Title
A Thermal Sensation Model For Use By The Engineering Profession

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A THERMAL SENSATION MODEL FOR USE BY THE ENGINEERING PROFESSION.

Results of Cooperative Research Between The American Society of Heating, Refrigeration, and Air-Conditioning Engineers, Inc. and Environmental Analytics

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EXECUTIVE SUMMARY

ASHRAE has funded a research project entitled, “Selecting and Preparing a Thermal Sensation Model for Use by the Profession.” This report describes how the model was developed and introduces a Windows™ software package that was developed during the course of this project. The software is straightforward and simple for professionals and researchers to use. A point-and-click interface allows easy adjustment of individual environmental paramenters with real-time updating of predicted sensation values.

Prediction of thermal sensation indoors has been an objective of ASHRAE since the early 1920’s.

Knowing how thermal environments affect human beings in buildings is important for HVAC engineers .

Thermal sensation models are tools that can accomplish the objective of predicting how people feel (thermally) indoors.

Several thermal sensation models have been developed and one of the primary objectives of this project was to select the models for inclusion in ASHRAE Standard 55, the thermal comfort standard. PMV developed by P.O. Fanger in Denmark has been incorporated as well as ET* created by Pharo Gagge at the John B. Pierce Foundation in the U.S.

BACKGROUND

Many state-of-the-art thermal sensation models arise from research conducted since the turn of the century at Kansas State University, the John B. Pierce Foundation, and the Technical University of Denmark. Out of this enormous body of work, two thermal comfort prediction methods, Fanger's PMV-PPD and Gagge's ET*-TSENS, have been most widely used. These models predict the thermal comfort (including but not limited to thermal sensation) of humans for steady-state conditions in homogenous physical environments. The International Standards Organization (ISO) has adopted the PMV-PPD model in its thermal comfort standard 7730 (ISO 1984) while ASHRAE uses ET* to define the boundaries of the comfort zone in its thermal comfort standard 55 (ASHRAE 1992).

Both PMV-PPD and ET*-TSENS can be generated by computer models that solve heat-balance equations for the human body. These models are in the public domain and available to professionals by request from any of several different sources. However, the lack of a user-friendly "front-end" and a manual to explain each of the models' limitations wards off many potential users. Incorporating existing thermal comfort models into a package with a user-friendly interface and providing a manual to make thermal comfort models more easily accessible to professionals was the goal of this project.

Physiologically-based thermal sensation models

Of eight existing "state-of-the-art" thermal sensation models (described below) that potentially could be included in the final "ASHRAE" thermal sensation software package, only half met several important criteria for this project.

1) Straightforward to explain, document and use.
2) Exist in computer code or can easily be coded
3) Are applicable to the problem posed, i.e. determining <u>thermal sensation</u> at a point in space

The eight indoor thermal comfort models that were identified for this project are listed below. First, a definition: 1) An indoor 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.

TABLE 1

Date	Author	Description
1964	Wissler	225-node finite element model
1967	Fanger	PMV steady state model
1970	Stolwijk	25-node basic heat flow model

1986*	Gagge	2-node basic heat flow model
1990	de Dear	40-layer finite difference skin model
1991	Int-hout	Modified PMV
1992	Jones	2-node with transient response
1992	Tanabe	Modified Stolwijk model

*most recent iteration; many have been released over the years beginning in 1970. Also includes KSU model which is very similar.

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 evapo-transpiration. 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 degrees Celsius. All the physiological models listed above except for Fanger's PMV-PPD use initial values for physiological constants and physiological variables, and then iterate for a variable, 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. The thermal comfort models listed above frequently yield very different results, especially away from thermally neutral conditions.

Fanger’s PMV-PPD is also physiologically based but instead of iterating for a specific exposure period, the exposure period is fixed and the iteration determines clothing surface temperature and the convective heat transfer coefficient in the Fanger Comfort Equation. The equation uses a steady-state heat balance for the human body and postulates a link between the deviation from the minimum load on heat balance effector mechanisms, e.g sweating, vaso-constriction, vaso-dialation, and thermal comfort vote. The greater the load, the more the comfort vote deviates from zero.

All physiologically-based 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 evapo-transpiration. 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 as best it can to maintain the body's core temperature at a setpoint of 37 degrees Celsius. All the models above except for Fanger's PMV-PPD use initial setpoints for physiological constants and physiological variables, and then iterate for a variable, 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. The thermal comfort models discussed frequently yield very different results, especially away from thermally neutral conditions.

The following table provides a list of possible model inputs, constants, and outputs. All models need the complete input set, but no model uses or produces all of the constants or outputs.

Model Inputs:

Physical Variables	**Subject Variables**
Air Temperature	Body Weight
Air Velocity	Body Surface Area
Mean Radiant Temperature	Metabolic Rate
Relative Humidity	Clothing Insulation

Model Constants:

Reference Skin Temperature
Reference Core Temperature
Sweating Constant
Vaso Constriction Constant
Maximum Skin Blood Flow
Maximum Sweating Rate
Area factor due to clothing
Maximum evaporation efficiency
Effectiveness of clothing mass transfer

Model Outputs:

Physiological Variables	**Psychological Variables**
Core temperature	DISC
Skin temperature	TSENS
Skin Wettedness	PMV
Skin to Total Mass Ratio	PMV*
Skin Blood Flow	PPD
Total Skin Evaporative Heat Loss	PMV-ET

Rationally Derived Indices:

Operative Temperature
Humid Operative temperature
Standard Operative temperature
Standard Humid Operative Temperature
Effective temperature
New Effective temperature
Corrected Effective temperature
Standard Effective temperature
New Standard Effective Temperature
Modified Temperature
Equivalent temperature

Resultant Temperature
Index Temperature
Heat Stress Index

DESCRIPTION OF MODELS:

Wissler's 225-Node Model:

Wissler has produced a number of models for a wide-range of environments. One that fits the description of "indoor" is the 225-node model developed in 1964 (Wissler 1964). In this model the body is divided into 15 sections, the head, thorax, abdomen, upper and lower arms and legs, hands, and feet. Each section has 5 layers composed of tissue, bone, viscera, fat and skin. Each layer has three vascular subsystems representing arteries, veins and capillaries; and each layer has its own metabolic heat generation. Beginning with the first law of thermodynamics stated as the heat conduction equation, Wissler formulates the heat and mass transfer relationship for each individual element of the 225-node model and uses finite-different techniques to solve for tissue and blood temperatures of the surrounding elements. Those temperatures in turn generate new heat and mass flows for computing new temperatures with each time-step. The model predicts transient conditions, using smaller time-steps when necessary, and allowing heat transfer between arteries and veins. Wissler decries "core and shell" models as containing "a relatively small amount of information," and observes that although the relative volumes in a "core and shell" model depend on peripheral blood circulation, existing models do not allow this adjustment.

