional calculation.

Three empirical models are also included in the software tool:

1) PD, or "predicted percent dissatisfied due to draft," a fit to data of persons expressing thermal discomfort due to drafts,

2) PS, a fit to data of comfortable persons choosing air velocity levels, and

3) TS, a fit to data of thermal sensation as a linear function of air temperature and partial vapor pressure.

Two adaptive models are provided that include the variations in outdoor climate for determining thermal preferences indoors. Auliciems' neutral temperature model fits sensation data based on field investigations of thermal comfort in Australia spanning several climates. Humphreys' neutral temperature equation is a fit to considerable data for climate-controlled and non-climate controlled buildings:

Different type of thermal comfort models require different levels of input detail to accomplish their predictive task. Heat balance models require information on the physical environment (air temperature, mean radiant temperature, air velocity, and humidity) and the person being modeled (metabolic activity and clothing).

In addition, heat transfer coefficients are either assumed or calculated, thermoregulatory control constants are invoked, and detailed relationships between physical, physiological, and psychological processes are utilized.

In contrast, empirical models rely on a simple relationship between two or more variables that dominate the phenomena. Draft risk, for example, is predicted solely by an algebraic relationship between air temperature, air velocity, and turbulence intensity.

While the heat balance models change with even slight alterations of almost any input variable, the empirical and adaptive models respond only to changes in their respective subset of inputs.

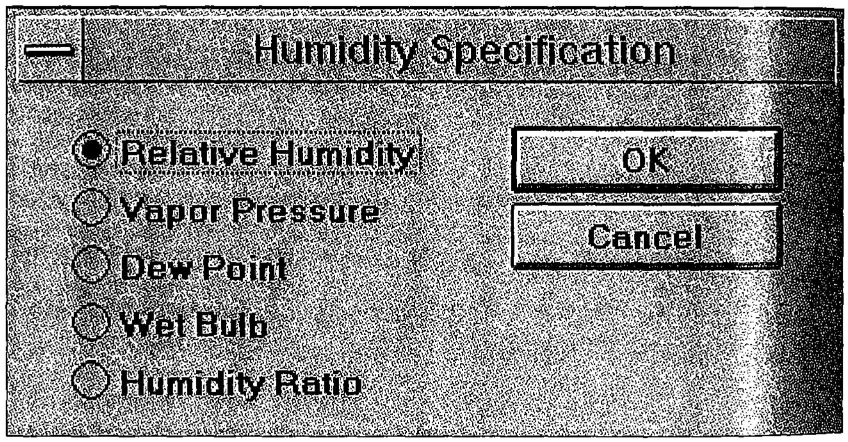

Figure 3: The humidity input window lets users select between relative humidity, partial vapor pressure, dewpoint, wetbulb, or humidity ratio.

Using the Tool

Users adjust input values and outputs are updated in real-time on the main screen (*Figure 1*). The right hand side of the screen controls the input variables while the left hand side presents the output from the models. Values can be either 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 run. 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.

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 model to show ASHRAE standard compliance as not all of the requirements of ASHRAE 55-92 are incorporated in this tool. For example, many of the comfort requirements in ASHRAE 55-92 are based on operative temperature and no explicit calculation of operative temperature is provided in this tool. Operative temperature can be estimated by averaging the air temperature and mean radiant temperature calculated by the model but is not explicitly presented on the screen.

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. "Help" runs the on-line help.

