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Title	Comfort Chart : An Index for Evaluating Thermal Sensation
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Citation	Memoirs of the Faculty of Engineering, Hokkaido University, 15(2), 175-185
Issue Date	1979-12
Doc URL	http://hdl.handle.net/2115/37977
Type	bulletin (article)
File Information	15(2)_175-186.pdf

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Comfort Chart——An Index for Evaluating Thermal Sensation

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(Received June 30, 1979)

Abstract

A comfort chart is proposed as an index of comfortable sensation and for environmental assessment based on a rational heat balance equation which describes both physical and physiological human responses. The chart is applied to predict thermal sensation under any unexperienced environment from an integrated assessment of six important variables concerned, namely, ambient air temperature, mean radiant temperature, humidity, air movement, metabolic rate and clothing worn. The four main channels of heat exchange are analysed from an engineering angle. For the heat loss by radiation, a new coefficient of radiant heat transfer is derived by extending Gebhart's absorption factor and applying it to the space between the human body and the surrounding walls. A convection coefficient for the human body is also derived based on the heat and mass transfer theory. For the heat loss by skin evaporation besides the mass transfer equation to describe sweat evaporation a new model is proposed, i. e., a model has different control systems for sweat evaporation at either high or low humidity environments. The characteristics of the proposed model are verified by comparing calculated values with physiological data observed in expreiments and the indices by earlier workers. Lines of equal temperature sensation can be drawn based on heat balance equations derived. The comfort chart proposed is prepared for some relevant combinations of variables concerned, namely, clothing insulation, metabolic rate and air movement in a uniform temperature field.

1. Introduction

Many attempts have been made by biological engineers and physiologists to establish thermal criteria, i. e., evaluation of levels of thermal sensations. However, the complexity of thermal environments have prevented the establishment of an exact quantitative thermal sensation index in terms of both environmental and physiological parameters. With the recent growth of unlimited mechanization and industrialization, artificial living environments have been widened even to space and undersea laboratories. Wherever man-made climates are required, optimum thermal environments for the occupants must be technically created.

By applying heat and mass transfer theory, an analysis of thermal comfort

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sensation in a steady state is carried out from an engineering angle and a comfort chart is proposed. The present proposed index is used to predict thermal comfort sensation from the integrated evaluation of environmental and physiological variables concerned, i. e., ambient air temperature, mean radiant temperature, humidity, air movement, clothing worn, and metabolic rate.

2. Nomenclature

M: metabolic rate, kcal/m^{2}h
H_c: heat loss by convection, kcal/m^{2}h
H_r: heat loss by radiation, kcal/m^{2}h
H_e: wet heat loss from skin surface, kcal/m^{2}h
H_n: heat loss by respiration, kcal/m^{2}h
Q_r: heat released by radiation exchange, kcal/h
A_s: effective skin area which relates to heat exchange (effective skin area for the convection, radiation and evaporation heat loss is assumed to be equal to the whole body surface area respectively in the present study), m^2
S_i: surface area of surrounding wall, m^2
W: wettedness, N. D.
G: quantity of moisture (insensible perspiration and sweat secretion; at comfort condition, only insensible prespiration), g/m^{2}h
L: latent heat, kcal/g
h_c: convective heat transfer coefficient in man, kcal/m^{2}h°C
h_r: linear radiation exchange coefficient in man, kcal/m^{2}h°C
ε_s: emissivity of man, N. D.
ε_i: emissivity of wall, N. D.
σ: Stefan-Boltzmann constant, kcal/m^{2}h°K^4
k: temperature factor on radiation exchange, °K^3
κ: modified Lewis relation, °C/(g/kg)
b_{is}: absorption factor from wall to man, N. D.
b_{si}: absorption factor from man to wall, N. D.
T_s: mean skin temperature, °C
T_a: ambient air temperature, °C
T_r: mean radiant temperature, °C
V: air movement, m/s
X_{ss}: humidity ratio for boundary layer at skin surface, g/kg
X_a: humidity ratio in ambient air, g/kg
ϕ_s: percentage humidity at skin surface, N. D.
ϕ_a: percentage humidity in ambient air, N. D.
I: clo unit (1 clo = 0.18 m^{2}h°C/kcal), N. D.
η: moisture permeability coefficient, N. D.

