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DYNAMIC INSULATION - RECENT EXPERIMENTAL AND THEORETICAL STUDIES

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SYNOPSIS

Dynamic insulation is a very good example of a ventilation system integrated with the building envelope. The paper describes two recent studies carried out at Nottingham on dynamic insulation.

One study concerns a system based on mechanical ventilation. The other describes a purely natural system. Although there are few existing applications of dynamic insulation, it is argued that there is potential for both systems, particularly with certain types of building. The natural system is technically more challenging than the mechanical system, but the potential energy savings are larger.

Dynamic insulation with mechanical ventilation has been investigated for an agricultural building (a pig-fattening house). The investigation has taken the form of experimental measurements in a quarter-scale model in a laboratory, coupled with CFD calculations for both the scale model and the full-scale building. The dynamic insulation is formed from lightweight re-cycled cellulose material. Measurements carried out include permeance and temperatures and velocities in the building.

The system based on natural ventilation has been studied with a theoretical envelope-flow model, supported by experimental tests on components of the system. The required flow direction through the insulation material is maintained by the novel use of a wind-powered fan, combined with a passive chimney stack. At low wind speeds, buoyancy gives the required flow direction. At high wind speeds the wind-powered extract fan comes into operation. The system is completely self-regulating i.e. the higher the wind speed, the higher is the extract rate, which leads to increased pressure drop inside the building and thus the flow direction is maintained. The potential energy savings with this system are large.

1. INTRODUCTION

Dynamic insulation refers to the use of porous material for insulating the envelope of a building. The flow of ventilation air through the material reduces the heat loss by conduction to the exterior at the external surface, when the air flow direction is opposite to the heat flow direction (counter-flow). The loss through the insulation can be reduced to virtually zero with a low air velocity (of order 1 m/h), which corresponds to the ventilation requirement. The reduced heat loss is accompanied by pre-heating of the ventilation air before it enters the building. This is an additional benefit, since the risk of discomfort due to cold draughts is eliminated.

Over the past 50 years or so, there have been a number of buildings constructed with dynamic insulation throughout the world e.g. Europe (particularly Scandinavia), N. America, Japan, Australia (e.g. Refs. 1 and 2). Despite the potential benefits and the fact that porous materials are readily available and cost no more than conventional materials, dynamic insulation has not been exploited in practice to any significant extent. The reasons for this are briefly discussed in the following, and it will be seen how they have shaped the research which is described in this paper.

2. PROBLEMS OF APPLYING DYNAMIC INSULATION

The major problems of applying dynamic insulation (for reducing energy consumption for space heating in the winter) are believed to be as follows.

(i) The direction of the air flow needs to be maintained in the opposite direction to the heat flow (counter-flow). If the air and heat flows are in the same direction (co-flow), the conductive loss is increased and for this reason (and to prevent any problems of condensation in the material) it is necessary that counter-flow be maintained. All known applications employ mechanical ventilation to maintain the desired flow direction, either by de-pressurisation (extract) or pressurisation (supply). In so doing the electricity consumption of the fan and the increased ventilation rate can seriously reduce the cost savings from the insulation, particularly if natural gas is used for space heating. One solution to this problem is to employ a heat pump to recover heat from the mechanical ventilation extract, however the cost of a heat pump can seriously reduce the cost-effectiveness of the system, at least in the milder climates. A cheaper alternative is to employ heat recovery with the mechanical ventilation. However this is of dubious advantage, because heat recovery requires both mechanical supply and extract. To achieve the required pressurisation it is necessary for the supply and extract rates to be very different, whereas heat recovery is best achieved with supply and extract rates which are fairly close. This contradiction, plus the fact that heat exchanger efficiencies are typically 70 % or less, means that mechanical ventilation with heat recovery is unlikely to be cost-effective.

(ii) It is necessary to achieve the required volume flow rate through the dynamic insulation in such a way that it does not significantly increase the total ventilation rate beyond that for the conventional building i.e. the ventilation rate should not be increased with dynamic insulation compared to the conventional building. This basically means that a low adventitious leakage is needed with dynamic insulation.

(iii) The energy saving (and hence cost-effectiveness) depends on the surface area of the dynamic insulation. Buildings for which a relatively large proportion of the envelope area can be dynamically insulated are therefore desirable.

(iv) The pressure required to maintain the required flow direction through the insulation can easily be eliminated by the opening of doors, windows and air vents. Brief and infrequent opening times are probably acceptable, but there could certainly be problems with occupant actions in certain types of building (particularly domestic).

On the above basis, the ideal application would be one where

(a) mechanical ventilation is not required
(b) it is easy to minimise adventitious leakage e.g. the envelope is pre-fabricated and of simple construction
(c) the surface area of the insulation is maximised e.g. there is little glazing

(d) there are no undesirable occupant actions.

