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energy conservation by regulation of the central mechanical ventilation in high-rise buildings: realistic or not? *)

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Samenvatting

Teneinde meer inzicht te verkrijgen in de mogelijkheden tot energiebesparing door regeling van mechanische ventilatie in flatgebouwen is een onderzoek verricht. Hierin zijn in een flatgebouw, met een centraal mechanisch afzuigsysteem, volumestromen en luchtdrukverschillen gemeten en is de stand van de afzuigventielen genoteerd.
Met de gegevens uit deze metingen is een rekenmodel opgezet. Met dit rekenmodel is nagegaan hoe de ventilatie in een flatgebouw zich wijzigt bij verandering van de omstandigheden, zoals verkeerde afstelling van de afzuigventielen, al of niet openstaan van ramen en verlaging van het ventilatietoerental. Zo zijn voor ruim zestig omstandigheden alle luchtstromen en de daarbij behorende warmtestromen berekend.
Voor het geval de bewoners het nodig vinden om bij verlaagd ventilatortoerental de ventilatie in hun flatwoning op te voeren door het openen van extra raampjes, is nagegaan of- en in hoeverre er dan nog sprake is van een energiebesparing ten opzicht van de situatie bij vol ventilatortoerental en gesloten ramen.
Dit bewonersgedrag is hier echter niet onderzocht.

1. Introduction

Within the framework of energy conservation in dwellings, the Steering comittee, Energy and Buildings (SEG) has ordered the TNO Institute for Environmental Hygiene (IMG) to perform an investigation into the possibillities of achieving energy savings by the regulation of the mechanical ventilator units in high-rise buildings. [5]. The SEG was formed some years ago upon request of the Dutch Ministry of Housing and Physical Planning and the Ministry of Economic Affairs. The idea of regulating the ventilators at times when there is less requirement for ventilation, for example at night and outside the peak cooking and showering periods, has without doubt arisen from the popular conception that mechanical ventilation wasted energy. This supposed energy waste can be divided into:

- the energy consumption of the ventilator
- higher energy losses due to the ventilation air flow.

The energy consumption of the ventilator is only a small fraction(ca. 4%) of the energy required to warm up the ventilation air flow. It has not yet been shown that the average ventilation air flow for a heating season with mechanical ventilation is higher than that with natural ventilation. Dwellings that are equipped with mechanical ventilation systems have no natural ventilation channels and are therefore more impervious to air. Above a certain windspeed,it appears that the ventilation air flow in a dwelling with natural ventilation is greater than that for a dwelling with mechanical ventilation. Dwellings that are equipped with mechanical

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ventilation systems have no natural ventilation channels and are therefore more impervious to air. Above a certain windspeed,it appears that the ventilation air flow in a dwelling with natural ventilation is greater than that for a dwelling with mechanical ventilation. The wind speed at which this occurs depends, among other factors, on the

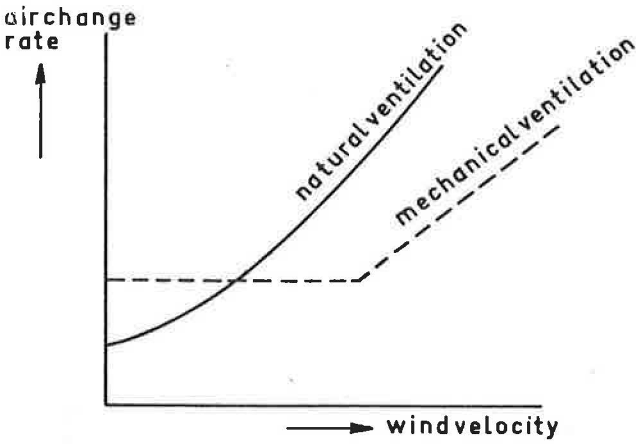

Fig. 1. The relation between the air change rate and the wind velocity.

wind direction and the hermeticity of the dwellings. (See Fig.1). The air flow in mechanical ventilation systems is, in principle, regulated according to the values given in the Dutch standard "Ventilation in Dwellings" (NEN 1087) [1].

This standard is based upon:
- health of the occupants
- technical and hygienic considerations.

According to the ventilation standard NEN 1087, a person needs a ventilation air flow of 0.007 m^3/s. This is equivalent to 25 m^3/hour. In a recent investigation of limited extent in office buildings [4], it was found that with such a ventilation air flow, about 10% of the occupants found the inside air unacceptable in terms of freshness.

