Energy Impact of Ventilation and Air Infiltration
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The Energy Impact of Ventilation and Air Infiltration in an Atrium

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Synopsis

Many modern office and residential buildings in Sweden include an atrium. The atria are often mechanically ventilated and sometimes they are heated. Very little is known about the ventilation and air infiltration in built atria. These issues were examined in an apartment building with a non-heated and mechanically ventilated atrium, built in 1986 in Sweden. The ventilation of the atrium is coupled to the apartments.

The paper examines the ventilation, air infiltration, airtightness and the energy impact of an atrium. Fan pressurization was employed to characterize the air leakage of the atrium and the apartments. The energy use and temperatures in the atrium and in the apartments were monitored continuously for a year. A multi-zone network model was used to further evaluate the ventilation and the air infiltration. The energy balance was estimated using a dynamic simulation model.

The roof of the tested atrium is very leaky and therefore the exfiltration is large. The energy use for space heating of the tested apartments can be reduced if the atrium and the apartments are made airtighter. The knowledge concerning the real airtightness and ventilation of atria and surrounding buildings is insufficient. There are also many ideas as to how to ventilate an atrium.

1. INTRODUCTION

The research and the measurements carried out by the Department of Building Science at Lund University concerning different atria have resulted in valuable knowledge concerning the technical problems that arise for different running conditions in buildings with atria (Lange 1986, Wall 1992). This experience has been used when determining the general principles for an apartment building with atrium in Malmö. Requirements on climate and energy conservation have influenced the design of the atrium and the heating and ventilation system.

The building was designed during 1985 and built during 1986. Performance monitoring and evaulation were carried out during 1987 - 1991. A detailed description of the building and the results from the performance monitoring and evaluation is given in a final report (Blomsterberg 1993).

2. THE ATRIUM TESTED

The building includes an atrium with a floor area of 240 m^2. The atrium is surrounded on three sides by a building with 3.5 floors. The building contains 28 apartments with a total floor area of 2034 m^2. The entrance to each apament is from the atrium. The atrium has two glazed areas, the singel glazed roof and the double glazed south facade. The atrium together with the modestly insulated wall facing the atrium has a U-value corresponding to a well insulated exterior wall. The building including the atrium has the same calculated conduction losses as the same building excluding the atrium, but with the wall facing the courtyard insulated according to the Swedish Building Code of 1980. The atrium has a distribution of conduction and ventilation loss coefficients, between the wall area facing the atrium and the glazed area facing the outside, of 1 : 1. This means that the temperature in the atrium should always at least be equal to the average of the temperature in the apartments and outside. Solar radiation will raise the temperature above this average. There is no heating system in the atrium. The sun will heat the atrium and reduce the conduction losses from the apartments to the atrium and preheat the supply air to the apartments.

The building is equipped with a balanced ventilation system including an air-to-air heat exchanger. The outdoor air preheated by the heat exchanger first ventilates the atrium and then the apartments. The apartments are equipped with exhaust ventilation, where the exhaust air is passed through the heat exchanger.

3. MONITORING PROGRAM

The overall aim has been to monitor and evaluate the energy use and the indoor climate. This has been done by examining: the energy balance of the apartments, the energy balance of the atrium, the air temperatures in the apartments, and the air temperatures in the atrium.

The monitoring period was started with one-time tests: depressurization of five apartments, air leakage detection using thermography in three apartments, depressurization /pressurization of the atrium, and measurements of the air flows in the ventilation system,

The test of the airtightness of the atrium was carried out using a specially developed fan (Lundin 1986), with a maximum capacity of 85000 m^3/h at 50 Pa. The air flow through the fan was measured using tracer gas technique. A constant tracer gas flow was supplied upstream the fan and the concentration was measured downstream. The fan is attached to the main entrance of the atrium by means of a specially developed door.

After the one-time tests, continuous measurements were started. They were focused on energy use, indoor climate and outdoor climate. The building was occupied.

4. RESULTS

4.1 Energy use

A comparison between measured and predicted use of energy for space heating during the heating season shows that the measured value, 57 kWh/m^2, is 1/6 higher than the design value, 48 kWh/m^2 (January - March and October - December). The predictions were made using the BKL-method (Källblad 1984). The boundary conditions were almost the same but not quite the same during the measurements as for the calculations which complicates a comparison (see table 4.1).

