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Air flows in dwellings—simulations and measurements

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Abstract

A study of the reliability of systems by considering the ability of different systems to maintain a required air flow rate over time is included in a subtask of IEA Annex 27 'Evaluation and Demonstration of Domestic Ventilation Systems'. Measurements and calculations were performed to determine the variation in ventilation rates due to variation in climate and variation in performance of the ventilation system. Dwellings with passive stack, mechanical exhaust and mechanical exhaust-supply ventilation, representative of the Swedish housing stock, were studied. Diagnostic tests were carried out, to discover if the installed ventilation system was functioning as designed e.g. air flows in mechanical ventilation systems and to determine certain values e.g. airtightness. The continuous monitoring included tracer gas measurements in dwellings of overall and local (individual rooms) ventilation rates, and measurements of boundary conditions, during three different periods, each lasting 1–6 days. Predictions of air flows were made for the measuring periods using COMIS, a multi-zone network model. This article presents and discusses the measurements and the calculations and compares the two. The predicted and measured average total outdoor air ventilation rates agree reasonably well. The agreement is less good for individual rooms.

Keywords: Air flow; Measurements and calculations; Ventilation system

1. Introduction

The overall scope of IEA Annex 27 'Evaluation and Demonstration of Domestic Ventilation Systems' is to establish a general evaluation tool, which makes it possible to pre-evaluate the overall performance of different ventilation systems for domestic buildings in different climates. A number of performance criteria are dealt with within the annex. They include e.g. air quality, thermal comfort, energy, noise, life-cycle costs, moisture and reliability. The Swedish part of the research in the annex covers the reliability aspect of domestic ventilation, i.e. the ability of different systems to maintain a required flow rate over time. The work is divided into:

1. numerical simulation of ventilation in typical dwellings
2. measurements in representative dwellings
3. numerical simulation of measured dwellings and comparison with the measurements
4. development of a design tool for determining the reliability of a ventilation system
5. application of the developed design tool on typical dwellings.

This article presents results from phase 2 and 3, which were carried out during 1995.

2. The dwellings tested

The dwellings which were examined in this project represent typical Swedish buildings. They are representative as to building technology, size of the building and ventilation system (see Figs. 1 and 2).

Important criteria, when choosing the dwellings, were type of ventilation, year of construction, and number of storeys (see Table 1).

The dwellings with passive stack ventilation have exhaust air terminal devices in rooms such as bathrooms, kitchens and laundryrooms and sometimes outdoor air supply to the other rooms through outdoor air vents near windows. The exhaust air terminal devices are attached to a vertical shaft to the outside. Space heating is provided for by radiators located below windows.

The dwellings with exhaust fan ventilation have exhaust air terminal devices in rooms such as bathrooms, kitchens

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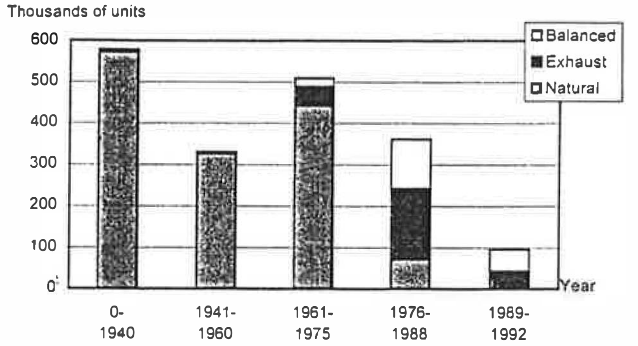

Fig. 1. Year of construction and ventilation system for the Swedish one-family housing stock [11].

and laundry-rooms and outdoor air supply to the other rooms through outdoor air vents near windows. The tested one-family house does not have any outdoor air vents. Space heating is provided for by radiators located below windows.

The dwellings with balanced ventilation have exhaust and supply ventilation. Air is exhausted from rooms such as bathrooms, kitchens and laundryrooms and air is mainly blown into bedrooms and living-rooms. The dwellings are equipped with radiators for space heating and with heat recovery.

3. Methods

3.1. Introduction

The measurements were started with diagnostic tests to discover if the installed systems were functioning as designed and to determine certain values:

–measurements in order to determine air flows in ducts of mechanical ventilation systems
–pressurization in order to determine airtightness of building envelope and ducts
–IR-scan in order to determine location of the leakage paths
–measurements of size of air terminal devices in passive stack ventilated dwellings

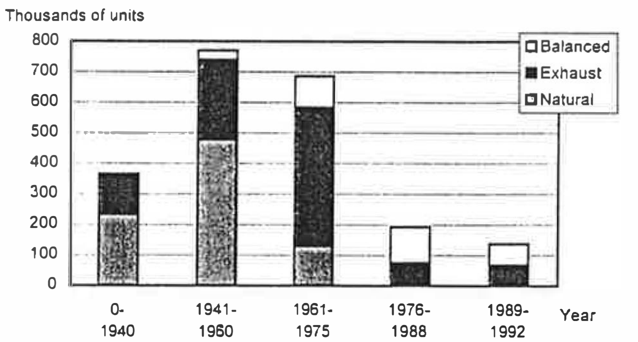

Fig. 2. Year of construction and ventilation system for the Swedish multi-family housing stock [11].

Table 1
The tested buildings

Ventilation system	Year of construction	Number of storeys	Floor area (m^2)	Remark
Apartment building				
Balanced	1988	4	120	Ground floor
			114	Top floor
Exhaust	1990	3	58	Ground floor
			50	Top floor
Passive stack	1955	3	56	Ground floor
			55	Top floor
One-family house				
Balanced	1991	1 1/2	128	Crawl-space
Exhaust	1976	1 1/2	160	Slab on grade
Passive stack	1958	1	114	Basement

The actual monitoring phase (during a winter, spring/fall and summer period) included:

–constant concentration tracer gas during 1–6 days to determine hourly variations in ventilation rates in unoccupied dwellings.
–passive tracer gas in order to determine monthly averages of ventilation rates in occupied dwellings. These measurements are not presented in this article.

