

## **Statistic Selection of Coincident Solar Irradiance, Dry-bulb and Wet-bulb Temperatures for Determining Design Cooling Loads**

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### **SUMMARY**

Near-extreme solar irradiance, ambient dry-bulb and wet-bulb temperatures are fundamental data for determining the peak building cooling load. Design solar irradiance has been separately and independently selected by both ASHRAE and CIBSE. This may result in over-estimated cooling loads, and in turn over-sized air-conditioning systems. Hence, a statistic method based on probability theory and heat transfer principles was developed for rational selection of the three coincident design weather data used for calculating peak cooling loads in a building with thermal lag less than one hour. The new method was applied to historic weather records of 25 years in Hong Kong to rationally generate design weather data. These data were compared with those produced by the traditional method. Results show that traditional design solar irradiance, dry-bulb and wet-bulb temperatures may be significantly overestimated when a room or building faces east, south and west. Generating sequences of three coincident weather variables for heavy buildings is also discussed.

### **INTRODUCTION**

Near-extreme weather conditions, including dry-bulb temperature, moisture content and solar irradiation, are essential and fundamental data for the design of building air-conditioning systems [1,2]. They simultaneously act on a building, and are driving potentials of heat transfer through building envelope and direct mass exchange by infiltration and ventilation. Near-extreme coincident design weather conditions are required in determining the peak cooling load for sizing air-conditioning systems [1,2]. Improper design weather conditions may lead to oversized or undersized HVAC system, which will result in unnecessary extra capital cost and low part-load efficiency or frequent failures in providing sufficient cooling. Even a small difference in the design temperature and solar irradiance may have significant economic implications. Hence, coincident solar irradiation, dry-bulb and wet-bulb temperatures should be properly selected.

Engineering design involves a trade-off between maximizing system reliability and minimizing cost [3]. The probability of failure in meeting the required load is expressed as the ratio of the number of hours that the capacity would fail to meet the load to the total operating hours. This probability is called as risk factor here, which is the complement to the system reliability, and equals the difference of one subtracted by the system reliability. It is highly desirable that the design method and the associated design data can help optimize this trade-off. Several professional institutes have revised their design guidelines to incorporate probabilistic design concepts or reliability into design. For instance, the American institute of

Steel Construction Load and Resistance Factor Design specifications and the European and Canadian structural design specifications have been revised [3].

Many researchers have made valuable contributions to the development of weather design conditions in the past decades. ASHRAE has launched a number of research projects, such as ASHRAE RP-754 [4], RP-828 [5], RP-890 [6], and RP-1171 [7]. These ASHRAE research project were aimed at providing, improving and rationalizing the fundamental weather data for HVAC system design.

Thom [8] developed a statistical method for proper selection of outdoor design dry bulb temperatures in winter for heating system sizing. The method took into account the probability that the system could fail to meet the actual load. He found five design dry bulb temperatures with different cumulative probabilities. HVAC engineers may select reasonable design temperatures, based on their experience, for various types of buildings to properly size the system to match the capacity reliability required. Holladay [9] analyzed design weather data from three sources: Summer Weather Data 2.5 percent, the Guide 2.5 percent and Common Use. He found that large differences existed among these data for some locations. He developed a simple weighted average equation for determining the design dry bulb temperature.

Colliver et al [4] statistically determined near-extreme dew-point temperatures and mean coincident dry-bulb temperatures using a 30-year set of hourly weather data from 239 US and 143 Canadian locations. They found that humidity ratios computed from the design extreme dew-point temperature and mean coincident dry bulb temperature is greater, on average, than those from the design extreme dry bulb temperature and mean coincident wet bulb temperature. Colliver et al. [5] further developed criteria and procedures for statistical analysis of weather data and generated sequences of near-extreme weather records for four design parameters. The four parameters are high and low dry-bulb temperature, high dew-point temperature, high enthalpy level, and low wet-bulb depression. They determined four different extreme sequences for each parameter for the 0.4%, 1.0% and 2.0% annual frequencies of occurrence. Colliver et al [6] also analyzed historical weather data to produce annual frequency-of-occurrence design dry-bulb, wet-bulb, and dew-point temperatures with mean coincident values at the design conditions. Their analysis showed that the design dew-point directly derived from coincident dry-bulb and dew-point temperatures had a much higher humidity than that generated from coincident dry-bulb and wet-bulb design conditions.

