ENERGY CONSUMPTION DUE TO AIR INFILTRATION

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ABSTRACT

An important reason for making houses airtight is that air leakage leads to higher energy consumption. However, the impact of air leakage on energy consumption is usually calculated in a very simplified way.

Air leakage can occur through large apertures such as cracks around windows and similar large leakage points. The leakages can also be more equally spread over the whole building envelope. In this paper these two cases are referred to as concentrated and diffuse air laekage, respectively. Normally, energy consumption is calculated without taking into account the fact that air leakage changes the temperature distribution in the building envelope and, hence, also influences transmission losses. The normal calculation method is acceptable when the air leakage is mainly concentrated but not when it is mainly diffuse. As is shown in the paper, the normal calculation method leads to an overestimation of energy losses due to air leakage.

In the paper a reduction factor, R, is presented. This reduction factor, by which the total ventilation losses should be multiplied, isillustrated for different percentages of diffuse air leakage. If the air leakage is totally diffuse, then the reduction factor is almost zero, i.e., there are practically no energy losses due to air leakage.

In reality, air leakage takes place both through concentrated, larger cracks and through evenly distributed, smaller leakages. It is difficult to classify the different leakages as concentrated or diffuse. Apertures around windows might be considered as concentrated leakages but here, too, the effect discussed above is present. A small hole in the inner surface of a timber framed wall could lead to a widespread airflow in the mineral wool insulation, which would give the air leakage a more diffuse character. More research is needed in this field. It is impossible at present to recommend any values for the reduction factor, R.

INTRODUCTION

There is no doubt about the advantages of making houses airtight. If the building envelope is not airtight, then moisture problems can occur when warm, moist air penetrates the indoor surfaces. Furthermore, it is only when a house is airtight that the ventilating system can be adjusted in such a way that every room gets the desired amount of ventilation, irrespective of the outdoor climate.

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Another important reason for making houses airtight is that air leakage also leads to higher energy consumption. However, the impact of air leakage on energy consumption is usually calculated in a very simplified way. Normally energy losses are calculated without taking into account the fact that air leakage also changes the temperature distribution in the building envelope.

Air leakage can occur through large apertures such as cracks around windows and similar large leakage points. The leakage can also be more equally spread over building envelope. In this paper, these two cases shall be referred to as concentrated and diffuse air leakage, respectively. Normally the additional energy consumption is considered not to influence the transmission losses. This might be quite true when the air leakage is concentrated, but it is not true when it is diffuse. As will be shown below, the simplified calculation method leads to an overestimation of energy losses due to air leakage.

DIFFUSE AIR LEAKAGE: TEMPERATURES

Let us consider the case where air is penetrating a wall from the external to the internal side. The temperature distribution in the wall will then change (see Figure 1). If the wall consists of only one material, the initial straight line distribution will change to a curved distribution. The temperature in the whole wall is reduced and the temperature on the external surface will be decreased. If the air infiltration is high, the external surface will have nearly the same temperature as the outdoor air.

The temperature distribution will also change when the direction of the airflow is reversed. In this case the temperature will rise in the whole wall. If the airflow is high, the internal surface temperature will be close to the indoor temperature.

In both cases, air leakage reduces the amount of energy lost by transmission. This might seem surprising at first, as one could think that what is gained in the first case, would be lost in the second case, or vice versa. However, it can easily be shown, without any calculations, that transmission losses are reduced both when the air is entering and leaving the house.

DIFFUSE AIR LEAKAGE: ENERGY LOSSES

Let us study Figure 2. It shows one house where the air leakage takes place through concentrated cracks, case a, and another house where the air leakage is diffuse, case b. We can choose any closed volume within which we want to study the energy balance, and we will define this volume as follows. Where the air is entering the volume, the boundary will be on the external surface of the wall, and where the air is leaving the volume, we place the boundary on the internal side. This means that in both case a and case b the temperature of the inlet air is the same and equal to the outdoor temperature. The temperature of the outlet air is also the same in both cases and equal to the indoor temperature. Therefore, the energy losses caused by air leakage are the same in both cases.

Now let us compare the transmission losses in the two cases. At the boundaries chosen, the temperature difference between the surface and the air is smaller in case b, both for the wall through which air is entering the house and for the wall through which air is leaving the house (see Figure 1). This means that the transmission losses are reduced and, obviously, that the total energy demand for air ventilation and transmission is reduced.