During the monitoring phase the boundary conditions were determined as follows:

–the outdoor temperature at the site was measured
–the indoor temperature was measured in at least two rooms
–the wind speed and direction was measured at a nearby weather station

Simulations of the air flows during the monitoring phases were made using COMIS, a multi-zone network model.

3.2. Airtightness

The standard method for finding the leakage function of a building is fan pressurization. According to the Swedish standard for fan pressurization [10] all openings in the exterior envelope intended for ventilation purposes must be sealed before the test is performed. Other openings are kept closed. For the purpose of modelling air infiltration and exfiltration, a second test was also made, with open supply vents in the dwellings with exhaust ventilation and with open vertical shafts in the dwellings with passive stack ventilation. Rooms with separate ventilation such as boiler rooms and garages were disregarded. The estimated inaccuracy in the measured airtightness is $\pm 10\%$.

3.3. Ventilation

The most straightforward method of measuring the total ventilation rate i.e. the combined effect of mechanical ventilation and natural ventilation or natural ventilation

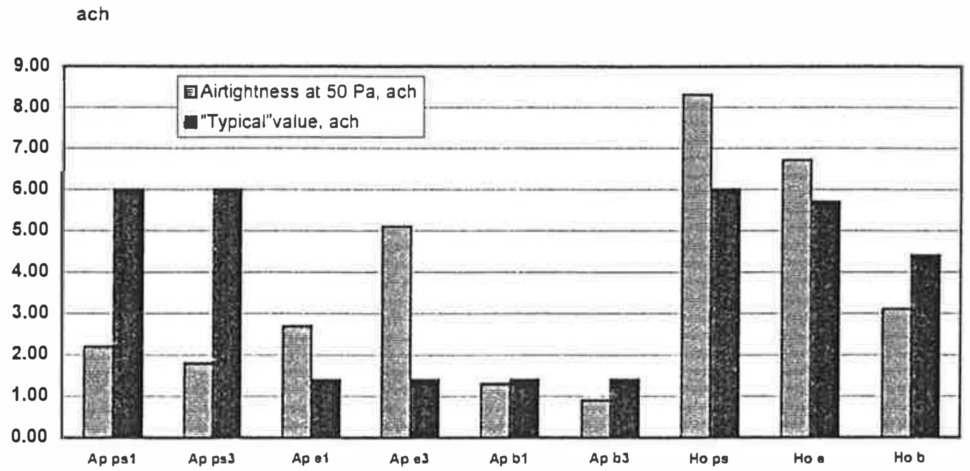

Fig. 3. Measured airtightness of tested buildings compared with estimates for the Swedish housing stock ('Typical'). Ap = apartment, Ho = house, ps = passive stack ventilation, e = mechnical exhaust ventilation, b = mechanical balanced ventilation.

only is to measure it directly. There are many ways of measuring total ventilation, and almost all of them involve a tracer gas, which permits the indoor air to be labelled so that the outdoor air ventilation can be traced [3]. If the ventilation is mechanical with ducts, then in most cases the air flow in the ducts should first be measured using techniques for volume and mass flow rate measurements, without a tracer gas [1,8]. These air flows were measured at the air terminal devices, with an anemometer fitted with a hood. The estimated inaccuracy for the measured exhaust air flows is $\pm 5\% + 0.5$ l/s and for the measured supply air flows $\pm 7\% + 0.5$ l/s.

The short-term measurements in the dwellings tested were carried out using the constant concentration technique in order to evaluate hourly variations in the total and individual room ventilation rates [2]. The outdoor air ventilation is obtained directly. The supply of outdoor air to several individual rooms simultaneously is monitored continuously, i.e. outdoor air which enters an individual room directly instead of first passing through an adjacent room. The estimated inaccuracy in the measured outdoor air ventilation rate is $\pm 8\% + 0.5$ l/s.

3.4. Temperature

The indoor and outdoor temperatures were recorded using thermistors connected to one-channel dataloggers. Each logger stores 1800 values. The duration of the measurements can be varied from 15 min to 360 days. The estimated inaccuracy is ± 0.5 K.

3.5. Simulations— input

Average pressure coefficients were determined using values from wind tunnel measurements [9,4]. Each façade was given an average value, as it is very difficult to determine pressure coefficients for individual openings, whose location are uncertain anyway. The shielding conditions in different directions were considered when choosing the pressure coefficients. The ceiling was given the pressure coefficient 0.0, as being well shielded by the roof. The total ventilation rate is not very sensitive to this pressure coefficient. Calculations for the dwellings tested show that, if the pressure coefficient is -0.25 instead of 0.0, then the change in total ventilation rate will be in the range of 3%. For the passive stack ventilated dwellings, the pressure coefficient at the top of the passive stacks was assumed to be -0.3 [9]. A previous study showed that this pressure coefficient is important. A reduction to 0.0, reduced the total ventilation rate by 15% at a wind speed of 2.1 m/s [2]. Wind direction and velocity were measured at a weather station 10 km from the site. Local wind conditions were calculated by COMIS, taking building height and surrounding buildings into account.

