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Diffuser Selection for All-Air Heating Systems: Effective Draft Temperature Development

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ABSTRACT

The current diffuser selection guide described in ASHRAE handbook-fundamentals provides a correlation between diffuser characteristics, such as throw length and type, and the performance to distribute supply air and thereby to optimize space air diffusion. The performance of a diffuser is evaluated by using an Air Diffusion Performance Index (ADPI). ADPI is defined as the percentage of occupied zone falling into an acceptable velocity and temperature region determined by measuring effective draft temperature (EDT) that is a calculated temperature difference combining air temperature difference and air speed. However, the EDT was developed in 1960s in terms of limited experimental results of subject experiments, which needs further analysis and more justification. In addition, the current EDT for diffuser selection confines the application to cooling mode only, as stated in ASHRAE Standard-113. This paper presents findings from the project of ASHRAE TRP-1546: Expansion and updating of the Air Diffusion Performance Index Method. In this paper, we analyze the current cooling mode EDT and propose a heating mode EDT by comparing EDT's criteria with Fanger's PMV (Predicted Mean Vote) method adopted by ASHRAE Standard-55. The results indicate that the criteria region of current EDT for cooling mode and proposed EDT for heating mode show compliance to that of 80% thermal acceptance predicted by PMV for occupants in the typical office summer and winter condition, respectively.

INTRODUCTION

Many commercial buildings use all-air delivery systems as a part of Heating, Ventilation, and Air Conditioning (HVAC) systems. The air distribution in an indoor space is created by terminal diffusers, ranging from simple-geometry grills to complicated swirl diffusers. The selection and positioning of diffusers depend on many factors, such as building function, aesthetic requirements and occupant comfort. The main task of air diffusers is to distribute supply air, and to remove indoor cooling or heating loads while providing air velocity and temperature distribution that can achieve occupant comfort. The widely accepted and applied design index that quantifies the performance of diffusers when considering the spatial uniformity of air velocity and temperature and their contribution to thermal comfort is Air Diffusion Performance Index (ADPI) (Miller and Nevins 1969). ADPI is defined as the percentage of occupied zone falling into the acceptable velocity and temperature region determined by measuring local Effective Draft Temperature (EDT); EDT is a calculated temperature difference that combines air temperature and air speed (ANSI/ASHRAE Standard-113 2009).

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As EDT quantifies the deviation of local air temperature from room control temperature (e.g. spatial average temperature) and air speed in the occupied zone, it relates to thermal comfort. However, thermal comfort also depends on other important factors such as relative humidity (RH), mean radiant temperature, metabolic rate and clothing insulation (Fanger 1970, ANSI/ASHRAE Standard-55 2010). Even though Fanger's thermal comfort model is a more comprehensive tool for the holistic evaluation of a wide range of influencing parameters, the EDT provides an easier way - ADPI method - to guide the diffuser selection to maximize occupancy thermal comfort in the building design stage by using the properties of diffusers instead of measuring environmental parameters after the completeness of building construction. Employing the ADPI selection guide in terms of EDT in ASHRAE-Handbook Fundamentals (2009), designers have been more or less successfully designing air diffusion systems for cooling mode since the 1970s (Miller and Nevins 1969, Miller and Nash 1971).

When the first EDT and ADPI-based diffuser selection guide were developed, HVAC systems for delivering warm air in heating mode were uncommon. Nowadays, however, the operation of HVAC systems for heating has been much more popular than before, and HVAC systems have to meet both heating and cooling requirements in most climates (Krarti 2008, Platt et al. 2010). Even though ANSI/ASHRAE Standard-113 (2009) states that "the ADPI method for mixing systems should be applied to traditional overhead air distribution systems under cooling operation only", the same diffusers are used for heating in the winter. The lack of EDT and ADPI method for heating mode often cause underperformance of all-air delivery systems when used for heating (Novoselac and Srebric 2003, Krajčik et al. 2012 and Tomasi et al. 2013). Since EDT is the most important element of the ADPI method, the development of heating EDT is required for future ADPI method used at heating operation.