Mason and Kingston [10] indicated that the use of separately selected coincident dry-bulb and wet-bulb design temperatures would lead to computed cooling loads much higher than actual loads. ASHRAE [1] and CIBSE [2] presented two forms of coincident design dry-bulb and wet-bulb temperatures; one is the dry-bulb temperature at a certain cumulative frequency of occurrence associated with the mean coincident wet-bulb temperature; and the other is the wet-bulb temperature at a certain cumulative frequency of occurrence associated with the mean coincident dry bulb temperature. These coincident design weather data are well applicable to systems the thermal time constant of which is less than one hour [5].

Chen et al [11] pointed out that the dry-bulb temperature at a certain percentile of occurrence together with the mean coincident wet-bulb temperature may not indicate the frequency of occurrence of the cooling load. This is because the defined percentile may not equal the real probability of occurrence of coincident dry-bulb and wet-bulb temperatures. Hence, they developed a statistical method for rational selection of coincident design dry-bulb and wet-

bulb temperatures. These design weather conditions allow engineers to do risk-based air-conditioning design when the effect of solar irradiation on the peak cooling load is negligible. Their study shows that the rationally derived coincident dry-bulb and wet-bulb temperatures could be largely different from the traditional ones.

Generally, solar irradiation should have a significant contribution to building cooling loads, especially for passive or active solar cooling buildings [12]. From the above literature review, however, it can be seen that less attentions have been paid to the design solar irradiance. The current design solar irradiance data do not simultaneously occur with the coincident dry-bulb and wet-bulb temperatures for air-conditioning system design. Therefore, this study is first aimed at developing a method for rational selection of coincident solar irradiation, dry-bulb and wet-bulb temperatures. The second objective is to apply this novel method to historical hourly weather data observed in Hong Kong to generate the coincident design weather conditions. These selected design weather data can be used to design an air conditioning system that can match system reliability desired for a building with thermal time constant less than one hour.

## THEORETICAL METHOD

For a building or room whose thermal lag is less than 1 hour, hourly cooling load  $Q(k)$  may be expressed by [1]

$$Q(k) = \sum_{j=1}^n (UA)_j (t_e(k) - t_{rc}) + m_o c_{pa} (t_{db}(k) - t_{rc}) + m_o h_l (W_o(k) - W_{rc}) + A_{wd} (IAC) [SHGC(\theta(k)) E_D(k) + \langle SHGC \rangle_D E_{dt}(k)] \quad (1)$$

where  $n$  is the number of external envelopes;  $k$  is discrete time, hr;  $A_{wd}$  is window area,  $m^2$ ;  $A$  is the area of external envelope components of a building or room,  $m^2$ ;  $h_l$  is air latent heat,  $2430 \times 10^3$  J/kg;  $c_{pa}$  is the sensible specific heat capacity of air,  $1010$  J/(kg °C);  $E_D$  is direct irradiance,  $W/m^2$ .  $E_d$  is diffuse sky irradiance,  $W/m^2$ ;  $E_{dt}$  is diffuse irradiance,  $E_{dt} = E_d + E_r$ , where  $E_r$  is ground-reflected irradiance,  $W/m^2$ ;  $E_t$  is total solar irradiation incident,  $W/m^2$ ;  $IAC$  is inside shading attenuation coefficient;  $SHGC$  is direct solar heat gain coefficient as a function of incident angle  $\theta$ ;  $\langle SHGC \rangle_D$  is diffuse solar heat gain coefficient;  $t_{rc}$  is presumed constant room air temperature, °C;  $U$  is the overall heat transfer coefficient of walls, roofs or windows  $W/(m^2 \cdot K)$ ;  $m_o$  is outdoor air mass flow rate introduced into room, kg/s;  $W_o$  is outdoor air humidity ratio, kg/kg;  $W_{rc}$  is presumed constant room air humidity ratio, kg/kg;  $\theta$  is incident angle, °;  $n$  is the total number of external envelope components of a building or room;  $t_e$  is sol-air temperature, °C and its calculation may be referred elsewhere [1]. In the small range of near extreme weather conditions, outside air humidity ratio may be approximately expressed by  $W_o(k) = w_1 t_{wb}(k) + w_0$ , where  $w_o$  and  $w_1$  are constants;  $t_{wb}$  is outdoor air wet-bulb temperature, °C.