3. Heat loss by radiation

When applying and developing Gebhart's absorption factor[1] which deals with reciprocal radiation exchange, the rate of radiation heat exchange between a human body and its surrounding surfaces is given by the following equation[2].

$$\begin{aligned} Q_r &= \varepsilon_s\sigma(T_s+273)^4A_s - \sum b_{is}\varepsilon_i\sigma(T_i+273)^4S_i \\ &= \varepsilon_s\sigma k(\sum b_{si}T_s - \sum b_{si}T_i)A_s \\ &= h_r(T_s - \sum b_{si}T_i)A_s \qquad (1) \end{aligned}$$

$$H_r = \frac{Q_r}{A_s} = h_r(T_s - T_r) \qquad (2)$$

Although the effective surface area for radiation exchange may vary with posture and clothing worn, in the present paper a whole body surface area is applied as an approximation. Since the temperature factor k in Eq (1) can be treated as a constant and the skin of a human body and garment surface would have an emissivity close to that of a black body. A term $\varepsilon_s\sigma k$ can be assumed as a constant value in a temperature range of our daily life. The radiation heat transfer coefficient for an unclothed man is now defined by

$$hr = \varepsilon_s\sigma k \fallingdotseq 5.1 \text{ kcal/m}^2\text{h}^\circ\text{C}$$

The value substituted ;

$\varepsilon_s = 0.95$ N. D.

$\sigma = 4.88 \times 10^{-8}$ kcal/m²h°K⁴

$k = 1.1 \times 10^8$ °K³

Since the surface temperature of clothing worn is less than that of skin, the coefficient value under clothed conditions was also examined[3]. The radiation coefficient resulted in the value of 4.8 to 5.0 kcal/m²h°C corresponding to 1.0 to 0.5 clo and it is justified to use practically $h_r = 5.0$ kcal/m²h°C.

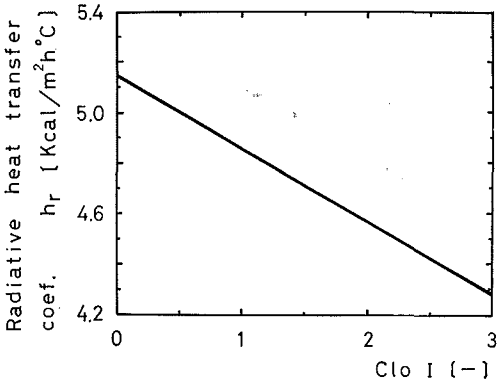

Fig. 1. Relation between radiative heat transfer coefficients and clo value.

Moreover, $T_r = \sum b_{si}T_i$ in Eq (2) expresses a kind of mean radiant temperature and it is defined by a weighted mean of the temperatures of the surrounding surface with absorption factor which includes angle factor. In order to differentiate the mean radiant temperature weighted by angle factor or by area ratio and to avoid confusion brought about by the difference in averaging, a new mean radiant temperature $T_r = \sum b_{si}T_i$ will be refered to as "environmental radiant temperature"[4].

4. Heat loss by convection

The rate of convective heat transfer from a human body to the atmosphere is described by an equation analogous to Newton's cooling law.

$$H_c = h_c(T_s - T_a) \qquad (3)$$

The coefficient takes widely varying values affected by the velocity of air flow and physical properties, shape and size of a human body. Eq (4), a mean convective heat transfer coefficient for a man, was theoretically derived by the author[2]. The diameter of a man-equivalent thermal cylinder model was set at 18 cm and moreover by applying it to the dimensionless equations by Hilpert[5] and by Oosthuizen et al[6], convective heat transfer coefficient with both natural and forced convection taken into considerations at the same time was calculated. Effective convection area is assumed to be equal to a whole body surface area as the same as the case of radiation exchange. As a consequence of surveying various aspects, the equation which calculates the convective heat transfer coefficient for an unclothed and a clothed man was proposed as follows[3].

