The redefinition of the functions of a window to achieve improved air quality and energy performance in European Housing.

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ABSTRACT: WHOLE-pvs (an innovative whole-house low-energy ventilation system) has been the subject of a research and demonstration project funded by the EU and UK DTI. This has followed from previous laboratory and test cell experiments carried out in conjunction the UK Building Research Establishment, that were the first to combine supply air windows and passive stack vents (PSV) as a solution to the competing demands of domestic energy and indoor air quality in temperate climates. At each of the test locations in Denmark, Ireland, Poland and England the performance of the system has been monitored in test dwellings and in comparison with an identical control dwelling equipped with a conventional ventilation system appropriate to each country. Test measurements have been compared with computer simulations developed during the previous experimental phase, and for the latter part of the test period the dwellings have been monitored whilst occupied. An interactive website is being developed that will give access for potential users to the design considerations necessary for successful operation under individual site and climatic conditions, its use will be demonstrated at the conference.

Conference Topic: 5 Materials and building techniques
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INTRODUCTION

We are about to conclude testing WHOLE-pvs, an innovative passive house ventilation system (Fig. 1), after a three-year research and demonstration project. The installations in Ireland, Denmark and Poland have been funded by the EU 5\(^{th}\) Framework Programme, and in the UK by the Department of Trade and Industry.

Ongoing revisions to Building Codes across Europe, requiring reduced energy consumption, are resulting in dwellings being more tightly sealed to reduce infiltration and conserve heat in winter. Health concerns about the poor internal air quality that is the consequence of tightly sealed construction do however argue in favour of increased background ventilation rates. Consequently whilst heat loss through the fabric of buildings is diminishing as insulation standards increase, the heat lost as a result of ventilation (both intended and unintended) is an increasing problem.

In temperate climates the principal indoor pollutant is condensation, particularly since the resulting mould growth is associated with the increasing incidence of asthma. A variety of other pollutants such as oxides of nitrogen, the toxins present in many building products, micro-organisms and particulates are also a cause for concern.

At each test site ‘supply air’ windows have been combined with passive stack ventilation (PSV)[1] to form the low-energy whole-house ventilation system WHOLE-pvs. Tests have been carried out in dwellings at first unoccupied for comparison with the adjoining control dwelling, and then with each being occupied to elicit the response of the users.

Figure 1.
cavity, by solar gain, but also by the reclaim of heat escaping from the room, and is delivered into the room as pre-warmed background ventilation. It is important that the flow is laminar because the window is then very efficient at reducing conductive heat loss. Extremely low window $U_e$-values can be achieved when flow-regulating vents are integrated within the window design, and by the inclusion of a low-E hard coating on the surface of the inner pane facing into the air path.

Figure 2: The ‘supply air’ window: showing the inner and outer sashes which separate for cleaning, and the vents at the top of the inner sash and bottom of the outer sash.

For optimum performance the system depends on the building’s construction being airtight, and design requirements for the PSV installation being met, in order to achieve the desired combination of low energy efficiency and improved indoor air quality. Because the system is climate-dependent and dynamic, the extent to which the incoming air is preheated and the window $U_e$-values that are achieved, have to be averaged over time. Consequently the design has to be optimised relative to location and the type and configuration of the dwellings [4].

TEST SITE LOCATIONS

Within the European project the test locations were chosen to represent a range of climates: a maritime climate at Armagh, N. Ireland (which has mild wet summers and winters), a Scandinavian climate at Fredericia, Denmark (having cold wet winters, and mild summers), and a Continental European climate at Wroclaw, Poland (cold dry winters, warm dry summers). The English site is at Norwich in East Anglia where two identical two-storey houses have been completely fitted with supply air windows and passive stack vents. The purpose of this demonstration was to characterise the performance of the system with regard to different lifestyles and occupancies rather than the intensive monitoring undertaken at the other locations.

‘Supply air’ windows and PSV extract ducts have been installed in test houses in Ireland and Denmark, and in a flat in Poland. Adjacent to each test dwelling there is a control dwelling of identical plan and orientation that has been equipped with a conventional ventilation system, and windows that represent typical construction in that particular country.

