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Outdoor design conditions for HVAC system design and energy estimation for buildings in Hong Kong

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Abstract

Outdoor design conditions are important for heating, ventilating and air-conditioning (HVAC) system design and energy estimation for buildings. A research study on the determination of outdoor design conditions for HVAC applications in Hong Kong is presented here. Methods for determining outdoor design conditions are examined and the existing data for Hong Kong are studied. New design data developed from the latest weather database compiled for Hong Kong are provided. The characteristics of the Hong Kong climate are studied from the 33-year long-term statistical distributions of its hourly dry-bulb and wet-bulb temperatures. Significance, properties and proper selection of outdoor design conditions for HVAC design are then discussed. It is hoped that designers can assess critically the outdoor design conditions they have taken for granted for their building design and evaluate suitable data for design weather based on their applications and risk levels.

Keywords: HVAC system design; Outdoor design conditions; Energy estimation

1. Introduction

Outdoor design conditions are weather information for design purposes showing characteristic features of the climate at a particular location. They may include data on climatic variables like air temperature, humidity, wind conditions and solar radiation. The design conditions are important because they form the basis for heating, ventilating and air-conditioning (HVAC) system design and energy estimation for buildings. However, designers often find it difficult to understand and to assess the precise effect these conditions may have upon the design and load/energy performance of buildings.

The usual approach in HVAC system design involves computation of peak design load at a specific hour of a design day using indoor and outdoor design conditions [1]. Design weather data, established from outdoor design conditions, are used to represent severe and prevailing climatic conditions under which the building is to function. They are employed in design load calculations for determining peak design loads and appropriate capacity of HVAC equipment and plants. Once the equipment sizes and system configurations are determined, year-round energy calculations can then be performed to estimate the annual and seasonal energy requirements using typical weather data [2].

The design conditions directly affect the load on HVAC equipment by influencing the transmission of heat across exterior building structure and the difference in heat content between outdoor and inside air [3]. Equipment and plant sizes (hence the first cost of the system), building operational strategies and responses, indoor thermal comfort and subsequent building energy consumption will be affected when different sets of outdoor design conditions are used. If optimum design is to be achieved on initial costs and building energy efficiency, the design conditions should be selected with care and the effects and implications of them on load and energy performance should be better comprehended and evaluated with considerations for the application in hand.

Data for outdoor design conditions are usually determined by statistical analyses of long-term meteorological records collected from relevant weather stations. Traditionally, outdoor design temperatures which indicate extreme conditions for thermal load calculations are most important [4–7]. Other supporting design data may be included depending on the situation. The types and quality of data required for the design conditions

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may range from a very simple set of design temperatures to detailed descriptions of the local weather conditions. For example, values for summer and winter design temperatures may be all that are needed to be specified in the outdoor design criteria in a building project design report and in a building energy code; whereas more comprehensive design weather data are required for carrying out building energy analysis and simulation. In either case, data for the design conditions should be established based on acceptable standards and detailed research studies well supported with background information and explanations.

Existing data on local climatic conditions of Hong Kong for HVAC applications are very limited. Standard method and detailed data for outdoor design conditions are not presently available. Usually, building designers tend to adopt their past experiences and the general recommendations from relevant professional bodies such as ASHRAE and CIBSE [1]. The design data from these bodies are often established from approximate method and general world weather data [8]. The design conditions have not been properly validated and updated, and they are not detailed enough for building energy simulation and analysis. Therefore, there is a need to establish more comprehensive data on weather information for Hong Kong based on more recent and detailed local meteorological data. With a better understanding of outdoor design conditions for HVAC applications, it is hoped that building designers can evaluate suitable design data on weather for their applications and acceptable risk levels.

2. Methods for determining outdoor design conditions

Appropriate methodology for determining outdoor design conditions depends on the availability of weather data, use of the information and any relevant local regulations. Different methods and types of data may be required for different applications and situations. In general, the design conditions for HVAC applications usually include the following data:

- information on location such as latitude, longitude and elevation;
- outdoor design temperatures including dry-bulb temperature (DBT) and wet-bulb temperature (WBT);
- data on diurnal and seasonal variations of temperatures such as daily ranges, yearly ranges and extreme values;
- wind data such as prevailing wind directions and speeds;
- data on humidity or moisture content;
- cloud data and solar radiation data;
- other data such as rainfall (precipitation), degree-days and temperature distributions.

Current methods for determining outdoor design temperatures are similar in basic principle. Design temperatures for the summer and winter periods (for cooling and heating designs) are specified respectively by the highest and lowest temperatures likely to be encountered at a specific frequency of occurrence, expressed as a percentage or the number of days/hours per year. The lower the frequency level, the more stringent will be the design temperature. Basically, the usefulness of these design temperatures is based on the assumption that the frequency level of a specific temperature over a suitable time period will repeat in the future [1]. Therefore, the design data can be used for assessing the effects on proposed design.

Different bodies have provided different data on outdoor design conditions, some in very different format and quality. A survey of the available methods and data which may be suitable for Hong Kong has been conducted. Four approaches to outdoor design conditions for HVAC applications are identified and they are briefly explained below. Detailed descriptions of the methods can be found in the relevant sources in the references.

2.1. The ASHRAE method

Developed by the American Society of Heating, Refrigerating and Air-Conditioning Engineers, this method is most widely accepted in the HVAC industry. Design temperatures for the summer frequencies of 1%, 2.5% and 5%, and the winter frequencies of 99% and 97.5% are provided, and full hourly temperature data are required for this approach [1]. Other design data given include mean daily range of temperatures, mean annual extreme of DBT, wind direction and wind speed. Design data developed from the ASHRAE method for locations in the United States, Canada and some selected places in the world (including Hong Kong) can be found in Refs. [1,9].

When determining the design temperatures, the months of June, July, August and September with a total of 2928 hours are taken as the summer period in the northern hemisphere whereas the months of December-March with a total of 2904 hours are taken in the southern hemisphere. Similarly, the months of December, January and February with a total of 2160 hours are taken as the winter period in the northern hemisphere whereas the months of June, July and August with a total of 2208 hours are taken in the southern hemisphere.

From an energy conservation point of view, ASHRAE Standard 90A-1980 [10] recommended that values from

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[1] ASHRAE is the American Society of Heating, Refrigerating and Air-Conditioning Engineers and CIBSE is the Chartered Institution of Building Services Engineers.

the significance levels of 97.5% values for winter and 2.5% for summer should be used. The latest ASHRAE/IES Standard 90.1-1989 [11] however stipulates that cooling design temperatures (for the summer period) shall be no greater than the design DBT listed in the 2.5% column or statistically similar to 0.5% annualized value. For the winter period, the heating design temperature shall be no lower than the design DBT listed in the 99% column or statistically similar to 0.2% annualized value.

2.2. The Australian method

The Australian method, also known as the "summer 3pm and winter 8am" design conditions [12–14], is developed based on the method in the Carrier Air Conditioning Handbook [3]. Two severity levels, namely the comfort and critical design criteria, are specified for both summer and winter design conditions. Only 3pm and 8am data are required for establishing the comfort criterion while full hourly data are required to establish the critical criterion [15,16]. The frequency of occurrence over the year is taken for the design temperatures and no summer and winter periods have been defined. Other weather information given includes the average daily and yearly range of DBT. Temperature corrections using the yearly range and daily range can be applied to the design temperature to establish hourly values for a design day in each month [12,13].

For comfort summer design temperatures, the 3pm DBT and WBT which are individually exceeded on 10 days per year ($10/365 \approx 2.7\%$) are chosen. For critical process installations, summer design temperatures are the DBT and WBT which are individually exceeded on 0.25% of the plant operating hours. Similarly, for comfort winter design temperatures, the 8am DBT which is not exceeded on 10 days per year is chosen. The design outdoor relative humidity should be taken as 80%. For critical process installations, winter design temperature is the DBT which is not exceeded on 0.25% of the plant operating hours. Two sets of values, one for 24-h plant operation and one for 08:00–18:00 operation, are given for both the summer and winter design conditions.

Outdoor design conditions developed based on the Australian method for locations in Australia and Papua New Guinea can be found in Refs. [13,14]. Design data for New Zealand are also provided but they are determined in the 1%, 2.5% and 5% format similar to the ASHRAE method. Unfortunately, there is no design data for Hong Kong developed nowadays using the Australian method.

2.3. The CIBSE method

By studying the frequency, duration and coincidence of weather parameters in the cold and warm periods, the Chartered Institution of Building Services Engineers has established climatic design data for the UK including degree-days, percentage frequency, banded weather data, wind data, precipitation, etc. [8,17,18]. Emphasis was put on heating system design essential to the UK climate, and consideration was given to the thermal time-lag of building structure and overload capacity of the heating system [7].

An approximate method using average monthly and daily extremes of DBT and relative humidity has been employed to establish general design data for some selected locations around the world (including Hong Kong) [8]. The ASHRAE data (winter 97.5%) were also referred to for the winter design temperatures under this method. A summary of the general design data for Hong Kong recommended by ASHRAE and CIBSE is shown in Table 1. It can be seen that some of their data agree with each other and some do not.

