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A passive–active dynamic insulation system for all climates

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Abstract

Common features of Passive House design are thick walls and air tight construction, to minimise heat loss and infiltration respectively. This is due to the use of thick conventional insulation to achieve the very low *U*-values required for the Passive House Standard, which adds to the overall cost of construction and also potentially contributes to problems such as interstitial condensation. High performance, exotic insulation materials such as silica aerogels and vacuum insulation products could help to reduce thickness but at a cost that is at present prohibitive. In this paper the author introduces the basic concept and some illustrative simulated performance results of a new Void Space Dynamic Insulation (VSDI) technology that couples low cost conventional insulation materials with efficient ventilation to deliver low loss building envelopes and high indoor air quality in thin wall construction. The advantages of VSDI are that it eliminates the risk of interstitial condensation and the risk of over-heating during extreme summer months. Importantly, VSDI can be used as a 100% passive component, without a fan to drive the air flow.

Keywords: Void Space Dynamic Insulation (VSDI); Passive-active systems; Passive house design

1. Introduction

The Passive House concept was originally conceived by Adamson and Feist (1988), and has since defined the gold standard for energy efficient construction. The first houses that were built to the Passive House Standard were constructed in Darmstadt, Germany in 1990 and occupied by their owners the following year. The passive house concept has since been applied to other building types, such as schools, offices and shops. Today, the number of passive house structures that have been certified is in excess of 25,000, mostly in Germany but with examples to be found in many other countries.

At the time, the first passive houses used 90% less space for heating energy compared to a new house. This was achieved primarily through the use of superinsulation in the envelope, good quality doors and windows to deliver air tight construction and efficient ventilation. Special attention was paid to reduce thermal bridging, which can significantly degrade the thermal performance of the building envelope.

The Passive House Planning Package (PHPP) requires that the building must be designed to have a calculated annual heating demand of not more than 15 kWh/m^2 in heating and the same in cooling energy, or to be designed with a peak heat load of 10 W/m^2. Also, the annual primary energy consumption (i.e., the energy used for heating, hot

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water and electricity) must not exceed 120 kWh/m^2. Finally, the building must not leak more air than 0.6 times the house volume per hour at 50 Pa (PassivHaus Institute, 2012).

In Sweden, experience has shown that to achieve Passive House Standard the wall insulation thickness on its own would have to be around 335 mm (U-value ~0.10 W/m^{2}K) and the roof insulation thickness around 500 mm (U-value ~0.067 W/m^{2}K). Both the external walls and roof would be more than 500 mm thick as a result of this. The increase in cost is much more than just the added cost of insulation, which is probably manageable.

The increase in depth of structure required to physically accommodate the much thicker than normal layers of super insulation is proportionally much higher, with a greater detrimental effect in absolute terms on the cost of the building. The situation is further exacerbated by the loss of floor plate efficiency through having to cope with thick walls, which in the absence of free land to accommodate the increased girth of the building would lead to a sizeable reduction in the available floor area and higher cost/m^2 of the building.

But it is not just the higher cost that is the problem. A potential recipe for disaster is the application of superinsulation without enough consideration being given to ventilation of the insulation layer, to minimise or eliminate the risk of interstitial condensation (Hens et al., 1996; Kumaran, 1996; Taylor and Imbabi, 1998). The combination of reduced heat flow and air tight construction, each desirable in isolation, means that infiltration and exfiltration can no longer be relied upon to keep the superinsulation dry, thus increasing the potentially very serious consequences of moisture deposition and all the known, inherent problems of mould growth and its many health-related negative impacts, degradation of the insulation material and reduced insulation performance.

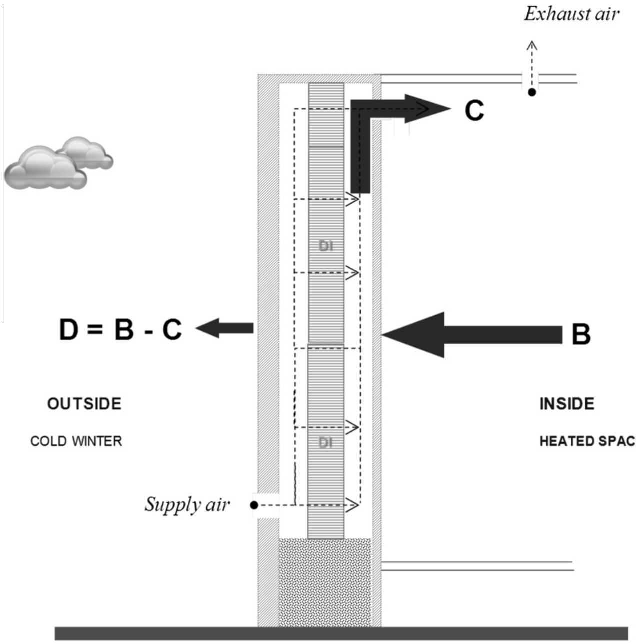

Fig. 1. Permeodynamic wall construction.

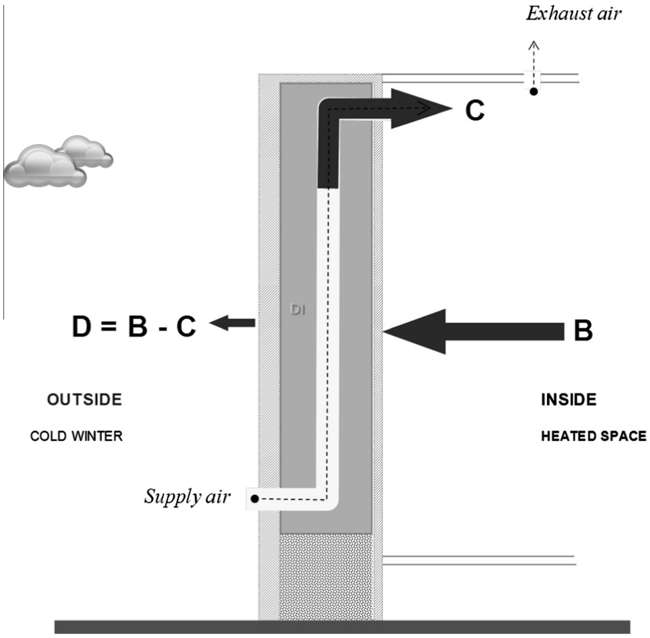

Fig. 2. Parietodynamic wall construction.

Every one of these outcomes would be more than enough to defeat the purpose of using superinsulation in the first place (Ueno et al., 2010).

The key to overcoming all the issues that have been outlined surrounding the use of thick layers of conventional superinsulation is a new type of superinsulation that can deliver even lower envelope heat losses, use less thick conventional (low cost) insulation materials and offer near-zero risk of interstitial condensation. This new type of superinsulation is called Void Space Dynamic Insulation (VSDI).

2. Working principles of dynamic insulation

Research into dynamic insulation dates back to the 70s and has been dominated in recent decades by the author and his co-workers (Taylor et al., 1996; Taylor and Imbabi, 1997; Taylor and Imbabi, 1998; Taylor and Imbabi, 2000; Imbabi et al., 2004; Imbabi, 2006; Wong et al., 2007; Imbabi et al., 2010; Elsarrag et al., 2012; Imbabi et al., in

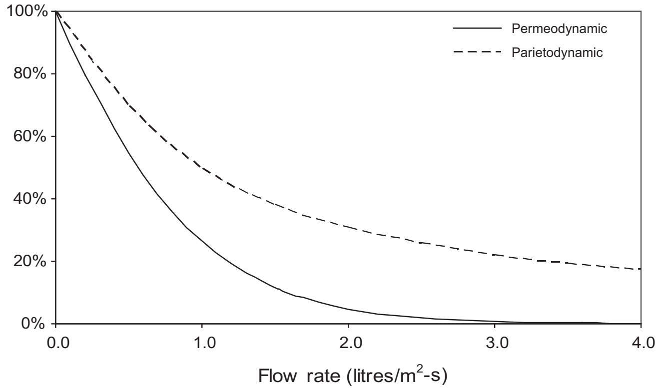

Fig. 3. Normalised plots of (Ud/Us) versus the air flow rate in v_a.