The technical and hygienic considerations include:
- the prevention of the air in "wet" areas, such as the toilet, the kitchen, the bathroom and the shower; from becoming too damp, in which case mould growth could occur.
- the prevention of odours spreading from the above 'wet' areas to other parts of the dwelling.

A specified air flow is therefore required for these 'wet' areas. The ventilation standard (NEN 1087) states that the occupant of a dwelling must be able to achieve the required ventilation air flow with the use of the ventilation system provided. However, the occupant is left completely free in the manner in which he regulates the ventilation system: windows or grilles open or closed, ventilator fan(s) on or off. Mechanical ventilation is required in high-rise buildings and for open kitchens. Regulation of the ventilation is also permitted with mechanical ventilation, provided that the occupant is able to regulate the system so that it fulfills the requirements of the ventilation standard.

Recently, more and more publications have appeared on the subject of excessive radiation levels in dwellings as a result of radioactive gasses coming from building materials, and reports of excessive concentrations of other gasses, for example from chipboard.
In a number of these publications, the consequences of too low a level of ventilation are considered. In Sweden, in these circumstances, an air change rate standard of at least 0.5 per hour is used. The air change rates used in Holland are estimated to be between 0.5 and 1.0 per hour for mechanical ventilation. The air change rates for mechanical ventilation systems are thus certainly not excessive when compared to the Swedish standard.

The opening of windows will affect the energy consumption of a dwelling. In order to see how much the occupant can affect the energy consumption in this respect, a number of calculations with windows open and closed have been performed in this investigation.

2. Objectives

The object of this investigation was to see what energy saving could be achieved by the regulation of mechanical ventilation systems in high-rise buildings.

3. Investigation

The investigation can be divided into a number of parts:

(1) measurements on a mechanical ventilation system

(2) calculation model for this mechanical ventilation system

(3) measurements on the air leakage on the façades of a flat

(4) calculation model for this flat.

A calculation model (2) has been built for a mechanical ventilation system with twelve extractor points and a ventilator fan that can be used in two settings: "half" and "full speed". The system is based on the results of measurements on a flat in Delft (1). The calculation model provides the air flow in a building or part thereof, for example air flow through the:

- façades
- roof
- internal walls
- ventilation system.

For this, the calculation model uses data concerning:

- wind pressures
- air temperature differences that result in pressure differences
- fan characteristics
- characteristics of seams, joints, windows, doors, ducts and extractor vents.

In this calculation procedure, the air pressure at which the incoming and outgoing air flows are balanced, for each room, was ascertained.
The results from the first calculation model (2) and the air leakage values (3) which were determined within the framework of another project [2] were used to set up a second calculation model (4) of a flat. This can take account of variations in the positions of windows and doors, the wind speed and direction and the temperature inside and outside. This model delivers a prediction of the amount of energy lost due to the ventilation. The effect of open windows is simulated from the results of another investigation [3]. At this point it should be noted that in this project [3] measurements on windows were made on buildings mostly sheltered from the wind.

Many windows in high-rise buildings will not be in such a sheltered position, so that the wind will have a correspondingly greater effect on the ventilation and energy loss than the results calculated. The effect of an open window in an otherwise closed room can best be imagined by considering the window in two parts:

- one part through which air enters
- one part through which air exits.

The average air speed in such an open window lies in the range 0.1 to 0.5 m/s. In the case of a high building, with a high wind speed and an open window that catches the wind, the wind can actually blow as hard in the window opening as it does outside. An open window thus gives, per square metre of opening, an exchange of 0.5 x (0.1 ... 0.5) = 0.05 ... 0.25 cubic metres of air per second, and in certain circumstances even more. This is equivalent to 180 to 900 m^3/hour per square metre of window opening. This is an important factor for heating or cooling calculations, since large heat flows can arise as a result of an open window.

4. Methods of measurement and results

4.1 Measurements on a mechanical ventilation duct

Figure 2 shows a schematic diagram of the layout of the ventilation ducts from the kitchens of the block of flats in which the measurements were made. The toilets and the bathrooms in these flats were also mechanically ventilated.