Paradoxically, Wissler's 225-node model is not only the most complex, but also the earliest developed. The reason newer models for comfort are simpler is that Wissler's model exists entirely within the physiological realm. Its complexity is justified by the lack of a necessary link to sensation. In Wissler's world, physiological precision is ultimate goal. If Wissler had attempted to generate predictions of sensation near or within the comfort zone, he might have reached the conclusion that using more than two nodes is not justified in light of inaccuracies in sensation prediction. Wissler states that this 225-node model represents the limit of accuracy justified by available physiological experimental data, e.g. rates veneous/arterial heat transfer.

Fanger's PMV:

Fanger's equation for thermal is a steady-state model. It is an empirical equation for predicting the mean vote on a ordinal category rating scale of thermal comfort of a population of people. The equation uses a steady-state heat balance for the human body and postulates a link between the deviation from the minimum load on heat balance effector mechanisms, e.g sweating, vaso-constriction, vaso-dialation, and thermal comfort vote. The greater the load, the more the comfort vote deviates from zero. Fanger estimated the partial derivative of the load function by exposing enough people to enough different conditions to fit a curve. PMV (Predicted Mean Vote), as the integrated partial derivative is now known, is arguably the most widely used thermal comfort index today. The ISO (International Standards Organization) Standard 7730 (ISO 1984), "Moderate

Thermal Environments -- Determination of the PMV and PPD Indices and Specification of the Conditions for Thermal Comfort," uses limits on PMV as an explicit definition of the comfort zone.

Fanger begins his analysis with the statement that his comfort equation will only apply to humans exposed for a long period to constant conditions at a constant metabolic rate. Under this assumption, conservation of energy must apply or the person will die. The heat balance equation is:

H-Ed-Esw-Ere-L=R+C

Where:
H = internal heat production
Ed = heat loss due to water vapor diffusion through the skin
Esw = heat loss due to sweating
Ere = latent heat loss due to respiration
L = dry respiration heat loss
R = heat loss by radiation from the surface of the clothed body
C = heat loss by convection from the surface of the clothed body

Fanger expands the equation by substituting each component with a function derivable from basic physics. All of the functions have measurable values with exception of clothing surface temperature and the convective heat transfer coefficient which are functions of each other. To solve the equation, an initial value of clothing temperature must be estimated, the convective heat transfer coefficient computed, a new clothing temperature calculated etc., by iteration until both are known to a satisfactory degree. Using results from numerous climate chamber experiments, Fanger concluded that satisfaction of the heat balance equation, or Comfort Equation, is required for optimal comfort. He produced the widely used Fanger Comfort Charts, each presenting a combination of conditions satisfying the Comfort Equation.

Now let us assume the body is not in balance and write the heat equation as:

L = H-Ed-Esw-Ere-L-R-C,

where L is the thermal load on the body.

Define thermal strain or sensation, Y, as some unknown function of L and metabolic rate. Holding all variables constant except air temperature and metabolic rate, Fanger uses mean votes from climate chamber experiments to write Y as function of air temperature for several activity levels. Then substituting L for air temperature, determined from the heat balance equation above, Fanger evaluates the partial derivative of Y with respect to L at Y=0 and plots the points versus metabolic rate. An exponential curve is fit to the points and integrated with respect to L. L is simply renamed "PMV" and we have (in simplified form):

PMV = exp[met]*L.
Where:
L=F(Pa,Ta,Tmrt,Tcl)

PMV is "scaled" to predict thermal sensation votes on a seven point scale (hot,warm, slightly warm, neutral, slightly cool, cool, cold) by virtue of the fact that for each physical condition, Y is the mean vote of all subjects exposed to that condition. The major limitation of the PMV model is the explicit constraint of skin temperature and evaporative heat loss to values for comfort and "neutral" sensation at a given activity level.

Stolwijk's 25-Node Model:

Stolwijk divides the body into six segments, each with four layers and a central blood compartment to link the segments together for a total of 25 nodes. The segments represent the heat capacitance of the head, trunk, arms, hands, legs and feet each with its own metabolic heat generation. Each segment has core, muscle, fat, and skin compartments or layers. Heat exchange occurs through conduction to adjacent layers and convective heat transfer via the blood. The skin layer is also subject to convective and conductive heat transfers and shares the total evaporative losses with the basal compartments of the trunk and head. Before iteration begins, the model's physiological parameters for vaso-dialation and skin blood flow etc. are set to default "neutral" values. The first step of the model is to determine thermoreceptor signals by taking the difference between the compartment setpoint and its current temperature. If there is a temperature difference, the appropriate nature and magnitude of thermoreceptor signals is calculated and the resulting effects are incurred on compartment-specific basis (that is, segment-by-segment and layer-by-layer). The range of effects includes sweating, vasodialation, vasoconstriction, and shivering depending on the compartment. When any of these four effects occurs, heat flows between compartments; how **much** heat depends on the integration time-step. Stolwijk sets a limit of 0.1 degrees Celsius as a maximum temperature step per iteration and the time-step is adjusted accordingly. Final output of the model is the temperature of any compartment, total heat loss or production, and mean body temperature. The weak points of this model are inaccuracies in the coefficients that regulate heat flow between compartments and also the thermoregulatory controller itself.