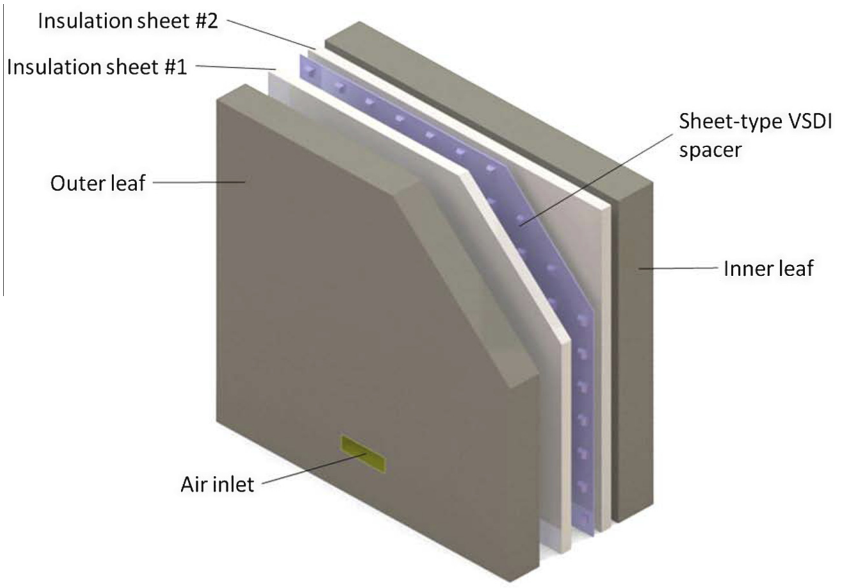

Fig. 4. Illustrative example of full-fill VSDI wall using 2 insulation sheets.

preparation). Dynamic insulation offers an energy-efficient approach to thermal insulation that can be used in place of, or in certain cases in tandem with, conventional insulation in buildings. An important property of dynamic insulation is that it is permeable to air flow. This enables fresh ventilation air to be drawn into (or exhausted from) the building via appropriate inlet and outlet vents in the external fabric. As the air flows inwards through the dynamic insulation layer it is tempered using the waste heat or cold normally lost through the building fabric. Under steady state conditions and ignoring inertial effects the heat flux through a conventional 'static' wall is the same as leaving the wall, its magnitude determined by the resistance to heat flow of the materials used to build the wall. Conversely, Fig. 1 shows a dynamically insulated wall, where cold outdoor air is drawn in through the dynamic insulation layer and pre-heated by the heat loss (B), recovering part of that heat loss (C) to the building as tempered air.

The balance (D), which is the difference between (B) and (C), is what is lost from the building. In the absence of air flow, the dynamically insulated wall will act as a static wall (i.e., C = 0 and D = B). Dynamic *U*-value is the parameter that has been used in the past to quantify heat loss as a function of air flow rate through a dynamically insulated wall. It is also convenient and often preferable for dynamic energy recovery to be quantified and expressed as a dynamic *R*-value. This allows different wall constructions to be evaluated by the designer using any approved *U*-value calculation tool in the normal manner.

2.1. Generic types of dynamic insulation

2.1.1. Permeodynamic insulation

With permeodynamic insulation the air flow is through the insulation, normal to the plane of the dynamically insulated wall and counter to the direction of heat flow. The materials used are air permeable. Fig. 1 is a schematic of a permeodynamic wall.

The dynamic *R*-value R_{d-ef} of permeodynamic insulation within a wall or building envelope element is (Imbabi, 2006).

$$R_{d-ef} = \frac{\exp(v_a \rho_a C_a R_c) - 1}{v_a \rho_a C_a} \tag{1}$$

where v_a is the air flow rate per unit area of insulation, ρ_a is the density and C_a the specific heat capacity of air and R_c is the static thermal resistance (*R*-value) of the dynamic insulation layer in the absence of air flow.

2.1.2. Parietodynamic insulation

Parietodynamic insulation offers an alternative approach where air flow is confined to a channel or channels within the plane of the wall and the direction of flow is orthogonal to the direction of heat flow. The materials used are ideally impermeable to air flow and channels may be enclosed or exposed. Fig. 2 is a schematic of a parietodynamic wall.

The height-averaged dynamic *R*-value of a parietodynamically insulated wall is (Imbabi, in preparation).

$$\overline{R}_{d-ch} = \frac{(T_i - T_o) \times NR_o}{(M - T_o)((e^{-N} + N - 1)} \tag{2}$$

where $M = (R_oT_i + R_iT_o)/(R_o + R_i)$, $N = (R_o + R_i)/(\rho_a C_a v_u R_o R_i)$, T_i and T_o are indoor and outdoor temperatures, R_o and R_i are aggregated thermal resistances (*R*-values) between the air flow channel and the cladding to ambient and indoor interfaces respectively, ρ_a the air density, C_a the specific heat capacity of air and v_u is the volume flow rate of air through the channel per unit width of wall.

Normalised dynamic *U*-values based on the thermal resistances obtained from Eqs. (1) and (2) for standard wall constructions are compared in Fig. 3. They exclude tran-

