Numerical Study of Hybrid Ventilation of Apartments in a Densely-Populated Urban Neighbourhood

Yunlong Liu, Alfred Moser

Air & Climate Group, Swiss Federal Institute of Technology
ETH-Zentrum WET A1, CH-8092 Zurich, Switzerland

Abstract

The demand for buildings with high quality indoor environments is growing, especially in developing countries, where more and more energy will be consumed in the near future. Air flow pattern, air temperature and humidity are among the main parameters that contribute to indoor thermal comfort. Care must be taken to design the most energy-efficient air distribution system that provides comfort for the occupants. To achieve this it is very helpful to know the air flow patterns and the temperature and humidity field in a building at the design stage.

This paper presents results derived from the numerical modelling of air flow and heat and mass transfer within an apartment building in a densely populated urban neighbourhood. Typically, such apartment blocks are in close proximity to each other and cross contamination between apartments in the same and adjacent buildings can occur.

As the Reynolds number is large, the air flow is fully turbulent. After validation of the numerical procedure and the turbulence model against benchmark cases, the k-ω turbulence model was employed to evaluate the air flow pattern, temperature, and contaminant concentration in the ground floor and top floor apartments.

Based on the numerical results, suggestions are given for the design of hybrid ventilation systems for use in high-rise buildings in densely populated residential regions. For the configuration of shared ventilation shafts, considered in this paper, it is concluded that a built-in fan should be used to control the direction of the air flow and to avoid cross contamination. It is also concluded that this, fan assisted, ventilation system approach provides thermal comfort in a temperature band somewhere above 20°C and below 30°C. This approach it is much cheaper to operate than full air-conditioning.

Key words: hybrid ventilation, air distribution, thermal comfort, urban high rise housing

1. Introduction

Recently, researchers of the IEA Annex 35 of the Energy Conservation in Buildings and Community Systems Program and others have proposed the idea of sustainable and environmentally-friendly buildings with ventilation technologies that have higher energy efficiency and improved indoor air quality, comfort, health, and safety (Moser and Lui 2001, Heiselberg 2000 and Shinsuke and Murakami 2000). One key factor is to use natural or hybrid ventilation. This technology can reduce greenhouse gas emissions and save capital, running and maintenance costs.

This paper discusses the feasibility of a particular energy saving ventilation approach for densely populated regions during the summer season. With the aid of computer modelling, indoor air movement, air temperature and pollutant transport were investigated, and the benefits assessed.

2 Physical Model and Numerical Method

2.1 The Mathematical Models

The size of a room in an apartment is of the order of metres, whereas air velocity has a scale of the order 0.1 m/s and is mostly turbulent. By definition, turbulent flow is three-dimensional and transient. During the past thirty years the development of turbulence models has been very successful. Both large eddy simulation (LES) and Reynolds-averaged Navier-Stokes equation (RANS) models have been employed in the simulation of ventilation (Chen et al 1990 and Su et al 2001), though some problems still remain to be resolved.

The general form of the governing RANS equations of turbulent flow may be found in the literature (Wilcox 1994). For the Reynolds stress, the eddy-viscosity concept with the so-called Boussinesq assumption (Kenjeres et al 2000) is employed to 'close' the system of equations. In the near wall regions, where viscous effects become dominant, wall functions are used.

The numerical method used in this paper is based on the three-dimensional Reynolds-averaged Navier-Stokes equations which is 'closed' by the k-ω turbulence model. Discretisation of the space is made by the finite volume method. The commercial code CFX-TASCFlow of AEA-CFX was used to undertake the computations.

