THERMAL PERFORMANCE OF A RESIDENTIAL DYNAMIC WALL

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ABSTRACT

Results are presented from a numerical heat transfer analysis of a dynamic wall suitable for Canadian residential construction. The air-permeable dynamic wall acts as a heat exchanger between the building envelope and infiltrating air.

The objectives of this study were to assess the sensitivity of thermal performance to weather and design variables, recommend design options to enhance energy efficiency, and characterize the thermal performance of the recommended design.

The performance is seen to be insensitive to airflow rate, insulation thickness, and size of the air opening in the inner wall. However, the location of the air opening has a moderate impact. Good thermal contact between the solar absorbing surface and infiltrating air is recommended to capitalize on the passive solar qualities of the dynamic wall. Although the dynamic wall has the potential to reduce the heating load, simulation of all relevant heat transfer processes is required to estimate energy savings.

INTRODUCTION

Houses need to be ventilated with outdoor air to maintain acceptable indoor environments. Although some houses are ventilated with balanced mechanical systems, most rely upon natural ventilation or exhaust-only ventilation systems. With these latter ventilation schemes, air infiltrates through the building envelope at unintentional openings around the sill plate, plumbing stack, and electrical service entrance, between basement floor and footings, and through window and door cracks. Thermal coupling between envelope heat losses and infiltration is weak and unintentional—energy must be supplied to warm the air to room temperature. A large fraction of the energy consumed for space heating is used to heat ventilation air.

In current residential construction, efforts are taken to prevent air and moisture from flowing through insulated walls. Air barriers, vapor diffusion barriers, and weather barriers are utilized to guard against moisture damage and avert excess ventilation and the associated energy costs. Contrary to this, the design of the dynamic wall system encourages ventilation air to flow through the insulated walls. Dynamic walls are made intentionally porous; a negative pressure is created in the house with an exhaust fan, outdoor air enters the wall, flows through the insulation, and enters the living space. Heat is transferred from the wall to the incoming ventilation air—the air enters the living space at a warm temperature. Essentially, dynamic walls act as heat exchangers for the infiltrating air.

Although it has been claimed that the dynamic wall concept originated in Sweden during the late 1970s, an examination of the literature shows that dynamic wall research in the area of animal housing was conducted in Canada in the early 1960s (Milne 1962; Pattie 1966; Callen 1967). Notwithstanding the origin of the concept, Thorén (1982) postulated that the dynamic wall could reduce envelope heat losses while supplying preheated fresh air to a building.

Previous dynamic wall work has characterized the heat transfer and fluid flow processes (Lenat 1982; Anderlind and Johansson 1983; Langlais and Arquis 1987; Caruso 1988; Tassone 1989), confirmed that space-heating energy requirements can be reduced (Kuebler and Timusk 1990), and assessed the performance of some designs for Finnish weather conditions (Kohonen et al. 1985, 1987; Ojanen and Kohonen 1989; Ojanen 1991). To date, four Canadian dynamic wall houses have been monitored, two in Sarnia (BLP 1991), one in Edmonton (MacKay 1990), and one near Hanover, Ontario (Timusk et al. 1986; Timusk 1987; 1989a; 1989b; 1990; Kuebler and Timusk 1990).

Envelope walls in standard Canadian housing typically consist of cladding, weather barrier/sheathing, fibrous batt insulation in stud wall cavities, air barrier/vapor diffusion barrier, and gypsum board. There are two significant construction difference between the four Canadian dynamic wall houses and standard houses: orifices are placed in the gypsum board/air barrier and porous sheathing is used (Figure 1).

OBJECTIVES OF PRESENT STUDY

The present work pertains to designs of dynamic walls that could be suitable for Canadian residential construction, as described above. The first objective was to assess the sensitivity of the thermal performance to weather and design variables. The second objective was to recommend design details to enhance energy efficiency. The final objective was to accurately characterize the thermal performance of the recommended dynamic wall design. These objectives were met through numerical analysis.

