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DESIGN, CONSTRUCTION AND PERFORMANCE OF A DYNAMIC WALL HOUSE

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SYNOPSIS

The construction and performance of a dynamic wall house are described. It is suggested that such houses function much like the traditional houses with leaky walls and active chimneys. Only here ventilation is controlled while a significant part of the energy required to heat the ventilation air can be recovered from part of the conducted heat which would otherwise be lost. A model is proposed to explain how such walls function at relatively low ventilation rates. This approach promises to improve indoor air quality and thermal envelope performance at reduced construction and energy costs.

1. OLDER HOUSES

Older houses were virtually free from indoor air quality and moisture problems because of the combination of a relatively leaky thermal envelope and an active chimney. The volume of air moved through the house was more than adequate to dilute moisture and contaminants from the building interior. Not only was much of the spent air exhausted harmlessly through the chimney, but also the resulting depressurization counteracted positive pressures due to stack and wind to reduce exfiltration through the envelope and associated concealed condensation in walls and attic space.

The raising of the neutral pressure plane by the active chimney also led to infiltration through a larger portion of the thermal envelope, assuring a supply of ventilation air to all of the rooms with exterior walls. In a cold climate, such as that in Canada, low indoor relative humidity was the heating season indoor air quality problem.

The major drawback of the above approach was of course excessive energy consumption: heat could not be recovered from the spent air which was exhausted through the chimney and which exfiltrated through the thermal envelope. Also, the process was largely uncontrolled because total leakage opening area, leakage opening distribution and the pressure across the envelope to drive air leakage were not controlled.

In summary, older houses performed well with respect to air quality and moisture problems because the active chimney exhausted spent air, imposing in the process a negative pressure on the enclosure. They could be classified as negative-pressure houses.

2. THE NEGATIVE PRESSURE HOUSE

The shortcomings of the chimney-vented, leaky house can be largely avoided if the following is done.

1. The chimney is replaced with an exhaust fan. The fan can now be operated as needed, exhausting air at a controlled rate. Heat from the exhaust air can, in turn, be recovered with a heat pump. If the recovered heat is transferred to domestic hot water, the efficiency of the heat pump is improved because heat is recovered from the air stream which is at room temperature. Continuous operation of the ventilation system is now virtually guaranteed as ventilation is coupled to domestic hot water, which is a necessity.

2. The total envelope leakage area is controlled. Exfiltration can be completely eliminated if the envelope is made sufficiently airtight so that the negative pressure arising from the exhaust of spent air at the prescribed ventilation rate overpowers positive pressures due to wind and stack action.

When air-to-air heat exchangers are used, heat can only be recovered from air exhausted through it. Here the building enclosures have to be built airtight since heat cannot be recovered from exfiltrating air. Wind, stack and unbalanced fan pressures drive such exfiltration.

In the exhaust-only approach, on the other hand, pressure is controlled, which means that all of the air leakage openings need not be eliminated. As long as the exhaust rate is sufficient to overpower positive wind and stack pressures, no heat is lost with exfiltrating air. Moisture damage due to the condensation of moisture from exfiltrating air can also not occur. Performance now becomes less dependent on workmanship.

3. Air leakage openings are uniformly distributed. This way ventilation air is supplied uniformly through all of the walls, provided that pressure distribution across the walls is also reasonably uniform. As room volume is more or less proportional to extrior wall area, the air change rate in all the rooms then tends to become uniform. In other words, ventilation air is evenly distributed throughout the house without having to resort to an internal air circulation system.

An air barrier made with an air-permeable membrane will make it possible to minimize air leakage through larger openings while providing a controlled flow over the entire air barrier.

4. The wall is built as a dynamic wall. Once the above three requirements have been satisfied, it is a relatively simple matter to build a wall which also acts as a heat exchanger, transferring conducted heat entering the wall to the incoming ventilation air stream. In the following the heat and mass transfer mechanisms in a dynamic wall will be considered.

3. THE DYNAMIC WALL

The dynamic insulation and wall concepts are not new. They were first proposed in Sweden by Torgny Thoren[1]. The possibilities of recovering conducted heat to preheat ventilation air, to capture solar heat, to control moisture damage and to improve indoor air quality were recognized. An experimental dynamic wall house was also built in Sweden in 1978 but "in spite of good indoor climate the energy goals were not satisfied."[2] In a theoretical treatment of heat and mass transfer through dynamic insulation Anderlind and Johansson developed a heat transfer model where the temperature gradient in dynamic insulation becomes curved and where the overall wall temperature is lowered.[3]

It often happens that new concepts have to wait for the development of new materials before they can be put into practice. This appears to be the case with dynamic insulation; a material had to be developed which makes it possible to provide the required control of air entering the dynamic insulation. It has to, however, be added and that it is still not generally understood how such walls actually function.

