AT-90-5-3

THERMAL COMFORT CALCULATIONS/ A COMPUTER MODEL

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ABSTRACT

Calculation of the predicted comfort level of occupants of buildings served by modern HVAC systems is a complicated process, requiring analysis of up to seven variables. Equations and tables are provided in Chapter 8 of the ASHRAE Handbook of Fundamentals (ASHRAE 1989) but it is both difficult and impractical for the average mechanical engineer to use this information to make accurate comparisons of design conditions. The analysis, however, can be more easily accomplished with the aid of modern personal computers, given the proper model.

Different models have been used over the past several years and all require the input of the seven basic comfort variables. In the preparation of the revision to ASHRAE Standard 55-1981 (ASHRAE 1981), members of SPC 55-1981R evaluated several available models. In order to provide the HVAC engineer with a tool to better understand the response of individuals to the environment, a computer model developed from that evaluation is presented.

INTRODUCTION

Calculation of the predicted comfort level of occupants of buildings served by modern HVAC systems is a complicated process, requiring analysis of up to seven variables. Equations and tables are provided in Chapter 8 of the ASHRAE Handbook of Fundamentals (ASHRAE 1989), but it is both difficult and impractical for the average mechanical engineer to use this information to make accurate comparisons of design conditions. The analysis, however, can be more easily accomplished with the aid of modern personal computers, given the proper model.

Different models have been used over the past several years, and all require the input of the seven basic comfort variables. There is, however, some difference in the comfort predictions of the different available models, but all must come up with a single number to describe the predicted comfort level of a "typical" human occupant. The most common and probably best understood unit is PMV, or Predicted Mean Vote, and the associated Percent Persons Dissatisfied, or PPD. The International Standards Organization's (ISO) Standard 7730 (ISO 1984) provides a Fortran program as an appendix for predicting PMV and PPD.

The ASHRAE comfort standard, Standard 55-1981 (ASHRAE 1981), is currently undergoing a review and update. In the course of this update, a computer program was considered as an attachment to the standard. While such a model is not presently included in the standard, several models were evaluated by a subcommittee. From this evaluation, a model has been developed and is presented. This model is a combination of the elements of two different approaches to the solution of the comfort problem:

ET*: The Effective Temperature is defined as that operative temperature at 50% RH which would cause the same heat loss from a person as would the actual conditions being evaluated.

ISO 7730: The ISO comfort standard 7730 (ISO 1984) includes a Fortran program listing as an appendix to the standard. The program allows for a solution of the comfort equations with a number of unknown variables. The model solves for two terms PMV and PPD, and the standard recommends acceptable limits for the PMV of between 0.5 and −0.5 for an 80% comfort level.

Both the comfort models are based on research that was conducted during the past 40 years over a wide range of subjects. As a result, the predicted values should be representative of the average comfort level for the environmental conditions that are input providing the result is relatively close to a satisfied state. As the level of discomfort increases, so does the variability in the prediction.

A number of descriptive terms are used to define comfort and human response. Both the ISO and ASHRAE standards utilize the term "operative temperature." This is defined as a weighted value representing both the (dry-bulb) air temperature and the radiant temperature at a point. A number of researchers, however, suggest the term "ET*", or effective temperature, as a better temperature index, as it includes humidity effects.

The ISO standard and other researchers have utilized scales of subjective response to describe an occupant's feeling of warmth or coolness in a situation. The ISO's Predicted Mean Vote predicts the thermal sensation for the body as a whole. It does not predict local discomfort, i.e., compliance with the limits for thermal nonuniformity as contained in ASHRAE Standard 55-1981 and ISO Standard 7730 should be checked separately. PMV is the mean vote of a large group of persons on the following scale:

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+3 hot
+2 warm
+1 slightly warm
0 neutral
−1 slightly cool
−2 cool
−3 cold

In addition to the PMV data, a Predicted Percent Dissatisfied, PPD, is also calculated. This is a normalized curve of response of a "standard" population to the resulting PMV. This is an idealized response curve and a number of comfort researchers feel that actual human variability is considerably greater than indicated here. Additionally, some data suggest that the actual number of dissatisfied may depend on a number of additional factors not included in the model. Some data (Schiller et al. 1988) also indicate that thermal neutrality is not necessarily the optimum condition, as might be predicted by the PPD calculation. Many recent studies suggest that a −0.1 to −0.2 (slightly cool) response may be preferred to a 0 (neutral) condition.

Two criticisms have been addressed toward the ISO 7730 model:

1. The ISO standard and its calculations do not take into account the possibility of skin wettedness and the resultant change in human response. At the temperature and humidity levels intended for the proper use of the model, this seldom is a serious problem but may lead to slight differences from other models at high humidities.