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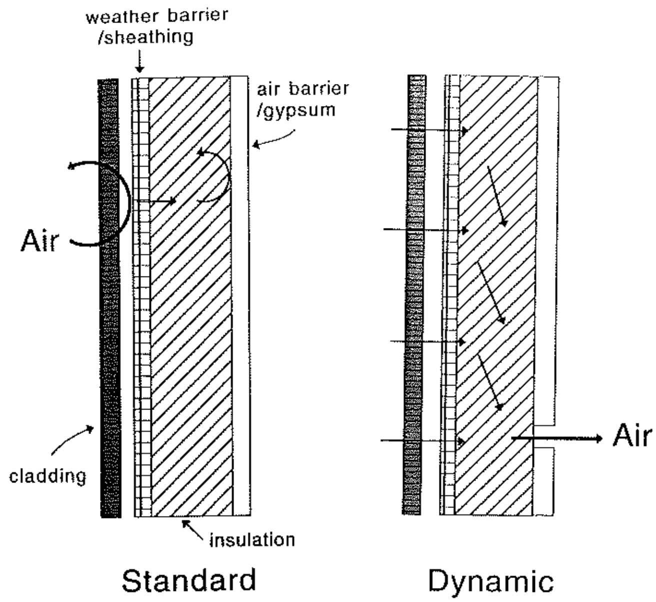

Figure 1 *Typical standard and dynamic walls.*

ANALYSIS

A computer model developed in Finland was used for the numerical analysis of dynamic walls. It is a general model for conducting hygrothermal analyses of residential building walls (Kohonen et al. 1985). It models two-dimensional heat, air, and moisture transport processes through multi-layered building envelopes. The transport equations are based on temperature, pressure, and water vapor pressure acting as driving potentials. Darcy's flow equation with Boussinesq approximation for incompressible fluids is used for convective flows. The balance equations are solved using a finite-difference technique. The model has been applied to numerous configurations including counterflow dynamic walls (Ojanen and Kohonen 1989; Ojanen 1991).

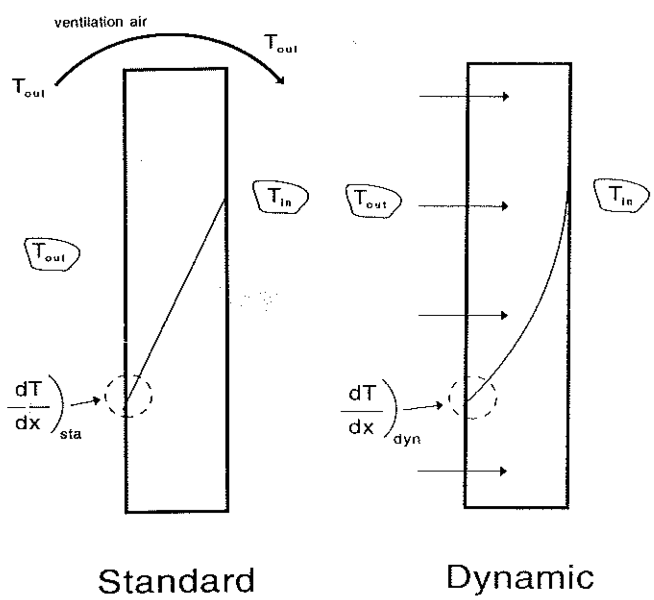

Figure 2 *Heat losses and temperature distributions in standard and dynamic walls.*

Cross sections of dynamic walls (infinitely long) were modeled. Corners, studs, and other three-dimensional effects were not included in the treatment. A DOS386 computer was used for the sensitivity analysis, which permitted 9 finite-difference nodes in the horizontal direction and 16 in the vertical direction (9 × 16 grid); with this coarse mesh, the wall cladding was not modeled. The recommended design was analyzed on a UNIX workstation with a 60 × 30 grid that allowed treatment of the cladding.

