IMPACT OF AIR INFILTRATION AND VENTILATION ON ENERGY LOSSES OF BUILDINGS

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ABSTRACT

Improving the quality of the thermal insulation of a building's enclosure reduces the total heat losses by lowering the conductive heat flow. As ventilative heat losses due to air infiltration and ventilation are not affected by improving the insulation these will remain constant. Thus the contribution of ventilative heat flow to the total heat losses expressed as percentage increases. The amount of ventilative heat flow is characterized by the hourly air-change rate, which is dependent upon a wide variety of influence factors in a rather complex way. The ensure an acceptable air quality and thus the occupant's health and comfort the supply of fresh air cannot be reduced below a minimum ventilation rate. As air-change rates prevailing in buildings lie generally well above the necessary minimum rates there exists a considerable potential of energy saving by reducing ventilation. In addition waste heat recovery can be applied to preheat resp. precool - in the case of cooling demand - the fresh incoming air. The energy-saving potential given by applying these measures will be estimated for the Federal Republic of Germany.

KEY-WORDS

Energy balance in buildings, air infiltration, ventilation of buildings, air-change rate, waste heat recovery, controlled ventilation, energy-saving potential.

INTRODUCTION AND SCOPE OF WORK

The fraction of energy used for heating residential buildings amounts up to 20 % of the total annual net energy consumption in countries lying in a moderate climatic zone as is the case for the Federal Republic of Germany (Fig. 1). In southern countries, where cooling of buildings is required, a considerable amount of enery is spent for cooling. Facing shortages in support of energy and rising energy prices efforts have to be made to lower the demand for heating and cooling energy by means of a more rational utilization of energy.

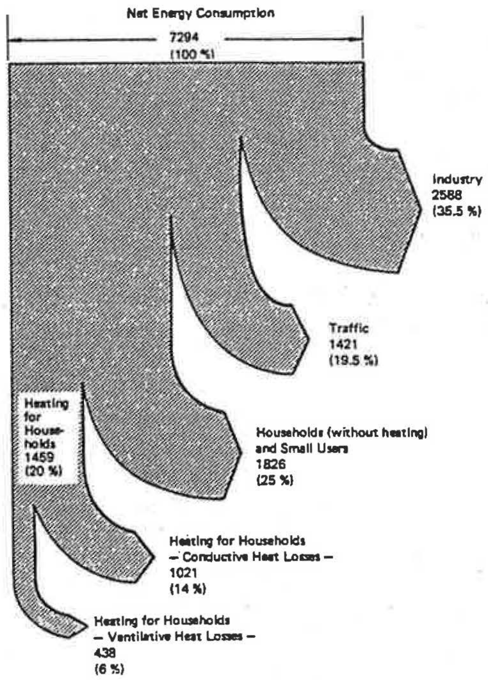

Fig. 1. Net Energyflows for the Federal Republic of Germany 1976 - in Peta Joule (10^{15} Joule)

The importance of air infiltration and ventilation for the total heat balance of a building is illustrated by comparing the heat flow due to air infiltration and ventilation with the heat flows due to conductivity and radiation as well as to the internal sources of energy (section 2). The results show that in multistory residential buildings, having a good standard of thermal insulation, the energy spent for heating the cold incoming fresh air amounts up to 30 - 50% of the total energy required for heating (section 3).

The air-change rate, which mainly determines the demand for ventilative heat, is influenced by a large number of different factors. Each of these factors can be associated to one of the categories: external climate, technical and structural conditions of the building and habitants behaviour.

The complex interaction between the various factors and their influence on the air-change rate is discussed (section 4).

Typical rates of air-change due to these factors lie above those required for the occupants' health and comfort. Thus, reducing the energy losses due to ventilation can yield a considerable amount of energy saving. The energy that can be saved by using mechanical ventilation systems is illustrated and marginal conditions for the suitable application of such systems are discussed (section 5). For the Federal Republic of Germany the amount of energy-saving has been calculated that could be achieved by successively introducing improved systems for natural and mechanical ventilation and reducing air leakages during the next 20 years (section 6).

MODELING OF TEMPERATURES AND HEAT FLOWS IN BUILDINGS

To demonstrate the contribution of heat flows due to ventilation and air infiltration to the total heat balance of a building it suffices to take the mean temperature of the entire building into consideration. Thus temperature differences between different rooms can be neglected.

