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Summary Dynamic insulation refers to the use of porous insulation material through which ventilation air enters a building, thereby reducing the conductive heat loss through the material to very low levels. The technical success of dynamic insulation relies on maintaining the required flow direction through the material. This is normally achieved by means of an electrically driven mechanical ventilation system. The energy consumption of the electric system must be offset against the saving from the dynamic insulation, with the result that dynamic insulation becomes much less attractive. This paper describes a theoretical study of the technical feasibility of using dynamic insulation with natural ventilation alone. It also considers the novel use of wind-driven mechanical ventilation to extend the range of application of dynamic insulation while retaining a 'natural' system. The results of the study are promising. They indicate that dynamic insulation and natural ventilation are compatible and that there is a strong synergy between dynamic insulation and wind energy. This could lead to significant reductions in the energy consumption of buildings.

Dynamic insulation and natural ventilation: Feasibility study

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Nomenclature

- a, b Coefficients in quadratic flow equation (Pa s m^{-6}), (Pa s m^{-3})
- A $u\rho c/k$ (m^{-1})
- A_T Exposed surface area of building (m^2)
- A_d Area of dynamic insulation (m^2)
- A_f Area of dynamic insulation on floor (m^2)
- A_v Open area of stack vent (m^2)
- c Specific heat capacity of air (J kg^{-1}K^{-1})
- C_p Surface pressure coefficient
- H Height to upper ceiling (m)
- L Thickness of material (m)
- P Permeance (m^{3}h^{-1}m^{-2}Pa^{-1})
- q Flow rate through opening (m^{3}s^{-1})
- Q Ventilation rate of building (m^{3}s^{-1})
- Q_m Mechanical flow rate (m^3 s^{-1})
- Q_{m0} Extract rate for $u_{45} = 0$ (m^3 s^{-1})
- Q_{50} Adventitious leakage at 50 Pa (volumes per hour)
- U Wind speed (m s^{-1})
- U_d U-value of dynamic insulation (W m^{-2}K^{-1})
- U_s U-value of static insulation (W m^{-2}K^{-1})
- u Velocity through insulation (m s^{-1})
- u_{45} u at $z/H = 0.45$ on leeward wall (m s^{-1})
- z Height above ground floor (m)
- β Exponent in power-law flow equation
- ρ Density of air (kg m^{-3})
- Δp Pressure difference across opening (Pa)
- ΔT Internal/external temperature difference (K)

Subscripts

1,2,3 Refer to walls 1 and 2 and stack outlet respectively

1 Introduction

'Dynamic insulation' refers to the use of porous materials for the fabric insulation of a building envelope[1–3]. The flow of air through the material reduces the thermal conduction rate at the external surface when the flows of air and heat are opposed (counter-flow), and increases it when the two flows are in the same direction (co-flow). With counter-flow the conductive heat loss at the external surface of a building can be reduced virtually to zero by arranging for a proportion of the ventilation air to flow into the building through the surface at a speed of 1 m h^{-1} or more[1]. Provided the ventilation rate with dynamic insulation is not much greater than that with conventional insulation the total heat loss (ventilation heat loss plus conduction heat loss) is similarly reduced.

Despite the potential benefits, dynamic insulation is not common, and although its use with natural ventilation has been raised the only applications known to the authors rely on the use of mechanical ventilation. There are several such examples in Scandinavia[4] and one in the UK[5]. One major reason for this is the problem with natural ventilation of maintaining counter-flow through the porous material under all wind conditions. Stack effect (buoyancy) can be employed, but the effects of wind are variable and will in general temporarily overcome the stack effect and can lead to co-flow through parts of the porous material. Thus mechanical ventilation is used to maintain the desired flow through the material. In so doing the electricity consumption of the fan (plus the increased ventilation rate) can exceed the energy savings from the dynamic insulation. To overcome this problem it is then necessary to employ a heat pump, with the extracted air acting as the heat source for the pump.

The use of electrical devices as described above considerably reduces the benefit of dynamic insulation. It would clearly be preferable if dynamic insulation could be used with natural ventilation. The aim of the present paper is to discuss how this might be achieved, and to present the results of calculations which have been made to investigate the possibilities. Included in the term 'natural ventilation' is mechanical ventilation provided by a wind-driven turbine. This is potentially an ideal application of wind turbines.

2 Benefits and problems

2.1 Reduction in heat loss

Dynamic insulation offers at least two benefits. The main one is a large reduction in the heat loss from the building envelope. The subsidiary one is pre-heating of the air which enters through the insulation.

For dynamic insulation a U-value can be defined in terms of the conduction heat flux through the material at its outer surface[2]. For one-dimensional heat transfer and flow (and neglecting the effect of surface heat transfer factors), the dynamic U-value U_d depends on the speed of the airflow through the insulation, u, and on the static U-value U_s. The ratio of the dynamic U-value to the static value is given by[2]

$$U_d/U_s = AL/(\exp(AL) - 1)$$

where $A \equiv u\rho c/k$ and L denotes the thickness of the insulation material.

In the above expression the effect of surface heat transfer factors has been neglected. In a recent paper[12] it has been shown that this is justifiable for calculating the relative change in U-value due to the air flow (but not for calculating surface temperatures).

If one considers the steady-state heat balance for a section of porous wall with counter-flow, the passage of air modifies the temperature distribution compared to the linear variation of the static insulation in such a way that the conductive heat loss to the external air is reduced. Since the ventilation air enters the building at this point at nominally the same temperature as in the static case, it can be seen that (for the same ventilation rate) the heat loss is reduced for the dynamic case. The conductive heat flow into the material at the internal surface is increased as compared with the static case. However the net heat flow through the material is of course the same as at the outer surface, due to the fact that the convective heat flow at the inner surface is increased. The present paper is concerned with the feasibility of using dynamic insulation with natural ventilation, rather than with the theory of dynamic insulation itself. However, for completeness the basic theory is given in the Appendix. This differs somewhat from the analysis given in References 2 and 12.

If the air reverses direction and flows in the same direction as the heat conduction, the U-value is increased (albeit at a smaller rate), and it is therefore desirable to maintain an inflow through the insulation during periods of heating. A possibly more important reason for maintaining the inflow is avoiding problems relating to moisture transport and mould growth. These and other problems are discussed at the end of the paper. The concern here is with the fundamental problem of maintaining the required flow direction through the insulation.

2.2 *Problems with natural ventilation*

The main problem with natural ventilation is to maintain counter-flow through the insulation under all weather conditions. It is the direction which is most important, rather than the magnitude of u, provided that u takes reasonably high values during periods of high ΔT. Note that the latter requirement is automatically satisfied by buoyancy, because the ventilation flow rate increases with ΔT.

