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Conserving Energy Without Sacrificing Thermal Comfort

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In the quest towards energy conservative building design thermal comfort must not be sacrificed. This paper explores energy conservation strategies and their impact on the thermal environment. Parametric variations in envelope design and HVAC operation on energy performance and thermal comfort of a typical commercial office building in Singapore are investigated. With proper plant operation, the resulting internal environment suffers no loss in comfort level, and the savings in energy arising from the various conservation measures are realistic. These measures are ranked according to their effectiveness, and provides valuable knowledge for achieving energy conservation without introducing occupant discomfort.

INTRODUCTION

PREDOMINANT energy consuming sectors are buildings, industries and transportation. A recent research has shown that 35% of all electricity generated within the Association of Southeast Asian Nations (ASEAN) is consumed by commercial buildings [1]. In Singapore 30% of the nation's electrical consumption is expended in commercial buildings [2]. The Singapore government responded to the need for energy conservation by legislating building regulations [3] and codes of practice [4, 5] aimed at improving the thermal performance of buildings to reduce energy consumption. Unlike codes which directly specify energy targets, for example the Energy Conservation Standards for New Non-residential Buildings of California [6], the regulations in Singapore, expressed in the form of the Overall Thermal Transfer Value (OTTV) which is modelled after the ASHRAE Standard 90A-1980 [7], are targeted at controlling the thermal transfer value of the building envelope. However, the OTTV was found to be deficient as an indicator of the cooling energy requirement [8, 9] and attempts to provide more accurate versions of the OTTV were undertaken [10, 11] as part of the Singapore building control authority's effort to upgrade its building energy conservation standards.

Meanwhile, strategies for building energy conservation were explored [1]. Recently researches were conducted on building energy performance and the impact of fabric design, HVAC operation and utilization of daylighting [8, 12]. However, in these studies energy conservation was examined *per se* without reference to the resulting thermal environment. Buildings are built for the occupants; in the case of commercial buildings, the purpose is to provide a pleasant work environment conducive to the occupants for engaging in their activities so as to enhance work productivity and a sense of health and well-being. Visual, aural and thermal comfort must be maintained within acceptable levels.

This paper addresses the issue of exploring various energy conservation measures without sacrificing thermal comfort. The exploration is conducted by means of an energy simulation program applied to a typical commercial office building in Singapore.

THERMAL COMFORT

Thermal comfort is a complex issue, involving many parameters. Macpherson [13] identified six factors that affect thermal sensation—air temperature, mean radiant temperature, humidity, air speed, metabolic rate and clothing levels. He documented nineteen indices for the assesment of the thermal environment. Each of these indices incorporate one or more of the six factors.

Thermal comfort studies may be based on field surveys [14, 15] or on controlled climatic chambers [16–19]. Among the many thermal comfort indices Fanger's general comfort equation (FCE) is the most commonly adopted [20]. The FCE establishes the relationships among the environment variables, clothing type and activity levels. It represents the heat balance of the human body in terms of the net heat exchange arising from the effects of the six factors identified by Macpherson [13]. The satisfaction of the comfort equation is a necessary condition for optimal comfort. Studies have shown that the FCE is applicable across national-geographical locations and age-groups [16, 18, 19, 21].

In the FCE, the thermal sensation index is the Predicted Mean Vote (PMV) which is a standard psychophysical scale for a large group of persons. PMV values range from -3 (cold) to $+3$ (hot) with 0 as the neutral sensation representing the most comfortable condition. Fanger also derived an indicator, the Predicted Percentage Dissatisfied (PPD), which represents the percentage of a large group of people who can be expected to feel definitely uncomfortable in a given environment. PPD would seem a meaningful index in rating the quality

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of the indoor climate as it is the decidedly dissatisfied who will be inclined to complain.

In the interest of thermal comfort, the architect and engineer must pay attention to climatic parameters, building fabric and HVAC system operation. These parameters ultimately influence the environmental variables which affect the thermal sensation of the occupants of the building. Even for a particular internal environment, variations in dressing and activity level produce different thermal comfort sensations.

METHODOLOGY

A square multi-storey office building, similar to the ones used in previous studies relating to building energy conservation standards study in Singapore [8, 9, 11], was adopted as a reference. The plan of a typical floor is shown in Fig. 1, the building specifications are depicted in Table 1, the characteristics of the plant and VAV systems are shown in Table 2, while the building operating schedules relating to occupancy, lighting and infiltration are shown in Figs 2 through 4.

Features of the envelope design and HVAC system considered to affect the cooling load and energy consumption of the building were identified and their ranges in value specified (Table 3). Parametric simulation runs were then conducted with the DOE2.1B computer simulation program by holding all parameters at their reference values and varying the value of the chosen parameter over its selected range. By construing the variations in each parameter as an energy conservative measure, the impact on energy consumption was analysed, and the measures were ranked according to their effectiveness in energy conservation. In the simulations, the Singapore climatic data for the year 1979 was used. The DOE-2 weather tape contains hourly data on dry-bulb and wet-bulb temperatures, wind velocity, and measured direct and diffuse solar radiation.

Automatic sizing of the cooling capacities of the HVAC system, chiller and cooling towers were performed by the computer program DOE2.1B. Plant capacity was determined by the peak coincident load of the building rather than the sum of the maximum requirements of each zone. Appropriate sizing factors were applied to the cooling capacities of the HVAC to ensure that the resulting average temperatures of the various zones were close to each other during the hours of operation.

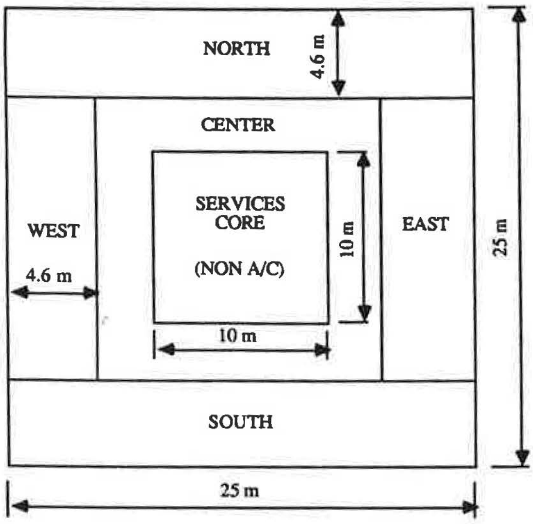

Fig. 1. A typical floor of the reference building.