The variation of the building's temperature T with time t is described by the differential equation:

$$m^{*}c^{*}\frac{dT}{dt} = Q_{int} + Q_{c} + Q_{v} + Q_{R}$$

effective heat capacity $m^{*}c^{*}$ times the temperature gradient	internal heat sources and sinks	conduction	ventilation and air infiltration	radiation

The internal heat sources and sinks Q_{int} can be split up into different fractions according to their origin: heat flows due to heating resp. cooling $Q_{H/C}$ and heat flows due to illumination, electrical appliances and persons Q_I.

Heating or cooling loads are supplied to a building to keep the inside temperature at a nearby constant value within the range of thermal comfort. The term on the left side of equ. (1) then becomes zero and we obtain:

(2) $- Q_{H/C} = Q_I + Q_c + Q_v + Q_R$

$Q_{H/C}$ is of positive sign, if heating has to be applied and negative, if there is a demand for cooling. In detail, the terms on the right side of equ. (2) are given by

Q_I - dependent upon individual occupant habits and thus has to be estimated

(3) $Q_c = U_o \cdot A\ (T_o - T)$

Where T_o is the time dependent outdoor temperature and A the total area of the building's enclosure. U_o denotes the average thermal transmittance of the gross enclosure area, calculated from the U-values and areas of windows, doors, floors, walls and ceilings being part of the enclosure.

(4) $Q_v = n \cdot V \cdot \rho_a c_a\ (T_o - T)$

$\rho_a c_a$ denotes the specific heat capacity of air per unit volume and V the air volume of the building. The hourly air-change coefficient n is a measure of how often the building's air volume is exchanged by fresh outside air per hour.

Introducing the ratio of the gross area of the enclosure to the building's volume SVR = A/V then equ. (4) becomes

(5) $$Q_V = \frac{n \, \rho_a c_a}{SVR} \, A \, (T_o - T)$$

For reasons of simplification the flow of latent heat due to air humidity has been omitted in equs. (4) and (5).

(6) $$Q_R = AI_{tot} \, (\underbrace{f \, . \, \tau}_{\text{Radiation through windows}} + \underbrace{w \, . \, s}_{\text{Radiation through walls}})$$

f is the percentage of window area from the total enclosure area A and w the percentage of walls. The radiation transmittance of glass τ is in the order of 80% and the effective radiation absorptance for walls lies around 2 - 4 %. The global solar radiation I_{tot}, dependent on the hour of the day and on the year's season, is taken at an perpendicular angle of incidence to a certain part of the enclosure area A.

Using equs. (3) to (6) the time dependent heat balance equation (2) for heating resp. cooling becomes

(7) $$- Q_{H/C} (t) = Q_I (t) + (U_o + n \frac{\rho_a c_a}{SVR}) \, . \, A \, . \, (T_o(t) - T) + A \, I_{tot} (t) \, (f \, \tau + ws)$$

Demand for heating is given if the second term of equ. (7) is negative (T_o (t) < T) and cannot be counterbalanced by the other two terms which are of positive sign. Cooling demand is not only given if T_o (t) > T, but also if the ambient temperature T_o (t) is equal or lower than the indoor temperature T and if the heat gains by radiation (term 3) and internal sources (term 1) exceed the heat losses due to conduction and ventilation (term 2).

If the different terms representing heat losses or heat gains balance each other, no heating or cooling will be required.

(8) $$Q_I (t) + (M_o + n \frac{\rho_o c_a}{SVR} \, . \, A \, . \, (T_o(t) - T) + A \, I_{tot} (t) \, (f \, \tau + ws) = 0$$

Small disturbances in the balance of equ. (8) will cause only marginal variations in the building's temperature T, if the heat capacity of the building is large enough. Heating or cooling actions will thus not be required.

COMPARISON OF VENTILATIVE HEAT FLOWS TO OTHER HEAT TRANSFER MODES IN BUILDINGS

To give an impression of the orders of magnitude involved with the different heat flow terms in equ. (7) a calculation using characteristic values at a given daytime was performed for a bungalow-type and a multi-story building. The results are listed in Table 1. Therefrom it can be seen that ventilative heat losses play a major role in the heat balance of a building.