2.2 The Model of the Ventilated Apartment

To study the thermal interaction between apartments, facing the same narrow courtyard, during the summer season, two neighbouring 4-storey buildings were considered as illustrated in Figure 1. All simulations in this paper were performed in two dimensions. The third dimension was nominally set at 1m, although the actual apartments may have different sizes in the third direction. To simplify the problem, one apartment on each floor was assumed, with each apartment treated as a single room or zone. The air flow and pollutant transport patterns through the apartments on the ground floor and on the top floor were

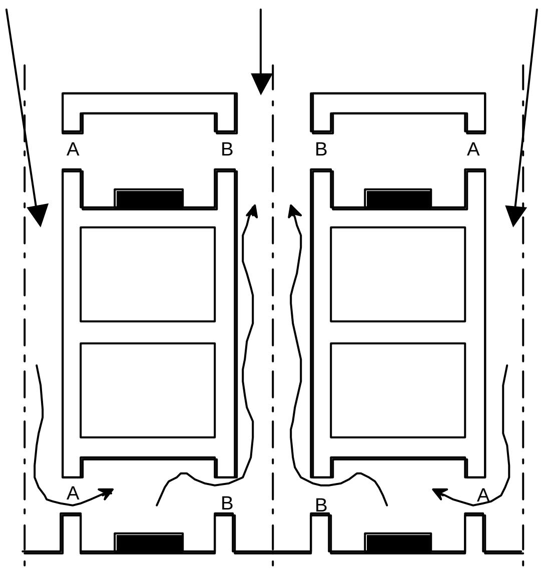

Figure 1: General building layout, side view

Table 1: Details of the cases involved

Case #	Case description	Comments
1	No fan, outdoor air temperature 20°C, each apartment floor heat source 1kW. Air rises from central shaft	Natural ventilation
2	Same as case 1, but outdoor air temperature is 30°C	Natural ventilation
3	Ground floor apartment and top floor apartment both use blow out fan of 0.5N force to the central shaft, outdoor air temperature 20°C, each apartment floor heat source 1kW	Hybrid ventilation
4	Same as case 3, fan force 0.5N,but outdoor temperature 30°C	Hybrid ventilation
5	Same as case 4, but fan force 2.5N,outdoor temperature 20°C	Hybrid ventilation
6	Same as case 5, fan force 2.5N,but outdoor temperature 22°C	Hybrid ventilation
7	Same as case 5, fan force 2.5N,but outdoor temperature 24°C	Hybrid ventilation
8	Same as case 5, fan force 2.5N,but outdoor temperature 26°C	Hybrid ventilation
9	Same as case 5, fan force 2.5N,but outdoor temperature 28°C	Hybrid ventilation
10	Same as case 6, fan force 2.5N,but outdoor temperature 30°C	Hybrid ventilation

computed. This was because it can be assumed that the pollutants and hot air emitted from the ground floor apartment could, probably, affect apartments on the upper floors in both the same building and neighbouring buildings. A 1kW volume heat source of size 5m x 0.02m x 1m was used to represent heat emission from the occupants and from electrical or cooking loads. Each apartment is connected via two short ducts to adjacent shafts (locations 'A' and 'B' in Figure 1). These ducts are 1mx2m in cross-sectional area and are located 1m above floor level. Pollutant sources were introduced in the ground-floor apartments only, so that the movement of pollutant from the ground floor to the upper floor could be observed. Each apartment has an electrical fan built into the central duct ('B') that extracts air to the shaft. These fans are turned *off* for natural ventilation and *on* for hybrid ventilation. There are no other openings to the main shafts that would allow air to bypass the fan. All ducts in all the apartments are assumed to be open.

The computation domain includes three shafts, the air space in four selected apartments, and a 20-metre high region extending above the buildings. By means of symmetry, only half of each of the outer shafts are represented. A non-uniform grid layout was applied to make a fine mesh in the near-wall region, where the velocity and temperature gradients are high, while a very coarse mesh was employed in the area above the buildings. All rooms and building walls were assumed to be adiabatic with no-slip boundary conditions.

3 Results and Discussion

In the following ten cases, several parameters were varied, including outdoor air temperature, apartment floor heat source, and built-in fan power. Thermal comfort was assessed by the PMV-PPD value proposed by Fanger (1990). It was assumed that the indoor relative humidity was 40 percent. It was also assumed that the occupants in the apartment wore typical summer clothes of 0.6 clo and undertook sedentary work at a metabolic rate of 1.2 met.