2.4. The Chinese method

General design conditions for HVAC applications for major cities in China (including data for Hong Kong) can be found in the relevant National Standard [19]. Norms for major meteorological elements are also offered in addition to the general HVAC design data. Weather information like design temperature and humidity, average wind speed, prevailing wind direction and frequency, atmospheric pressure, extreme temperatures, daily range, etc. are provided together with some guidelines for simplified design temperature calculations [20]. Unlike the ASHRAE and Australian methods, design temperatures and humidity are specified for different applications including heating, ventilating and air-conditioning, respectively. The criteria for determining the design temperature and humidity for these applications are summarized in Table 2.

Frequency levels in number of days/hours per year are usually employed and they are called 'not-guaranteed' days/hours in the Chinese Standard [19]. The annualized percentage frequencies for the criteria have been calculated from these frequency levels and are given in parentheses in Table 2 for comparisons. For example, the annualized percentage frequencies of design DBT for air-conditioning purposes are 0.3% (1 day not-guaranteed) and 0.6% (50 hours not-guaranteed) for winter and summer respectively. Extracts of the design data for Hong Kong and some selected locations in mainland China are shown in Table 3.

2.5. Comments

Three of the four methods surveyed above have offered general design data for Hong Kong. But their data, very different in type and quality from each other, are not detailed and accurate enough for the purposes

Table 1
General outdoor design conditions for Hong Kong from ASHRAE and CIBSE

(a) Information on location (same for both ASHRAE [1] and CIBSE [8])
Country and station: Hong Kong, Hong Kong
Latitude = 22° 18′ N Longitude = 114° 10′ E Elevation = 33 m

(b) Design data from ASHRAE [1]

Summer (°C)								Winter (°C)			Prevailing wind		
Design dry-bulb			Mean daily range	Design wet-bulb				Mean of annual extremes	Design dry-bulb		Wind direction		Wind speed (m/s)
1%	2.5%	5%		1%	2.5%	5%			99%	97.5%	Summer	Winter	
33	33	32	6	27	27	27		6	9	10	west	north	5

(c) Design data from CIBSE [8]

	Summer	Winter
Design month	July	–
Design dry-bulb temp.	33 °C	10 °C
Design wet-bulb temp.	28 °C	–
Average diurnal range	5 °C	–
Precipitation	Annual = 2162 mm; average monthly: wettest month = 394 mm, driest month = 30 mm	

Table 2
Criteria for determining the design conditions using the Chinese method

Intended system application	Design parameter considered	Criteria for determining design conditions [a]	
		Summer	Winter
Heating	design temperature		5 days per year of daily mean DBT (1.4%)
Ventilating	design temperatures	mean DBT at 14:00 of the hottest month	mean DBT of the coldest month
Air-conditioning	design temperature	50 h per year of hourly DBT (0.6%)	1 day per year of daily mean DBT (0.3%)
	design humidity	50 h per year of hourly WBT (0.6%)	mean %RH of the coldest month
	daily mean temperature	5 days per year of daily mean DBT (1.4%)	

[a] The percentage figure given in parenthesis is the annualized frequency level estimated from the criteria.

of design evaluation and building energy analysis. Not all of the design data suggested from these methods are directly useful to building designers and to the situations in Hong Kong because the bodies developing these methods and data may have different emphases and assumptions. Where possible, references made to detailed meteorological data and local conditions are always preferred if accurate and reliable design conditions are required [2,8].

Discussions with practising building services engineers in Hong Kong indicate that most designers tend to take the external design conditions of 33 °C DB/28 °C WB for summer and 10 °C for winter as the rule of thumb. However, very few of them can understand and are aware of the degree of uncertainty borne with these values and their likely consequences. The basic concepts of design temperatures from these four methods are similar but users of the design data are often puzzled by the various formats proposed for the frequency levels which are usually not directly compatible with each other. There is a need to examine the design conditions, to develop accurate and reliable design data for building designers, and to study the implications that the selection of these conditions will have on optimum design of the building system.

Table 3
Extracts of outdoor design conditions for Hong Kong and some selected locations in China [a]

Location [b]	Winter design DBT (°C) [c]				Summer design DBT (°C)				A/C WBT (°C)
	Htg	A/C	D_{min}	Vent	Vent	A/C	AC_{mean}	D_{range}	
Hong Kong	10	8	6	16	31	32.4	30.0	4.6	27.3
Guangzhou	7	5	2.9	13	31	33.5	30.1	6.5	27.7
Fuzhou	6	4	1.6	10	33	35.2	30.4	9.2	28.0
Shanghai	−2	−4	−6.9	3	32	34.0	30.4	6.9	28.2
Beijing	−9	−12	−15.9	−5	30	33.2	28.6	8.8	26.4

Location	Annual mean DBT (°C)	Hottest month mean DBT (°C)	Design relative humidity (%)			Absolute min DBT (°C)	Absolute max DBT (°C)	Mean of daily extreme DBT (°C)	
			Mean for coldest month	Mean for hottest month	Mean of hottest month at 14:00			Daily min	Daily max
Hong Kong	22.8	28.6	71	81	73	0.0	36.1	5.6	34.4
Guangzhou	21.8	28.4	70	83	67	0.0	38.7	1.9	36.3
Fuzhou	19.6	28.8	74	78	61	−1.2	39.8	0.9	37.7
Shanghai	15.7	27.8	75	83	67	−10.1	38.9	−6.7	36.6
Beijing	11.4	25.8	45	78	64	−27.4	40.6	−17.1	37.1

[a] The information given in this Table is extracted from Ref. [19] (in Chinese).

[b] General information for the five locations:

	Longitude	*Latitude*	*Elevation*	*Period of records*
Hong Kong	22° 18′ N	114° 10′ E	32 m	1951–1980
Guangzhou	23° 08′ N	113° 19′ E	6.6 m	1951–1980
Fuzhou	26° 05′ N	119° 17′ E	84 m	1951–1980
Shanghai	31° 10′ N	121° 26′ E	4.5 m	1951–1980
Beijing	39° 48′ N	116° 28′ E	31.2 m	1951–1980

[c] Abbreviations: DBT = dry-bulb temperature; WBT = wet-bulb temperature; Htg = heating; A/C = air-conditioning; Vent = ventilating; D_{min} = average daily minimum; AC_{mean} = daily mean DBT for A/C; D_{range} = daily range; A/C WBT = design WBT for A/C in summer; min = minimum; max = maximum.

3. Determining outdoor design conditions for Hong Kong

The Royal Observatory Hong Kong (ROHK) is the local weather station in Hong Kong. Weather data and climatic information for Hong Kong have been collected from the ROHK [21,22] and hourly temperature data have been analysed in this study. A Hong Kong weather database for HVAC applications and building energy analysis is being established at the City Polytechnic of Hong Kong and the database forms an important basis for this research study. Table 4 shows a summary of the long-term monthly averages of DBT, WBT and global solar radiation (GSR) on a horizontal surface. It can be seen that monthly DBT ranges from 15.7 °C in January to 28.6 °C in July. The monthly profile for WBT is very similar to that for DBT with a minimum of 13 °C in January and a maximum of 26 °C in July. GSR ranges from 10.9 MJ m^2 in February to 19.1 MJ m^2 in July. It is interesting to see that maximum GSR coincides with DBT and WBT, but minimum GSR does not.

3.1. The summer and winter periods

The summer and winter periods serve to indicate respectively the cooling and heating seasons for the design of thermal systems. In general, they should include the warmest and coldest months in a year during which cooling/heating requirements dominate. However, no clear-cut definition can be found because locations with cold climate may have large heating requirements in summer while locations with tropical climate may have large cooling requirements in winter. The general approach is to select the four calendar months with the highest long-term monthly average of DBT as the summer period, and the three months with the lowest long-term monthly average of DBT as the winter period [1,9]. For the present study, the approach has been extended to consider long-term monthly averages of WBT and GSR as well. Long-term data for DBT, WBT

Table 4
Monthly average dry-bulb temperatures (DBT), wet-bulb temperatures (WBT) and global solar radiation (GSR) of Hong Kong [a]

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
DBT	15.7	15.9	18.5	22.0	25.8	27.6	28.6	28.3	27.5	25.0	21.2	17.6	22.8
(°C)	(12)[b]	(11)	(9)	(7)	(5)	(3)	(1)	(2)	(4)	(6)	(8)	(10)	
WBT	13.0	13.9	16.6	20.1	23.7	25.4	26.0	25.8	24.7	21.1	17.7	14.4	20.3
(°C)	(12)	(11)	(9)	(7)	(5)	(3)	(1)	(2)	(4)	(6)	(8)	(10)	
GSR	11.6	10.9	11.2	13.2	16.1	16.4	19.1	17.4	16.5	15.7	13.4	12.0	14.5
(MJ/m^2)	(11)	(12)	(10)	(8)	(5)	(4)	(1)	(2)	(3)	(6)	(7)	(9)	

[a] Monthly average DBT and WBT are based on data for the 45-year period from 1948 to 1992 while monthly average GSR is based on data for the 35-year period from 1958 to 1992.

[b] The numbers given in parentheses below each figure are the rankings for the respective monthly values in descending order.

and GSR have been analysed and their respective rankings are shown in Table 4 (in parentheses).