Table 1. Construction, thermal, luminaire and infiltration characteristics of the reference building

	Materials
Exterior wall	25 cm concrete 1.9 cm air layer 0.8 cm spandrel glass
Interior wall	25 cm concrete 1.9 cm plaster
Interior partition	1.59 cm gypsum board 10.2 cm air layer 1.59 cm gypsum board
Roof	1.27 cm roof gravel 0.95 cm built up roofing 2.5 cm polystyrene insulation 15.2 cm concrete 10.2 cm air layer 1.3 cm acoustic tile
Floor	15.2 cm concrete
	Solar Absorptivities
External walls	0.45
Roof	0.7
	Windows, Luminaires and Infiltration
Window wall ratio	0.44
Shading coefficient of window	0.47
Glass conductance of window	3.2 W m^{-2} K^{-1}
Window setback	none
External shading devices	none
Lighting type	recessed fluorescent vented to return ducts
Lighting power	1.9 W m^{-2} in occupied areas
Infiltration	0.6 ac/hr when fans off

Each building and equipment system design produced an internal environment which was evaluated for thermal comfort. The area-weighted temperature and relative humidity of the building were used as inputs to Fanger's comfort equation, and the Predicted Mean Votes (PMV) and the Predicted Percentage Dissatisfied (PPD) were calculated assuming a metabolic rate of 64 W m^{-2} for general office work, a tropical work dressing of 0.5 clo and no relative air motion. The effects of varying clothing level (0.4 clo to 0.6 clo), metabolic rate (58 W m^{-2} to 70 W m^{-2}) and relative air velocity (0 to 1.25 m s^{-1}) on PMV and PPD were examined to reflect the full range of thermal sensation experienced by the occupants clothed differently, engaged in various activities and located a various distances from the air supply grilles. The vari

Table 2. Characteristics of VAV system and plant

Outside air flow rate	13 cu m/hour/person
Cooling setpoint	25°C
Throttling range	1.1°C
Thermostat type	proportional
Minimum air flow ratio	0.5
Chiller type	open centrifugal
Chiller coefficient of performance	4.5
Chiller control	standby
Chiller resource	electricity
Cooling tower type	water-cooled

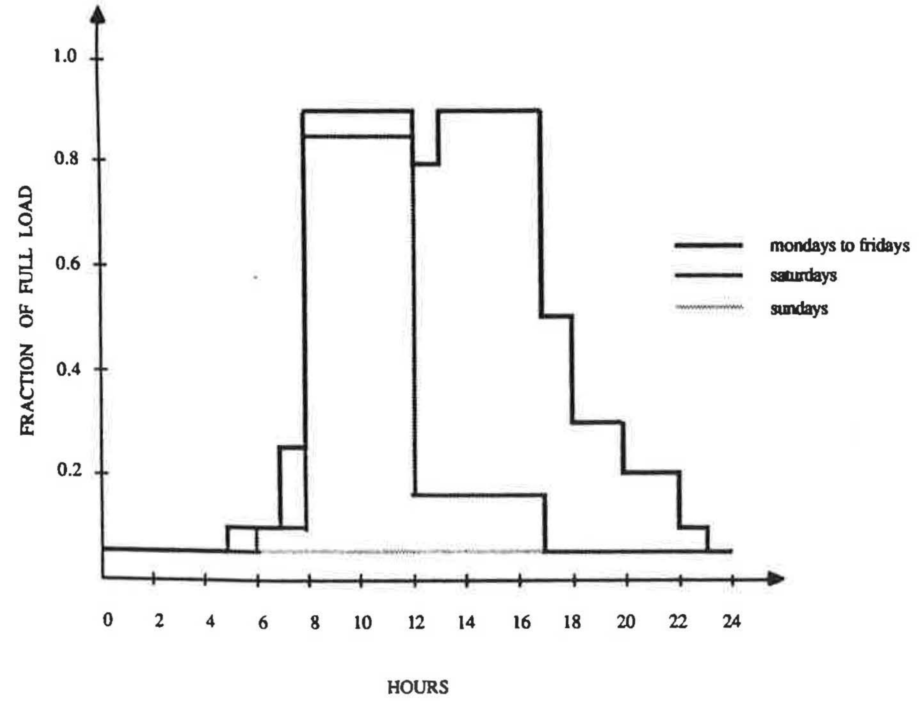

Fig. 2. Building lights schedule.

ation in clothing level is limited to this practical range given the tropical climate and cultural dressing norms. The range in activity level spans the common office work types as identified by Fanger. The upper limit of the relative air velocity of 1.25 m s^{-1} is the maximum permissible under the Singapore regulations [3].

Reduction in cooling energy achieved by each conservation measure was assessed against its tradeoff in thermal comfort. Comfort-energy grids (Figs 5 through 12) have been designed to aid in the analysis of the tradeoffs between energy conservation and thermal comfort. Each comfort-energy grid essentially graphs the relationship between energy consumption and thermal comfort sensation resulting from parametric variations under a set of circumstances determined by the metabolic rate, relative air motion and clothing value.

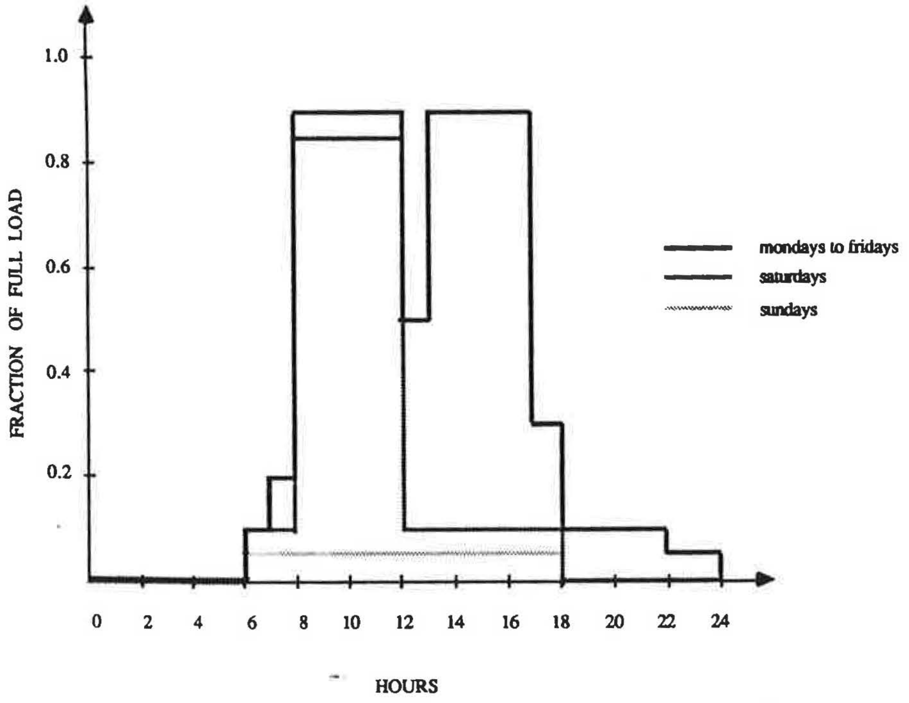

Fig. 3. Building occupancy schedule.

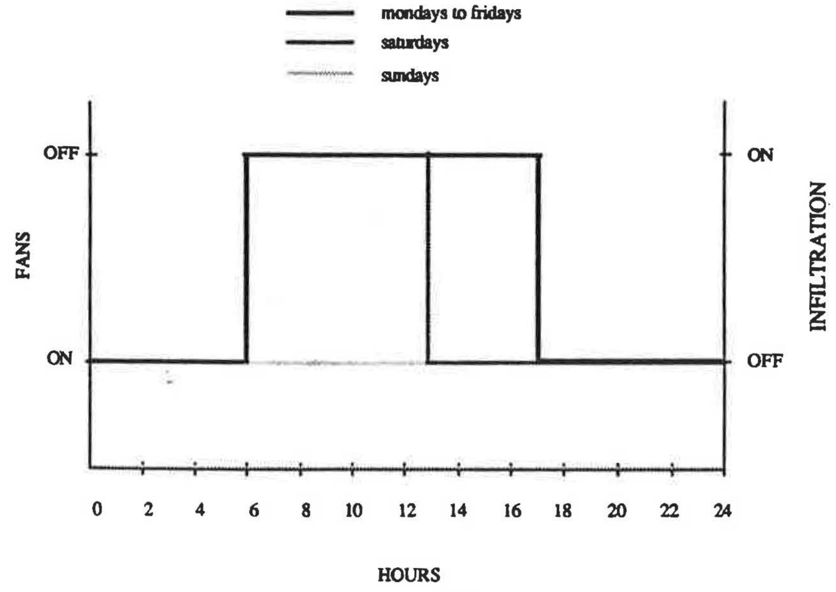

Fig. 4. Building fans and infiltration schedule.

