The use of dynamic and diffusive insulation for combined heat recovery and ventilation in buildings

B J Taylor[1] , R Webster[1] and M S Imbabi[2]

Introduction

Modern buildings, domestic and commercial, have attempted to reduce their energy requirements by improving the airtightness of the envelope and increasing the thickness of insulation. However, this trend has developed simultaneously with increased use of synthetic materials in construction, furnishings and decorations, which give off volatile organic compounds, and increasing living standards which result in higher indoor temperature and moisture generation rates within homes. The result has been a reduction in indoor air quality which directly affects occupant health and increasing problems of dampness in homes, particularly for the poor.

Dynamic and diffusive insulation, which permit the movement of air, moisture, etc., through the external walls of a building, were seen as two potentially complementary methods for reducing ventilation and building envelope heat losses and achieving high indoor air quality. Dynamic insulation is also known as “pore ventilation” which is a more accurate description of the technology. A dynamically insulated envelope is constructed using air permeable materials so that air is able to flow through the wall driven by a pressure difference between inside and out created by fans or stack effect. The distinguishing feature between dynamic and diffusive insulation envelopes is that the former has neither an air barrier nor a vapour retarder whereas the latter is any construction without a vapour barrier.

The EPSRC funded research project was set up in January 1995, to provide a firm scientific understanding of dynamic and diffusive insulation. An important outcome of the research will be the development of building envelope designs which effectively and economically employ dynamic insulation in UK climatic conditions, without detriment to existing UK building practice and standards.

A theoretical understanding of heat, air and moisture transfer, which has been empirically verified, has been achieved. The resulting model has been used to study the energy and air flow balance within a dynamically insulated home, enabling general conclusions to be drawn about the effectiveness of this form of construction. The paper outlines the key theoretical and empirical results which will permit a designer to explore the potential for using dynamic and diffusive insulation in any proposed building.

Although work is still in progress, some general conclusions about dynamic and diffusive insulation will be presented. The results to date indicate that the energy saving produced by dynamic insulation alone is small in comparison with that obtained using conventional ventilation air heat recovery methods. The two can however be cumulatively combined to produce additional savings. Contrary to popular belief, our study of diffusive insulation suggests that it does not offer the possibility of significant improvements in air quality.

[1] The Scott Sutherland School of Architecture, The Robert Gordon University, Aberdeen, AB9 2QB
[2] The Department of Engineering, Kings College, The University of Aberdeen, Aberdeen, AB9 2UE

Dynamic and Diffusive Insulation

Heat Transfer

Physical insight into the heat and mass transfer processes in dynamic and diffusive insulation for any proposed envelope design can be gained from a simple 1-D analytical model. The model can be used to predict the effective or dynamic U-value for the envelope and the mass transport rate for any gas species. The dynamic U-value can be incorporated into an energy and air flow balance for the whole building to estimate the overall energy savings. This simple analysis which can be carried out on a spreadsheet is ideal for the conceptual design of buildings. However, for the design of the air permeable envelope details, 2-D models of the heat air and moisture transport should be used to assess (i) air bypassing the insulation through defects or construction details, (ii) buoyancy effects in the porous insulation, defects and cavities, and (iii) increased heat losses and vapour transport due to the above.

There are a number of such models in existence but they tend to be research tools and not available for use by practitioners. Hens [1] provides an excellent review of heat air and moisture transport modelling in general and specific computer programs in particular.

This paper will describe the practical results of the 1-D analytical model. Taylor, Cawthorne and Imbabi [2] showed that the dynamic U-value for a multi-layer envelope can readily be calculated from the total thermal resistance of the wall (R_s) and the air flow through the wall (*v*)

$$U_d = \frac{v\rho_a c_a}{\left(\exp(v\rho_a c_a R_s) - 1\right)} \qquad 1^1$$

The dimensionless group of variables that controls the behaviour of dynamic insulation has a formal resemblance to the Péclet number

$$Pe = \frac{v\,\rho_a\, c_a\, L}{k} \qquad 2$$

Unlike boundary layer analysis where it is the fluid physical properties that are employed, the thermal conductivity, *k*, in this case refers to the porous material. The density, ρ_a, and specific heat, c_a' are that of the air.