The number of building characteristic parameters in Equation (1) may be reduced by the following methods. Figure 1 shows how the diffuse solar gain coefficient  $\langle SHGC \rangle_D$  varies with  $SHGC(0)$  in the normal direction for all glazing and window systems listed in ASHRAE Handbook [1]. It can be seen from Figure 1 that  $\langle SHGC \rangle_D$  is approximately equal to  $SHGC(0)$  since their relation can be expressed by

$$\langle SHGC \rangle_D = SHGC(0) - 0.063 \approx SHGC(0) \quad (2)$$

$SHGC$  ratio is defined by

$$r_{SHGC}(\theta) = \frac{SHGC(\theta)}{SHGC(0)} \quad (3)$$

which is the ratio of  $SHGC$  at any incident angle to  $SHGC(0)$  at the normal angle. Analysis of all the glazing and window systems listed in ASHRAE Handbook [1] shows that  $SHGC$  ratios vary similarly at most of the incident angles with the upper and lower limits. Therefore, all the glazing or window systems listed in ASHRAE Handbook [1] are classified into three classes: I, II and III based on the ratio of  $SHGC(\theta)$  to  $SHGC(0)$ . Table 1 shows the average  $SHGC$  ratio values at different solar incident angles.

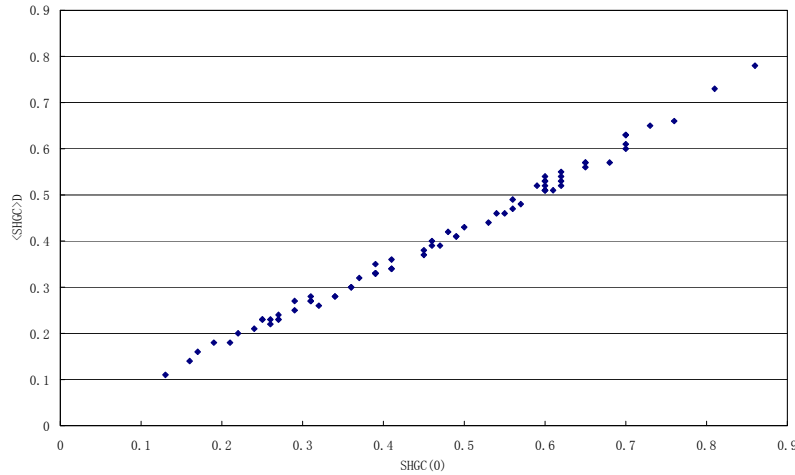


Figure 1 Relation between  $\langle SHGC \rangle_D$  and  $SHGC(0)$  of glazing

Table 1  $SHGC$  ratio values at different solar incident angles

Glazing classes	$r_{SHGC}(\theta)$					
	Normal	40°	50°	60°	70°	80°
I	1.0	0.980	0.940	0.920	0.80	0.50
II	1.0	0.955	0.900	0.855	0.70	0.40
III	1.0	0.920	0.860	0.785	0.60	0.30