The author's work on dynamic insulation came about as an afterthought. Earlier work on moisture problems had suggested that relatively minor changes to the design of wood frame house walls could significantly improve their performance. For example, by locating a moisture-permeable air barrier on the outer face of the wall insulation, it becomes easier to install and to inspect because it is not penetrated by partition walls, joist assemblies and electrical wires. The exterior air barrier will also prevent wind from blowing through air permeable insulation and, in the process, cooling the wall. Also, a more uniform room-side wall surface temperature would result if insulating sheathing is used to blunt the thermal bridges formed by the framing members.

The introduction to the market of a spunbonded polyolephin (SBPO) sheet-covered glass fibre insulating sheathing board and special tape for joining the boards to each other and to window and door frame made it practical to evaluate the above concept in a house the author was building. The SBPO membrane is for all practical purposes air and watertight, yet sufficiently water vapour permeable so that it can be located on the cold side of the insulation. Its air permeability is of just the right magnitude required for the air flow control membrane of a dynamic wall.

Air leakage tests conducted on the partially completed house a year after the building had been closed in showed that not only did the house with the SBPO air barrier for its walls meet the Canadian R-2000 Low Energy housing program envelope airtightness requirements, but the thermal envelope was sufficiently air permeable to allow all the ASHRAE Standard 62-81 and the Canadian R-2000 specified ventilation air to be drawn in uniformly through the building walls at a moderate negative pressure of about 10 Pa.

Calculation indicated that of the 1.56 air changes per hour at 50 Pa, 0.9 ACH was through the SBPO membrane. In effect, more than half of the air infiltration was by diffusion through the air barrier, which is an essential feature of a dynamic wall. The walls were then completed as dynamic walls.

Before the house wall designs and performance results are presented, an attempt will be made to examine the heat and mass transfer process in such a wall. The model presented here is limited to a narrow set of conditions and is tentative at best. Much needs to be done to completely model the process. In the meanwhile, it is presented to encourage critical discussion.

4. THE HEAT AND MASS TRANSFER MODEL

The purpose of the following is to examine the effect of an air stream moving through glass fibre insulation in a sense opposite to that of heat flow on wall temperature distribution and the associated energy balance. Of these the former has to do with the physical performance of the wall and the associated thermal confort while the latter concerns energy saving possibilities.

A rather narrow set of conditions will be dealt with: where outdoor and room temperature remain constant, where solar radiation is negligible and where the rate of air movement through the wall is equal to or less than the optimum rate. Optimum is with reference to a conventional no-air-flow or "static" wall, where the rate of heat flow into the dynamic wall is equal to that of the static wall. In other words, it is proposed that at low air flow rates the temperature gradient of a dynamic wall is the same as that of its "static" counterpart.

If the temperature gradient through the walls remains unchanged, so does the rate at which heat is transferred through the wall by radiation and by conduction through the solid components of the wall. In the case of glass fibre insulation, the amount of heat conducted through the fibres is very small because the majority of fibres are oriented in a direction parallel to the plane of the wall.

Heat transport through the still air between the fibres of the insulation can be examined on the molecular level. As a result of random molecular motion molecules moving toward the cold side of the wall generally carry more kinetic energy than those moving toward the warm side; the net velocity in still air is however zero.

The ability of a gas to transfer heat, expressed by its coefficient of thermal conductivity, depends on the specific heat of its molecules, the mass density of the gas, the average velocity of its molecules and the mean free path between collisions. To see how this process can be stalled, one can picture molecule 1 of the gas move through one mean free path in the direction of the temperature gradient and collide with molecule 2 and in the process transfer its energy to molecule 2. In a static wall this molecule-to-molecule transfer process would continue until the heat carried per molecule has traversed the thickness of insulation.

If a flux of air is moved through the insulation in a direction opposite to heat transfer so that when molecule 1 has transferred its energy to molecule 2, molecule 2 is moved with the flux of air to the position originally occupied by molecule 1. After a sufficient number of repetitions of this process molecule 2 will emerge from the warm side of the insulation, having moved in steps of one mean free path, acquiring additional energy from molecule 1 at the end of each move. In effect, all the heat entering the wall and transmitted by conduction through the still air is used to heat the incoming air so that its temperature follows the static wall temperature gradient.

In the above heat and mass transfer process the mechanisms by which heat is transferred in the gas has not changed; only now it is occurring within a moving air mass. The only effect the glass fibres have on the process is to avoid the formation of convective loops in the air stream. There is no transfer of heat from the fibres to the air or vice versa as their temperatures do not differ at any point within the insulation.

It could be argued that only a very small increase in the slope of the temperature gradient through the air film and the gypsum wall board would be sufficient to result in a relatively large increase in the rate at which heat enters the wall. This could however not occur since there would be nowhere for the additional heat to go once the insulation is reached. The slope of the remaining part of the temperature gradient through the insulation would have been decreased so that the rate of radiant and conductive heat trnsfer through the glass fibres would be decreased. The incoming air could not absorb any of the extra heat because it is already at the interface temperature. Nor could the rate at which heat is conducted through the air be increased because it is fixed by the coefficient of thermal conductivity of air.