The dwellings were divided into different zones where each room is equal to a zone. This was done in order to be able to better compare with the constant concentration

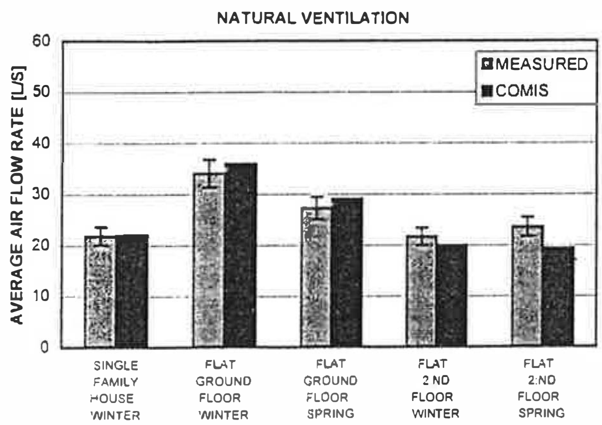

Fig. 4. Comparison between measured and predicted average total outdoor air ventilation rates in the passive stack ventilated dwellings.

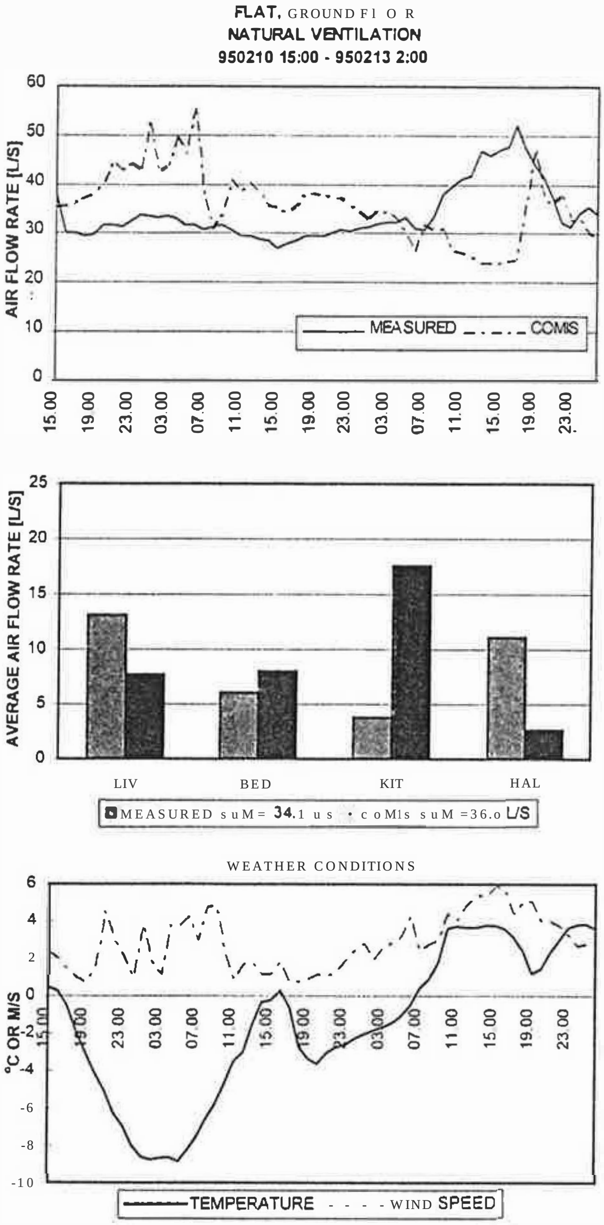

Fig. 5. Measured and predicted outdoor air ventilation rates for the passive stack ventilated apartment on the ground floor. The top figure shows the total ventilation, the middle one shows the ventilation of individual rooms and the lowest one shows the weather.

tracer gas measurements. The indoor temperatures were measured and stored as hourly averages. Most doors were closed. The leakage through an open door was calculated using the standard equation for a non-ideal sharp-edged orifice. The open door was usually divided into two leakage paths at 1/4 and 3/4 of the door's height. For closed doors the geometry of the crack round the doors was measured. Using the basic equations for fluid flow [5,6] through ducts and obstructions a power function was determined describing the air flow through the closed door. The interior walls and intermediate floors were assumed to be airtight, which in comparison with open doors and the crack around an interior door should be correct.

The air leakage of the building envelope is based on the results from a fan pressurization/depressurization test combined with an IR-scan of the entire dwelling. The air leakage of the entire dwelling is described with a power function. The average value of the pressurization and depressurization test was used, as the leakage paths are likely to experience positive and negative pressure differences.

The result of the IR-scan and knowledge of the construction technique was used to determine the location of the leakage paths. Firstly the overall leakage was distributed to the facades, the ceiling and the floor according