Gagge 2-Node Model:

The Gagge 2-node model was introduced in 1970 (Gagge, Stolwijk, and Nishi, 1970) specifically to formulate a new effective temperature scale. The purpose was to determine particular combinations of physical conditions producing equal physiological strain. Backed by extensive data from climate chamber experiments, Gagge claimed that while skin temperature is a good indicator of sensation in cold environments, skin wettedness is a better indicator in warm environments where sweating occurs because skin temperature changes are small by comparison. His model represents the human body as two concentric cylinders, a core cylinder and a thin skin cylinder surrounding it. Clothing and sweat are assumed to be evenly distributed over the skin surface. At time "zero", the cylinder is exposed to a uniform environment, and the model produces a minute-by-minute simulation of the human thermoregulatory system. After the user-specifed time period is reached, the final surface temperature and surface skin wettedness of the cylinder are used to calculate a standard effective temperature (SET*). SET* numerically represents the thermal strain experienced by the cylinder relative to a "standard" person in a "standard" environment. SET* has the advantage of allowing thermal comparisons between environments at any combination of the physical input variables, but the disadvantage of also requiring "standard" people.

The Gagge model uses the same thermoregulatory system and controls as the Stolwijk model but takes the extra step of predicting sensation. Based on a laboratory study with a large number of subjects, Gagge developed empirical functions between two comfort indices, and skin temperature and skin wettedness. These functions (both linear) are used in the 2-Node model to produce predicted values of the votes of populations exposed to the same conditions as the cylinder. TSENS, the first index, represents the model's prediction of a vote on the seven point thermal sensation scale. DISC, the second index, predicts a vote on a scale of thermal **discomfort**:

DISC:
Intolerable
Very uncomfortable
Uncomfortable
Slightly uncomfortable
Comfortable

The 2-Node model has undergone many iterations and refinements. In Gagge's most recent iteration, he defines a new temperature index, PMV*, that incorporates skin wettedness into Fanger's PMV equation using SET* or ET* to characterize the environment. Researcher's at Kansas State University produced a 2-Node model that avoids the SET* restrictions on "standard" people by calculating TSENS directly from physiological strain instead of converting to SET*.

de Dear's transient skin model:

Richard de Dear points out that a human's instantaneous response to thermal changes in the environment must be driven solely by cutaneous thermoreceptors (de Dear, 1990). Thermal transients propagate too slowly in the human body to allow sub-cutaneous receptors to respond in the required time-frame (seconds).

Most multi-node physiological models, e.g. Gagge (1986), are referred to as "transient" since they model conditions changing over time (minutes or hours) as opposed to steady-state conditions. But in general these models cannot predict thermal sensation responses to very rapid changes in physical conditions often experienced by humans. de Dear suggests that a verifiable transient model of thermal sensation capable of responding in seconds can be constructed from representation of neural thermoreceptors coupled to a numerical model of heat transfer through clothing and skin layers.

Prior constructing a transient model, de Dear collected climate chamber data on human subjects using a factorial design of temperature up-steps and down-steps. Subjects were exposed to temperatures between 17.7 and 29.6 degrees Celsius in two side-by-side climate chambers. The chambers differed in temperature by several degrees for each experiment and subjects stepped between chambers when instructed. de Dear's key results with respect to the model generation were: 1) instantaneous thermal sensation closely matched final steady state response for temperature up-steps, and 2) instantaneous response to temperature down-steps was greater than to up-steps and over-predicted final steady state response.

To construct his model, de Dear represents thermoreceptor response as a linear function of the temperature of the receptor and it's partial derivative with respect to time. The thermoreceptor outputs are scaled in impulses per second and vary with depth below the surface of the skin with the cold receptors being nearer the surface than the warm receptors. At time "zero", a temperature ramp is applied to the surface and is propagated below the surface using standard finite difference heat diffusion techniques. As the temperature wave travels into the body, the thermoreceptor outputs are monitored for peak discharge frequency, cumulative impulses, and mean discharge frequency. When the model was tested using the same conditions as in the human subjects transient sensation experiments, the correlation between impulses per second from the model and thermal sensation votes from the subjects was very high. Furthermore, the cold response was greater than the warm response by exactly the amount indicated in the subject experiments due to the difference in depth of warm vs. cold receptors in the skin. This fortuitous result contributes greatly to the parsimonious appeal of this model.

Int-Hout's Model:

This model isn't really a “new” model at all, but an attempt to Fanger and Gagge models, both of which receive widespread use but yield markedly different results. Int-Hout constructed a model using parts of both the Fanger and Gagge models. Essentially, Int-hout added two types of accommodation for humidity variations to the Fanger PMV model. First he modifies the heat loss through the skin to account for the vapor resistance of clothing, and second he uses the difference between ET* and skin temperature for calculating L, the thermal load, instead of the difference between air temperature and clothing surface temperature that the PMV model uses. Int-hout now feels that Tsk should be changed back to Tcl but the that the switch from Ta to ET* should be retained. Further examination of Int-Hout's computer code also reveals that latent heat-loss due to sweating is triggered only by metabolic rate, regardless of ET*, a situation that should be investigated during this research project.