It can be seen that rankings for DBT and WBT are identical, whereas the rise and fall of GSR do not always follow the DBT and WBT. Based on these three climatic variables, June, July, August and September are selected as the summer months. For the winter period, DBT and WBT indicate December, January and February as the winter months whereas GSR indicates January to March. It is believed that for outdoor design conditions, DBT and WBT will have greater influences, and consequently, December, January and February are selected as the winter period.

3.2. *Design temperatures*

Analyses for the summer, winter and whole-year periods have been conducted on hourly temperatures for the 33-year period from 1960 to 1992. Design temperatures at significant levels from 0.1% to 10% have been determined and the percentile results are summarized in Table 5. Coincident wet-bulb (CWB) is the mean of all WBT occurring at the design dry-bulb (DDB) while coincident dry-bulb (CDB) is the mean of all DBT occurring at the design wet-bulb (DWB). The design temperatures are also plotted against the significance levels in Fig. 1.

It can be seen from Fig. 1 that for both the summer period and the low percentage range of the whole-year period, CDB are lower than DDB, and CWB is lower than DWB. However, for both the winter period and the high percentage range of the whole-year period, the coincident values are higher than their design ones. This suggests that independently determined design temperatures are more stringent than their corresponding coincident values. For the low percentage range (0.1–10%) the difference between DDB and its CWB is larger than that between DWB and CDB. But for the high percentage range (99–99.9%) the situation is reversed. This means lower humidity conditions are assumed if DDB and its CWB are taken for the summer period or if DWB and its CDB are taken for the winter period. It will be explained further in the analysis of frequency distributions for coincident DBT and WBT pairs.

3.3. *Significant levels*

Choice of significance level and hence the corresponding basic design temperatures are empirical. The decision is often based on considerations for local practices, numerical neatness and their effects on overload capacity and operation [7]. Significance levels in percentage frequency (e.g., 1%, 2.5%, 97.5% and 99%) are more systematic and flexible when used for risk analysis calculations. They can also be expanded easily to cater for other requirements.

When different frequency levels are compared, care should be taken that the summer and winter frequencies are not the same as the annualized frequencies because they employ different bases in the denominator. By studying the frequency distributions for all these periods, it is possible to find out the equivalent frequency level for a different period. The frequency curves in Fig. 1 can be used to estimate the equivalent annualized frequency for each summer and winter frequency, and vice versa. For example, at summer frequency of 2.5%, the DDB is 32 °C. From the DDB curve of the whole-year period (at low % range), 32 °C would mean about 1% annualized value. Similar techniques have been employed by Mason [15,16] for evaluating the design conditions in Australia.

Considering the common design practices and general acceptance by designers, the following significance levels are recommended for HVAC applications in Hong Kong:

- For comfort conditions, summer 2.5% and winter 97.5% should be taken for the design temperatures (the equivalent annualized values are 1% and 99.3% respectively as determined from Fig. 1).
- For critical conditions, summer 1% and winter 99% should be taken for the design temperatures (the equivalent annualized values are 0.4% and 99.6% respectively as determined from Fig. 1).

Table 5
Outdoor design temperatures for Hong Kong based on data for the 33-year period from 1960 to 1992

(a) Design temperature for the summer period at various significant levels: Jun.–Sep., total 2928 h

	10%	5%	2.5%	1%	0.5%	0.1%
DDB (°C)[a]	30.8	31.5	32.0	32.6	32.9	33.6
CWB (°C)	26.5	26.7	26.9	26.9	26.9	27.0
CDB (°C)	30.0	30.7	31.0	31.3	31.7	32.3
DWB (°C)	26.9	27.2	27.5	27.8	28.0	28.5

(b) Design temperature for the winter period at various significant levels: Dec.–Feb., total 2160 h

	90%	95%	97.5%	99%	99.5%	99.9%
DDB (°C)	12.2	10.8	9.5	8.3	7.4	5.6
CWB (°C)	9.4	8.1	6.7	6.0	5.3	3.3
CDB (°C)	13.0	11.7	10.5	9.1	8.5	6.5
DWB (°C)	8.8	7.4	6.2	5.0	4.2	2.7

(c) Design temperature for the whole year period at various significant levels: Jan.–Dec., total 8760 h

	10%	5%	2.5%	1%	0.5%	0.1%
DDB (°C)	29.3	30.4	31.2	32.0	32.4	33.2
CWB (°C)	26.1	26.3	26.6	26.9	27.0	26.8
CDB (°C)	29.0	29.7	30.2	30.8	31.4	32.0
DWB (°C)	26.3	26.7	27.0	27.4	27.7	28.2

	90%	95%	97.5%	99%	99.5%	99.9%
DDB (°C)	15.3	13.6	12.0	10.3	9.1	7.0
CWB (°C)	12.7	11.0	9.1	7.6	6.6	5.0
CDB (°C)	15.6	14.0	12.7	11.2	10.3	8.4
DWB (°C)	12.4	10.4	8.7	6.9	5.8	3.9

[a] DDB is the design dry-bulb and CWB is the coincident wet-bulb temperature with it. DWB is the design wet-bulb and CDB is the coincident dry bulb with it.

3.4. Annual extreme temperatures and mean daily range

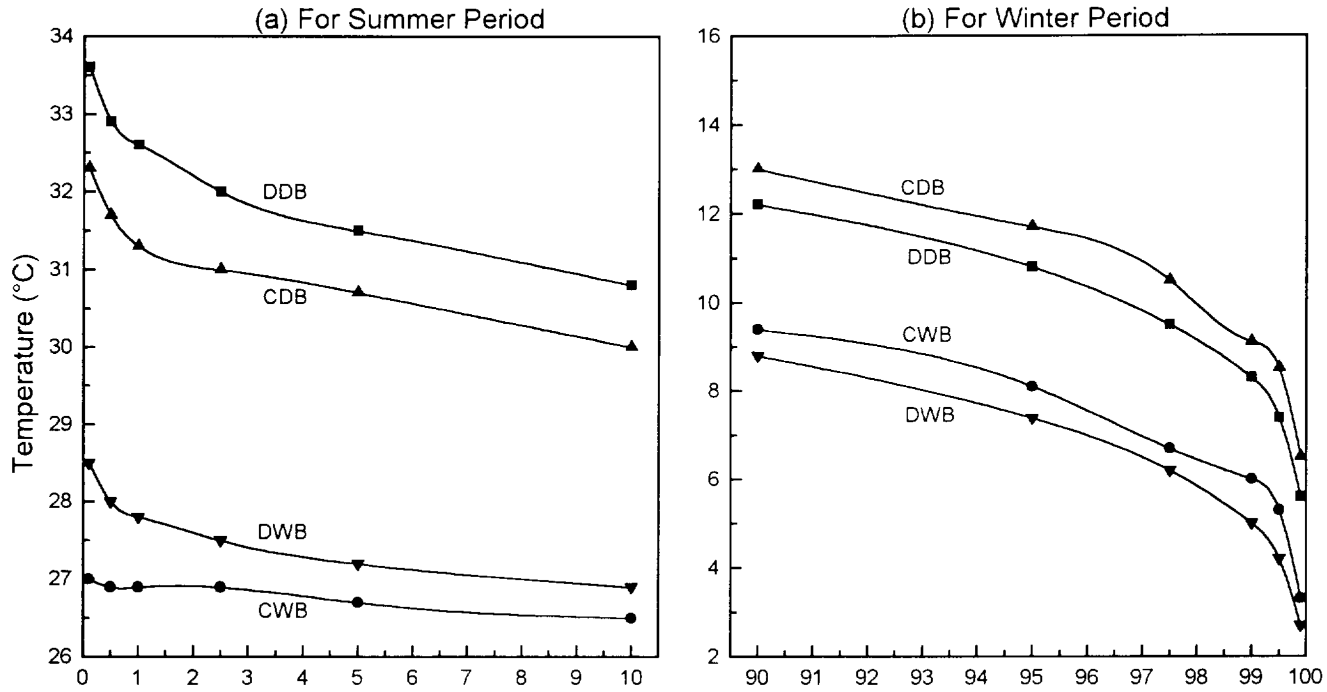
Annual extreme temperatures refer to the absolute maximum and minimum DBT in each year. These absolute maximum and minimum temperatures are from instantaneous daily values, not hourly mean values as employed in the determination of design temperatures. Records of hourly temperatures have a shorter history than extreme temperatures because meteorological measurements were taken at larger time intervals (say, twice a day) in the past early decades. Estimations based on the data for the 45-year period from 1948 to 1992 [21,22] suggest that the means of annual extremes are respectively 34.3 °C for maximum DBT and 6.2 °C for minimum DBT.

Mean daily range is determined from the difference between the average daily maximum and average daily minimum DBT. The daily maximum and minimum temperatures are also obtained from instantaneous values, not hourly mean values as in design temperatures. Fig. 2 shows the monthly averages of these daily maximum and minimum dry-bulb temperatures based on the data for the 45-year period from 1948 to 1992 [21,22]. It can be seen that the mean daily range for Hong Kong is rather constant at about 5 °C all year-round. For the summer and winter periods, the mean daily ranges are 4.95 °C and 5.01 °C respectively. The diurnal variation of temperatures in Hong Kong is comparatively small, which implies that HVAC systems have to operate most of the time on a narrow temperature range.