RANKING THE ENERGY CONSERVATION STRATEGIES

The energy conservation strategies are ranked according to their effectiveness as shown in Table 4. The lower ranges of a few parameters may presently be impractical from aesthetics, environmental or thermal consideration, but show promise of being attainable with evolution of architectural style and technology in response to energy conservation. A window wall ratio of 0.2 would hardly be acceptable; low shading coefficients produce too gloomy a visual environment; a lighting power density of 10 W m^{-2} while maintaining adequate lighting levels is not commercially available yet; a chiller COP of 5 is possible for new chillers but would deteriorate once in operation. The lower limits for window wall ratio is set at 0.33, shading coefficient at 0.35 and the lighting power density at 16 W m^{-2} as the practical extremes.

First measures of energy conservation should focus on the reduction of lighting energy. Use of natural lighting should be accorded particular attention as justified by the magnitude of savings achievable With the use of higher efficacy luminaires, the savings may even be higher. Even without daylighting, high efficacy lighting would reduce energy consumption by about 13%.

Regarding window design, the size, setback and glazing have important consequences. Energy conservation seems to suggest the reduction in their values, but if daylighting was to be adopted, then a careful evaluation of the tradeoff between the two 'conflicting' strategies need be made. It appears that daylighting considerations would predominate because of its greater reduction in

Table 3. Fabric, system and plant parameters studied

Parameter	Reference value	Range
Fabric		
Window wall ratio	0.44	0.2 to 0.8
Shading coefficient	0.47	0.2 to 0.8
Glass conductance	3.2 W m^{-2} K^{-1}	3.2 to 8.4 W m^{-2} K^{-1} (double pane to single pane)
Window setback ratio	none	none to 0.8
Roof insulation	25.4 mm	25.4 mm to 50.4 mm polystyrene
Wall insulation	none	25.4 mm to 50.4 mm polystyrene
Wall absorptivity	0.45	0.3 to 0.7
Roof absorptivity	0.7	0.7 to 0.9
Infiltration	0.6 ac/hr	0.3 to 0.9 ac/hr
Lighting power	20 W m^{-2}	10 to 20 W m^{-2}
External wall thickness	25.4 cm	10.2 to 25.4 cm
Building orientation	0	0 to 90 degrees clockwise
VAV system and control		
Cooling setpoint	25°C	23 to 27°C
Ventilation rate	13 cu. m/hr/person	8.5 to 25.5 cu. m/hr/person
Minimum air flow ratio	0.5	0.3 to 0.5
Throttling range	1.1°C	0.56 to 1.67°C
Plant		
Chiller COP	4.5	3 to 5

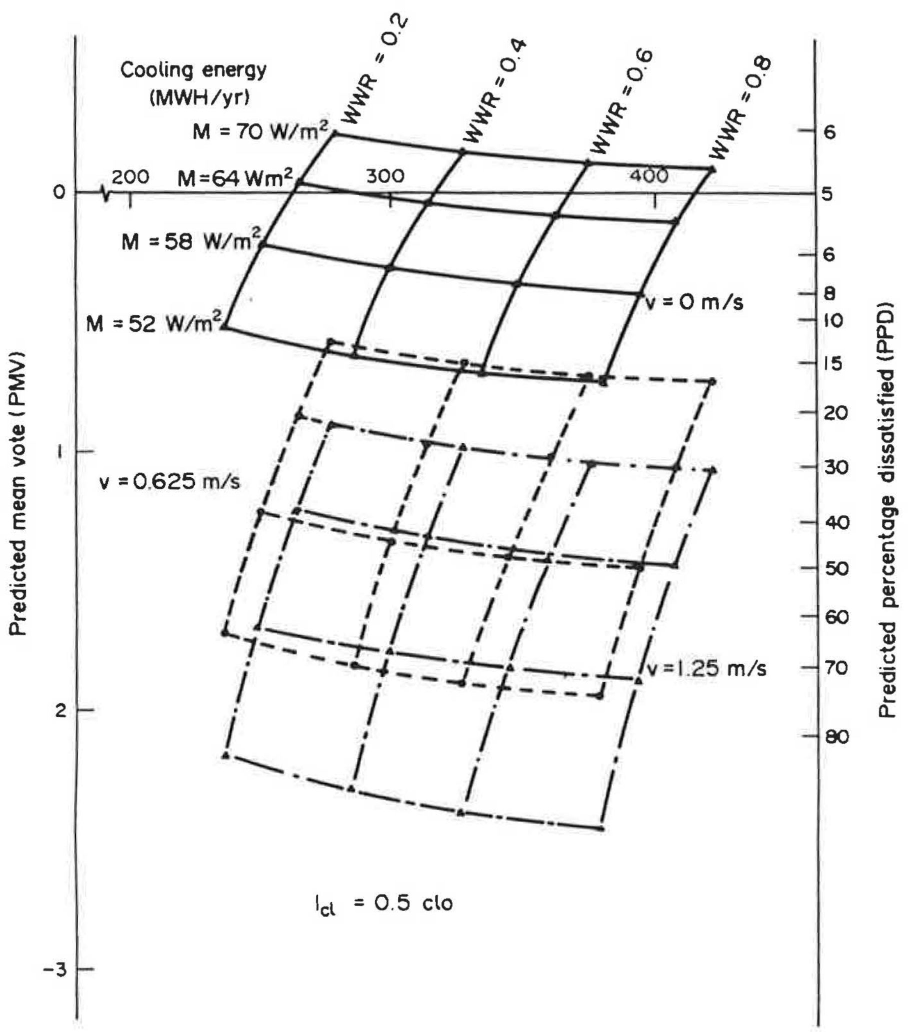

Fig. 5. Comfort-energy grids showing the impact of window wall ratio on cooling energy and thermal comfort.

energy savings. Besides, a larger window area offers more visual contact with the outside.

Equipment operation, notably of cooling setpoint and chiller COP could decrease energy consumption by 11.8% and 3.5% respectively. However, the deterioration of the internal environment resulting from a higher space temperature must be reckoned with.