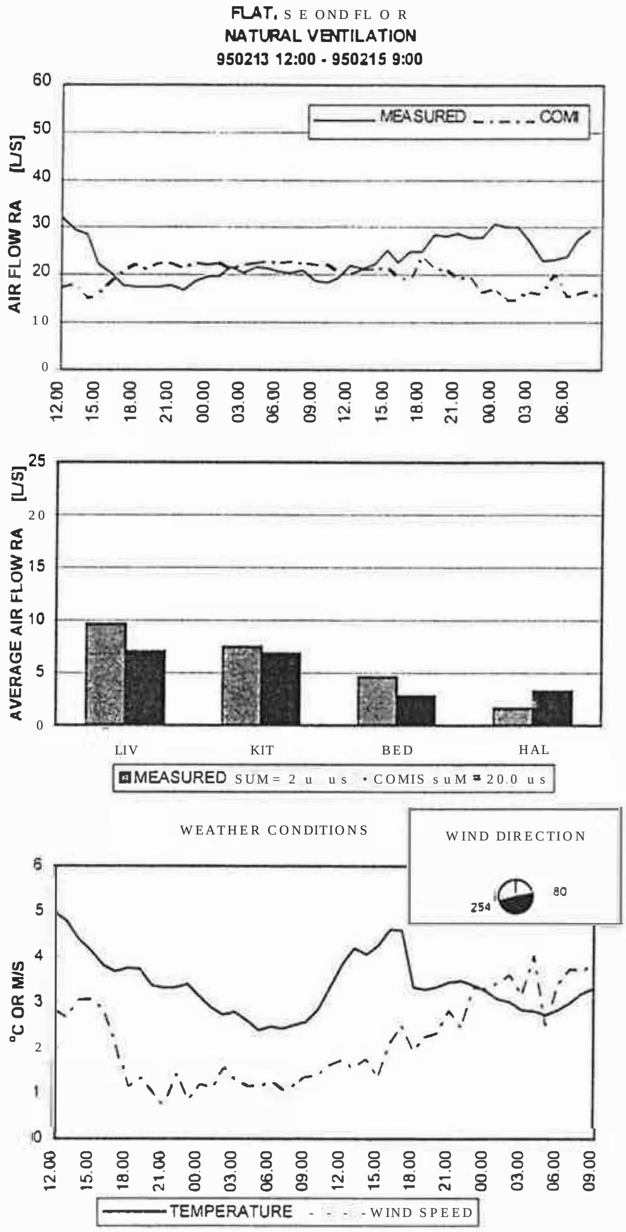

Fig. 6. Measured and predicted outdoor air ventilation rates for the passive stack ventilated apartment on the second floor. The top figure shows the total ventilation, the middle one shows the ventilation of individual rooms and the lowest one shows the weather.

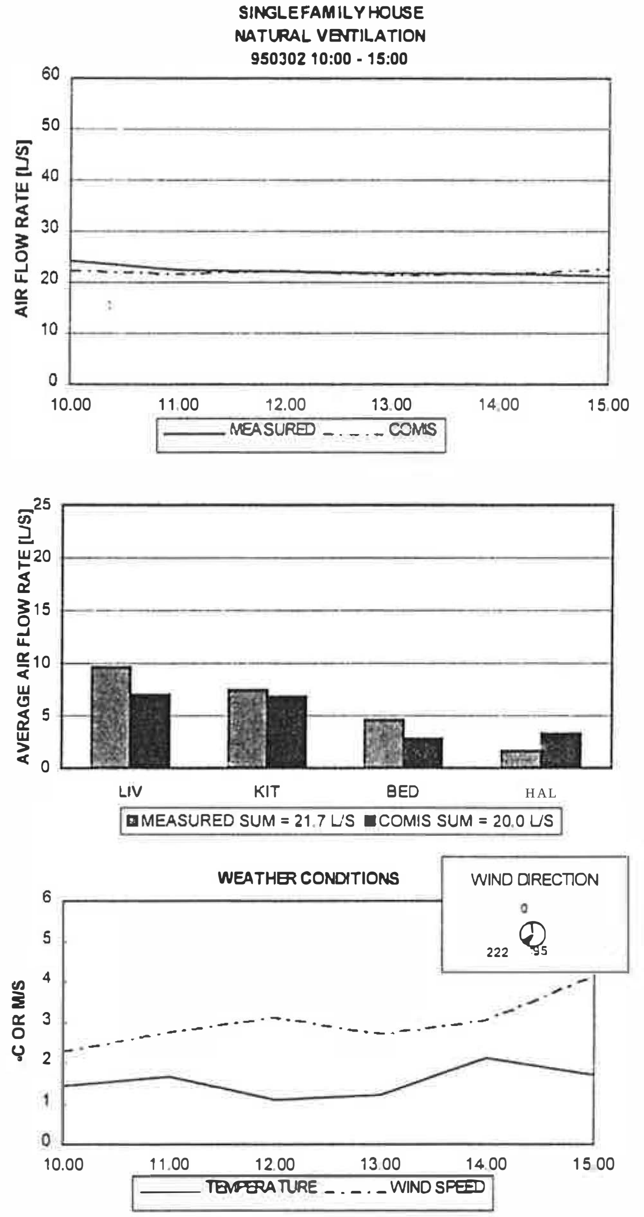

Fig. 7. Measured and predicted outdoor air ventilation rates for the passive stack ventilated one-family house. The top figure shows the total ventilation, the middle one shows the ventilation of individual rooms and the lowest one shows the weather.

to each components area. For some dwellings the overall leakage of an individual room was increased based on the result of the IR-scan. Secondly on each facade 50% of the air leakage was assumed to be located 0.6 m above the floor (representing cracks between the floor and the wall, and windows), and 50% 1.8 m above the floor (representing windows and cracks between the ceiling and the floor). All leakage paths were given the same air flow exponent i.e. the one determined by the airtightness test. It is almost impossible for a real dwelling to determine the leakage characteristic for all the individual leakage paths.

The mechanical ventilation systems themselves weren't simulated, as the main interest was to study the interaction between air flows and the building envelope. For each air terminal device a fixed flow was given based on measurements. For the dwellings with passive stack ventilation, the stacks were simulated as zones with openings in the bottom and at the top. The flow resistance of the duct part of the passive stacks was included as a single resistance. The characteristics of the exhaust air terminal devices in the passive stack systems, were taken from data supplied by the manufacturer and from laboratory measurements.

4. Results

4.1. Airtightness

The average airtightness of the tested apartments is 2.3 air changes per hour (at 50 Pa), compared with 6.0 for the tested one-family houses. In a previous study the airtightness as a function of year (–1940, 1941–1960, 1961–1975, 1976–1988) of construction was presented [7]. Most of the tested buildings are fairly representative for their year of construction, with the exception for the apartments with passive stack and exhaust ventilation. The tested apartments with passive stack ventilation are much tighter and the ones with exhaust ventilation leakier (see Fig. 3).

4.1.1. Passive stack ventilation

The average total outdoor air ventilation rates for the measuring periods show a reasonable agreement between simulations and measurements (see Fig. 4). The simulation is very close to the measurement for the one-family house. The underprediction is 1%, while for the apartments the differences are larger.

