A Systems Approach to Extend the Limit of Envelope Performance

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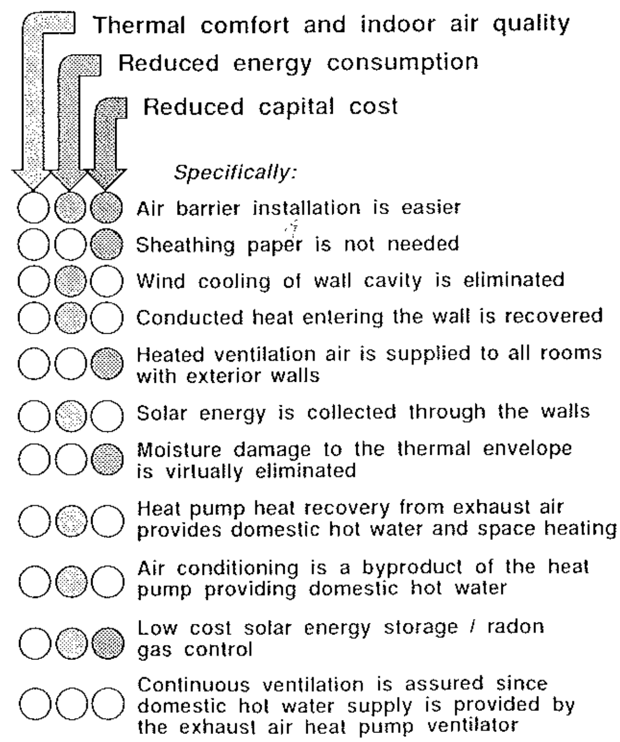
ABSTRACT

A dynamic-wall system is described with a view to enhancing building envelope performance. The dynamic-wall house, when coupled with a heat pump exhaust air heat recovery system, provides a potential means of gathering solar energy. This paper also describes a system where heat storage and radon gas control can be managed together. Through the systems approach, the building envelope becomes an integral part of the space heating, solar collection, domestic hot water heating, and heat storage system.

INTRODUCTION

By designing, building, and operating a house as a system where individual components perform several functions and complement the performance of others, a number of advantages can be realized. This paper describes a house where the walls become a part of the ventilating and solar energy system, where surplus heat storage is coupled with radon gas control, and where a heat pump provides heating, air conditioning, and domestic hot water. The assertions presented in this paper are based on measurements made in our laboratory and in a prototype house, as well as theoretical calculations. The advantages of the approach dealt with in this paper are summed up in Table 1.

TABLE 1
Advantages of a House System Using Multi-Function Components



THE TRADITIONAL WALL

The traditional approach has taken the building thermal envelope, developed for a heating climate, to the point where additional improvement can only be realized at costs that become difficult to justify in terms of associated energy cost reduction.

In the writers' opinion, the 2-by-4 wood frame wall with an insulating sheathing, insulated stud cavity, and effective air barrier capable of minimizing both in and through-the-wall air leakage—in effect, an R-20 wall—represents a comfortable balance between building costs on one hand and energy costs on the other.

The 2-by-4 frame is structurally efficient and, at the same time, available to accommodate electrical wiring and thermal insulation within its thickness. Insulating sheathing will, in turn, blunt the thermal bridges formed by the framing members, thereby providing a more even wall surface temperature and improving thermal efficiency. Finally, a vapor permeable air barrier on the cold side of the insulating sheathing, where it is easy to install and inspect, will prevent air leakage through the wall and wind cooling of the insulation (Timusk et al. 1991).

A further increase in thermal resistance would not only increase the cost of the wall itself, but the gross dimensions of the house and the width of the building lot would also have to be increased if indoor space is not to be reduced. In a house of modest dimensions, an increase in wall thickness

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of one inch would otherwise reduce the floor area by some 20 square feet.

If the traditional house built with the above walls is all that the homeowner can justify in terms of personal finances, it falls far short of what society requires. Global warming, pollution, and the high cost of new electricity mandate a reduction in energy consumption.

