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Numerical evaluation of thermal comfort in rooms with dynamic insulation

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Abstract

The thermal environment in a room with dynamic insulation was evaluated using CFD. It was shown that a properly designed dynamically-insulated room could provide thermal comfort with energy savings and this would require that the room be air-tight and provided with controllable heat input. However, dynamically-insulated rooms might pose problems of local thermal discomfort when the interior surface temperature is well below the room air temperature.

Keywords: Dynamic insulation; Heat recovery; Air flow; Thermal comfort; Computational fluid dynamics

1. Introduction

Dynamic insulation is a means by which ventilation air is passed through the fabric of a building. The concept of dynamic insulation is well known in Scandinavia. To be effective, on the one hand, the materials of the building fabric for dynamic insulation must be permeable enough to allow the ventilation air to pass through at a reasonable pressure difference between indoors and outdoors. On the other hand, the building must also be sufficiently air-tight to minimise air infiltration through the rest of the envelope. The use of dynamic insulation can lead to improved insulation performance, reduced interstitial condensation and improved indoor climate [1].

One of the methods to achieve dynamic insulation is to use a ventilation system to extract room air. The resultant under-pressure draws air in through the building fabric in a counter or opposite flow direction to conduction heat loss in heating seasons. Heat from the building fabric is thus absorbed by the incoming air. In this way, the incoming air is heated and thereby the resultant heat loss due to ventilation and conduction is reduced. As the air flow rate increases, the amount of heat absorption increases and so the *U*-value of the insulation decreases. The theoretical *U*-value can be reduced towards zero [2]. Also, because the incoming air flows through a large area and the speed is extremely low, say, <10 m/h [3], the risk of draught from the incoming air stream is avoided. Besides, a heat recovery system such as a heat pump or a heat pipe unit could be inserted in the exhaust air duct to reclaim heat from the outgoing air stream to pre-heat the incoming air. Moreover, use can be made of solar energy to further boost the temperature of the incoming air. This can be achieved by adding a layer of glazing to the outside of dynamic walls. Such a measure could result in heat gains of 200–300 kWh/m^2 per heating season [3].

Measurements and theoretical calculations on a scaled-up single family house by Dalehaug [4] indicated that dynamic insulation could reduce the conduction heat loss by more than 50%. To achieve the full benefit of the system the rest of the house must be rather air-tight and there must be a demand for ventilation most of the day. Jensen [5] showed that the re-

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duction of normal insulation and ventilation heat losses when using single dynamic insulation was limited to 0.23. The equivalent limit on the ventilation heat recovery efficiency was 50%. Krarti [6] analysed the thermal efficiency of a one-layered dynamic wall for various ventilation rates and building thermal loads. It was found that the dynamic walls could achieve energy savings of up to 20% of total building thermal load. The operation of a dynamic wall involves both heat and mass transfer. The physics of simultaneous heat and vapour transport through dynamically-insulated building envelopes was elucidated by Taylor, et al. [7].

A major difference in the thermal environment between conventionally- and dynamically-insulated rooms is the internal surface temperature. In a room insulated with conventional 'impermeable' walls, the mean surface temperature is generally close to the room air temperature. Dynamically-insulated walls in heating seasons, however, have internal surface temperatures lower than the room air temperature. If the difference between the air and surface temperatures is substantial, the dynamic walls could cause draught due to radiation cooling and also create downdraught of air nearby. The relation between the air and surface temperatures involves a number of variables including the heat transfer coefficient. Taylor and Imbabi [8] demonstrated that when assessing the relative change in the heat loss of dynamic insulation over the static equivalent, both the outer and inner heat transfer coefficients could be neglected. However, the effect of the heat transfer coefficients should be included when calculating the surface temperatures and the heat transfer processes with the other surfaces of the room.

The performance assessment of dynamic insulation has so far been limited mainly to the relative energy savings as a result of reduced conduction heat loss. The assumption of an improved indoor climate by the use of dynamic insulation is solely based on low velocity, draught-free incoming air without taking into consideration the effect of room surfaces in contact with the incoming air. The room surface interacts with room air flow and temperature distribution and hence influences human thermal comfort. The consequence of such interactions has not been studied. An accurate assessment of these requires detailed measurements of all the relevant parameters or implementation of general air flow modelling. The objective of this study is to evaluate thermal comfort in rooms with dynamic insulation using computational fluid dynamics (CFD) modelling.

