

Sheltering effect of trees on reducing space heating in an office building with large glazing area in a windy city

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Abstract: Roles of trees and woodland are not only restricted to those of aesthetically and landscaping. They also include moderating micro/macro climate. Reducing wind speed in the vicinity area of a woodland or a windbreak place an important role in urban planning. Although the sheltering effects of vegetation have been known and utilized in urban planning and landscape design, there is lack of quantitative studies on reducing wind speed and thereafter space heating in Scotland and even in the UK. The study carried out earlier computes that a shelterbelt that reduces 50% of its leeward wind speed can save about 4.5% heating energy in a conventional medium size office building. The saving could be large in a modern office with large glazed façade. To quantitatively evaluate the sheltering effect, a modeling study is to be carried out, consisting of three elements: Firstly a statistical analysis of weather data was carried out to identify the prevailing wind direction during a typical winter heating season. That would ensure that the rows of trees were placed rightly to maximize their sheltering benefits for the buildings in their leeward. The second part was the development of a computer model that simulates the effects of shelter trees on space heating of a building. The last one was the parametric study applying the model to the same building modeled in a previous study but with significantly larger area of glazed façade to estimate the sheltering effect on energy saving and CO₂ reduction. This forms a continuation of study for various types of offices.

Keywords: sheltering effect, computer mode, parametric study

1. Introduction

The effects of trees, such as shelterbelts, hedges and woodlands have been known on reducing wind speed and thereafter space heating for many decades. Suffered from strong wind in winter, many Scottish cities, such as Edinburgh benefit from well planned and planted trees for their shelter and ameliorative effect on wind flows and local climate. The effects of trees, such as hedges, shelterbelts and woodlands have been well known on reducing space heating for many decades. Much research has been done on various aspects of this issue. A comprehensive survey confirms that this reduction will be more significant in windy places [1].

Due to the nature of turbulent boundary layer flow, wind effects on shelter trees and consequently on space heating in buildings are complex and individual. They are subject to many factors, such as local climate, topography, landscape, shelter vegetation, the building and its surroundings. And these will consequently affect the reduction on heating energy consumption, this has been confirmed by Heisler and his colleagues in a series of studies [2-5]. Although there have been many studies carried out investigating the shelter and ameliorative effect on heat losses in buildings, the

evident is that the results span over a wide range which gives only qualitative information if not confusing. For instance the prediction of reduction of annual energy saving to shelter trees varies from 3% to 50%, and for infiltration only there is a huge discrepancy in predicted reduction[1]. Obviously such variation is due to local topography, surrounding terrain, physical characteristics of the shelterbelt, building geometry, and the relative location of surrounding buildings. They all influence the mechanism of heat dissipation from any specific building. The research in UK was carried out in 50's and the results were actually rather qualitative [6]. The most recent investigation conducted in Milton Keynes was quantitative. But only speed reduction and solar access were measured, heating in buildings was excluded in this study [7].

Moreover, many of the studies were actually on the reduction on wind speed and then on infiltration[8]. This uncontrollable infiltration, although important, is only one part of the total heat losses from a building. Dissipation via the external surfaces of a building envelope accounts about half of the total heat losses and this portion is even higher for new buildings which are normally more airtight and with large glazed areas. No much research, however, has been found on the

shelter effect on the surface heat exchange of building envelope. This might be due the facts that surface heat exchange is extremely complex and measurement in either field or laboratory is difficult. The shelter effect on reduction of heating energy would be incomplete without studies on convection heat dissipation on the external surfaces of a building.

This study was to continue the quantitative estimation carried out earlier on energy benefits due to the wind shelter effects on an office building[9]. This modelling confirms that the traditional converted office building could save about 4.5% energy for heating annually due to a windbreak planted in its prevailing direction. This part of study examined some new office buildings with larger windows, of which the structural thermal resistance is lower than a normal wall and surface convection plays a more important part in its overall U-value. The objective of this study was to examine the relationship between the window ratio and the potential energy saving due to the shelterbelt for new office buildings. A computer model office was created to simulate thermal performance of a building under various wind conditions. The method to model wind reduction for its effects on infiltration and convection was also established. A sensitivity test confirmed that the model was sensible enough to response the changes of the wind speed due to the presence of a windbreak in windward direction. The

model was then used for the simulation over a heating season of six-month.