In Denmark and Poland the properties had been newly built, and were sufficiently air tight, particularly in Poland. The homes in Northern Ireland are approximately 40 years old, and a substantial amount of remedial work had to be carried out within them, but even then achieving uniformity between the two houses was problematic, and due to the age of their construction air leakage rates were relatively high. At each location the dwellings have been monitored to establish the levels of indoor air quality (IAQ) and comfort, and overall energy consumption. The occupants are currently being surveyed to establish their pattern of use of the controls to the windows and PSVs, and to establish user satisfaction.

Figure 3: ‘Supply’ air windows installed at the test house in Fredericia, Denmark.

In Denmark (Fig. 3) a passive stack vent (PSV) system was installed in the test house that extracts air from the kitchen, bathroom and utility room and delivers it into a central stack within the roof space. The control house had been fitted with a high efficiency mechanical ventilation heat reclaim (MVHR) system, it was built with standard double glazed low-E coated, argon filled windows having a U-value of 1.2.

In Poland (Fig. 4) two flats with mirror image plans have been monitored, one being used as the test dwelling and one the control. They consist of a bedroom/kitchen space, bathroom and hall. Both windows within the flat have been replaced with ‘supply air’ windows, 1.5m by 1.5 m in size. A PSV system had already been installed into all the flats in the development, since this is the conventional method of ventilation within flats in Poland. Extracts
were located in the kitchen and bathroom venting into the central stack that runs up the whole height of the building. Both flats are on the third floor of a 4-storey block and so a significant height of stack has been achieved. The control flat is served by the same PSV system, but its standard low-E windows, which have a U-value of 2.0, were not altered for the project since they conform to the local standard for new multi-storey residential construction.

**Figure 4:** Test and control flats in Poland

The houses in Norwich had a PSV system installed in the kitchen, WC and bathroom. The stacks terminate at ridge vents. Seven of the ten windows in each house are supply air windows. On the front elevation there are two supply air windows: one in the kitchen and one in the front bedroom. On the rear elevation there are two in the living room, and one in each of the rear bedrooms. There is also one ‘supply air’ window on the side elevation in the living room.

**TEST MEASUREMENTS**

**Figure 5:** Comparison of $U_e$-values achieved by the supply air windows (SAW) and the conventional windows within the Danish test house.

In Denmark the houses, test and control, were pressure tested and shown to represent a good level of air-tightness. Initial air leakage was 4.8 $\text{ach}$ at 50 Pa. During the tests a small number of sources of significant air ingress were discovered, but once sealing of these gaps was completed the air tightness improved to 3.0 $\text{ach}$ at 50 Pa. Using the 1/20 rule this indicated an air leakage rate of 0.15 $\text{ach}$ under normal conditions, a level of infiltration that would not significantly interfere with the window's performance.

As shown in figure 5 the average night-time $U_e$-value for the ‘supply air’ window and the control house’s standard specification window was 0.69 and 1.09 respectively. Ventilation pre-heat, excluding any solar input averaged approximately 38% of the average heat load, so that even at high ventilation rates there was greater than expected pre-heating of the incoming ventilation air. In terms of thermal comfort, the maximum reduction in general room air temperature in the vicinity of the window was 1.4 deg C, whereas the maximum reduction in general room air temperature in the vicinity of the MVHR outlet in the control house was 2.6 deg C.

In Poland the building was very airtight having only 0.2 ACH background leakage as constructed. Average night-time $U_e$-values in November were 0.52 and 0.64 for the two windows (the disparity being due to proximity of the left window to the kitchen stack or more likely slight differences in the manufacture of the vents). The average January window $U_e$-value was 0.52. At a total ventilation rate of 16 l/s (57.6 m$^3$/hr), suitable for two people, the windows achieved 0.5 and 0.6 W/m$^2$K for January and May. The wind was also a contributing factor.

Stack flow in the control flat was much reduced compared with the test flat due to the lack of air ingress points (the local building codes not having a prescribed level of air intake in winter). It was found that the test flat achieved higher flow rates and air changes than the control. Kitchen stack flow rates averaged 32 m$^3$/hr in the test flat and 15 m$^3$/hr in the control flat. Both of the flats provided adequate ventilation for one occupant, to comply with CIBSE criteria if the bathroom door was open but only the test flat achieved adequate ventilation for a couple. The average ventilation pre-heat for the insolated and shaded window was 2.6 °C and 2.2 °C respectively, and the average proportion of the ventilation heat load delivered by the windows was 22% and 18%. At higher flow rates through the PSV outlet it was still possible to deliver over 10% of the ventilation heat load.