Byron Jones' transient 2-Node model:
Dr. Jones begins with the basic Gagge 2-Node model and after making some modifications, interfaces it with a transient model of heat and moisture transfer through clothing (Jones and Ogawa, 1992). The 2-Node modification concerns accounting for the energy shift between core and skin that occurs when blood is pumped around the body. When blood flow increases, the skin gains an additional fraction of the total body mass and hence and additional fraction of the body's internal energy. For long-term steady state conditions this isn't important because it is small compared to other heat flows, but for transients, it might be significant. Unfortunately, adding this term to the heat equation makes it very difficult to solve. The second modification alters the rate of heat transfer between skin and core. While Gagge allows the transfer to occur instantaneously, Jones adds a time delay that has the added benefit of allowing analytical solutions to the equations resulting from his first modification. Finally, Jones divides the skin layer into segments so he can vary clothing, skin temperature, sweat rate, and total heat loss over the body's surface and two benefits result. The first is that skin wettedness can be abandoned as a concept in favor of skin-surface vapor pressure. Skin wettedness (percentage of skin completely covered in a layer of moisture) is unrealistic because clothing over wet skin is always saturated while clothing over dry skin is totally dry, clearly not true in the real world. Using the segmented skin model, different segments can sweat at different rates and evaporative heat loss is calculated from the skin surface vapor pressure on a segment-by-segment basis. The second benefit to dividing the skin is that modelling heat and moisture transfer through clothing also becomes straightforward. Using the 2-Node regulatory sweat rate for a given instant in time, heat and moisture transfer are calculated for each segment. The transient nature of the model is provided simply by adjusting the time-step for reevaluating the heat and moisture transfer downward (to fractions of a second) directly with the magnitude of the transient. Although the Jones model is unverified, i.e. untested against human subject data, he claims the model predictions follow intuition and will be soon validated.

Tanabe's Non-Uniform Modified Stolwijk Model:
A modified version of the Stolwijk 25-Node model has been recently completed by Shin-ichi Tanabe (Tanabe 1992). Tanabe's new model computes the mean thermal sensation predicted when the hypothetical human is in an environment with up to three different temperatures as might be experienced in a stratified

workspace. Tanabe's approach was to view the Stolwijk model as essentially robust, only in need of fine tuning. Using the 1971 NASA version of Stolwijk's model as a starting point, he adjusted several heat transfer coefficients, initial values, and altered the thermoreceptor controller. In particular, Stolwijk used an initial value for skin wettedness before the onset of sweating of approximately 3%; Tanabe claims 6% is more realistic. He measured the surface temperature distribution of a segmented, heated mannikin for a variety of physical conditions in a climate chamber to refine the initial values for skin temperature. The time-constant for thermoreceptor response is set to zero in Stolwijk's version. Tanabe uses a non-zero value and suggests that eventually it would be desireable to attach de Dear's transient response function (discussed above) as a front-end filter, an option that could be available on the “detailed anlaysis” level of the software package.

Empirical comfort models

There is another class of thermal comfort models that have been developed over the past twenty years and although they do not specifically predict thermal sensation at a point in space, they can be of substantial use in predicting thermal comfort. Four of these models are listed in Table 2 and X have been included in the software package.

TABLE 2

1976	Humphreys	Neutral temperature model
1983	Auliciems	Neutral temperature model
1988	Fanger	PD, draft prediction model
1993	Fountain	PS, air movement preference model
1994	Humphreys + Nicol	?????

These models are empirical, that is, they are expressed as equations that represent a fit to data. No simulation of physiological processes is used for the predictions. Humphreys model is a fit to over 100,000 observations of thermal comfort that relates neutral temperature to mean indoor air temperature. Auliciems finds that neutral temperature is also closely related to mean monthly outdoor temperature. Fanger’s PD model predicts the percent of persons that will feel a draft when exposed to specific combinations of air temperature, air velocity and air turbulence. Fountain’s PS model predicts the percent of persons that will be satisfied by specific combinations of air temperature and locally-controlled air velocity.

The two models that relate neutral temperatures to air temperatures are useful because they incorporate data from a wide range of climates. In contrast, the physiological models discussed in the previous section quickly become unreliable when applied to physical environments that deviate from the center of the comfort zone. The two models that predict air-movement-related comfort are important because air movement is of increasing importance as it impacts building design for energy-conservation and perceived indoor air quality.

METHOD

Model selection:

Four thermal sensation models (listed in Table 1) were incorporated in the software package.

Model Preparation

The objective was to select and prepare a thermal sensation model for use by the profession. PMV-PPD, ET*-TSENS, and other indices were be included. A special publication (with software) has been produced that facilitates the use of thermal sensation models by the profession. The software includes an interactive front-end that allows a professional to estimate the predicted thermal sensation at a location in space.

The model includes:

1) Fanger's PMV
2) Fanger's PPD
3) Fanger's PD (predicted percent dissatisfied due to draft)
4) Gagge's ET*
5) Gagges TSENS

This model is not a "design tool" for determining thermal sensation in any specific building. No effort has been made to prescribe measurement methods, measurement accuracy, HVAC system type, internal and external heat loads etc., that such a “design-tool” will requires, rather the scope is limited to:

1) Producing a comprehensive manual describing how the state-of-the-art in thermal comfort models are applied in rapid and easy manner.

and

2) Developing a piece of software with an interactive front-end that allows prediction of thermal sensation using input in both SI and IP units.

DESCRIPTION OF SOFTWARE PACKAGE

User interface:
The user interface is interactive, allowing input from either keyboard or file. The screen presentation is as follows:

Documentation
The documentation manual (special publication attached as Appendix A) includes the following sections:

Quick start
Why do we do thermal comfort modeling?
Description of models included in this package
Installing the software
How to run a simple analysis
How to run a detailed aanalysis
Limitations of the models
Three examples
Parametric analyses
What to do if the program crashes
Additional reading

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HELP

This help file introduces the program, gets you started quickly, provides help on program operation, help on thermal comfort in general, and help on interpreting your output.

Click the left mouse button on a topic to get help. Green underlined items throughout the file are linked to additional help topics. If you don't immediately see help on the topic you want, use the scroll bar on the right to scroll down to the topic. Items highlighted in fuschia are detailed topic explanations, not links to other topics.

Introduction
Quick Start
Program Help
Thermal Comfort Help
Interpreting Your Output
Sample Runs
Parametrics

Introduction

This program was developed by Environmental Analytics (Berkeley, CA) for The American Society of Heating, Refrigeration, and Air-Conditioning Engineers (ASHRAE) under RP-781.

The program predicts human thermal response to the environment using several thermal comfort models, including PMV-PPD, ET*-DISC. This software allows you to calculate the predicted thermal comfort for a human at a point in space. All you need to run the program is a few things about the thermal environment you want to model and a few things about the person you want to put in that environment.