2. The methods

The methodology applied in this quantitative study comprised of three parts, statistical analysis of local weather data, wind reduction prediction and thermal dynamic modelling of a representative building. A dynamic thermal performance package, TAS was used to assess the impact of shelterbelts on the energy consumption of space heating in office buildings[10].

2.1 The weather features

The statistical analysis was carried out using the facility of report generator in TAS. Rewriting the scripts with various "filters" allows the some weather features to be counted, such as the wind speed and wind directions, solar radiation and cloud cover. One of the major tasks of this statistical analysis was to find the direction of the prevailing wind during the heating season, so that the windbreak could be planted to this direction for a maxim protection.

2.2 The physical background

Heat losses through a building are mainly in two ways: air infiltration and heat conduction through the building fabric (Fig 1).

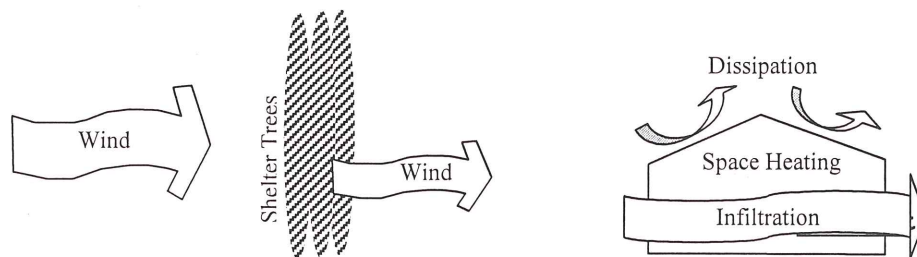


Fig. 1 Schematic diagram of sheltering effect of trees on space heating

2.3 Air infiltration

Air infiltration is the passage of air into a structure through joints, pores, cracks, and other openings. Such flows result from pressure differences between inside and outside air, which is mainly caused by the force of the wind. The mass flow rate of air infiltration is expressed as follows:

$$m = 0.62(2\rho)^{1/2} fA|\Delta p|^{1/2} \quad (1)$$

where m is mass flow rate of air infiltration, $\text{kg}\cdot\text{s}^{-1}$; ρ is the air density on the inlet side of the aperture, $\text{kg}\cdot\text{m}^{-3}$; and fA is the area of the aperture, m^2 .

The heating load due to the air infiltration is:

$$Q_i = 0.62(2\rho)^{1/2} fA|\Delta p|^{1/2} C_p (T_{ao} - T_{ai}) \quad (2)$$

where C_p is the specific heat capacity of air at constant pressure, $\text{J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$; T_{ao} is the outside air temperature, K; and T_{ai} is the inside air temperature, K

In addition, the wind pressure on an aperture is assumed to be:

$$p_w = \frac{F_s c_w \rho v(h_b)^2}{2} \quad (3)$$

where P_w is the wind pressure, Pa; c_w is the wind pressure coefficient; $v(h_b)$ is the wind speed at the building reference height h_b , $\text{m}\cdot\text{s}^{-1}$; and F_s is the adjustment factor applied to certain apertures.

2.4 Dissipation

The heat losses due to conduction through the building fabric are dependent on the thermal transmittance, areas of the fabric and the difference in temperature between the outside and the inside air. The effect of the wind on influencing this heat dissipation is limited to the external surface heat transmission. The external surface heat flow can be written as follows:

$$Q_{ext} = A(h_c + h_r)(T_{ao} - T_{ext}) \quad (4)$$

where Q_{ext} is external surface heat flow, W; A is external surface area, m^2 ; h_c = external convective coefficient, $\text{W}\cdot\text{m}^{-2}\text{K}^{-1}$; h_r is radiative heat transfer coefficient, $\text{W}\cdot\text{m}^{-2}\text{K}^{-1}$; and T_{ext} is the external surface temperature, K.