In the remainder of this paper we describe two different applications which go some way to satisfying the ideal application. The first is an agricultural building. This employs mechanical ventilation, but satisfies (b), (c) and (d). The second is of a more general nature and is capable of satisfying all four requirements by making use of dynamic insulation in a naturally ventilated building.

3. APPLICATION TO PIG FATTENING HOUSE

Experimental tests have been carried out in a quarter-scale model of a pig fattening house, shown in Figure 1, and these tests have been complemented by two sets of CFD calculations. The first set was aimed at confirming that a quarter-scale model would provide reasonable similarity of a full-scale building. For the second set, calculations for the quarter-scale model were compared with the experimental data.

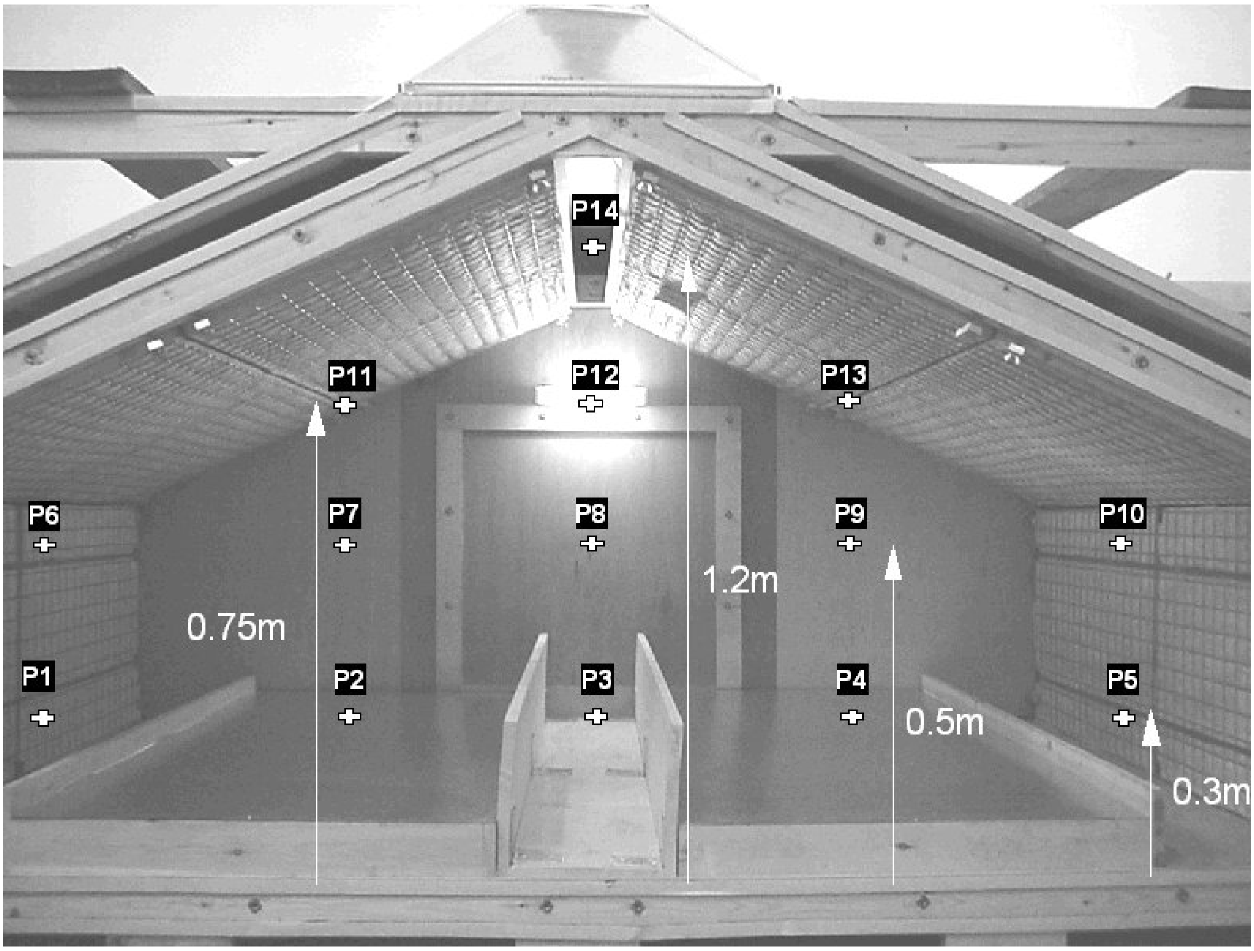

Figure 1 Interior of quarter-scale model

3.1 Basic design

The basic design is intended to maximise the area of dynamic insulation. In this type of building it is not practical to apply dynamic insulation to the floor, but it can be applied to the walls and ceiling, as shown in Figure 1. For winter operation, a mechanical fan installed at the top of the pitched roof extracts air from the space through the rectangular opening which extends over the length of the apex of the ceiling. There is a cavity between the dynamic insulation and the outer skin of the building and the air is drawn through the insulation material via this cavity.