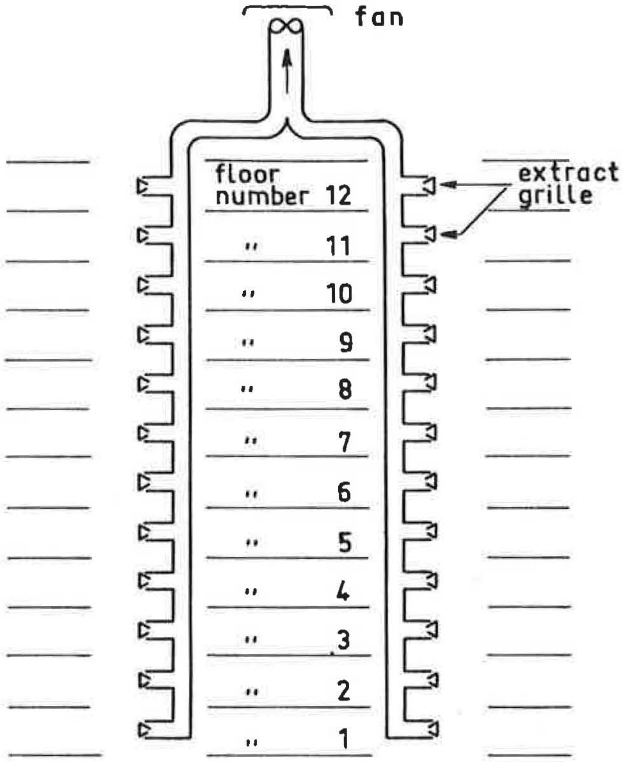

Fig. 2. Schematic diagram of the mechanical ventilation duct.

The measurements could not be performed simultaneously at all points. However, it appeared that the wind and the positions of windows and doors do not have great influence on the air flow and the pressures in the ventilation duct. Thus, the overall result of the measurements can be considered a good average. In Fig. 3, the arrows indicate the air flows and the dotted lines indicate the measured negative pressures in the duct.

The air flows were measured with a measuring orifice.

The pressure loss due to this orifice was compensated by an additional ventilator.

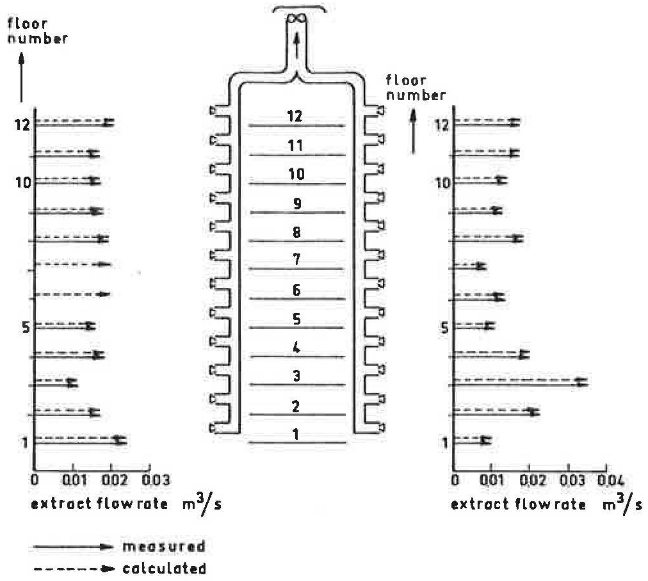

Fig. 3.1. Extract flow rates.

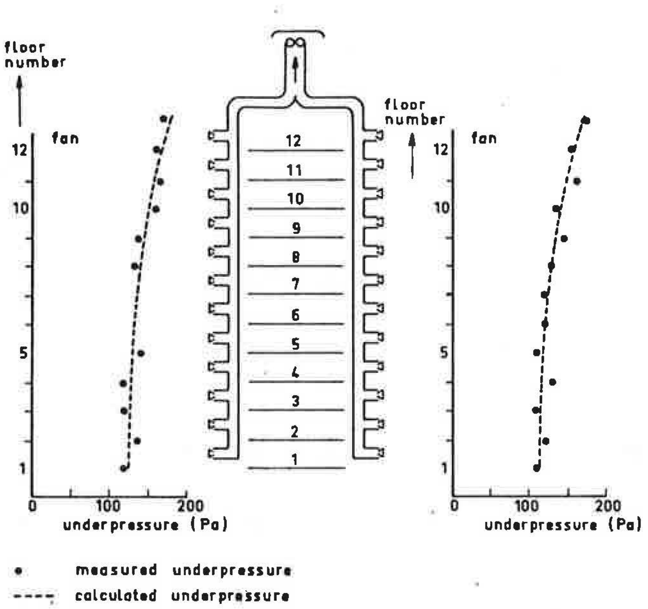

Fig. 3.2. Under pressure in the mechanical ventilation duct.