Application of the above simplifications to Equation (1) yields

$$Q(k) = \left[ \sum_{j=1}^n (UA)_j + m_o c_{pa} \right] t_{db}(k) + m_o h_l w_1 t_{wb}(k) + \frac{\alpha}{h_o} \sum_{j=1}^{n_w} (UA)_j E_t(k) + A_{wd} (IAC) SHGC(0) [r_{SHGC}(\theta(k)) E_D(k) + E_{dt}(k)] + C_o \quad (4)$$

where

$$C_o = m_o h_l w_o - \left[ \sum_{j=1}^n (UA)_j + m_o c_{pa} \right] t_{rc} - m_o h_l w_{rc} - \sum_{j=1}^{n_{rf}} (UA)_j \frac{\varepsilon \Delta R}{h_o} \quad (5)$$

where  $n_w$  is the number of building opaque envelopes and  $n_{rf}$  is the number of roof types;  $t_{db}$  is outdoor air dry-bulb temperature, °C;  $h_o$  is heat transfer coefficient by long-wave irradiation and convection at outer surface, which is equal to 17 W/(m<sup>2</sup> °C);  $\Delta R$  is difference between long-wave irradiation incident on surface from sky and surroundings and irradiation emitted by blackbody at outdoor air temperature, W/m<sup>2</sup>;  $\varepsilon \Delta R / h_o = 4$  for horizontal surface, =0 for vertical surface;  $\alpha$  and  $\varepsilon$  are the absorptivity and emissivity of the exterior surface of building opaque envelope, respectively.

$C_o$  in Equation (5) is constant when building design and required indoor air conditions are known. It does not impact the selection of design weather data, and hence will not be considered in the statistical analysis of weather data. Only those terms associated with solar

irradiance, dry-bulb or wet-bulb temperature will be analyzed. They can be combined into a single index, which may be called as equivalent weather temperature. Neglecting the constant term and rearranging Equation 6 yields

$$T_e(k) = t_{db}(k) + at_{wb}(k) + bE_t(k) + c[r_{SHGC}(\theta(k))E_D(k) + E_{dt}(k)] \quad (6)$$

with

$$a = \frac{m_o h_l w_1}{\sum_{j=1}^n (UA)_j + m_o c_{pa}}, \quad b = \frac{\alpha \sum_{j=1}^{n_w} (UA)_j}{h_o \sum_{j=1}^n (UA)_j + m_o c_{pa}}, \quad c = \frac{A_{wd}(IAC)SHGC(0)}{\sum_{j=1}^n (UA)_j + m_o c_{pa}} \quad (7)$$

Coefficients  $a$ ,  $b$  and  $c$  in Equation (6) are constant for a given building or room. It can be easily observed from Equations (7) that these coefficients only depend on building design parameters and some constants. Therefore, they reflect the thermal characteristics of buildings, and describe the effect of wet-bulb temperature and global solar irradiance incident on opaque and transparent envelope on cooling loads, respectively. In addition to the three weather variables, the  $SHGC$  ratio and  $r_{SHGC}(\theta(k))$  in Equation (6) also varies with time. Nevertheless, the annual distributions of the  $SHGC$  ratio are fixed for a building or room with one external envelope in a given orientation. Thus, the selection of coincident weather conditions should only depend on the building characteristic parameters,  $a$ ,  $b$  and  $c$  as well as glazing types, and the required capacity reliability for a building or room with one external envelope in a given orientation.

## NEW DESIGN WEATHER CONDITIONS

Air-conditioning system design should aim to optimize system reliability and cost. Coincident design weather data to be selected should allow engineers to design an air-conditioning system that can satisfy the target system reliability or risk. Examination of Equations (4) to (6) indicates that the variation of cooling loads is proportional to the equivalent weather temperature. This means that the percentile of coincident solar irradiance, and dry-bulb and wet-bulb temperatures should be equal to the capacity risk of air-conditioning systems designed with the corresponding weather data.