The general objective of this study is to propose an EDT for heating mode. Specifically, the study uses the established thermal comfort model (Fanger 1970) to analyze the current EDT for cooling and develop EDT for heating.

PREVIOUS RESEARCH ON EFFECTIVE DRAFT TEMPERATURE

The current ADPI method specifies the range of EDT in which most people feel thermally comfortable. EDT indicates effective temperature drop at a local position affected by air jets from diffusers. EDT was first introduced by Rydberg et al. (1949) through the deviation of temperature in an air jet from surroundings as a function of jet velocity, as shown in Equation 1:

$$EDT (\theta') = T_i - T_a - 8.0V_i \quad (1)$$

where T_i is air temperature at the test point, T_a is spatial average air temperature (room control temperature) in the occupied zone and V_i is local air speed.

$(T_i - T_a)$ represents dry-bulb air temperature difference between room average temperature and local air temperature. Similar to local cooler air than surroundings, air motion also leads to a cooling feeling that is equivalent to the feeling of cooler air at a certain level of temperature drop. The coefficient of 8.0 in Equation (1) indicates the equivalent temperature drop caused by air motion at the same coldness felt by a subject. The relationship between temperature difference and air speed when the two factors lead to equivalent cooling effect was investigated at the Technical University at Stockholm by Norbäck (1946). The investigation placed subjects in a horizontal jet of hot air and regulated air temperature and jet velocity to cause the same temperature feeling as the surroundings, according to statements by the subjects. When the subjects were free from draft, Norbäck (1946) obtained the relationship between temperature difference $(T_i - T_a)$ and air velocity (V_i) . The relationship as represented by the coefficient of 8 indicates that the cooling effect due to 1.8 °F (1 °C) temperature drop is equivalent to the effect by increasing air motion of 24.6 fpm (0.125 m/s).

The EDT in Equation (1) considers conditions that heat sources/ sinks are absent in a region where EDT was applied. When considering a subject in still air at the thermal neutral condition, thermal buoyancy by the subject generates thermal plume at a velocity of approximately 30-40 fpm (0.15-0.2 m/s) (Rim and Novoselac 2009). In a discussion of the paper by Koestel and Tuve (1955), Straub modified the EDT described in Equation (1) to account for human buoyancy effect by subtracting its contribution to air velocity, as described in Equation (2).

$$EDT(\theta) = T_i - T_a - 8.0(V_i - 0.15) \quad (2a \text{ SI})$$

$$EDT(\theta) = T_i - T_a - 0.07(V_i - 30) \quad (2b \text{ IP})$$

EDT reflects subjective feeling for coldness in terms of temperature deviation from surroundings and air motion; a probable high percentage (e.g. >20%) of occupants would object to the caused draft when EDT is lower than a critical point. The critical point was determined based on a pioneering study of thermal comfort by Houghten et al. (1938). The study carried out subject measurements for skin temperature of subjects' ankles and necks when exposed to cooler air than surroundings, representing summer cooling condition. Figure 1 illustrates the original experimental setups for skin temperature measurements. Room air temperature and relative humidity were maintained at 70.0 °F (21.1°C) and 50%, respectively. To minimize the effect of room air motion on the results, air velocities in the surroundings of the test subjects were approximately 19.7 fpm (0.1 m/s). The study recorded the drop of local skin temperature of a neck or ankle at various discharge air temperatures and velocities, and surveyed percentages of subjective thermal acceptance accordingly. The results showed that skin temperature drop of 4.0 °F (2.2 °C) represents the border line between satisfactory and unsatisfactory conditions, resulting in approximately 80% thermal acceptance, for the draft feeling at the neck. In addition, a relationship curve between air temperature ($T_i - T_a$) and velocity (V_i) was obtained when skin temperature drop was kept constant of 4.0 °F (2.2 °C) that indicates 80% thermal acceptance.