Table 1 illustrates how the material thermal conductivity and the air flow combine to determine the dynamic U-value for two envelopes, one comprising 200 mm of cellulose insulation and the other 200 mm thick porous masonry block such as Pumalite. The masonry wall requires an air flow approximately ten times that of cellulose to achieve a comparable improvement (U_d/U_s) in U-value. However, to achieve the same insulation value the air flow through a Pumalite wall would have to be about 100 times that for cellulose. Consideration of the pressure drop across the wall (280 Pa) at a flow rate of 100 m/h leads to the conclusion that it is not a practical proposition. Thus dynamic insulation works best with materials that are inherently good insulators. However, the thermal capacity of the masonry can be combined with the insulating properties of the cellulose to produce a composite permeable wall with a low U-value and high thermal capacity.

Table 1: Dynamic U-Value versus thermal conductivity and air flow rate

	Cellulose (k = 0.035 W/mK)		Pumalite (k = 0.3 W/mK)	
v (m/hr)	1	10	1	10
Pe	1.91	19.1	0.224	2.24
U_d / U_s	0.33	9.5 E-8	0.89	0.27
U_d (W/m^{2}K)	0.058	1.7 E-8	1.34	0.4

[1] Error in this formula corrected 7/01.11

Another reason why this is the case is that the analytical theory assumes that the air and the solid matrix of the porous insulation are in local thermal equilibrium. This assumption is valid for low air flows. Calculating the air flow at which the equilibrium theory is not applicable in terms of the physical properties of the porous medium is one of the useful results to be obtained from a non-equilibrium theory of dynamic insulation which is under development. It is sometimes suggested that with dynamic insulation less insulation material may be used in the wall. From Table 2 it can be seen that to get a significant reduction in U-value for a wall with only 40 mm of insulation high air flows are again required.

Table 2: Dynamic U-Value versus insulation thickness

	Cellulose (L= 200 mm)		Cellulose (L= 40 mm)	
v (m/hr)	1	10	1	10
Pe	1.91	19.1	0.382	3.82
U_d / U_s	0.33	9.5 E-8	0.82	0.085
U_d (W/m^{2}K)	0.058	1.7 E-8	1.23	0.13

Another feature of dynamic insulation is that as the air flow increases the inner surface temperature decreases [3]. This is because more heat has to be put into the inner surface of the wall to heat the increasing amount of air which in turn increases the temperature drop across the air film thermal resistance. The temperature drop is about 0.5 ºC for a flow of 1 m/h through a wall with 200 mm of cellulose insulation increasing to over 5 ºC at 10 m/h. Even at low air flows this temperature depression will significantly alter the radiant heat exchange within a room.

Mass Transfer

Diffusive insulation is merely a special case of dynamic insulation where the air flow is zero. In other words its thermal behaviour is no different from a conventional wall. Indeed diffusive insulation is merely a wall which does not include a vapour retarder with a high vapour resistance such as polythene or metal foil. Such wall constructions are acceptable in certain circumstances and BS 5250 [4] quotes a useful but not infallible rule of thumb that the vapour resistance on the warm side of the insulation be at least five times greater than that on the cold side. It is claimed that diffusive insulation permits the diffusion outwards of indoor pollutants such as water vapour and volatile organic compounds. However, diffusion, even without a vapour barrier, is such a slow process that water vapour is transported much more quickly through the wall by air flowing through cracks and crevices. Diffusion can be stopped if the air is flowing in the opposite direction to the diffusion process. The critical air velocity v_c required to do this is dependent only on the ratio of the concentrations of the gas (inner concentration C_i assumed to be greater than the outer concentration C_o) and the total diffusion resistance of the multi-layer wall R_d [2]:

$$v_c = \frac{\ln\left(C_i / C_o \right)}{R_d} \qquad 3$$

This explains how dynamic insulation can act as a vapour barrier. If the air velocity is greater than v_c then water vapour will be carried from outside to inside despite there being a higher water vapour concentration on the inside. For a typical timber frame insulated wall construction with total thermal resistance of 6.434 m^{2}K/W (200 mm cellulose insulation) and the indoor and outdoor temperature and humidity conditions of 15 ^{o}C, 85% RH and 5 ^{o}C, 95% RH respectively as specified in BS 5250, this critical air velocity is very low at 0.0063 m^3/m^{2}h. This is very much lower than the air flows of 0.5 to 1.5 m^3/m^{2}h recommended by Dalehaug [5]. The partial vapour pressure difference corresponding to the standard internal and external conditions, stated above, is 621 Pa. The authors have measured the air permeability of a variety of insulating materials and the air permeance of 200 mm of cellulose is found to be 1.5 m^3/m^{2}hPa. and that for 12 mm thick softboard was 0.116 m^3/m^{2}hPa (Appendix 1). The controlling resistance to air flow in a wall construction comprising of wood wool board (air permeance too high to measure), 200 mm cellulose, 12 mm softboard is the softboard. The pressure drop across the wall at the critical air flow corresponds to a difference in air pressure of only 0.054 Pa Thus water vapour cannot flow from inside to out through a wall operating in contra-flux (heat and mass flow in opposite direction) mode.

There is then a conflict between the air flow requirements to minimise heat losses and that necessary to maximise the removal of water vapour or other indoor pollutants. On the other hand provided one can ensure that air is flowing inwards through the envelope at all time then there should, in general, be no problem of interstitial condensation. However, if the outer wall cladding is saturated by wind-driven rain followed by heating by the sun then the temperature and relative humidity in the cavity could rise very quickly and condensation could occur in the still relatively cool insulation.

One of the most useful outcomes of the recently completed IEA Annex 24 on heat air and moisture (HAM) transport in buildings has been the compilation by Kumaran [6] of data on air permeability, water vapour permeability and hygroscopicity for many building materials.

Systems Analysis

Equation (1) can be readily incorporated into an air flow and energy balance for a whole house to calculate the heat loss through the air permeable parts of the envelope [7]. A fact that is often overlooked by the proponents of dynamic insulation is that whilst the heat loss to the outside is reduced more heat needs to be put into the interior surface of the wall in order to warm the incoming air than would be the case without air flow. Therefore, if the air coming through the wall is merely vented to atmosphere without heat recovery little is gained. With an air-to-air heat recovery scheme as shown in Figure 1 the ventilation requirements are supplied partially through the wall, m_p, and partially through the heat exchanger, m_f. The model also allows for air leakage through doors and windows, m_l. The heat input to the building Q (partly supplied by incidental gains) compensates for the heat lost through the porous envelope Q_p, the non-porous part of the envelope, Q_n and the ventilation loss.

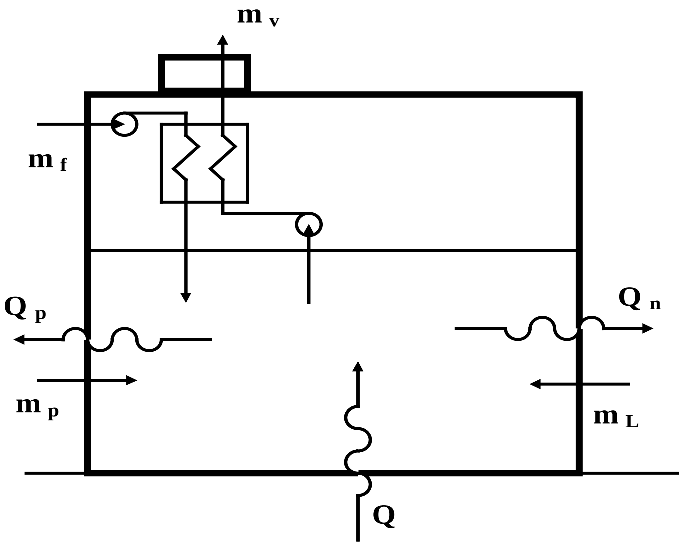

Figure 1: Dynamic insulation with air to air heat recovery

The only way a building can be reliably depressurised in the mild and variable UK cilmate is by using fans. In northern Scandinavia with a 40 °C temperature difference between indoors and out in winter a reliable and significant stack affect may be obtained. The depressurisation must be no greater than 5 to 10 Pa otherwise the occupants will have difficulty opening doors and windows [4]. This restriction on depressurisation could be relaxed if the opening and closing of windows and doors were mechanically assisted. Since the pressure drop through an air-to-air heat exchanger and associated ductwork is in the region of 50 to 100 Pa both a supply and an extract fan are required.