2. Methodology

Room air flow is simulated by means of the CFD technique and the results are then used for the evaluation of thermal comfort.

2.1. Air flow model

The air flow model consists of a system of governing equations representing continuity, momentum, turbulence, enthalpy and concentration. Air turbulence is represented by the renormalisation group turbulence model developed by Yakhot, et al. [9]. For an incompressible steady-state flow, the time-averaged air flow equations can be written in the following form

$$\frac{\partial}{\partial x_i}(\rho U_i \phi) - \frac{\partial}{\partial x_i}\left(\Gamma_\phi \frac{\partial \phi}{\partial x_i}\right) = S_\phi \tag{1}$$

where ρ is the air density, ϕ represents the mean velocity component U_i in x_i direction, turbulent parameters and mean concentration and enthalpy, Γ_ϕ is the diffusion coefficient and S_ϕ is the source term for variable ϕ.

Details of the model equations and solution are described elsewhere [10].

For a dynamic wall, the temperature of the inner surface at a steady state is calculated using the following equation based on Krarti [6] and Taylor and Imbabi [8]:

$$\frac{T_i - T_s}{T_i - T_o} = \frac{R_i \ \exp\ (Pe)}{R_i \ \exp\ (Pe) + \dfrac{\exp(Pe) - 1}{\lambda Pe/d} + R_o} \tag{2}$$

where T_i is the temperature of air at the wall boundary (°C), T_o is the temperature of outdoor air or supply air from a heat recovery unit (°C), T_s is the temperature of the inner surface of the dynamic wall (°C), R_i and R_o are the local thermal resistances of inner and outer air films based on the heat and momentum transfer at the boundaries, respectively (m^{2}K/W), Pe is the Peclet number ($Pe = V_w \rho C_p d/\lambda$), C_p is the specific heat of air (J/kgK), d is the thickness of the dynamic wall (m), V_w is the mean velocity of air flowing through the dynamic wall (m/s) and λ is the thermal conductivity of the wall (W/mK).

2.2. Thermal comfort

The evaluation of thermal comfort is based on the thermal sensation and draught risk. The thermal sensation is assessed using the predicted mean vote and resultant temperature.

The calculation of the predicted mean vote (PMV) involves four environmental parameters, namely, air temperature, velocity, humidity and mean radiant temperature and two personal factors (clothing and activity levels) [11]. All the environmental parameters can be predicted by the air flow model together with a radiation heat exchange model [12].

The resultant temperature is a simplified description of the thermal environment as follows [13]:

$$T_{res} = \frac{T_{mr} + T\sqrt{10V}}{1 + \sqrt{10V}} \tag{3}$$

where T_{res} is the resultant temperature (°C), T is the mean air temperature (°C), T_{mr} is the mean radiant temperature (°C) and V is the resultant mean velocity (m/s).

The risk of draught is calculated for isotropic turbulence based on the draught model developed by Fanger, et al. [14]:

$$PD = (3.143 + 52.26\sqrt{k})(34 - T)(V - 0.05)^{0.6223} \tag{4}$$

where PD is the percentage of dissatisfaction due to draught (%) and k is the turbulent kinetic energy (m^2/s^2).

3. Room description

Simulations are performed for a hypothetical room 4 m long, 3 m wide and 3 m high. Fig. 1 shows the cross-section of the room at mid-width. There is a double-glazed window 1.5 m high and 2 m wide exposed to the outdoor air in one of the walls and this is designated as the south wall and the opposite wall as the north wall. It is assumed that the south and north walls are dynamically-insulated while other walls are connected to adjacent rooms of same conditions, i.e. no heat transfer. The floor is assumed to be insulated. The roof is composed of 10 mm tile, loft space, 100 mm glassfibre quilt and 10 mm plasterboard ceiling. The calculated U-value of the roof is 0.35 W/m^{2}K. Room air is extracted through an exhaust opening of a cross-sectional area 0.01 m^2 in the ceiling. When required, a heat exchanger is used to recover heat from the exhaust air to pre-heat the supply air.