The extractor vents often had to be cleaned before measurements could be made. With a dirty extractor vent, the air flow was often less than 5% of the nominal flow. Many occupants had not previously realized that it is possible to clean extractor vents.

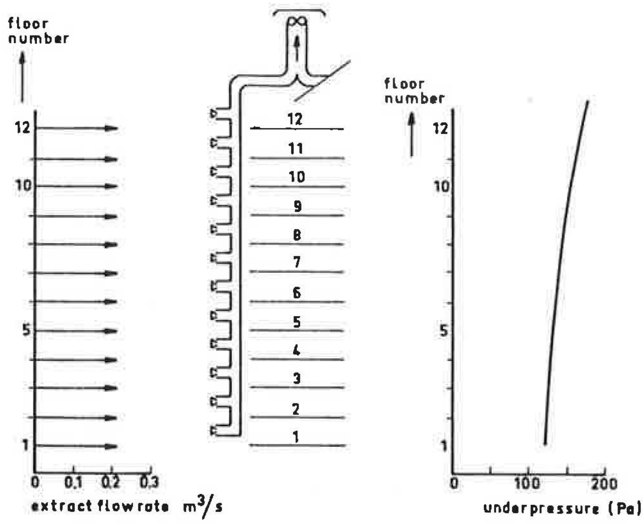

Fig. 4. The model used in further calculations. A flow rate of 0,021 m^3/s is extracted at every grille.

Most occupants were actually not satisfied with the air extraction in the kitchens. They often thought that the cooking vapours should disappear directly into the extractor vents. Even an extractor hood is not always capable of doing this. The kitchen window was therefore often opened during cooking. Moreover, some occupants had changed the original setting of the vent to achieve better air extraction. The kitchen door had been removed in many flats. This allows considerable spreading of vapours from the kitchen through the flat and, via the staircase, to other flats. The occupants complained about this and the mechanical ventilation system for these odours, while the cause must mainly be attributed to the missing kitchen doors and the, generally inevitable, chimney effect of the staircase.

4.2 Calculation model of the mechanical ventilation system

The calculation model was used to perform a simulation of the mechanical ventilation system in the block of flats in Delft. In fig. 3, the calculated air flows and negative pressures are indicated with broken lines. In this simulation, the air resistance of the different parts of the system and the capacity of the ventilator were chosen so that calculated air flows agreed with the measured values. The calculated negative pressures were at times at variance with the measured negative pressures. This is partly caused by the fact that all measurements could not be made simultaneously.

To limit the number of situations to be calculated, a model of the ventilation system for a column of twelve

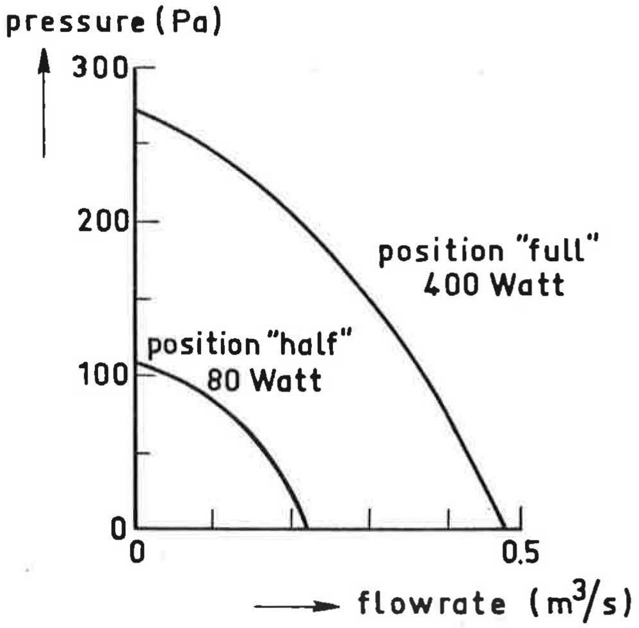

Fig. 5. Fan characteristics.

flats was made, in which nominally 0.021 m^3/s air was extracted per kitchen. (See Fig. 4). Calculations were performed for about sixty situations with this model, which included combinations of the following parameters:

- ventilator setting ''full'' or ''half''
- several windows open
- the setting of several extractor vents changed, or even one removed for cleaning purposes
- regulation to hold the negative pressure in the duct, at the ventilator, constant
- outside temperature 15°C or -5°C.