3.5. Wind data

The effects of wind data on HVAC design and energy calculations are difficult to define and quantify. Except in locations where severe wind conditions predominate, it is believed that the influences of wind on design load and building energy consumption are relatively less important. Wind data are usually needed when ventilation air exchange and infiltration wind pressure are being studied. In those cases the prevailing wind conditions (directions and speeds) that represent average conditions are required.

The ASHRAE method suggests taking only the coincident wind data with the 2.5% summer design DBT and 97.5% winter design DBT. The wind data so



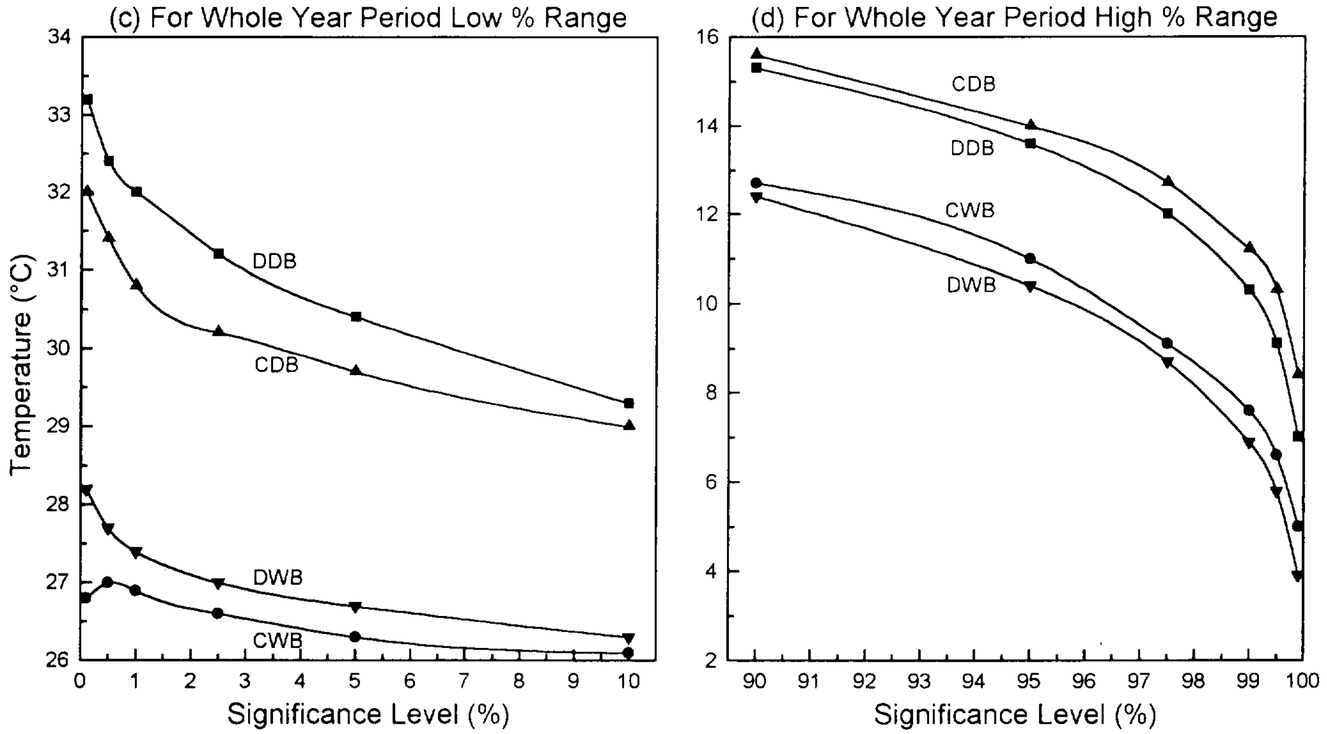


Fig. 1. Outdoor design temperatures for Hong Kong at different significance levels: –■– design dry-bulb (DDB); –●– coincident wet-bulb (CWB); –▼– design wet-bulb (DWB); –▲– coincident dry-bulb (CDB).

determined may not be able to reflect the prevailing wind conditions necessary for use in ventilation and infiltration studies. Therefore, for practical design purposes, the prevailing wind directions and wind speeds as obtained from the ROHK's summary for the 30-year period from 1961 to 1990 are taken here in the outdoor design conditions [21] (a similar approach is taken in the Chinese method). Table 6 gives the monthly values of prevailing wind directions and mean wind speeds in Hong Kong. The prevailing wind direction and speed for the summer period are calculated to be 090 (east) and 5.7 m/s respectively, while those for the winter period are 070 (N 70° E) and 6.8 m/s respectively. For the whole-year period the prevailing

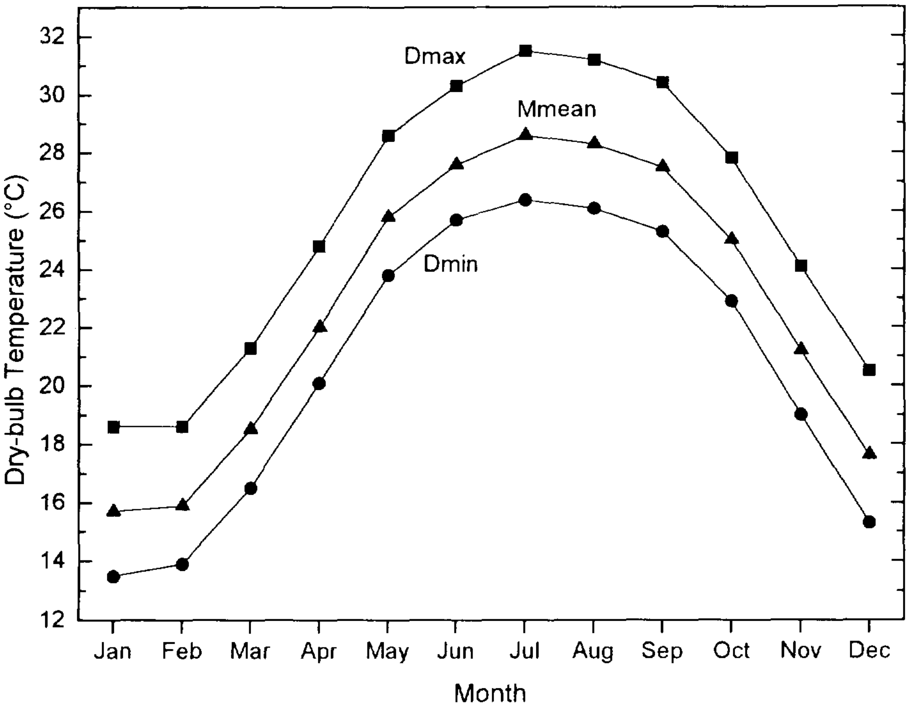


Fig. 2. Monthly average daily maximum and minimum dry-bulb temperatures of Hong Kong, based on monthly data from 1948 to 1992: -■- average daily maximum dry-bulb temp. (D_{max}); -●- average daily minimum dry-bulb temp. (D_{min}); -▲-monthly mean dry-bulb temp. (M_{mean}); D_{max} and D_{min} are based on instantaneous extremes for 1948–1992.

Table 6
Prevailing wind directions and average wind speeds of Hong Kong [a]

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
WDR [b]	070	070	070	080	090	090	230	090	090	090	080	080	080
WSP	6.7	6.6	6.1	5.5	5.3	6.0	5.6	5.1	6.1	7.7	7.6	7.1	6.3

[a] The data are based on the weather summary of the Royal Observatory Hong Kong for the 30-year period 1961–1990 [21].

[b] WDR is the prevailing wind direction in degrees clockwise from north (e.g. 080 = N 80° E) and WSP is the monthly mean wind speed in m/s.

wind direction and speed are 080 (N 80° E) and 6.3 m/s respectively.

3.6. *Summary of outdoor design conditions*

Recommendations on outdoor design conditions for HVAC applications in Hong Kong are summarized in Table 7. Many of the design conditions are close to the general design data suggested by ASHRAE and CIBSE (see Table 1), but more reliable and useful data for HVAC design are offered. It can be seen from Fig. 1(a) that the usual 33 °C DB/28 °C WB rule of thumb for summer is approximately equivalent to taking 0.5% design DBT and 0.5% design WBT for the summer design conditions. That is considered conservative which means over-sizing HVAC plants. As seen from Fig. 1(b), the 10 °C DB for winter lies between 97.5% and 95% design DBT for the winter design conditions which is considered not quite stringent enough for design purposes. However, the slightly undersizing of heating equipment is not crucial because of the short and mild winter in Hong Kong. Percentage frequencies with other values of DBT and WBT can also be found from Table 5 and from the frequency curves in Fig. 1 by interpolations.

4. Analysis on frequency distributions of temperatures

4.1. *Frequency distributions of hourly temperatures*

Frequency distributions of individual hourly DBT and WBT for the 33-year period from 1960 to 1992 are shown in Figs. 3 and 4, respectively. Statistical factors including maximum, minimum, range, mean, median, mode and standard deviation have been calculated for each distribution and the results are summarized in Table 8. Skewness and kurtosis which describe the shape of the curve as compared to a normal distribution are also provided.