As the temperature gradient has not changed, then the rate of conductive heat flow through the glass fibres and the rate of radiant heat transfer will not have changed. As far as the rate of heat leaving the wall is concerned, the wall behaves as if the k-value of the insulation had been decreased by 0.025 W/mK, the value for still air. The rate at which heat enters the wall will still be indicated by the conventional k-value of the insulation.

What has been described above is a 100 per cent efficient heat exchanger. It has no solid component and film resistances to retard heat transfer from one working fluid to another. The role of the glass fibres is passive: to assure laminar air flow and to resist radiant heat transfer.

4.1 The Optimum Air Flow Velocity

Optimum velocity is defined here as the velocity of ventilation air through the insulation at which all the heat conducted through the still air in static insulation is transferred to the ventilation air.

The heat transferred through the still-air phase in our wall comprising glass fibres insulation only is given by:

$$Q = (k/d)\ A\ (t_i - t_o) \qquad (1)$$

where

Q = conductive heat flow rate through air in the insulation, W
k = coefficient of thermal conductivity of still air, 0.025 W/mK
d = thickness of insulating layer, m
t_i = temperature at the insulation-wall board interface, °C
t_o = temperature at the outside surface of the insulation, °C

The rate at which heat has to be supplied to the incoming air stream to heat it from t_o to t_i is given by:

$$Q = q\ \rho\ c_p\ (t_i - t_o) \qquad (2)$$

where

Q = rate of heat absorption by the incoming air to heat it by $(t_i - t_o)$, W
q = rate of air flow through the wall, m^3/s
ρ = density of air, kg/m^3
c_p = specific heat of dry air, J/kg.

At the optimum rate the still air component of the conductive heat flow entering the wall is equal to the rate of heat supply to the incoming air mass to heat it to inside temperature. Equating the two equations yields the equation for dynamic air flow:

$$q = (k/\rho\ c_p)\ .\ (A/d) \qquad (3)$$

This equation gives the optimum or maximum "free" ventilation rate in cubic metres per second. Even in the idealized model this ventilation air is not quite free in that it enters the room at the insulation/wall-board interface temperature. Purchased heat would have to be spent to bring it to room temperature. The first term in brackets gives the diffusivity of air while the second term relates to the physical dimensions of the wall. At ventilation rates which are equal to or less than q, the temperature gradient remains linear, there is no cooling of the wall surface and the ventilation air enters at the insulation-wall board interface temperature. As expected, the temperature difference across the insulation does not appear in Equation 3.

When the optimum rate is exceeded, the rate at which heat can be transferred through air is not sufficient to heat up the air to the static wall temperature gradient. The wall surface now becomes cooled while the air stream also starts to absorb some of the radiant heat. Eventually the temperature gradient at the exterior face of the insulation becomes horizontal, indicating that no heat, radiant or conducted, escapes from the wall. While such flow rates could be justified because of the energy conserved, the associated cooling of the wall surfaces may not be acceptable.

The above is in agreement with measured temperature gradients by Jönsson and presented by Anderlind and Johansson[3]. Here at the lowest ventilation rate of 1.1 cubic metres per hour for a 150 mm thick layer of insulation the temperature gradient has become nearly linear, even though this rate is still more than twice the optimum value according to Equation 3.

5. DYNAMIC WALL DESIGN

According to Equation 3 the choice of variables is rather limited. Wall area is fixed by other considerations which leaves the thickness of insulation and the choice of dynamic air flow rate to the discretion of the designer and of these only one is an independent variable.

In the case of the author's house, the thickness of insulation was established by the thickness of framing lumber and the decision to use insulating sheathing. With a wall area of 138 m^2 and 127 mm of insulation the optimum flow rate would yield 0.26 ACH whereas the specified rate is 0.46 ACH. This would result in energy savings of 2240 kWh in a climate with a 4350 k-day heating requirement.

The above suggests that relatively little additional expenditure to build a dynamic wall can be justified purely on financial grounds. Tradeoffs such as the elimination of internal air circulation systems, additional energy recovery from solar radiation and exhaust-air heat recovery could change this.

6. PERFORMANCE EVALUATION OF THE DYNAMIC WALL HOUSE

6.1 House Details

The two-storey wood frame house faces south and is surrounded by open fields. Except for some shielding provided by a sparse pine hedge on the east side and one some distance away from the house on the west side, the house can be considered to be located in open terrain.

An expanded section through the wall, in Figure 1, shows the wall construction. It comprises: 12.5 mm gypsum board, 0.05 mm vapour retarder, 38 x 89 mm wood-frame wall filled with glass fibre batt insulation, 38 mm glass fibre insulating sheathing covered with a SBPO air barrier and 25 x 200 mm rough-sawn pine board and batten siding.