Problems also arise from the presence of adventitious openings in the envelope. First, infiltration air (i.e. ventilation through the adventitious openings) will not pass through the dynamic insulation, and the greater the infiltration, the less is the flow through the dynamic insulation. Second, the distribution of the adventitious leakage may be such as to cause co-flow through the dynamic insulation. Third, adventitious leakage will reduce the effectiveness of mechanical ventilation in its role of eliminating co-flow through the insulation.

2.3 *Sizing the dynamic insulation*

The ventilation rate through the dynamic insulation is given by $A_d u$, where A_d is the area of the insulation and u is the mean speed through it. The value of u must be greater than about 1 m h^{-1} to obtain substantial reductions in U-value. For a ventilation rate of 300 m^{3}h^{-1} (e.g.1.0 volumes per hour for a typical dwelling), this means that A_d must be less than about 150 m^2 if the design value of u is taken to be 2 m h^{-1}. The permeance P (m^{3}h^{-1}m^{-2}Pa^{-1}) of the material is defined as the flow rate per unit area with a pressure difference of 1 Pa. Knowing A_d, u and typical pressure differences at the design condition it is a simple matter to calculate the required values of P for the different surfaces. As noted above, the value of u will vary with different weather conditions, but this is not serious, provided it does not fall too low or become too large (see section 7 below).

2.4 *Potential energy savings/cost benefits*

There are of course limits to the energy which can be saved by dynamic insulation. Consider two identical dwellings, one with static insulation and one with dynamic insulation. The two have the same ventilation rate and the same thermal conductivity for the envelope material, k. In the Appendix it is shown that the reduction in the total heat loss rate due to the application of dynamic insulation, when expressed as a fraction of the *fabric* heat loss of the static building is given by equation 15 as

$$(A_d/A_T)[1 - AL/(\exp(AL) - 1)]$$

where A_T is the total surface area of the envelope and A_d is the surface area of the dynamic insulation. For $u > 2$ m h^{-1} the fraction tends to A_d/A_T.

In a well insulated house, the fabric heat loss and the ventilation heat loss are of similar size. In this case the potential maximum reduction in space heating energy consumption is about 50%. However since A_d is likely to be much less than A_T, a saving of around 25% is probably more realistic; this is nevertheless substantial. The saving will be reduced if the ventilation rate of the dynamically insulated dwelling is greater than that for the conventionally insulated dwelling. Thus if the ventilation rate were to be increased by 50%, the saving from the dynamic insulation would be offset and the only benefit would be a higher ventilation rate for the same energy consumption.

The above simple calculations illustrate two points. First, there is a potential for substantial reductions in energy consumption, provided the technical problems can be overcome. Second, increases in the ventilation rate compared with that for a conventionally insulated dwelling need to be kept to a minimum, otherwise they can negate the savings from the dynamic insulation. This is a particular problem with mechanical ventilation, since it will tend to lead to higher ventilation rates (and any electricity consumption for the fan will further reduce the savings). Whether the use of passive stack ventilation (one of the measures referred to below) will lead to an increased ventilation rate is open to question. The problem here is that the natural ventilation rate of a conventionally insulated dwelling is impossible to specify precisely. However, passive stack ventilation is a recognised means of ventilating dwellings. Providing it is properly designed, and particularly if it is accompanied by a reduction in the adventitious leakage, there is no reason why it should lead to ventilation rates higher than normally occur in naturally ventilated dwellings.

Economic justification will of course depend on the relative costs of dynamic and static insulation. There seems to be no obvious reason why the former should be more expensive than the latter. The need for mechanical ventilation and its associated running costs is obviously an important factor. Hence the concern here with natural ventilation. Two important factors which determine the technical feasibility of natural methods are (*a*) any increase in ventilation rates compared with those with conventional insulation and (*b*) the need to achieve counter-flow.

The ceiling is relatively easy and inexpensive to insulate to very high levels with normal materials and it is the walls and ground floor which are of most interest here. The floor is of particular interest for the reasons given below.

3 Ventilation characteristics in relation to dynamic insulation

The underlying problem is to ensure that the required flow direction (counter-flow) is maintained across the dynamic insulation. The important parameter here is the pressure difference generated across the insulation. The magnitude of the flow is less important, provided it exceeds a nominal value for most of the time.

Figure 1 shows the three basic cases of natural ventilation for a simple envelope: buoyancy alone, wind alone, wind and buoyancy combined. (The effect of mechanical ventilation is addressed separately in section 3.4.)

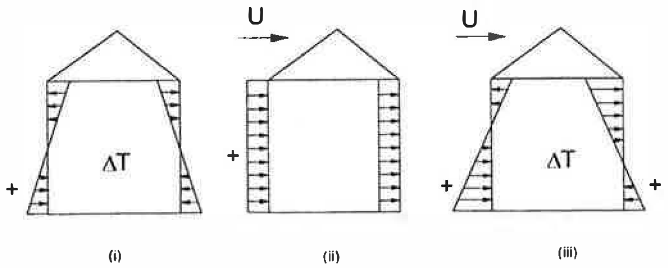

Figure 1 Basic ventilation flow patterns for (i) buoyancy alone, (ii) wind alone and (iii) buoyancy and wind combined

The nature of the pressure differences acting across the walls and floor is shown qualitatively. The aim is to achieve a positive pressure difference across the dynamic insulation.

3.1 Buoyancy alone

When ventilation is purely due to buoyancy, it is relatively easy to arrange for the required flow pattern simply by the use of a stack which is sized so that most or all of the outgoing air passes through it. The two crucial parameters here are the area and the height of the stack. The greater these are then the greater is the flow through the stack. It is perfectly feasible to achieve a positive pressure difference across all of the walls, with all of the outflow passing through the stack.

3.2 Wind alone

The typical case for wind alone is a positive pressure on the windward wall and a negative pressure on the leeward wall; the latter is clearly undesirable. The situation is complicated, partly because the driving pressures on the external surfaces are determined by wind speed and wind direction. The wind direction determines the distribution of the surface pressure coefficients C_p. The distribution varies with time. It must be assumed that each surface will experience the complete range of C_p values which are appropriate to the particular shape and situation of the building.

Another important parameter is the distribution of openings in the envelope, which will interact with the C_p distribution and wind speed and affect the flow pattern through the envelope.

There are ways, however, of exercising some control over the flow pattern. The first is to try to position the stack so that the outlet is situated in a region where the C_p value is more negative than at other points on the envelope. The second way is to make use of a plenum chamber, whereby the effects of wind speed and direction on the pressure in the plenum are minimised. This measure can be adopted for the floor and ceiling. In the former case an underfloor space is vented to all exposed surfaces, so that the pressure inside the plenum is the average of the wind pressures on the exposed surfaces. For the ceiling, a vented loft can be used.