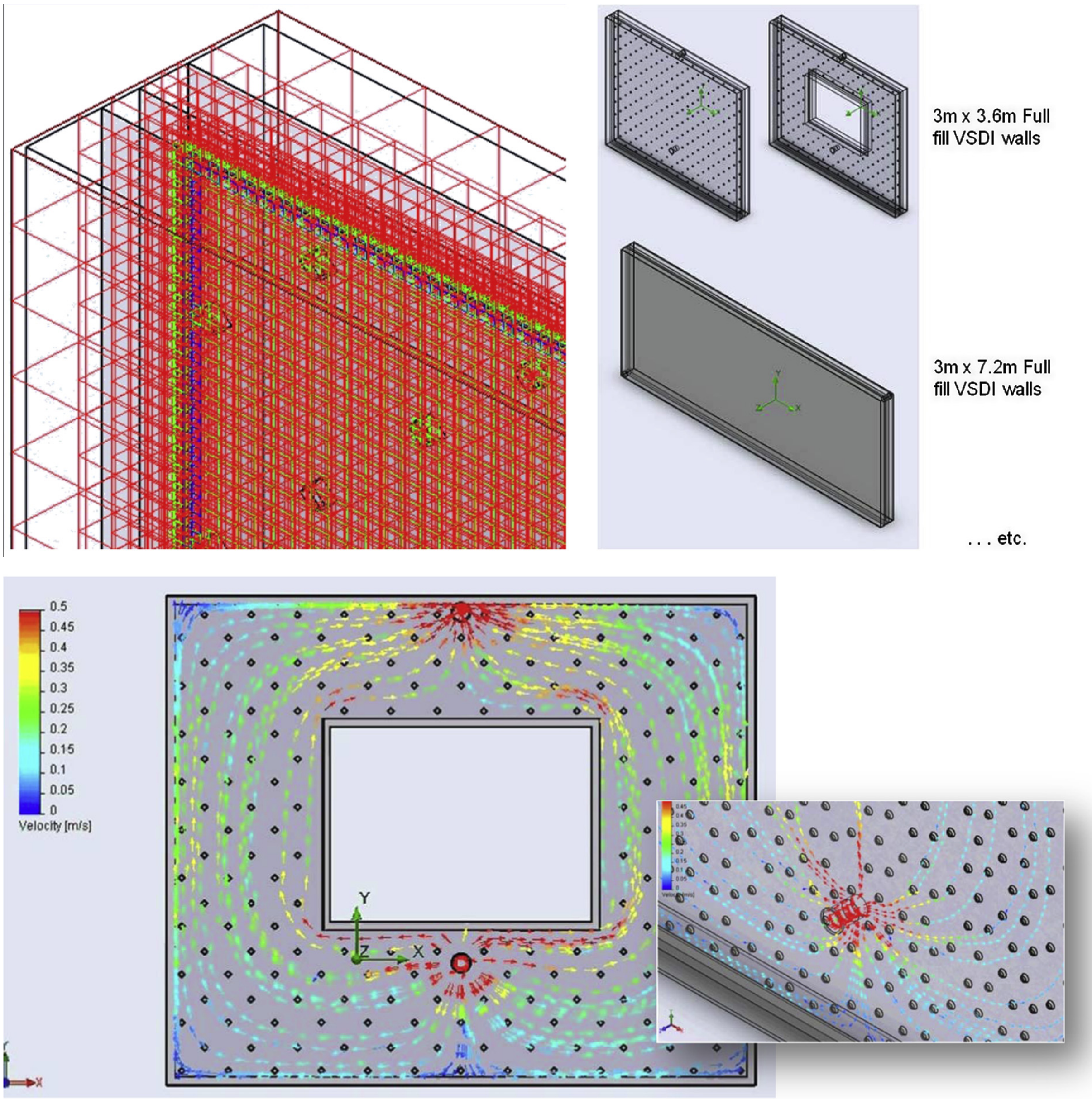

Fig. 5. VSDI wall models.

sient radiant or convective heat transfer and thermal inertia effects of the external and internal cladding materials. Eq. (2) also excludes the contribution of the air channel. They can be used to approximately evaluate the dynamic *U*-value of the wall construction under steady state conditions in the design. The 50% reduction in *U*-value at $v_a = 1$ l/m^{2}s for the parietodynamic case is roughly equal to a 50% reduction in conventional insulation material thickness required to achieve a comparable performance.

In order to analytically model transient response it is necessary to specify a dynamic *R*-value for the insulation layer on its own, thus permitting the inertial effects of the rest of the wall construction to be represented (if applicable) using any one of the several tried and tested methods the modeller wishes to use. Alternatively, an experimentally calibrated advanced conjugated computational fluid dynamic and heat transfer model may be used.

2.2. Void Space Dynamic Insulation

Void Space Dynamic Insulation (VSDI) is a new type of parietodynamic insulation in which the air flow is confined within a co-planar void space bounded by one or more layer(s) of insulation material and the wall structure. Thus, with VSDI any flat sheet insulation product can be readily and cost effectively used to dynamically insulate any building envelope or facade. A special VSDI fixing/air distribution component, which can be either separately or integrally installed, is used to form the co-planar void between the layer(s) of insulation.

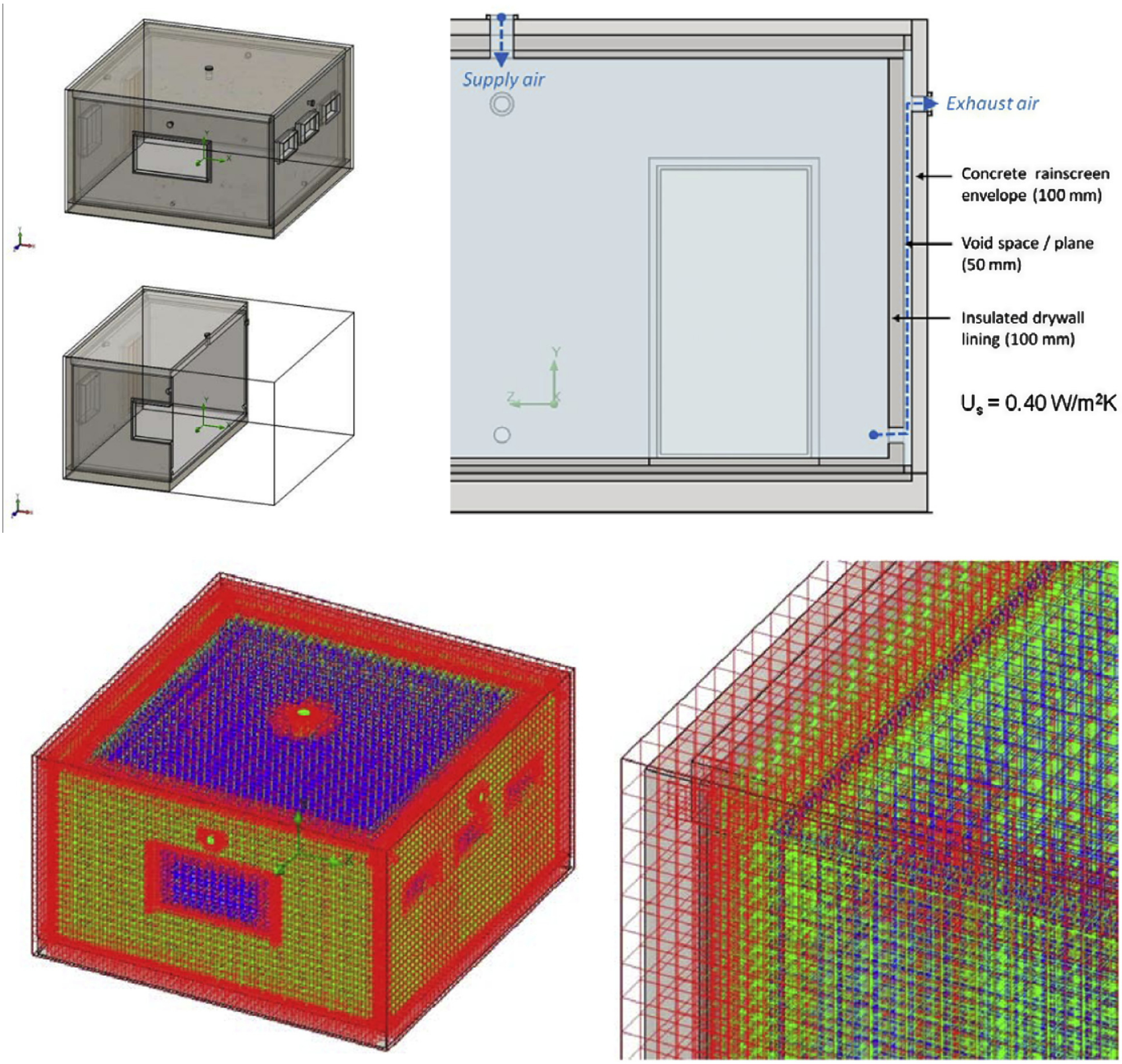

Fig. 6. Simple building model.

The basic concept is illustrated in Fig. 4 for a full-fill VSDI assembly employing a sheet-type spacer. Many other wall constructions and void spacer types exist to facilitate versatile deployment of the VSDI technology across the range of new and retrofit building applications.