2. The ISO model is essentially a "black-box" solution, and the calculations are not easy to understand by the user. In addition, a "relative velocity" term, rather than an air velocity, is utilized, which has been criticized by some as difficult to categorize.

The ET* equations, on the other hand, have not been published by ASHRAE as a formal computer program but have been presented as equations in a number of ASHRAE technical papers. An early version of the two-node model was presented by Gagge in 1973. The Gagge two-node model has been used by researchers in recent studies (Schiller et al. 1988). Attempting to derive computer models from the available technical papers and from Chapter 8 of the ASHRAE Handbook, however, can yield different solutions, depending on the use of constants and interpolation of tabular data. An in-depth comparison of the differences between the ISO and the Gagge models can be found in ASHRAE technical papers (Parsons 1987; Gagge et al. 1986).

COMPUTER MODEL

To resolve these issues, a model has been created that is based on the ISO program, but which includes the effective temperature, ET*, in place of the operative temperature. In addition, the terms that were not described fully in the ISO model have been modified and annotated so as to be better understood by those wishing to analyze the mathematics involved.

The resultant program, including the above factors, may be found in Appendix A. Using this program, a design engineer can develop realistic and repeatable design limitations for space temperature setpoints and determine the effect of changes in the space variables on the building occupants.

The outputs are:

PMV: The Predicted Mean Vote based on effective temperature, ET*, is an indication of the thermal acceptability of a space. Zero indicates neutral, a positive value indicates warmth, and negative means coolness. ISO Standard 7730 suggests that limits of −.5 to +.5 be used as design limits for 80% acceptability. Some research indicates that a PMV of slightly less than 0 may be optimum (Schiller 1988).

PPD: The Percent Persons Dissatisfied is calculated from the PMV by a statistical evaluation of a large population of subjects. These equations have been basically proven in research conducted in a number of laboratories but are realized to be somewhat idealized. The variability of human populations probably will increase beyond the predictions as conditions vary from ideal.

The following inputs are required for using the computer program. The outputs are valid only for determining a predicted thermal comfort level for building occupants engaged in sedentary tasks in an indoor environment. Inputs in this program are in S-I (metric) units.

Met: The metabolic rate of most people in indoor spaces ranges from a low, sedentary rate of about 50 W/m to a high of about 130 W/m, with a traditional level of 58 W/m (1.0 Met) used for these calculations. Analysis of the data obtained in recent studies by Schiller (1988) in a number of operating office spaces suggests that activity levels may be higher than the 1 Met typically used and should be around 1.2 Met or 68 W/m for typical office spaces.

Wme: This term is for external work, and it is used to represent stored energy, such as that accumulated in the body while climbing a flight of stairs. The stored heat is released over a few minutes, adding to the need for cooling. In most cases, this transient case can be ignored.

Ta: Air temperature is the value one would measure if all radiant effects were excluded. This value is what the room thermostat should sense, if shielded from sunlight. If there are radiant effects present during air temperature measurements, specially designed air temperature sensors are available to exclude the radiant component from a measured value.

Tr: The radiant temperatures experienced in offices can be calculated from known surface temperatures, but the approach is time-consuming. In modern offices, there is seldom more than 5°F (2.5°C) difference between air and radiant temperatures. This difference can increase in the presence of direct sunlight or radiant heaters.

Clo: The insulating quality of a subject's clothing can be calculated, but typical values are presented in the standards. Some typical values are listed below (ICL):

Light summer attire = 0.5
Light business suit = 0.9

Medium weight suit with vest = 1.1

Heavy suit with vest = 1.5

VEL: The air speeds present in most modern offices are on the order of 15 to 30 fpm (0.07 to 0.15 m/s). Along cold windows and in summer perimeter zones, higher air speeds may be observed. It is unlikely that sustained air speeds in excess of 50 fpm (0.25 m/s) are to be found in most office spaces. Typical winter air speeds in modern offices (heated perimeter offices) are < 10 fpm. Air speeds less than 20 fpm give the same result as air speeds = 20 fpm. If an occupant is moving, the apparent air speed resulting from that movement should be added to the expected room air motion levels.

RH/PA: Utilizing a humidity conversion equation, the program calculates the partial pressure of moisture in the air from an input relative humidity. Alternately, the partial pressure can be input directly, if known. The barometric pressure is fixed at sea level as 29.92 mm Hg. Experimentation over a range of altitudes has shown that altitude and barometric pressure probably have little effect on calculated PMV values.