Another complicating factor is the fluctuating nature of the wind pressures. Since the frequencies are relatively high and the air speeds through the dynamic insulation are low, it is assumed here that any short-term flow reversal will not cause a problem, because the air will not have time to pass a significant distance into the material.

3.3 Wind and buoyancy combined

When wind and buoyancy act together the pressure difference distribution is typified by positive pressures at low level on the leeward side, changing to negative pressures at higher levels. The use of a stack has the same controlling influence when wind and buoyancy act together. Moreover, the use of an underfloor plenum also remains valid and will in fact be enhanced by the stack. However the use of the loft as a plenum is not consistent with a stack which communicates with the interior of the main envelope.

The relative strength of the wind and buoyancy pressures on the leeward wall is clearly an important factor in determining the success of dynamic insulation. It is more difficult to arrange for counter-flow at high levels than it is at low levels. This is particularly important for dwellings which are exposed to the wind. For this reason it was decided to consider cases where dynamic insulation is applied only at low levels, i.e. to the floor and to the walls on the ground storey.

Of particular interest is the use of dynamic insulation for the floor. This is often a significant source of heat loss, and it is ideally suited to maintaining a constant flow direction, because (*a*) the buoyancy force is at its greatest and (*b*) by venting the underfloor void to atmosphere the effect of wind pressures will be minimised.

3.4 Mechanical ventilation

Mechanical extract or supply offers a high degree of control over the flow pattern. The control follows from the imposition of a uniform pressure over the internal surfaces of the envelope by the mechanical fan. This delays any change in pressure difference across the envelope due to, say, an increase in wind speed. However there are limitations to this control, because very high flow rates may be required when the wind pressures are high, due to the dependence of the mechanical pressure on the leakage of the envelope. This problem is exacerbated by the presence of adventitious leakage, because it increases the flow rate required to obtain the required uniform pressure.

The control is achieved only at the expense of increased energy consumption. This occurs for two reasons; the increased ventilation rate and the energy consumption due to the fan. There is however a novel and elegant way of largely overcoming this disadvantage, as follows.

3.5 Wind-driven mechanical ventilation

Mechanical ventilation is strictly only needed when wind pressures are present. The higher the wind speed, the higher is the mechanical flow rate required. In view of this, a mechanical fan driven by wind energy offers an elegant solution to the problem in the sense that it is self-regulating. The inherent problem with wind turbines, namely that the power supply does not match the demand, does not apply here.

The fan could be driven directly by a roof-mounted wind turbine or indirectly from electricity generated by a wind turbine. The fan power required is quite low, and should easily be achieved by a relatively small turbine.

3.6 Promising configurations

From the discussion given above, a promising configuration for employing dynamic insulation in a naturally ventilated two-storey dwelling (in the climate of the UK) is as follows:

- dynamic insulation of (*a*) the external walls on the lower storey and (*b*) the ground-level floor with a vented underfloor plenum
- coupled with a stack for passive extract, with the outlet situated at high level to maximise buoyancy force and wind suction.

The configuration is illustrated in Figure 2 and calculations to assess its feasibility are described below.

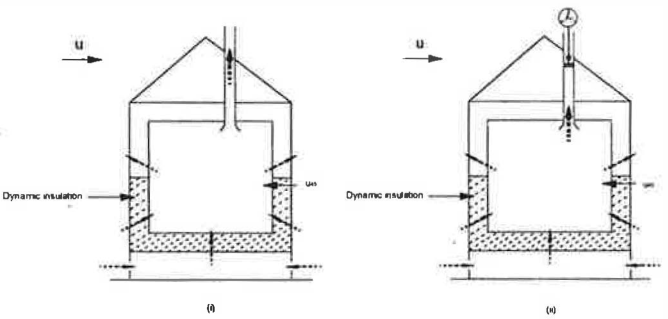

Figure 2 Promising configurations for employing dynamic insulation with natural ventilation: (i) dynamic insulation on lower walls and on floor with ventilated plenum, plus stack; (ii) as (i), with wind-powered extract fan

A major question concerns the extent to which mechanical extract is required and where this is the case, a wind-powered extract fan should if possible provide it. This would ideally be incorporated in the stack.

4 Envelope flow calculations

The IBT envelope flow model was used for the calculations; this is the same in its basic equations as the VENT[6] model. Figure 3 shows the dwelling configuration and the main parameters.

The dwelling is a two-storey terraced house with a nominal volume of 300 m^3 and a height to the upper ceiling H of 6 m. It has an underfloor plenum which is vented to the atmosphere. The lower ground floor walls and the floor itself are dynamically insulated. Table 1 gives the permeance P and the areas of the dynamic insulation A_d and of the stack A_v. These were chosen to give a reasonable value of air change rate with a temperature difference of 10 K (no wind) and were kept constant for all the calculations.

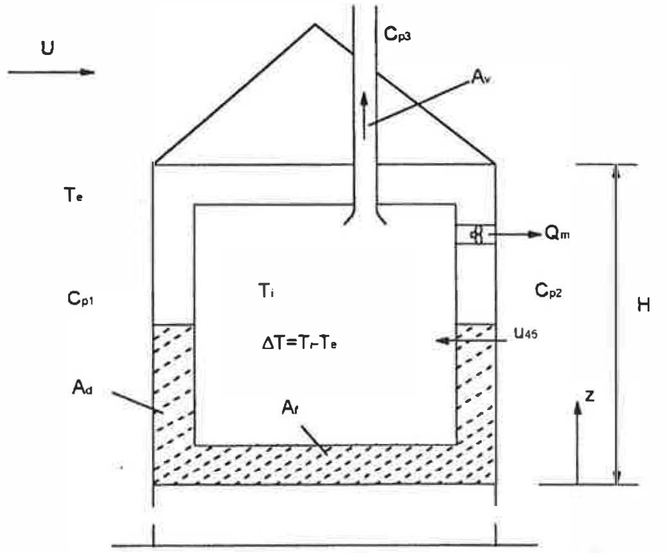

Figure 3 Dwelling configuration and main parameters used for VENT calculations

Table 1 Properties of the dynamic insulation material

Component	Area (m^2)	Permeance (m^{3}h^{-1}m^{-2}Pa^{-1})
Wall 1	15	0.6
Wall 2	15	0.6
Floor	50	0.6

The wind pressure coefficients on the two exposed walls are denoted by C_{p1} and C_{p2}, and that at the top of the stack by C_{p3}. The pressure coefficient inside the plenum was taken to be the sum of C_{p1} and C_{p2}. Table 2 shows the main values used for the calculations. They were chosen to reflect the different building environments which are encountered in the UK and to be representative of the worst cases (the most negative values of C_p on the leeward wall). They were based on data given in Reference 7. The values quoted are defined in terms of the reference wind speed at height H, rather than the gradient wind speed as used in Reference 8. However, compatibility between the two approaches was checked by comparing the respective values of the absolute pressure differences at the maximum wind speed, i.e. $0.5\rho U^2(C_{p1} - C_{p2})$.