Table 7
Recommended outdoor design conditions for Hong Kong

(a) Country and location: Hong Kong, Hong Kong
Weather station: Royal Observatory, Hong Kong
(latitude = 22° 18′ N, longitude = 114° 10′ E, altitude = 33 m)
(b) The summer and winter periods (from the 4 hottest and 3 coldest months):
Summer period = Jun., Jul., Aug. and Sep. (total 2928 h)
Winter period = Dec., Jan., Feb. (total 2160 h)
(c) Design temperatures based on hourly data from 1960 to 1992

	Summer	Winter
For comfort HVAC	(based on summer 2.5% or annualized 1%)	(based on winter 97.5% or annualized 99.3%)
DDB/CWB (°C) [a]	32.0/26.9	9.5/6.7
CDB/DWB (°C)	31.0/27.5	10.5/6.2
For critical processes	(based on summer 1% or annualized 0.4%)	(based on winter 99% or annualized 99.6%)
DDB/CWB (°C)	32.6/26.9	8.3/6.0
CDB/DWB (°C)	31.3/27.8	9.1/5.0

(d) Extreme temperatures based on data from 1960 to 1992

	Hottest month	Coldest month
Design month	Jul. (mean DBT = 28.6 °C)	Jan. (mean DBT = 15.7 °C)
Absolute max./min. [b]	Absolute max. DBT = 36.1 °C	Absolute min. DBT = 0.0 °C
Mean daily max./min.	Mean daily max. DBT = 25.7 °C	Mean daily min. DBT = 20.9 °C

(e) Mean and daily range based on data from 1960 to 1992

	Summer	Winter	Whole year
Mean DBT (°C)	28.2	16.4	23.0
Mean daily range of DBT (°C)	4.95	5.01	5.0

(f) Wind data based on data from 1961 to 1990

	Summer	Winter	Whole year
Prevailing wind			
Wind direction	090 (East)	070 (N 70° E)	080 (N 80° E)
Mean wind speed (m/s)	5.7	6.8	6.3

[a] DDB is the design dry-bulb temperature and CWB is the coincident wet-bulb temperature with DDB. While DWB is the design wet-bulb temperature and CDB is the coincident dry bulb with DWB.

[b] Absolute maximum and minimum DBT are determined based on extreme values between 1884–1939 and 1947–1992 [21].

It can be seen from Fig. 3 that the frequency distributions of summer and winter DBT are close to a normal distribution curve with summer and winter mean DBTs at about 28.2 °C and 16.5 °C, respectively. The shape of the distribution curve for the whole-year DBT is interesting because it shows two marked peaks (one higher than the other) at DBT between 26 °C and 30 °C, and at DBT between 16 °C and 20 °C, respectively. This indicates that mid-seasons in Hong Kong are quite warm and that the year-round temperatures are influenced significantly by the summer and winter distributions. As for the summer WBT in Fig. 4, the distribution is skewed to the right (skewness = -1.513 and kurtosis = 4.357 from Table 8) with a sharp rising platykurtic curve centred at a WBT of about 26 °C. The frequency distribution of winter WBT is close to normal with winter mean WBT at 13.8 °C. The resultant whole year WBT tends to cluster at a WBT between 24 °C and 27 °C but with a mean WBT of only 20.3 °C because of the relatively even spread at the low and mild temperature range on the left-hand portion of the curve.

It has been found that the distributions of temperatures in Hong Kong are skewed to the right (high temperatures) during the summer and to the left (low temperatures) during the winter. One possible expla-

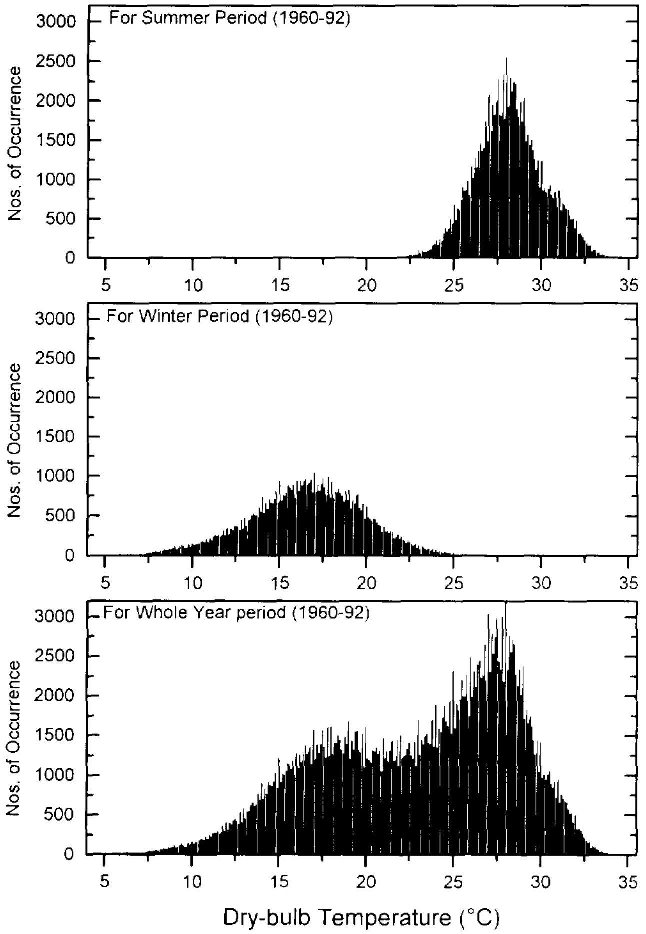


Fig. 3. Frequency distribution of dry-bulb temperatures of Hong Kong based on hourly data from 1960 to 1992.

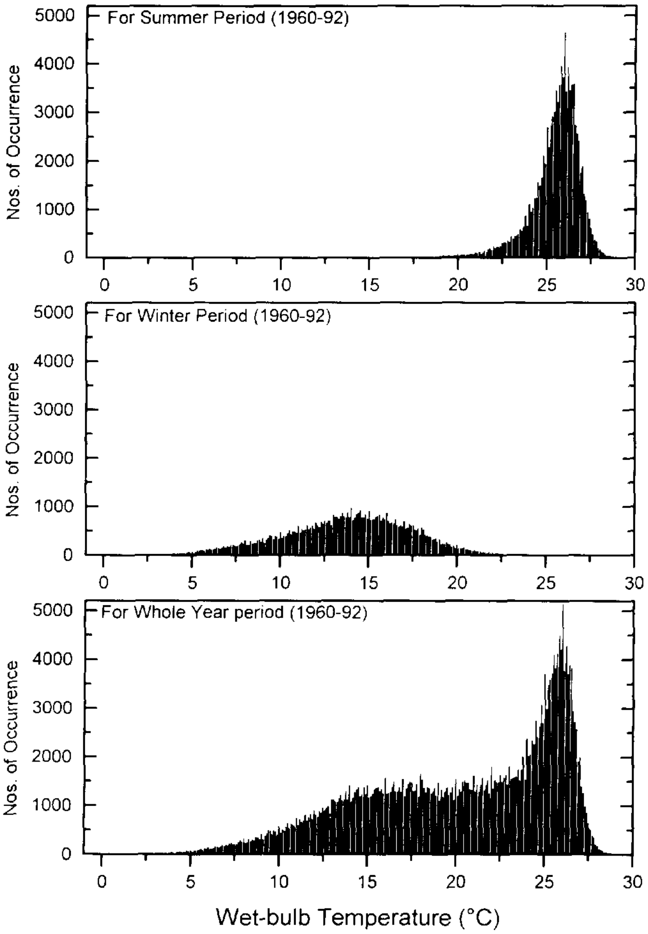


Fig. 4. Frequency distribution of wet-bulb temperatures of Hong Kong based on hourly data from 1960 to 1992.

nation for the skewness is the warming effect during the long summer months due to the close proximity to the ocean and the breeze with humid air brought from the sea. On the other hand, the winter months are affected by the cold and dry northerly wind coming from mainland China.

4.2. Frequency charts

In order to study the effects of coincidence of the hourly DBT and WBT data, simultaneously occurring DBT and WBT pairs have been used to plot on a psychrometric chart the frequencies of occurrence of the DBT and WBT pairs. Figs. 5–7 show such plotting constructed in one-degree intervals for the summer, winter and whole-year periods, respectively. This type of frequency chart was proposed by Kowalczewski and Cunliffe [23] and has been used for assessing the year-round climate and characteristics of building energy consumption by design engineers [24]. The figure adjacent to each dot of the DBT/WBT pair on the chart represents the number of hourly occurrences in that 33-year period and the temperatures indicated are class mid-values (i.e., 20 °C represents the range between 19.5 °C and 20.5 °C). The percentage frequencies of hourly DBT and WBT can be obtained by dividing the number of occurrences by the total number of data concerned. For example, in the summer period on Fig. 5, the percentage frequency of the point with DBT = 28 °C and WBT = 26 °C is equal to 12 796 divided by 96 626, which is about 13%. Outdoor air envelopes [25] which indicate the span of the outdoor conditions have also been constructed on the respective frequency charts.