The program produces temperature, air velocity, and pressure fields. Post-processing of these results is then required to assess dynamic wall performance. The energy performance is characterized here by a dynamic wall efficiency, f (Langlais and Arquis [1987]), which represents the fraction of ventilation and wall transmission losses saved by *dynamic* action (Figure 2),

$$f = 1 - \frac{q_{dynamic}}{q_{standard}} =$$

$$1 - \frac{-k\left.\frac{\partial T}{\partial x}\right]_{dyn} + \frac{V_{air}}{A_{wall}}(\varrho C_p)_{air}\,(T_{in}-T_{out})}{-k\left.\frac{\partial T}{\partial x}\right]_{sta} + \frac{V_{air}}{A_{wall}}(\varrho C_p)_{air}\,(T_{in}-T_{out})},$$

where $q_{dynamic}$ is the heat loss (W/m^2), $q_{standard}$ is the heat loss for a hypothetical standard wall (W/m^2), $-k(\partial T/\partial x)_{dyn}$ is the heat flux from the outer surface (W/m^2), $-k(\partial T/\partial x)_{sta}$ is the heat flux from the outer surface of the hypothetical standard wall (W/m^2), V_{air} is the infiltration rate for the house (m^3/s), A_{wall} is the total dynamic wall surface area (m^2), (ϱC_p) is the product of density and specific heat for air (J/m^{3}K), T_{in} is indoor air temperature (K), and T_{out} is the outdoor air temperature (K).

The efficiency represents the reduction in heating load relative to a *hypothetical* standard wall (Figure 2). This hypothetical standard wall has no thermal coupling between transmission losses and ventilation; infiltrating air enters the living space at the outdoor temperature. Correlation to this hypothetical standard wall provides a basis for comparison and is not intended to represent *actual* standard walls in which there is some thermal coupling between envelope and infiltrating air.

RESULTS AND DISCUSSION

Sensitivity Analysis

The sensitivity of the following design parameters on dynamic wall performance was assessed: flow rate of air through the wall, insulation thickness, and location and size of openings in gypsum board. The weather variables that