According to CIBSE Guide [11], the external convective coefficient is defined as:

$$h_c = 5.8 + 4.1V \quad (5)$$

where V is the windspeed. The windspeeds at roof surfaces are taken as 1.0, 3.0 and $9.0\text{m}\cdot\text{s}^{-1}$ corresponding to sheltered, normal and severe exposures [11], and 2/3 of these values are assumed for wall surfaces. The definition of the windspeed is vague. No precise definition of 'at roof surfaces' is given, even though there must be some height above the roof surfaces associated with the windspeed since the windspeed at the surface itself is zero. The same problem occurs for wall surface windspeeds. Therefore, there is a need for further research aimed at standardising the position on or around a building at which surface windspeed should be recorded for use in clarifying the CIBSE definition.

The radiative heat transfer coefficient may be expressed by the following equation:

$$h_r = \frac{\sigma(T_{ext}^2 + T_{env}^2)(T_{ext} + T_{env})}{1/\varepsilon_{ext} + (A_{ext}/A_{env})(1/\varepsilon_{env} - 1)} \quad (6)$$

where σ is Stefan-Boltzmann constant and $\sigma = 5.669 \times 10^{-8} \text{W}\cdot\text{m}^{-2}\text{K}^{-1}$; T_{env} is temperature of surrounding environment ($^{\circ}\text{C}$); ε_{ext} is emissivity of the external

surface; ε_{env} is emissivity of the surrounding environment; A_{ext} is surface area of the external element (m^2); and A_{env} is relative area of the radiating environment (m^2).

It seems that the radiative heat transfer coefficient is not affected by the wind speed, but is influenced by the surface temperature. In fact, the surface transmission due to radiation is affected by wind speed. The higher the wind speed, the lower the absolute temperatures of the external surfaces, thereby reducing the rate of radiation heat transfer.

2.5 Wind Speed Reduction of Shelter Trees

It is difficult to specify the types of trees of a shelterbelt and to quantify accurately its effects on wind. Hence it was decided to combine findings of a literature survey and the results of a CFD modelling carried out in the School. There following assumptions were made, the shelterbelt was a straight windbreak with a height of 18m and length of 120m, both of which were three times of those of a building located downwind within a distance of 54m, three times of the height trees. It had a medium porosity (optical porosity: about 30%) in winter [12]. Supported by the literature review, the CFD modelling carried out in house calculated respectively a wind reduction of the windbreak in the leeward area about 50% for the prevailing wind, 35% for 15° asides of the direction and 15% for 45° . Zero reduction was assumed for all other wind directions [13].

It was assumed that the shelterbelt was planted to the Southwest of the building to gain the maxim sheltering protection. Furthermore the building in the leeward of a shelterbelt experienced the wind conditions as it had been in an open space with reduced wind speeds, and the reduction rate were direction dependent as mentioned above. Throughout the whole heating seasons (about 6 months), the hourly wind speed values in the weather file for Edinburgh were individually adjusted to reflect these changes in the wind speed parameter. Running TAS with the original weather file and the modified file would produce two performances: one with not shelter protection and the other taking into account of the sheltering effect.

2.6. The sensitivity test

A sensitivity test was conducted to explore how a building could be correctly built with TAS that its

thermal performance, namely its infiltration and external surface heat exchange, would response adequately to the changes of wind speed. This model was a three-story building of $5 \times 4 \times 3 \text{ m}^3$. The test room was on the first floor to avoid heat transfer on its ceiling and floor, as the other floors were maintained at the same internal conditions. The façade examined faced to the south, had a wall and a single glazed windows (Table 1). The rest of the envelope was deliberately made with high insulation, so that heat losses through them would be negligible.