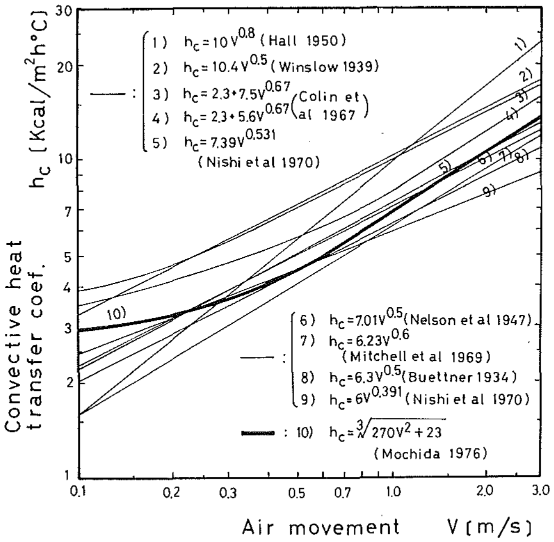

Fig. 2. Convective heat transfer coefficients for human body[2].

$$h_c=\sqrt[3]{270V^2+23} \qquad (0.1 \leqq V \leqq 3.0\ \mathrm{m/s}) \qquad (4)$$

5. Wet heat loss from skin surface

5-1 Two-control model

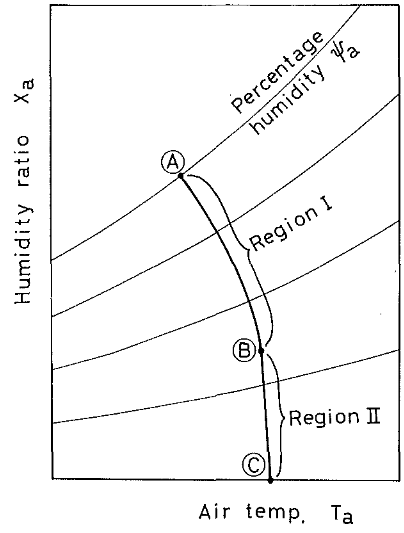

Fig. 3. A schematic line of equal skin temperature by the present model[7].

Wet heat loss means insensible heat loss from skin surface and heat loss of regulatory sweating in this paper. We know from experience that the thermal sensation in the high humidity range differs from that in the low humidy range even if the ambient air temperature in the environment is same. Taking the effect of humidity on thermal sensation into consideration, we make a model which consists of two control regions with regard to wet heat loss—an environmental region where the rate of moisture exceeds the maximum environmental capacity to accept evaporated moisture and an environmental region where the rate of moisture is less than the environmental capacity. We call the former region I and the latter region II[7]. In the present study the discussion is limited within a range where no sweat dripping occurs in the heat and no shivering takes place in the cold.

A locus of equal skin temperature drawn by heat balance equation containing the present model is shown in Fig. 3.

5-2 Rules of wet heat loss

Region I

An environmental region where the rate of moisture exceeds the maximum environmental capacity to accept evaporated moisture is discussed first.

By applying and developing wettendness model by Gagge et al[8] with regard to skin evaporation, the evaporation heat loss in the region I is given by the following equation.

$$H_e = \kappa h_c(\phi_s X_{ss} - X_a) W \qquad (5)$$

Although percentage humidity ϕ_s for boundary layer at skin surface is always unity in wettedness model, that in the present model is assumed to be not always unity and to have a close relationship to environment humidity. As a consequence of a survey from clothing worn, air movement and so forth, we obtained the relation shown in Fig. 4.[7]

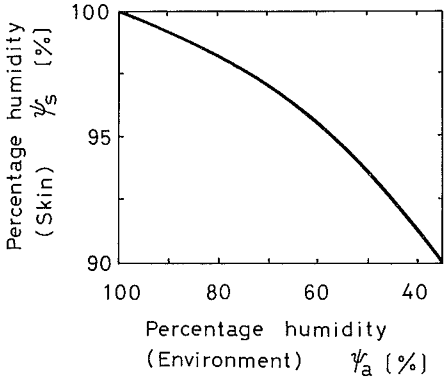

Fig. 4. Relation between percentage humidity at skin and percentage humidity at environment[7].