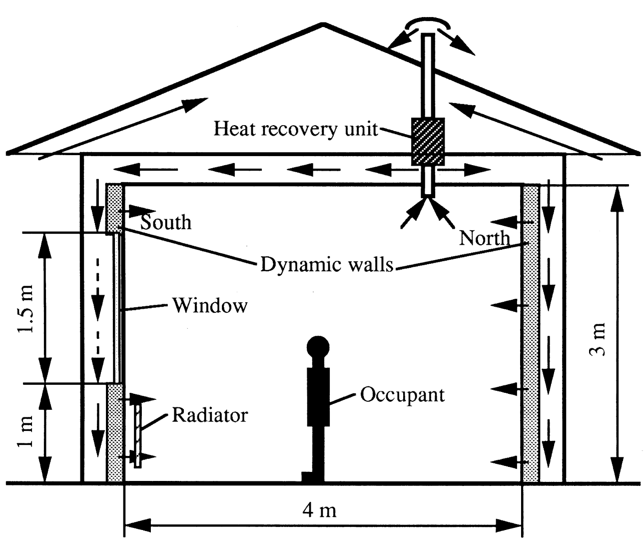

Fig. 1. Schematic diagram of mid-section of the simulated room.

The dynamic walls are composed of a material equivalent to 0.1 m thick felted mineral wool with a thermal conductivity of 0.042 W/mK. The total air flow through the dynamic walls is equivalent to one air change /h, i.e. 10 l/s, which gives an average air velocity of 2.4 m/h (0.67 mm/s). In an initial prediction, it is assumed that this air flow rate is the same as the extract rate, i.e. no other air infiltration. The 'dynamic' U-value of the walls defined by Brunsell [2] would vary with the internal film coefficient which depends on room air movement in addition to wall construction and air velocity. The average 'dynamic' U-value for these dynamic walls under natural convection is approximately 0.12 W/m^{2}K.

The room is occupied by one person with heat generation of 70 W/m^2 and clothing level of 1 clo. Another heat source of 20 W/m^2 is uniformly distributed on the floor, which could result from underfloor heating or other room heat gains, for example, due to lighting. The radiator shown in the figure is absent initially and is added for improving thermal comfort when there is no heat production from the floor. The outdoor air is set at 0°C and saturated.

The room arrangement is symmetrical along the plane of the mid-width and so only half of the room is considered. A nonuniform computational grid size of 56 × 40 × 26 (for room length, height and half width, respectively) is used for the prediction of three-dimensional room air flow.

4. Results and discussion

The thermal environment is predicted for the room with and without air infiltration, a heat recovery unit or a radiator. Under the base conditions, all the incoming air flows through the dynamic walls; both the heat recovery unit and radiator are absent.

4.1. Room environment

Fig. 2 shows the predicted air movement and thermal comfort on the symmetrical plane in the room under the base conditions. The predicted interior surface temperature of the dynamic walls varies between 16.1°C and 18.5°C depending on the surface boundary conditions, with a mean value of 17.5°C. This is higher than the window temperature of 11.7°C but is lower than could be achieved for a mechanically-ventilated room with conventionally-insulated impermeable walls. For example, for the same room without dynamic