Table 1. Thermal properties of some building elements applied in the test building

	Surface area $/\text{m}^2$	Transmittance $/(\text{Wm}^{-2}\text{C}^{-1})$
Test wall	11.55	5.0
Single Glazed window	2.00	100.0
Other walls	35.70	0.005

A special weather file was prepared for this test, in which, six hourly-variables, in 60 days were fixed to constant values, whilst the wind speed varied from $0.0 \sim 10.0 \text{ ms}^{-1}$. The two components of radiation were 200; the outdoor temperature, 5°C ; the relative humidity, 80%; cloudiness, 1; and the wind direction, south. The wind speed was set to 0.0, for the first 10 days, then 0.5 ms^{-1} for next ten days, 1.0 ms^{-1} for day 21 to 30, 3.0 ms^{-1} ; day 31-49, 5.0 ms^{-1} ; day 41-50 and 10.0 ms^{-1} ; day 51-60. The 10-day period would allow the building to settle thermally.

In the first run, the infiltration was fixed to a very small value to avoid its effects, so that all heat losses were through the structure. In the second run, another window was added onto the north facade creating a complete cross building airflow path along with the original window on the south facade. This simulation tested if the air infiltration modeled was a dependent of wind speed. the window was turned to allow the room to have a small percentage of opening that led to a 0.5 ACH at wind speed of 3.0 ms^{-1} , and temperature difference of 5°C between the ambient and indoor air.

The Model Building

The model building was intended to be “representative” as well as to allow the key problem to be address – quantifying wind sheltering benefits for buildings with large glazed façade area. Based on the classification of the Energy Consumption Guide 19

[14], the building was created as a two-story building with cellular offices (Fig 2& 3). Each of cellular office was 3 m wide and 4.5 deep. The floor height was 3.6 m, including a ceiling void of 0.9m high. All other rooms and spaces, such as entrance lobby, staircases, toilets, services rooms were all located at the two ends of the buildings. The U-value for the external walls, internal walls, windows, floors and roof was set to 0.418, 1.03, 5.882, 1.002 and $0.173 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$ respectively.

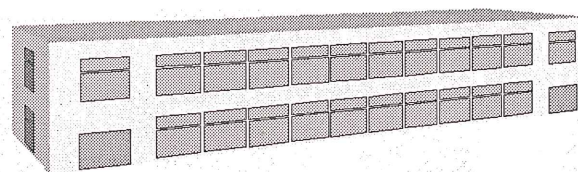


Fig. 2 The model office building (glazing ratio small, left and large right).

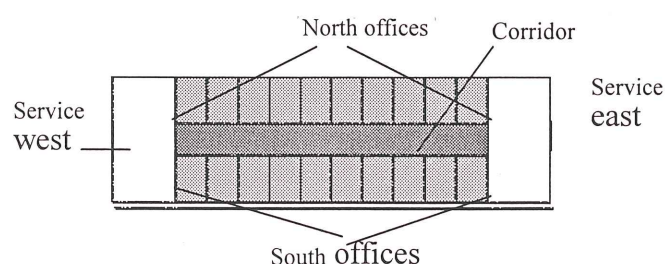


Fig. 3 The zones on the ground floor

In the offices, the occupancy pattern was 0900 to 1800, Monday to Friday, with one hour preheating. The heating period was accounted from September to March, when all rooms in the office were maintained at 20°C throughout the heating season during the occupied period. The casual heat gains during the daytime were due to occupants, equipment and lighting, which were set to 10, 15, and $15 \text{ W}\cdot\text{m}^{-2}$ respectively. All other spaces were maintained at 12°C all the time. The only casual gain was due to the lighting, $5 \text{ W}\cdot\text{m}^{-2}$. Out of the working hours plus one hour preheating the whole was unheated.

Each of the windows was made of two parts; a top one with a fixed glass panel and a low one with an operable panel. The open area of the window for the infiltration was fixed to 0.025 (window area 1.96, 2.5%), so that the room air change rate could be 0.5 ACH when the temperature difference between the indoor and outdoor was 15°C and the wind speed was 3 ms^{-1} from the South. The internal doors were made with a 0.1% open area, allowing airflow to travel throughout the building. All together four cases were