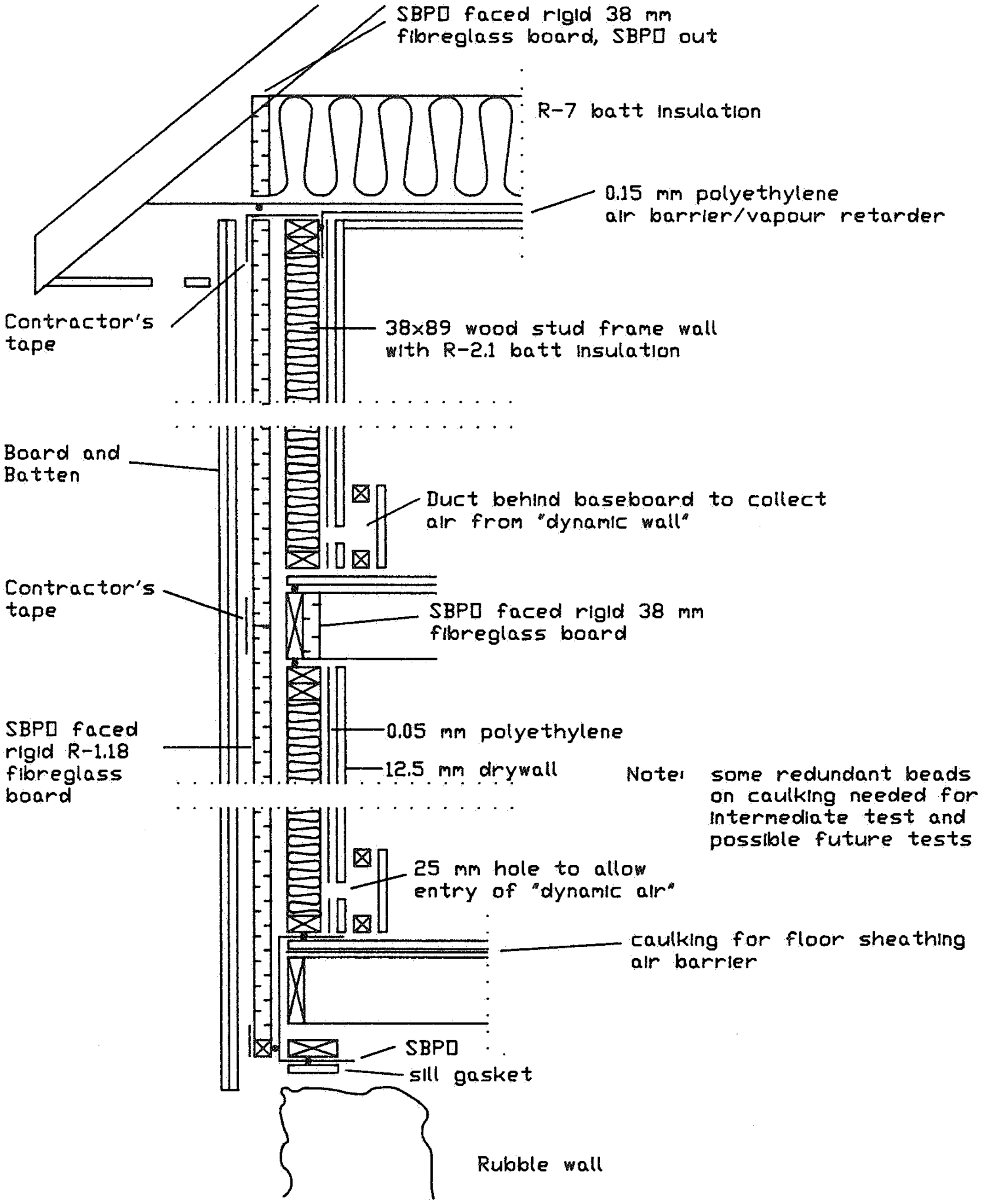


Figure 1. Expanded section through the thermal envelope of the dynamic wall house.

The wall air barrier, perhaps more appropriately the air retarder, is formed by a SBPO membrane attached to individual insulating sheathing boards. Commercially available sheathing tape, specially manufactured for the purpose, is used to provide air barrier continuity with door and window frame, the first storey floor and second storey ceiling air barriers (see Fig. 1). The SBPO membrane also performs the functions of sheathing paper to prevent rain penetration and, for the dynamic wall, the control of ventilation air flow.

The second storey ceiling air barrier is formed by 0.15 mm polyethylene sheet. Acoustical sealant is used to make it continuous at lapped joints. The forst storey floor completes the thermal envelope air barrier. It comprises tongue and groove plywood sheathing with acoustical sealant between the floor joists and the floor sheathing. Access to the unheated basement was provided through a gasketed hatch which was screwed in place during the evaluation of the house.