Wall insulation by adding 50 mm of polystyrene reduces total consumption by only 1.7%. Savings in operation cost must be compared with the cost of insulation and is unlikely to be economically feasible. The savings of 2.1% resulting from the reduction of ventilation rate to 8.5 m^3 per hour per person is excluded as this measure violates the building regulations which

Table 4. Ranking of energy conservation measures

Conservation measure	Parametric value	Reference value	% reduction in total energy
Daylighting	500 lux	none	25.1
Lighting power density	16 W m^{-2}	20 W m^{-2}	12.8
Cooling setpoint	27°C	25°C	11.8
Shading coefficient	0.35	0.47	5.6
Window wall ratio	0.33	0.44	5.1
Window setback ratio	0.6	0	4.6
Chiller COP	5.0	4.5	3.5
Wall insulation	50 mm polystyrene	none	1.7
Wall absorptivity	0.3	0.45	0.9
Throttling range	1.67°C	1.1°C	0.6
Minimum air flow ratio	0.3	0.5	0.5
Building orientation	75° clockwise	0°N	0.3
Infiltration	0.9 ac/hr	0.6 ac/hr	0.2
Roof insulation	50 mm polystyrene	25 mm polystyrene	0.1

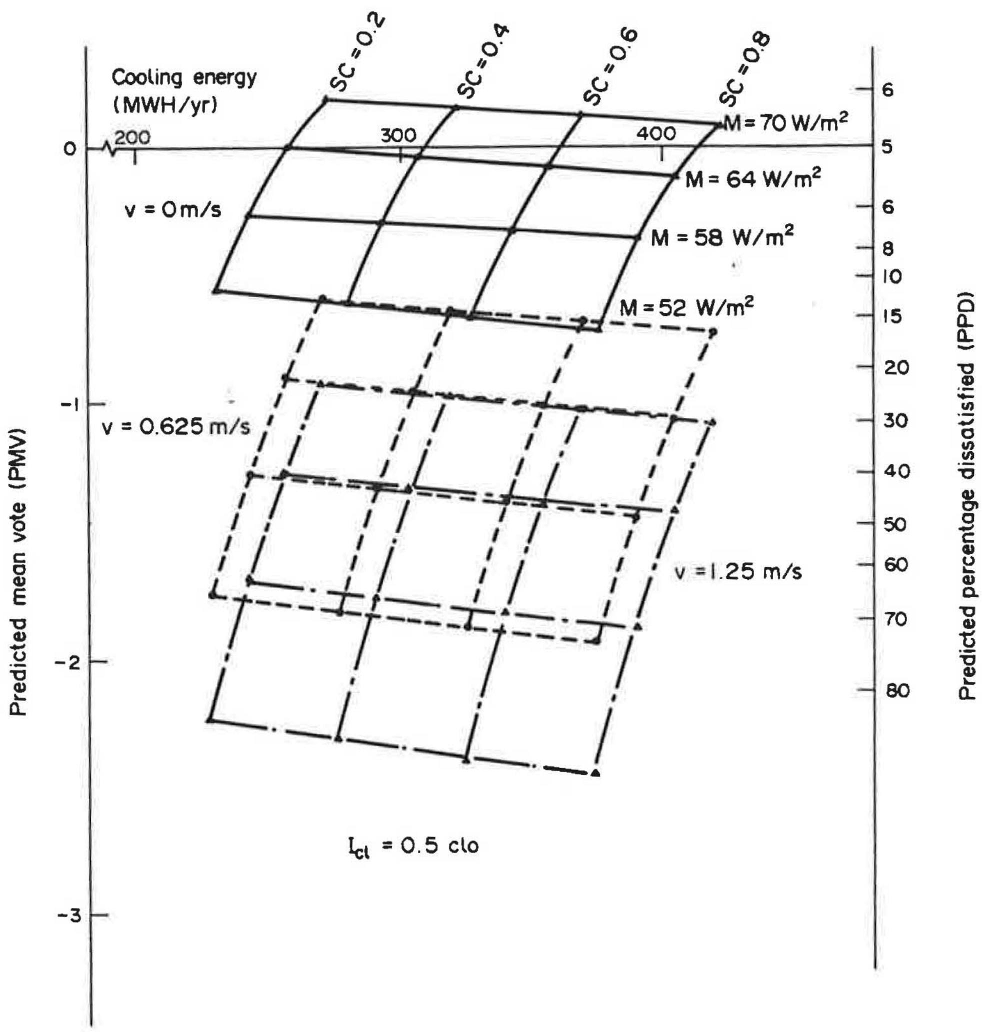

Fig. 6. Comfort-energy grids showing the impact of fenestration shading coefficient on cooling energy and thermal comfort.

specify a minimum of 13 m^3 per hour per person [3]. Other measures produce less than 1% impact on the total energy used and can be neglected as energy conservation measures.

The results provide a broad indication of the consequences of various building designs and can be used as preliminary guidance on the energy implications on the fabric design and system operation adopted.

THE IMPACT OF VARIOUS ENERGY CONSERVATION MEASURES ON THERMAL COMFORT

The parameters were first examined for their implications on the thermal environment over the entire range of their simulated values. This would show the impact of the parametric design not only in terms of energy values, but also indicate the deterioration (or improvement) in the resulting environmental conditions. Variation in thermal sensation for the full range of activity level was studied with the clothing insulation assumed fixed at 0.5 clo.

The impact of varying the values of each design parameter on cooling energy use and thermal comfort are depicted in the form of comfort-energy grids as shown Figs 5 through 11. Three grids are shown in each of the figures, corresponding to the relative air motions of 0, 0.625 and 1.25 m s^{-1}. Each upward sloping line of the grid traces the variation in cooling energy, Predicted Mean Vote (PMV) and Predicted Percentage Dissatisfied (PPD) for the range of activities for each value of the building parameter. Horizontal grid lines show the variation at each activity level as the parameter assumed the full range of its chosen values.

For each combination of metabolic rate and relative air velocity the drift in thermal comfort, as indicated by the change in PPD as each design parameter varies across the range of its values, are summarized in Table 5.

Window setback ratios and lighting power densities have negligible effects on the range in PPD, causing less than 2.5% variation in PPD. At low air motions, the change in PPD is almost zero, but the difference increases with relative air velocities. Window to wall ratios and shading coefficients introduce PPD differences of the order of 6% at no relative air motion, 9% when the relative air velocity is 0.625 m s^{-1}, and up to 12% when