Table 1 gives a detailed description of the cases involved; Tables 2 and 3 show the computation results. The temperature and air velocity were taken at a location in the centre of each room, 1m from the floor. To enable computation of the PMV value, the averaged wall temperature (also called radiation temperature) was obtained by averaging the room surface temperature. Two cases without assisting fan (natural ventilation), and eight with assisting fan (hybrid ventilation) were investigated.

Table 2: Results for the apartments on the ground floor

Case #	Outdoor air temperature (°C)	Indoor air temperature (°C)	Indoor air speed (m/s)	Average Wall Temperature (°C)	PMV at 0.6 clo	PPD at 0.6 clo
1	20	21.29	0.298	23.62	-1.0	28.3
2	30	31.29	0.298	33.62	2.2	84.4
3	20	20.41	0.327	22.74	-1.4	44.7
4	30	30.41	0.327	32.74	1.9	70.9
5	20	20.03	0.379	22.12	-1.6	57.7
6	22	22.03	0.379	24.12	-0.98	25.1
7	24	24.03	0.379	26.12	-0.32	7.1
8	26	26.03	0.379	28.12	0.35	7.5
9	28	28.03	0.379	30.12	1.1	26.8
10	30	30.03	0.379	32.12	1.7	61.3

Table 3: Results for the apartments on the top floor

Case #	Outdoor air temperature (°C)	Indoor air temperature (°C)	Indoor air speed (m/s)	Average Wall Temperature (°C)	PMV at 0.6 clo	PPD at 0.6 clo
1	20	24.59	0.023	27.36	0.5	10.3
2	30	34.59	0.023	37.36	3.4	99.9
3	20	23.95	0.021	26.24	0.3	6.3
4	30	33.95	0.021	36.24	3.1	99.6
5	20	20.57	0.111	23.41	-0.7	14.6
6	22	22.57	0.111	25.41	-0.12	5.3
7	24	24.57	0.111	27.41	0.44	9.1
8	26	26.57	0.111	29.41	1.01	26.5
9	28	28.57	0.111	31.41	1.59	55.6
10	30	30.57	0.111	33.41	2.2	83.9

3.1 Natural Ventilation

The outdoor air temperature of case 1 was set at 20°C and the air flow was assumed to be driven by buoyancy alone (i.e. no fan). Multiple solutions may develop. Results of temperature and PMV are summarised for the ground floor and top floor in Tables 2 and 3 respectively. These results show that the air temperature in the apartment on the top floor is 3 degrees higher than that on the ground floor. This is also illustrated in Figure 2 where the change in shading from dark to pale is approximately 3ºC.

The PMV value was found to be positive for the top floor and negative for the ground floor. Thus, for an outdoor temperature of approximately 20°C, and according to the PMV-PPD criteria, thermal comfort is achieved on the top floor, by means of natural ventilation, but the ground floor is slightly too cool. The corresponding pollutant distribution for natural ventilation is illustrated in Figure 3 and shows (by the presence of pale shading) that the top floor is contaminated by ground floor pollutants. Thus, from the air quality aspect, this is not a good ventilation solution.

Case 2 represents a similar configuration to case 1 but the outdoor temperature was set at 30°C to represent a hot day. The PMV value was calculated to be above 2 for all apartments hence more than 80% of the occupants would be dissatisfied. At this outdoor temperature it is not possible to maintain a comfortable indoor environment by natural ventilation, and an electrical fan or even an air-conditioner would need to be used.