The material chosen for use as dynamic insulation was cellulose fibre. This is simply re-cycled paper that has been treated with a fire retardant. The material is loose-fill, and so the density of the material, and therefore the permeance, may be adjusted by simply increasing or reducing the mass of material in a given volume. For the present purposes the material was contained by porous cloth, which was held in place in trays by means of a rigid wire mesh. These trays were then mounted on the walls and ceilings, as can be seen in Figure 1

Test were carried out on the material to determine the density to achieve the desired permeance. A density of 100 kg/m^3 gave a permeance of 1.79 m^3/hPa.m^2 and this was used in the quarter scale building.

Dynamic insulation works best when the adventitious leakage is low. A combination of pressurisation and tracer gas measurements was used to determine the adventitious and total leakage of the model. Despite efforts to build an airtight structure, there was still a considerable amount of adventitious leakage. This is believed to be due to leakage in the trays containing the insulation material i.e. it was very difficult to eliminate air gaps at the corners of the trays. The adventitious leakage constituted about 12 % of the total leakage.

In a pig fattening house the main heat input to the space is from the pigs themselves and this can be estimated from empirical relations (Ref. 3). The quarter scale heat output was produced using two heated plates, either side of the central walkway. They are heated on the underside by resistive light bulbs with variable output power.

3.2 Scale modelling and similarity

It is not possible to satisfy all the requirements for dynamic similarity i.e. partial modelling is necessary, whereby the aim is to satisfy the most important requirements. Thus equality of Archimedes number between model and prototype was satisfied, whereas the requirements relating to Reynolds number and Grashof number were relaxed to the requirement that they should exceed a “critical” value. For the temperature boundary conditions, the temperatures in the model were chosen such that the Boussinesq approximation is valid i.e. small temperature differences. With the Boussinesq approximation, dynamic similarity means that the values of u/U_0 and $\Delta T/\Delta T_0$ at corresponding points in two flows will be equal, where U_0 and ΔT_0 are the characteristic (reference) values of velocity and temperature difference. Equality of Archimedes numbers leads to the following relationship between U_0 and ΔT_0

$$\frac{U_{0p}}{U_{0m}} = \sqrt{\frac{K_L}{C}} \qquad (1)$$

where K_L is the length scale factor and C is defined by

$$\frac{\Delta T_{0m}}{T_{0m}} = C\frac{\Delta T_{0p}}{T_{0p}} \qquad (2)$$

For the present tests C was taken as 1 i.e. temperatures in the model were set to be the same as at full-scale. The aim of this is to obtain approximate similarity of heat flow rates (convective and radiant heat output from the pigs, ventilation heat loss, wall heat loss) for the model and full-scale. There is some justification for this with small values of K_L (see Chapter 14 in Ref. 4). With C =1, the relation between the heat output from the pigs at model and full scale is

$$\frac{H_m}{H_p} = \frac{1}{K_L^{2.5}} \qquad (3)$$

and this was used to determine the heat input to the model.

3.3 CFD Calculations – effect of scaling

The effects of scaling were investigated by carrying out CFD calculations for the following cases:- full scale, half-scale, quarter-scale and eighth-scale. The CFD code was Phoenics, with a three-dimensional grid. For the results presented here, internal surface temperatures were specified for the boundary conditions (calculations were also carried out with a specified heat flux from the heated plate).