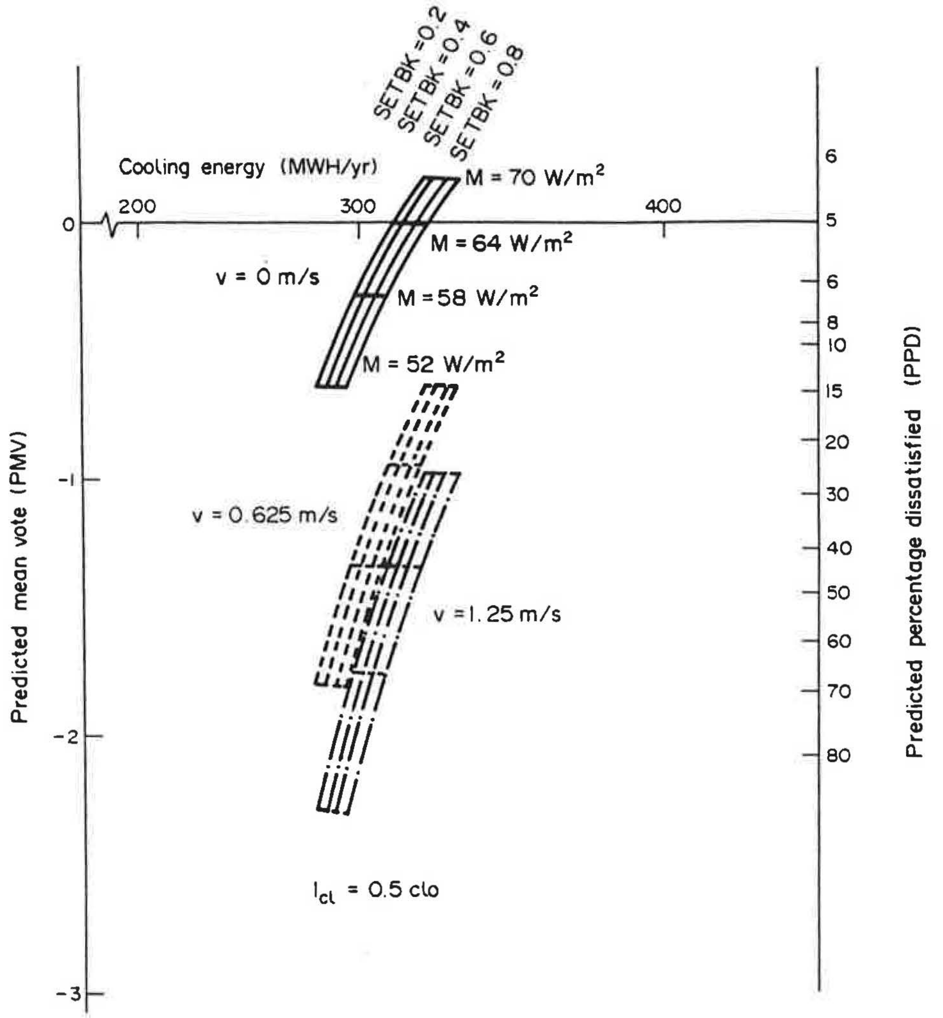

Fig. 7. Comfort-energy grids showing the impact of window setback ratio on cooling energy and thermal comfort.

the relative air velocity reaches the maximum allowable value of 1.25 m s^{-1}. Changes in cooling setpoint produce the maximum change in PPD, ranging from 6 to 52%. The chiller COP affects the energy efficiency of energy conversion and does not affect occupant comfort.

These figures indicate the maximum percentage of dissatisfaction among all activity levels exposed to various degrees of relative air motion. As most of the points are on the cold side of the neutral PMV, the maximum PPD arise from the group with the lowest metabolic rate experiencing the highest air movement rate. At the average metabolic rate of 64 W m^{-2} the following implications on thermal comfort were observed:

(1) Window setback ratio and lighting power density have no effect on the resulting thermal comfort level

Table 5. Change in PPD as design parameters vary across the range of simulated values for a typical tropical work dress of 0.5 clo

		Changes in PPD (%)											
		$v = 0$ m s^{-1} Metabolic rates				$v = 0.625$ m s^{-1} Metabolic rates				$v = 1.25$ m s^{-1} Metabolic rates			
Parameter	Range	52	58	64	70	52	58	64	70	52	58	64	70
Window wall ratio	0.2 to 0.8	5.9	2.3	0.2	0.9	8.8	12.1	7.8	5.2	*	12.2	12.3	8.4
Shading coefficient	0.2 to 0.8	4.5	1.7	0.2	0.7	5.9	9.0	8.9	3.9	*	8.8	8.9	6.1
Window setback ratio	0.2 to 0.8	0.3	0.1	0.1	0.1	2.4	0.6	0.4	0.3	*	1.2	0.6	0.4
Lighting power density	10 to 20	0.3	0.1	0.0	0.3	0.4	0.4	0.3	0.2	*	0.4	0.4	0.2
Cooling setpoint	23 to 26	15.6	13.6	5.8	3.0	*	*	38.5	27.7	*	*	45.3	44.5
Chiller COP	3.0 to 5.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Note: lighting power density in W m^{-2}; cooling setpoint in degrees Celsius; metabolic rates in W m^{-2}.
* Denotes that the change in PPD is not computed as the values for the PPD are in excess of 80% reflecting unacceptable discomfort.

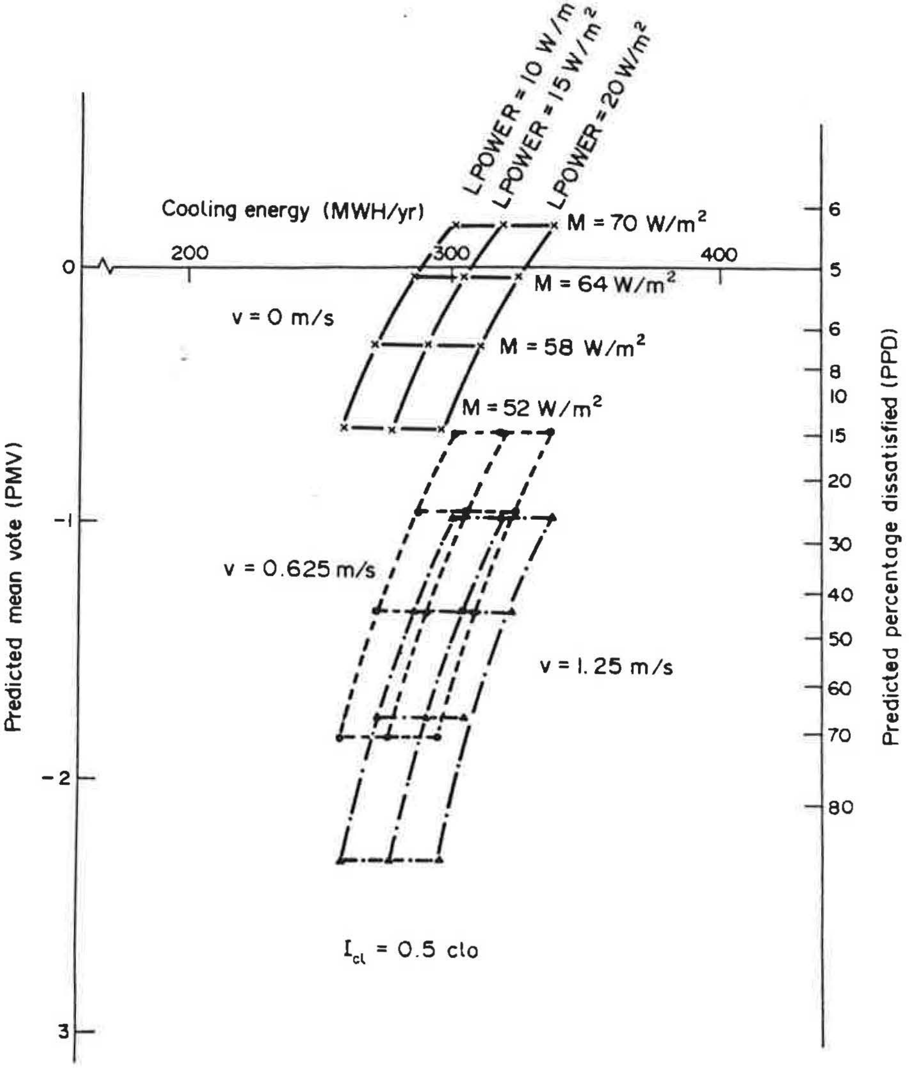

Fig. 8. Comfort-energy grids showing the impact of lighting power density on cooling energy and thermal comfort.

for each combination of metabolic and air motion rate.

(2) For different activity levels in still air conditions, all parameters with the obvious exception of cooling setpoint, have negligible impact on PPD.