Quick Start

In the upper left corner of the screen you'll find four boxes with up/down arrows beside them. Clicking the left mouse button on the up/down arrow changes the value in the box.

Input Variables
Air temperature
Mean radiant temperature (MRT)
Air velocity
Relative humidity
Activity
Clothing

Try adjusting these values and see what happens to the output side (right side) of the screen.

Program Help
Thermal Comfort Help

Environmental Conditions

Air Temperature

Air Temperature is also referred to as Dry Bulb Temperature. Air Temperature is typically measured with a mercury thermometer, thermistor, or thermocouple, inside a shield. The shield prevents an offset of the measurement due to radiation.

Mean Radiant Temperature (MRT)

MRT is the uniform temperature of an imaginary enclosure in which an occupant would exchange the same amount of radiant heat as in the actual environment. MRT is used to calculate the radiant heat exchange between the body and the environment. MRT can be calculated from measurements of Air Temperature, Globe Temperature, and Air Velocity.

Air Velocity

Air Velocity is the speed at which air moves from point-to-point. For thermal comfort, we are concerned with air velocity from any direction so we generally use an omni-directional anemometer. Air velocity is used to calculate convective heat transfer.

Relative Humidity

Relative humidity is the amount of water in air relative to the maximum amount of water that air can hold at that temperature. We use Relative Humidity to calculate latent heat transfer. You can also input dewpoint temperature, partial pressure, wet bulb temperature, or humidity ratio.

Personal Conditions

Personal Conditions

Activity

Heat is generated in the body by the metabolic functioning of muscles and other internal organs. Metabolic heat must be released at the rate it is generated or the body temperature will rise. The rate at which metabolic heat is expressed in watts per square meter of skin surface area and is called "metabolic rate". A special unit called the "met" is defined to be 58.2 watts per square meter. Metabolic rate is raised if the body's activity increases.

Metabolic rates for common activities (Met units followed by watts per square meter)

	Met	Watts per square meter
sleeping	0.7	40.7
sitting quietly	1.0	58.2
sitting and typing	1.1	64.0
sitting and filing	1.2	69.8
standing	1.2	69.8
standing and filing	1.4	81.5
walking	1.7	98.9
lifting and packing	2.1	122.2
running	3.0	174.6

Elevated metabolic rate can also result in decreased effective clo value and increased relative air velocity (as air is pumped through clothing). One relationship that has been proposed for increased air velocity (but not yet included in this software) is Vnew=Vactual+0.3(Met-1) for Met>1.

Clothing

Clothing is the insulation that keeps metabolic heat trapped near your skin. For this model, clothing insulation is expressed in terms of clo units. The clo unit is an index that combines the effect of all the different items you wear into one number.

Clo values for common clothing ensembles (Clo units)

walking shorts, briefs, shoes, socks, and a short-sleeved shirt	0.36
knee-length skirt, short-sleeved blouse, panty hose and sandals	0.54
pants, underwear, shoes, socks and a short-sleeved shirt	0.57
lightweight business suit with jacket	0.96

The model includes a clo calculator to allow you to check off individual items of clothing and include them in an ensemble.

Program Help

On the left side of your screen you'll find a box labeled Environmental Conditions and below that you'll see Personal Conditions labeled "Activity" and "Clothing". Clicking the left mouse button on the up/down arrows changes the value in the box. You can change:

Input variables
- Air temperature
- Mean radiant temperature
- Air velocity
- Relative humidity
- Activity
- Clothing

Other topics
- Interpreting your output
- Program commands
- Detailed model input
- Physiological inputs

Thermal Comfort Help

Thermal comfort defined
Thermal comfort has been defined in various ways as comfort standards have evolved. The most recent, widely used definition is "Thermal comfort is that condition of mind that expresses satisfaction with the thermal environment." Other definitions include "Thermal comfort is the lack of discomfort", and "Thermal comfort is the state of mind where you don't know whether you want to be warmer or cooler". This last statement is now used as a definition of "thermal neutrality". In the past, thermal neutrality and thermal comfort were considered the same thing. More recently, thermal neutrality and thermal comfort have been disassociated to some degree.

Thermal comfort terms and definitions
Thermal comfort models
Thermal comfort scales

Who needs thermal comfort?
Thermal comfort is, in addition to ventilation of air pollutants, the product that an HVAC system delivers to building occupants. Thermal comfort can also be achieved in many cases with an architectural design that reduces or eliminates the need for HVAC . Therefore, thermal comfort is relevant to the practice of:

HVAC engineering
Architectural design
Building Operation
Building Maintenance

Thermal comfort and air quality
"Most indoor air quality problems are thermal comfort problems"
-Dan Int-Hout- 'a noted air quality and comfort expert'

There can be substantial overlap between the perception of air quality problems thermal discomfort. People who are feeling like the air is not clean are often feeling stuffy and hot as well. When the temperature is reduced or the air motion increased, the air quality may appear to have improved.

Thermal comfort problems and possible causes
Drafts
Drafts are defined as "unwanted local cooling". Drafts can be caused by several sources including air motion, cool air, and nearby cool surfaces.

Asymmetry
Asymmetry related discomfort arises when one part or side of the body is exposed to a very different temperature than the opposite part or side (even if the average temperature is comfortable).

Stuffiness
Stuffiness occurs when air motion is too low.

Variations
When thermal variations (drifts, ramps or cycling) are too rapid. Discomfort can be experienced

For those who are interested in more reading about thermal comfort, a list of references has been provided.

Thermal Comfort Standards

ASHRAE 55

The comfort standard for the American Society of Heating, Refrigeration, and Air-Conditioning Engineers (ASHRAE), numbered "55", is entitled "Thermal Environmental Conditions for Human Occupancy". This standard, first created early in this century, was updated in 1992 to incorporate the most recent work on thermal comfort. The standard recommends thermal environmental conditions to achieve comfort indoors in all types of buildings.