The hourly averages show that the overall ventilation rate varies over time. This is especially true for the winter measurements in the apartment on the ground floor, where

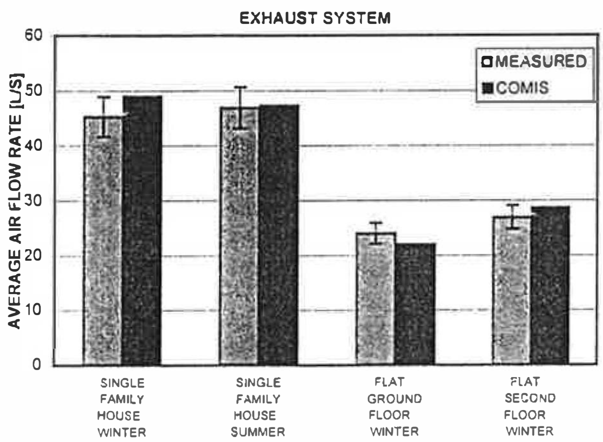

Fig. 8. Comparison between measured and predicted average total outdoor air ventilation rates in the exhaust fan ventilated dwellings.

the total outdoor air ventilation varies between 27 l/s (0.6 ach) and 52 l/s (1.4 ach) (see Fig. 5). During this period the outdoor temperature varied between −9°C and +4°C, and the wind between 0.7 m/s and 6 m/s. Simulations and measurements show hourly variations in the total ventilation rate of the same magnitude, but not always at the same time. For the apartment on the ground floor the simulations indicate a temperature dominated ventilation, while the measurements indicate more of a wind dominated ventilation (see Fig. 5).

The outdoor air ventilation rates are very different for different rooms (see Figs. 5–7) and is e.g. too low in the bedrooms of the one-family house (see Fig. 7). The disagreement between predictions and measurements is fairly large for some individual rooms e.g. the kitchen in the apartment on the ground floor.

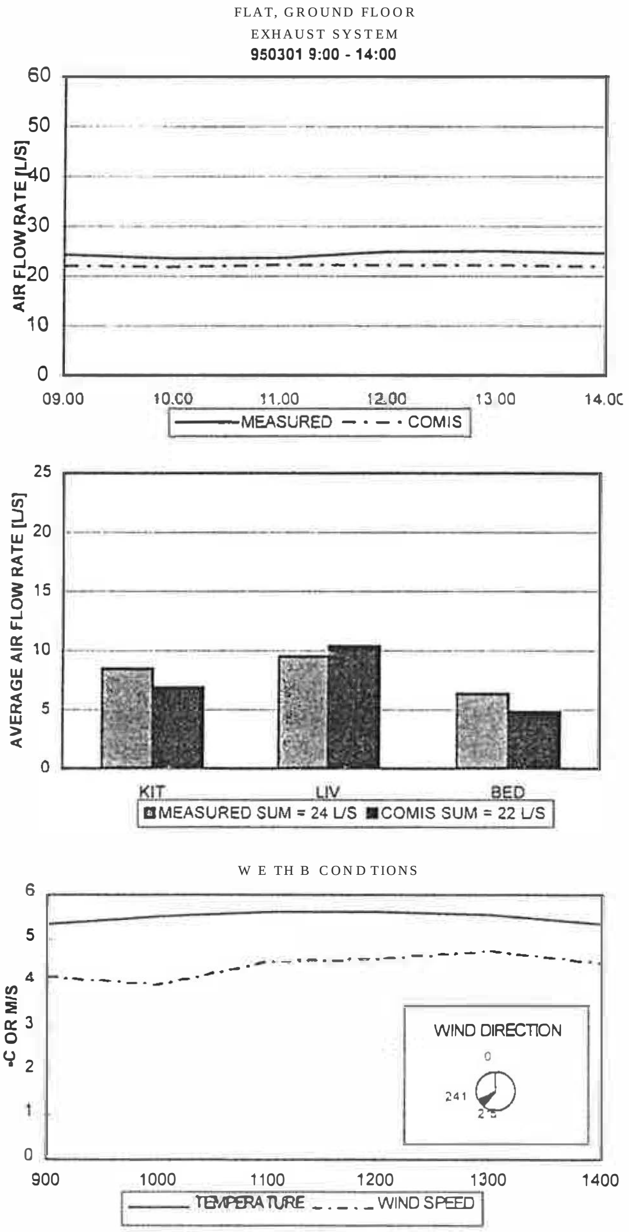

Fig. 9. Measured and predicted outdoor air ventilation rates for the exhaust fan ventilated apartment on the ground floor. The top figure shows the total ventilation, the middle one shows the ventilation of individual rooms and the lowest one shows the weather.