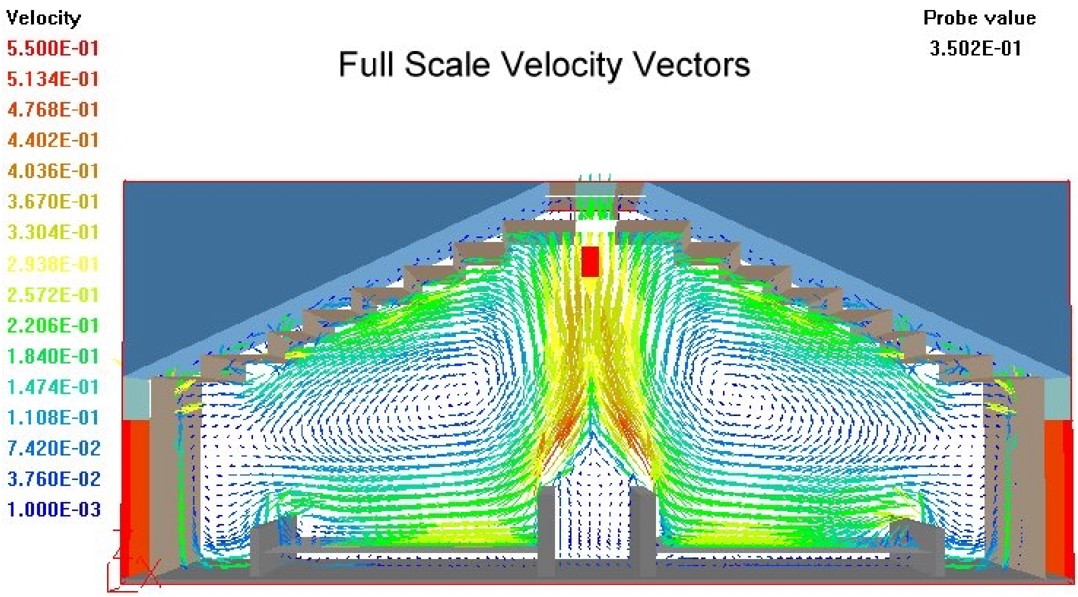

Figure 2 CFD results - velocity vectors, full scale

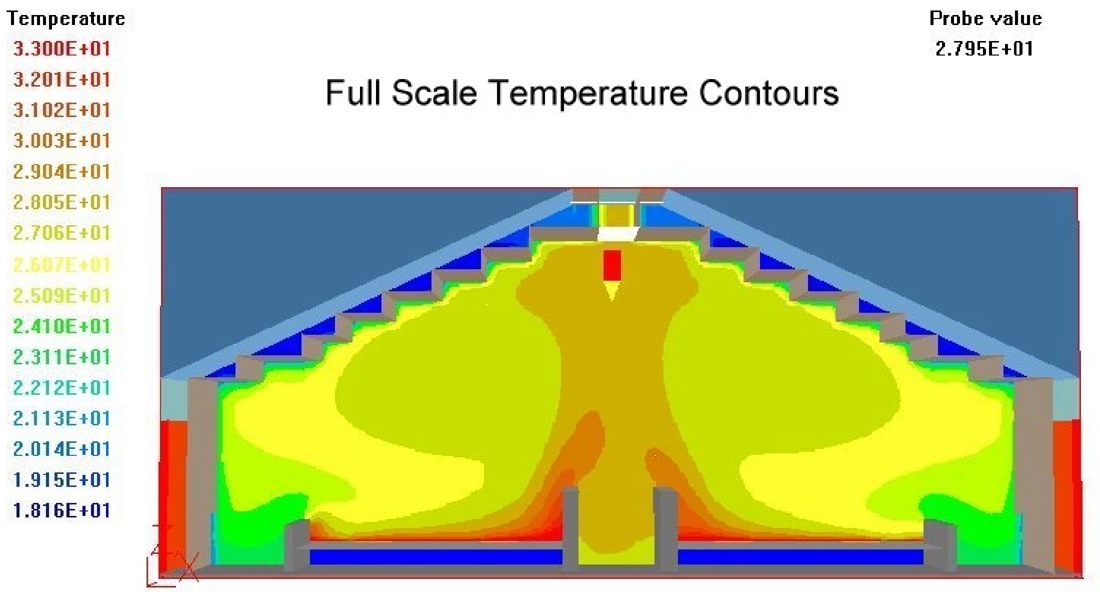

Figure 3 CFD results - temperature contours, full scale

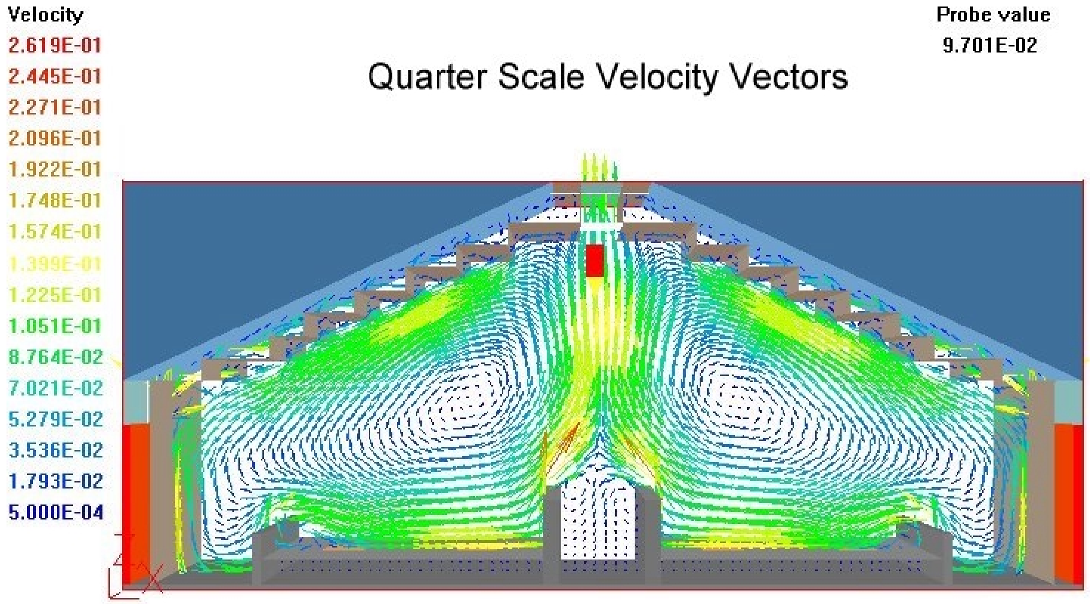

Figure 4 CFD results - velocity vectors, quarter scale

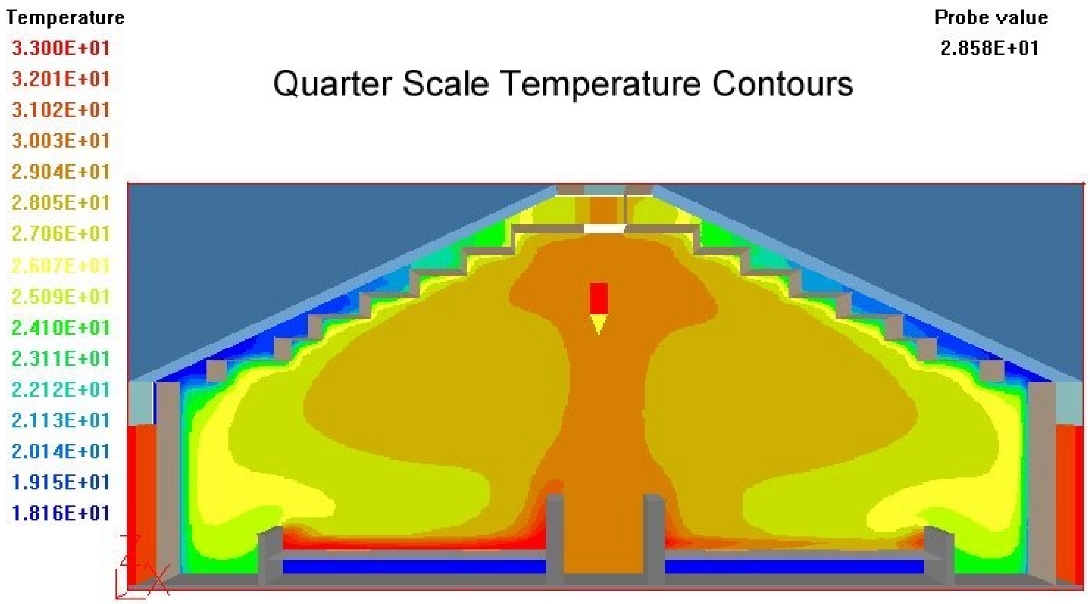

Figure 5 CFD results - temperature contours, quarter scale

Not surprisingly it was found that departures from exact similarity increased as the scale factor was increased from 2 to 8. Some results for velocity and temperature distributions at the centre section of the building are given in Figures 2 and 3 for the full-scale case and in Figures 4 and 5 for the quarter-scale case.

Comparison of the Figures indicates that a quarter scale model gives reasonable similarity. Qualitatively the flow patterns and the temperature distributions are in good agreement. Theoretically, with exact similarity one would expect the velocities in the quarter scale model to be 0.5 times the velocities at full scale (see equation 1). Analysis of the results showed that on average the ratio was closer to 0.4 than 0.5 (slightly better agreement was obtained with the heat flux boundary conditions). Contributory factors to this difference are the differences between the temperature distributions at the two scales and the different Reynolds numbers.

3.4 CFD Calculations – comparison with experiment

Figures 6 and 7 compare measured and calculated velocities and temperatures at the measurement points shown in Figure 1. The velocities (resultant) were measured with a Dantec Omnidirectional anemometer and the temperatures with specially calibrated thermistors and PRTs.