The results of analysis of such a scheme are shown in Figure 2. The ordinate plots the reduction in energy consumption over a conventional envelope construction of the same static U-value for the same air change rate to maintain an indoor temperature of 20 °C when it is 0 °C outside. The curves show how a dynamically insulated building and conventional envelope compare when both use air-to-air heat recovery. At low air change rates the conventional building performs better than the dynamically insulated building. The bigger and better the heat exchanger the higher is the air change rate before it becomes worth while to think about dynamic insulation. Both schemes show a maximum saving at around 1.5 to 2 ach. This level of ventilation in a conventional house could be achieved merely by opening the windows.

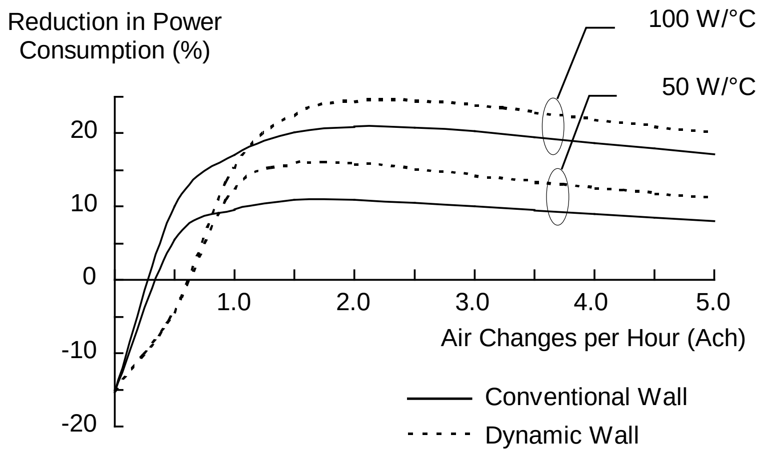

Figure 2: Heat recovery with conventional and dynamic envelopes

An air-to-water heat exchanger operating at 2.0 ach would require a continuous steady flow of water of the order of 1550 kg/day in a home. This flow rate is much larger than the domestic requirements for bathing, showering, laundering also the temperature constraints imposed by the exhaust air flow and the heat exchanger mean the water temperature will rise only from about 5 °C to 15 °C. If the warm air were used instead to melt snow the water it would provide at, say, 10 ºC is a more manageable 170 kg/day. However, snow is not a reliable heat sink in most areas of the UK.

With the simple tools developed so far the designer can explore, for example, how the proportion of non-permeable surfaces (such as glazing) to permeable surfaces and how the size of the building affect thermal performance. The results are much as one might expect. To make the most effective use of dynamic insulation as great a proportion of the external envelope as is practical should be air permeable. This has obvious implications for the use of incident solar radiation for lighting and heating. It also means that a detached house is a more suitable candidate for dynamic insulation than a small apartment with only one or at most two external surfaces. As the volume of the building increases, the ratio of volume to surface area increases and so the relative importance of the ventilation heat loss to envelope loss increases. In general, where energy conservation is the main objective, dynamic insulation would appear to be appropriate only for small detached buildings.

Indoor Air Quality

A porous wall will inherently act as a filter. Studies of porous ceilings in barns where the ventilation rate can be as high as 80 m^3/m^2h have shown that over a span of 20 years the pressure increase due to dust accumulating in mineral wool insulation is insignificant [8]. This may be due in part to the relatively low density (15 kg/m^3) of the insulation. In homes, the ventilation rate will be an order of magnitude smaller and the rate of dust accumulation in the walls will be correspondingly slower. The authors are not aware of any data on the filtration efficiency of cellulose insulation as a function of particle size. Insulation materials such as cellulose and mineral wool will not remove chemical pollutants in the way that activated charcoal filters would.