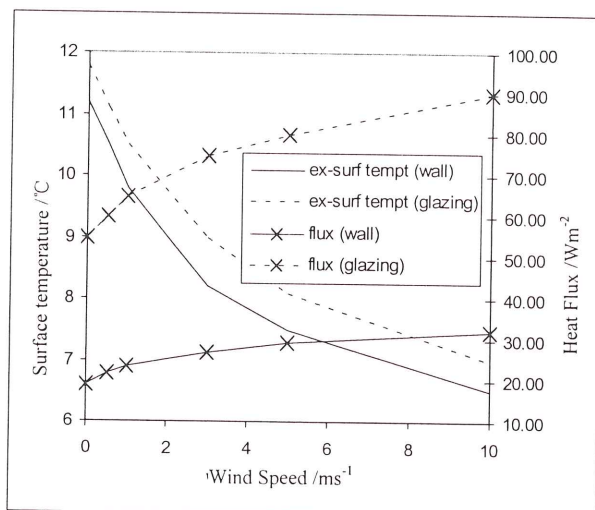
simulated, in which the fixed window panels increased their sizes so that the glaze ratio varied from 14, 23, 31 to 41%. All other parameters were kept same, therefore the sheltering effects due to various window ratio could be assessed.

Like the test case, the infiltration rate of the model building was set to 0.5 ACH-1, by tuning the opening areas of all apertures on the external walls to achieve the given rate at an external wind speed of 3 ms^{-1} . The air infiltration of the building would be then responsive to changes of wind speed in wind data in simulation. More details regarding to this TAS model can be found in reference[15]

3. Results

3.1 The sensitivity test

As expected, the average temperature and the heat flux increased on the external surface of the building



varied with the wind speed. The surface temperatures at both surfaces lowered by the increasing wind. The heat flux at the window surface had a more rapid increase when the wind became stronger. It was 6.6 W m^{-2} in a calm condition at the wall, and increase very slowly to 7.4 W m^{-2} when wind blew at 10 m s^{-1} , a total increase of 12%. But the same variable increase 24% from 9.1 W m^{-2} at windless moment to 11.2 W m^{-2} in the wind of 10 m s^{-1} . (Fig 4, left). The heat losses from the surface of the window increased more quickly than that on the wall surface. This was due to the fact that the window had lower thermal transmittance and consequently it had a higher external surface temperature. The external surface transmittance was constantly higher at the windows than that on the walls. All of these suggest that a building with large glazed facade area would benefit more shelter effect during the winter heating seasons.

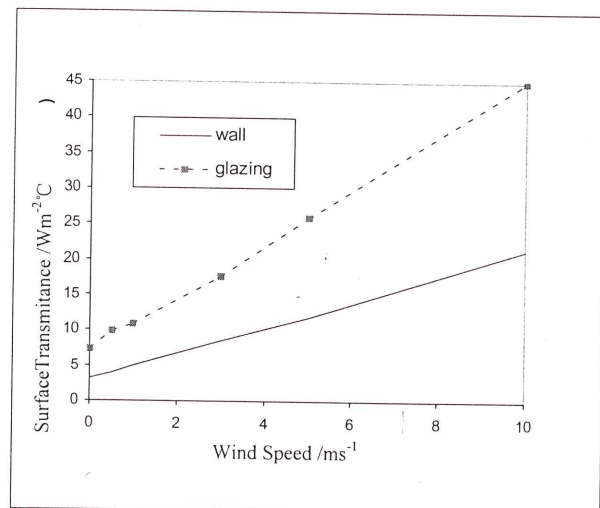


Fig. 4. Surface temperature and heat losses vs. the wind speed (left) and surface heat transmittance (right).

On the whole, these sensitive tests confirmed that the modelling techniques developed here were able to simulate the thermal behaves of the building under various wind conditions. The infiltration and external surface convection, dependent of the wind speed, were reasonably simulated.

3.2 Total energy consumption over the heating season

Compared with the previous modelling study where the traditional office building could save about 4.5% heating energy [9], the new office building with small window ratio would have a higher energy saving, about 5.5% (Table 3). As expected, the saving will be more remarkable when it converted to per treated floor area. The saving increased from 0.86 to $1.22 \text{ kW}\cdot\text{h}\cdot\text{m}^{-2}$ when the window areas enlarged from 14-44% of façade area.