COMPUTATIONS

The model has inputs for the several primary variables, allowing for either the relative humidity or a known water vapor pressure (lines 100 through 210). All model inputs are in SI units. The sequence of calculations is as follows:

1. First, the moisture effect is calculated from RH, entered as the whole number fraction. If partial pressure of water is known, a 0 is entered for RH and the known partial pressure is entered (in kilo-pascals [kPa]). Some units are converted from input units to engineering units at this time (lines 212 through 240).

2. The program loops through a calculation for the surface temperature of the individual's clothing. This calculation includes an iterative solution including both convective heat transfer and a factor for forced ventilation (lines 240 through 450).

3. Following the clothing surface temperature, a calculation of the body's heat loss factors is accomplished, with a reduction effect for the vapor resistance of clothing (lines 460 through 520). The program calculates the effective temperature of the occupant, using the heat loss factors just computed. The ET* is also determined by an iterative approach using a calculated operative temperature (TO) and moisture effects (lines 550 through 840).

4. The program then proceeds to PMV calculation (line 1520) and the PPD determination (line 1530).

5. The remainder of the program is for data output.

The program was written in BASIC, however, any form of BASIC should yield similar calculated values. Some minor differences may be expected due to math precision and round-off errors. These will not significantly affect the analysis, however, as they are expected to be very slight.

Comparison to Other Models

The only direct comparison that can be made with a published standard's model is with the ISO Standard 7730 Fortran equation. Outputs cannot be easily compared with the existing ASHRAE Standard 55-1981 requirements without knowing the proper assumed values for the necessary inputs, which are not clearly defined. The ASHRAE standard indicates that the recommended range of acceptance is for an 80% comfort level, which agrees, in general, with the ISO ±0.5 value. This model does not cover the effect of transient conditions, either due to ramping or cyclical temperature changes (that is, it is for steady-state conditions), nor does it address the effect of air turbulence recently discussed by some researchers (Fanger 1987).

Other researchers have suggested different subjective rating scales than those presented here (Laviana and Rohles 1987); however, they cannot be directly compared with the model presented here since no developed calculation model for them has been presented to date.

Table 1 is presented with the PMV and PPD calculated at the limits of the current ASHRAE Standard 55-1981 recommended summer and winter conditions, showing both the ISO standard's and the proposed model's values. The comparison shows that the ASHRAE-recommended conditions are similar to the calculated conditions but generally favor lower temperatures than the ASHRAE or ISO model, data which are in agreement with recent field studies (Schiller 1988).

SUMMARY

While there is some difference between ISO Standard 7730 and this model, the differences are not significant in terms of actual room setpoints or energy use calculations. This model does provide a usable tool for the design engineer to determine the effect of changing room environmental variables on occupant comfort, and it is presented in a more rational format than the ISO model.

From this model, simpler "rules of thumb" and new routines can be developed for use in applications such as digital controls and energy use models. If unfamiliar with thermal comfort standards, it is suggested that the reader obtain a copy of both ISO Standard 7730 (ISO 1984) and ASHRAE Standard 55-1981 (ASHRAE 1981), and read Chapter 8 of the ASHRAE Fundamentals Handbook (ASHRAE 1989) to gain a better understanding of the comfort parameters, limits, and applications.

ACKNOWLEDGMENTS

The author appreciates the assistance of Dr. P. Ole Fanger, the Technical University of Denmark, and especially Dr. A. Pharo Gagge, the John B. Pierce Foundation, for their assistance in the preparation of the computer program listed in the Appendix.

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TABLE 1
Thermal Comfort Calculation Comparison In Accordance With ISO 7730 and Compromise PMV-ET

Run #	Air Temp	Bar. Pres	R.H.	Rad Temp	Air Spd	Act.	Clo	Predicted Mean Vote PMV		Percent Discomfort PPD	
	°C	mmHg	%	°C	m/s	W/m	CLO	ISO	-ET	ISO	-ET
ASHRAE 55-1981 Points/Winter Conditions											
1	19.6	29.92	85	19.6	0.15	58	1.20	−0.53	−0.27	10.85	6.49
2	20.2	29.92	30	20.2	0.15	58	1.20	−0.73	−0.44	16.33	9.02
3	22.5	29.92	68	22.5	0.15	58	1.20	0.10	0.43	5.22	8.80
4	24.5	29.92	20	24.5	0.15	58	1.20	0.24	0.45	6.24	9.19
ASHRAE 55-1981 Points/Summer Conditions											
1	22.2	29.92	68	22.2	0.35	58	0.80	−1.05	−0.77	28.07	17.47
2	23.0	29.92	25	23.0	0.35	58	0.80	−1.11	−0.80	30.71	18.39
3	25.8	29.92	58	25.8	0.35	58	0.80	0.13	0.46	5.36	9.31
4	27.0	29.92	20	27.0	0.35	58	0.80	0.20	0.40	5.86	8.33

Note: ISO-PMV = ISO 7730; PMV−ET = Proposed Model

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Schiller, G.E., et al. 1988. "A field study of thermal environments and comfort in office buildings." *ASHRAE Transactions*, Vol. 94, Part 2.