The Irish properties are two-storey semi-detached houses in a small development in Armagh. The houses have ‘mirror image’ plans and consist of hall, living room, kitchen and bathroom on the ground floor, and three bedrooms on the first floor. A PSV system was installed in the test house extracting from the kitchen and back bedroom to a vent above the roof. In the control house extract fans were fitted in the kitchen and bathroom (automatically timed during
the initial unoccupied period of testing). ‘Supply air’ windows were installed in the kitchen and back bedroom adjacent to the PSV extracts. This was done intentionally as it was felt that the poor air tightness of the houses would ‘short-circuit’ the window-PSV flow if they were placed too far apart. The single glazed windows and trickle vents in the control house were left unaltered, but extensive air-sealing was carried to try and bring the houses in line with the new-build properties in Poland and Denmark.

An interesting feature of the Irish installation was the disparity between the $U_e$-values delivered by the upstairs and downstairs windows. The ground floor window operated much as expected with a night-time $U_e$-value averaging 0.78 (equivalent to the predicted simulation values for a dual single-pane design) but the upper storey window delivered an average $U_e$-value of 2.52, a value worse than for a typical sealed double glazed unit. This was due to reverse flow through the upper storey window, which caused air at room temperature to be separated from the ambient temperature by only a single pane of glass, imparting to the window the behaviour of a single glazed window for significant periods of time. This reverse flow at the upper storey can be mimicked by simulation if enough air leakage is included in the model. What appeared to be happening therefore was that excessive fabric leakage resulted in bypassing of the reverse flow control mechanism within the ventilators, causing too much air to enter the building. This excess of air entering at the ground floor, and rising up the stairwell by stack effect, created higher pressure conditions on the first floor, and reverse air flow through the upper windows.

Figure 6. Pre-heat data for the kitchen windows within the Irish test houses.

A similar disparity was also observed in the results for air pre-heat within the window due again to reverse flow at the upper storey window. When the flow was reversed no pre-heat actually occurred but the temperature at the top of the window was close to room temperature giving the impression of high pre-heat values. Figures 6 and 7 show the pre-heat values for the two windows. The upper window regularly saw pre-heat values between 80% and 90% indicating that reverse flow was occurring for a significant proportion of the test period.

Figure 7: Pre-heat data for the bedrooms within the Irish test houses.

CFD and ESP-r modelling.

A variety of simulation methods have been used throughout the programme of testing from a first algebraic model, to a steady state verification carried out using CFD, and finally a dynamic model constructed in ESP-r. This has enabled the performance of the WHOLE-pvs system in real buildings to be anticipated, and the construction of simulations for the dwellings in the countries being used for the current tests.

Figure 8: CFD model showing temperature distribution throughout the single storey houses being used for testing in Denmark.

The CFD model created accurate steady state analyses of the window $U_e$-Values, and simulated thermal comfort conditions within rooms. Figure 8 shows the simulated $U_e$-Values of the two windows in Denmark that verified the performance of the 30mm gap between the glass panes forming the air path, an important dimension for the achievement of laminar flow within the window cavity.

Dynamic ESP-r Simulations were also used to predict the extent of pre-heating of the ventilation air.
within the 'supply air' windows, and the dynamic thermal comfort levels that could be expected. These simulations showed that on clear days in Poland, the pre-heat reached 50% of the ventilation heat load, on cloudy days 38%, and at night pre-heat averaged 27%.

**Economic Viability**

As part of the European funded project a complete economic viability analysis has been undertaken.

The most commonly used method for assessing the cost-effectiveness of energy saving components is the "Simple Pay-back Time". This is the ratio of the capital cost to the net annual savings.

The simple pay-back time (PT) is given by the expression:

$$PT = \frac{I}{S - M}$$

where

I: is the total cost of the installation (extra cost compared with a conventional installation).
S: annual savings.
M: annual maintenance cost.

Enhanced results are achieved by use of the Net Present Value (NPV) method whereby the net present value of all cash outflows (such as the cost of the investment) and cash inflows (returns) are calculated using a given discount rate.