The important thing is that the sum of the transmission and ventilation losses is reduced if the air leakage is diffuse. It is not possible to specify which one of the two losses is reduced because this depends on where we choose to place the boundaries. So far we have been discussing reduced transmission losses, but it is more logical to consider the transmission losses as being constant. If this is the case, the energy losses caused by air leakage are less than those normally calculated. Let us try to analyze how large this reduction is or at least give some limits for the energy losses caused by air leakage. For this purpose we need some equations.

ENERGY TRANSFER THROUGH A WALL WITH DIFFUSE AIR INFILTRATION

Figure 3 shows a wall with diffuse air infiltration or exfiltration. The air temperatures are T_1 and T_2, respectively. T_2 is the temperature on the side where air penetrates into the wall. The coordinate direction is opposite the airflow direction. Let us first define heat flow as energy transferred according to Equation 1 and convective energy flow as energy transferred according to Equation 2. The total energy flow is the sum of heat flow and convective energy flow. All energy flows are positive in the x direction.

$$q_h = -\lambda \, dT/dx \tag{1}$$

$$q_c = - \; Mc_p(T-T_r) \tag{2}$$

$$q_t = q_h + q_c \tag{3}$$

where

q_h = heat flow, Btu/ft^2·h (W/m^2)
q_c = convective energy flow, Btu/ft^2·h (W/m^2)
q_t = total energy flow, Btu/ft^2·h (W/m^2)
λ = thermal conductivity, Btu·in/h·ft^2·F (W/m°C)
T = temperature in the section x, F (°C)
T_r = arbitrary reference temperature, F (°C)
M = air leakage rate, lb/ft^2·h (kg/m^{2}s)
c_p = specific heat capacity of air, Btu/lb·F (Ws/kg°C)

It is assumed that the thermal conductivity of the material and the specific heat capacity of air are constant, that the air and the material in the wall have the same temperature for a given coordinate, x, and that the flows are one-dimensional and stationary.

Both the heat flow and the convective energy flow vary with x because dT/dx and T vary with x. However, if we assume that the flows are stationary, the total energy flow will be independent of x. We can therefore calculate the derivative of the total energy flow, which gives

$$\frac{d^2T}{dx^2} + \frac{Mc_p}{\lambda} \frac{dT}{dx} = 0 \tag{4}$$

Let us use a dimensionless parameter to simplify the equations:

$$a = Mc_p/(\lambda/d) \tag{5}$$

This parameter is, in principle, the ratio between ventilation and transmission losses. Let us also simplify the boundary conditions by ignoring the surface thermal resistance. The boundary conditions are then

$$T = T_1 \quad \text{for } x = 0$$

$$T = T_2 \quad \text{for } x = d \tag{6}$$

This simplification overestimates the energy losses to a relatively small extent. For further details and other boundary conditions, see Anderlind and Johansson (1980,1983) and Jensen (1982).

The solution of Equation 4 is obtained as

$$T = T_2 + (T_1 - T_2) \frac{e^{-ax/d} - e^{-a}}{1 - e^{-a}} \tag{7}$$

The total energy flow through a wall with diffuse air leakage can now be calculated from Equation 1, 2, and 3. The arbitrary reference temperature T_r is put at zero.

$$q_t = \frac{\lambda a}{d} \frac{T_1 - T_2 e^a}{e^a - 1} \tag{8}$$

TOTAL ENERGY LOSSES DUE TO AIR LEAKAGE

Consider now Figure 4, which shows a house where the air leakage is diffuse. We calculate the total losses for transmission and air leakage for wall A, where air is penetrating into the house, and for wall B, where air is leaving the house. (Later on we will study a house, where the air is entering the house through the building envelope and leaving the house through an exhaust pipe.) If the area of each wall is A/2, then the total losses from the house are:

$$A/2\ (q_{tA} - q_{tB}) \tag{9}$$

If the indoor temperature is T_i and the outdoor temperature is T_o, the boundary conditions are

$$\text{Wall A:}\quad T_1 = T_i\ ,\quad T_2 = T_o$$

$$\text{Wall B:}\quad T_1 = T_o\ ,\quad T_2 = T_i \tag{10}$$

From Equation 8, 9, and 10, we then express the total losses as;

$$A/2\ \frac{\lambda a}{d} \frac{T_i - T_o e^a}{e^a - 1} - A/2\ \frac{\lambda a}{d} \frac{T_o - T_i e^a}{e^a - 1} =$$

$$= A/2\ \frac{\lambda a}{d} (T_i - T_o) \frac{e^a + 1}{e^a - 1} \tag{11}$$

This expression can be compared to normally calculated energy losses for transmission and air leakage:

$$\frac{A\lambda}{d}(T_i - T_o) + \frac{A\lambda a}{2d}(T_i - T_o) \tag{12}$$

Equation 11 and 12 are two ways of expressing the total energy losses for transmission and diffuse air leakage. If Equation 12 is used, the losses obtained are too high. Let us study the quotient between air leakage losses in the two cases, assuming that the transmission losses are the same in both cases. The air leakage losses are obtained by subtracting transmission losses from the total losses.