Region II

This region is an environmental one where the rate of moisture is less than environmental capacity to accept evaporated moisture. In this case man's ability to exude moisture is assumed to have a certain limit. A moisture control center regulates the quantity of moisture G. And wet heat loss is given by the following equation, i. e., the product of the quantity of moisture and the latent heat at skin temperature.

$$H_e = GL \qquad (6)$$

6. Heat loss by respiration

In order to calculate respiration heat loss, the following expression proposed by Fanger[9] is applied in the present paper.

$$H_n = M(0.148 - 0.0014\, T_a - 0.0028\, X_a) \qquad (7)$$

7. Comfort chart

7-1 Heat balance equation

In a steady state a human body exchanges heat with the surroundings through four main channels, namely, radiation, convection, evaporation and respiration and the heat balance between man and his environment is expressed by substituting all the heat loss terms derived above in the form of

$$\text{at region I; } M=P(T_s-T_a)+\kappa R(\phi_s X_{ss}-X_a)W+M(0.148-0.0014T_a-0.0028X_a) \quad (8)$$

$$\text{at region II; } M=P(T_s-T_a)+\eta GL+M(0.148-0.0014T_a-0.0028X_a) \quad (9)$$

where,

$$P=\frac{1}{0.18I+\dfrac{1}{h_c+h_r}}$$

$$R=\frac{1}{0.18I\eta+\dfrac{1}{h_c}}$$

In the above equation, I is clo unit to evaluate thermal resistance of clothing and η is the moisture permeability coefficient[10] as a measure of vapor diffusion through clothing ensemble. The theoretically derived relation between moisture permeability coefficient and clo value is shown in Fig. 5.

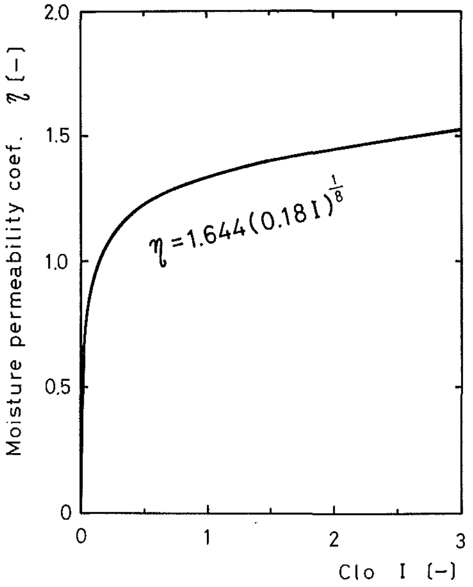

Fig. 5. Relation between moisture permeability coefficient and clo value[10].

7-2 Comfort chart in the original

Line of equal temperature sensation is drawn on a Carrier psychrometric chart as shown in Fig. 6 for an unclothed resting man in a standard condition of uniform temperature with still air movement. The theoretical comfort line in a steady state may show approximately the central line of the measured values. In the present study, skin temperature 33.5°C and wettedness 0.1 represents a combination of variables concerned for a comfortable condition.

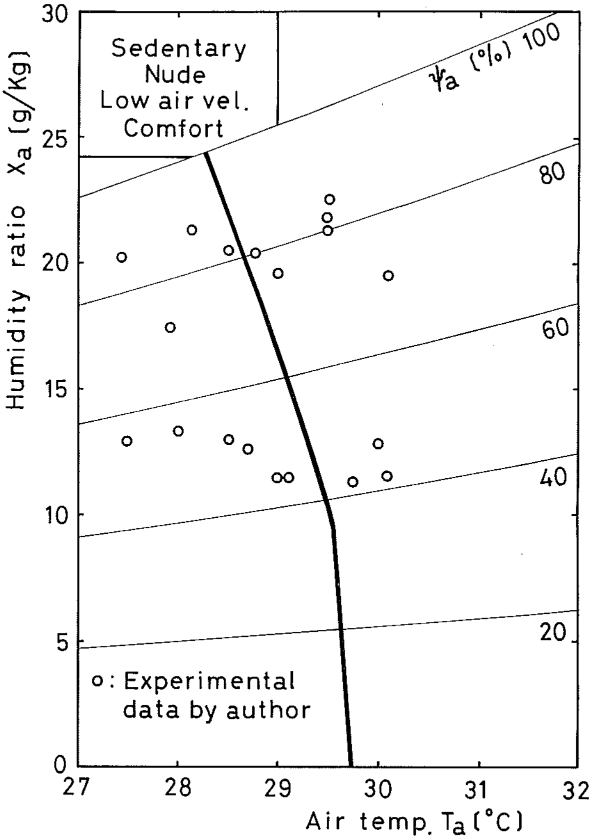

Fig. 6. Verification of the present comfort line.