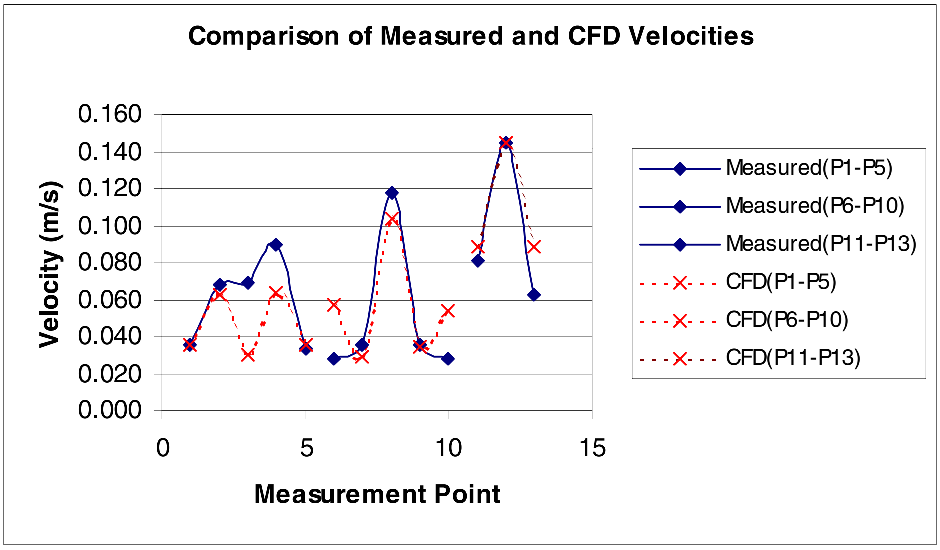

Figure 6 Comparison between measurement and CFD – resultant velocity

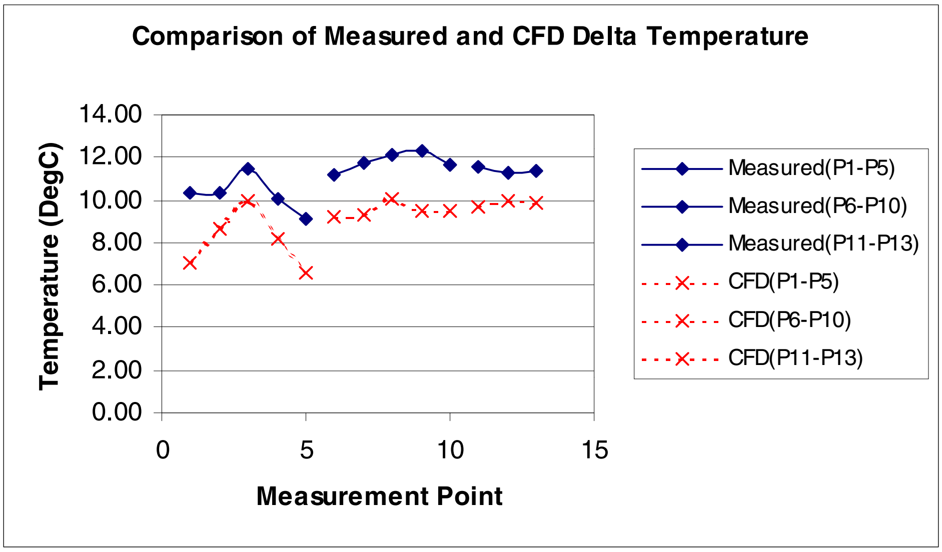

Figure 7 Comparison between measurement and CFD – temperature

The comparisons show generally good agreement, the main differences being some lack of symmetry in the measured velocities and a consistent underestimation of the internal temperatures of about 2 K.

The next stage of the work is to carry out measurements and calculations for the conventional case (static insulation with air vents) and to compare these results with those with dynamic insulation.

4. DYNAMIC INSULATION WITH NATURAL VENTILATION

4.1 Basic design In Reference 5 it is shown theoretically that dynamic insulation can work without the need for a mechanical ventilation system. The basic problem is to maintain the required flow direction (the magnitude of the flow is less important) under all weather conditions during the heating season. Specifically, it is necessary to achieve a positive pressure difference across those parts of the envelope where dynamic insulation is installed. When the wind pressures are low, buoyancy can be relied on to provide the required pressure distribution, particularly when it is enhanced by a chimney, as shown in Figure 8. It is also necessary for the insulation to be concentrated at the lower heights and the surface area can be maximised by applying dynamic insulation to the floor.