The values of wind speed used for the calculations were 0, 2, 4, 6, 8 and 10 m s^{-1}. The maximum value of 10 m s^{-1} is greater than the values for the hourly mean wind speed exceeded for 10% of the time over the UK at a height of 10 m (see Figure A2.14 of Reference 9). It should therefore be representative of the worst effects of wind speed.

Table 2 Surface pressure coefficients

Location	C_{p1}	C_{p2}	C_{p3}	$C_{p1}-C_{p2}$	$C_{p1}-C_{p3}$
City centre	0.05	−0.05	−0.06	0.1	0.11
Suburban (medium density)	0.06	−0.3	−0.45	0.36	0.51
Suburban (low density)	0.2	−0.25	−0.3	0.45	0.5
Exposed	0.7	−0.2	−0.5	0.9	1.2

Three values of adventitious leakage were used, as shown in Table 3. Q_{50} denotes the flow rate in house volumes per hour generated by a pressurisation of 50 Pa. The 'ideal' case corresponds to a value equal to zero, whereas the 'tight' case represents the best that can reasonably be achieved in practice and the 'average' case is typical of modern UK dwellings.

Table 3 Adventitious leakage

Type	Q_{50} (House volumes per hour)
Ideal	0
Tight	2
Average	6

The calculations were carried out with a temperature difference ΔT of 0 or 10 K. The latter value was felt to be a reasonable compromise between the 'best' and 'worst' situations, i.e. ΔT values of 21 and 0 K respectively. With $\Delta T = 0$ there is no stack effect and the ventilation flow pattern is determined solely by the wind, with a consequent tendency for co-flow to be induced through the leeward wall.

Mechanical ventilation (extract only) was applied when necessary to maintain counter-flow through the dynamic insulation. The velocity through the porous strip at $z/H = 0.45$ on the leeward wall, u_{45}, was used as the determining factor (z denotes the height above the ground floor level). When this velocity was found to be negative with natural ventilation at a certain wind speed, the calculations were repeated with the addition of a mechanical extract rate Q_m. By a process of trial and error, the value of Q_m required to give $u_{45} = 0$ was found. This is an important parameter and is denoted by Q_{m0}. When u_{45} is greater than zero, all velocities through the insulation are positive. (Strictly speaking, one should use the velocity at the top of the insulation, $z/H = 0.5$, but the calculation procedure splits the insulation into strips of depth $z/H = 0.1$ so the mid-point of the top strip corresponds to $z/H = 0.45$.)

It should be noted that the extract rate was applied in the simplest way possible, i.e. as an additional fan separate from the stack. This means that when the fan is operating there is a downward flow through the stack. In practice it would be preferable to place the fan in the stack, but this is more difficult to model and it was decided to consider the simpler cases for this exercise.

4.1 Flow equations

Within the model three types of opening need to be treated, the stack opening, the porous walls and the adventitious openings. This was done as follows.

The stack opening was represented by a simple square-law opening at the top of the stack so that the flow rate q generated by a pressure difference Δp is given by

$$q = 0.6A_v(2\Delta p/\rho)^{1/2}$$

The flow rate through the porous wall was calculated by dividing it into five equal strips and treating each strip as an opening with a linear flow relationship, using the pressure difference at the mid-point of the strip, i.e.

$$q = \Delta p/b$$

$$b = 3600/(PA_d/5)$$

The floor was treated as a single entity with the value of b in the flow equation given by $3600/PA_f$. (The factor 3600 arises from the use of hours in the definition of P.)

The adventitious openings were assumed to be uniformly distributed over the two exposed walls with ten identical openings on each wall, each of which has a leakage at 50 Pa given by $Q_{50}/20$. The flow equation for each opening was taken to be of quadratic form, i.e.

$$\Delta p = aq^2 + bq$$

The value of the shape parameter a/b^2 was taken to be 0.1, which corresponds to a commonly observed value of the power law exponent β of 0.65. Knowing Q_{50}, the values of a and b were then known.

5 Results

As noted above, the determining factor of whether the dynamic insulation is feasible is taken to be a value for u_{45} on the leeward wall which is greater than zero. If this condition is met, the velocities through all other parts of the insulation will be correct with respect to direction, and as will be seen below, the magnitude will generally exceed 1 m h^{-1} if the permeance P is appropriately chosen.

Figure 4 shows the variation of u_{45} with wind speed for the suburban (medium density) situation for the two values of ΔT and with $Q_{50} = 0$. For $\Delta T = 10$ K, u_{45} has a high value with $U = 0$. This is maintained up to a wind speed of about 6 m s^{-1}, above which it decreases until it passes through zero for $U = 9.3$ m s^{-1}. For the dynamic insulation to operate up to $U = 10$ m s^{-1}, mechanical extract will need to be provided for $U > 9.3$ m s^{-1}. For $\Delta T = 0$, the velocity is clearly equal to zero with $U = 0$, and as wind speed is increased the velocity initially increases and then decreases to zero at $U = 8.8$ m s^{-1}. Mechanical extract will be needed at higher wind speeds. It is interesting to note that for wind speeds below 6 m s^{-1}, the wind has a beneficial effect on u_{45}. This is due partly to the fact that C_{p3} is more negative than C_{p2}. As will be seen below, the value of C_{p3} is an important parameter.

5.1 Effect of dwelling situation (C_p distribution)

The variation of u_{45} with wind speed for a given C_p distribution is a good way of looking at the effect of dwelling site. Figure 5 shows the variation for the four situations, with $\Delta T = 10$ K and $Q_{50} = 2$ h^{-1}.