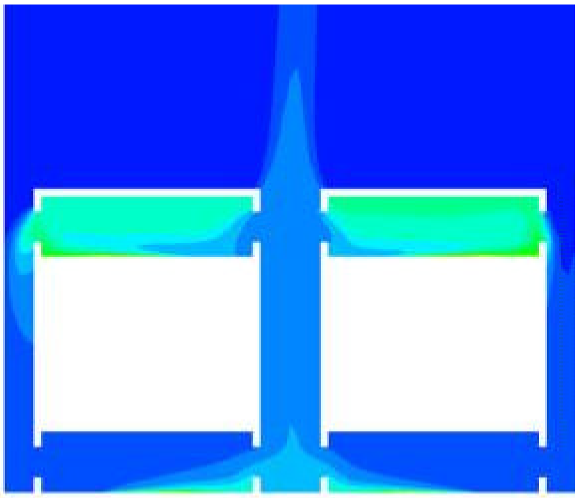

Figure 2: Temperature distribution in the room (without fan), case 1

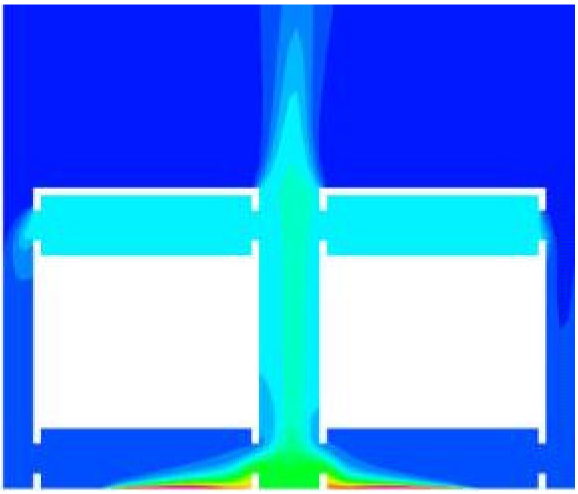

Figure 3: Pollutant distribution in the room (without fan), case 1

3.2 Hybrid Ventilation:

Cases 3-10 illustrate examples of hybrid ventilation in which a built-in fan is turned on to extract air from the central shaft while drawing air in naturally from the outside shafts. For cases 3 and 4, a fan that represents a 0.5N force over the fan face (about 1W power) was activated in each apartment. At 20°C outdoor temperature (case 3) the PMV is negative on the ground floor and slightly positive on the top floor. The result indicates that 55% of all occupants on the ground floor would be too cold, while 94% of the top floor occupants would feel comfortable. When the outdoor air temperature is increased to 30°C (case 4), this fan force is not enough to make the occupants on any floor feel comfortable. To increase the air speed, a higher fan force was applied in cases 5 to 10. At an outdoor temperature of 20°C, a fan force of 2.5N (about 3W power) is predicted to make occupants feel slightly cold. When the outdoor air temperature is around 22 - 24°C, this hybrid ventilation works well, as shown in case 6 and case 7. For these cases, the PMV value is between -1.0 to 0.5, and hence about 80% of the occupants on any floor would feel satisfied. At 30°C ambient temperature, it is not possible, without using air-conditioning, to produce a comfortable indoor environment, even at a fan force above 2.5N.

3.3 Arrangement of Built-in Fans:

From case 1 it can be seen that the pollutants and heat emitted from the ground floor apartment will enter the apartments at the top floor, as shown in Figure 2. Figure 3 shows the pollutant concentration field with the built-in fan turned off. Even though no pollutant source exists in the rooms on the top floor, pollutant concentration is very high as a consequence of pollutant emitted from the ground floor. To avoid polluted air cross contaminating apartments, it is concluded that forced ventilation is necessary when ventilation shafts are shared.