Energy for air leakage calculated from Equation 11:

$$Q_{c11} = \frac{A\lambda a}{2d}(T_i - T_o)\frac{e^a + 1}{e^a - 1} - \frac{A\lambda}{d}(T_i - T_o)$$

$$= \frac{A\lambda}{2d}(T_i - T_o)\frac{a + ae^a - 2e^a + 2}{e^a - 1} \qquad (13)$$

Energy for air leakage calculated from Equation 12:

$$Q_{c12} = \frac{A\lambda a}{2d}(T_i - T_o) \qquad (14)$$

Equations 13 and 14 give:

$$Q_{c11} = \frac{a + ae^a - 2ea + 2}{a(e^a - 1)} Q_{c12} \qquad (15)$$

The quotient in Equation 15 is a reduction factor, by which the total air infiltration losses should be multiplied if the simplified Equation 12 is used and if the air leakage is totally diffuse. In reality the reduction factor, R, depends on the relationship between diffuse and concentrated air leakage. It is shown in Figure 5 for different percentages of diffuse air leakage. R is very small for the curve marked 100%, which means that the air leakage is totally diffuse.

Let us now consider a house where the air is entering the house through the building envelope and leaving the house through an exhaust pipe. In this case, the equations numbered (x) will change to the ones numbered (x').

$$A/2\ (q_{tA} + \frac{\lambda}{d}(T_i - T_o) + \frac{a\lambda}{d} T_i) \qquad (9')$$

$$A/2\ (\frac{\lambda a}{d}\ \frac{T_i - T_o e^a}{e^a - 1} + \frac{\lambda}{d}(T_i - T_o) + \frac{a\lambda}{d} T_i) \qquad (11')$$

$$Q_{c11} = \frac{A\lambda}{2d}(T_i - T_o)\frac{1 + ae^a - e^a}{e^a - 1} \qquad (13')$$

$$Q_{c11} = \frac{1 + ae^a - e^a}{a(e^a - 1)}\ Q_{c12} \qquad (15')$$

Here, the reduction factor, R, by which the total ventilation losses should be multiplied if the simplified Equation 12 is used, is shown in Figure 6. In this case the reduction factor is closer to one, but if the air infiltration is mainly diffuse, then ventilation losses should be considerably reduced, i.e., up to 50%.

The conclusion, after studying Figure 5 and Figure 6, must be that if diffuse air leakage is present then energy losses are considerably reduced.

DISCUSSION AND CONCLUSION

In reality air leakage takes place both through concentrated, larger cracks and through evenly distributed, smaller leakages. It is difficult to classify the different leakages as concentrated or diffuse. Apertures around windows might be considered as concentrated leakages, but there also the effect discussed above is present. A small hole in the inner surface of a timber framed wall could lead to a widespread airflow in the mineral wool insulation, which would give the air leakage a more diffuse character.

In many cases there is a clear relation between energy consumption and wind speed, which indicates that air leakage is important for energy consumption. In other cases the influence of wind on energy consumption is negligible. This is often the case in Sweden, where the houses in general are quite tight, see Norlén (1985). The effect discussed above is one of the reasons why energy consumption increases only slightly, if at all, when the wind speed increases.

More research is needed in this field. It is impossible at present to recommend any number for the reduction factor, R, in the following equation, which, in principle, should be used for calculating the energy losses due to ventilation when transmission losses are calculated in a normal way.

$$q_v = R\, Mc_p(T_i - T_o) \qquad (16)$$

where

q_v = energy losses due to ventilation, $Btu/ft^2 \cdot h$ (W/m^2)
R = energy reduction factor for air leakage
M = ventilation rate, $lb/ft^2 \cdot h$ $(kg/m^2 s)$
c_p = specific heat capacity of air, $Btu/lb \cdot F$ $(Ws/kg^\circ C)$
T_i = indoor temperature, F $(^\circ C)$
T_o = outdoor temperature, F $(^\circ C)$