The ASHRAE Standard uses the ET*-DISC model to delineate lines of comfort on a psychrometric chart. The lines form a parallelogram on the chart defining the "comfort zone". If the physical conditions that you are testing lie within the comfort zone, then a person exposed to those conditions is presumed comfortable provided that there is no air velocity, the person's activity is sedentary, and the person is wearing 0.6 clo (summer) or 0.8 clo (winter). This software calculates ET*-DISC to determine ASHRAE 55 compliance.

ISO 7730

The comfort standard for the International Standards Organization (ISO) is entitled, "Moderate thermal environments - determination of the PMV and PPD indices and specification of the conditions for thermal comfort". This standard is used by most of the world outside the U.S. and incorporates the PMV-PPD model.

PMV is an empirical function derived from the physics of heat transfer and the thermal responses of people in climate chamber tests. PMV establishes a thermal strain based on environmental conditions and attaches a comfort vote to that amount of strain. If the environmental conditions combined with the activity and clothing of the person you are modelling produce a PMV within the range of -0.5 to +0.5, then you meet the ISO comfort zone recommendation. This software calculates PMV and thereby determines compliance with the ISO standard comfort recommendation.

Thermal Comfort Terms and Definitions

Below are listed a number of terms commonly used in thermal comfort research, literature, standards et cetera. To avoid undue repetition, some words are linked to descriptive text in other locations.

Acceptable thermal environment - an environment which at least 80% of the occupants would find thermally acceptable

Air velocity

Air movement - combined effect of air velocity and turbulence or variations in air velocity and flow direction

Air motion - same as air movement

Air temperature

Clo

Comfort - the experience of a pleasing or satisfying thermal sensation. Also, lack of discomfort.

Comfortable - That condition of the mind that expresses satisfaction with the thermal environment.

Comfort zone - a set of environmental conditions considered to be "comfortable" by 80% of people exposed. Also, a range of subjective votes recommended for comfort, e.g. -0.5<PMV<0.5 regardless of environmental conditions.

Discomfort - the experience of a displeasing or unsatisfactory thermal sensation.

Draft - Unwanted local cooling.

Dry bulb temperature - same as air temperature.

Dry heat transfer -see sensible heat transfer below.

Latent heat - heat transfer that involves the mechanism of evaporation.

Mean radiant temperature

Met

Neutral sensation - the sensation of feeling neither warm nor cool.

Neutral temperature - the temperature at which a person will feel neither warm nor cool.

Occupied zone - the region between the floor and 1.8 meters above the floor and more than 0.6 meters from the walls.

Operative temperature - the average of air temperature and mean radiant temperature weighted by their respective heat transfer coefficients.

PMV

PPD

Sensible heat transfer - same as dry heat transfer. Heat transfer that involves the mechanisms of radiation, conduction, and convection.

Thermal acceptability - the answer to the question, "Do you find the thermal environment acceptable?"
-also used to define bands of thermal sensation votes: -1.5 to +1.5, -1 to +1 or -0.5 to +0.5 have variously been defined as thermally acceptable and votes outside those bands defined as thermally unacceptable.

Thermal comfort

Thermal neutrality - the state of feeling neither warm nor cold.

Thermal preference - the answer to the question. "Do you want the thermal environment warmer or cooler, or do you want 'no change'?"

Thermal satisfaction - the answer to the question "Are you satisfied with the thermal environment?"
-also used to define bands of thermal sensation votes: -1.5 to +1.5, -1 to +1 or -0.5 to +0.5 have variously been defined as thermally satisfied and votes outside those bands defined as thermally dissatisfied.

Thermal sensation - the sensations of feeling warm, cool, or neither warm nor cool. See thermal sensation scales.

Total heat transfer - the sum of latent and sensible heat transfers.

Turbulence

Two-node

Workspace - the immediate area where someone works, including their desk and the space occupied by their chair and body.

Thermal Comfort Scales

Thermal sensation scale - also referred to as the ASHRAE scale. A seven-point psychophysical scale of warmth.

+3 - Hot
+2 - Warm
+1 - Slightly warm
0 - Neutral
-1 - Slightly cool
-2 - Cool
-3 - Cold

Used alternately as either an ordinal or continuous scale, subjects are asked to select a response that describes how they feel thermally.

Thermal preference scale - A three-point ordinal scale psychophysical scale of warmth preference.

"I want to be cooler"
"I want no change"
"I want to be warmer"

Thermal comfort scale - A seven point ordinal scale of comfort and warmth.

+3 - Much too warm
+2 - Too warm
+1 - Comfortably warm
0 - Comfortable
-1 - Comfortably cool
-2 - Too cool
-3 - Much too cool

PMV

The PMV equation for thermal comfort is a steady-state model. It is an empirical equation for predicting the mean vote on a ordinal category rating scale of thermal comfort of a population of people. The equation uses a steady-state heat balance for the human body and postulates a link between the deviation from the minimum load on heat balance effector mechanisms, e.g sweating, vaso-constriction, vaso-dilation, and thermal comfort vote. The greater the load, the more the comfort vote deviates from zero. The partial derivative of the load function is estimated by exposing enough people to enough different conditions to fit a curve. PMV (Predicted Mean Vote), as the integrated partial derivative is now known, is arguably the most widely used thermal comfort index today. The ISO (International Standards Organization) Standard 7730 (ISO 1984), "Moderate Thermal Environments -- Determination of the PMV and PPD Indices and Specification of the Conditions for Thermal Comfort," uses limits on PMV as an explicit definition of the comfort zone.

The PMV equation only applies to humans exposed for a long period to constant conditions at a constant metabolic rate. Conservation of energy leads to the heat balance equation:

H-Ed-Esw-Ere-L=R+C

Where:
H = internal heat production
Ed = heat loss due to water vapor diffusion through the skin
Esw = heat loss due to sweating
Ere = latent heat loss due to respiration
L = dry respiration heat loss
R = heat loss by radiation from the surface of the clothed body
C = heat loss by convection from the surface of the clothed body

The equation is expanded by substituting each component with a function derivable from basic physics. All of the functions have measurable values with exception of clothing surface temperature and the convective heat transfer coefficient which are functions of each other. To solve the equation, an initial value of clothing temperature is estimated, the convective heat transfer coefficient computed, a new clothing temperature calculated etc., by iteration until both are known to a satisfactory degree.

