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Modelling sheltering effects of trees on reducing space heating in office buildings in a windy city

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Abstract

Using statistical weather analysis, computational fluid dynamics and thermal dynamic simulation, a systematic method was developed to assess quantitatively the effects of a shelterbelt on space heating, particularly with regard to the energy consumption and CO_2 emission. It was then applied to estimate the heating loads of two typical office buildings in a windy city located at 57.2North, with and without a shelterbelt. Firstly, the statistical analysis of weather data was carried out to identify the prevailing wind direction during a typical winter heating season in the location. It was to ensure the windbreak planted rightly to maximise its sheltering benefits for the buildings in its leeward. This analysis, which revealed the main weather features in the location, would help to better comprehend the results of the thermal modelling and gain insight of how the load responses to the climate. In the second part, CFD modelling predicted wind reduction due to the shelterbelt under various wind directions. The predicted data were then used to prepare two sets of weather data, the original weather file and the revised one, in which the wind data had taken into account the reduction effect of the windbreak. The third part was a dynamic thermal modelling study where two types of office buildings were selected as the representative offices in Edinburgh for the assessment of sheltering effect on energy saving and CO_2 reduction. The predicted savings over a heating season due to the shelterbelt were in a range of 16–42% and the actual values in space heating were about 2.2 kWh m^{-2} for new office buildings and 14.5 kWh m^{-2} for offices converted from conventional houses without insulation improvement. These significant savings were due to the local weather that is typically known as long windy winter with many cloudy days.

Keywords: Modelling; Office building; Shelter effect; Windbreaks; Space heating; Wind

1. Introduction

Although climate change has resulted in slightly warmer winters in the UK yet the air temperature difference between the outdoor and indoor has increased remarkably in the last three decades, from 7.2 °C in 1970 to 10.8 °C in 2000 [1]. Despite the various measures being undertaken, such as better building insulation and more efficient heating systems, this 3.6 °C increase has contributed significantly to the 24% rise in energy consumption for space heating in every household across UK since 1970. This figure is magnified further by the increasing number of buildings within UK in past two decades. Above all the Kyoto protocol on reduction on total energy consumption and the restriction on CO_2 emission demands immediate actions of all parties, from regulatory bodies and governmental agencies to designers and end users. Seeking various measures to further reduce energy consumption in buildings has become an urgent task in government's agenda.

Reducing space heating in Scottish houses is important for many reasons. Firstly, the long windy winter with many overcast days contributes to high heating energy consumption in buildings. The average wind speeds across Scotland are still increasing although over all UK the speed is slightly slower [2]. Secondly, even for a normal external wall its thermal resistance rises 50% when wind speed decreases from 5 m s^{-1}, the average wind speed in many Scottish places, to 2 m s^{-1} [3]. Such increase will be more significant for glazed areas, of which the resistance is already rather small. Thirdly, the new trend in design for large glazed areas in buildings, such as conservatories, atria and curtain walls, has inevitably led to large heat losses through building fabric via higher conduction and stronger infiltration. Finally, the results of recent climate change in Scotland have drawn the attention of designers and governmental organisations to revision of the building

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regulations set up about a century ago. This can be seen through a recent call for research for updating British Standards for better insulation of external walls from Scottish Executive. Seeking measures to reduce further the heat losses through the building envelope is therefore a timely research goal.

Reducing *U*-values and infiltration rates are the most obvious measures to lower the energy uses in buildings. These however are almost at their limits. The proportion of opaque walls in a building envelope is shrinking with the trend of increasing glazed areas for better daylighting. A double glazed window has a *U*-value much higher than that of a standard wall. Therefore increasing insulation for a part of the envelope is not the most effective way to bring down the heat losses through the envelope. Moreover, the overall thermal resistance of an envelope consists of three parts which include the resistance of the internal surface, the main body, and the external. Increasing the resistance of the external surface is a very effective way to improve the overall performance of insulation of the whole construction. Infiltration, on the other hand, seemingly has already reached to its limits particularly in new buildings, where windows and doors are better draught-proofed. A background infiltration of about 0.5 air change per hour has been confirmed to be essential for keeping indoor air fresh.

Arguably, the increased glazed area would allow more solar gain into the building. Over half of the space heating in the UK is actually required by residential houses, where half of the heating time in winter is at night. Moreover, sun hours in the UK particularly in Scotland are extremely short due to the facts that daytime is short and overcast days are dominant during the heating seasons [4]. Even during a sunny day, the low solar altitude can hardly reach many indoor environments due to its low incident angle. The balance between solar gain and excessive heat loss through the glazed areas really need to be quantified to actually justify the claim of the benefits of enlarging glazed areas.

Among all of the measures mentioned above, the effects of trees, such as hedges, shelterbelts and woodlands have been well known on reducing space heating for many decades. A comprehensive survey confirms that this reduction will be more significant in windy places [5].

Due to the nature of turbulent boundary layer flow, however, the effects of trees on winds 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. These will consequently affect the reduction on heating energy consumption, which has been confirmed in a series of studies in the US [6]. Although there have been many studies carried out investigating the shelter and ameliorative effect on heat losses in buildings, the evidence is that the results span over a wide range which gives only qualitative information. For instance, the prediction of reduction of annual energy saving due to shelter trees varies from 3% to 50%, and for infiltration only there is a huge discrepancy in predicted reduction [5]. 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 the UK was carried out in the 1950s when both buildings and living standards were very different, and the results of energy conservation were actually rather qualitative [7]. The most recent investigation conducted by Milton Keynes was quantitative. But only speed reduction and solar access were measured, heating in buildings was excluded in this study [8].

Moreover, many of the studies were actually on the reduction of wind speed and then on infiltration and the significance of the effects on this part of heat dissipation has been justified [9]. This uncontrollable infiltration, however, is only one part of the total heat losses from a building. Dissipation via the external surfaces of a building envelope accounts for about half of the total heat losses and the figure is even higher for new buildings which are normally more airtight. This heat loss will be even greater in buildings with large glazed areas, increasingly favoured in current office designs, as their *U*-values are much higher than those of walls and roofs. Not much research, however, has been undertaken on shelter effects on the surface heat exchange of building envelopes. 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 studying the convective heat dissipation on the external surfaces of a building.

All of these facts highlight the need to carry out a study to estimate the benefits quantitatively and assess the potential energy savings due to the existence of a shelterbelt. This is further justified by the government determination on sustainable development that welcome all efforts on energy saving and CO_2 emission reduction [10].

This study was an attempt to develop a systematic approach of predicting sheltering effects on space heating and CO_2 emission of buildings in winter. This involved firstly statistical weather analysis to identify the prevailing wind direction during the heating periods, including the months in a year and the occupied hours in a day. Second part was modelling prediction of wind reduction in leeward of a shelterbelt of specified aerodynamic feature. These data were then used to modify the weather file of Edinburgh, a typical windy city in the east coast of Scotland, in a thermal dynamic modelling program. Running the program using the modified and original weather files, thermal performance of a building was predicted respectively as with shelterbelt protection and as without it. Finally, this approach was applied to a parametric study, to investigate the quantitative benefits of shelterbelts to two typical office buildings to simulate thermal performance under the two wind conditions, with and without the protection of a shelterbelt. The sheltering benefits were then assessed for both the offices refurbished from traditional house buildings and new offices built under new thermal standards.

Initially, this paper discusses the theoretical background of the effects of wind on heat exchanges between a building and its surroundings. In Section 3, methods applied in this study are presented, namely the statistical wind analysis, CFD wind reduction prediction and the development of thermal models for