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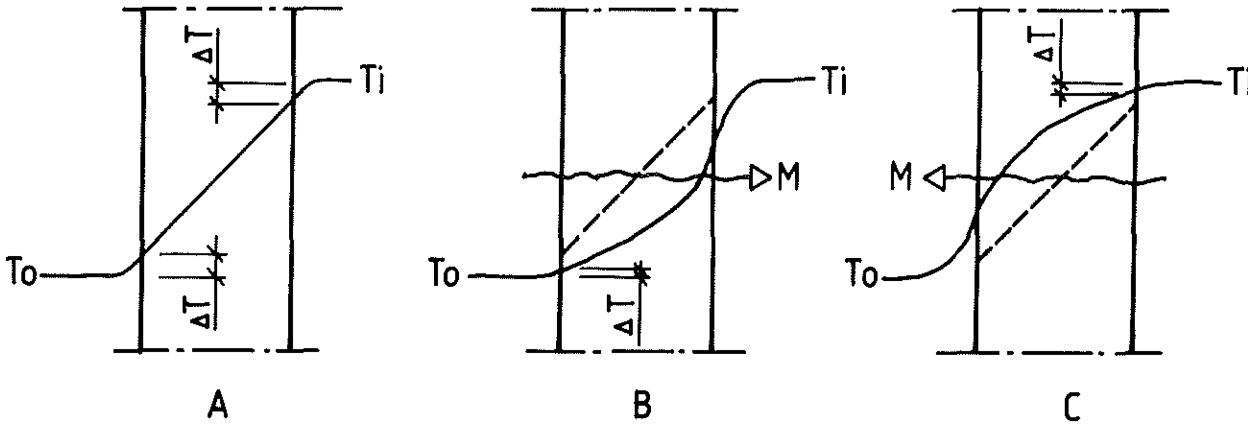