Table 4.1 Boundary conditions during measurements and design calculations.

	Measured, 1988	Design
Mechanical ventilation, apartments	0.6 air changes/h	0.7 air changes/h
Infiltration from outside, apartments	0.13 air changes/h	0.10 air changes/h
Indoor temperature, apartments	+ 21 °C	+ 20 °C
Mean yearly outdoor temperature	+ 8.6 °C	+ 8.6 °C
Mean outdoor temperature, Oct - March	+ 4.2 °C	+ 3.7 °C
Internal gains excl. solar	217 kWh/day	200 kWh/day
Atrium curtains, winter	none	double and airtight
Airtightness, atrium	failed	good

The yearly use electricity for household purposes is reasonable, appr 2000 kWh/apartment. The use of electricity for running the building (shared laundry, shared lights, elevator, fans etc) is fairly large, 2600 kWh/apartment. The main part of this is the use of electricty for running the fans.

4.2 Airtightness of the apartments

The results from the tests of the airtightness are presented as airchanges per hour at a pressure difference between inside and outside of 50 Pa (see table 4.2). The results can be compared with the requirements in the Swedish Building Code of 1980, 1 air change per hour i.e. no apartment fullfills the requirement.

Table 4.2. Airtightness at 50 Pa, air changes/h ± 10 %. The values are an average of negative pressure and positive pressure. For the case with counter-pressure only negative pressure (depressurization) is given.

Apartment nr	Swedish standard	Entrance to neighboor open	Open supply ducts	Counter-pressure in atrium
11	1.81	1.82	1.83	0.7
12	1.69	-	1.80	0.58
23	1.47	-	1.96	0.73
28	1.85			
31	1.61			

The measurements in apartment no 11 according to the Swedish standard resp. with main entrance to neighboor open indicates that the air leakage between the apartments is small. This makes sense as the partition walls and the intermediate floors are made of concrete.

In order to illustrate the distribution of the leakage paths the effective leakage area was determined from the measurements (see table 4.3) (Sherman 1980). The effective leakage area was determined for a pressure difference of 4 Pa, which is a value which is more representative for the conditions in the real building when the fans are running. As the apartments are ventilated by an exhaust fan the leakage area was determined for a negative pressure. There are reasons for assuming that more air enters the apartments from the atrium than directly from outside, as the walls facing outside are airtighter than the ones facing the the atrium.

Table 4.3. Effective leakage area at a pressure difference of 4 Pa for the apartments, cm^2. The leakage area of the walls facing the atrium does not include the supply duct.

Apartment no	All walls	Walls facing atrium	Supply duct from atrium	Walls facing outside
11	63 ± 6	41 ± 6	0 ± 8	22 ± 2
12	44 ± 4	39 ± 4	11 ± 7	5 ± 1
23	36 ± 4	22 ± 4	14 ± 6	14 ± 1

4.3 Airtightness of the atrium

The entire atrium was depressurized and pressurized. All fans in the ventilation system were closed and the air terminal devices taped over during the measurements. The atrium was shown to be very leaky, according to a curve fit to the measurements, 12.5 air changes per hour (average of depressurization and pressurization) at 50 Pa. The main part of the air leakage is located in the roof of the atrium. In the roof there are four longitudinal 1 cm wide cracks, which according to an estimate could account for all air leakage.

Using the results from the tests of airtightness, the air leakage through the apartments was calculated to account for 7 % of the air leakage of the atrium. The inaccuracy in this determination is of little importance as the dominating air lekage is through the glazed roof. If the glazed south facade of the atrium is assumed to leak 3 m^3/m^2h at 50 Pa, then the roof will leak 64 m^3/m^2h, which can be compared to the requirement of the new Swedish Building Code of 1988, 3 m^3/m^2h for dwellings.

5. ANALYSIS

5.1 Ventilation of the atrium

The real total ventilation of the atrium is unknown. The air flow rates which can be measured are the supply to the atrium and the exhaust from the apartments. The unknown air flows are the air flow between the atrium and the apartments, the air flow between the atrium and the outside, and the air flow between the apartments and the outside.