As Q_I (t) and Q_R (t) vary strongly with time and even can become zero-dependent on the occupant's behaviour resp. on the climatic conditions - it is not very convenient to refer to Q_I (t) and Q_R (t) as a measure for the significance of the ventilative heat flow Q_v. The best information, however, is given by relating Q_v to the sum of the conductive and ventilation heat flows $Q_c + Q_v$, which represent the total heat flows in the case of internal sources and insolation being absent:

$$\frac{Q_v}{Q_c + Q_v} = \frac{n}{n + U_o \cdot \frac{SVR}{\rho_a c_a}} \tag{9}$$

TABLE 1 Heat Balance of a Bungalow-Type and a Multi-Story Building

Definition of Terms	Units	Data for Bungalow	Data for Mulit-Story Building
Building data:			
V - Enclosed volume	m^3	600	2400
A - Total area of enclosure	m^2	460	1120
SVR - A/V	m^{-1}	0.767	0.467
f - Percentage of window area	%	12	19.6
w - Percentage of wall area	%	36	59.0
U_o - Average heat transmittance	W/m^2K	0.858	1.02
τ - radiation transmittance of windows	%	80	80
s - effective radiation absorptance of walls	%	2.5	2.5
Basic assumptions:			
n - air-change rate	n^{-1}	1.3	1.3
AI_{tot} - insolation on enclosure	kW	21.51	86.04
ΔT - outside/inside temperature difference	K	± 10	± 10
Q_I - Heat release by persons and electrical equipment	kW	1.5	6.0
Results:			
Q_I - assumed internal heat release	kW	1.50	6.00
Q_c - conductive heat flow	kW	± 3.95	± 11.39
Q_v - ventilative heat flow	kW	± 2.21	± 8.82
Q_R - heat gain by solar irradiation	kW	2.26	14.76

For a multi-story building according to SVR = 0.7 m^{-1} this relationship is shown in Fig. 2 for different air-change rates n and by letting the building's average transmittance U_o vary from 0.5 to 2.5 W/m^2 K. The hyperbolic curve shows that with increasing quality of thermal insulation, corresponding to low values of U_o, the fraction of ventilative heat flow increases strongly. The German standard, as stated in EnEG (1977), allows a maximum U_o-value of 0.88 W/m^2k for a building with

$SVR = 0.7\ m^{-1}$. This $U_{o,max}$-value yields a percentage of 25 % to 55 % ventilative heat flow of the total heat transfer load depending upon the rate of air change presumed.

As the Ratio of enclosure area to building volume SVR becomes smaller with increasing size of the building the fraction of ventilative heat flow will be higher for a multi-story or high-rise building than for a single-story one. This is shown in Fig. 3. Herein it is taken into account that U-values for multi-story buildings are allowed to be higher than for a single-story one, which has to have a better quality of thermal insulation. In Germany this is stated by the standards in EnEG (1977):

$$(10)\quad U_{o,\ max} \leq (0.61 + \frac{0.19}{SVR})\quad W/m^2\ k$$

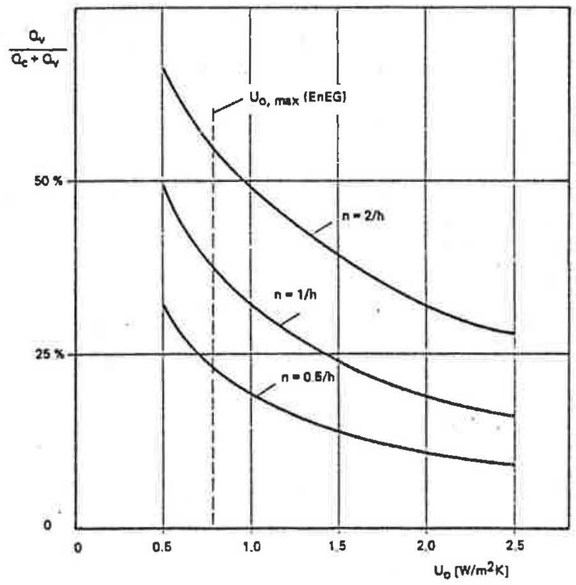

Fig. 2 Fraction of ventilative heat losses (Q_v) from the total heat losses ($Q_c + Q_v$) for a multi-story residential building having a $SVR = 0.7\ m^{-1}$. The dependence on the air-exchange rate n and on the heat transmittance U_o is shown.