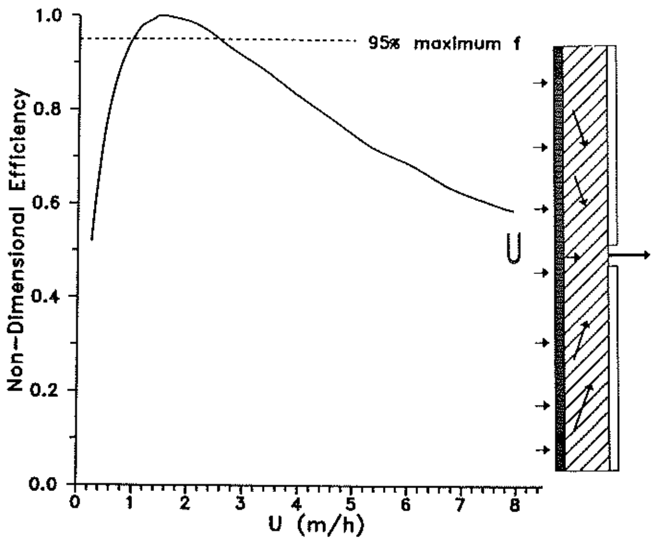

Figure 3 *Effect of infiltrating airflow rate on nondimensional efficiency.*

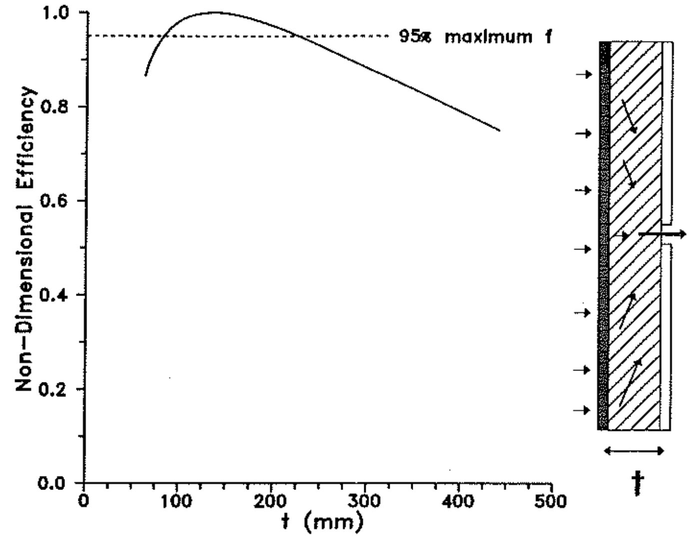

Figure 4 *Effect of insulation thickness (fiberglass) on nondimensional efficiency.*

were considered in the analysis were ambient temperature, air pressure, and absorbed solar irradiance.

More than 200 runs were performed with the 9 × 16 grid. Cross sections of a 2.5-m-high wall were modeled with the two-dimensional code. For each run, a single design parameter or weather variable was altered. The base values were as follows: 1 m/h airflow rate, 115 mm of insulation, 25 mm opening located at the mid-height, -10°C ambient temperature, no solar irradiance, and the air pressures acting on the inner and outer wall surfaces varied hydrostatically.

The results are presented in Figures 3 through 9. In these figures, the efficiencies have been normalized because the 9 × 16 runs did not produce grid-independent results. The maximum efficiency found for each design parameter and weather variable was used for the normalization. This nondimensional presentation illustrates the sensitivity to each of the design and weather variables.

As seen in Figure 3, the optimum mean airflow rate is 1.5 m/h. This corresponds very closely to the desired flow rate for typical house volumes, envelope areas, and ventilation rates. In the vicinity of this optimum point, efficiency is only mildly sensitive to airflow rate. For example, an 8 m × 10 m two-story house with full basement has approximately 150 m^2 of envelope area available for dynamic walls. For this house, 95% of maximum efficiency is achieved for 0.25 ach (1 m/h) to 0.6 ach (2.4 m/h).

Figure 4 shows the impact of insulation thickness on performance. Although there is an optimum value, 95% of maximum efficiency is achieved with 2 × 4 (89 mm insulation), 2 × 6 (140 mm insulation), and staggered 2 × 4 (180 mm insulation) stud walls.

The influence of the position of the opening in the gypsum board and air/vapor diffusion barrier is displayed in Figure 5. The opening location has an impact on airflow patterns within the wall and on the resulting thermal performance. However, although performance degrades as the opening is moved from the mid-height of the wall, 95% of maximum efficiency is achieved for any opening location between the one-quarter height and the three-quarters height.

The size of the opening is seen to have much less of an impact upon performance, as seen from Figure 6. Although efficiency increases with opening size, the difference between an opening of 5 mm and one of 500 mm is only 4%.

As shown in Figure 7, the impact of ambient temperature on efficiency is minor. Naturally, heating energy requirements increase as the ambient temperature drops; however, the performance relative to a standard wall remains approximately constant.