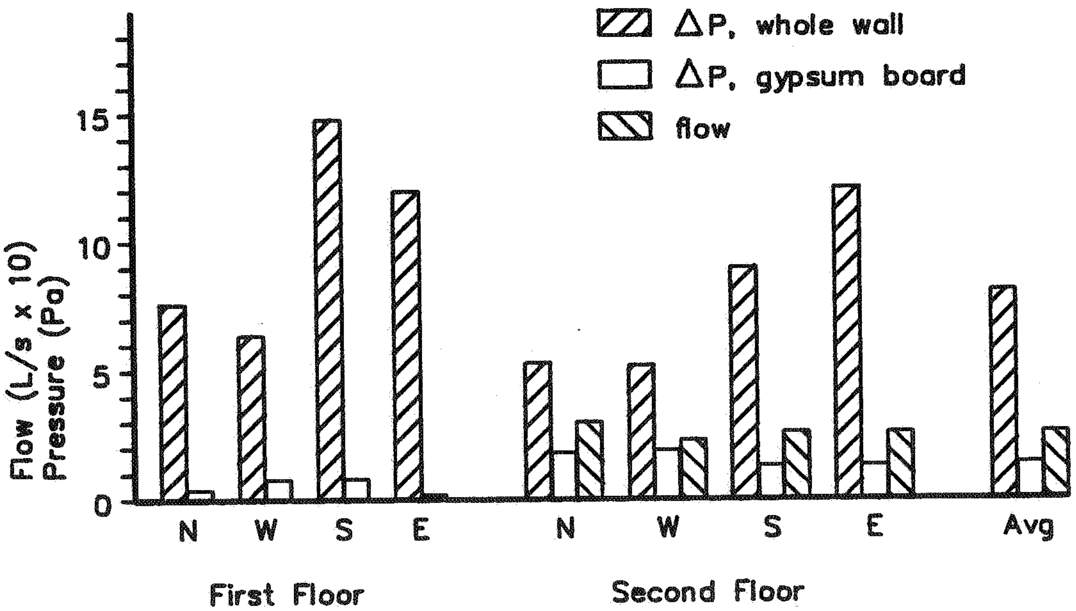
Three years after starting, construction had reached the stage where a limited performance evaluation could be carried out. Emphasis was on the flow of air through the walls and the effect of it on wall performance and indoor comfort.

6.2 Pressure Across and Flow Through the Walls

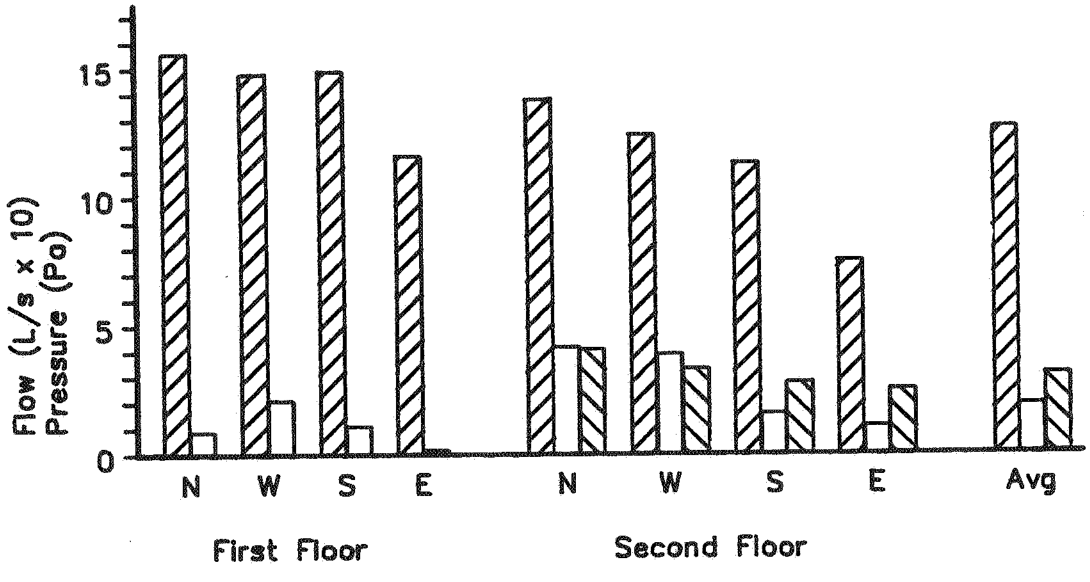
At the age of one year, before any of the gypsum wall board had been installed, the 50 Pa air leakage rate was 1.56 ACH. Two years later, after the second storey gypsum board has been fully sealed while the first storey exterior walls were covered, but the joints around windows and along the top and the bottom of the wall were not sealed, the 50 Pa ACH value had decreased to 1.33.

To admit ventilation air to the interior 25 mm diameter holes were drilled through the wall board in the middle of the 400 mm wide stud cavities and some 100 mm above floor level. Fifty-four and twenty-five such holes were drilled into the walls of the second and first storeys respectively. The smaller number of holes for the first storey was to compensate for yet-to-seal air leakage openings of the first storey wall board and the larger pressure difference due to stack action. The 50 Pa air leakage rate was now 1.51, suggesting that the SBPO air barrier was still intact. A direct comparison of the first and third-year values cannot be made in that all of the holes were not drilled into all of the stud cavities while the installation of electrical services and a chimney no doubt increased the equivalent leakage area of the envelope.