Figure 5 shows the ventilator characteristics for the settings ''full'' and ''half''. It is assumed that the pressure change in the kitchen due to opening a window is +40 Pa on the windward side and -40 Pa on the lee side. These pressure changes can be expected for a wind speed of 10 m/s. Figure 6 shows a summary of several situations that were calculated. In Figures 6.1 to 6.4, the ventilator was set to ''full'', while in Figures 6.5

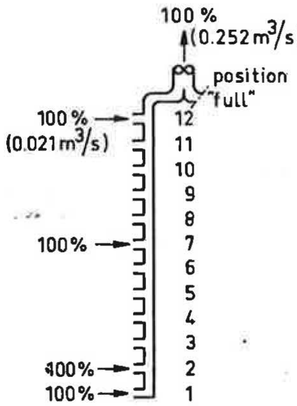

Fig. 6.1. Reference situation. Fan switched on ''full''.

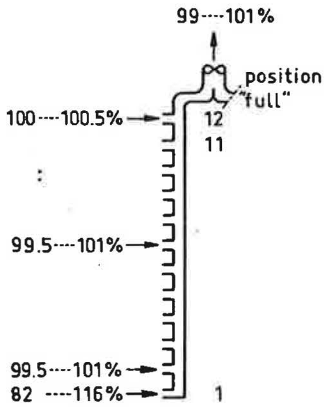

Fig. 6.2. Open window on the first floor. (leeward...windward side)

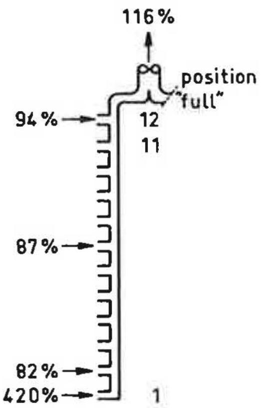

Fig. 6.3. Grille on the first floor removed.

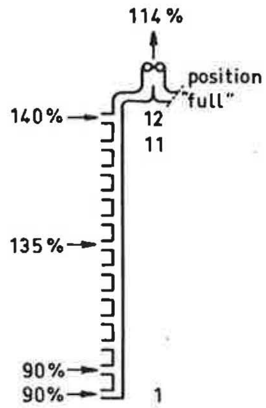

Fig. 6.4. Upper six grilles opened 1.5 x more wide.

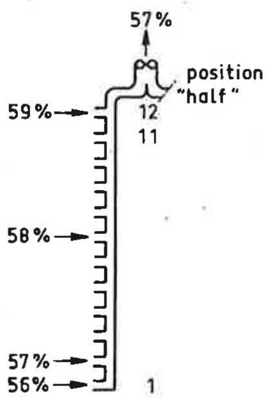

Fig. 6.5. Reference situation. Fan switched on ''half''.

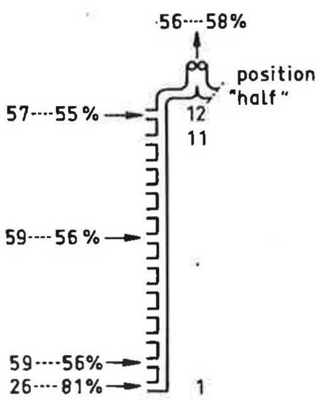

Fig. 6.6. Open window on the first floor. (leeward...windward side)

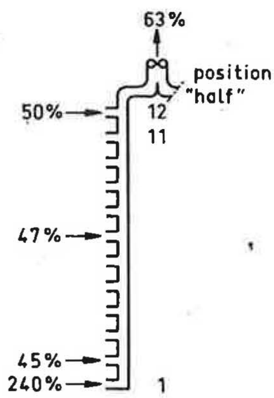

Fig. 6.7. Grille on the first floor removed.

to 6.7 it was set to "half". The values adjoining the figures give the ratio of several air extraction flows compared to a reference situation (0.021 m^3/s in Fig. 6.1 and 0.012 m^3/s in Fig. 6.5).
The effect of opened windows on the air flows on other floors appears to be a maximum of 1% in Fig. 6.2 and a maximum of 3% in Fig. 6.6. The removal of an extractor vent reduces the air flow on other floors by a maximum of 8% in Fig. 6.3 and by a maximum of 24% in Fig. 6.7.