7-3 Comparison of comfort lines

The proposed comfort line shown in Fig. 6 is based on a "two-control model" and rational heat and mass transfer equations. In Figs 7 and 8 the present comfort line is compared with experimental data and theoretically derived comfort lines by earlier workers. In Fig. 7 we can see good agreements between the comfort lines by Gagge et al, Rohles et al and Fanger and the present line in the high and middle humidity range. On the other hand, in the low humidity range the gradient of the present comfort line has a resemblance to that of the line by Koch et al. This means that the effect of humidity on thermal sensation is small in the low humidity range. Although good agreements between the comfort line by Fanger and that of the present study can be read off Fig. 8 in the high and middle humidity range, we can also see the characteristics of the present model that the slope of

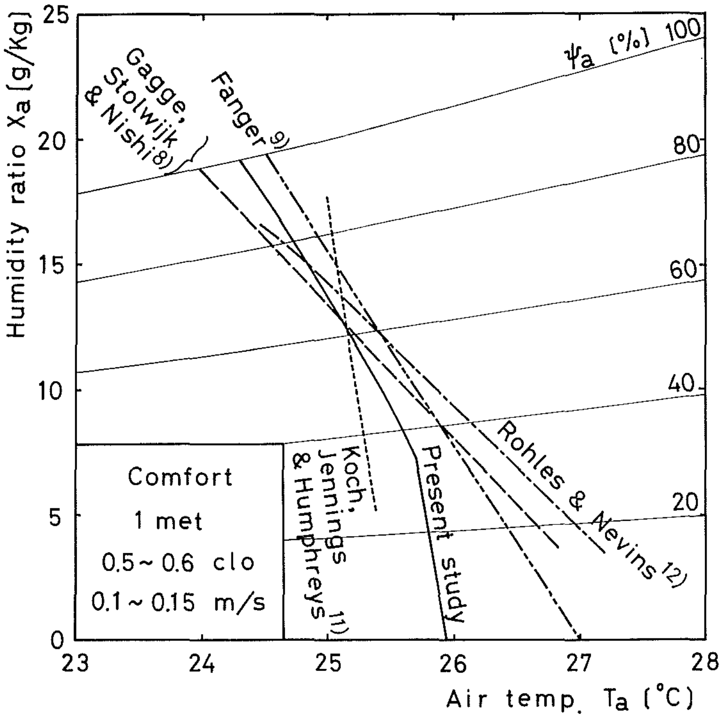

Fig. 7. Comparison of comfort lines (0.6 clo).

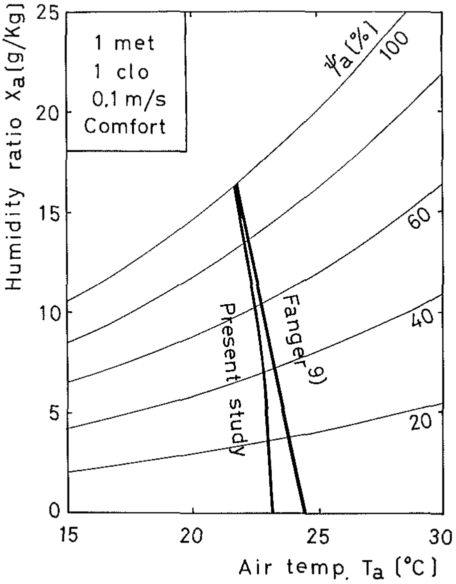

Fig. 8. Comparison of comfort lines (1 clo).