To satisfy the ASHRAE Standard 62-81 ventilation requirements, air had to be provided continuously at the rate of 40 L/s and intermittently at 65 L/s. Forty litres per second corresponds to 0.46 ACH. The associated depressurization due to exhaust at 40 and 65 L/S was 9.1 and 12.7 Pa respectively. Air was exhausted by a rheostat-controlled centrifugal fan. Flow rate was



E to SE wind, 40 L/s exhaust



N to NW wind, 63 L/s exhaust

Figure 2. Pressure drop across the entire wall, the gypsum wall board and flow per stud cavity for the four walls with different wind directions and exhaust rates.

determined by measuring the pressure drop in the calibrated air supply duct to the fan by means of a micro-manometer.

Wind speed and direction were continually monitored with a propeller-type anemometer. Pressure drop across the wall and the gypsum wall board was measured with micro manometers. Whenever appropriate, data acquisition systems were used for continual monitoring of parameters. Infiltrating air flow rates through the air inlets were determined manually with the aid of a flow meter employing a hot-wire anemometer for flow sensing.

In Figure 2 pressure across the entire wall and also the wall board as well as flow through the air inlets is presented for exhaust rates of 40 and 64 L/s. The values presented here represent the average of a number of sets, acquired over a period of time when wind varied in direction and ranged in speed from calm to over 30 km/h. Here it is seen that wind direction did affect the pressure distribution. The pressure drop across the wall board was comparatively small, which shows that the SBPO membrane provided the greatest part of the resistance to flow. Variation in flow rates through the four walls were, however, less sensitive to wind speed and direction, suggesting that the individual rooms in this house do receive an adequate share of the ventilation air. The effect of wind on dynamic ventilation air distribution in an urban environment is expected to be even less pronounced due to shelter provided by surrounding buildings. The measured net pressure difference across the walls for the first storey was from 2 to 2.5 Pa higher than for the second storey, which is in close agreement with the calculated difference due to stack action.

6.3 Temperature of the Dynamic Air

In Figures 3 to 5 the temperature of outside air, outside wall surfaces, dynamic air and room air is plotted against time. Figure 3 for the south-facing wall shows that the temperature of dynamic air is close to room temperature. Detailed analysis indicated that at the above ventilation rate the dynamic air was heated to 84 percent of the indoor-outdoor temperature difference. At the higher ventilation rate of 63 L/s, shown in Figures 3 and 4, the degree of tempering has dropped to some 62 percent. The percent tempering is, however, independent of the actual indoor-outdoor temperature difference; dynamic air temperature mimics that of the outside. These observations are in agreement with the model presented earlier and Equation 3.

The effect of solar heating, indicated by the peaks in the south-facing wall surface temperatures and reflected in the temperature of the dynamic air is clearly evident in Figures 4 and 5. Here dynamic insulation could be compared to a diode; it allows solar heat to penetrate the insulation while retarding the flow of heat from the interior. In the meanwhile, there is considerable scope for improvement of dynamic wall design to more efficiently capture solar heat.

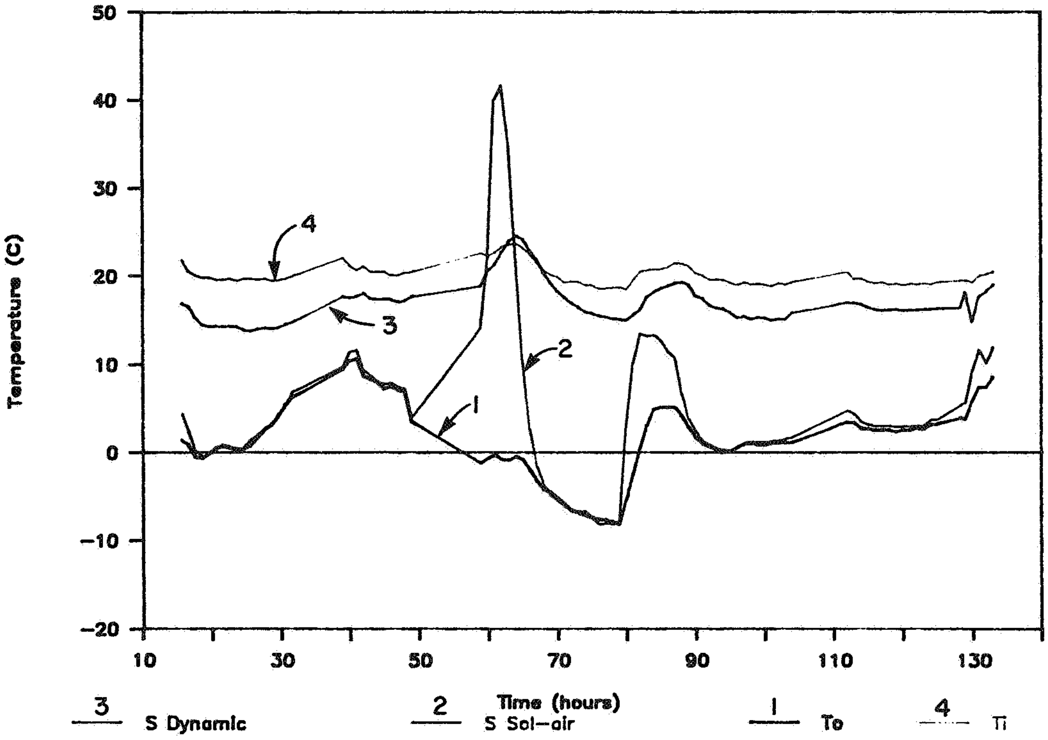


Figure 3. Temperature plot for the south-facing wall for a five-day period while the ventilation rate was 40 L/s. Temperatures are in ascenting order: outside air, wall surface, dynamic air and room.