THE DYNAMIC WALL

The thermal efficiency of the 2-by-4 wall described above can be significantly enhanced by making a slight modification to it and altering the way it is operated. Traditionally, every effort is made to avoid air movement within or through the insulation lest the thermal performance of the wall be impaired. The ability of air to absorb and transport heat can, however, be used to advantage by moving air through the insulation under controlled conditions.

Walls that are built so that a controlled flow of air can be passed through the glass fiber insulation in the wall have been termed "dynamic" walls and the insulation "dynamic" insulation. The construction and performance of such walls is described in Timusk (1987). The walls in our test house and laboratory evaluations include

1. one-inch rough-sawn board and batten siding;
2. 1.5-in.-thick glass fiber insulating sheathing board, covered with a layer of vapor permeable and slightly air permeable spunbonded polyolephin (SBPO) membrane;
3. glass fiber batt-fitted 2-by-4 study cavity;
4. four-mil stapled polyethylene vapor retarder; and
5. gypsum drywall.

The above wall construction is common in Canada. What makes this a dynamic wall are the following:

1. The SBPO membrane is sealed with specially manufactured tape to turn it into the air barrier. Since the SBPO membrane is slightly air permeable, it is the control element that admits a uniform flux of air through the insulating sheathing and into the batt-filled stud cavity.
2. In each stud cavity, one-inch-diameter holes have been drilled through the gypsum board and the polyethylene vapor retarder.
3. A sustained pressure difference between the exterior surface of the SBPO membrane and the opening in the drywall is created.

The pressure difference can be created either by exhausting air from the house, whereby the entire interior volume becomes depressurized, or from a plenum connecting all of the openings in the drywall. A disadvantage of the first method is that airflow through the dynamic wall is only assured if other leakage openings do not compete with those in the SBPO membrane. In other words, the house has to be built and maintained airtight. A second disadvantage of this approach is that a negative pressure may adversely affect the venting of any naturally aspirating fuel-burning devices present, as well as promote the ingress of radon gas in areas where it is found in the soil.

Aside from the radon concern, which will be addressed in detail, and chimney backdrafting, there are no safety issues of which the authors are aware. Every house with an active chimney is a dynamic-wall house, albeit not a very efficient one. The negative pressure required for the dynamic wall is less than 10 Pa, the order of magnitude produced by an operating fireplace or an indoor barbecue fan. If a door or a window is left open, all that happens is that the dynamic wall loses the forced air movement through it and acts like an ordinary, but well-built, wall. If the exhaust fan is turned off, the air quality will suffer, as it will in any airtight house where the mechanical ventilation is turned off.

No problems associated with the dynamic wall have surfaced in our test house during the eight years since it was built. Detaching the walls from the house by exhausting air from them by means of a plenum appears, however, to be preferred. Improved control possibilities result from the use of a depressurized plenum. Real and perceived air quality concerns may also be alleviated.

THE HEAT EXCHANGE PROCESS IN THE DYNAMIC WALL

Briefly, when an airstream is moved through the insulation in a sense opposite to heat flow, heat that is transferred through the still air phase in static insulation is returned to the building interior with the airstream. At flow rates where the heat conducted through the still air phase is sufficient to heat the air moved through the insulation, the temperature gradient through the wall remains essentially unchanged (Tassone 1989). This means that the radiant and solid-conducted components of heat flow through the wall remain unchanged, as does inside wall surface temperature.

In the process, there is a slight increase in the rate at which heat enters the wall from the heated interior, whereas there is a significant decrease in the rate at which heat leaves the wall. The difference is absorbed by the incoming airstream. By substituting the temperature difference across the wall and the rate at which heat leaves the wall into Fourier's equation, one would obtain an "effective" thermal resistance for the wall. Such values, obtained from laboratory tests (Tassone 1989), are plotted in Figure 1 against the airflow rate through the wall described above.

In Figure 1, it is seen that as the flow rate increases, the effective thermal resistance also increases but eventually at a diminishing rate. At higher flow rates, heat flow into the wall is increased by increasing the temperature gradient at the room side of the wall. The outboard temperature gradient would now become shallower than in the static case, indicating that part of the radiant and solid-conducted heat is also used to heat up the incoming air.