Figure 4: Temperature distribution in the room (with coordinated fans), case 5

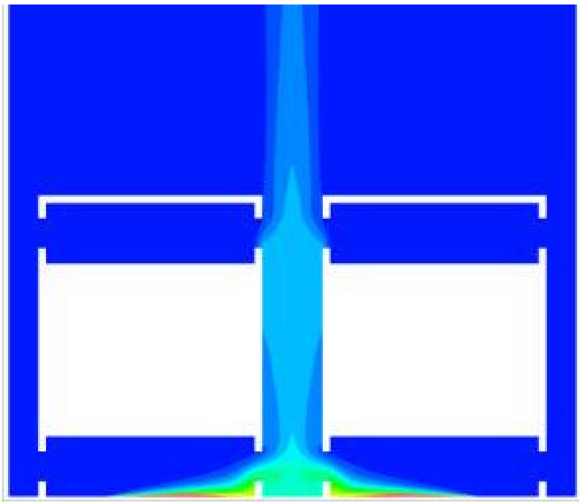

Figure 5: Pollutant distribution in the room (with coordinated fans), case 5

For a co-ordinated operation, suitable for all apartments, the air exhausted from all apartments should enter the same shaft, and fresh air should be drawn from a different shaft. Cases 3-10 illustrate how this idea works. Figure 4 shows the temperature distribution of case 5 and Figure 5 shows the pollutant concentration field when the built-in fan is turned on. As indicated by the dark shading, in Figure 5, the air quality on both the top floor and the ground floor is much improved. In particular the ground floor air does not contaminate the upper floor. Figure 4 shows that, similarly, there is little temperature ingress, although the paler shading of the top floor indicates a slightly higher temperature. The ground floor temperature is at approximately 20°C (rising at the shaft, as indicated by the paler shading) while the top floor temperature is a degree or so warmer (peaking at approximately 24°C as illustrated by the pale region close to the shaft.

4. Conclusions

Based on the CFD analysis presented in this paper it can be concluded that:

- To prevent cross contamination, a ventilation system in which apartments share the same network of ventilation ducts, the supply and extract ducts must be separated. This requires the co-ordinated use of fans to establish a system of forced extract ventilation combined with passive supply;
- Thermal and air quality comfort can be achieved in the outdoor temperature range between 20°C and below 30°C, without the need for air conditioning. This approach is much cheaper to operate and more energy efficient than full air-conditioning;
- Natural ventilation alone can supply comfort to the lower apartment floors but will result in contamination and over heating of the upper floors. Thus natural ventilation alone is not recommended;
- By using the mechanical extract configuration proposed, only very low energy fans are required yet they can achieve substantial improvements in thermal comfort and pollutant control.

References

Chen Q, Moser A and Huber A.: (1990) "Prediction of Buoyant, Turbulent Flow by a low-Reynolds-Number k-ω Model", *ASHRAE Transactions*, **96**, Pt1, pp 564-473.

Fanger O: (1990) ISO 7730: "Moderate thermal environments - Determination of the PMV and PPD indices and specification of the conditions for thermal comfort", October 5, 1990.

Heiselberg P: (2000) "Design Principles for Natural and Hybrid Ventilation", *Healthy Buildings 2000, 6th Int. Conf.*, Helsinki, Aug. 2000, Vol. 2, ISSN 1395-7953 R0036, no. 113, Aalborg Univ., AUC, August 2000.

Kenjeres S and Hanjalic K: (2000) "Convective rolls and heat transfer in finite-length Rayleigh-Benard convection: A two-dimensional numerical study", *Physics Review E*, **62**, N6, pp7987-7998.

Moser A. and Liu Y: (2001) "Fan-in-wall for hybrid ventilation in hot climate", *IAQVEC 2001, 4th International Conference on Indoor Air Quality, Ventilation and Energy Conservation in Buildings*, Changsha, China, October 2001, pp 2031-2040.

Kato S, Murakami S et al: (2000) "Room air distribution and cooling load of hybrid air-conditioning system utilizing natural ventilation in an office", *Roomvent 2000*, edited by H. B. Awbi, pp 801-806.

Su M, Chen Q and Chiang C: (2001) "Comparison of different subgrid-scale models of large eddy simulation for indoor airflow modeling", *Transactions of ASME*, **123**, pp 628-639.

Wilcox D: (1994) "Turbulence modeling for CFD", November 1994, ISBN 0-9636051-0-0.