The performance of the dynamic wall is highly de-

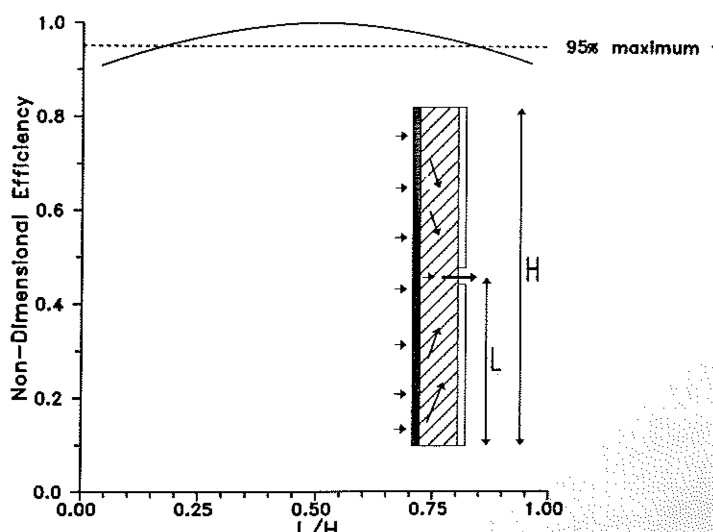

Figure 5 *Effect of opening location on nondimensional efficiency.*

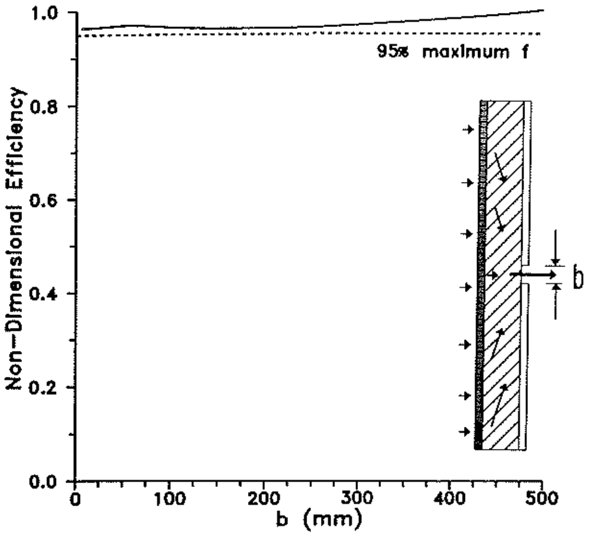

Figure 6 *Effect of opening size on nondimensional efficiency.*

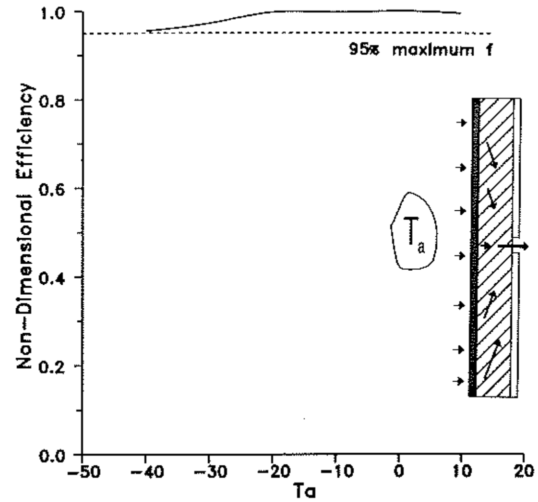

Figure 7 *Effect of outdoor temperature on nondimensional efficiency.*

pendent upon absorbed solar irradiance, as shown in Figure 8. Although this analysis assumes that the radiation is absorbed by the sheathing and not the cladding, it does indicate the importance of solar irradiance on thermal performance. Dynamic walls have the potential to act as passive solar collectors for ventilation air.

Airflow through the dynamic wall is driven by pressure gradients created by a number of factors including the house's exhaust-only ventilation system, wind loading, stack effects, thermal boundary layers, and indoor air movement. The aggregate behavior of these phenomena is not well understood, and this creates uncertainty in prescribing boundary conditions for finite-difference modeling. To assess the importance of pressure boundary conditions on thermal performance, two scenarios were modeled and the results are presented in Figure 9. The lower curve is for hydrostatic air pressure distributions, while the upper curve corresponds to a uniform airflow rate over the height of the wall. As thermal coupling is maximized when the air flows uniformly over the height of the wall, the latter case represents an upper bound on performance. The former case results in higher airflow rates in the vicinity of the opening. This scenario does not reflect real conditions perfectly but does give a more representative estimate of thermal performance. The effect of boundary layers surrounding dynamic walls is an area that should be addressed in future research due to the impact upon performance.