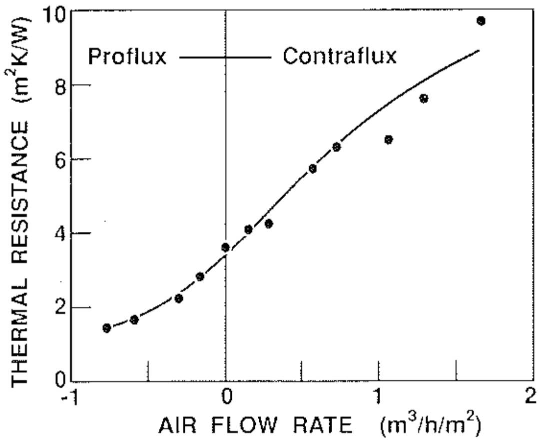

Figure 1 *Effective thermal resistance plotted against dynamic airflow rate.*

There could be several reasons why one would want to draw exterior air through a wall. Exfiltration and associated moisture damage could not take place; in the process of being heated, the relative humidity of the air drawn through the wall would decrease, thus enhancing the drying of moisture from the wall construction. The air drawn through the wall could be used for ventilation purposes or as an enhanced heat source for a heat pump. Drawing air through the wall, therefore, only makes energy sense if the air is needed, as stated above, for ventilation or heat source purposes.

When heat and airflow are in the same direction, the resistance of the wall is decreased. This is of interest when the outside air temperature is low enough to call for heating while the sun-heated building surface temperature exceeds indoor air temperature. A plot of air, wall surface, incoming ventilation air, and room temperatures are shown versus time in Figure 2. These are measurements from our prototype Dynamic-Wall House (Timusk 1987). For this house, no attempts were made to enhance the solar collection efficiency of the wall.

The above can be summarized as follows: dynamic insulation behaves much like a diode, resisting heat flow in one direction while enhancing it in the opposite. In effect, it is both an efficient insulator and a solar collector, a solar collector that can provide more heat than required for space, ventilation air, and domestic hot water heating. Whatever it lacks in efficiency is more than offset by having all sun-exposed opaque walls act as solar collectors. At the same time, it also shares the problems common to all solar heating systems—overheating during sunny conditions.

HEAT PUMP EXHAUST AIR HEAT RECOVERY

The dynamic wall forms a part of the mechanical ventilation system, providing warmed ventilation air by gathering heat that would otherwise be transmitted through exterior walls. In the process, it provides an opportunity to recover heat from the exhaust air. This, itself, affords a systems solution. Since the exhaust air is at a predictable and relatively high temperature, it becomes an ideal source for heat pump heat recovery. Since ventilation and domestic hot water are to be provided on a continual basis, it would seem reasonable to use the heat pump-recovered heat first of all to provide domestic hot water and what is left over for space heating, when needed. During the air-conditioning season, the same heat pump can still be used to supply domestic hot water. By duct switching rather than refrigerant cycle switching, heat can be taken from the interior circulation air, thereby providing air conditioning.

The strategy has a number of advantages: hot water is provided with the advantage associated with a coefficient of performance that is greater than one; the same mechanical unit provides a number of services; and perhaps most important, continuous operation of the ventilation system becomes assured since domestic hot water can only be provided if the ventilation system is in operation.

With ventilation air as the sole heat source, the heat pump cannot provide sufficient surplus heat to also meet all the envelope heat loss demand. Nor is it adequate to provide air conditioning in all but marginal demand cases. The cost of increasing the capacity of the heat pump to handle both space-heating and air-conditioning demand is not very large. Excess solar heat could be stored in a system, which would have to be provided, for later extraction by the heat pump.