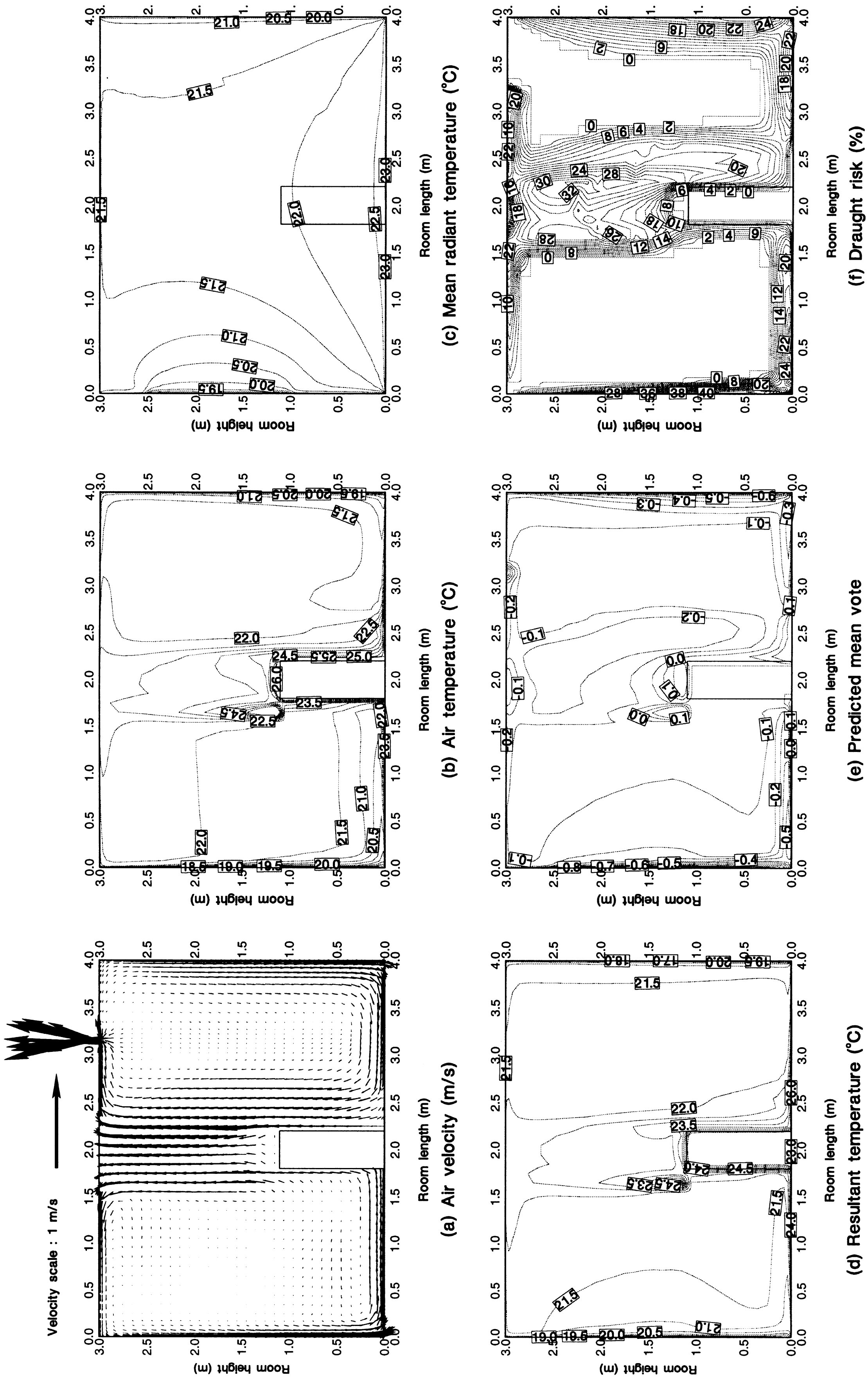

Fig. 2. Predicted thermal environment on the symmetrical plane in the room with 100% air flow through dynamic walls.

insulation but with the same amount of supply air pre-heated by a heat pump with heat recovery efficiency of 50%, the mean interior surface temperature of the impermeable walls with a *U*-value of 0.4 W/m^2K is about 20°C. The low surface temperature of dynamic walls is due to the flow of cold incoming air into the room through the walls. Thus, the two walls in this case behave somewhat like full-length cool windows, resulting in downdraught (Fig. 2a).

As the cool air flows downwards along the walls and then the floor, it picks up heat from the floor with heat generation. The air is further heated up when flowing upwards along the warm occupant, forming a thermal plume due to the buoyancy effect. Since the incoming air velocity is extremely small and since the effect of local extract on room air movement is normally negligible, the air movement in the room is essentially caused by thermal buoyancy. The predicted mean velocity in the room is 0.05 m/s but the velocity along the dynamic walls and occupant is over 0.2 m/s. The air movement away from the walls resembles displacement ventilation, resulting in certain vertical temperature gradient (Fig. 2b). However, because the heat is produced from the floor, the mean temperature difference between 1.1–0.1 m above the floor is less than 1 K.

The mean radiant temperature near the cold window is low and the resultant temperature is below the comfort level of 20°C for office use [13]. The air near the floor flowing from the wall surfaces is slightly cool (air temperature <20°C) but the floor temperature and mean radiant temperature near the floor are high due to heat production (Fig. 2c). The resultant temperature in this area is therefore at an acceptable level (>21°C) (Fig. 2d). The downdraught caused by the window leads to the thermal sensation (predicted mean vote in Fig. 2e) near and beneath the window below the lower comfort limit of −0.5 [15] and the draught risk (Fig. 2f) above the limit of 15% [14]. Similarly, the low air temperature and high air velocity near the floor result in local thermal discomfort due to draught. The draught risk above the head level is also over the comfort limit. The reason for this is that the flows of cool air along the two walls and floor converge at the occupant's position, which assists the buoyant flow along the body. The resulting air velocity above the head is consequently over 0.3 m/s while the air temperature in this area is not as high as the temperature around the body surface. The highest air temperature occurs in front of the occupant (facing the window) at head level. This is the spot where moisture is produced as a result of occupant's respiration at the body temperature.