It is clear that under these conditions, dynamic insulation is feasible with natural ventilation for the city centre dwelling, but some mechanical extract is needed for the other three situations. The values of Q_{m0} required at each wind speed for the these situations are shown in Figure 6. Very little mechanical

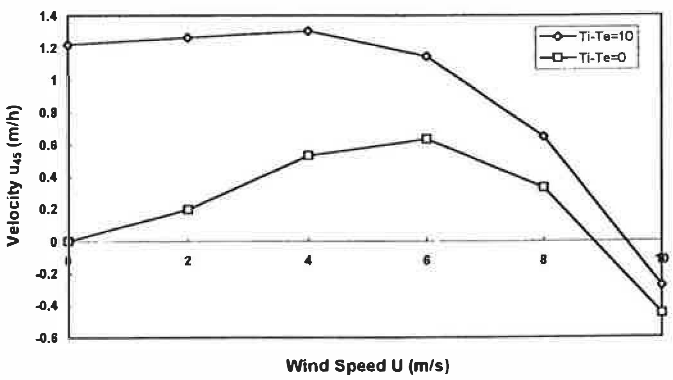

Figure 4 Variation of u_{45} with wind speed for the suburban (medium density) situation for $\Delta T = 0$ and 10 K and with $Q_{50} = 0$

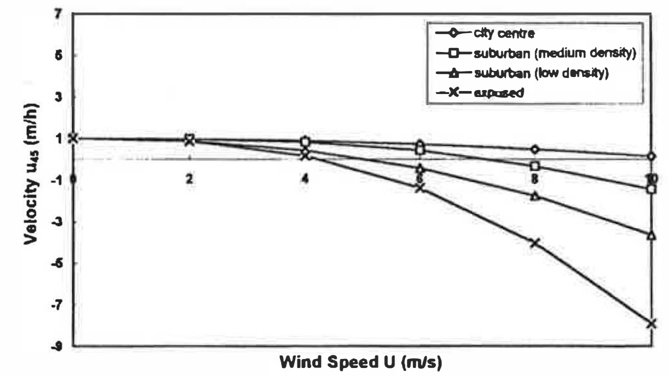

Figure 5 Variation of u_{45} with wind speed for the four C_p distributions showing the effect of dwelling site, with $\Delta T = 10$ K and $Q_{50} = 2$ h^{-1}

extract is needed for the suburban (low-density) case. The percentage of time required is probably less than 10%, even when allowance is made for the greater requirement at lower values of ΔT. Significant amounts of mechanical ventilation are required for the suburban (medium density) case and particularly for the exposed case. It is important to note however that the extract rate does not simply add to the natural ventilation rate (see 5.2 below).

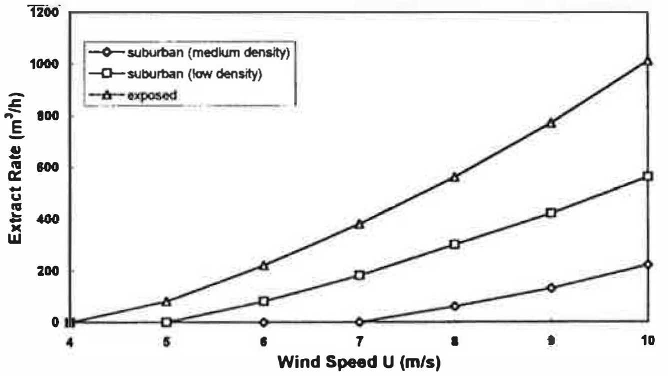

Figure 6 Values of mechanical extract Q_{m0} required at each wind speed for three dwelling sites, with $\Delta T = 10$ K and $Q_{50} = 2$ h^{-1}

It was noted above that the pressure coefficient at the stack outlet, C_{p3}, is an important parameter. More precisely, it is the difference between C_{p3} and the pressure coefficient on the leeward wall, C_{p2}, which is important. The more negative the value of C_{p3} in relation to C_{p2} the better, because a greater proportion of the outward flow then occurs via the stack. For example, for the suburban (low-density) case, changing C_{p3} from -0.3 to -0.5 reduces the mechanical extract required from 560 m³h^{-1} to 260 m³h^{-1} ($Q_{50} = 2$ h^{-1}, $\Delta T = 10$ K). This is a substantial reduction and there are clear benefits to siting the stack outlet in a region where the wind pressure is as negative as possible. A similar effect is achieved by increasing the effect of buoyancy by increasing the stack height, but it is less substantial. For the same dwelling configuration (with $C_{p3} = -0.3$), increasing the stack height from $z/H = 1.5$ to 2.0 reduced the extract rate from 560 to 520 m³h^{-1}.

Clearly, the pressure coefficients listed in Table 2 are limited in range, but it is believed that they are representative of the most unfavourable pressure distributions for dynamic insulation. Calculations have been carried out with distributions where C_{p1} and C_{p2} are equal and negative, so that counter-flow is impeded by the wind on both walls. Provided C_{p3} is less negative, the wind pressures do not lead to co-flow, even when $\Delta T = 0$ K. As noted above, it is the difference between the C_p values which is important.

5.2 *Effect of mechanical ventilation rates*

Figure 7 shows the effect on the ventilation rate of the mechanical extract for the suburban (low-density) dwelling ($Q_{50} = 2$ h^{-1}, $\Delta T = 10$ K). The lower curve shows the extract rate which must be applied to give $u_{45} = 0$ at each wind speed and the upper curve shows the resulting ventilation rate. The middle curve shows the natural ventilation rate and it can be seen that the additional ventilation arising from the extract fan is only about 50% of the extract rate. This is a well known phenomenon and is due to the manner in which the internal pressures interact.

The importance of this is that the energy penalty arising from the increased ventilation rate is smaller than might be expected. For the case shown above a rough estimate of the loss is as follows. Mechanical extract is only required above a wind speed of about 5 m s^{-1}. The average wind speed when mechanical ventilation is required is about 7.5 m s^{-1}, for which the increase in ventilation rate is about 30% compared to natural ventilation(with the stack). The wind speed lies above 5 m s^{-1} for about 40% of the time over much of the UK, so the average increase in ventilation rate over a year is about 12%.

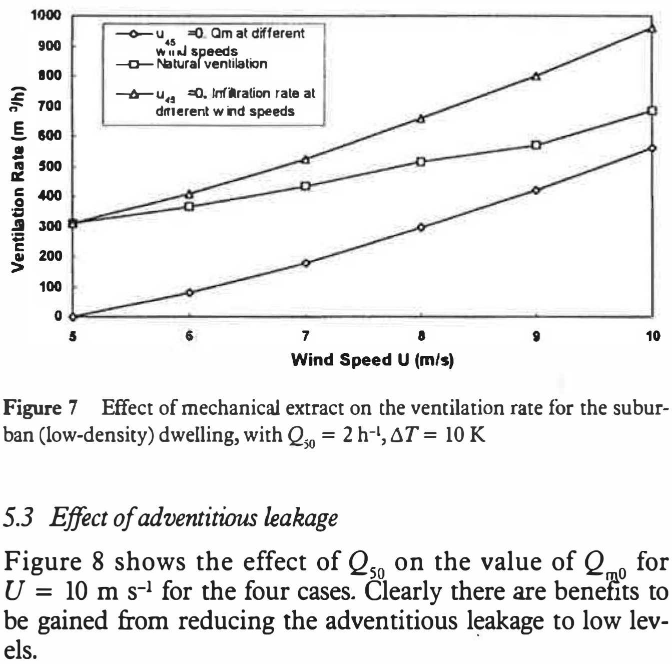

Figure 7 Effect of mechanical extract on the ventilation rate for the suburban (low-density) dwelling, with $Q_{50} = 2$ h^{-1}, $\Delta T = 10$ K

5.3 *Effect of adventitious leakage*

Figure 8 shows the effect of Q_{50} on the value of Q_{m0} for $U = 10$ m s^{-1} for the four cases. Clearly there are benefits to be gained from reducing the adventitious leakage to low levels.