There are a number of very important differences between VSDI and channel-type dynamic insulation products. The key features of VSDI are (a) uniform, bi-directional airflow through the entire wall area, (b) simple, robust installation, (c) low cost, and (d) its passive performance. These are unique features that allow full envelope coverage, and with it maximum energy efficiency and carbon reduction to be achieved at a minimum cost in all building types.

The VSDI concept and underpinning technology is under development, but early small-scale prototype tests have established the technical feasibility of the approach.

It is anticipated that full-scale field trials of internal wall and full-fill sandwich wall VSDI systems will be completed sometime in 2013.

3. Performance simulation of VSDI

This paper presents a sample of simulation results for different wall configurations – i.e., different wall sizes, walls with and without apertures (doors and windows), different inlet/outlet configurations, different climatic conditions and different spacer types. The paper also summarises the findings obtained from simulation of a small, single-zone building subjected to different ambient environments – i.e., cold versus hot, and different operating modes – i.e., active versus passive. Solidworks Flow Simulation (2010/11) was the simulation tool, configured to support dynamic

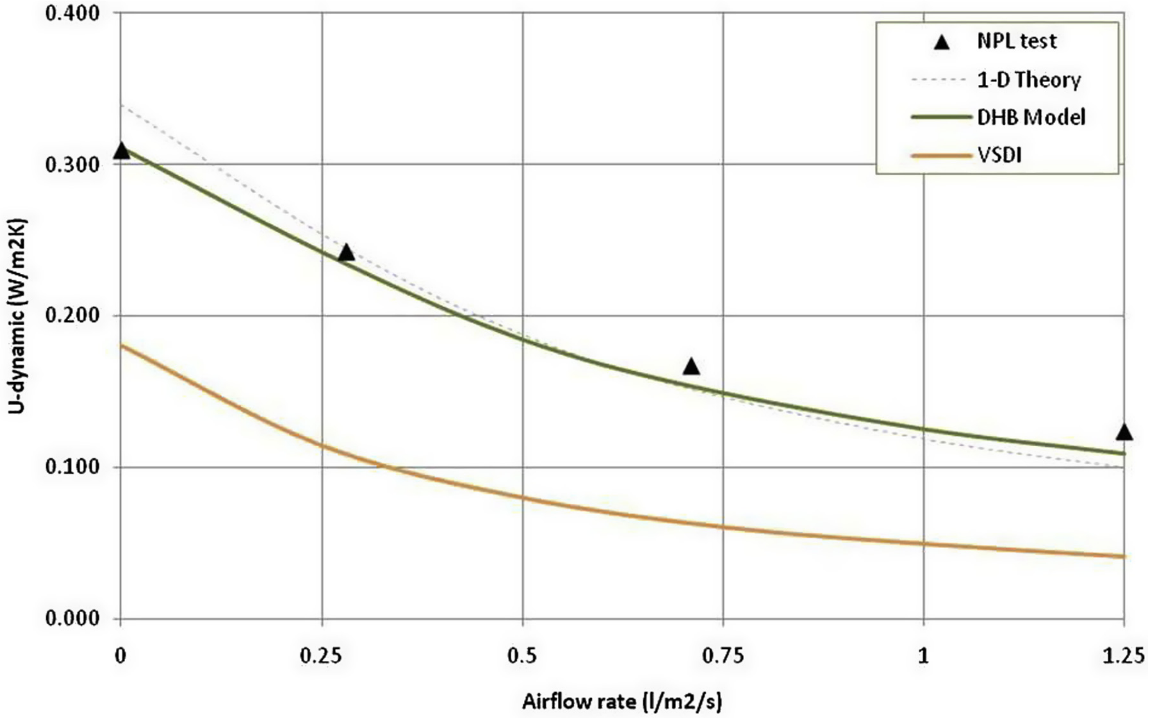

Fig. 7. Comparative results for dynamic U-value using NPL test results from (NPL, 2010).

turbulence modelling, radiant heat transfer and conduction through fluid and solid components. Realistic material and physical properties and thermal boundary conditions were used in the model.

This experimentally calibrated, conjugated computational fluid dynamic and heat transfer code was used in simulation. An example of the types of wall models evaluated using this code and the results showing uniform air flow through the void space is shown in Fig. 5.

A similar approach was used to produce a model of a small, square footprint building – a small flat-roofed house – comprising a single 5.0 × 5.0 × 2.6 m single zone (5.5 × 5.5 × 2.95 m external dimensions). Wall construction was 100 mm XPS insulated drywall + 50 mm void space + 100 mm concrete shell, resulting in a static *U*-value of 0.40 W/m^{2}K.

A better insulation material would produce a lower *U*-value, but for comparative evaluation the construction described will suffice. The 4 walls of the building included one with a door and window (east-facing far side), one with a single central window (north-facing front), one with three small windows (west-facing near side) and one with no windows exposed to 400 W/m^2 of incident solar radiation (south-facing back) – see Fig. 6 for the general layout.

Cold winter (20 °C inside, 0 °C outside) and hot summer (20 °C inside, 40 °C outside) scenarios were examined using the model. For simplicity, fresh tempered air was supplied in both cases via a mid-ceiling inlet vent to the indoor space and exhausted through the VSDI walls, although in practice fresh ventilation air would be supplied through the VSDI walls in the cold winter case to ensure against interstitial condensation. Energetically, the dynamic *U*-value is nearly the same in both supply and extract modes. In the active mode the air change rate was fixed at 0.5 ACH. In the passive mode it was free to find its own equilibrium.

4. Results

4.1. VSDI model calibration

The simulation code that was introduced in this paper was initially used to predict the performance of a 1.2 m × 1.2 m channel-type dynamic insulation sample moulded in EPS ($\lambda = 0.04$ W/mK) that was tested by the National Physical Laboratory (NPL) in 2010. With reference to Fig. 7, the empirical data shown were obtained at air flow rates of 0, 0.3, 0.7 and 1.25 l/m^{2}s using their Hot Box test facility after it had been modified to facilitate controlled air flow rates through the sample.

The solid green line is the performance of the sample predicted by the model and is in excellent agreement with both the measured and analytical performance (more so in the case of the former because of the 1-D limitations of the analytical model).

The solid yellow line is the simulated performance of a similar size VSDI sample made of phenolic foam ($\lambda = 0.022$ W/mK), reflecting the expected trend as a