Table 3. Total heating load over the heating season (September to March)

	Heating load/ (kW·h)			Saving /%	Saving/floor /($\text{kW}\cdot\text{h}\cdot\text{m}^{-2}$)
	Normal	Sheltered	Saving		
Case 1	15 689	14 826	863	5.5	0.86
Case 2	19 329	18 308	1021	5.3	1.01
Case 3	21 717	20 608	1109	5.1	1.10
Case 4	25 056	23 826	1230	4.9	1.22

Fig. 5 shows that the air change rate due to infiltration varied with the wind speed. As the air change rate was caused by both the wind and the temperature difference between the ambient and the indoor air, the two forces offset a bit at low wind speeds, lower than 0.5 ms^{-1} . Under a stronger wind the air change rate increased lineally with the wind speed,

which agrees well with the theory expressed in equation 1, 2 and 3.

A close look at the breakdown heat losses provides a better picture how the savings were achieved. The contribution was made almost equally by the cut on infiltration and reduction on the heat losses on the windows (Table 4). It also shows that the heat losses through the walls were at the same level of those of infiltration. But the losses through the windows were much higher. For a building with larger windows, the reduction on window heat losses was therefore much more significant. When the glazed area became 44% of the total facade, the saving due to the window contribution was twice of that of infiltration (Table 5).

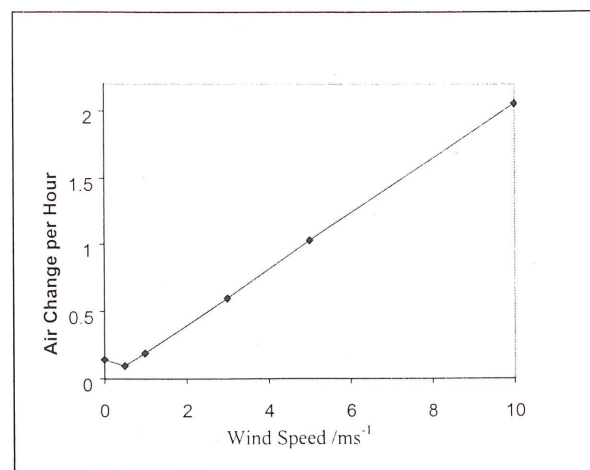


Fig. 5. The indoor air change rate vs. the wind speed

Table 4. Breakdown heat losses in the south-facing offices (September to March)

	Heat Losses (not sheltered) /(kW·h)			Heat Losses (sheltered) /(kW·h)		
	Infiltration	Conduction		Infiltration	Conduction	
		Wall	Windows		Wall	Windows
Case 1	2776.57	2139.60	4785.20	2661.81	2154.30	4698.98
Case 2	2631.67	2119.93	7503.76	2520.13	2131.39	7372.72
Case 3	2549.52	2129.35	9466.52	2438.04	2139.25	9307.14
Case 4	2443.72	2123.81	12268.81	2333.29	2135.45	12070.83

Table 5. Energy savings in the South-facing offices

	Difference of heat losses /(kW·h)			Loss difference per square meter of floor /(kW·h/m ²)		
	Infiltration	Wall	Windows	Infiltration	Wall	Windows
Case 1	114.76	-7.94	118.25	0.11	-0.01	0.12
Case 2	111.54	-11.46	131.04	0.11	-0.01	0.13
Case 3	111.48	-9.90	194.09	0.11	-0.01	0.19
Case 4	110.43	-6.36	226.65	0.11	-0.01	0.22

The infiltration heat losses decreased when the window area increased, although the air change rates in the building remained the same (the second and fifth columns in Table 4). This is due to the fact that the indoor air had a lower temperature due to more heat losses through larger windows. Hence for the same air change, larger temperature difference in/outdoor resulted higher heat losses.

It is very interesting indeed to note that the shelterbelt causes slightly increase on the heat losses through the walls. This can be explained by three facts:

firstly the strong wind would lower the indoor air temperature during the winter (Fig 6 right). Secondly the total U-value was not sensitive to the change of the wind speed, as the structural U-value of the wall was the dominant. The external surface transmittance of the window had a higher weight in its total U-value. Thirdly, the heat flux is a production of total U-value and the temperature difference. When the wind became stronger, the heat losses on the wall dropped as the temperature difference decreased, whilst the losses on the windows increased (Fig 6 left).