The average air, radiant and resultant temperatures in the room are 21.7, 21.3 and 21.5°C respectively. The mean values of PMV and PD for the room are −0.1 and 4.1% respectively. Therefore, the average room thermal environment is acceptable, despite some local thermal discomfort near the room surfaces.

4.2. Effect of air infiltration

The above prediction is based on the assumption that air flows into the room through the dynamic walls only. In practice, there will always exist air infiltration through other room envelopes such as window and wall joints. In the following predictions, the air flow through the dynamic walls is assumed to be one half of the total ventilation rate and the other half results from air infiltration through wall joints.

The predicted thermal environment in the room with air infiltration is unsatisfactory. The mean surface temperature of the dynamic walls decreases to 14.8°C, compared with 17.5°C without air infiltration. The predicted air, radiant and resultant temperatures in the room are 18.5, 18.0 and 18.3°C respectively; the average PMV in the room is −0.8. Consequently, the room is slightly cool. The decreased room temperatures are partly attributable to the increased 'dynamic' *U*-value (from 0.12 to 0.23 W/m^2K) because of the reduced air velocity through the walls. The main cause of the deteriorated thermal environment is, however, the flow of part of the cold outdoor air straight into the room. The room thermal environment can be improved using a heat recovery unit or an extra heater. The room may also be comfortable at a higher outdoor air temperature.

4.2.1. Use of a heat recovery system

The temperature of air through the dynamic walls can be pre-heated by means of a heat recovery system (Fig. 1). However, at the assumed rate of air infiltration, using a heat recovery system may not be sufficient to achieve a completely satisfactory thermal environment. Fig. 3 shows the predicted room thermal environment with air infiltration and heat recovery at an efficiency of 50%. It can be seen that the temperatures near the floor are below the comfort level, resulting in local thermal discomfort. The predicted room air, radiant and resultant temperatures are approximately 1.4°C lower than those for the room without air infiltration and heat recovery. To achieve thermal comfort, extra heat input into the room is therefore needed by increasing heat production from the floor for example.

For the dynamically-insulated room with air infiltration, the average increase of room air temperature due to heat recovery at 50% efficiency is only 1.8°C because the outdoor air infiltrating the room remains cold (0°C). This is not much more than that could result from the air temperature rise through a mechanical ventilation system, assuming that the air infiltra-