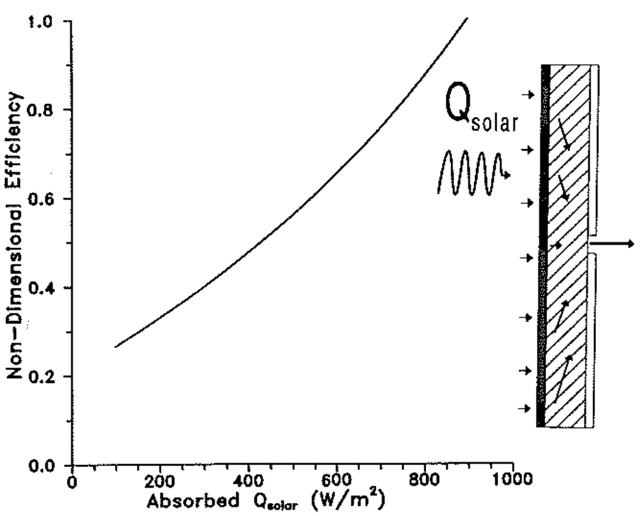

Figure 8 *Effect of absorbed solar irradiance on nondimensional efficiency.*

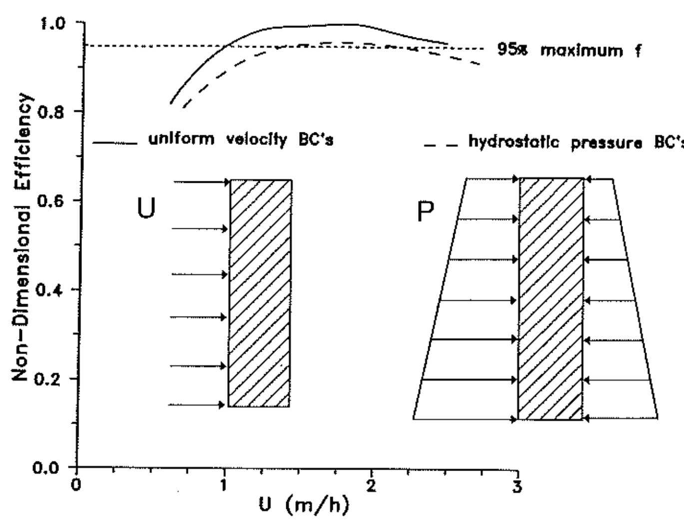

Figure 9 *Effect of air pressure boundary conditions on nondimensional efficiency.*

Design Recommendations

The sensitivity analysis showed that 95% of the optimum efficiency can be achieved for all ventilation rates and envelope insulation thicknesses of interest. Thus, no special attention needs to be given to airflow rates or insulation thickness when designing dynamic walls for typical Canadian housing.

Since the location of the opening was seen to have a moderate impact, it should be placed as close as possible to the mid-height of the wall. Although not evaluated, multiple openings over the height of the wall would likely produce acceptable performance as well. However, this design would be more obtrusive. Furthermore, as the size of the opening had little effect, very small openings could be used, as they deliver acceptable performance while being less conspicuous.

The sensitivity analysis showed that performance was augmented by absorption of solar radiation. To exploit the passive solar potential of the dynamic wall, a porous cladding is ideal since it maximizes the transfer of absorbed solar energy to the infiltrating air.

Thermal Performance of Recommended Design

The thermal performance of a dynamic wall, consistent with current construction practices and the recommendations of the previous section, was assessed with the computer model using a 60 × 30 finite-difference grid. The wall design, as depicted in Figure 10, was as follows: 2.5-m high, 25-mm wood siding, 25-mm air space, 12-mm porous wood sheathing, 140-mm glass fiber insulation, and 12-mm gypsum board with a 25 mm opening located at mid-height. The average airflow rate was 1.2 m/h, corresponding to 0.3 ach for an 8 m × 10 m two-story house with full basement and all envelope walls dynamic except 30 m^2 for windows and doors. The ambient temperature was −10°C and hydrostatic air pressure boundary conditions were assumed.