(3) As relative air motion increases, the change in PPD increases to 9% for variations in shading coefficient, and 12% for variations in window wall ratios.

(4) Cooling setpoint variations resulted in changes in PPD from 6% in still air to 50% and 65% when relative air velocities reach 0.625 m s^{-1} and 1.25 m s^{-1}, respectively.

Thus, for reference conditions of 0.5 clo, metabolic rate of 64 W m^{-2} and no relative air motion, parametric variations produce negligible influence on the thermal environment. The HVAC operating setpoints have been appropriately selected and the equipment adequately sized by the program to meet the loads. The implications on energy use may be interpreted *per se* with negligible deterioration in occupant comfort. The exception is the cooling setpoint. The greater the deviation of the cooling setpoint from the neutral temperature, the greater will be the PPD. A detailed discussion of the tradeoff between energy consumption and thermal comfort arising from a variation in setpoint is presented in the next section.

Energy conservation measures were applied to the reference building by adopting parametric values consistent with acceptable architectural design and technical feasibility. The consequent changes in PPD values relative to the reference building due to each measure are shown in Table 6. Positive changes indicate increases in PPD and therefore deterioration of the thermal environment. Negative changes, by the same token, imply improvements.

Daylighting produces a more acceptable therma environment. In the absence of air motion, PPD amon the more sedentary workers was reduced by about 3% while only a 0.5% increase in PPD resulted from th more active workers. At higher air velocities, occupant tend to feel less cool compared with the reference build ing. The decrease in PPD amounts to as much as 6%.

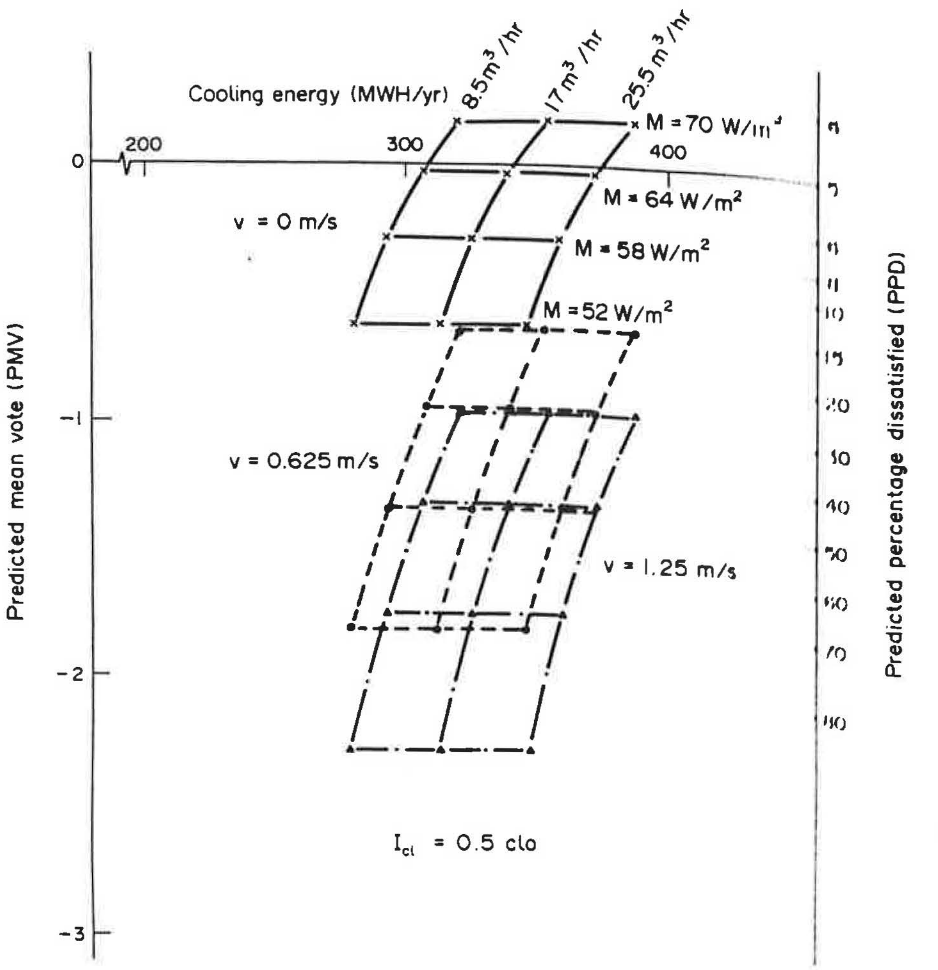

Fig. 9. Comfort-energy grids showing the impact of ventilation

Reducing lighting power density to 16 W m^{-2} led to a marginal increase in PPD of less than 0.5%. A window wall ratio of 0.33 improves the thermal environment slightly when there is no perceivable air motion, and by as much as 6% as air motion increases. Only when the highest activity level was performed in a relatively calm zone did the PPD increase. Even so, the increase of 0.2% was negligible. Adopting glazing of lower shading coefficients (0.35) produced the same effect in manner and magnitude as that obtained by using a window wall ratio of 0.33. A window setback of 0.6 resulted in a slightly more acceptable thermal environment. Raising the cooling setpoint to 26°C had the effect of improving the thermal sensations of those performing low activity level work (58 W m^{-2} or less), but increasing the discomfort of the higher metabolic rate workers performing their tasks in the absence of air motion. Though the upper limit of environmental temperature permissible for air-conditioned buildings under the Singapore regulations is 27°C, the resulting thermal sensation is deemed

Table 6. Change in PPD between energy conservative design adopted and the reference building for a typical tropical work dress of 0.5 clo

		Change in PPD (%)											
		$v = 0$ m s^{-1}				$v = 0.625$ m s				$v = 1.25$ m s^{-1}			
		Metabolic rates				Metabolic rates				Metabolic rates			
Parameter	Value	52	58	64	70	52	58	64	70	52	58	64	70
Daylighting	yes	−2.8	−0.8	0.0	0.5	−5.5	−5.1	−3.0	[illegible]	*	−3.8	−3.6	−2.4
Lighting power density	15 W m^{-2}	0.2	0.1	0.0	0.0	0.3	0.3	0.2	[illegible]	*	0.4	0.4	0.2
Window wall ratio	0.25	−3.0	−0.4	−0.2	0.2	−6.5	−4.0	−3.0	[illegible]	*	−6.0	−4.0	−2.0
Cooling setpoint	26°C	−5.3	−1.8	0.8	2.5	−21.3	−18.1	[illegible]	[illegible]	*	−19.8	−16.8	−11.0
Shading coefficient	0.35	−2.0	−0.04	−0.2	0.2	−5.0	−4.0	−3.0	[illegible]	*	−0.2	−1.3	−0.8
Window setback ratio	0.6	−0.6	−0.2	0.0	0.1	−3.2	−1.2	−0.7	[illegible]	*	−0.2	−1.3	−0.8
Chiller COP	5.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	[illegible]	0.0	0.0	0.0	0.0

Note: metabolic rates in W m^{-2}.

* Denotes that the change in PPD is not computed as the values for the PPD are in excess of 80% [illegible] unacceptable discomfort.