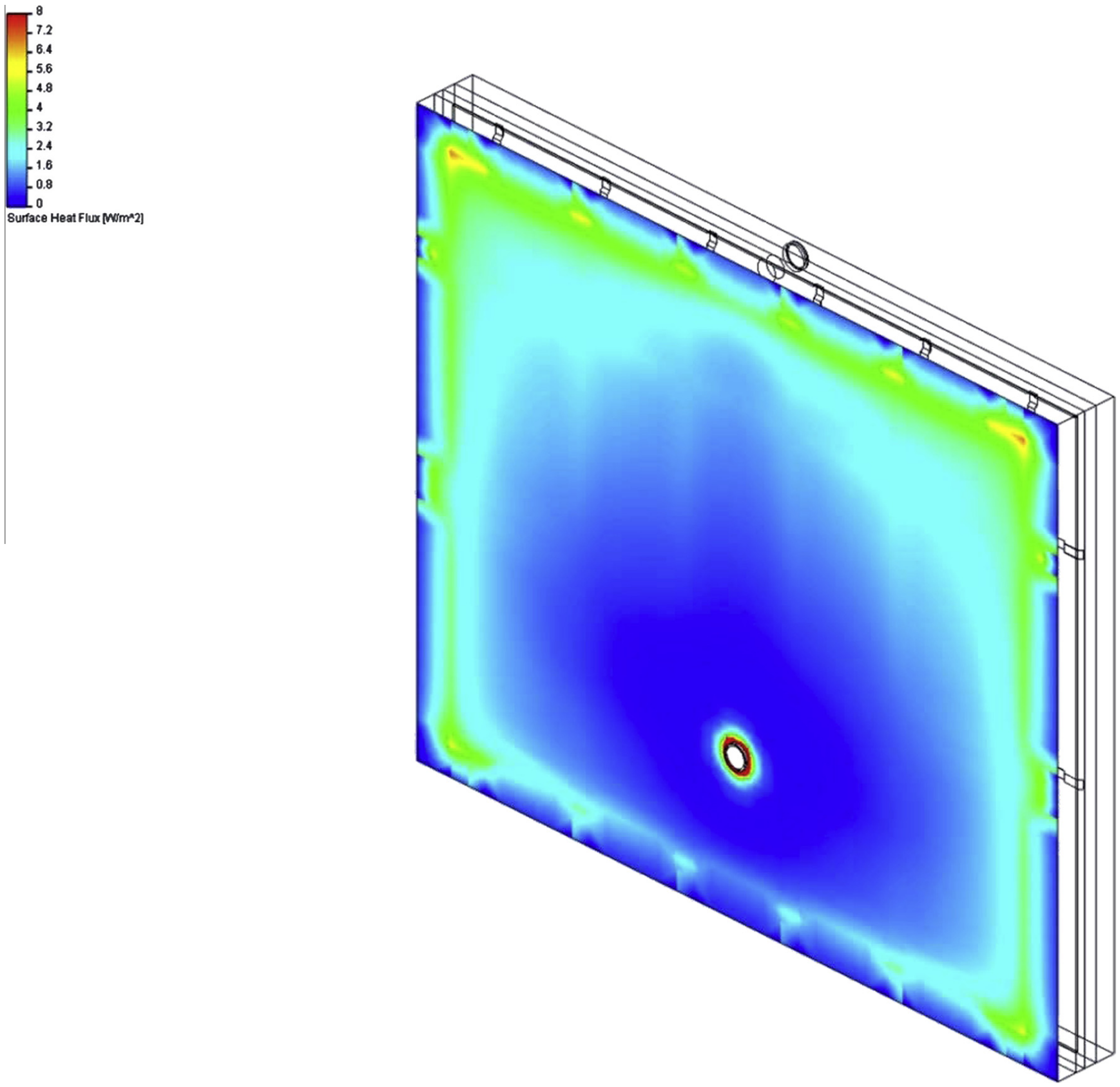

Fig. 8. Heat flux through a full-fill VSDI wall at $v_a = 0.5$ l/m^{2}s, $\delta T = 20$ °C.

function of air flow rate and the superior performance that can be achieved if better quality insulation is used.

4.2. *VSDI wall results (F3600 series)*

The heat flux lost through the external surface of a 3.6 m (w) × 3.0 m (h) × 325 mm (d) full-fill VSDI wall at an air flow of 0.5 l/m^{2}s, $\delta T = 20$°C, is shown in Fig. 8. The average dynamic *U*-value for this wall is 0.092 W/m^{2}K. The *U*-value of the same wall employing an equivalent unvoided thickness of insulation material ($\lambda = 0.022$ W/mK), in static ‘no airflow’ mode, is around 0.20 W/m2 K.

Detailed parametric analysis was used to investigate the effect of different wall sizes, aperture arrangements, void spacer types, void space depth, inlet/outlet locations, flow direction (supply or extract), ambient environment, etc., and to compare simulation model predictions against those obtained from the 1-D analytical model (the solid green line). In the case of the static baseline (the dashed red line) the *U*-value was calculated in accordance with BS EN ISO 6946.

In all the dynamic cases the air flow rate was fixed at a constant, steady-state value of 0.5 l//m^{2}s and the external inlet (or outlet in the extract mode) to the wall was always positioned lower than the outlet to (or inlet in the extract mode) the indoor space.

The results are summarised in the case of the F-3600 series (wall size 3.6 m × 3.0 m × 325 mm) in Fig. 9. From these results it is clear that:

- The lower dynamic *U*-values in the cold climate supply mode compared to the hot climate extract mode are due to the inlet/outlet vent locations, where in the former the air flow uniformity is enhanced by the buoyancy of the incoming air as it warms up and in the latter it is diminished by the same effect.
- The performance of the VSDI wall can be significantly enhanced by the correct choice of void spacer type.

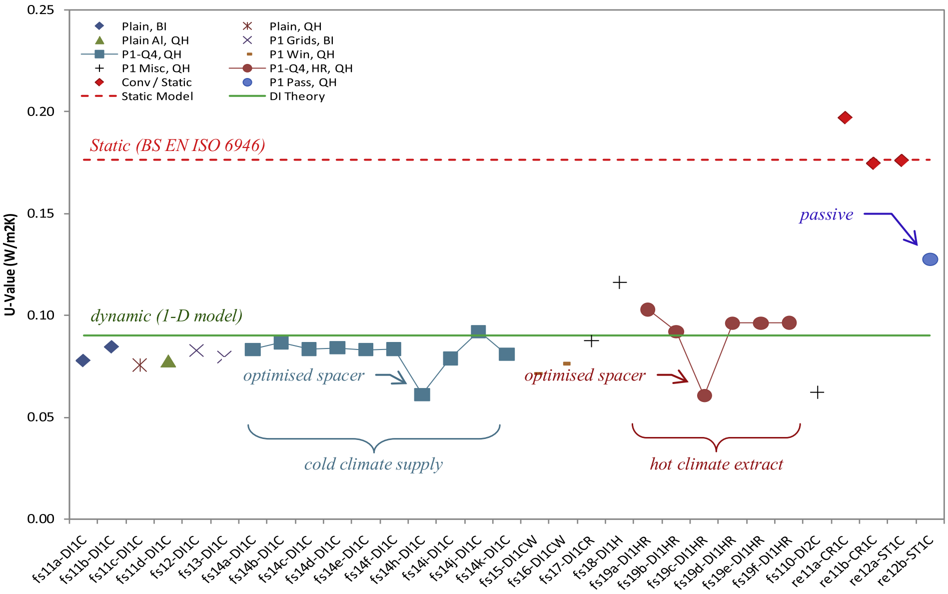

Fig. 9. FF-3600 series parametric analysis results.