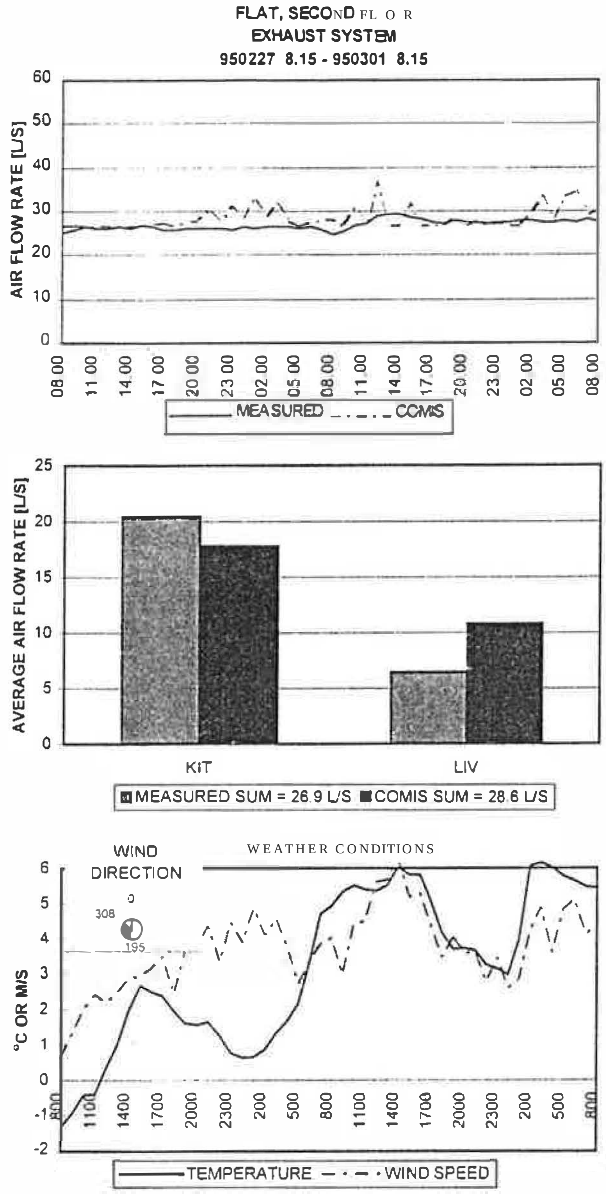

Fig. 10. Measured and predicted outdoor air ventilation rates for the exhaust fan ventilated apartment on the second floor. The top figure shows the total ventilation, the middle one shows the ventilation of individual rooms and the lowest one shows the weather.

4.1.2. Exhaust ventilation

The agreement between simulations and measurements of the average total outdoor air ventilation rates for the measuring periods is good (see Fig. 8). The predictions vary between an overprediction of 8% and an underprediction of 8%.

The continuous measurements of the overall outdoor air ventilation in two apartments show some variation over time in the ventilation rate (see Figs. 9 and 10). For the apartment shown this is probably due to fairly leaky exterior walls. The average measured ventilation rate was 27 l/s (0.75 ach). Both predictions and measurements show a slight variation in total ventilation rate. It is difficult to determine whether the variations are correlated to each other or not.

The outdoor air ventilation rates of individual rooms show some rooms to have too low a ventilation rate e.g. bedroom 3 and 4 upstairs in the one-family house (see Fig. 11) and some rooms to have too high a ventilation rate e.g. the kitchen in the apartment on the second floor (see Fig. 10). The agreement between predicted and measured ventilation rates is for most rooms good.

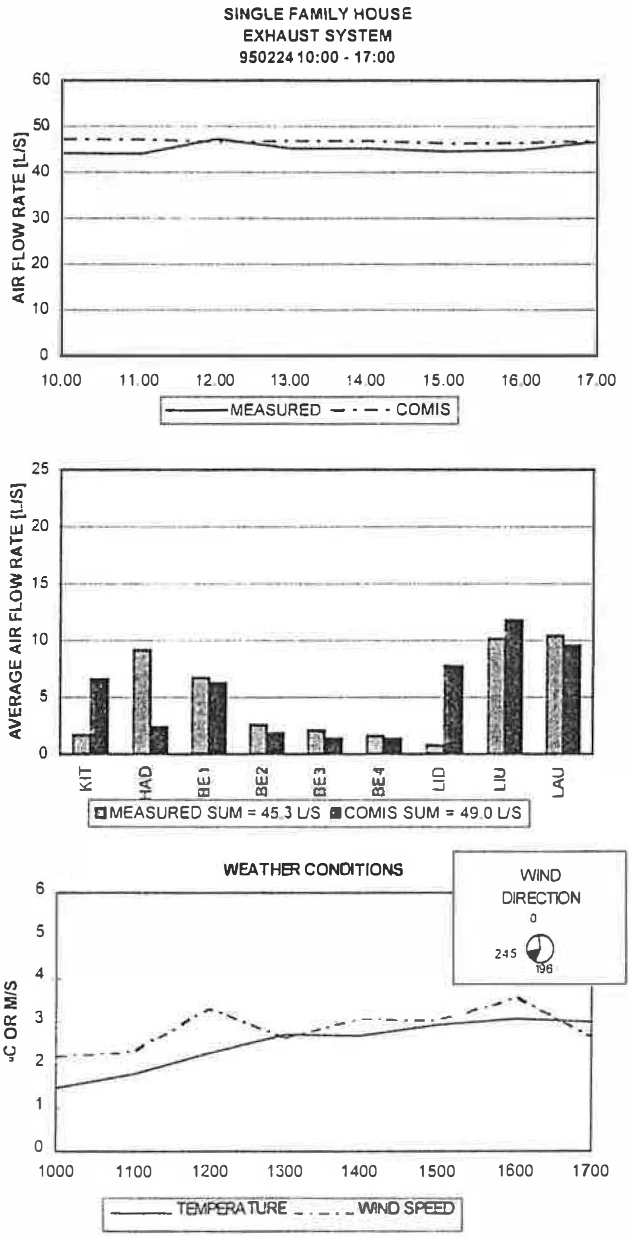

Fig. 11. Measured and predicted outdoor air ventilation rates for the exhaust fan ventilated one-family house. The top figure shows the total ventilation, the middle one shows the ventilation of individual rooms and the lowest one shows the weather.

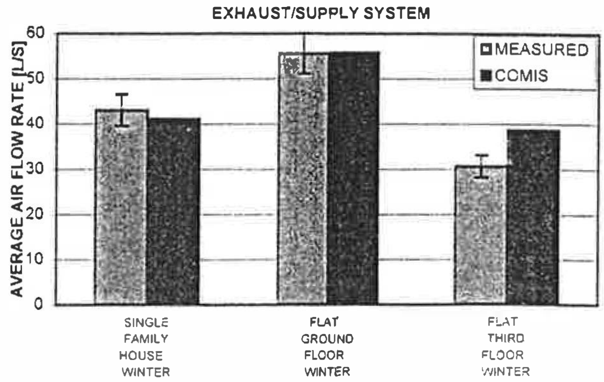

Fig. 12. Comparison between measured and predicted average total outdoor air ventilation rates in the dwellings with mechanical exhaust and supply ventilation.