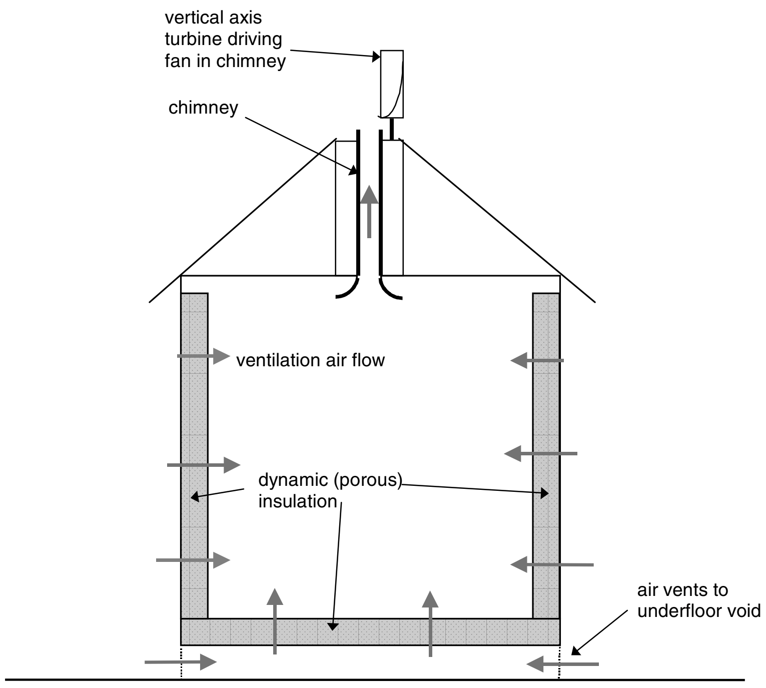

Figure 8 Proposed system for dynamic insulation with natural ventilation

The main problem arises with moderate to high wind speeds (dependent on the surrounding environment). There will be a tendency for the pressure difference on the leeward surface to become negative. The proposed innovation allows the problem of wind effects to be overcome, such that dynamic insulation can operate successfully with natural ventilation. The basic idea is to use the wind energy from a wind turbine to oppose the undesirable effects of wind i.e. the turbine drives an extract fan which maintains the required flow direction. This application is particularly novel, because the major problem of wind-powered devices (i.e., that they do not operate at low wind speeds) is eliminated. The device is self-regulating in that it will not operate at low wind speeds when it is not needed and the de-pressurisation it generates will increase with wind speed. There is a very strong synergy between wind power, dynamic insulation and natural ventilation which has not been recognised before.

4.2 Theoretical results The theoretical study was carried out using an envelope flow model based on the quadratic flow equation (*VENT*) and investigated the effects of wind speed, *U*, temperature difference, ΔT, surface pressure coefficient (values ranged from "city centre" to "exposed" sites) and adventitious leakage. Calculations were carried out to determine the extract rates required to maintain the required inward flow through the insulation material under a wide range of conditions. Figure 9 shows some example results which illustrate the effects of adventitious leakage for a building in suburban surroundings with a medium density of buildings (with $\Delta T = 10$ K).

If the building is tight (leakage at 50 Pa equal to 2 h^{-1}), it can be seen that the wind turbine is required only when the wind speed exceeds 7 m/s. If the building is leaky (leakage at 50 Pa equal to 6 h^{-1}), the turbine has to provide extract when *U* exceeds 4 m/s.

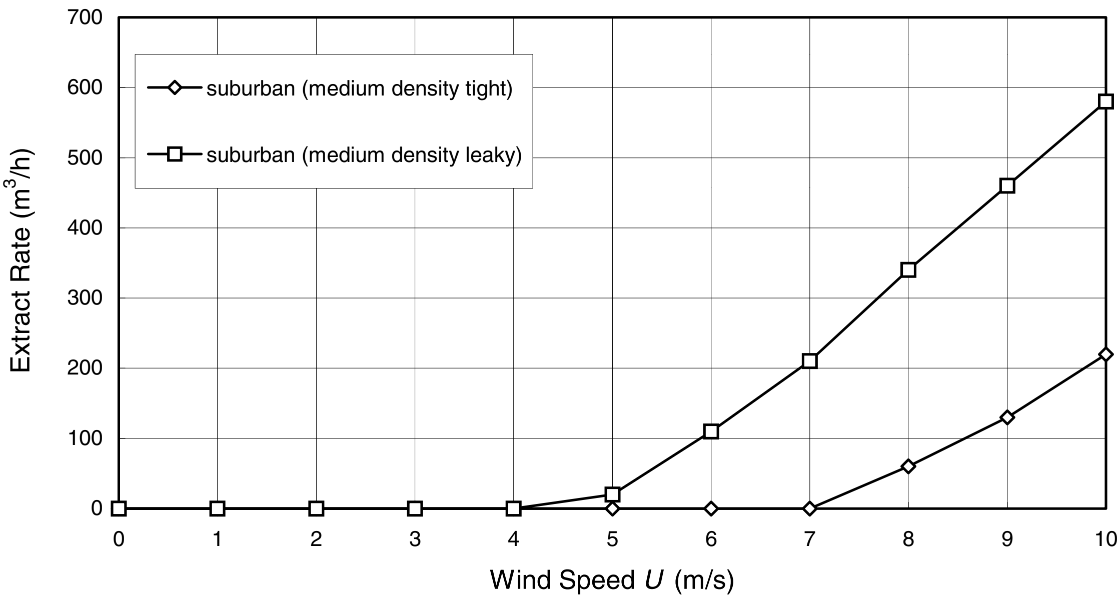

Figure 9. Extract rate required as a function of wind speed for "tight" and "leaky" buildings (N.B. only about 50 % of the extract rate adds to the natural ventilation)