INFLUENCE FACTORS AND THEIR EFFECT ON DETERMINING THE AIR-CHANGE RATE

In the heat balance equation (7) the air-change rate n was set equal to a certain constant value. In practice, however, the air-change rate can vary considerably depending on a variety of different influence factors. These can be associated with one of the main categories:

- External climate, which mainly determines the pressure forces acting on the building envelope due to the effects of wind and indoor-outdoor temperature differences.

- Structural properties of the building and types of installed ventilation systems. These define the sources of air leakage and ventilation as well as the paths of flow inside the building.

- Occupants can exercise influence on ventilation by opening windows and doors and by adjusting ventilating systems.

The interaction of the different influence factors is schematically shown in Fig. 4 (IEA, 1978). The left side of the scheme exhibits the parameters which cause the distribution of pressure forces on the building envelope. Via the openings in the envelope these determine the air flows inside the building and thus the rate of air exchange.

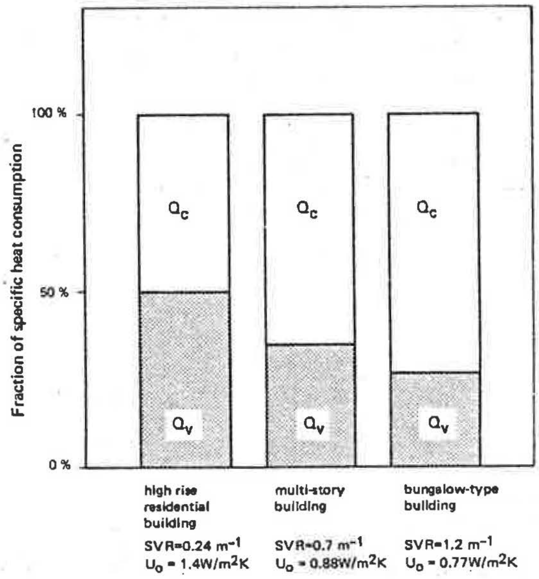

Fig. 3 Fractions of ventilative (Q_v) and conductive heat losses (Q_c) for different types of buildings with a thermal insulation according to EnEG (1977). The hourly air-change rate is taken as n = 1/h.

Leaving occupants' behaviour apart for a moment, the air-change rate can be determined basically by three different calculation procedures:

(i) crack-length-method, described in ASHRAE-Handbook of Fundamentals (1977)

(ii) correlation method, where the air-change is determined by linear correlation to wind velocity u and indoor-outdoor temperature difference ΔT

(11) $n = a + bu + c\Delta T$
a,b,c-empirical constants (IEA, 1978)

(iii) numerical analysis of nonlinear networks, based on the calculation of air mass flow and pressure drop balance (Esdorn and Brinkmann, 1975; Hausladen, 1978)