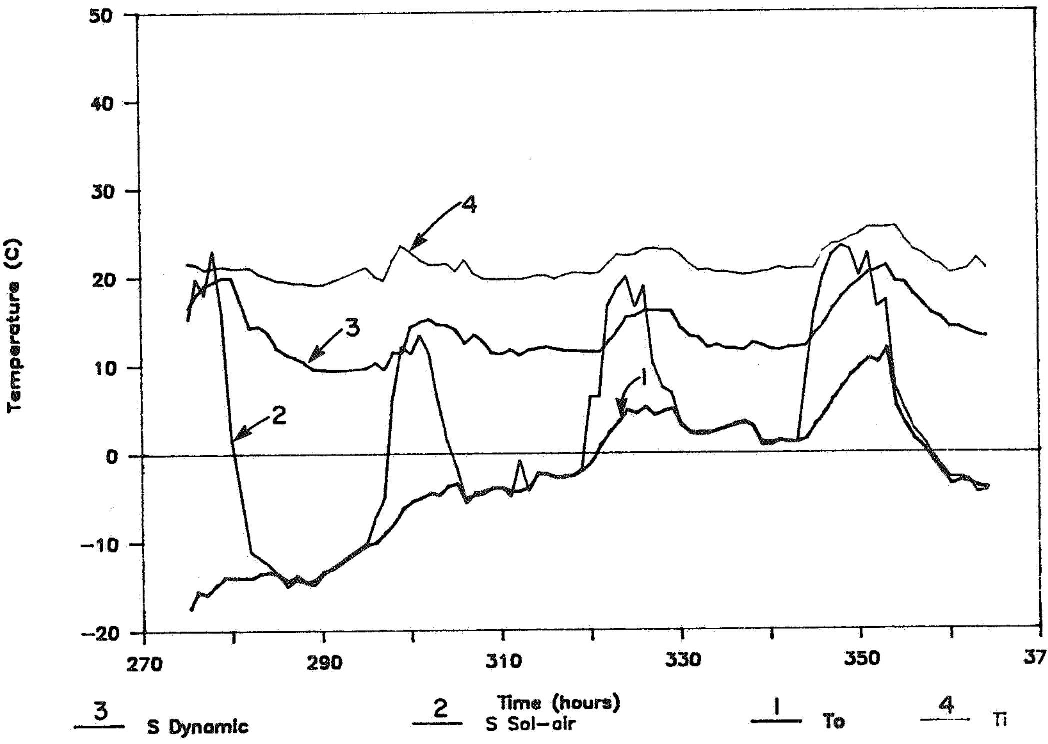


Figure 4. Temperature plot for the south-facing wall while the ventilation rate was 63 L/s.