Now let us assume the body is not in balance and write the heat equation as:

L = H-Ed-Esw-Ere-L-R-C,

where L is the thermal load on the body.

Define thermal strain or sensation, Y, as some unknown function of L and metabolic rate. Holding all variables constant except air temperature and metabolic rate, we use mean votes from climate chamber experiments to write Y as function of air temperature for several activity levels. Then substituting L for air temperature, determined from the heat balance equation above, evaluate the partial derivative of Y with respect to L at Y=0 and plot the points versus metabolic rate. An exponential curve is fit to the points and integrated with respect to L. L is simply renamed "PMV" and we have (in simplified form):

PMV = exp[met]*L.
Where:
L=F(Pa,Ta,Tmrt,Tcl)

PMV is "scaled" to predict thermal sensation votes on a seven point scale (hot,warm, slightly warm, neutral, slightly cool, cool, cold) by virtue of the fact that for each physical condition, Y is the mean vote of all subjects exposed to that condition. The major limitation of the PMV model is the explicit constraint of skin temperature and evaporative heat loss to values for comfort and "neutral" sensation at a given activity level.

ET*-DISC

The 2-node model was introduced in 1970 specifically to formulate a new effective temperature scale. The purpose was to determine particular combinations of physical conditions producing equal physiological strain. Backed by extensive data from climate chamber experiments, it was determined that while skin temperature is a good indicator of thermal comfort sensation in cold environments, skin wettedness is a better indicator in warm environments where sweating occurs because skin temperature changes are small by comparison. The model represents the human body as two concentric cylinders, a core cylinder and a thin skin cylinder surrounding it. Clothing and sweat are assumed to be evenly distributed over the skin surface. At time "zero", the cylinder is exposed to a uniform environment, and the model produces a minute-by-minute simulation of the human thermoregulatory system. After the user-specified time period is reached, the final surface temperature and surface skin wettedness of the cylinder are used to calculate ET*, SET*, and other indices. ET* is the temperature of an environment at 50% relative humidity in which a person experiences the same amount heat loss as in the actual environment. SET* numerically represents the thermal strain experienced by the cylinder relative to a "standard" person in a "standard" environment. SET* has the advantage of allowing thermal comparisons between environments at any combination of the physical input variables, but the disadvantage of also requiring "standard" people.

Based on a laboratory study with a large number of subjects, empirical functions between two comfort indices, and skin temperature and skin wettedness, were developed. These functions (both linear) are used in the 2-Node model to produce predicted values of the votes of populations exposed to the same conditions as the cylinder. TSENS, the first index, represents the model's prediction of a vote on the seven point thermal sensation scale. DISC, the second index, predicts a vote on a scale of thermal **discomfort**:

DISC:
Intolerable
Very uncomfortable
Uncomfortable
Slightly uncomfortable
Comfortable

The 2-Node model has undergone many iterations and refinements. In the most recent iteration, a new temperature index, PMV*, that incorporates skin wettedness into the PMV equation using SET* or ET* to characterize the environment.

Interpreting Your Output

Which output should you use? There is no simple answer to this question and you will often find conflicting results when you compare outputs. However, the following general observations can be used as a rough guide:

Comfort zone testing

The ASHRAE comfort zone (ASHRAE 55-92) only applies to a sedentary person wearing standard clothing, if you want to test other cases, use the ISO comfort recommendations (ISO 7730). The program will lighten the color of the ASHRAE comfort zone icon when other than default met and clo are selected.

The ASHRAE comfort zone calculation automatically accounts for seasonal changes in clothing by adjusting the ET* boundary. The ISO comfort zone recommendation is based only on PMV so if you want to compare winter comfort zone boundaries you must manually change the clothing to appropriate winter dress for PMV. This feature initially makes the comfort zones seem disparate when in fact they are similar.

Comfort vote prediction

The TSENS output is a predicted vote on the seven-point thermal sensation scale.

DISC is similar to TSENS except that it accounts for discomfort due to sweating in warm conditions. In non-sweating conditions, you can ignore DISC.

PMV is a predicted vote on the seven-point thermal sensation scale.

PPD is a non-linear function of PMV. As PMV deviates from zero in either direction (i.e. as people get warmer or cooler), PPD increases.

Remember that these predictions are for large populations. Individual differences in thermal preference vary widely so these models cannot be used to reliably predict the response of an individual.

Air movement testing

If you would like to determine the risk of feeling a draft in an office environment, use the model. PD is designed to protect draft sensitive persons when they have no control of the air movement in their workspace. As the air temperature increases, the risk of draft decreases. In this model, as the turbulence intensity in the air increases, the heat transfer from the body increases, and the draft risk also increases. The default turbulence intensity is 40% which corresponds to a typical office environment. Turbulence intensity is rarely lower than this except when plug flow or 'displacement' ventilation is used. If a fan or other air mixing device is nearby, the turbulence can substantially increase.

If you want to find out the air movement level people choose in an environment when they have control, use the PS model. The PS model is designed to provide satisfactory levels of air motion to people who desire it and have control of the air movement in their workspace. PS tells you the cumulative percent of people choosing a particular air velocity at a specific temperature. If your PS is below a certain percent, say 50%, then you know that half of the people would prefer more air motion if they could get it and adjust it themselves.

PD and PS usually give different recommendations within the comfort zone because they are designed for different segments of the population.

Adjusting the inputs

If you are trying to model a location in the interior zone of a large office building, you might try using a mean radiant temperature that is slightly (1 or 2 degrees) higher than air temperature . Large offices are typically internal-gain dominated (with local heat sources like computers and copiers) and the interior zones tend to run with slightly higher MRT than Ta in both winter and summer.

Alternatively, if you are modelling an exterior zone with a window nearby, you might try using a slightly lower MRT than Ta for winter conditions and a slightly higher MRT than Ta for summer.