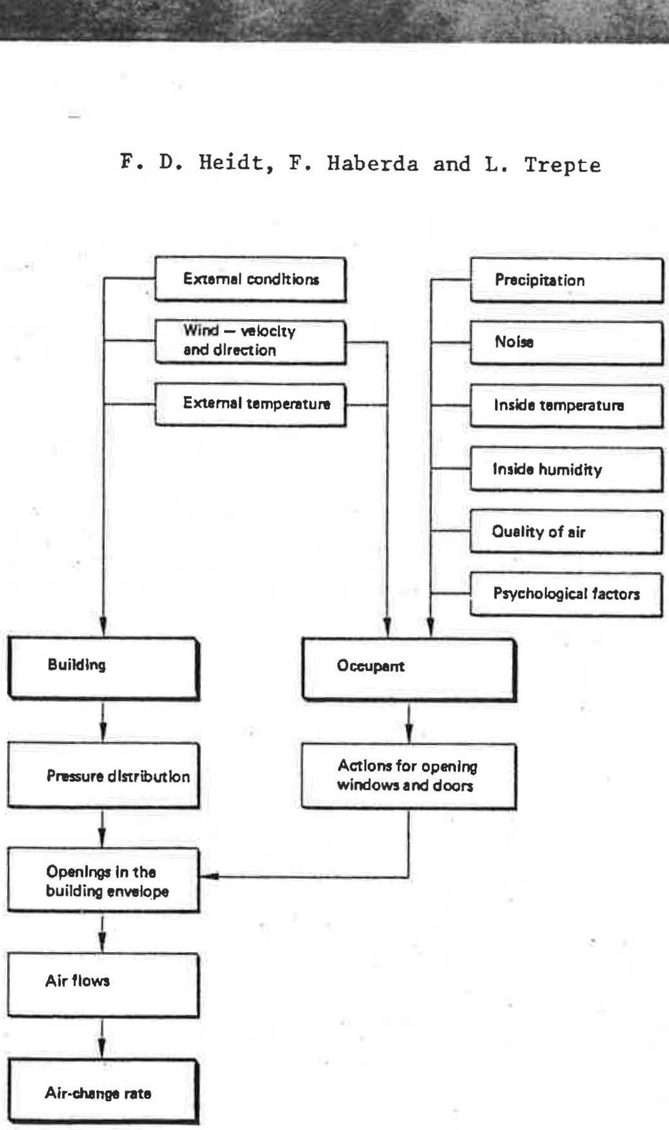

Fig. 4 Interactions between various influence factors and the air-change rate (IEA, 1978) showing the central role of occupants behaviour.

However, disadvantages of these calculation procedures are that they are either rather inaccurate (i), too much specialized for a certain type of building and external conditions (ii) or very complicated in handling (iii). Nevertheless, calculation results can give us some insight on how some influence factors act upon the air-change rate.

Not included in the pure mathematical calculation methods, described above, are the influence factors that cause occupants to open windows and doors. These factors can be summarized within three groups:

- External conditions as wind, temperature, precipitation and noise
- Internal conditions as temperature, humidity and quality of air
- Psychological factors as energy-saving consciousness, behaviour learned in early childhood, stress factors and others.

The effects of external temperature and velocity of wind on the window-opening habits are known from the early investigations of Dick and Thomas (1951). During the heating season the tendency to open windows increases with temperatures becoming higher, Fig. 5. On the other hand, higher velocity of wind causes occupants to keep windows more closed than during times of less wind.

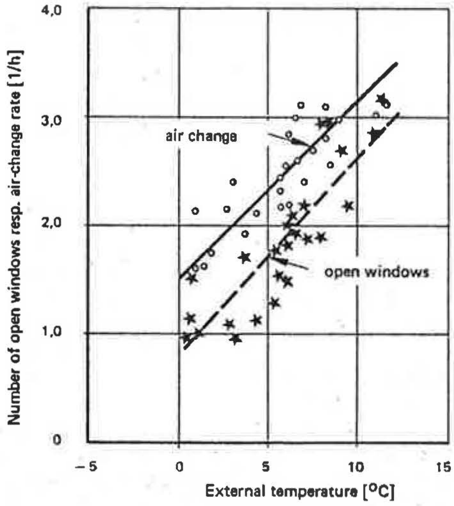

Fig. 5 Effect of external temperature on window-opening behaviour and corresponding air-change rate (Dick and Thomas, 1951 - Abbots Langley)

The effect of the remaining influence factors on the occupants behaviour, as listed in Fig. 4, is rather poorly understood. To the knowledge of the authors only two recent investigations try to find explanations for the behaviour of occupants by means of systematically questioning resp. observing (Künzel, 1979; Hartmann and others, 1978).

To give an impression of the extent occupants can exert influence on the air-exchange some results of various investigations are listed in Table 2 (Gertis, 1979).

TABLE 2 Increase of Air-Change Rate with Position of Window

position of window	air-change rate $[h^{-1}]$
window closed, door closed	0 - 0,5
window tilted roller blind closed	0,3 - 1,5
window tilted no roller binds	0,8 - 4,0
window half opened	5 - 10
window full opened	9 - 15
window and window-doors full opened (on opposite sides of the building)	about 40

ENERGY-SAVING VENTILATION SYSTEMS

According to German standards the hourly requirement of fresh air for one Person should be around 40 m^3/h. From the average living area of 25 to 30 m^2 per person and a room height of 2.5 m a minimum air-change rate of 0.5 to 0.6 h^{-1} has thus to be provided. Measurements of the air-change rates in buildings, however, usually indicate average values of 0.8 to 2.0 h^{-1}. This excessive rate of air infiltration and ventilation implies considerable waste of heating resp. cooling energy, as outlined in the foregoing sections. Avoidance of this energy waste can be accomplished in two basic ways:

1. Reducing not controllable air infiltration by tightening the building envelope.
2. Supplying the necessary fresh air flow in a controlled manner by using ventilation systems. In addition some of these systems can be used to recover the waste heat of the exhaust air, at least partially.