Figure 11 shows the relationship between the efficiency of this dynamic wall and solar absorption on the cladding. The efficiency depends strongly upon the incident direct, diffuse, and ground-reflected solar radiation and upon the solar absorptivity of the cladding surface.

Under favorable solar conditions (1000 W/m^2 direct, sky diffuse, and ground-reflected solar radiation), a south-facing, white glossy painted (solar absorptivity = 0.26) dynamic wall has an efficiency of 36%, whereas for a black-painted (solar absorptivity = 0.98) wall it is 95%. An east- or west-facing wall has a maximum efficiency of 31% (800 W/m^2 irradiance) if it is painted glossy white and 79% if it is black. For a north-facing wall, the highest efficiency is 21% (400 W/m^2 irradiance) for glossy white paint and 47% for black paint. The efficiency for all cladding colors and orientations is 13.6% if there is no solar radiation.

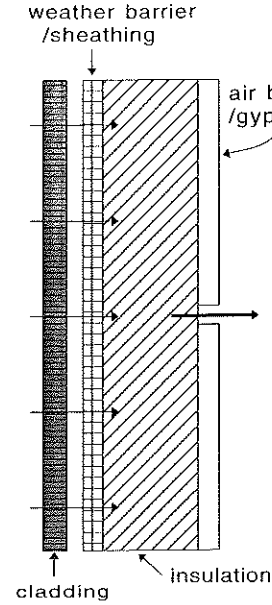

Figure 10 Selected dynamic wall design.

As a measure of energy-saving potential, the efficiency equals the fraction of ventilation and wall transmission heat losses saved relative to a hypothetical standard wall. Since these two components can represent half of the space-heating demand of a house, the efficiencies reported above can represent significant heating-load reductions. However, consideration of the following two points is imperative in interpreting these data. First, the efficiency compares the dynamic wall to a hypothetical standard wall in which there is no thermal coupling between infiltration and wall transmission losses and in which sol-air effects are neglected; the envelope walls in real houses perform better than this reference hypothetical wall. Second, in sunny conditions,

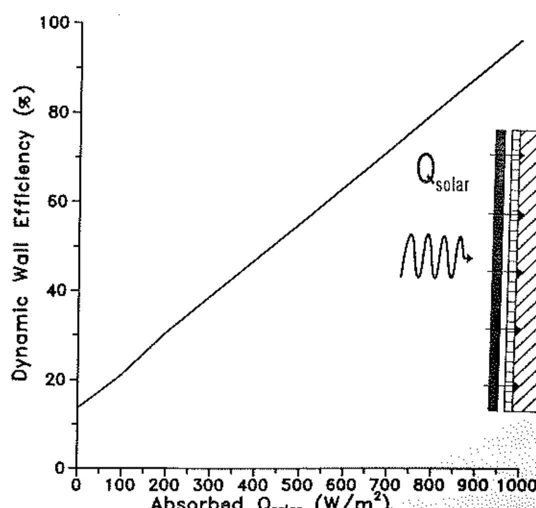

Figure 11 Effect of absorbed solar irradiance on dynamic wall efficiency for selected design.

the reduction in heating load, affected by dynamic walls, coincides with a low heating load due to direct solar gains through windows. Therefore, the passive solar potential of the dynamic wall may not be fully exploitable.

CONCLUDING REMARKS

Near optimum thermal performance of dynamic walls can be achieved for all ventilation rates and envelope insulation thicknesses of interest for typical Canadian residential applications. The size of the orifice in the inner wall is inconsequential, while placement has a moderate impact. Maximizing solar absorption can greatly enhance thermal performance. These factors should be considered in the design of residential dynamic walls.

Ambient air temperature has little affect on efficiency, but detailed knowledge of conditions in air boundaries surrounding the wall is extremely important. Future research and modeling of dynamic walls should consider these points.

Although the dynamic wall may be able to significantly reduce the heating load during sunny conditions, coincidence with direct solar gains through windows may negate some of the passive solar benefits. Energy simulation of a dynamic wall house is necessary to assess the net impact upon energy consumption.

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