4.1.3. Balanced ventilation

The agreement between simulations and measurements of the average total outdoor air ventilation rates for the measuring periods is good (see Fig. 12). The predictions vary between an overprediction of 26% and an underprediction of 4%.

Both apartments have an almost constant outdoor air ventilation due to a high level of airtightness (see Figs. 13 and 14).

The measured (tracer gas) ventilation rates of individual rooms, in the dwellings with balanced ventilation, agree well with the measurements of the air flows through the supply air terminal devices (Fig. 15). The exfiltration is very low, as the building envelopes have a good level of airtightness. Therefore the predictions should agree well with the tracer gas measurements and so they do.

5. Conclusions

The outdoor air ventilation rates in the dwellings with passive stack ventilation varied over time, as could be expected. Some of the individual rooms had an outdoor air ventilation rate, which at times were too low. The predicted and measured average total outdoor ventilation rates agree reasonably well. The hourly variations often disagree. For individual rooms the predicted and tracer gas measured outdoor air ventilation rate can be very different.

The exhaust ventilated dwellings had a reasonably constant outdoor air ventilation rate over time. The ventilation rate would have been more constant, if the dwellings had fulfilled e.g. the airtightness requirements of the Swedish Building Code. Individual rooms sometimes had too low an outdoor air ventilation rate. This was especially true for the leaky one-family house, which had no outdoor air vents. If the house had fulfilled e.g. the airtightness re-

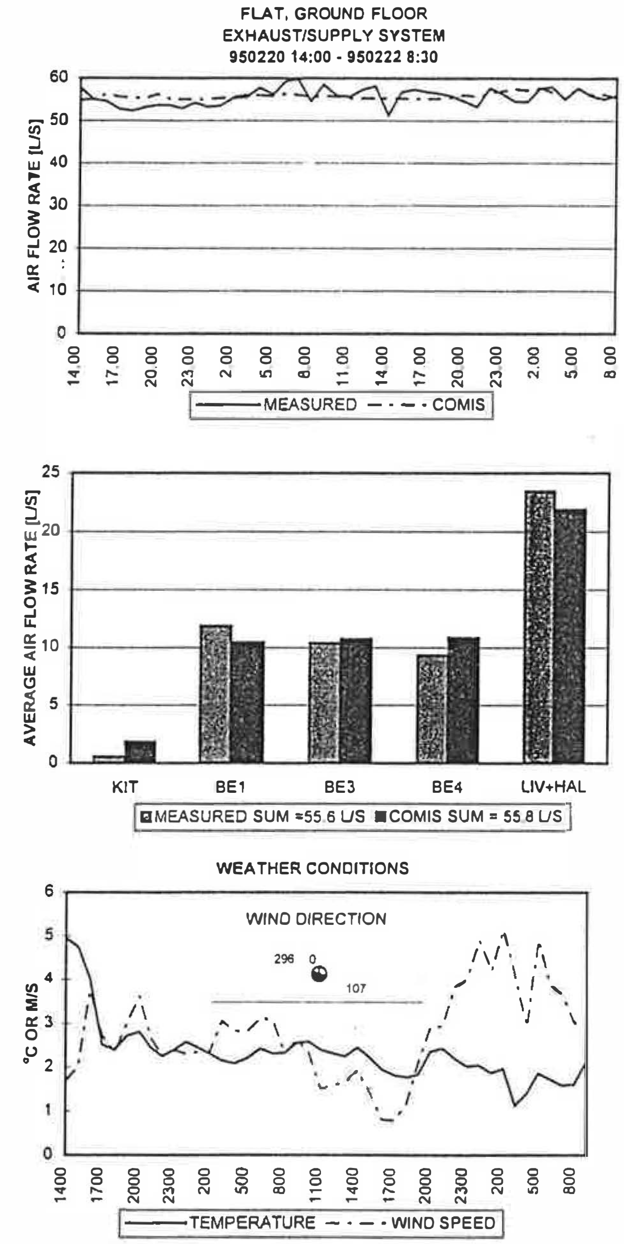

Fig. 13. Measured and predicted outdoor air ventilation rates for the balanced ventilated apartment on the ground floor. The top figure shows the total ventilation, the middle one shows the ventilation of individual rooms and the lowest one shows the weather.

quirements of the Swedish Building Code and had outdoor air vents, then the distribution of outdoor air to individual rooms would have been better. The agreement between predicted and tracer gas measured average total ventilation rates is good. For individual rooms the agreement is less good.

The dwellings with balanced ventilation had,over time, an almost constant outdoor air ventilation rate. This was due to the fact that the air leakage of the dwellings was very low. The dwellings fulfilled the requirements on airtightness as given in the Swedish Building Code. The ventilation systems in these dwellings were well adjusted, which meant that the individual rooms were supplied with a reasonable amount of outdoor air. The agreement between tracer gas measured and predicted outdoor air flows was good.