With the ventilator at "full" setting, the effect of changing the setting of the extractor vents was examined: the vents on floors 7 to 12 were opened an extra 50%. (See Fig. 6.4). On the other floors (1 to 6) the air flow appeared to be reduced by about 10%. The negative pressures with the ventilator at "half" setting were about 50 Pa (170 Pa at "full" ventilator setting). With the wind pressures of +40 Pa and -40 Pa that are assumed, no flow reversal will occur in the ventilation duct. A further reduction of the negative pressure could well lead to flow reversal (see Fig. 7).

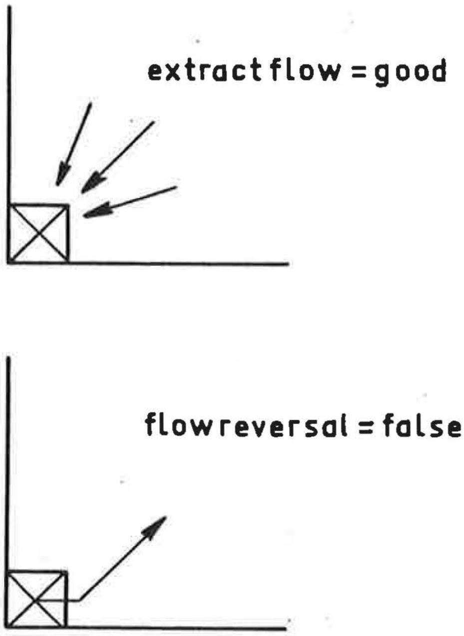

Fig. 7. Extraction and flow reversal in ventilation ducts.

4.3 Air leakage

Figure 8 shows the plan of the flat for which, in the scope of another project [2], air leakage measurements were made on the facades. Equation [1] gives the air flow through a façade as a function of the air pressure difference Δp across the element, the air leakage C and the exponent n that describes the cause of the flow.

$$q = C \cdot (\Delta p)^{1/n} \quad \text{(1)}$$

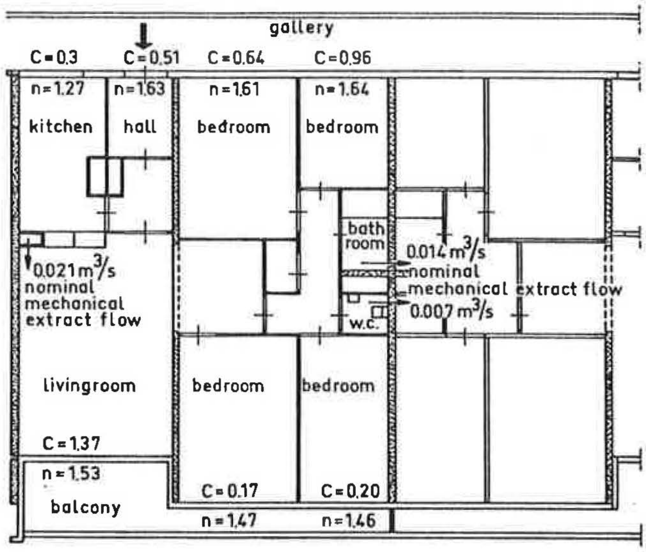

Fig. 8. Floorplan of the flat in Delft. Air leakage coefficients and exponents are indicated.

4.4 Calculation model for the flat

A calculation model for one of the twelve flats was set up based on the measured air leakge of the flat. Using this model, the air leakage through the facades, internal walls and the extractor vents of the kitchen, toilet and bathroom and the heat flow due to ventilation were calculated. This was performed for about 95 situations in which combinations including the following parameters were chosen:
- setting of the ventilator "full" or "half"
- several windows open
- air leakage of the flat
- wind speed and direction
- situation and surroundings of the block of flats from a wind protection point of view.