Frequently used commands from the pull-down menus are linked to icons in the toolbar (*Figure 2*). 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. User's can select between relative humidity, partial vapor pressure, dewpoint, wetbulb, or humidity ratio by

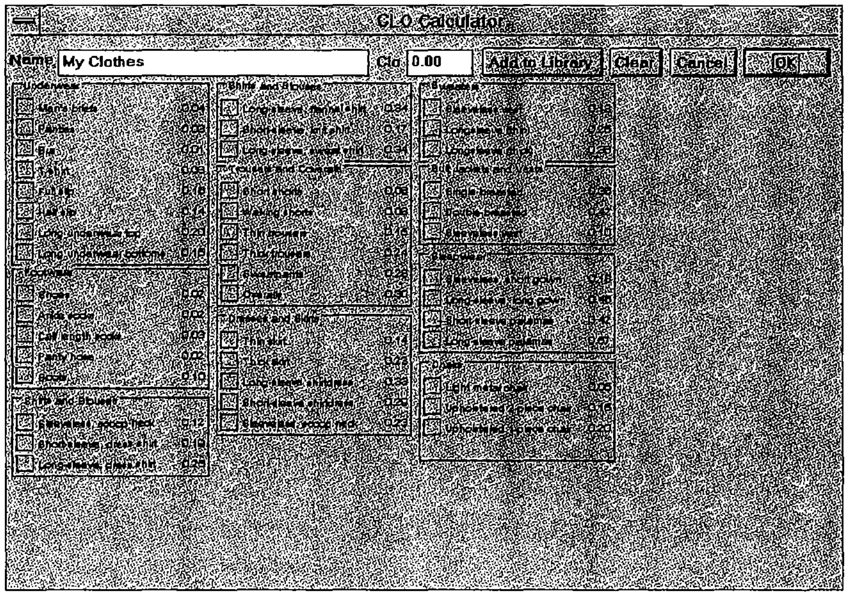

Figure 4: The 'clo calculator' and the 'globe calculator' (not shown) are modules that pop-up for specific computations. The clo calculator allows the user to compute a clo value for a clothing ensemble or by selecting each item of clothing individually.

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" (not shown) are modules that pop-up for specific computations. Clothing insulation is input to the heat balance model's 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 any sized globe thermometer. 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.

Engineering Applications

Engineering applications for the tool are numerous.

One application for the tool is examining the relative tradeoffs between 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* using PMV-IH as a measure. This effect is 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 and 78°F but this effect is extremely non-linear - it takes more air movement (+20 fpm) to provide the equivalent cooling effect between 78 and 79°F.

Another application for the tool is determining the design deadband required to maintain comfort for groups of people performing a 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. The lower limit is 66.3°F. and the recommended upper limit (using PMV) is 74.7°F. But would that temperature range be suitable for people seated quietly at desks? For seated quiet persons, the temperatures shift up to 75.0, 77.7, and 80.4°F respectively. Clearly, since the temperature ranges do not overlap, people performing these different activities cannot be comfortable in the same zone.

Finally, the tool is useful for modeling various scenarios that come up during design. We'll look at two common situ-

* *To obtain celsius -- °C=(°F-32)/1.8*

ations and see how the comfort models 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 and there is some radiant cooling occurring due to cold windows nearby (MRT = 68°F). 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 upwards nearly 5° F to bring these people up to the lower boundary of the comfort zone and 7.5°F 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 such 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 5 deg. (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 5°F (in the above example) differences between adjacent work areas.

Example #2: Air movement. Using the ASHRAE 55-92 winter optimum operative temperature of 71°F, 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 in ASHRAE 55-92 of 15%.

Does the same effect happen in the summer when higher space temperatures occur? If we raise the temperature to the ASHRAE 55-92 optimum operative temperature of 76°F, the draft risk drops to 16%, nearly meeting the standard 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.

The next step in the development of a true design and engineering tool is to graft a comfort model (such as one of the models incorporated in the tool presented here) onto a building energy simulation model that produces interior surface and space temperatures. Establishing this linkage will allow greater feedback between system design and predicted environmental effects.

On the other hand, in many parts of the U.S., summer temperatures indoors routinely exceed the ASHRAE 55-92 optimum operative temperature of 76°F. For a space temperature of 78°F, 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 comfort 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 true design and engineering tool is to graft a comfort model (such as one of the models incorporated in the tool presented here) onto a building energy simulation model that produces interior surface and space temperatures. Establishing this linkage will allow greater feedback between system design and predicted environmental effects. ■

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