For this purpose the cost of each installation has been taken as the extra cost compared to the standard solution installed in the control dwellings. In Poland and Denmark this was the additional cost of the supply air windows and pressure-regulating vents, and in Ireland the extra cost of the windows, vents and PSV system.

The site in Ireland has the highest extra cost associated with the WHOLE-pvs installation because of the larger number of windows required to equip a two-storey house, the installation of the PSV system, and because the control house was only single glazed. In Denmark the extra cost of the mechanical ventilation system within the control house was high, probably because of the experimental nature of the project.

The annual savings are equal to the difference in running cost between the test and control dwellings. The running cost includes energy for space heating and electricity for fans. Calculation of these savings has taken into account the different energy cost in the three countries.

**Table 1:** Simple pay-back times in years relating to estimated and monitored data

<table>
<thead>
<tr>
<th>Country</th>
<th>WHOLE-pvs (estimated)</th>
<th>WHOLE-pvs (monitored)</th>
<th>MVHR (estimated)</th>
<th>MVHR (monitored)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Poland</td>
<td>22.7</td>
<td>21.1</td>
<td>21.1</td>
<td></td>
</tr>
<tr>
<td>Denmark</td>
<td>16.3</td>
<td>11.1</td>
<td>29.6</td>
<td>405.1</td>
</tr>
<tr>
<td>Ireland</td>
<td>22.7</td>
<td>21.1</td>
<td>66.7</td>
<td></td>
</tr>
</tbody>
</table>

Due to the high initial cost of the test system in Ireland it did not prove cost effective when calculated in relation to the estimated or monitored energy consumption data, resulting in payback periods of 66.7 and 22.7 years respectively. The higher $U_e$-value of the upper storey window was also to the detriment of the cost effectiveness of the system. It would require a better standard of air tightness if the upstairs supply air window was to achieve equivalent performance to the one at the ground floor (this additional sealing would itself represent an additional cost).

The NPV analysis of the Polish installation demonstrated that the test system was marginally cost-effective, based on the monitored data, achieving a simple payback period of 21.1 years. The
NPV calculation also showed that the Danish installation would be cost-effective if the cost was lower than 800 euro per dwelling, or 250 euros per dwelling in Poland. The analysis is very sensitive to the mass production cost of the components, a variable that is difficult to predict even for the manufacturers who were partners on the project.

The energy savings for space heating due to WHOLE-pvs ranged from 5% in Denmark to 15% in Ireland, mainly because of different performance of the reference system in the two countries (low-energy windows are standard in new housing schemes in Denmark). Relative heating costs also have a considerable impact on the energy savings, energy costs in Denmark being three times greater than in Poland.

CONCLUSIONS

The installations in the three countries have been both monitored and satisfactorily modelled using CFD and ESP-r [5]. The best outcome was achieved in Poland because of the tightly sealed construction, the capacity of the passive stack duct that had been purpose designed for the building, and the proximity of the windows to the stack [6][7]. The lack of any provision for background ventilation in the control flat, the only incoming air being the result of infiltration made the benefits of WHOLE-pvs evident. On the other hand the installation in Ireland operated less well because of the difficulty of making the existing fabric airtight.

In terms of cost-effectiveness the low energy whole house ventilation system in Ireland is unattractive because of the high initial cost of the system, despite the poor performance of the control with which it was compared. In Denmark the cost-effectiveness is acceptable especially if it possible to reduce the investment cost by 10-20%. In Poland the new whole house ventilation system is more economically attractive mainly because of the low installation cost into a block that already incorporated a passive stack. The economics of the system in Poland would be even better if it was not for the low energy cost per unit.

The low energy whole house ventilation system cannot however be evaluated only by considering the cost-effectiveness of the installation. Indoor air quality is improved by WHOLE-pvs especially since the preheating of the ventilation air avoids draughts and contributes to comfort within rooms. A ‘supply air’ window can achieve very low Uw-values, and provide background ventilation by a method that is apparent to building users, thus avoiding the operational problems that beset mechanical systems. Depending on the standard of construction, the system is applicable to both refurbishment and new dwellings. This is particularly true in Eastern Europe, where passive stack ventilation is a usual method of ventilation, and where regulations are being recast to address worries about energy consumption and indoor air quality. We are in the process of constructing an interactive website that will enable potential users to enter pertinent design and climate data so the specification for best performance can be advised.

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REFERENCES