In order to estimate these unknown air flows, predictions have been performed using a multi-cell air flow program (MOVECOMP) (Herrlin 1987, Bring 1988, Blomsterberg 1990). The measured inputs used were: the airtightness of the atrium, the airtightness of the apartments, the air flows in the ventilation system, the air temperatures in the ventilation ducts, the air temperatures in the atrium, the air temperatures in the apartments, and the outdoor temperatures.

The simulations show that the exfiltration through the roof of the atrium varies with the outdoor temperature. When there is no wind the exfiltration is appr 1100 m^3/h or 30 % of the supply air at an outdoor temperature of - 10 °C and appr 800 m^3/h or 25 % of the supply air at an outdoor temperature of + 10 °C (see case 1 in table 5.1). If the average wind speed of the heating season prevails, then the exfiltration will increase by 20 %. The result is that during the heating season appr. 30 % of the preheated supply air vanishes out through the roof of the atrium.

All outdoor air to the apartments does not come from the atrium, but a not negligible part enters directly from the outside. The infiltration from the outside varies from 630 m^3/h or 20 % of the supply air at - 10 °C to 530 m^3/h or 17 % of the supply air at + 10 °C (see case 1 in table 5.1). This occurs when there is no wind. If the average wind of the heating season prevails, then the infiltration will increase by 30 %. There is no exfiltration from the apartments.

Next step was to repeat the simulations assuming that the roof of the atrium is very airtight e g fullfills the requirement of the new Swedish Building Code of 1988 for dwellings, 3 m^3/m^2h at 50 Pa. When there is no wind the exfiltration through the roof is reduced from 1100 m^3/h (or 30 % of the supply air) to 500 m^3/h (or appr. 15 % of the supply air) at an outdoor temperature of - 10 °C and reduced from appr 800 m^3/h (or 25 % of the supply air) to 350 m^3/h (or appr. 10 % of the supply air) at an outdoor temperature of + 10 °C (see case 2 in table 5.1). If the average wind speed of the heating season prevails, then the exfiltration will increase by 20 %. The result is that during the heating season appr. 15 % of the preheated supply air vanishes out through the roof of the atrium.

The infiltration from the outside is in this case reduced from 630 m³/h (or 20 % of the supply air) to 130 m³/h (or appr. 5 % of the supply) at - 10 °C and from 530 m³/h (or 17 % of the supply air) to 180 m³/h (or appr. 6 % of the supply air) at + 10 °C (see case 2 in table 5.1). This occurs when there is no wind. If the average wind of the heating season prevails, then the infiltration will increase by 60 %. Exfiltration will occur from the apartments at the top floor.

Next step was to repeat the simulations assuming that the roof of the atrium has the measured airtightness, but the supply air flow to the atrium is almost the same as the exhaust air flow from the apartments. When there is no wind the exfiltration through the roof is increased from the earlier 500 m³/h to 600 m³/h at an outdoor temperature of - 10 °C and reduced from 350 m³/h to appr. 250 m³/h at an outdoor temperature of + 10 °C (see case 3 in table 5.1). If the average wind speed of the heating season prevails, then the exfiltration will increase by 50 %. The result is that during the heating season appr. 35 % of the preheated supply air disappears out through the roof of the atrium.

The infiltration from the outside will in this case increase somewhat from the original 630 m³/h (or 20 % of the supply air) to appr. 675 m³/h at - 10 °C and from the original 530 m³/h (or 17 % of the supply air) to appr 550 m³/h at + 10 °C (see case 3 in table 5.1). This occurs when there is no wind. If the average wind of the heating season prevails, then the infiltration will increase by 30 %.

Table 5.1 Calculated air flows, m³/h. The exfiltration through the roof of the atrium and the infiltration to the apartments from the outside is calculated for an outdoor temperature of - 10 °C and + 10 °C. The exhaust air flow of 3050 m³/h for the apartments corresponds to 0,6 air changes per hour.

Case	1	2	3	4
Airtightness	As measured	New Code	As measured	No leakage
Supply air	3350	3350	2800	3350
Exhaust air	3050	3050	3050	3050
Atrium exfiltration				
- 0 m/s (wind)	780 - 1100	360 - 480	260 - 600	300
- 5 m/s (wind)	980 - 1330	450 - 570	450 - 830	300
Apartment infiltration				
- 0 m/s (wind)	530 - 630	130 - 180	550 - 680	0
- 5 m/s (wind)	710 - 830	220 - 270	730 - 880	0
Apartment - exfiltration	0	60 - 70	0	0

The last step, which does not require any calculations, is the case probably assumed by the designer i.e. all air to the apartments enters from the atrium (see case 4 in table 5.1).