The Hong Kong Observatory observes dry-bulb and web-bulb temperatures, horizontal global solar irradiance as well as other weather parameters hourly at latitude 22°18'N and longitude 114°10'N [13]. The hourly weather records of 25 years from January 1979 to December 2003 were used for statistic analysis of the peak cooling loads of different buildings. The hourly horizontal global irradiance was first decomposed into direct and diffuse irradiance using the formula given by Lam and Li [14]. The horizontal irradiance can then be converted to the vertical surfaces in eight orientations: north (N), northeast (NE), east (E), southeast (SE), south (S), southwest (SW), west (W) and northwest (NW), using the method given in ASHARE Handbook [1].

Building characteristics largely impacts the selection of design weather data. It can be fully described by the three building characteristic parameters  $a$ ,  $b$  and  $c$ , as well as glazing type. In addition to these three parameters, three classes of glazing are also taken into account. However, no windows were considered on the roof at this stage.

Table 2 shows a sample of coincident design weather data for buildings with the same building characteristic parameters  $a$  (0.60),  $b$  (0.03) and  $c$  (1.00), and glazing class III for the percentile or risk factor of 1.0. The combination of different coincident weather conditions may result in the same cooling loads [11]. In the other words, there are many equal cooling loads occurring at different weather conditions, month, day and time. The design conditions given in Table 2 represent the statistic center of them, which means most of the equal cooling loads occur in or around the design conditions shown in Table 3. Note that the 21<sup>st</sup> of each month can be used as the design day on which the peak cooling load is calculated, following the ASHRAE method [1].

Table 2 Coincident design weather data derived by the new method for Hong Kong

	Glazing class = III, $a = 0.60$ , $b = 0.03$ , $c = 1.0$ , Risk factor = 1.0%								
Orientations	N	NE	E	SE	S	SW	W	NW	H
Equivalent temperature (°C)	215	324	444	531	589	675	667	501	72
Dry bulb temperature (°C)	29.9	29.4	25.3	20.5	20.6	22.5	28.9	29.8	31.3
Wet bulb temperature (°C)	25.9	25.8	21.3	15.5	15.1	17.4	24.3	25.4	26.4
Beam irradiance (W/m <sup>2</sup> )	28	158	244	322	388	466	457	327	828*
Diffusion irradiance (W/m <sup>2</sup> )	155	166	185	203	205	194	181	160	
Month	6	7	10	12	12	11	7	5	7
Hour	15	11	10	11	12	15	16	16	13

Table 3 shows coincident horizontal design solar irradiance, and dry-bulb and wet-bulb temperatures generated by the traditional and new methods for the percentile or risk factor of 0.4 and 2.0. The building characteristic parameters  $a$ ,  $b$  and  $c$  that were used for generating Table 3 are respectively equal to 1.0, 0.03 and 1.0, and window glazing was class III. It can be seen that the rational design solar irradiance decreases with the increase of risk factor on the horizontal surface. The design solar irradiance is kept constant for all the risk factors because the traditional calculation of design solar irradiance does not depend on both the risk factor and the other weather parameters. Difference between the traditional and rational design solar irradiances is negligible at the percentile of 0.4, but about 19.5% at the percentile of 2. Difference between the traditional and rational design dry-bulb temperature is about 1.5 °C and the wet-bulb temperature 0.6 to 0.8 °C.

Table 3 Comparison of traditional and new design weather data on horizontal surface

Risk factor	0.4%			2.0%		
Glazing class III $a=1.0$ , $b=0.03$ , $c=1.0$	Dry temp	Wet temp	Solar irradiance	Dry temp.	Wet temp.	Solar irradiance
Traditional	33.0	27.1	907	32.2	26.8	907
Rational	31.5	26.5	895	30.6	26.0	759