Several results of this calculation model are presented in Fig. 9. The calculations were made for an air temperature difference of 20°C between inside and outside. The reduction in the energy consumption as a result of the lower power of the ventilator at low speed is not included in Fig. 9. This ventilator, for 24 flats, has a power of 400 W at "full" setting and 80 W at "half" setting. This means a saving of 13 W (electrical) per flat. These figures are extremely dependent on the type of ventilator used.

From Fig. 9, it can be seen that with the ventilator at "half" setting, the heat loss due to ventilation for a flat is 200 W to 400 W lower than with the ventilator on "full" setting. Comparing the heat flow due to ventilation for the ventilator at "half" setting and various windows open with that for the ventilator at "full" setting and all windows closed, we see from Fig. 10 that:

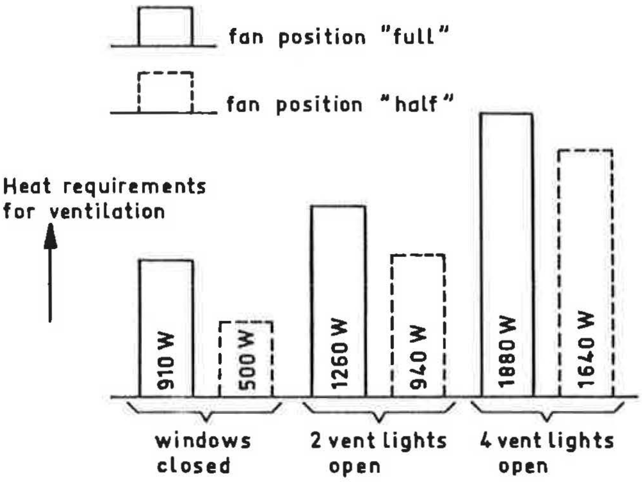

Fig. 9. Mean heat required for warming up the ventilation air per flat.

- by opening two windows the heat flow is already higher
- with four windows open, the heat flow is 700 W higher.

For a heating season of 200 days and a boiler efficiency of 60%, this value of 700 W is equivalent to 630 m^3 natural gas (35 MJ/m^3) per year. Despite the reduced mechanical ventilation, the energy consumption is thus increased by the extra opening of windows, see Fig. 11.

The calculation model was also used to see if, with the ventilator on "half" setting, odours could spread into the flat, for instance from the toilet, see Fig. 12. For these calculations, a temperature difference of 4°C was assumed between the toilet and the rest of the flat. Even with the ventilator on "half" setting, this temperature difference had virtually no effect on the air flow through the door joints of the toilet. No spreading of odours occurred. With the door open, however, there is certainly a spreading of odours, but this is almost independent of the size of the extraction air flow and

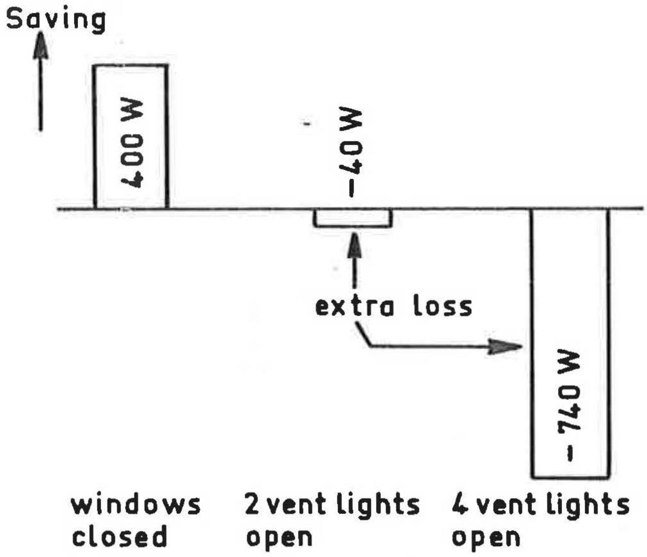

Fig. 10. "Energy savings" per appartment due to switching the fan from "full" to "half"