Cellulose insulation fibre is treated with borax to prevent fungal growth and infestation by insects and rodents. Bacteria cannot survive in the air on their own: they require dust particles to sustain small colonies. When these dust particles are trapped in the insulation, bacteria living on them may multiply unaffected by the borax in the cellulose. The microbes and or toxins they may produce may then subsequently be disseminated into the living space. The bacteria may provide the nutrients required by moulds and fungi to grow [9]. This potential health hazard requires investigation in order to identify the circumstances under which dynamic insulation may act as an amplifier and disseminator for bacteria, fungal spores and viruses.

In view of the risks attached to mechanical ventilation systems, which may be overcome by proper maintenance, the hybrid scheme (Fig 2) offers no health advantages over a purely mechanical ventilation system. An air to water heat exchange system might be better in this respect.

With contaminants released within the building such as volatile organic compounds (VOC's), body odours, cooking smells, spores from moulds these are best dealt with by extracting them at source and venting directly to outside. Dynamic insulation might be able to contribute to their dilution and removal by permitting higher ventilation rates or preventing their spread by plug flow of fresh air from a wall or ceiling. Diffusive insulation will not reduce the concentrations of these substances in the indoor air rapidly enough to be of any practical use.

Future for Dynamic and Diffusive Insulation

Diffusive insulation is not a practical method of ventilating a building designed for human activities. In contrast, it has been shown that dynamic insulation will, as has been claimed, cut down on the conductive heat loss through the wall. Dynamic insulation, operating in contra-flux mode, will also prevent water vapour getting into the wall from the interior. This had not previously been fully appreciated. However these benefits are not easy to achieve in practice:

- the rest of the building needs to be exceptionally air tight and air flow through the walls needs to be reasonably uniform
- difficult to ensure air flows inward through the wall under all internal and external climate conditions
- under certain conditions (e.g. sun shining on wet timber cladding) one may get interstitial condensation with air flowing inwards
- energy must be recovered from the ventilation air
- the building occupants need to understand how the building works and to behave accordingly.

In short, the design effort and quality control during manufacture and erection of a dynamically insulated building is greater than that required for a building with conventional air tight, well insulated envelopes in order to ensure acceptable hygro-thermal performance.

In the concluding stages of this project the thermal performance of an air-to-air heat exchanger with fans which are continuously and independently variable is being measured. The fans in commercially available air-to-air heat exchangers are electrically linked to provide step changes in air flow so that the exhaust flow is always about 10% greater than the supply flow. This data will provide greater confidence in the estimation of the heat recovered from the vented air and provide guidance on how best to couple dynamic insulation with ventilation heat recovery. Whilst the simple 1-D theory based on thermal equilibrium has been proven to be adequate for the air flow rates through the envelopes of houses it is quite likely at the high flow rates associated with porous ceilings in sports halls and swimming pools (greater than 20 m/h) a non-equilibrium theory is required.

Future research on dynamic insulation will need to focus on developing designs that are (a) safe for humans, (b) durable and (c) cost effective. In particular, when insulation materials are used as pore ventilation, a very effective disseminator, the safe assumption is to assume that some microbes will find that environment adequate to support a growing population. Research should be directed to finding which microbes will multiply and the environmental conditions that favour this growth.

Acknowledgements

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Appendices

Appendix 1: Measured Air Permeability of Building Materials

Material	Permeability (m^2/hPa)	Component	Permeance (m^3/m^2hPa)	Pressure Drop (Pa) [1]
Plasterboard	$1.06x10^{-5}$	12 mm sheet	$8.81x10^{-4}$	1140
Thermal block (density 850 kg/m3)	$1.6x10^{-5}$	100 mm block	$1.6x10^{-4}$	526
Fibreboard	$1.34x10^{-3}$	12 mm sheet	$1.16x10^{-1}$	8.6
“Pumalite” (density 870 kg/m3)	$3.6x10^{-2}$	100 mm block	$3.6x10^{-1}$	2.8
Cellulose / wet blown (density 47 kg/m3)	0.283	200 mm	1.50	0.67
Cellulose / dry blown (density 65 kg/m3)	0.25	150mm	1.67	0.60
Sheep's wool (density 28kg/m3)	1.8	140 mm	13.0	0.08

(1) Pressure drop calculated at flow rate of 1 m^3/m^2h