ENERGY DEMAND

A convenient way of dealing with the energy balance for a house is to divide it into two parts: the demand and supply. The demand is made up of heat losses through the

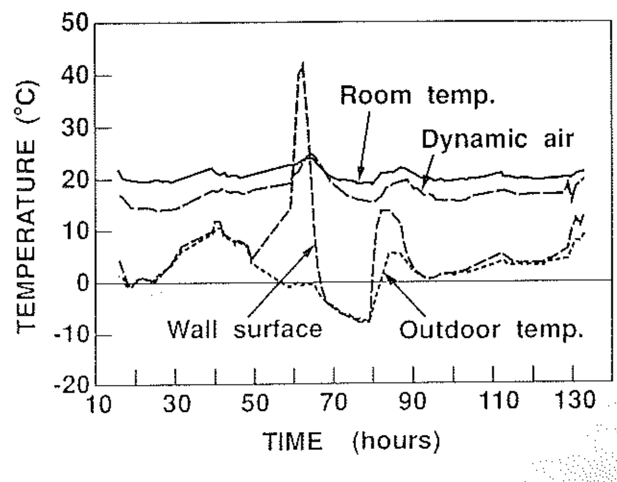

Figure 2 *Indoor air temperature, dynamic air temperature, wall surface temperature and outdoor air temperature plotted against time in hours. Note sharp wall surface temperature peak during bright sunny conditions.*

thermal envelope, heat required to condition the ventilation air, and heat to supply domestic hot water. The first two are determined by the thermal envelope characteristics, ventilation rate, and the climate. The supply side includes solar gain, domestic electricity, occupant metabolic heat, heat recovery by the dynamic wall, heat recovered from the exhaust air by the heat pump, and, if required, purchased heat.

Such a plot is shown in Figure 3 for the prototype house. It is for a 3650 Kelvin-day heating climate with mechanical ventilation provided at the rate of 0.3 air changes per hour, while heat is recovered from the exhaust air by means of a heat pump. The supply side does not include solar heat recovered through the opaque walls. In Figure 4, incident solar energy, striking the walls (Barakat 1980) and therefore available for recovery by the dynamic wall, has been added to all of the other supplies in Figure 3.

It is evident from Figure 4 that the dynamic-wall solar collection efficiency need not be very high in order to satisfy the total energy demand. Figures 3 and 4 are, however, based on monthly average values. Actual demand and supply are variable due to changes in weather conditions, the diurnal solar energy cycles, and variations imposed by occupant-controlled factors.

The homeowner's objective would be to minimize the total annual purchased energy use; the utility would be more concerned about minimizing power use during peak demand periods. Both would benefit from direct gain and surplus heat storage for periods when purchased heat would otherwise be required.

HEAT STORAGE AND RECOVERY

The dynamic-wall house resembles a passive solar house with excessive south-facing fenestration—both will overheat during bright sunny conditions. In the dynamic-wall house, overheating can easily be controlled by applying

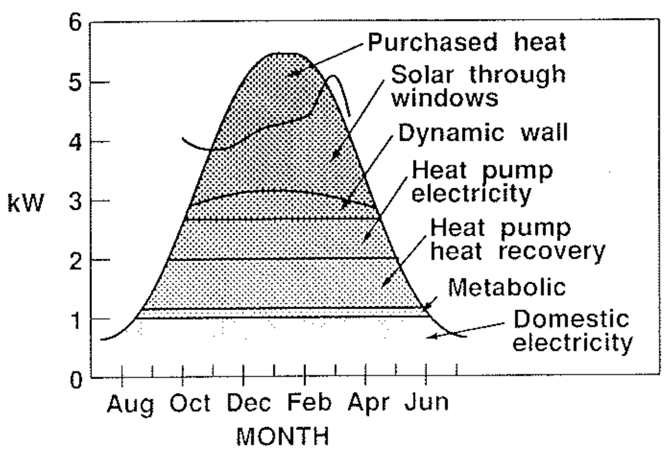

Figure 3 *Energy demand (heating, ventilating, domestic hot water) and energy supply plotted against the months of the year.*