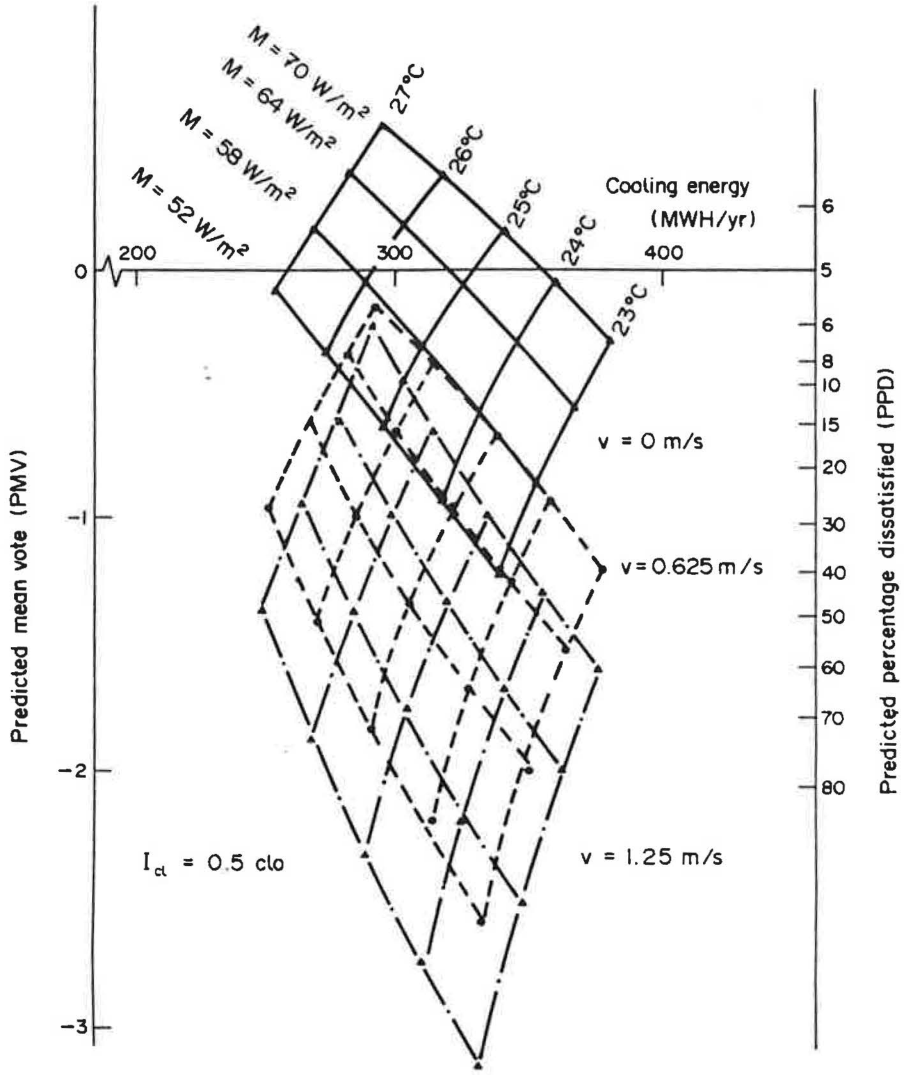

Fig. 10. Comfort-energy grids showing the impact of thermostat setpoint on cooling energy and thermal comfort.

unsatisfactorily warm in the absence of air motion. Thus the setpoint of 26°C was chosen. When relative air velocity is present, occupants felt cool at the reference temperature and would welcome this increase in setpoint, especially so when the relative air velocity is of a moderate value.

For the reference conditions, the energy conservation measures caused less than 1% drift in the PPD. Thus the savings arising from each energy conservative measure reflect its effectiveness without any loss in occupants' thermal comfort. Energy conservation has been achieved without tradeoff in thermal comfort.

TRADEOFF BETWEEN THERMAL COMFORT AND ENERGY PERFORMANCE RESULTING FROM VARIATIONS IN THERMOSTAT SETPOINTS

Thermostat setpoint differs from the other parameters in its impact on the resulting thermal environment. The other parameters act as filters to the heat gain of the building, modifying the cooling load on the HVAC system which attempts to maintain the indoor environment at its predetermined state, normally defined by the temperature and humidity setpoints. As these parameters do not alter the desired values, the resulting environment created by variations in their parametric values deviate little from the reference conditions. The HVAC system has been adequately sized and is performing well.

Changes in thermostat setpoint, however, modify the environmental state and cause variation in the perceived thermal sensation of the occupants. For a typical tropical clothing value of 0.5 clo and an absence of air motion, the neutral temperature corresponding to a PMV of zero is about 25°C. Figure 10 depicts how the thermal evaluation shifts from a cool sensation to a warm one as the setpoint is raised from 23°C to 27°C. Correspondingly, in a situation of cooling only, the energy consumption decreases. It appears that 25°C is a good setpoint for thermal comfort in still air conditions. Effective energy conservation could be achieved if a higher setpoint is chosen while simultaneously maintaining the comfort

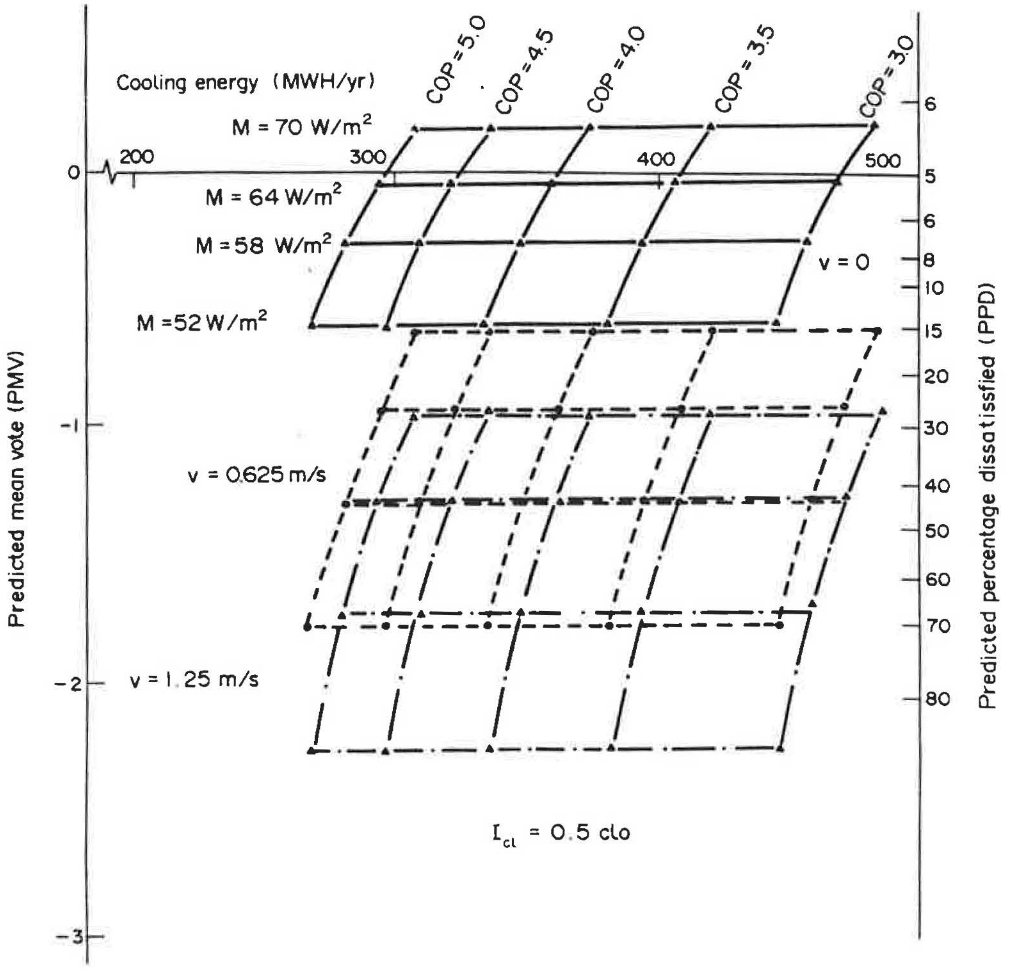

Fig. 11. Comfort-energy grids showing the impact of chiller coefficient of performance on cooling energy and thermal comfort.