It can be seen from Fig. 5 that a small range of DBT and WBT values covers a large fraction of the entire distribution in the summer period. For example, over 88% of the hours lie in the regime defined by DBT between 25 and 32 °C with simultaneous WBT between 23 and 27 °C. The mode of coincident dry-bulb and wet-bulb for the summer period lies in the group indicated by mid-values of 28 °C DBT and 26 °C WBT. The number of occurrences of that group constitutes 13% of the total hours in the summer period. The relative humidity and moisture content of air also have direct influences on the outdoor conditions. In the summer period shown in Fig. 5, the range of relative

Table 8
Statistical data for hourly dry-bulb temperatures (DBT) and wet-bulb temperatures (WBT) of Hong Kong for 1960–1992 [a]

Data	Period [b]	Max. (°C)	Min (°C)	Range (°C)	Mean (°C)	Median (°C)	Mode (°C)	S.D. (°C)	Skew.	Kurt.
DBT	Summer	35.0	19.6	15.4	28.16	28.1	28.0	1.937	0.067	−0.085
	Winter	28.2	4.2	24.0	16.53	16.7	17.0	3.287	−0.238	0.109
	Year	35.0	4.2	30.8	22.98	24.0	28.0	5.43	−0.439	−0.714
WBT	Summer	29.8	14.8	15.0	25.50	25.7	26.0	1.358	−1.513	4.357
	Winter	24.3	−0.8	25.1	13.77	14.0	14.0	3.581	−0.307	−0.161
	Year	29.8	−0.8	30.6	20.30	21.5	26.0	5.454	−0.615	−0.627

[a] Max. = absolute hourly maximum; Min. = absolute hourly minimum; S.D. = standard deviation of hourly data; skew. = skewness; kurt. = kurtosis.
[b] The summer period refers to the months Jun., Jul., Aug. and Sep. (total 2928 hours). The winter period refers to the months Dec., Jan. and Feb. (total 2160 hours). The year period refers to all twelve calendar months (total 8760 hours).

humidity in percentages (%RH) spans from about 30% RH to 100% RH with most of the time concentrated at high humidity above 60% RH. The values of moisture content also indicate that the summer period of Hong Kong is very humid and latent cooling is an important consideration in HVAC systems design and operation.

Distribution of simultaneous DBT and WBT in the winter period spreads over a wider range with larger differences between DBT and WBT. As shown in Fig. 6, the humidity level spreads more evenly from about 15% RH to 100% RH and the moisture content stays at relatively lower levels than in the summer period. No distinct region of data clustering similar to that in the summer period can be found. The intersection of individual mean DBT and WBT as determined previously (i.e., mean DBT = 16.5 °C and mean WBT = 13.8 °C) is located approximately at the centre of the outdoor air envelope in winter. This is because both winter DBT and winter WBT have a distribution close to normal.

The frequency chart for the whole-year period as shown in Fig. 7 indicates that the year-round weather conditions of Hong Kong, with other intermediate seasons taken into consideration, span a relatively small range in both temperature and humidity (see also Table 3 for comparison with other Chinese cities). Over 42% of the hours lie in the regime defined by DBT between 24 and 31 °C with simultaneous WBT between 23 and 27 °C. The mode of coincident dry-bulb and wet-bulb for the whole-year period lies in the group with DBT = 28 °C and WBT = 26 °C, which is the same as the summer period. This implies that the year-round outdoor weather conditions of Hong Kong are greatly influenced by the summer distribution curve. Design and operation of HVAC systems have to take into account these characteristics for achieving optimum performance.

4.3. Coincident DBT and WBT

The effects of WBT and humidity on air-conditioning system design and operation usually are not well addressed and understood [26]. Outdoor design conditions determined from design DBT may not be suitable for applications and locations which are more sensitive to WBT and humidity. For example, evaporative cooling systems which are affected by high WBT or high humidity may require special attention to design WBT [1,26,27]. Systems using enthalpy control strategies should also consider WBT carefully because it can be seen from the psychrometric chart that WBT and enthalpy have an approximately linear relationship. Basically, DBT affects the sensible component of building loads while WBT dictates ventilation component (enthalpy difference) associated with building loads. When calculating building cooling loads, it is advisable to determine whether the structure is most sensitive to DBT (i.e., extensive exterior exposure) or WBT (i.e., outside ventilation) [1]. Then appropriate temperature data may be used.

Three possible pairs of design temperatures may be used [14]: DDB with DWB, DDB with its CWB, and DWB with its CDB. The first pair, DDB and DWB, are not coincident and using them for computing cooling loads will give results greater than actual loads [1]. The other two sets of DBT and WBT design data have been determined here in this study for establishing the design conditions (see Table 5). The coincidence here is essential because a pair of coincident DBT and WBT is required for determining the outside air's heat content (enthalpy) needed for load and energy calculations.

It has been found that for cooling system design the coincident temperatures are lower than their corresponding design temperatures, while for heating system design coincident temperatures are higher than their corresponding design temperatures. This implies that for both summer cooling and winter heating, design DBT and WBT are slightly more conservative than their corresponding coincident ones. Similar findings have been reported in Australia [28]. The frequency distributions of DBT and WBT have suggested that the clustering of data at higher temperatures and the

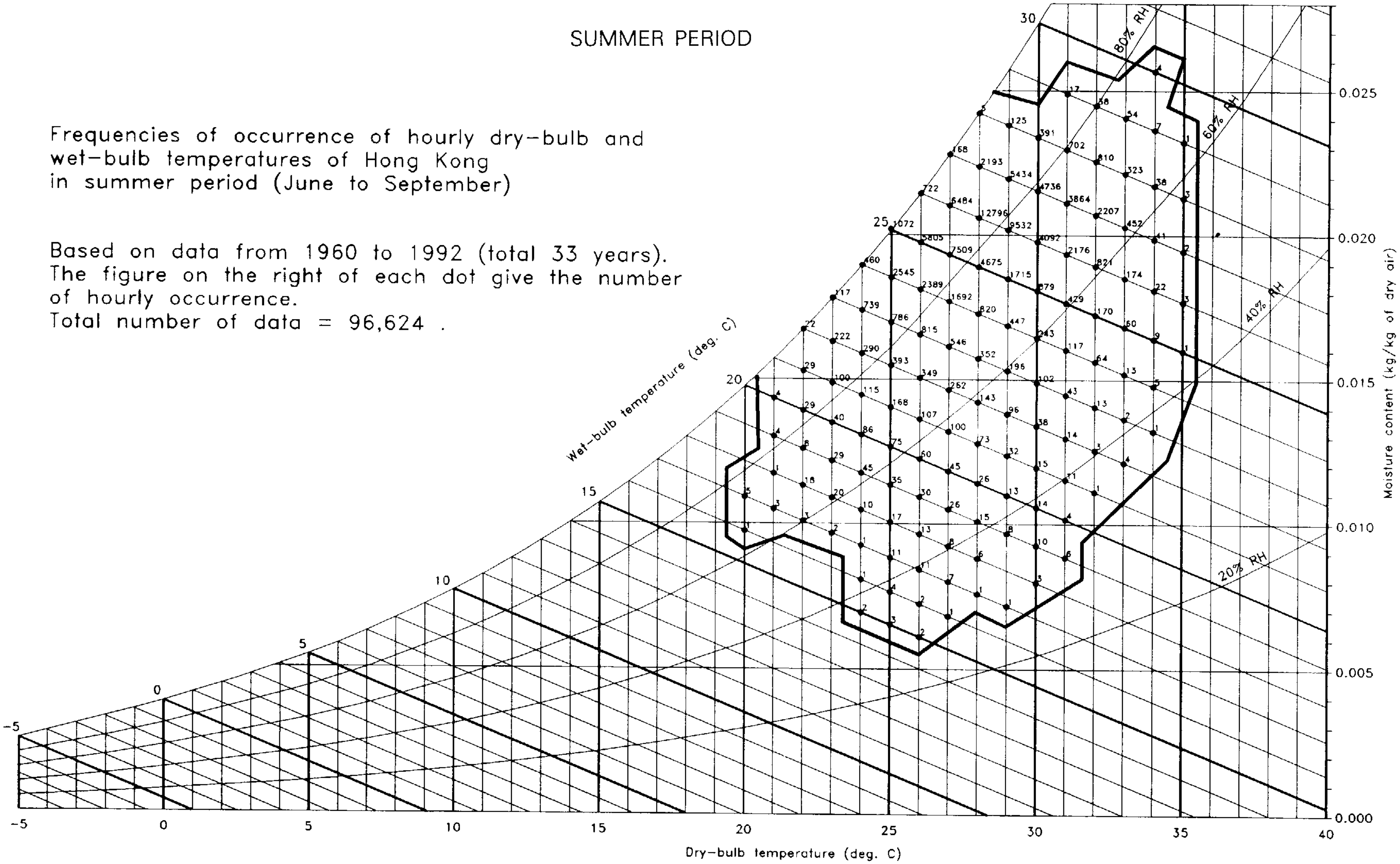


Fig. 5. Frequency distribution of simultaneous dry-bulb and wet-bulb temperatures of Hong Kong on psychrometric chart for the summer period; based on hourly data from 1960 to 1992.