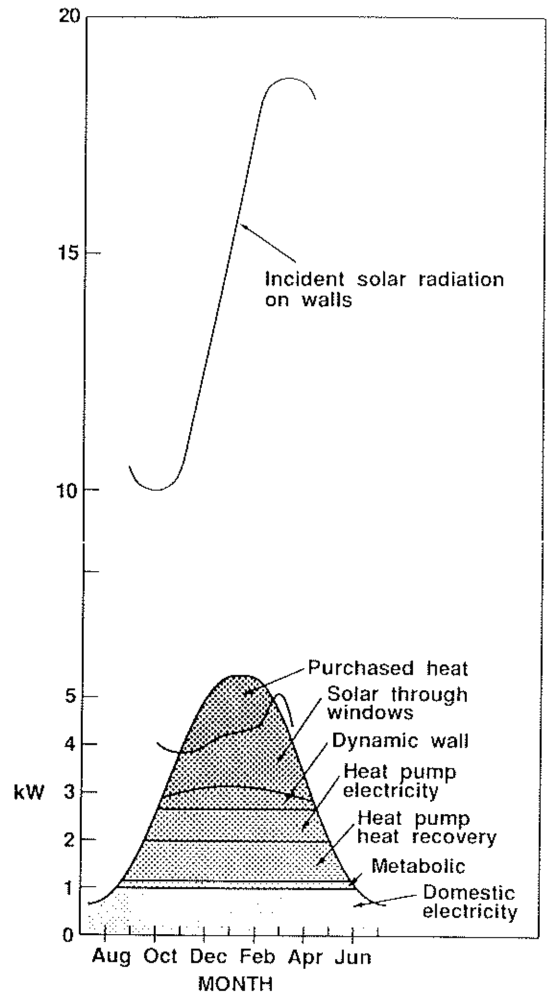

Figure 4 *Energy demand (heating, ventilating, domestic hot water) and energy supply plotted against the months of the year.*

air directly from the exterior, thereby "turning off" the dynamic wall. It would, however, be preferable to store excess heat for later recovery if the cost of creating the storage capacity is economically justifiable. Low-cost storage could be created by utilizing the basement floor slab and the crushed stone and soil below it.

By embedding perforated drainage tile in the crushed stone layer under the floor slab, sun-heated air could be forced into the underslab space. During the process of charging the storage space, a positive pressure could be maintained in it, thus excluding the entry of radon gas through the floor slab. The operation of such a system during surplus energy conditions is depicted in Figure 5.

When heat recovered from the ventilation exhaust air does not suffice, additional air can be withdrawn from the underslab space according to need. This would create a negative pressure in the underslab space. Gases, such as radon, could be drawn into this space and exhausted through a heat recovery system. Such a system would provide yet another way of controlling radon gas entry. Figure 6 depicts the operation of the system in this mode.