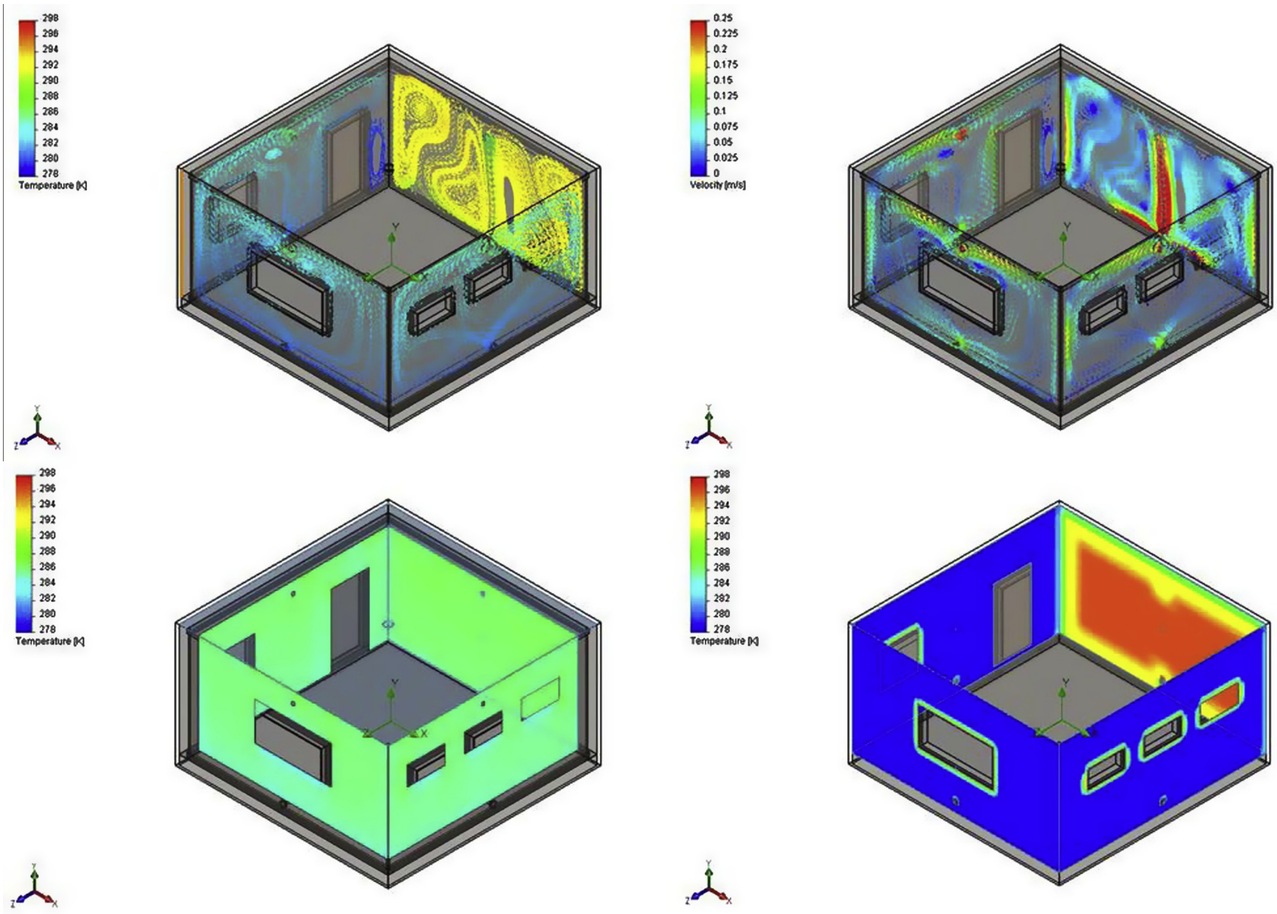

Fig. 10. Active simulation results for the cold winter case.

- The VSDI wall can perform in passive mode – not quite as good as the performance in the active mode for the case considered, which has not been optimised, but every bit as good as the active mode as revealed through a much more detailed investigation that, due to lack of space, will not be covered here.

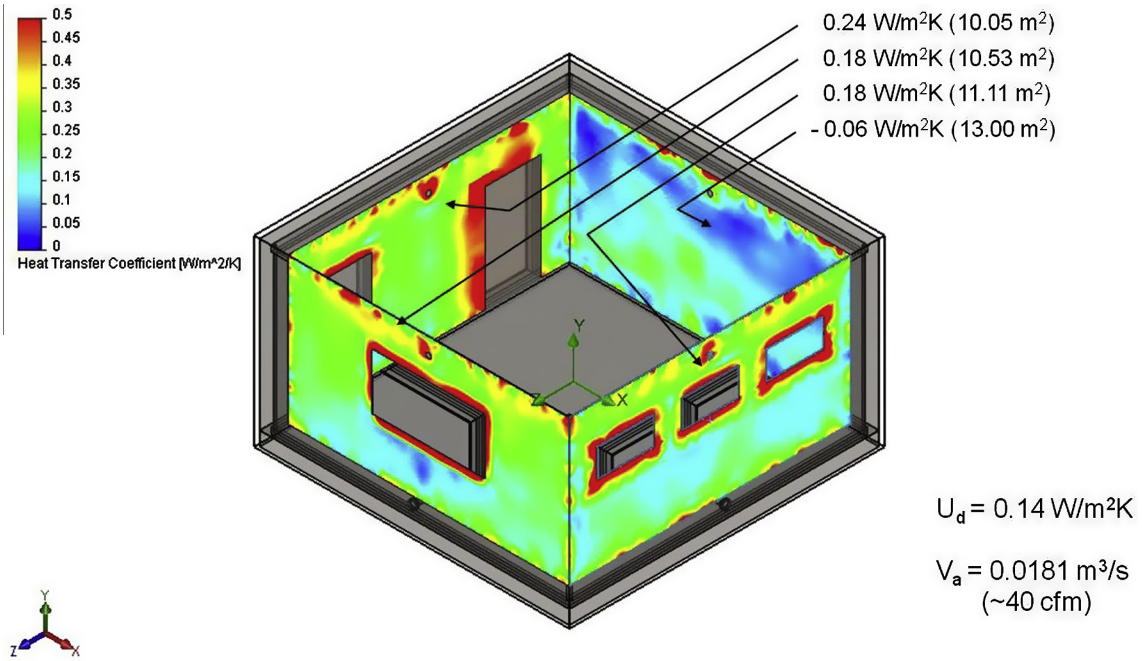

Fig. 11. Dynamic U-values in the active mode for the cold winter case.

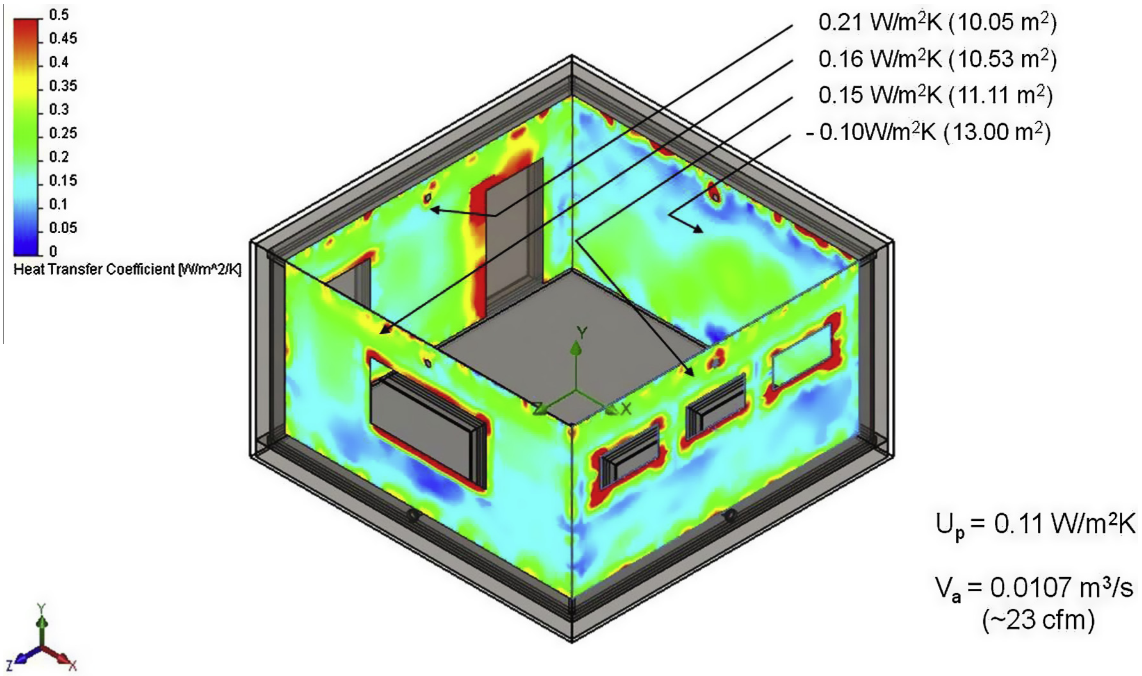

Fig. 12. Dynamic U-values in the passive mode for the cold winter case.