APPENDIX
Program Listing

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10 CLS
11 'A computer program to determine whether the ambient temperature
12 'level complies with ASHRAE Std 55-1981(R). The program calculates
13 'PMV (Predicted Mean Vote) and PPD (Predicted Percentage of Dissatisfied).
14 'Prepared by Dan Int-Hout in Microsoft (R) QUICK BASIC from an original
15 'written for the ASHRAE SPC 55-1981 R Committee by P.O. Fanger, T.U.
16 'Denmark, modified by recommendation by A.P. Gagge.
17 'The calculation for heat loss through the skin (line 470)
18 'has been modified from the original to allow for the effects
19 'of the vapor resistance of clothing. The data is valid only in the range
20 'of PMV > -3 < +3, and for optimum accuracy should be used to select PMV
21 'values within the range of the ISO and ASHRAE recommended -0.5 to +0.5
22 'range for acceptable spaces. 5/29/89
70 PRINT "Thermal Comfort Calculation Model—5/29/89"
80 PRINT
90 PRINT "Input Parameters:"
100 PRINT
110 INPUT "Clothing                              (CLO)"; CLO
120 INPUT "Metabolic rate                        (MET)"; MET
130 INPUT "External work                         (MET)"; WME
140 INPUT "Air temperature                        (°C)"; TA
150 INPUT "Mean radiant temperature               (°C)"; TR
160 INPUT "Air Speed Around Body                 (m/s)"; VEL
190 PRINT "ENTER EITHER RH OR WVP BUT NOT BOTH"
200 INPUT "Relative Humidity                       (%)"; RH
210 INPUT "Water Vapor Pressure                   (Pa)"; PA
212 '== INITIAL CALCULATIONS==
214 DEF FNPS (T) = EXP(16.6536 - 4030.183/(T + 235))
215                                 'Saturated VP, KPa
218 IF PA = 0 THEN PA = RH/100 * FNPS(TA)   'Water
                                     Vapor Press, Pa
220 ICL = .155 * CLO                'Thermal Insulation
222 M = MET * 58.15                 'Metabolic Rate, W/m²
224 W = WME * 58.15                 'External Work in W/m²
226 MW = M - W                      'Internal Heat Production
227 TSK = 35.7 - .028 * MW          'Fanger Eq. 29
228 FCL = 1 + .3 * CLO              'KSU Definition
230 HCF = 12.1 * SQR(VEL) 'Heat Txfr by forced ventilation
240 '== CLOTHING SURFACE TEMP LOOP==
250 TAA = TA + 273                  'Absolute Air Temp
260 TRA = TR + 273                  'Absolute Radiant Temp
270 TCLA = TAA + (35.5 - TA)/(3.5 * (6.45 * ICL + .1))
271                                 'first try for surface temp
280 P1 = ICL * FCL
290 P2 = P1 * 3.96
300 P3 = P1 * 100
310 P4 = P1 * TAA
320 P5 = 308.7 - .028 * MW + P2 * (TRA/100) ^ 4
330 XN = TCLA/100
340 XF = XN
350 N = 0                           'Number of Iterations
360 EPS = .00015                    'Stop criteria for iteration
370 '-- Iterate for clothing surface temp--------
380 XF = (XF + XN)/2
390 HCN = 2.38 * ABS(100 * XF - TAA) ^ .25 'Convection
                                     heat transfer coeff
400 IF HCF > HCN THEN HC = HCF ELSE HC = HCN
410 XN = (P5 + P4 * HC - P2 * XF ^ 4)/(100 + P3 * HC)
420 N = N + 1
430 IF N > 150 THEN PMVET = 99999!: PPDET = 100:
GOTO 1590
440 IF ABS(XN - XF) > EPS GOTO 370
```