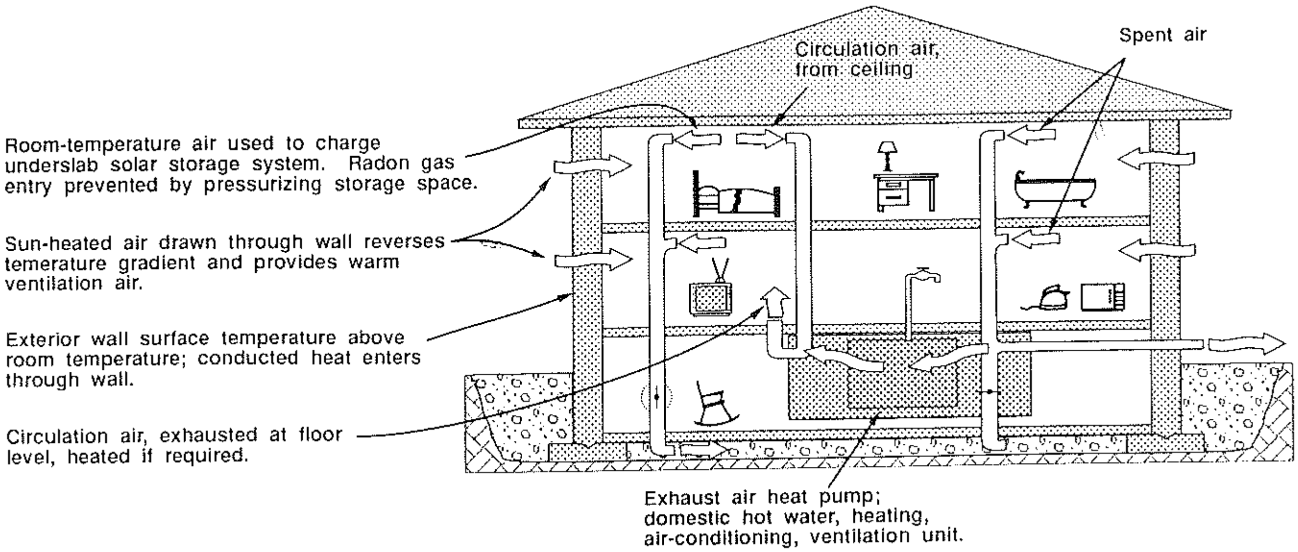

Figure 5 *Operation of a house during sunny conditions.*

CONCLUSIONS

The approach described in this paper is made up of a number of stand-alone components that are already generally in use. By bringing them together, a coherent building envelope is formed.

It is not necessary for a house to contain all of the elements described here. In its simplest form, the dynamic walls would be "driven" by the negative pressure created by the chimney of a wood stove. On the other extreme, the dynamic wall would be broken up into discrete elements and computer-driven with microprocessor-controlled switching to utilize walls and distribute the heat collected in order to best serve present and anticipated needs.

ACKNOWLEDGMENTS

The authors would like to acknowledge the support provided by the N.B. Hutcheon Bequest, The Ontario Ministry of Energy, the National Sciences and Engineering Council of Canada, and Fiberglas Canada Inc.

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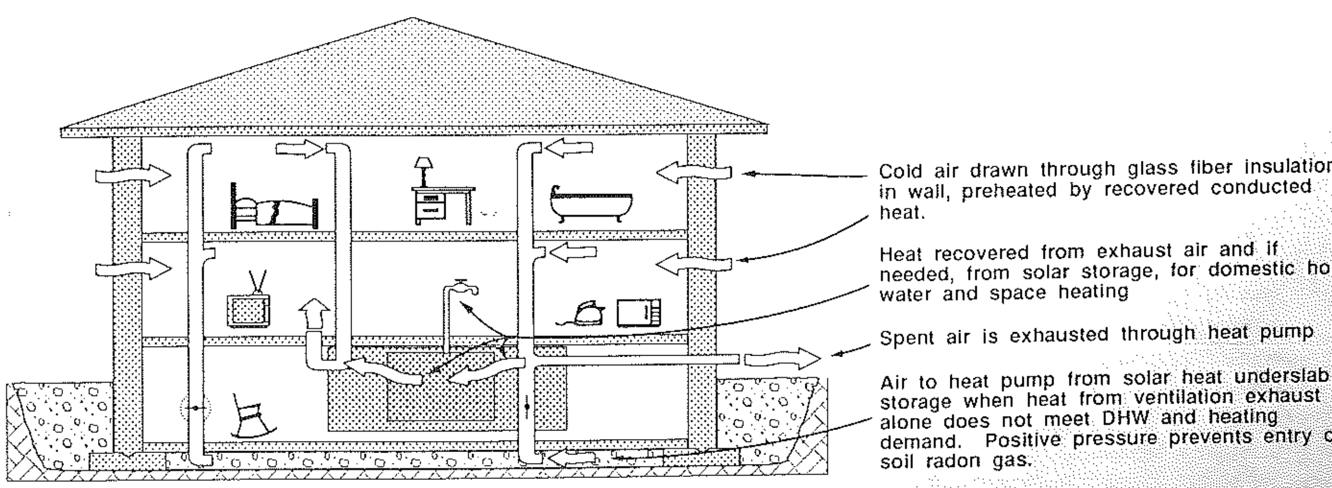

Figure 6 *Operation of a house during nighttime or cloudy conditions.*