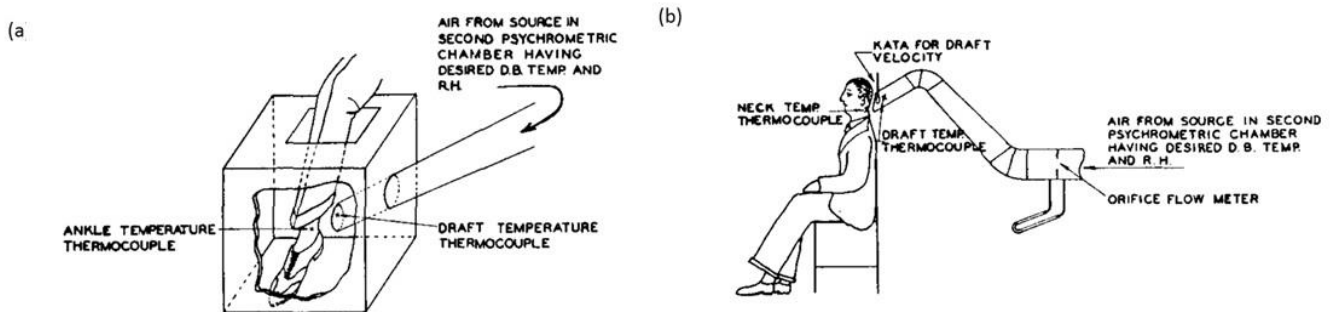


Figure 1 Test arrangements for determining the effects of drafts on the (a) ankle and (b) neck (Houghten et al. 1938); Room temperature: 70 °F (21.1 °C) and discharge air temperature: 62.1-70 °F (16.7-21.1 °C); Room relative humidity: 50%; Room velocity: ~19.7 fpm (0.1 m/s)

Employing Houghten et al.'s (1938) data for 80% of the occupants reporting comfort at exposed necks, Miller and Nevins (1969) determined the critical point of -3 °F (-1.7 °C) for EDT (Equation 2) at the condition of 80% thermal acceptance. Nevertheless, the upper boundary of EDT (Equation 2) of 2 °F (1.1 °C) expressing the feeling of warmth. However, the upper boundary was not well justified in the work by Miller and Nevins (1969), at least that sufficient subject tests were not conducted as the work by Houghten et al. (1938). Furthermore, neither Norbäck's nor Houghten et al.'s experiments took account of other factors that might influence EDT, such as humidity, metabolic activity and clothing insulation. A good example given in the discussion section of Houghten et al.'s study is that "if for any strange reason we are allowed to get rid of our collars in the summer time, and can wear low collars, or if high

shoes should come back, the results would be different”. Also, since the EDT was derived from Houghten et al.’s data based on exposing necks to air cooler than surroundings, the EDT in Equation (2) might be only applicable for summer cooling condition.

FURTHER ANALYSIS OF EFFECTIVE DRAFT TEMPERATURE AT COOLING MODE

As discussed in last section, the EDT derived from subject thermal comfort experiments by Houghten et al. (1938) considers only air temperature drop and velocity. However, thermal comfort involves four additional factors including (1) mean radiant temperature, (2) relative humidity, (3) metabolic rate, and (4) clothing insulation (Fanger 1970). By considering the six parameters, Fanger (1970) developed an index of Predicted Mean Vote (PMV) to physically assess body heat exchange with an environment and thermal comfort. As the PMV has been extensively used to evaluate the feeling of coldness and warmth, this section applies Fanger’s PMV to further analyze the EDT in Equation (2) and provides more justification by taking a typical office space as an example.

When considering mean radiant temperature, Int-Hout (1983) compared the mean radiant temperature and air temperature with common overhead air distribution systems and found that in many cases radiant temperature is relatively close to room air temperature, suggesting a small impact of radiation when included in comfort calculations. A similar conclusion was drawn by Walikewitz et al. (2015). When considering the metabolic rate (Unit: Met.), an office worker normally has a rate ranging from 1.0 to 1.3 Met. In addition, clothing insulation is also an important contributor to occupant thermal acceptance and should be considered in the analysis. The clothing insulation (Unit: Clo.) is typical 0.5 Clo. for an office environment in summer and 1.0 Clo. in winter (ANSI/ASHRAE Standard-55 2010). The only variable that may vary significantly in commercial buildings is relative humidity (RH) and it may have a significant effect on thermal comfort; because the EDT does not take into account RH, this study adopts a most desirable RH of 50% for summer and winter conditions.