Figure 1. Air infiltration affects temperature distribution

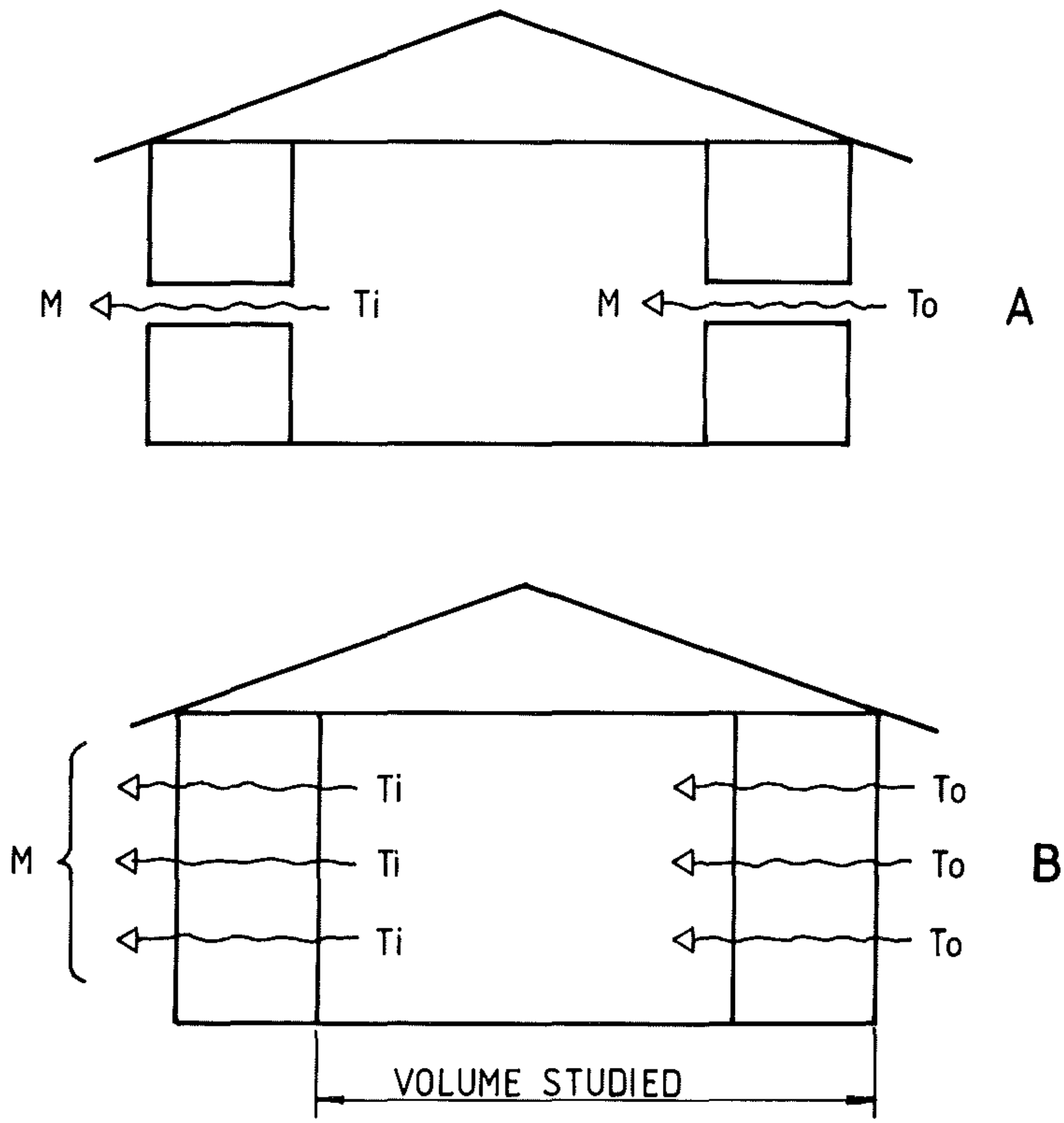

Figure 2. Concentrated and diffuse air infiltration

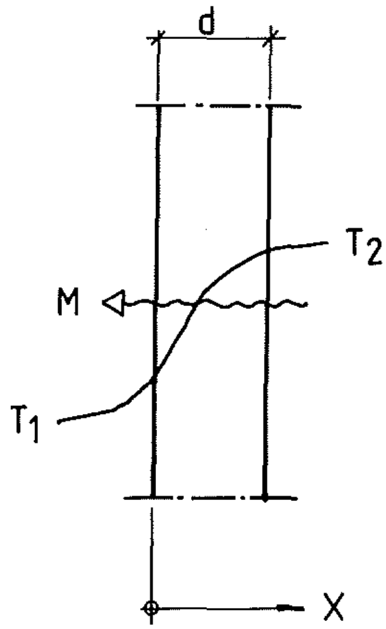

Figure 3. Symbols used

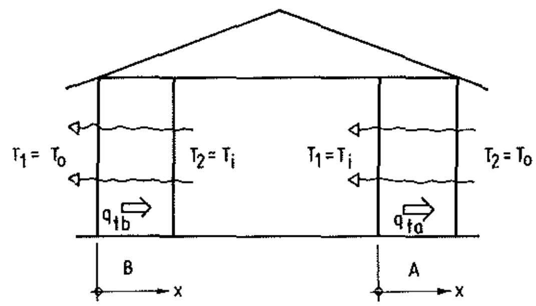

Figure 4. House with diffuse air infiltration

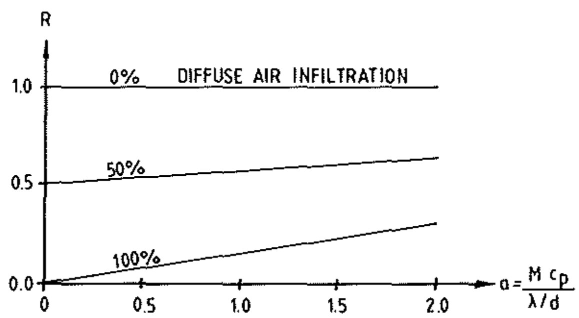

Figure 5. Energy reduction factor, R, for air infiltration. Air infiltration through building envelope is present both for inlet and outlet air

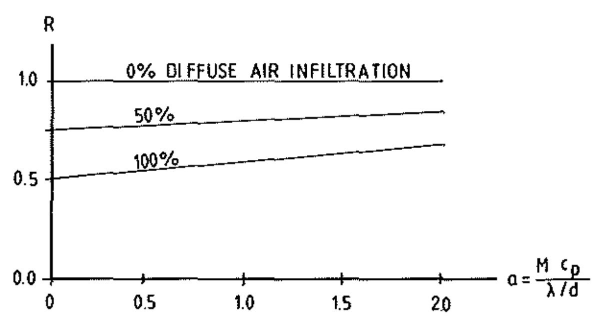

Figure 6. Energy reduction factor, R, for air infiltration. Air infiltration through building envelope is present only for inlet air