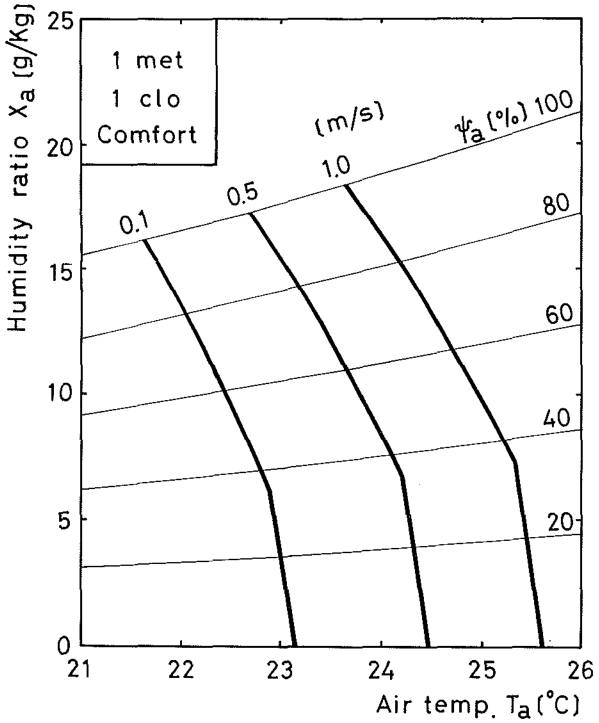

Fig. 9. Comfort lines.

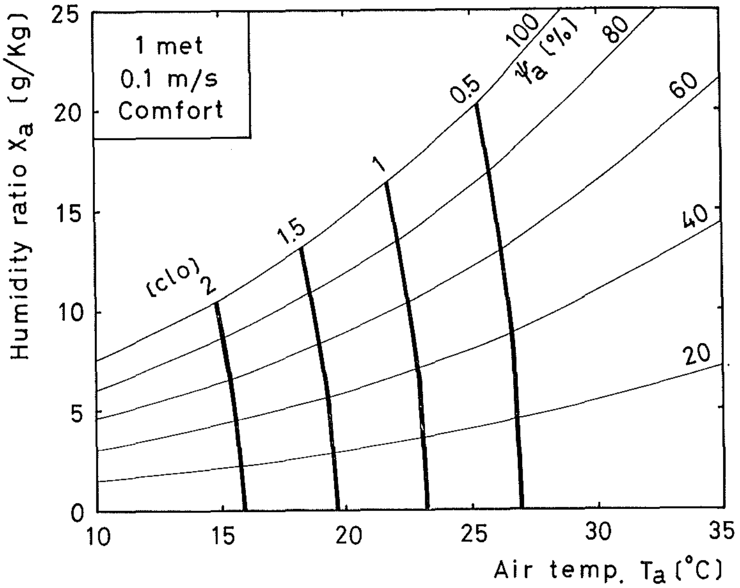

Fig. 10. Comfort lines.

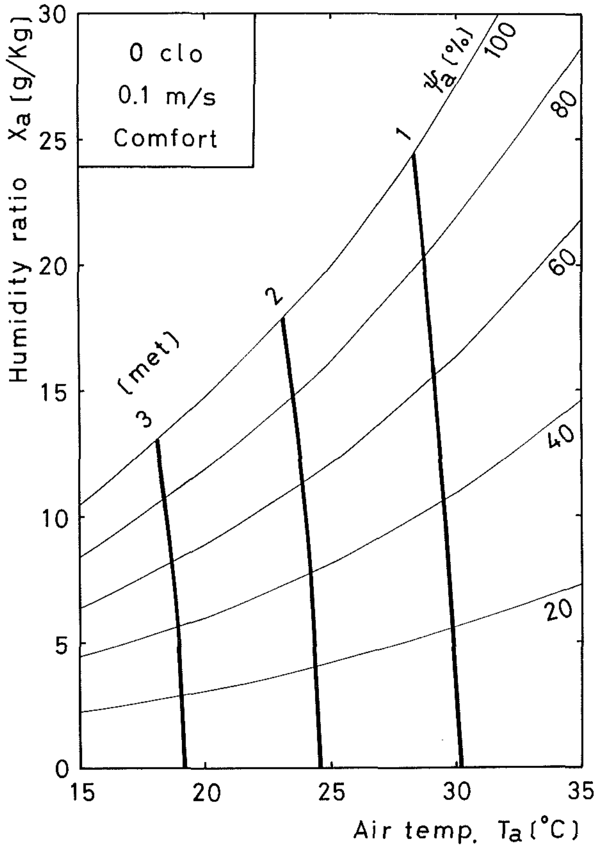

Fig. 11. Comfort lines.

the comfort line becomes steeper as the humidity decreases.

Lines in Figs. 9 to 11 represent combination of environmental factor to give equal thermal sensation for the denoted conditions.

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