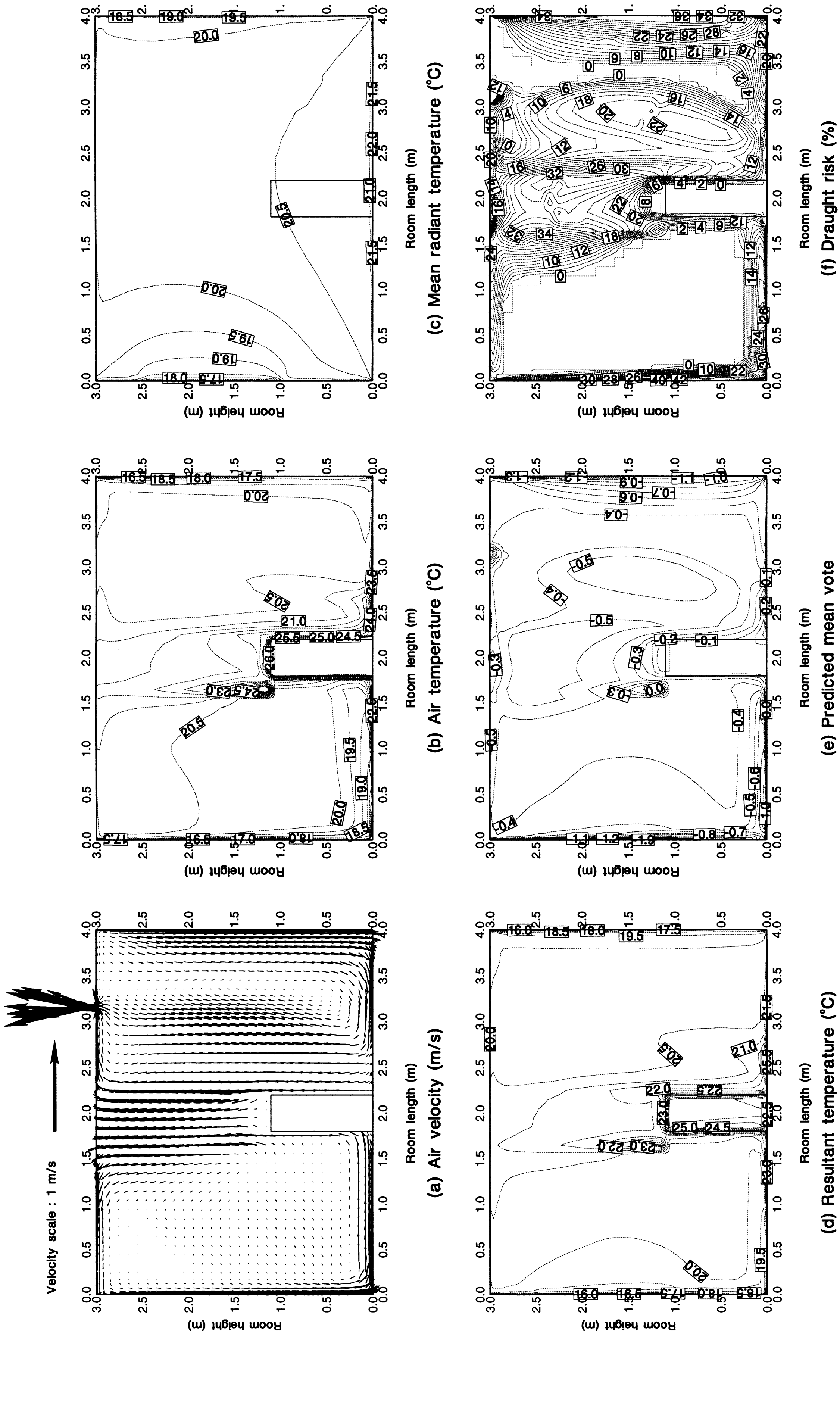

Fig. 3. Predicted thermal environment on the symmetrical plane in the room with 50% air flow through dynamic walls and heat recovery at 50% efficiency.