Table 4 shows the coincident design dry-bulb and wet-bulb temperatures generated by the two methods for a building with  $a = 0.60$ ,  $b = 0.03$ ,  $c = 1.00$ , glazing class III and risk factor = 1.0%. These design weather data are used for calculating the peak cooling load through vertical building envelopes in different orientations. The ‘Month’ shown in the table means that in the indicated month, the peak cooling load occurs for that vertical envelope in the given orientation. Careful examination of Table 4 shows that all the traditional design dry-bulb and wet-bulb temperatures are overestimated as compared to the rationally derived design temperatures. Difference between the dry-bulb and wet-bulb design temperatures generated by the two methods is generally very large for the vertical envelope in most of the orientations, especially in the east, southeast, south, southwest and west. The traditional

design dry-bulb and wet-bulb temperatures could be more than 6 °C higher than the two rationally derived design weather temperatures.

Table 4 Comparisons of traditional and new design dry-bulb and wet-bulb temperatures

Orient	Month for Peak Load	Traditional		Rational	
		Dry temp.	Wet temp.	Dry temp.	Wet temp.
N	6	32.1	26.7	29.9	25.9
NE	7	32.6	26.9	29.4	25.8
E	10	29.9	24.8	25.3	21.3
SE	12	24.0	20.4	20.5	15.5
S	12	24.0	20.4	20.6	15.1
SW	11	27.0	22.1	22.5	17.4
W	7	32.6	26.9	28.9	24.3
NW	5	30.8	26.0	29.8	25.4

Note:  $a = 0.60$ ,  $b = 0.03$ ,  $c = 1.00$ , glazing class III and risk factor = 1.0%

## DISCUSSION

New near-extreme coincident design solar irradiance, dry-bulb and wet-bulb temperatures have been generated using the novel method given in the second section. It can be seen from the model described by Equations (1) to (7) that the annual percentile of coincident design weather data is now statistically equal to the capacity risk factor of air-conditioning systems designed with the corresponding design weather conditions. This allows engineers to design air-conditioning systems that match the target system reliability probably required by the client. In the other words, the use of these outdoor design weather data will result in consistent sizing air-conditioning systems in different conditions.

Comparison between the traditional and rational design weather data shows that all the traditional data are higher than the rational ones. These differences are significant in many cases, especially when a room or building faces east, southeast, south, southwest and west. The current design solar irradiance could be more than 19% higher than the rational value. The current design coincident dry-bulb and wet-bulb temperatures could be more than 6 °C higher as compared to the newly generated design dry-bulb and wet-bulb temperatures. This will significantly impact the peak latent as well as sensible cooling load.

The new method can also tell us when the peak cooling load occurs, and hence HVAC engineers can avoid calculating 24 hour cooling loads on one design day in each month of the year. This significantly simplifies the design cooling load calculation.

Although the new design weather data can be used only for direct determining the peak cooling load in a building with a thermal lag less than one hour, the new method provides a basis for the further generating coincident design weather data for any buildings.

Based on the principle of the new rational method, all the independent heat sources may be described with the discrete Fourier series [15]. Cooling load,  $Q_{cl}$ , due to these sources can be computed by

$$Q_{cl} = \sum_{i=1}^4 \sum_{n=-N}^N H_i(j\omega_n) u_{n,i}(j\omega_n) \exp(j\omega_n t) \quad (8)$$

where  $H_i$  is Fourier transfer function with respect to any heat source,  $u(j\omega_n)$  is the coefficient for each harmonic ( $\omega_n$ ),  $t$  is time,  $n$  is the harmonic number, and  $j = \sqrt{-1}$ . The amplitude and phase angle of the complex transfer function represent the heat transfer level and thermal lag of building envelopes. Like building characteristic parameters  $a$ ,  $b$  and  $c$  in Equation (7), the amplitude and phase angle of transfer functions fully represent the physical characteristics of medium and heavy buildings. Therefore, the selection of sequences of three coincident design weather variables fully depends on these parameters. Similar to Table 2, sequences of the design weather data can be uniquely determined by glazing type, building characteristic parameters, and desired risk factor.

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