To achieve energy saving in reality by introducing controlled ventilation a series of marginal conditions has to be observed:

- Air leakages in the building envelope and thus air infiltration have to reduced to an absolute minimum. In the case of a poor tightness of the building the rate of air-exchange, accomplished by infiltration only, can exceed the necessary amount of fresh-air requirement. Outside air, introduced additionally by ventilation, would then imply a waste of energy in any case.
- The rate of air-exchange and the path of fresh air-flow inside the building has to be adjusted to the different usage of different rooms (living-room, kitchen, bathroom etc.).
- The regulation of ventilation systems has to be made adjustable to different intensities of usage at different hours of the day. Thus, for example a higher ventilation rate during cooking time in the kitchen has to be provided. During times of absence, however, only marginal ventilation will be required.
- Window-opening habits have to be changed in a manner, that during heating resp. cooling season windows are only opened for short periods in case of extreme bad air quality.

The possible reductions in the specific heat consumption by using ventilation systems are shown in Figs. 6 and 7 for a multi-story building. For the design case of a fairly tight building envelope, allowing only 0.2h^{-1} air-change by air infiltration and a controlled air-change of 0.6h^{-1} supplied by the ventilation system, a considerable amount of energy saving is possible, especially if waste heat recovery is applied. Most of this saving will be lost, however, if the building tightness is of poor quality or if window-opening habits introduce additionally outdoor air into the building.

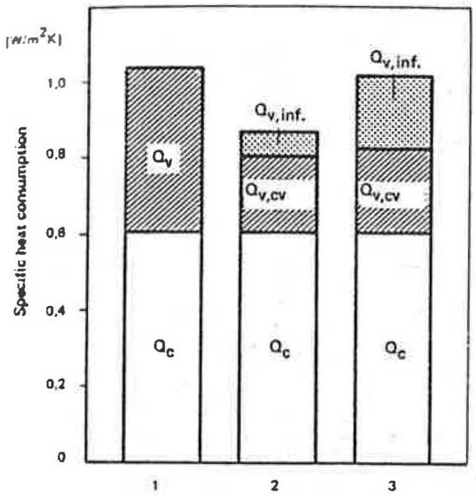

Fig. 6 Ventilation system without WHR

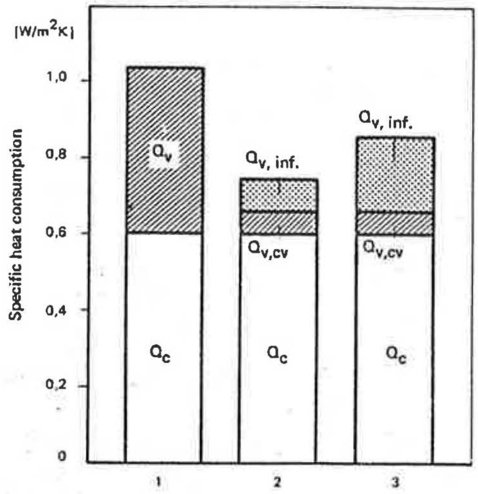

Fig. 7 Ventilation system using WHR

Ventilation heat losses due to air infiltration ($Q_{v,inf}$) and to controlled ventilation by the use of ventilation system ($Q_{v,cv}$)

1 - Only natural ventilation by air infiltration and by opening windows: air-change rate $n = 1.25h^{-1}$

2 - Design case for controlled ventilation, air-change rate by controlled ventilation $n_c = 0.6^{-1}$ and additionally by infiltration $n_{inf} = 0.2h^{-1}$

3 - Controlled ventilation providing $n_c = 0.6h^{-1}$ air-infiltration rate $n_{inf} = 0.6h^{-1}$ (major air leakages and/or window-opening habits)

ENERGY-SAVING POTENTIAL FOR THE FEDERAL REPUBLIC OF GERMANY BY THE REDUCTION OF VENTILATIVE HEAT LOSSES WITHIN 20 YEARS

The foregoing sections show that the time-mean ventilative heat losses amount up to 15 - 50 % of the entire heat losses for buildings. To estimate the total energy spent on ventilation in Germany we thus take an average value of 30 % for the ventilative heat loss per building (see Fig. 1).