condition. While a lower clothing insulation enhances bodily heat loss, the value of 0.5 clo is close to the minimum socially acceptable limit compatible with the dressing norms of Singapore. Thus, the only viable variable which can be relied on to achieve thermal comfort at a higher setpoint is the relative air velocity. As office work is sedentary in nature, relative air motion can be created by mechanical means and/or supply air grille and air velocity design. The feeling of slight air motion is psychologically advantageous in warm air temperature environments, the lack of which often conjures a sensation of stuffiness and inadequate ventilation. The air velocities must, however, not be high enough to cause discomfort draft and dislocate loose papers and documents. Preferably, a value of 0.5 m s^{-1} should not be exceeded.

Figure 12 shows a plot of the tradeoff between thermal comfort and energy consumption with relative air velocity as the moderating parameter. Each degree Celsius rise in setpoint represents a saving of approximately 6% in both cooling energy and total energy consumption. If a metabolic rate of 64 W m^{-2} is assumed as an average activity level, still air conditions at 25°C setpoint is almost at the neutral sensation. At a setpoint of 26°C, a relative air velocity of between 0.1 m s^{-1} and 0.2 m s^{-1} would provide a similar sensation, while at a setpoint of 27°C, a velocity of about 0.4 m s^{-1} is required for the same effect.

For the range in metabolic rates of different work types, it is possible to compensate for a high thermostat setpoint by varying the relative air velocity to maintain the neutral conditions. The magnitude of the air movement can be restricted to 0.4 m s^{-1} even for a metabolic rate of 70 W m^{-2} and a setpoint of 27°C. The combination results in a PMV of 0.2 corresponding to a PPD of 5.8% which is a mere 0.8% above the neutral PPD of 5%.

CONCLUSIONS

The energy implications of various building parameters relating to fabric, system and plant design and operation, and their impact on the thermal environment have been investigated.

By ranking their effectiveness in reducing energy consumption, strategies for energy conservation are derived. Utilization of daylighting and the use of high efficiency lighting systems produced the greatest savings of the order of 25% and 13% respectively. Thus, first measures of energy conservation should be directed to them. Window design regarding size, setback and shading

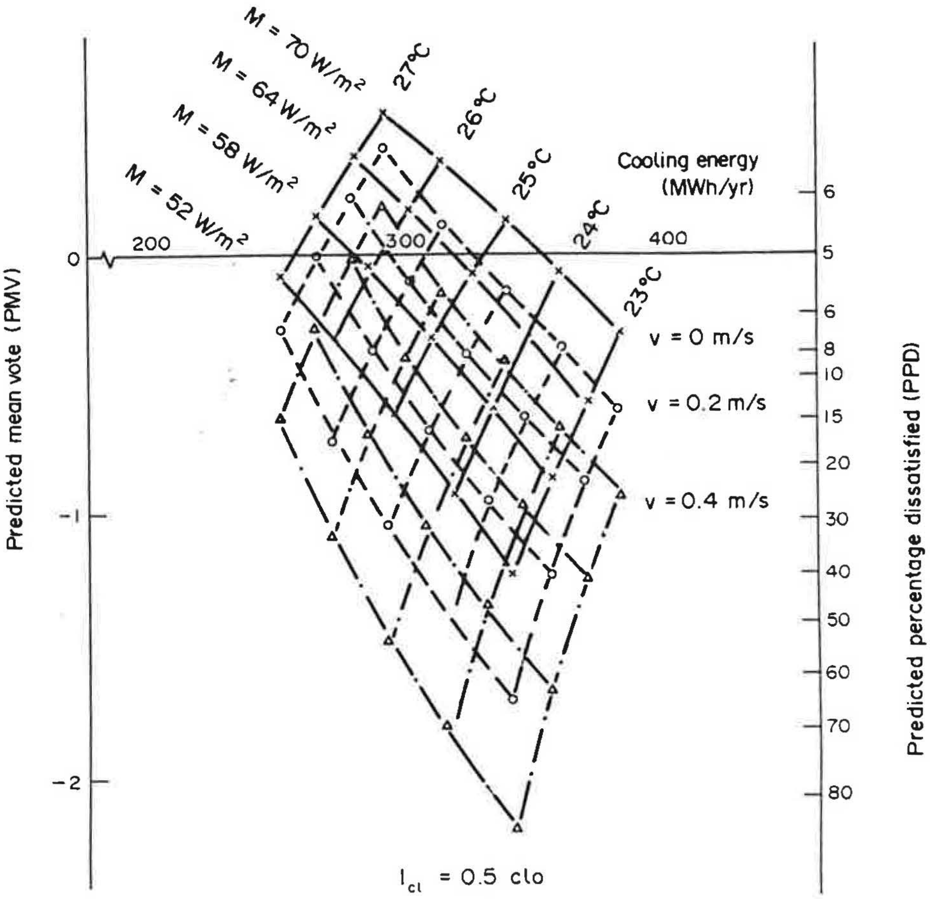

Fig. 12. Comfort-energy grids showing the tradeoffs between thermal comfort and energy consumption with relative air velocity as the moderating parameter.

coefficient have important consequences because they govern the amount of solar transmission which is the largest of the fabric loads. The conflicting demands between window design for daylighting and a reduction of solar transmission needs to be researched further though it seems that the consideration for daylighting would predominate because of its greater energy savings, and at the same time, providing more visual contact with the exterior.

Of the system and plant parameters, chiller coefficient of performance and thermostat cooling setpoint are important factors. Raising the temperature setpoint must be considered together with the implications on occupant thermal comfort. Thermostat throttling range and minimum air flow ratio have insignificant effects on energy consumption.

Using the concepts of PMV and PPD, the impact of various design parameters were evaluated for the tradeoffs between energy performance and thermal comfort. For average conditions of 0.5 clo, metabolic rate of 64 W m^{-2} and negligible air motion, parametric variations do not affect the thermal environment. For the range of the values of the parameters adopted for energy conservation, there is less than 1% drift in PPD. The exception is the parameter of cooling setpoint as it directly modifies the environmental state through its action on the HVAC system. Energy conservation by adopting a higher setpoint is possible without loss of thermal comfort if higher air velocities can be achieved through supply air grille and supply air velocity design or other mechanical means. However the air velocity must be acceptable within the constraints of the office environment such as not causing excessive drafts which dislocate papers.

Using appropriately sized and operated HVAC system and plant equipment, energy conservation can be achieved without deterioration of the thermal environment.

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