4.3. VSDI whole building results

In order to limit the volume of information that is presented in this paper to manageable proportions but at the same time to give a flavour of what one can expect to see when VSDI is applied to a whole building, the results in this section are separately presented in a dense graphical format for the cold season and the hot season cases.

For each case consideration is given to (first) active performance at 0.5 ACH, followed by passive performance at whatever equilibrium state is reached in simulation. In all cases it is a given fact that some heating (during the cold season) and cooling (during the hot season) energy is supplied to the building in the form of pre-tempered fresh air through the mid-ceiling vent. This was limited to 2 °C above and below the set point temperature of 20 °C for

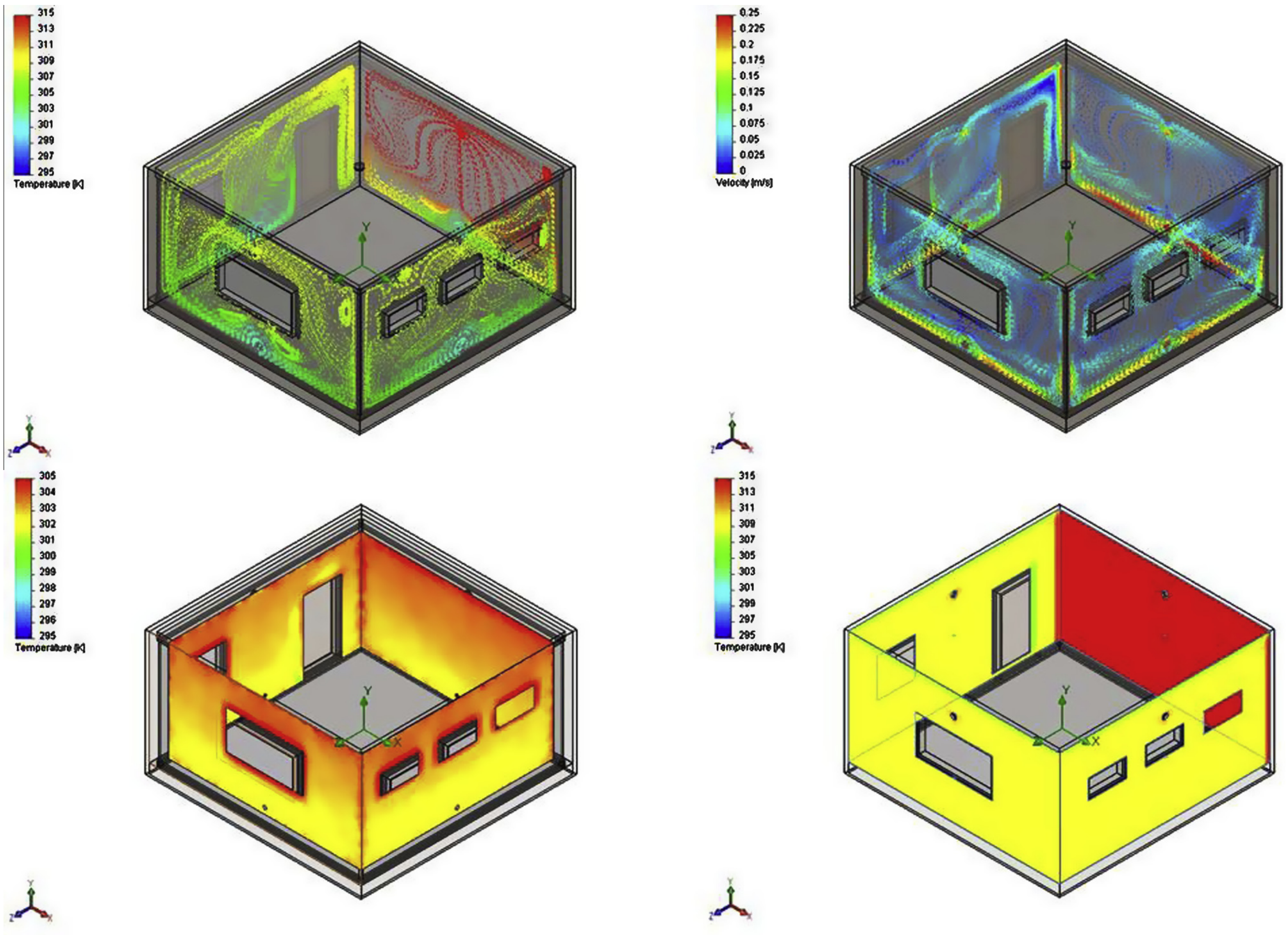

Fig. 13. Active simulation results for the hot summer case.

the cold and hot season simulation cases respectively. It was also assumed that the ground temperature below the building is higher than ambient in winter and lower in summer. No special effort was made to optimise inlet/outlet vent size and location, the type of void spacer used and the void space depth, nor was additional indoor heating or cooling introduced.

The resulting steady-state indoor environments do not comply with normal comfort conditions. It is important to note that the dynamic *U*-value *per se* is a function of air flow rate and not temperature difference; although in the passive case the air flow rate will increase with temperature difference.

4.3.1. Cold season results

Fig. 10 (clockwise from the top left hand corner) shows the temperature coded flow trajectories within the wall void spaces, velocity coded flow trajectories within the void spaces, external wall surface temperature contours and internal wall temperature contours.

In this case the warm exhaust air enters the wall close to the top and loses heat as it is pushed and falls through the void space. This effect is clear to see in the temperature coded flow trajectories, with the effect of solar radiation on the rear wall notably visible. The VSDI system will benefit from solar gain if operated in the supply mode (as opposed to the exhaust mode shown, with most of the heat captured in the supply air stream recovered to the building). The normalising effect of void space air flow is evident in the internal versus external wall surface temperatures.

Fig. 11 shows the average dynamic U-values (measured on the internal wall surfaces when it is warm inside, cold outside and the VSDI walls are operating in the active exhaust mode). The 'blotchy' variations in the dynamic *U*-value are due to the forced (active) nature of the flow, which clearly varies within the wall with red denoting zones of stagnation. The average dynamic *U*-value of 0.14 W/m^{2}K represents a 65% reduction compared to static *U*-value of 0.40 W/m^{2}K. Much of this is due to solar gain leakage at the rear wall.

Fig. 12 shows the average dynamic *U*-values (also measured on the internal wall surfaces when it is cool inside, hot outside and the VSDI walls are operating in the passive exhaust mode). The reduced 'blotchiness' is a feature of passive operation. The average dynamic *U*-value of 0.11 W/m^{2}K represents a 73% reduction compared to static *U*-value of 0.40 W/m^{2}K and is despite the 40% reduction in air flow to around 0.3 ACH. It is also possibly an artefact of solar gain on the rear wall. Further investigation is warranted.

4.3.2. Hot season results

Fig. 13 (clockwise from the top left hand corner) shows the temperature coded flow trajectories within the wall void spaces, velocity coded flow trajectories within the void spaces, external wall surface temperature contours and internal wall temperature contours.