For the prediction of the possible yearly energy saving accomplished by the reduction of ventilative heat losses we mainly consider two basic ways of saving:

- A 36 % reduction of ventilative heat losses by tightening the building, installment of improved systems for natural and mechanical ventilation (without waste heat recovery). Window-opening behaviour is supposed to conform with energy-saving measures. The 36 % reduction corresponds to a lowering in the air-change rate from 1.25 to 0.8 h^{-1}.
- A 68 % reduction, if additionally waste heat recovery (WHR) is applied to the portion of air-exchange of $0.6h^{-1}$ supplied by a mechanical ventilating system.

Not considered are additional savings by the change of heating habits or the use of energy-saving heating techniques.

The total amount of energy-saving that can be achieved by the 36 % and 68 % reduction measures, described above, depends upon the number of new and old buildings that satisfy these measures. These figures have been estimated on the basis of a moderate increase of energy prices (a), a medium increase (b) and a very high rate of price increase (c), Table 3 (Dornier, 1979). Based on these assumptions the number of buildings that will achieve a 36 % resp. 68 % saving of ventilative heat loss during the next 20 years was calculated.

The results for the calculation of energy-savings that could be achieved per year are given in Fig. 8. Depending on the assumptions of a moderate or an extreme high rate of energy-price development, in the year 2000 a saving of 105 to 190 Peta Joule (10^{15} Joule) can be expected. This is adequate to a percentage of 1.4 to 2.6 % of the 1976 net-energy consumption in the Federal Republic of Germany.

TABLE 3 Basic Data to the Different Presumptions for the Calculation of the Energy-Saving Potential by Reducing Ventilative Heat Losses in the Federal Republic of Germany

Presumptions	No. of retrofits per year for old buildings (built before 1980)	No. of new buildings per year	Yearly percentage of new and retrofitted buildings without energy-saving (scamped work in construction-incorrect occupant behaviour)	Yearly percentage of WHR in the construction year reached in the year 2000 (1980 less than 1 %)	
				New buildings	Retrofitted old buildings
a - moderate energy-price increase, few activities by legal authorities	700 000	350 000	30 %	30 %	12 %
b - medium energy-price increase, various legal activities	800 000	350 000	20 %	50 %	20 %
c - high energy-price increase, early and effective energy-saving measures by legal authorities	900 000	350 000	10 %	75 %	30 %

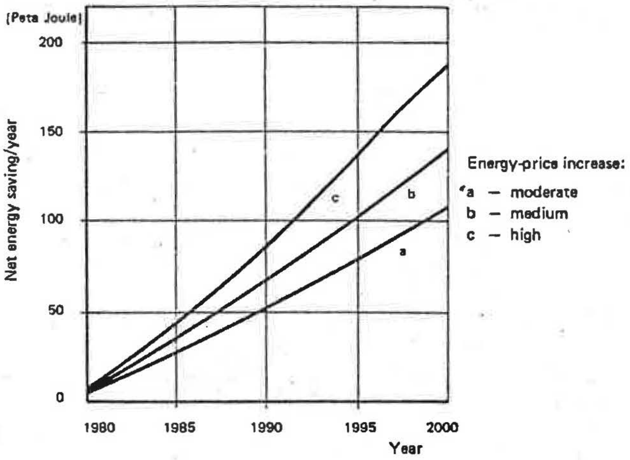

Fig. 8 Energy-saving potential by reduction of ventilative heat losses for the Federal Republic of Germany based on three different presumptions

SUMMARY AND CONCLUSIONS

By the application of simplifying assumptions to the heat balance in buildings it has been shown, that ventilation and air infiltration represent a major factor in the energy consumption of buildings. Feasible ways to reduce ventilative heat losses by reducing ventilation to a minimum demand necessary to ensure healthy and comfortable conditions have been discussed. If mechanical ventilation is being introduced additional savings can be achieved by waste heat recovery. For the heating demand in the Federal Republic of Germany possible energy-saving rates, accomplished by employing these measures have been estimated. In countries where different climatic conditions and different building structures from those prevailing in Germany exist, the method for the estimation of energy-savings due to the reduction in the ventilative heat losses, described above, basically can be applied if climatical and structural differences are taken into account.

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