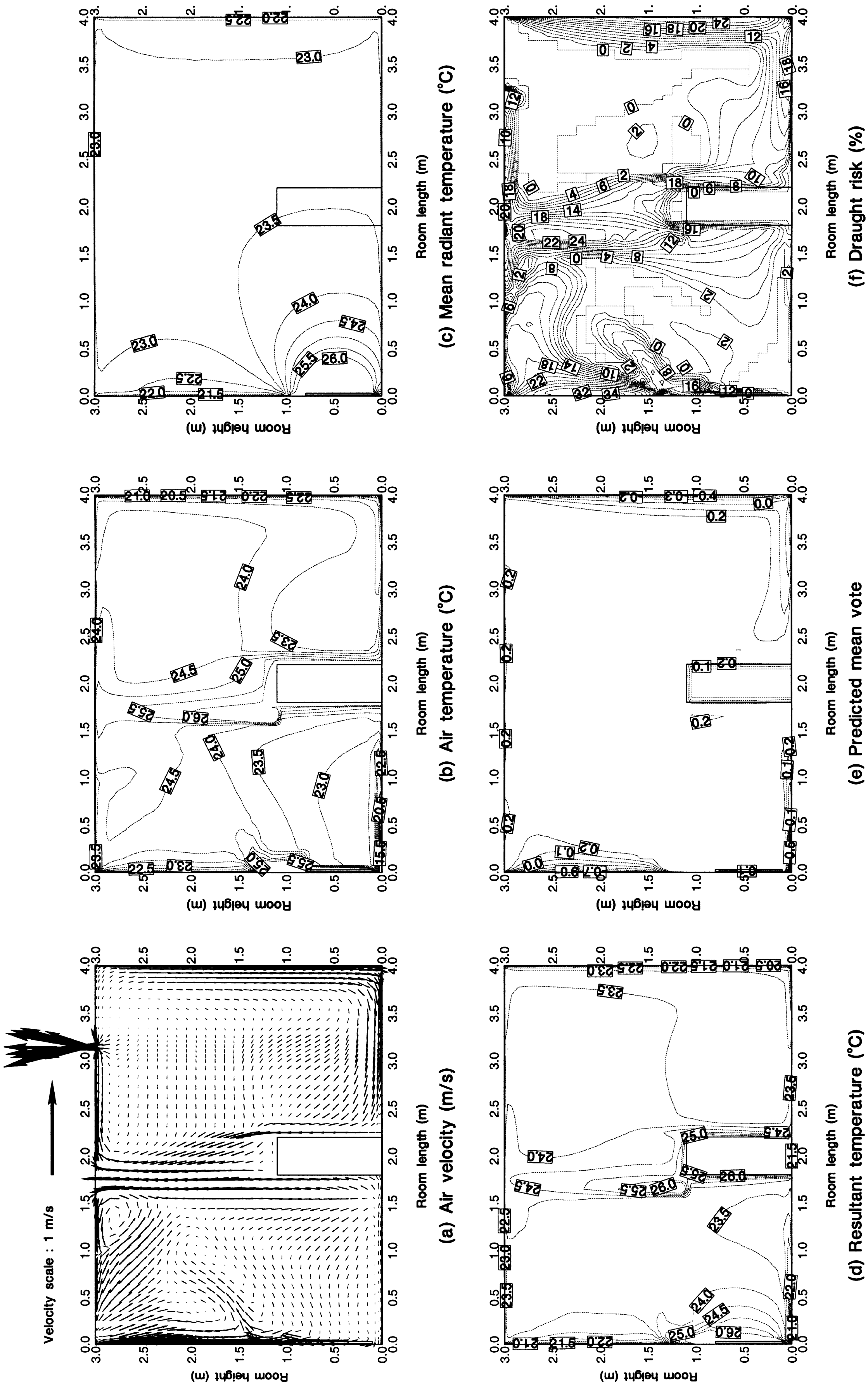

Fig. 4. Predicted thermal environment on the symmetrical plane in the room with 50% air flow through dynamic walls and a radiator at 50°C.

tion would be superseded by the supply air. Therefore, the heat recovery system is not cost-effective for this application unless the infiltration rate is reduced. In contrast, if all the outdoor air flows into the room through the dynamic walls, the average increase of room air temperature with the heat recovery unit would be much larger (4°C). The room with the heat recovery unit at 50% efficiency would then be overheated with a mean air temperature of 25.7°C. In this case, since the dynamic walls without heat recovery can provide an adequate room thermal environment, the installed heat recovery unit needs to be switched off. On the other hand, if the heat recovery unit is kept operating at 50% efficiency and the heat input into the room is adjustable, the dynamic walls can provide a comfortable room environment at a reduced heat production rate from the floor of 13 W/m^2. The predicted average air, radiant and resultant temperatures in the room are then 21.8, 21.4 and 21.6°C respectively; the average PMV in the room is −0.1. Hence, if the heat input is provided by an underfloor heating system, the heating load can be reduced by one third, approximately.

4.2.2. Use of a radiator

For the same room with air infiltration but without heat production from the floor and heat recovery, in order to achieve indoor thermal comfort at the outdoor air temperature of 0°C, a radiator of 2 m long and 0.7 m high and at 50°C mean surface temperature is installed under the window. The predicted thermal environment with the radiator is shown in Fig. 4. It is seen that the heat from the radiator overcomes the downward flow of air along the window. The mean values of air, radiant and resultant temperatures for the room are 23.8, 23.0 and 23.4°C respectively; the PMV and PD in the room are 0.2 and 1.7% respectively. The increase is most obvious in the radiant temperature near the radiator (Fig. 4c). The vertical gradient in radiant temperature offsets that of the air temperature. The air temperature above the head is also increased, which compensates for the cooling effect of high air velocity. The cooling effect of slight downdraught that exists near the north wall is also moderated by the increased surface temperature as a result of radiation heat transfer from the radiator (Fig. 4a and 4b). The consequence of these is a nearly uniform distribution of thermal sensation in the room (Fig. 4e). Also, the risk of draught near the floor is much reduced (Fig. 4f). Therefore, for this room, heating by the radiator gives rise to a more satisfactory thermal environment than underfloor heating supplemented by the heat recovery unit.

As a comparison, such a comfortable environment can also be achieved using the same heating system for the room with impermeable walls (U = 0.4 W/m^{2}K). The predicted mean values of air, radiant and resultant temperatures are then 23.3, 22.8 and 23.0°C respectively; the air temperature is 0.5°C lower than that in the room with dynamic insulation. Because the overall indoor thermal sensation is above the neutral point (PMV > 0), the radiator temperature can be reduced and so there is scope for saving energy through the use of dynamic insulation.