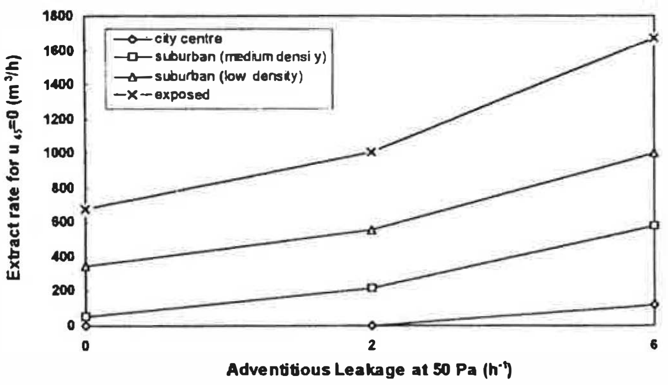

Figure 8 Effect of adventitious leakage on the value of Q_{m0} for $U = 10$ m s^{-1} for the four dwelling sites, with $\Delta T = 10$ K

5.4 *Variation of speed through porous surfaces*

Figure 9 shows the variation of u with wind speed at three different points for the suburban (medium density) case, with $Q_{50} = 2$ h^{-1} and $\Delta T = 10$ K. The points are at height $z/H = 0.25$ on the windward and leeward walls and at $z/H = 0$ (the ground floor).

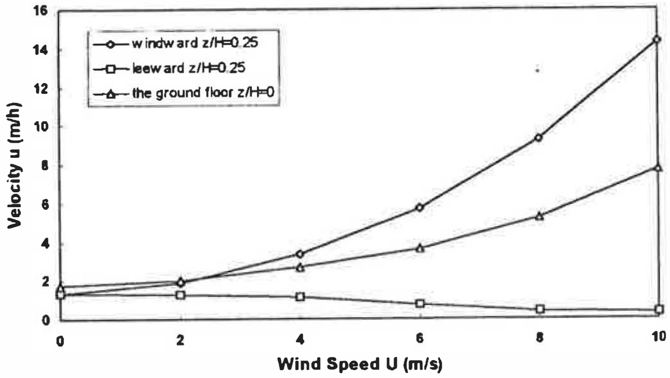

Figure 9 Effect of wind speed on the air speed through the porous surfaces for suburban (medium density) case with $Q_{50} = 2$ h^{-1} and $\Delta T = 10$ K

At high wind speeds the values of u at certain points can become large, and this could lead to problems, as discussed in section 7.

6 Wind-driven mechanical systems

The power required to drive an extract fan is given by $Q_e\Delta p/\eta$, where η denotes fan efficiency, Q_e the extract rate (m^3 s^{-1}) and Δp the pressure drop (Pa) across the fan. From Figure 6, the extract rate required for the suburban (low density) case at a wind speed of 8 m s^{-1} is 310 m^{3}h^{-1}. Assuming a pressure drop of, say, 50 Pa, which includes an allowance for ducting, the power requirement is 9 W, for a fan efficiency of 50%. The power available from a wind turbine with blade area A_w (m^2) in a wind of speed U (m s^{-1}) is given by $0.21U^3A_w$ (W)[10], where a turbine efficiency of 35% has been assumed. At a wind speed of 8 m s^{-1}, the power available from a turbine is 109 W m^{-2}, so even with further losses between the fan and the turbine, the area of turbine required is not excessive. Of course the optimum matching of the power input and output curves and the starting wind speed would need to be considered, but these should not be fundamental difficulties.

There are additional benefits to be gained by recovering heat from the ventilation air, but conventional air-to-air heat recovery (i.e. heating supply air from the extract air) is not beneficial for the cases considered here. The reason for this is that this form of heat recovery requires mechanical supply of air from the outside. Since the aim of the extract is to depressurise the building, the extract rate must exceed the supply rate by Q_{m0}. This means that the supply rate simply adds to the total ventilation, leading to excessive values. The heat recovery is at best 70% of the heat in the extract air, and this is further offset by electrical power consumption.

The best way of recovering heat from the extract air is to use it as a source for a heat pump. In this way the extracted heat can be input directly into the air within the building. In principle the heat pump could be driven by a wind turbine[11]. This would again be an ideal use for such a device, not only because the demand matches the available energy supply, but also because the available energy from the turbine is multiplied by the coefficient of performance of the heat pump.

7 Other potential problems

From the viewpoint of energy conservation it will not matter if co-flow occurs through the insulation at some times during the heating season, providing the periods are short. This may not be true from the viewpoint of moisture and mould growth problems. This must be investigated[3], because it is not really possible to guarantee the required flow pattern at all times; for instance the opening of doors and windows will upset the pressure distribution. This is a problem with mechanically powered systems as well as with natural ventilation.

Unsteady effects, e.g. turbulent pressure fluctuations and thermal storage in the envelope materials, will also affect the performance of the dynamic insulation, and these need to be investigated.

It has been noted[2, 3] that the counter-flow of air through the insulation reduces the surface temperature inside the building, with consequential effects on radiant heat exchange between surfaces and occupants. Reductions ranging from about 0.5 to 1.2 K m^{-1} h have been quoted[2,3]. (The reduction also depends on the thermal resistance of the material and the external temperature.) The larger values of air speed u which are evident in Figure 9 imply temperature reductions of 5 K or more, and these could certainly be a source of discomfort.

7 Non-domestic buildings

Non-domestic buildings are more amenable to the application of dynamic insulation in the sense that their operation is more regulated. Also, costs are less of a problem and mechanical ventilation is widely employed. Natural ventilation is becoming more acceptable in such buildings, and the results presented here can be scaled up to non-domestic buildings. However it is arguable whether the configurations given in Figure 2 would be appropriate.

8 Conclusions

The main conclusion to be drawn from the present study is that the use of dynamic insulation with natural ventilation alone appears to be technically feasible for two-storey houses in certain environments, i.e. city centres and medium-density suburban areas. The application of dynamic insulation to more exposed houses in suburban areas with a low density of buildings requires some form of mechanical extract at high wind speeds. This can be most effectively achieved by the use of a wind turbine to drive the extract fan, since this is self-regulating and retains the 'natural' element of the ventilation system. Houses in exposed sites can be similarly equipped with a 'natural' system if the wind turbine is enlarged to power a heat pump which uses the extract air as a heat source.