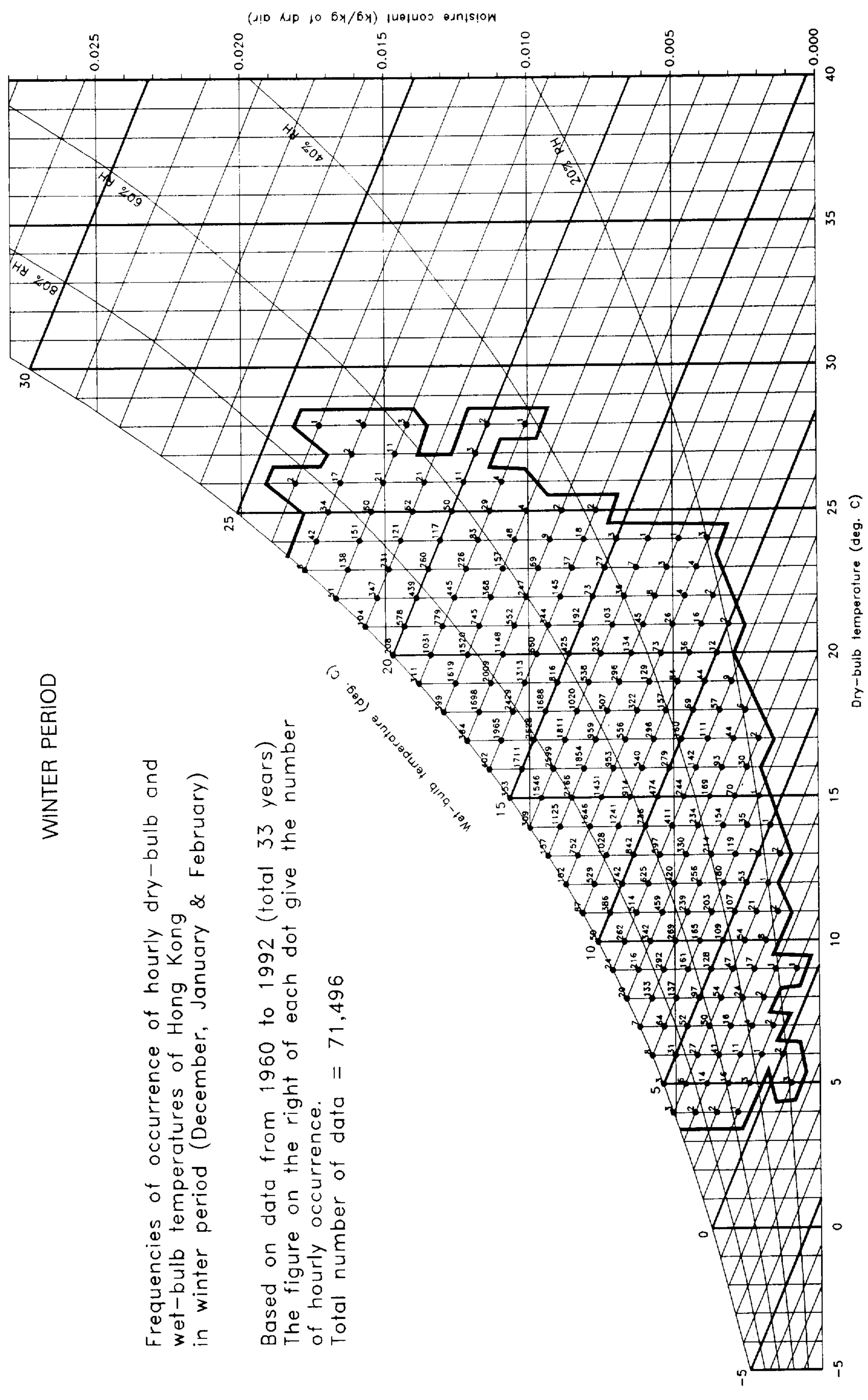


Fig. 6. Frequency distribution of simultaneous dry-bulb and wet-bulb temperatures of Hong Kong on psychrometric chart for the winter period; based on hourly data from 1960 to 1992.

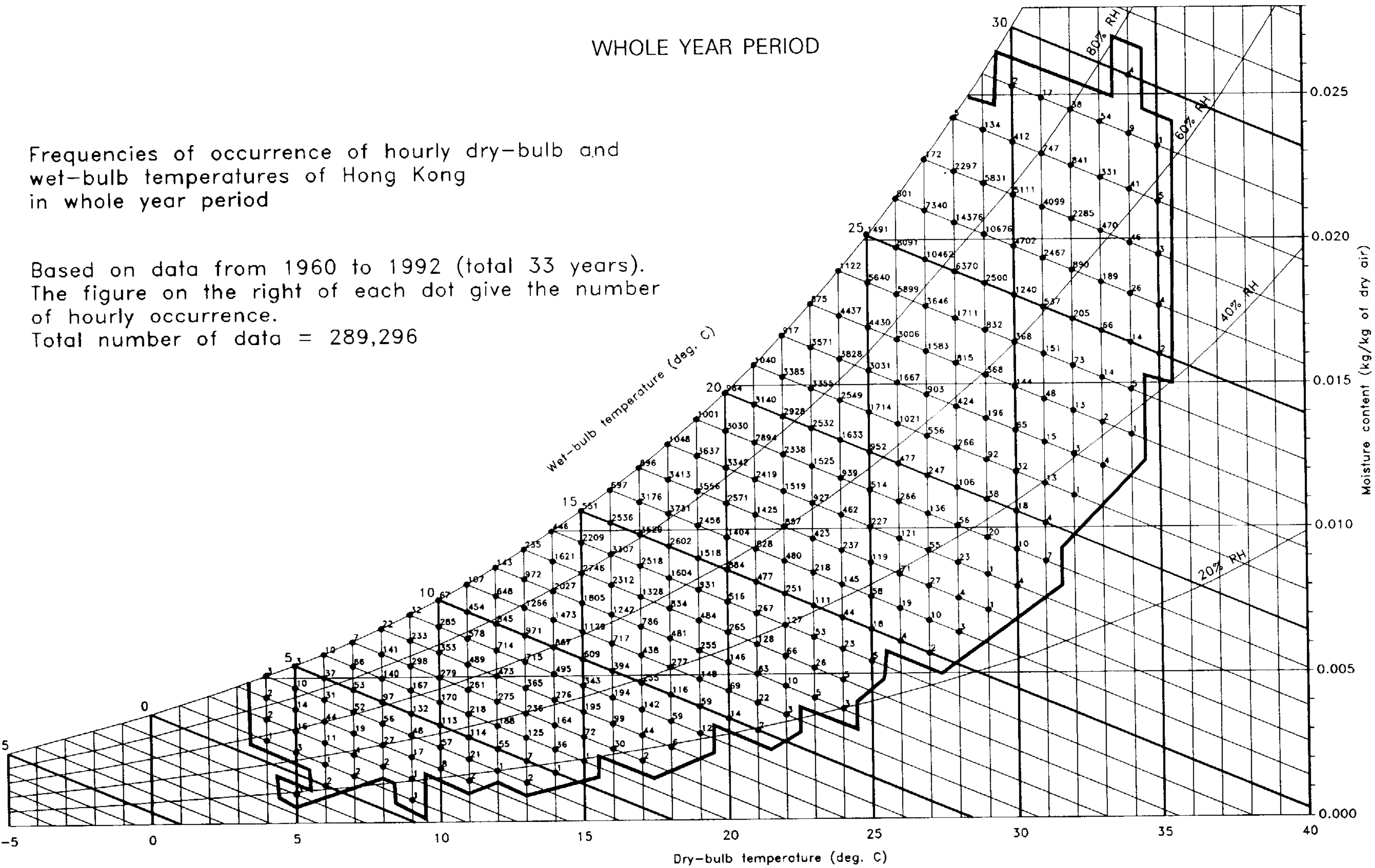


Fig. 7. Frequency distribution of simultaneous dry-bulb and wet-bulb temperatures of Hong Kong on psychrometric chart for the whole-year period; based on hourly data from 1960 to 1992.

similarity in the shapes of the distributions account for the observations in frequency levels. There is also close correlation between DBT and WBT which make the behaviours more complicated and difficult to be quantified with confidence [2].

5. Discussions

5.1. Optimum design and risk level

Outdoor design conditions affect building loads and economical design. The effect of incorrect selection of outdoor conditions in the design can be dramatic when system and plant operation are taken into considerations. If some very conservative and extreme conditions which are very unlikely to occur are taken, uneconomic design and oversizing may result. If design loads are exceeded, equipment and plant operations will be seriously affected (e.g., safety cut-off of equipment when design load is exceeded excessively). If a climatic factor to which the system is sensitive has not been considered and catered for, the resultant design may not be able to handle effectively the actual operating conditions (e.g., in high humidity conditions). Therefore, thorough understanding of the significance of outdoor design conditions and careful selection based on appropriate criteria are important for achieving optimum system design and performance of buildings.