The range of EDT in cooling mode for Equation (2) illustrates a region of the relationship between velocity and air temperature difference shown in Figure 2(a). Zero EDT ($\theta=0$) represents a neutral thermal sensation. Figure 2(b) shows the PMV range from -0.5 to 0.5 (80% thermal acceptance) in a plot of air velocity versus temperature for a typical office space in summer (cooling mode) assuming metabolic rate of 1.15 Met., clothing insulation of 0.5 Clo. and relative humidity of 50%. The plot was generated using PMV index according to ANSI/ASHRAE Standard-55 (2010). The region of PMV in this study is limited to air speeds below 0.2m/s as described in the Standard. Neutral thermal sensation is achieved when PMV is equal to zero. Since both EDT =0 and PMV=0 represent the condition of neutral thermal sensation, Figure 2(c) shifts the PMV region (-0.5 to 0.5) in Figure 2(b) to collapse PMV=0 to EDT=0 in Figure 2(a). It shows that the boundaries of PMV region -0.5 and 0.5 overlap with the EDT’s boundaries of -3°F (-1.7°C) and 2°F (1.1°C), respectively.

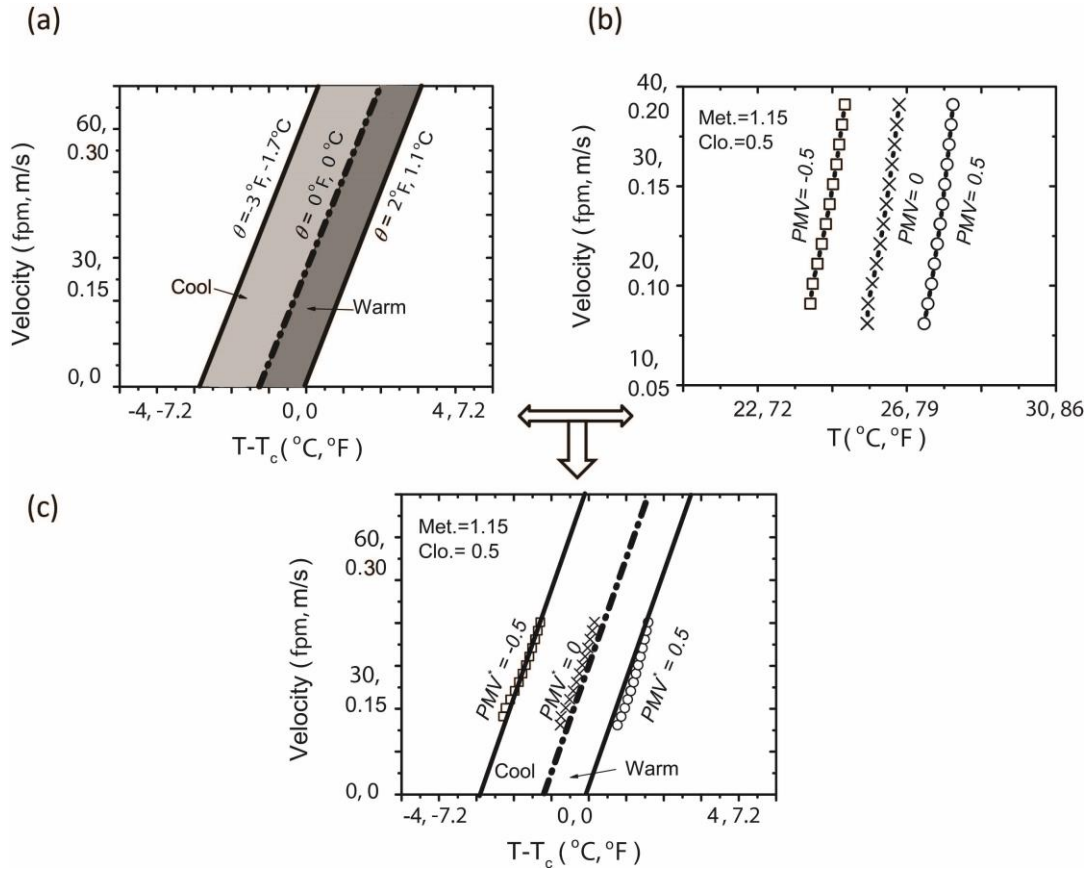


Figure 2 ADPI and PMV as a function of air temperature and velocity for cooling mode (Metabolic activity: 1.15Met., Clothing condition: 1 Clo., and Relative humidity: 50%); (a) The range of 80% comfort acceptance using EDT; (b) The range of 80% comfort acceptance using PMV; (c) Comparison of the comfort regions of EDT and PMV.

Figure 2 suggests that the PMV index for 80% thermal acceptance agrees well with Houghten's 80% thermal acceptance proposed in 1938 (Houghten et al. 1938). The range of the EDT from 80% thermal acceptance can be justified by the elaborate PMV model. The results also indicate that occupant's thermal acceptance has not changed significantly since 1930s.