The present study is only a preliminary one, and there are several practical problems with dynamic insulation which have not been addressed. Nevertheless, the results are promising and they indicate that there is a useful synergy between dynamic insulation and wind energy. This could lead to significant reductions in energy consumption of domestic buildings.

Acknowledgements

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Appendix: Heat loss reduction due to dynamic insulation

Additional nomenclature

A Defined by equation (12) (m^{-1})
H Rate of heat supply (W)
q_{c0} Conductive heat flux at $x = 0$ ($W\ m^{-2}$)
q_{u0} Convective heat flux at $x = 0$ ($W\ m^{-2}$)
q_{fd} Conductive heat flux for dynamic material ($W\ m^{-2}$)
q_{fs} Conductive heat flux for static material ($W\ m^{-2}$)
T Temperature (K)
T_i External air temperature (K)
T_a Internal air temperature (K)
T_0 Material temperature at $x = 0$ (K)
T_L Material temperature at $x = L$ (K)
x Distance through insulation (m)

A1 Heat balance for building envelope

Consider a building envelope (Figure 10) which has a thermal conductivity k and a ventilation rate Q_T.

With static insulation the rate, H_s, at which heat must be supplied to maintain the internal temperature can be expressed as

$$H_s = q_{fs}A_T + Q_T\rho c\Delta T \tag{1}$$

where ΔT denotes the temperature difference $T_i - T_e$

$$\Delta T \equiv T_i - T_e \tag{2}$$

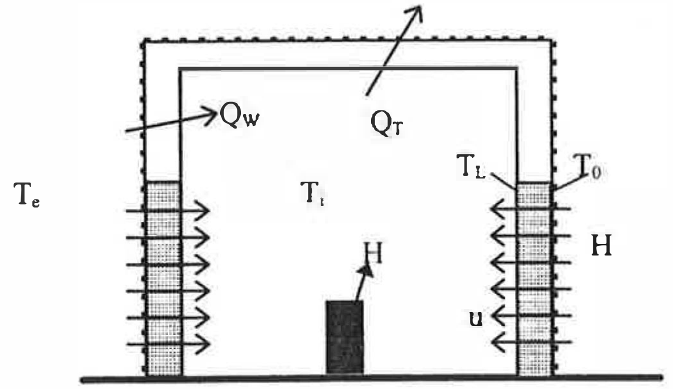

Figure 10 Steady-state heat flows through envelope

q_{fs} denotes the conduction heat flux (heat flow per unit area) through the fabric and A_T denotes the total external surface area.

Equation 1 applies to the system boundary coincident with the outer surface of the material as indicated by the hatched line in Figure 10. It is assumed that the external air passes through the boundary at temperature T_e, rather than at the surface temperature T_0 since the air enters through relatively large openings. The air leaving the building passes through the boundary at a temperature T_i, hence the expression for the ventilation heat loss in equation 1.

Now suppose that a part of the envelope, area A_d, is dynamically insulated with an air speed through the material u, while the thermal conductivity of the material is unchanged. Using the same system boundary, the heat loss with dynamic insulation can be written as

$$H_d = q_{fd}A_d + q_{fs}(A_T - A_d) + Q_d\rho c(T_i - T_{0d}) + (Q_T - Q_d)\rho c(T_i - T_e) \tag{3}$$

$$H_d = q_{fd}A_d + q_{fs}(A_T - A_d) + Q_T\rho c(T_i - T_e) - Q_d\rho c(T_{0d} - T_e) \tag{4}$$

where q_{fd} denotes the conduction heat flow in the material at its outer surface. Q_d denotes the rate at which ventilation air enters through the material, which passes through the boundary at temperature T_{0d}.

Now suppose that the total ventilation rate is the same for both the static and dynamically insulated cases. It then follows from equations 1 and 4 that the reduction in heat loss due to the dynamic insulation is

$$H_s - H_d = q_{fs}A_T - q_{fd}A_d - q_{fs}(A_T - A_d) + Q_d\rho c(T_{0d} - T_e) \tag{5}$$

$$H_s - H_d = q_{fs}A_D[1 - q_{fd}/q_{fs} + u\rho c(T_{0d} - T_e)] \tag{6}$$

since $Q_d = uA_d$.

Thus for two building envelopes with the same total ventilation rate, the reduction in heat loss due to the application of dynamic insulation is given by equation 6. The reduction can be expressed as a fraction of the fabric heat loss for the static building by

$$(H_s - H_d)/q_{fs}A_T = A_d/A_T[1 - q_{fd}/q_{fs} + u\rho c/q_{fs}(T_{0d} - T_e)] \tag{7}$$

Equation 7 is meaningful only when the ventilation rates for the two envelopes are the same. This is not surprising, because dynamic insulation is inseparable from the ventilation rate and a meaningful comparison can only be made when the total ventilation rates are the same.

It is now necessary to evaluate the term in brackets for given values of T_e and T_i. This can be done by considering a section of the wall, as follows.

A2 Heat balance for section of the wall

Consider a section of porous material (Figure 11) with a thermal conductivity k (W m^{-1}K^{-1}) and a thickness L (m) with surface temperatures at $x = 0$ and L denoted by T_0 and T_L respectively.

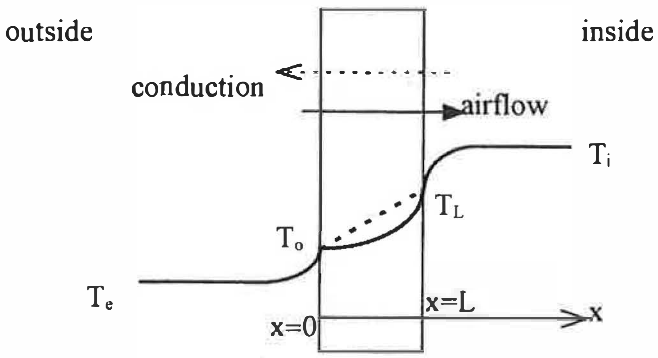

Figure 11 Section of porous material

Assuming that the air and the material are in thermal equilibrium (i.e. at any point they have the same temperature), it can be shown that the differential equation which governs the temperature variation with x is

$$d^2T/dx^2 - (u\rho c/k)dT/dx = 0 \tag{8}$$

The equation follows by considering a small element of material and setting the net heat flow into the element equal to zero. (The two components of the heat flow are convection by the air and conduction by the material.)

It can easily be confirmed that a solution to the above equation is

$$T\{x\} = T_0 + (T_L - T_0)[(\exp(u\rho cx/k) - 1)/(\exp(u\rho cL/k) - 1)] \tag{9}$$

where T_0 and T_L denote the temperatures at $x = 0$ and L respectively.