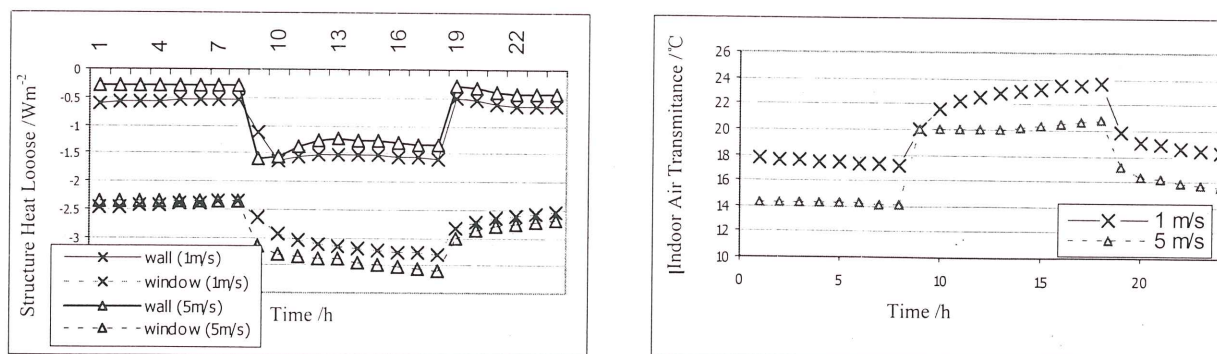


Fig. 6. The thermal response of large window building in two typical days when the wind speed was constantly 1 and 5 ms^{-1}

4. Conclusions

Although this modelling study was carried out under many assumptions, which simplified the complex issue of building heat losses in changing wind, the exercise has revealed many new findings as well as confirmed some established knowledge. Firstly the method of modelling wind shelter effect on thermal performance of building works reasonable well if the convection is dependent of the wind speed of a weather station. For more realistic modelling the relationship between the convection coefficient and the airflow speed needs to be locally defined. Secondly the large the glazed facade area is the more significant the shelter effect is. Compared with the office buildings converted from traditional old houses which has a total saving of 4.5%, a modern office building with large glazed facade and lower ceiling height will likely to save up to 5.5%. Thirdly the saving will be more remarkable when the saving is expressed in the energy consumption per treated floor area. As an example, a building with 14% glazed facade would have an energy saving of $0.86 \text{ kW}\cdot\text{h}\cdot\text{m}^{-2}$ over the heating season and the figure rises to $1.22 \text{ kW}\cdot\text{h}\cdot\text{m}^{-2}$ when the glazed facade increases to 44%.

This modelling exercise including the model tests all indicate that TAS can be used to develop detailed dynamic thermal models to investigate sophisticated physical phenomena, provided that each model developed has been thoroughly tested, as it is demonstrated in section 2. The limitation of the model is that the convection heat loss is calculated using the wind speed from weather file which is from weather station, and is regardless the surface location. This approximation would be more sufficient in most thermal modelling. In this investigate, however, it

would be better to have a set local convection heat exchange coefficients, which would allow this part of heat losses be assessed more accurately using a single reference wind speed. This could be done just like the wind pressure coefficient, which is associated with location and wind incidence direction. Using a reference wind speed and a local wind pressure coefficient, a wind pressure can be calculated locally.

This study also suggests some other possible research in the future. First of all a more comprehensive weather statistical analysis would give more support for the need of reduction on space heating. It will also help understand thermal behaves of building under the specific weather conditions. Secondly predicted results need to be examined individually to identify the details of heat transfer and causes of physical phenomena. Thirdly the modelling method developed here should be applied to other types of buildings, such as residential houses presenting a large portion of housing stock and they have a totally different occupancy, some need to be heated throughout a whole day and the other only during the nights. This would potentially receive more benefits from shelterbelt protection.

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