DEVELOPMENT OF EFFECTIVE DRAFT TEMPERATURE AT HEATING MODE

By employing the same manner as the cooling mode, Figure 3(a) plots the 80% comfort acceptance region calculated using PMV index for heating mode. Because EDT is a function of local air temperature difference and air velocity, EDT for heating mode should have a format of Equation (3):

$$\theta_1^* < EDT (\theta^*) = T_i - T_a - k(V_i - 0.15) ^\circ C < \theta_2^* \quad (3)$$

where θ_1 and θ_2 are the boundaries of EDT's range for heating mode, θ^* is the effective draft temperature (EDT) for heating mode, and k is a coefficient connecting temperature difference to air speed while considering thermal

sensation.

The heating mode EDT can be developed if the coefficient k and two boundaries (θ_1 and θ_2) are determined. Due to the consistence of EDT and PMV regions for 80% thermal acceptance, one can derive the heating mode EDT by curve fitting EDT boundaries with those of PMV. Figure 3(b) shows the best curve fitting of EDT's range according to PMV regions, which gives $k=9.1$, $\theta_1 = -4^\circ\text{F}$ (-2.2°C) and $\theta_2 = 3.6^\circ\text{F}$ (2°C). Therefore, the heating mode EDT* can be written as Equation (4):

$$\theta_1^* < EDT(\theta^*) = T_i - T_a - 9.1(V_i - 0.15)^\circ\text{C} < \theta_2^* \quad (4a \text{ SI})$$

$$\theta_1^* < EDT(\theta^*) = T_i - T_a - 0.08(V_i - 0.15)^\circ\text{C} < \theta_2^* \quad (4b \text{ IP})$$

The criterion's range of EDT (Equation (4)) is between -4°F (-2.2°C) and 3.6°F (2°C). Similar to cooling mode EDT, the velocity of 30 fpm (0.15 m/s) in Equation (4) stands for the velocity of human thermal plume.