If we now consider the heat flux (flow per unit area) through the material at $x = 0$ (just inside the material), there are two components. The convective heat flux q_{u0} (which is not zero) is given by

$$q_{u0} = u\rho cT_0 \tag{10}$$

and the conductive heat flux q_{c0} is given by

$$q_{c0} = -k[dT/dx]_{x=0} = -Ak(T_L - T_0)/(\exp(AL) - 1) \tag{11}$$

where A is defined by

$$A = u\rho c/k \tag{12}$$

The conductive heat flux q_{c0} is the same as q_{fd} in equation 7, so equation 11 is basically the required expression, except that we need to express q_{c0} in terms of T_a and T_e rather than T_a and T_0. This is done below. However, if the effects of the surface boundary layers are neglected for both the static and dynamic cases, then $T_e = T_0$ and $T_i = T_L$ hence

$$q_{fd} = q_{c0} = -Ak(T_i - T_e)/(\exp(AL) - 1) \tag{13}$$

$$q_{fs} = -k(T_i - T_e)/L \tag{14}$$

and equation 7 can be written

$$(H_s - H_d)/q_{fs}A_T = A_d/A_T[1 - AL/(\exp(AL) - 1)] \tag{15}$$

A3 Effect of surface boundary layers

In practice the concern is to express the heat flux in terms of given external and internal temperatures T_e and T_i. (The values of T_0 and T_L vary with u.) With conventional insulation it is normal practice to represent the heat transfer from the ambient to the surface of the material by the simplified expressions

$$-h_e(T_0 - T_e) = q_{fs} = -h_i(T_i - T_L) \tag{16}$$

where the heat transfer coefficients h_e and h_a and the temperatures T_e and T_a account for the combined effects of conduction, convection and radiation. (Heat flow is positive in the x direction).

The resultant heat flux with conventional insulation is then given by the well known expression

$$q_{fs} = -(T_1 - T_3)/(h_e^{-1} + h_i^{-1} + L/k) \tag{17}$$

and the values of T_0 and T_1 can be expressed in terms of T_e and T_i.

With dynamic insulation the velocity u is very small compared with the velocities encountered in the boundary layers. Also the porosity is very small, i.e. the surface area in contact with the external air can be taken to be the same as that for static insulation. It is therefore reasonable to assume that equations 16 (which relate to the radiation and conduction heat fluxes into the material at $x = 0$ and L) remain valid for the porous material. With the porous material, however, there is an additional heat flux at the surfaces, namely the convective heat flux $u\rho cT$.

Thus the heat fluxes through the boundary layers at $x = 0$ and L can be written as

$$-h_e(T_0 - T_e) + u\rho cT_0 = q = -h_i(T_i - T_L) + u\rho cT_L \tag{18}$$

where q is also given by

$$q = q_{u0} + q_{c0} = u\rho cT_0 - Ak(T_L - T_0)/(\exp(AL) - 1) \tag{19}$$

We wish to express q_{c0} in terms of T_e and T_i. Using equations 18 (of which there are two) and equation 19 leads to the following expression:

$$q_{c0} = -[(AkT_e + h_iT_i)/(Ak + h_i) - T_e]/[(\exp(AL) - 1)/Ak + (1 - Ak/h_e)/(Ak + h_i) + 1/h_e)] \tag{20}$$

Similarly, expressions for the variation of $(T_0 - T_e)$ and $(T_i - T_L)$ with u can be found. In particular

$$T_0 - T_e = -q_{c0}/h_e \tag{21}$$

$$T_i - T_L = -q_{c0}\exp(AL)/h_i \tag{22}$$

so that using equation 21, equation 7 can be written

$$(H_s - H_d)/q_{fs}A_T = A_d/A_T[1 - q_{fd}/q_{fs} - q_{fd}AK/q_{fs}h_e] \tag{23}$$

Figure 12 shows the variation of this quantity with u (for $A_d = A_T$, $k = 0.031$ W m^{-1}K^{-1}, $h_e = h_a = 10$ W m^{-2}K^{-1}). The variations of $(T_0 - T_e)/(T_i - T_e)$ and $(T_i - T_L)/(T_i - T_e)$ are shown in Figure 13. It can be seen that the variation of the former is much smaller than the latter. As u is increased T_L increasingly departs from T_i, i.e. the air entering the building does so at a lower temperature. This does not lead to a higher ventilation heat loss — the temperature of the internal air remains at T_i, at least in theory, by virtue of equation 16.

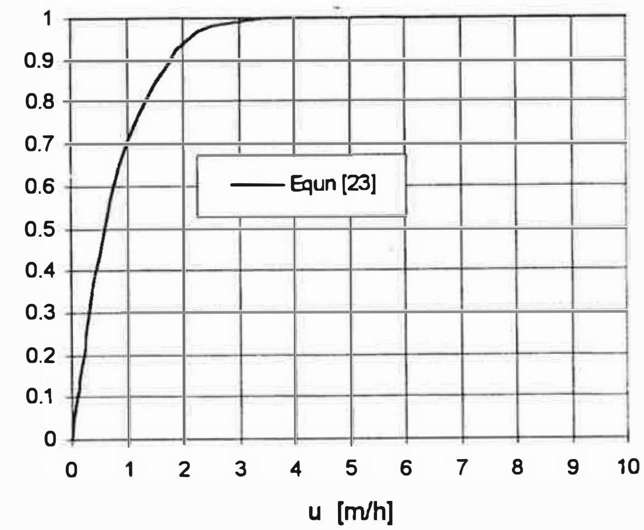

Figure 12 Normalised heat loss reduction as a function of velocity through insulation

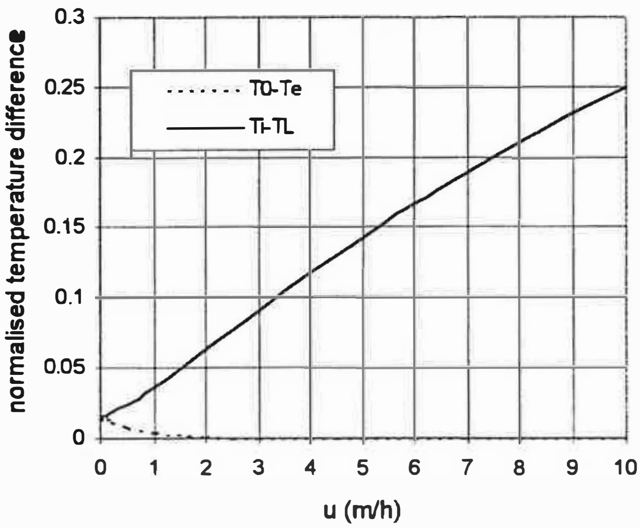

Figure 13 Normalised surface temperature differences as a function of velocity through insulation