4.3 Estimated energy savings Estimation of energy savings is best done by considering two naturally ventilated buildings, which are identical apart from the fact that one has static insulation and the other dynamic insulation. The ventilation rates of the two buildings are therefore the same, except at wind speeds for which the extract fan comes into operation. In a typical well-insulated building the fabric heat loss is about 60 % of the total (40 % ventilation), so the maximum reduction in the total heat loss is 60 %. This is a hypothetical maximum, mainly because it is impossible to apply dynamic insulation to the complete envelope. Assuming that 70 % of the envelope can be used, the maximum energy saving is 42 %. This value is still an overestimate, mainly because the operation of the extract fan will increase the ventilation compared to the static insulation case. However it is important to note that the increase in ventilation rate is less than the extract flow rate (by about 50 %). When averaged over a heating season in the UK, the increase in ventilation rate is about 12 % (Ref 5), corresponding to an increase in energy consumption of about 5 %, leading to a net reduction of 37 %.

On the basis of the above, it should be possible to achieve space heating energy savings of 30 % or more in the UK climate. These are substantial savings, particularly from a system which is simple, self-regulating and virtually maintenance-free.

4.4 Experimental results A simple wind-driven extract fan has been tested experimentally (Ref 6). It consists of a fan impellor, driven directly by a vertical axis wind turbine through gears. The suitability of the device, in particular its self-regulating nature, can be seen in Figure 10, which shows the rotational speed of the fan as a function of wind speed and gear ratio. The gear ratios tested ranged from 1:3 (i.e. three revolutions of the fan for one turbine revolution) to 1:10.

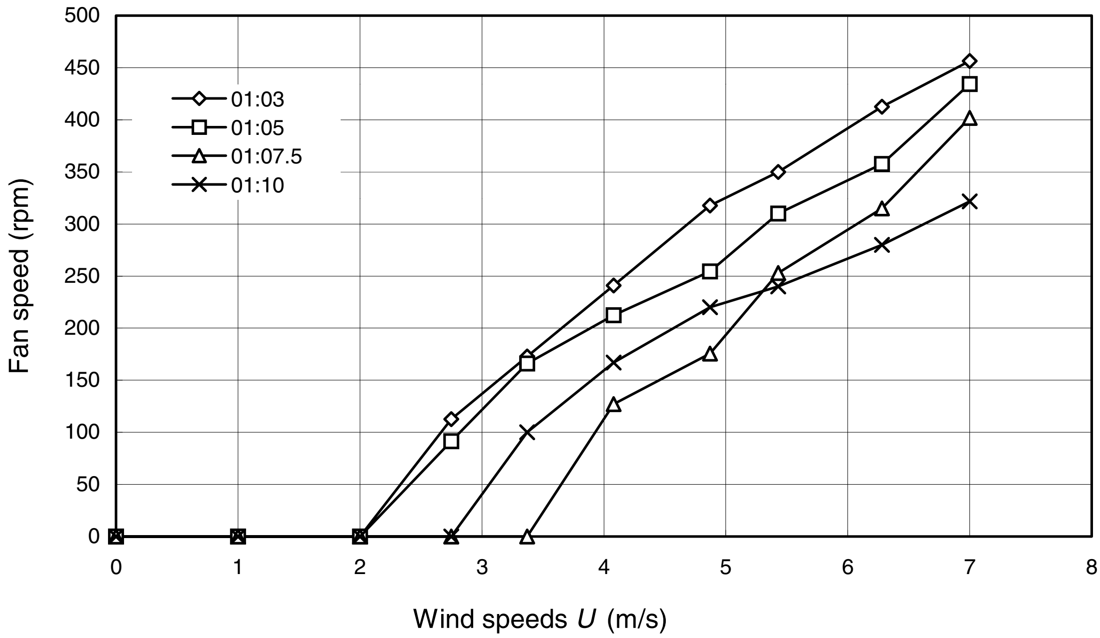

Figure 10 Rotational speed of fan as a function of wind speed for different gear ratios

The fan only operates above a certain wind speed and then increases with wind speed, which is what is required. Furthermore, the starting speed depends on the gear ratio and this offers a simple means of fixing the starting speed for different applications.

5. CONCLUSIONS

Dynamic insulation applied to an animal house has been tested experimentally in a quarter scale model and theoretically with CFD. The CFD calculations indicate that the scale model gives reasonable simulation of full-scale conditions. The next stage of the investigation will therefore be to test the conventional system (static insulation and air vents) and to compare the performance with the dynamic system.

Theoretical results with an envelope flow model indicate that dynamic insulation in a naturally ventilated building is feasible, when a wind-powered extract fan is employed to maintain counter-flow under high wind speeds. Experimental tests have shown that a simple direct-drive wind turbine/fan combination can provide the required operating characteristics. In particular, the fan is self-regulating and a control system is not required. The proposed system offers the potential for substantial reductions in space-heating energy i.e. 30 % or more.

ACKNOWLEDGEMENTS

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