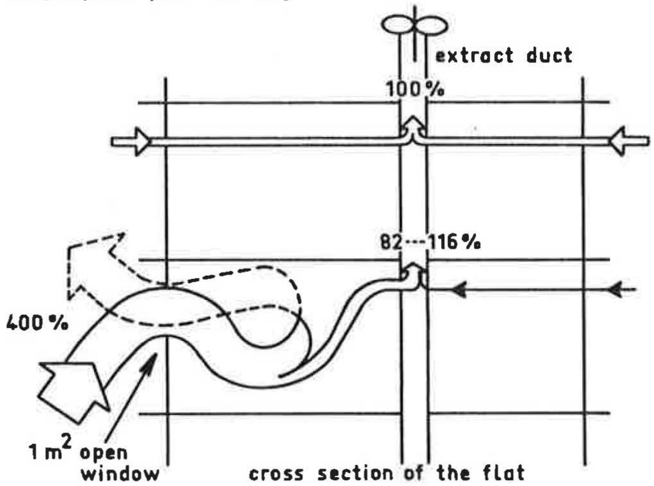

Fig. 11. Ratio of air flows through:
- *mechanical ventilation system*
- *closed windows*
- *open windows.*

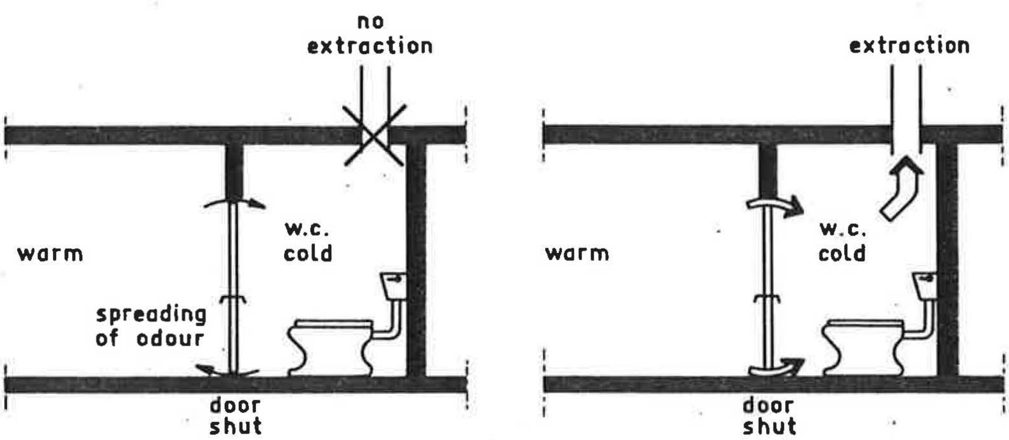

Fig. 12. Spread of odours through a shut door.

therefore will really not increase due to reduction of the ventilator speed. For internal spaces with all doors closed, the ventilation air flow will be lower than required by the ventilation standards. In these cases, the chance of damp problems arising will therefore be greater. We have known cases in which the regular switching off of the mechanical ventilation system has lead to condensation and mould growth in bathrooms.

5. Conclusions

The reduction of ventilator speed in a communal mechanical extractor system has no disadvantageous consequences for the operation of the system, provided that the negative pressure in the duct remains about 50 Pa.
From this investigation, it appears that the extracted air flow is affected more by incorrect adjustement and fouling of extractor vents than by opening of windows, regardless of whether the ventilator is at the "full" or "half" setting.
The extra energy loss due to several open windows appears to be greater than the energy saving possible by reducing the ventilator speed. The energy saving possible is then also completely dependent on the reactions of the occupants: if they open a window for a couple of hours a day, the overall energy consumption can be increased instead of being decreased, regardless of the lower speed of ventilation.
When the mechanical ventilation is reduced, the occupants are still able, in general, to set a sufficient ventilation air flow in rooms that have either a ventilation window or grille. Further, with reduced mechanical ventilation and windows and internal doors closed, the spreading of odours from the "wet" rooms is not to be expected. The chance of damp problems arising in these "wet" rooms will, however, be greater. The saving in electricity due to reduction of the ventilator speed is only a fraction (about 4%) of the energy losses that can be associated with the ventilation.

6. Acknowledgement

The author gratefully acknowledges the financial support provided by the Netherlands Ministry of Housing and Physical Planning.

7. List of symbols

C	air leakage	(m^3/s at 1 Pa)
n	exponent in equation (1) ($1<n<2$)	(-)
p	air pressure compared to external reference pressure	(Pa)
Δp	difference in air pressure, for example across a facade	(Pa)
q	air flow	(m^3/s)

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