In this case the cool exhaust air enters the wall close to the base and picks up heat as it is pushed and rises through the void space. This effect is clear to see in the temperature coded flow trajectories, with the effect of solar radiation on the rear wall clearly visible. The VSDI system will thus reduce significantly the sol–air temperature effect in such

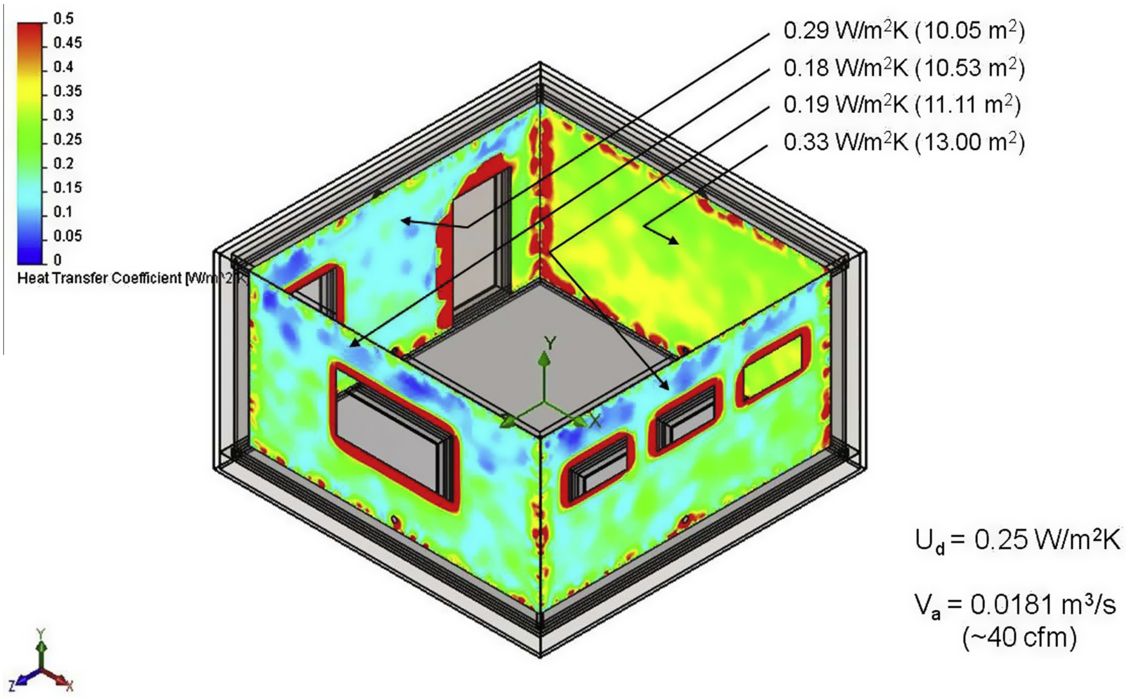

Fig. 14. Dynamic U-values in the active mode for the hot summer case.

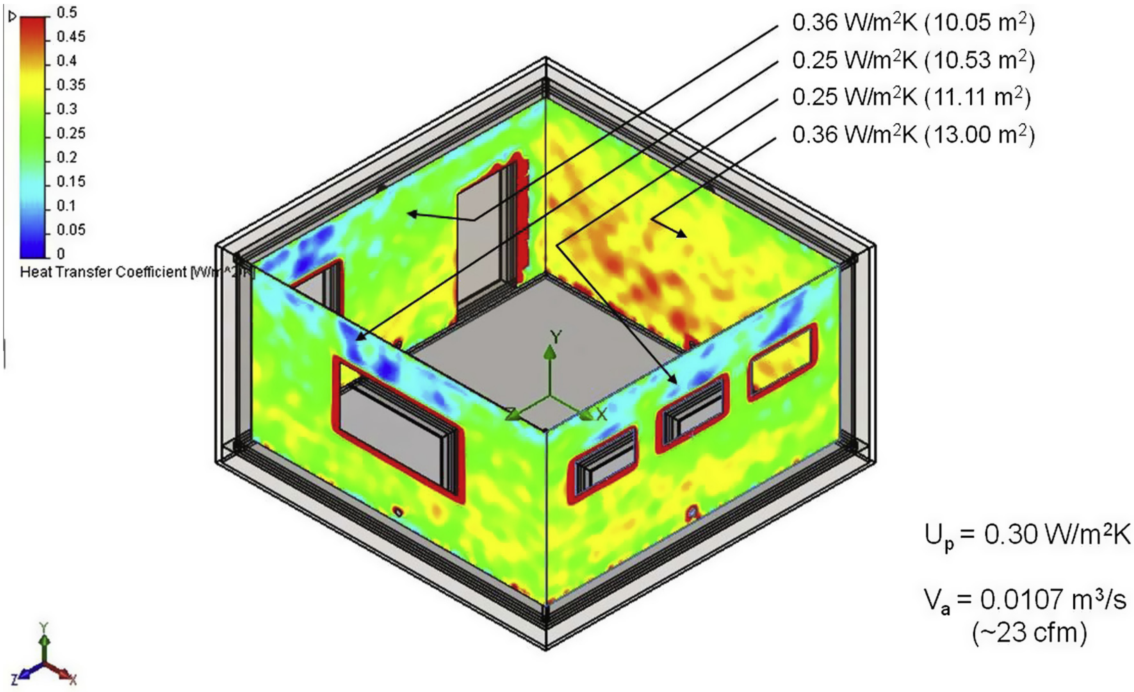

Fig. 15. Dynamic U-values in the passive mode for the hot summer case.

cases, with most of the heat expelled in the exhaust air stream from the building. The normalising effect of void space air flow is evident in the internal versus external wall surface temperatures.

Fig. 14 shows the average dynamic *U*-values (measured on the internal wall surfaces when it is cool inside, hot outside and the VSDI walls are operating in the active exhaust mode). The 'blotchy' variations in the dynamic *U*-value are due to the forced (active) nature of the flow, which clearly varies within the wall with red denoting zones of stagnation. What is also interesting is the front wall dynamic *U*-value, which is due to reduced flow along this wall. The imbalance is primarily due to the effect of solar radiation on the rear wall, which results in a higher void space air flows. Taken together, the average dynamic *U*-value of 0.25 W/m^2K represents a 38% reduction compared to the static *U*-value of 0.40 W/m^2K.

Fig. 15 shows the average dynamic *U*-values (also measured on the internal wall surfaces when it is cool inside, hot outside and the VSDI walls are operating in the passive exhaust mode). The reduced 'blotchiness' is a feature of passive operation. The average dynamic *U*-value of 0.30 W/m^2K represents a 25% reduction compared to the static U-value of 0.40 W/m^2K and is explained by the 40% reduction in air flow to around 0.3 ACH.

5. Conclusions

VSDI is a very compelling energy efficiency technology that works equally well in hot and cold climates.

The performance of VSDI in cold seasons can benefit significantly from solar gain. This is less so in hot seasons, where the effects of solar gain are mitigated to some extent.

Active and passive VSDI can provide order-of-magnitude reductions in building fabric energy use and carbon emissions.

Computer simulation results show that passive VSDI has promise, so further research, including full scale monitored building trials, is warranted.

VSDI should be very easy to implement in current building practice, to improve energy efficiency and gain valuable regulatory credits.

It can be used alone, as part of an active solution, or with passive, low energy and renewable technologies.

VSDI, which was conceived in the spirit of the Passive House Standard, is potentially the ideal solution for both new build and retrofit applications.

Further work to investigate and develop the use of VSDI in practice, at different locations and under different climatic conditions is underway.

Acknowledgement

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