You can use the check box in the input section of the program to link MRT and Ta. Checking this box allows you adjust Ta as usual but maintain a constant difference between MRT and Ta.

The sample clo ensembles should cover most typical situations but you are encouraged to build your own using the clo calculator. Small changes in clothing make a large difference in comfort so getting the clo as close as you can is important.

Adaptive models

Use neutral temperature from either the Humphreys or Auliciems model to find the temperature at which a large population will feel neither to warm nor too cold. If you have weather data, use the Auliciems model, if you do not, then use the Humphreys model.

Details

You can adjust some physiological aspects of the person you are testing by selecting the heart icon,  . Try changing the mass. or the exposure time. This will affect the output from the ET*-DISC model but none of the others. If you wish, you can change the sweating, vaso-dilation and vaso-constriction coefficients as well.

When an output is lightened in color by the program, a variable used to calculate that output is not within its acceptable range.

The ASHRAE comfort zone icon will be lightened in color when a clo other than 0.6 is selected. If you wish to test the winter clo value of 0.8, ignore the fact that the icon is lightened, the output is still valid.

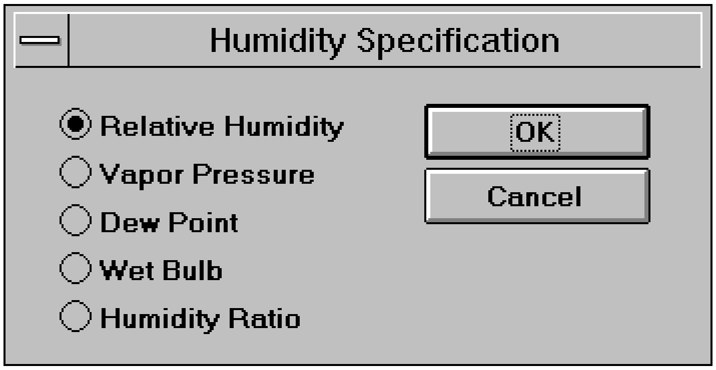
Thermal Sensation Scales
Thermal comfort terms and definitions

Options

Humidity parameter

This option item allows you to select how the humidity parameter is specified

Just click on the type of input you would like to use



Model detail

The model detail list item is not wired at this time.

Unit system

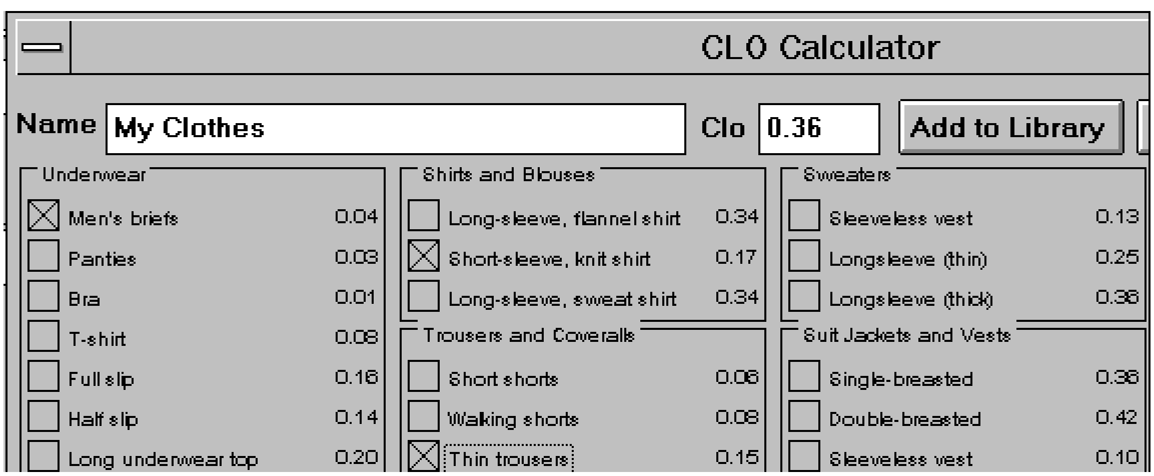
The unit system toggles between SI and IP units.

Show physiological data

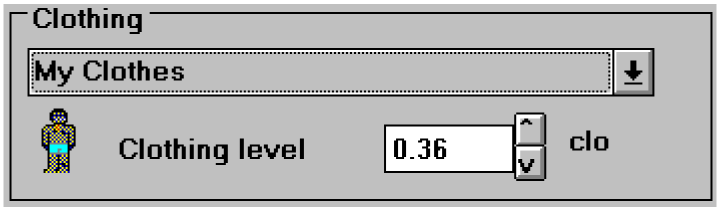
This list item shows you the physiology of the human being modeled. For most analyses, you won't need to change these values.

Clo calculator

The clo calculator is a tool you can use to generate and store your own clothing ensembles. Part of the clo calculator window is shown below. Just click on the items you would like to include in the clothing ensemble and the clo value is automatically calculated for you.



You can use the Add to Library button to store the clothing ensemble you created. It will then appear in the pull down list on the main screen



The icon is fixed for a range of clo values and does not show the individual items you selected.

Detailed model input

Detailed model input allows the adjustment of several variables that will not be adjusted for most analyses.

Detailed model input

For most types of analyses, inputs at this level won't need to be changed. But we've given you access to these inputs just in case you want to experiment.

These inputs are found under "detailed model input" in the "options" pull-down menu or by pressing the nuts and bolts icon in the toolbar.

Barometric pressure

You can change the barometric pressure to account for changes in altitude.

Turbulence

You can change the turbulence intensity to examine draft risk. The ASHRAE Standard 55-92 has a section on draft risk and you can view the help topic, thermal comfort models, for more information on "PD", the index of draft risk. Turbulence intensity is defined as the standard deviation divided by the mean for a measuring period (scaled to 100).

Mean monthly outdoor temperature

You can change the mean monthly outdoor temperature for the adaptive model from Auliciems. Mean monthly outdoor temperature is the mean of the daily minimum and the daily maximum (over one month) of the shielded dry-bulb temperature measured outdoors.

Physiological inputs