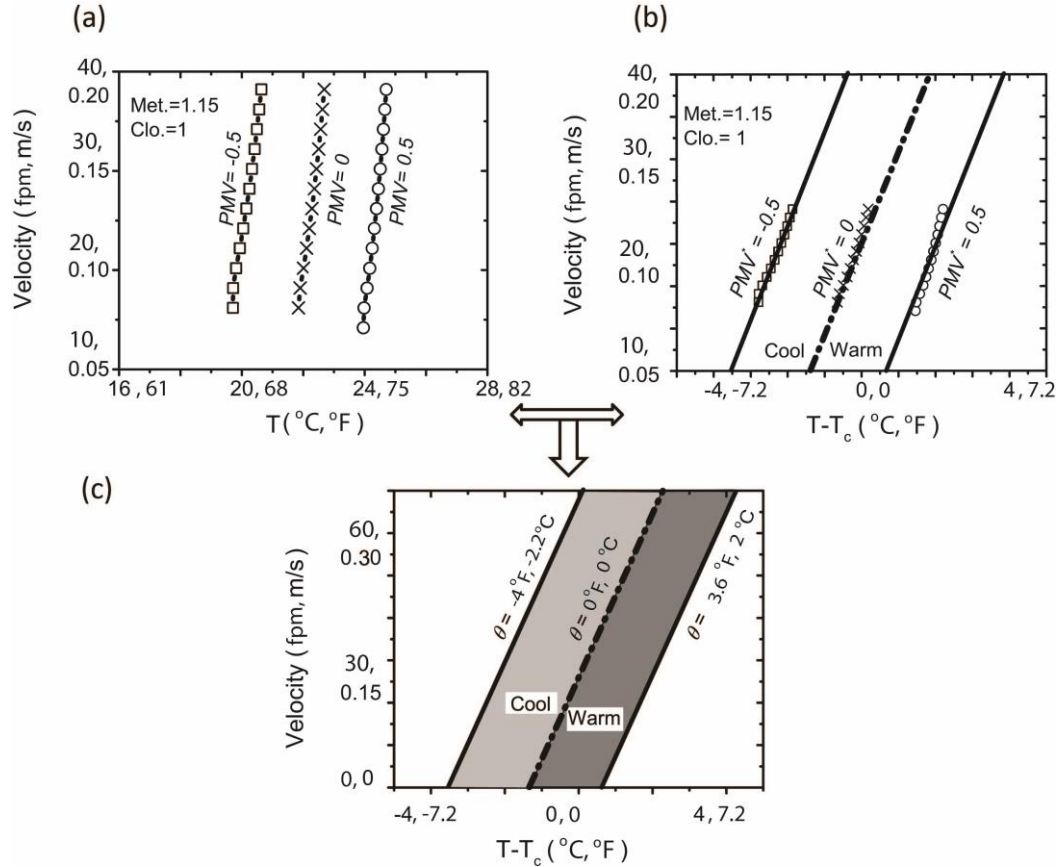


Figure 3 ADPI and PMV as a function of air temperature difference and velocity for heating mode (Metabolic activity: 1.15Met., Clothing condition: 1 Clo., and Relative humidity: 50%); (a) The range of 80% comfort acceptance using PMV; (b) EDT boundaries collapsing to those of PMV for 80% comfort acceptance. (c) The range of 80% comfort

The EDT only considers two variables: air temperature and local air speed. Besides these two variables, however, PMV involves four additional factors involving environmental effects and human behavior: radiant temperature,

humidity, metabolic rate and clothing insulation. This heating mode EDT compares PMV and EDT by fixing the four factors at values for a typical office environment in winter and for only a sedentary office-worker condition. However, indoor relative humidity might be much different in summer and winter. Therefore, the PMV region for 80% thermal acceptance could be different from that in Figure 2 and Figure 3. Under such conditions, the EDT might show less compliance to the PMV index if indoor thermal environment or occupant behavior deviates from the standard office condition used in this study. However, one can modify ADPI method according to PMV using the same manner presented in this paper if needed.

CONCLUSION

This work builds the connection between Fanger's PMV method in ANSI/ASHRAE Standard-55 and EDT method in ANSI/ASHRAE Standard-113 by comparing thermal acceptance using the PMV index and cooling mode EDT based on Houghten's 80% acceptance. The connection provides justification of EDT for cooling mode described in ANSI/ASHRAE Standard-113. Employing the same technique, in addition, a heating mode EDT is developed and shows compliance to PMV as well.

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NOMENCLATURE

θ	=	effective draft temperature for cooling mode, °C
θ^*	=	effective draft temperature for heating mode, °C
k	=	coefficient, °C
T	=	air temperature, °C
V	=	air velocity, m/s

Subscripts

a	=	spatial average
i	=	test point
1	=	left boundary of EDT
2	=	right boundary of EDT

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