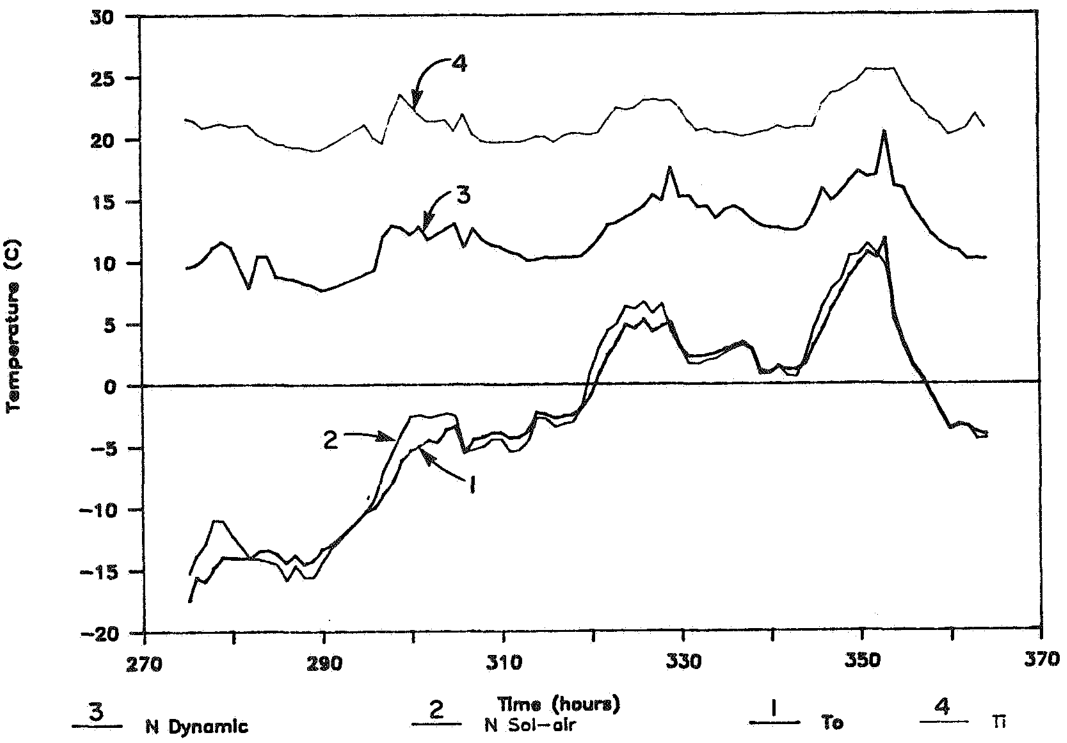


Figure 5. Temperature plot for the north-facing wall while the ventilation rate was 63 L/s.

6.4 Wall Surface Temperatures

One of the early concerns was that air movement through the wall could result in localized cooling of wall surfaces. It was to avoid such cooling by wind that the air barrier was located on the weather-side of the insulation in the first place.

Surface temperature measurements with the aid of thermocouples, an infra-red pyrometer as well as overall monitoring with an infra-red camera did not reveal any temperature anomalies. A closer examination of the air flow through the wall provides a partial answer to the above observation.

At the optimum ventilation rate for this wall, the ventilation air moves through the SBPO membrane at a speed of less than 0.2 mm/s. At this rate the resistance offered by the glass fibres in the insulating sheathing and the stud cavity is too small to channel flow to the inevitable unfilled spaces in the stud cavity. At the mid height of the stud cavity the average velocity is of the order of 3 mm/s. Only in the close proximity of the air supply opening does the velocity increase where the final exit velocity is still less than 0.5 m/s.

The average time it takes ventilation air to complete the passage through the wall is more than 10 minutes, apparently sufficiently long to complete the required transfer of conducted heat to the ventilation air. The air velocities through the bulk of the wall would be too low for the ventilation air to dislodge and carry glass fibres from the insulation. Before a baseboard cover is installed to shield the air supply openings, each air supply opening could be vacuumed to remove loose fibres from the wall.

6.5 Wall Drying

The elimination of exfiltration alone removes one of the major causes for concealed condensation. Controlled infiltration will further lower the relative humidity within the wall cavity to promote the drying of moisture of construction or moisture from other sources. Two conditioned studs, placed in ventilated stud spaces in the north and south walls, lost respectively 6.5 and 5.2 percent of moisture by mass after two months of dynamic operation. How much of this is to be attributed to dynamic action and how much to natural drying in the walls of a heated wood frame house is not clear. At the same time, the vapour pressure of the dynamic air from the north wall was some 320 Pa higher than that of the outside air which shows that moisture was absorbed from the wall by the ventilation air.

Concern has been expressed about a possible health hazard created by mould and mildew formation on the glass fibre insulation and within the wall cavity due to dynamic action. If this is the case, then it should be more of a problem in non-dynamic walls where the drying environment is less favourable. This should, nevertheless, be looked into.

6.6 Operation of Combustion Appliances

The spillage of combustion products and even the outright reversal of chimney drafts is a concern in all houses, and especially so in negative pressure houses. Similarly, radon gas entry with soil air must be controlled.

7. CONCLUSIONS

1. A model has been proposed to explain how dynamic insulation functions at low ventilation air flow rates. It is suggested that at operation at or below the optimum flow rate, wall temperatures remain unchanged while all the heat otherwise conducted through the still-air component of glass fibre insulation in a static wall can be recovered to heat ventilation air.

2. SBPO membrane can be used to form an air barrier on the weather-side face of wall insulation where its installation and inspection are simplified. Moreover, in this location it will also perform the functions of sheathing paper to control rain penetration and wind-cooling of insulation.

3. The SBPO membrane can be used to control air flow through a dynamic wall.

4. In spite of the lack of wind shelter, ventilation air was supplied reasonably uniformly through all the walls in the house described here.

5. Near the optimum ventilation rate the dynamic air was tempered by about 80 percent.

6. No anomalous cooling of wall surfaces was observed during dynamic operation.

7. Drying of wall construction occurred during dynamic action.

8. All indicators point to a substantial energy conservation potential.

Overall, wood frame houses can be modified with very minor changes to become dynamic wall houses. The overall construction cost and materials cost could be reduced on one hand while the quality of the indoor environment could be enhanced on the other. In effect, this can be accomplished by treating the house as a system rather than dealing with each component in isolation. With this approach an attempt was made to build a house where one thing enhances another; a house where the walls and the mechanical systems come together to form a coherent whole.

ACKNOWLEDGEMENTS

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