The difference between measurements and simulations can probably be explained by the inaccuracy in the tracer gas measurements of the air flows and the inaccuracy in the inputs to the simulations (distribution of leakage paths, characteristics of individual leakage paths, pressure coefficients, local wind speed and direction). An important factor for the exhaust ventilated dwellings is that as input

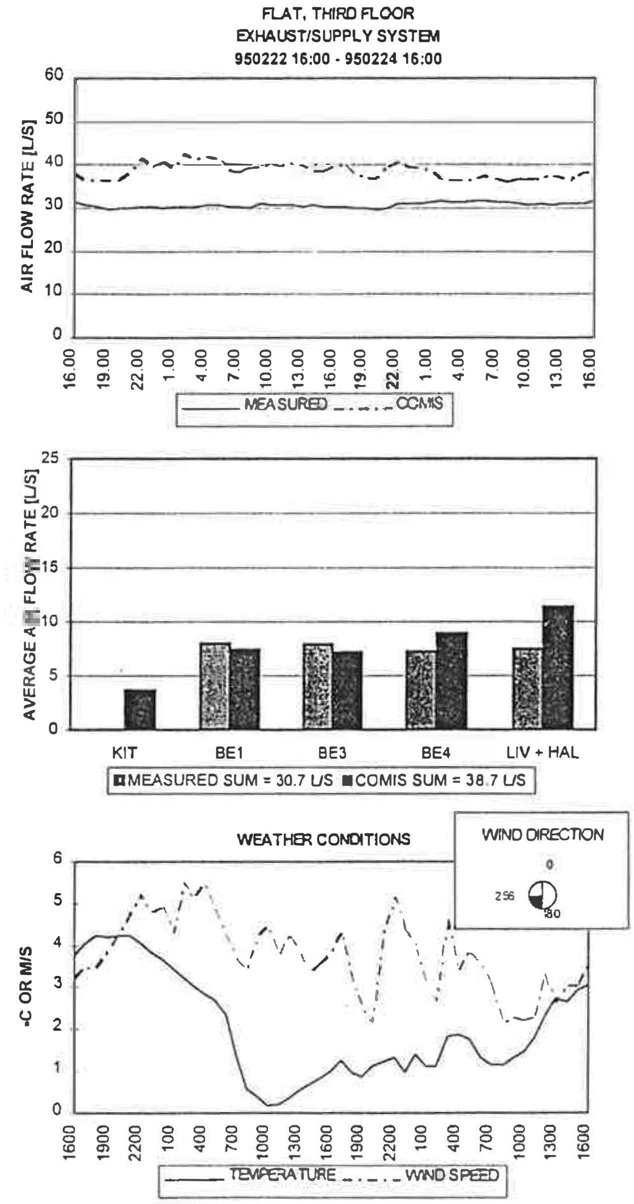

Fig. 14. Measured and predicted outdoor air ventilation rates for the balanced ventilated apartment on the second floor. The top figure shows the total ventilation, the middle one shows the ventilation of individual rooms and the lowest one shows the weather.

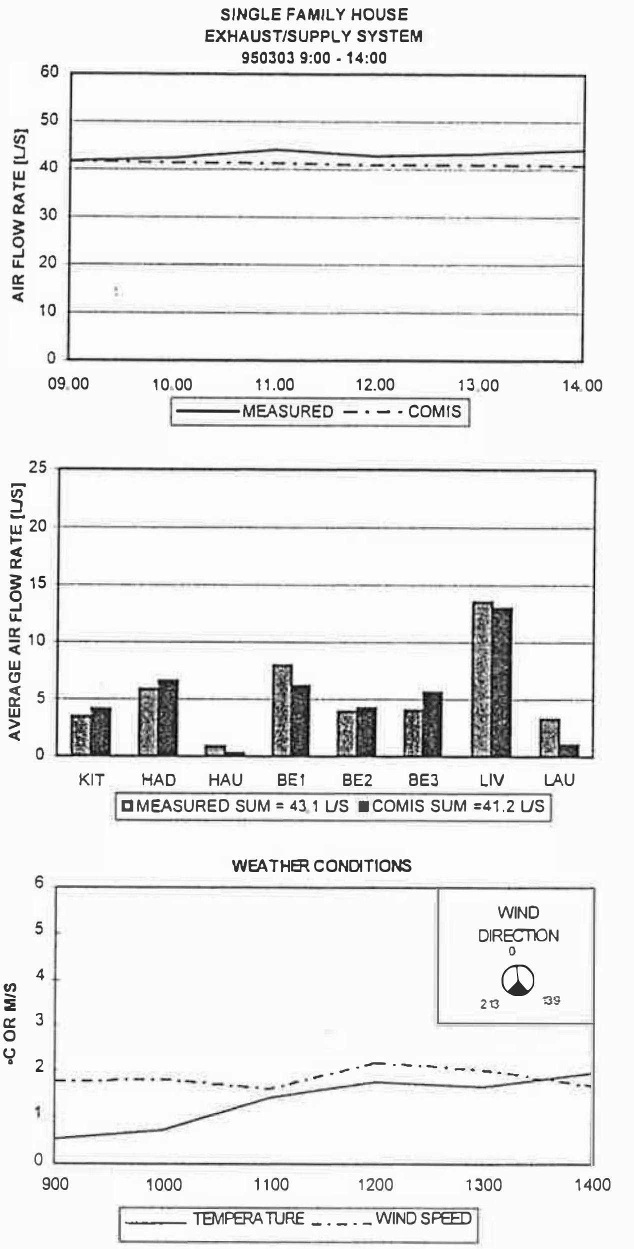

Fig. 15. Measured and predicted outdoor air ventilation rates for the balanced ventilated one-family house. The top figure shows the total ventilation, the middle one shows the ventilation of individual rooms and the lowest one shows the weather.

for the exhaust air flows through the air terminal devices measured values were used. The good agreement between predicted and measured (tracer gas) average total outdoor air ventilation rates can partly be explained by a good agreement between tracer gas measurements and measurements of exhaust air flows at the air terminal devices. For the balanced ventilated dwellings both measured exhaust and supply air flows through the air terminal devices were used as inputs.

6. Future work

Predictions will be made for the periods with passive tracer gas measurements in occupied dwellings.

Acknowledgements

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