5.2 Energy use

In order to evaluate the influence on the energy use for space heating of the apartments by the airtightness and ventilation of the atrium, simulations were performed using DEROB-LTH (Arumi-Noé 1979, Fredlund 1989). The first step was to see how accurately DEROB can predict the energy use for different measuring periods. Four different test period were chosen. Two-week periods with cold and mild weather, almost no sun and a lot of sun, small and large diurnal variations are represented. The agreement was shown to be good concerning the variation over time in space heating and the average temperature in the atrium.

The predictions underestimate the absolute level of space heating. For sunny periods the simulations tend to underestimate the space heating demand. This is most likely caused by the fact that DEROB-LTH assumes a perfect control system without any time delay for the heating system, which does not correspond to what actually happened. The predictions do no take into account that there are curtains in each apartment i e more useful solar energy in the calculations. If the sunny periods are corrected, then the agreement is reasonable.

The second step was to predict the energy use for space heating for a reference year, Malmö 1971. The third step was a prediction, based on previously calculated air flows assuming the atrium to fullfill the airtightness requirements of the new Swedish Building Code of 1988 (see case 2 in table 5.1). The fourth step was a prediction, where the supply air flow to the atrium is balanced with the exhaust air flow from the apartments (see case 3 in table 5.1). The last step was a prediction for the theoretical case with no infiltration (see case 4 in table 5.1). In all predictions the indoor temperature of the apartments was + 20 °C.

If the atrium had fullfilled the airtightness requirements of the new Building Code of 1988, then the energy use for space heating would have been reduced by 8 % (see table 5.4). This is due to the fact that if the atrium is made airtighter, then the exfiltration from the atrium and the infiltration directly from the outside to the apartments are reduced i. e. the air flow from the atrium to the apartments is increased. Balanced air flows do not mean any improvement compared with the base case. Neither the temperature in the atrium or the infiltration directly from the outside to the apartments are influenced. The theoretical case, where no infiltration to the apartments directly from the outside occurs, means of course the lowest energy use.

All predictions with DEROB-LTH show that the objective that the air temperature of the atrium always should be at least equal to the average value of the outdoor temperature and the temperature in the apartments is achieved for monthly averages. The measurements do however for 1988 show that during almost 100 days, when the daily mean outdoor temperature was below + 7 °C, the daily mean temperature in the atrium was 1 - 2 °C too low.

Table 5.4 Calculated yearly energy use for space heating of the apartments.

Case		Space heating, MWh
1	Measured airtightness and air flows, real occupancy	72
2	New Code airtightness, measured air flows, real occupancy	66
3	Measured airtightness, balanced air flows, real occupancy	73
4	Measured airtightness and air flows, real occupancy, no infiltration	63

6. CONCLUSIONS

The performance monitoring and evaluation show that it is possible to build a well functioning apartment building including an atrium. Apart from short periods with high temperatures the system has created reasonable temperatures in the atrium and the apartments.

The aim for the building was to always maintain a temperature in the atrium, which is at least the average value of the air temperature in the apartments and outside. This was met apart from 100 days during a year when the temperature in the atrium is somewhat too low. One reason was that the roof of the atrium never was equipped with double and airtight curtains. The curtains were also never used during the nights as was planned.

The energy use for space heating of the apartments was somewhat higher than predicted, probably due to lower solar gains than in theory.

The exfiltration through the roof of the atrium is large due to a very leaky roof. The infiltration from outside to the apartments is also large. The idea was that most of the air to the apartments was to enter from the atrium. The apartments were too leaky.

If the atrium had fullfilled the airtightness requirements of the new Swedish Building code of 1988, then the energy use for space heating of the apartments would have been reduced by 10 %. The airtightness of the atrium would have been even more important if the atrium had been heated to normal indoor temperature e g + 20 °C.

A study of several atria shows that many ideas exist as to how to ventilate an atrium and how to couple its ventilation with the surrounding building. Different requirements are made on what level of temperature is to be maintained in an atrium. The knowledge concerning the real airtightness and ventilation of atria and surrounding buildings is insufficient. The size of the total ventilation is of importance to the indoor air quality and the energy use.

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