4.2.3. Outdoor air temperature

For the room with air infiltration but without heat recovery or additional heat input, the thermal environment would also be acceptable when the outdoor air is at a temperature of 5°C. The predicted room air, radiant and resultant temperatures are 22.9, 22.4 and 22.6°C, respectively; the predicted mean vote is 0.1. Here, a distinction should be made between this prediction and a previous prediction for the outdoor air temperature of 0°C with heat recovery, i.e. results for Fig. 3. In this prediction, the air flowing into the dynamic walls and through the infiltration paths is at the same temperature (5°C). In the other prediction, however, the air flowing into the dynamic walls is preheated by the heat recovery unit and so is at a higher temperature (about 10°C) while the temperature of the air flowing through the infiltration paths is still 0°C.

4.3. Effect of clothing level

The above evaluation of thermal comfort in the room is based on occupant's clothing level of 1 clo in winter. In today's offices, people may wear clothes with lower clo values of 0.6 to 0.8. The effect of a lower clothing level on thermal comfort is the requirement for a higher mean resultant temperature and hence more heat input than used for simulations. Since the predicted thermal environment for the base conditions is between neutral and slightly cool (PMV = −0.1), PMV would be lower than −0.1 for the clo value of less than 1. Consequently, for given environmental conditions, thermal comfort for a lower clo value would not be as satisfactory as the prediction.

4.4. Controllability of dynamic insulation

Dynamic insulation for an air-tight building can reduce the requirement for heat input compared with conventional insulation. However, the maximum heat requirement for buildings is generally based on outdoor winter design conditions. At high outdoor air temperatures, there may be difficulties in controlling thermal comfort in dynamically-insulated buildings.

For example, as predicted above, the thermal environment in the dynamically-insulated room with 20 W/m^2 heat production from the floor or the room with

50% air infiltration and a radiator is satisfactory at the outdoor air temperature 0°C but would be too warm when the outdoor air is well above the freezing point. The room with 50% air infiltration without the radiator, comfortable at 5°C, would also be overheated at outdoor air temperatures higher than 7°C. Therefore, to prevent room overheating, the heat input needs to be reduced or the ventilation rate increased. If overheating is caused by the radiator or underfloor heating system, because of the air tightness of the room, an accurate and fast-response controller is required to regulate the amount of heat input according to the changing outdoor air temperature. If the floor heat production results solely from casual heat gains such as lighting, it may be difficult to control the indoor air temperature without increasing energy consumption while keeping the dynamic walls fully functioning. For a conventional room with impermeable insulation, the indoor air temperature can be decreased by increasing the ventilation rate mechanically or naturally by opening the window for example. For the dynamically-insulated room, opening the window would render the dynamic walls ineffective and they essentially would function like conventional walls. Increasing the ventilation rate for the dynamically-insulated room would require increasing the fan pressure and power requirements because of the functioning nature of dynamic walls. This would increase energy consumption for the mechanical system and reduce or even cancel the potential of energy savings for heating. It may be argued that it is unnecessary to keep dynamic insulation fully functioning when the outdoor air temperature is higher than a value that would lead to room overheating. The dynamic insulation would then have a very limited range of effective operation except for rooms with negligible casual heat gains. In addition, since the room air temperature changes according to a rather complex relationship among a number of variables (Eq. 2), it is not so easy to adjust the thermal environment of a room with dynamic insulation as that with conventional insulation.

5. Conclusions

The effectiveness of dynamic insulation and heat recovery is influenced by the air tightness of a building. For leaky buildings, it is not beneficial to employ dynamic insulation and/or heat recovery. Even for an air-tight building with a leakage rate as low as one half of the total ventilation rate of one air change /h, the use of a heat recovery system to boost the incoming air temperature through dynamic walls may not be cost-effective, either.

Application of dynamic insulation requires careful system design to ensure that the interior surface temperature of a room is at an adequate level. If the air flowing through a dynamic wall is cold, leading to low surface temperatures, dynamic insulation does not necessarily provide better thermal comfort than does conventional insulation. Also, controlling the thermal environment in fully-functioning dynamically-insulated rooms is not so easy as in conventionally-insulated rooms.

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