Criteria for outdoor design conditions should be determined according to the applications and category of importance of the system and the building considered. For example, in the selection of condensers for refrigeration systems, the categories shown in Table 9 have been set out by specifying the hours per year that the design temperature may be exceeded [29]. The percentage risk levels as calculated by dividing the number of hours by the total 8760 hours in a year have been added for comparison. Similar categories can be set when selecting the outdoor design conditions for different HVAC applications and for different degrees of importance for a building project.

The frequency of occurrence of the outdoor design conditions should be indicated so that designers can determine the one applicable to them and to their 'risk level'. The risk involved in selecting less than the extreme maximum condition can then be understood and assessed on a common basis. The extent to which reduced performance under extreme conditions can be tolerated will depend on the type and usage of the system and plant. Where possible, the significance (risk) level should be determined in consultation with the client or future end-users and operation team. Owing to economy and other factors, a client may be quite prepared to accept some loss of performance for a short period during excessively warm or cold weather if equipment costs can be reduced. Both designer and user should be warned of the consequences of exceeding the design conditions and be prepared for any remedial measures necessary in case of system failure resulting from design conditions being exceeded. With a clear idea of the consequences of outdoor design conditions, designers can then weigh up these factors with consideration for initial equipment costs and energy running costs in the life-cycle analysis of the proposed building design.

5.2. Selection of design data

Selection of design weather data for a project will depend on proper engineering judgement of the situation under concern. Different types of data will be required for different applications and uses. Outdoor design conditions for Hong Kong are provided in Table 7 for designers themselves to take into account in their evaluations. The data provided here are not meant to be exhaustive and definitive. It is hoped that designers can assess critically the design conditions they have taken for granted when working on their building design. Where there is justification for worst-case design conditions, extra attention should be given to the system design to ensure efficient part-load operation [9]. There are always situations where 'standard' design conditions may not be able to fully represent the case and additional information may be required. If the particular conditions can be identified (or felt!) at the design stage, proper precautions may be taken to account for that (or at least reasonable contingency plans made). Examples of conditions not expected in standard outdoor design conditions include:

- extremely high radiant heat transfers due to sunlight or radiation from surrounding buildings or sea surface;

Table 9
Categories of risk levels for the selection of condensers for refrigeration system

Category	Need for continued operation	Hours per year that design temp. may be exceeded
A	essential — life support	0 (0%) [a]
B	important — essential process	5 (0.1%)
C	important — essential process	35 (0.4%)
D	less important — general comfort	70 (0.8%)

[a] The percentages given in parentheses are calculated by dividing the number of hours by 8760 hours.

- changes of system capacity and performance due to elevation above sea-level and conditions different from the weather station;
- internally located or enclosed equipment and their 'micro-climate'.

5.3. Hong Kong climate

The research findings from the study of hourly temperatures agreed with the general feelings on the Hong Kong climate – hot and humid in summer and mild and dry in winter. Analysis of the frequency distribution of coincident DBT and WBT indicates that a small range of DBT and WBT values covers a large fraction of the entire hourly values. The year-round operational strategies for a HVAC system in Hong Kong should therefore be designed to operate effectively within these conditions, not just satisfying the design temperatures. The frequency plots on psychrometric charts (Figs. 5–7) can provide useful information for designers to choose alternative design points, to perform simplified energy analysis and to determine effective operating strategies for HVAC systems. For example, by dividing the year-round outdoor air envelope into four regions based on the enthalpy of indoor air, temperature and moisture content of air leaving a cooling coil, four operating schemes have been suggested for achieving optimum operation in a basic air-conditioning system [25]:

(1) *Region A*: enthalpy of outdoor air is larger than that of indoor air. Minimum outdoor air intake is recommended.

(2) *Region B*: enthalpy of outdoor air is lower than that of indoor air; DBT of outdoor air is higher than that of the air leaving the cooling coil and moisture content of outdoor air is higher than that of the air leaving the cooling coil. Economizer cycle with 100% outdoor air is recommended to take full advantage of 'free cooling'.

(3) *Region C*: enthalpy of outdoor air is lower than that of indoor air; DBT of outdoor air is higher than that of the air leaving the cooling coil but moisture content of outdoor air is lower than that of the air leaving the cooling coil. Economizer cycle with 100% outdoor air is recommended but space humidity may be a problem because of the low moisture content level.

(4) *Region D*: DBT of outdoor air is lower than that of the air leaving the cooling coil. Mixture of outdoor air and return air is recommended and heating may be needed.

The four regions have been constructed within the outdoor air envelope for the whole-year period. An estimate of the total frequencies of occurrence in the four regions has been made, and is shown in Fig. 8. Region A accounts for 68.7% of the total hourly frequencies, region B 16.4%, region C 11.9% and region D only 3.0%. This implies that minimum outdoor air intake is required for about two-thirds of a year and the economizer cycle can be used for about 28.3% of a year while possible heating requirements in region D are minimal. It should be noted that the previous

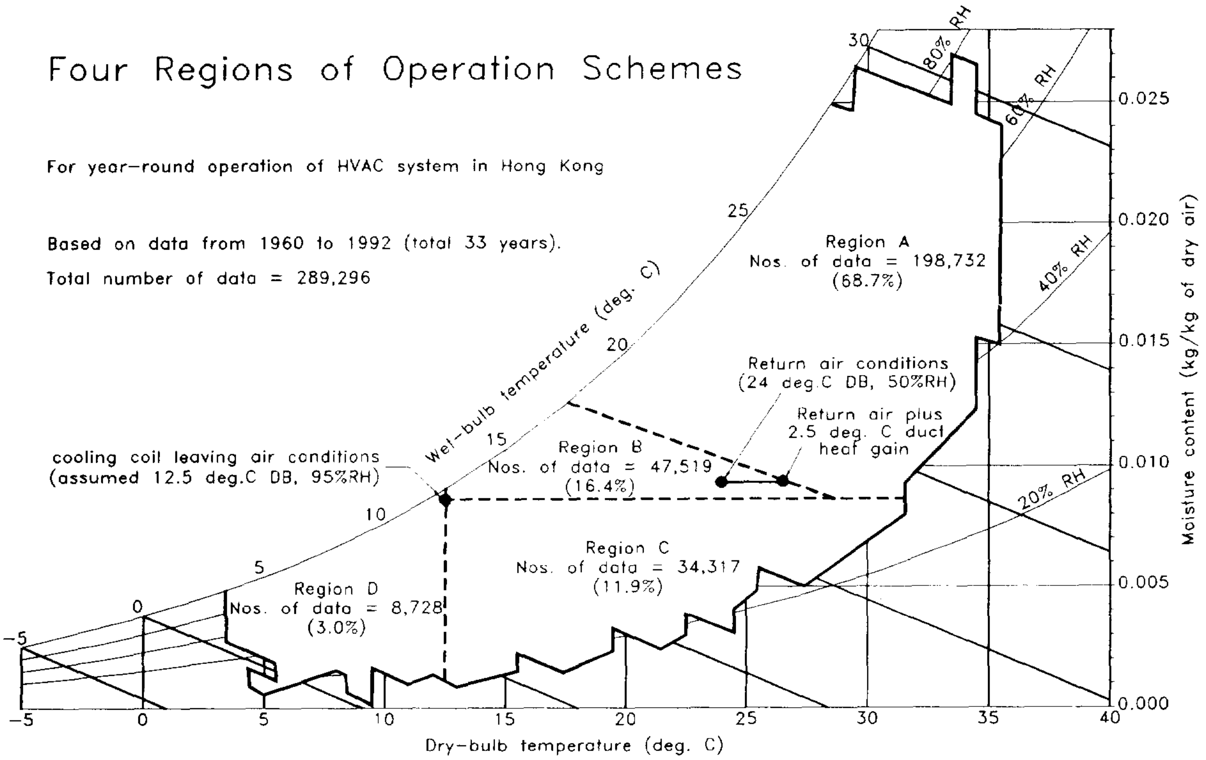


Fig. 8. An example of analysing year-round partload design and operation in Hong Kong.

analysis only serves as an example and different HVAC systems may require different operating schemes to achieve optimum design and operation.

6. Conclusions

Properties and significance of outdoor design conditions and their methods of determination have been critically examined. It has been found that the existing data of outdoor design conditions for Hong Kong are very limited and information on design weather data needs to be reviewed and expanded. Based on more recent meteorological data from the latest weather database developed for Hong Kong, new data for the outdoor design conditions have been established. These data are developed by referencing to the four common methods for outdoor design conditions and with consideration for local situations and design practices in Hong Kong. A large range of significance levels has been determined and provided for design temperatures.

Comparisons between the rule-of-thumb design data (summer 33/28 °C and winter 10 °C) in Hong Kong and the new design data suggest that the summer design temperatures in the former are considered too conservative while its winter design temperature is not quite stringent enough for design purposes. Analysis of the frequency distribution of hourly values of DBT and WBT indicates that a small range of DBT and WBT values covers a large fraction of the entire hourly values.

There is potential for achieving optimum design and energy savings if the outdoor design conditions are carefully selected and analysed. More information than just simple design temperatures is required for assessing the part-load performance of the building system. With a better understanding of outdoor design conditions and their significance, building designers can then select and evaluate outdoor design conditions for their applications and risk levels.

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