```
450 TCL = 100 * XN - 273   'Clothing Surface Temperature
460 '= = = HEAT LOSS COMPONENTS= =
470 HL1G = 3.062 * (FNPS(TSK) - PA) * .45 'Fanger Eq. 9 mod .45
480 IF MW > 58.15 THEN HL2 = .42 * (MW - 58.15) ELSE HL2 = 0!'Def of ECOMF
490 HL3 = .01725 * M * (5.8662 - PA)'Latent respiration loss
500 HL4 = .0014 * M * (34 - TA)     'Dry respiration loss
510 HL5 = .7 * 5.67 * FCL * (XN ^ 4 - (TRA/100) ^ 4)
                                    'Loss by radiation
520 HL6 = FCL * HC * (TCL - TA)  'Loss by convection
540 '= = = ET* Calculation= = =
550 IF VEL < .2 THEN A = .5         'Velocity Coefficient
560 IF (VEL >= .2) AND (VEL < .6) THEN A = .6
570 IF (VEL >= .6) AND (VEL < 1) THEN A = .7
580 TOP = A * TA + (1 - A) * TR  'Operative temperature
590 IM = .45                        'Woodcock ratio
600 LR = 16.5                       'Lewis relation
610 DRY = HL5 + HL6        'Dry heat loss from clothing
630 EFCTC = DRY/(TSK - TOP)  'Thermal transmittance
640 EREQ = MW - (HL3 + HL4) - DRY     'Required evaporation
650 EDIF = 3.062 * (FNPS(TSK) - PA) * IM'Diff eq. mod. by IM
660 EFCHE = IM * LR * EFCTC         'Mass txfr coeff
670 PSSK = FNPS(TSK)        'Sat w v press at skin temp
680 EMAX = EFCHE * (PSSK - PA)     'Max evap power
690 PWET = EREQ/EMAX                'Skin wettedness
700 IF PWET < EDIF/EMAX THEN PWET = EDIF/EMAX
710 IF PWET > 1! THEN PWET = 1!  'Assume wcrit = 1
800 '------Iterate for ET -------------------
810 ETOLD = ET
820 ET = TOP + PWET * IM * LR * (PA - .5 * FNPS(ET))
                                    'New approx ET
830 ET = .5 * ET + .5 * ETOLD
840 IF (ABS(ET - ETOLD)) > .01 THEN GOTO 800
1500 '= = CALCULATE PMV AND PPD= = =
1510 TS = .303 * EXP(-.036 * MW) + .028     'Thermal sensation trans coeff
1520 PMVET = TS * (MW - HL1G - HL2 - HL3 - HL4 - EFCTC * (TSK - ET))
1530 PPDET = 100 - 95 * EXP(-.03353 * PMVET ^ 4 - .2179 * PMVET ^ 2)
1590 '= = = = =OUTPUT= = = =
1600 PRINT
1610 PRINT "PMV Data Output"
1620 A1$ = "###.##"
1630 B1$ = "###.#"
1640 PRINT
1650 PRINT "PMV should be inside the range of -0.5 to +0.5 for 80% comfort"
1660 IF ABS(PMV) > .5 THEN PRINT "Warning—PMV out of Recommended Range"
1670 PRINT "PMV ";: PRINT USING A1$; PMVET
1680 PRINT "PPD (%) ";: PRINT USING B1$; PPDET
1690 PRINT "ET* ";: PRINT USING B1$; ET
1700 PRINT "Op. Temp ";: PRINT USING B1$; TOP
1705 PRINT
1710 INPUT "More data (Y) (N)"; N$
1720 IF N$ = "n" OR N$ = "N" THEN SYSTEM
1730 LOCATE (1), (1)
1740 GOTO 10
```

Sample Output:

```
Thermal Comfort Calculation Model—5/29/89
Input Parameters:
Clothing                                        (CLO)? .
Metabolic rate                                  (MET)? .
External work                                   (MET)?
Air temperature                                 ( C)? 23
Mean radiant temperature                        ( C)? 23
Air Speed Around Body                           (m/s)? .15
ENTER EITHER RH OR WVP BUT NOT BOTH
Relative Humidity                               (%)? 50
Water Vapor Pressure                            (Pa)?

PMV Data Output

PMV should be inside the range of -0.5 to +0.5 for 80% comfort
PMV 0.09
PPD (%) 5.2
ET* 23.0
Op. Temp 23.0
More data (Y) (N)?
```

DISCUSSION

J.T. Reardon, Research Officer, National Research Council of Canada, Ottawa, Ontario: You mentioned in your talk that other works being reported at this meeting contain experimental data that might be compared and studied using your computer program. Have your program and its prediction capacity been compared with real data yet?

D. Int-Hout III: In the paper, the program was compared with the output of the two previously used models. The comparison suggests that existing models yield higher preferred temperatures than the model presented in the paper. A field study by Shiller et al. (1989) reported a similar result. We expect there will be a better fit to field data with the proposed model than with previous ones. No direct studies have been conducted to compare the new model with actual response.