The ups and downs of airflow in building ventilation

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ABSTRACT
Almost all existing analysis methods for building ventilation airflows, such as the simple analytical methods, multi-zone methods and computational fluid dynamics (CFD), give only one unique solution for one set of identical input parameters when started with zero initialization or zero initial conditions. This can be shown to be incorrect in some situations. Multiple stable solutions are found in some very simple buildings, which indicate that the building airflows are of a nonlinear dynamical system. As a nonlinear dynamical system, air and smoke flows in buildings can be very sensitive to perturbations and/or initial conditions. Dynamical nonlinear phenomena can be of great significance for indoor air quality, heat transfer, and smoke transport in buildings, in particular in naturally and hybrid ventilated buildings. A number of examples are given in this paper to illustrate the situations where multiple steady solutions exist. Practical recommendations are suggested in terms of design and analysis based upon the current understanding.

INDEX TERMS
Air movement; Natural ventilation; CFD; Modelling; Multizone

INTRODUCTION
To predict airflow patterns in buildings, indoor air quality experts and ventilation engineers generally use a prediction tool such as a multi-zone program or a computational fluid dynamics (CFD) program with certain (most often zero) initial conditions or initializations. A steady solution or a transient solution at an instant in time is then obtained. The solutions may then be used to guide engineering decisions. No questions have been asked whether the obtained solution is unique or 'true', although the airflow problems are highly nonlinear. Limited checks might be performed for simple problems if experimental data were available. But for practical engineering applications, it has often been very difficult to carry out any experimental verification and the obtained solutions have simply been accepted to be 'correct'.

For some design problems, the issue of prediction accuracy can be significant, for example, in pollutant spread design and smoke control of building fires. By prediction accuracy, it is meant here not only how a predicted quantity is close to the 'real' value, but also whether the main characteristics of the physical phenomena are captured. Multiple solutions for various mechanical ventilation problems have been identified since at least 20 years, e.g. Nielsen *et al.* (1979) and Nielsen (1982). However, the dynamical phenomena in building flows have been overlooked in almost all subsequent CFD and experimental research work until today. Recently, a number of analytical studies have suggested that multiple states can also exist in naturally ventilated buildings. For example, Li and Delsante (1998) and Li *et al.* (2001) suggested that two stable solutions could exist in a naturally ventilated building driven by combined thermal force and opposing winds. Nitta (1996, 1999) tested a multi-zone coupled thermal and airflow program with different initial conditions, and found that more than one stable solution exists in multi-zone buildings.

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To demonstrate the existence of multiple solutions, this paper first revisits the analysis of a simple building. Various example flows where multiple solutions have been identified are then briefly listed. Practical guidelines for ventilation design and using the analysis tools are also given.

A ONE-ZONE BUILDING WITH OPPOSING WINDS

The simple one-zone building analysed by Li and Delsante (1998) has two openings at different vertical levels on opposite walls, as shown in Figure 1. The airflows are assumed to be fully mixed. Two flow patterns are possible; one is a wind-dominated flow and another is a buoyancy-dominated one, see Figure 1.

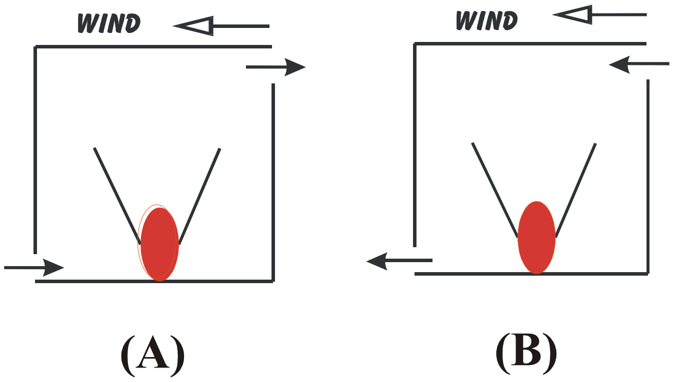

Figure 1 A simple fully mixed one-zone building with two openings with two possible flow states: (A) upward flow and (B) downward flow.

Two parameters are defined to characterize, respectively, the effects of thermal buoyancy and the wind force:

$$\alpha = (C_d A^*)^{2/3}(Bh)^{1/3} \tag{1}$$

$$\gamma = \frac{1}{\sqrt{3}}(C_d A^*)\sqrt{2\Delta P_w} \tag{2}$$

Both parameters have the same dimension as the ventilation flow rate. In Eqns (1) and (2), $A^* = A_t A_b / \sqrt{A_t^2 + A_b^2}$ is the effective area, and ΔP_w is the wind pressure difference between the two openings, which is always taken to be non-negative. B is the buoyancy flux, h is the height between the top opening A_t and the bottom opening A_b. C_d is the discharge coefficient.

The general equation for the ventilation flow rate q is as follows:

$$2\omega|q|\frac{dq}{dt} = -q^3 - 3\gamma^2|q| + 2\alpha^3 \tag{3}$$

where ω is a thermal mass parameter, defined as $w = c_M M/rc_p$, M is the mass of the thermal mass, C_M is the heat capacity of the thermal mass, ρ is the density of air and c_p is the heat capacity of air. The fixed points for the system (3) can be computed. Examination of the Eqn (3) shows that the equilibrium solutions can be easily presented as a function of α/γ. The results are shown in Figure 2, where some measurement data are also plotted as comparison. Three steady solutions can be found when α/γ is between 0 and 1.

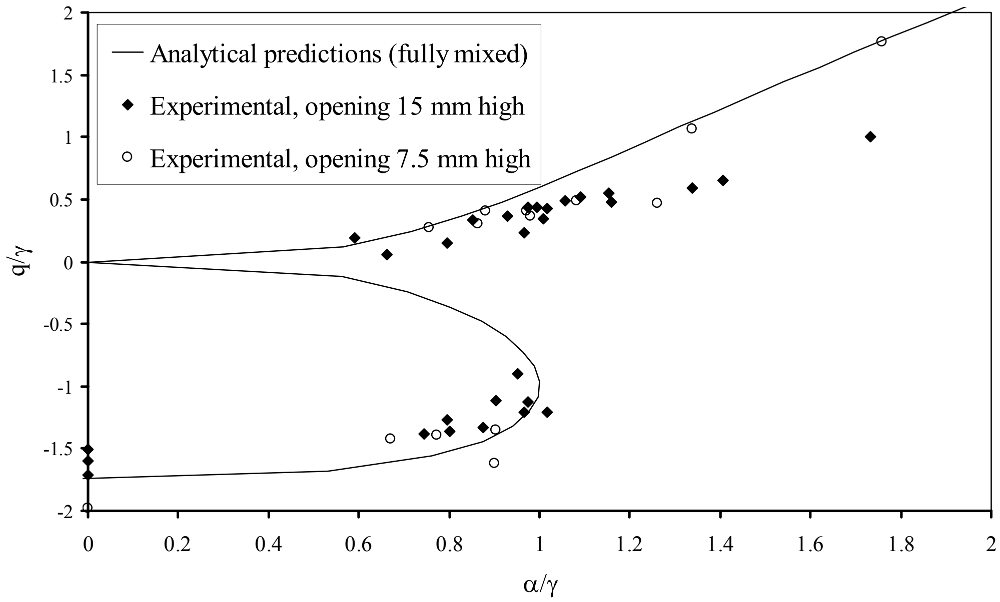

Figure 2 Comparison between experimental flow rates and the prediction for a single-zone building, Li *et al*. (2001).

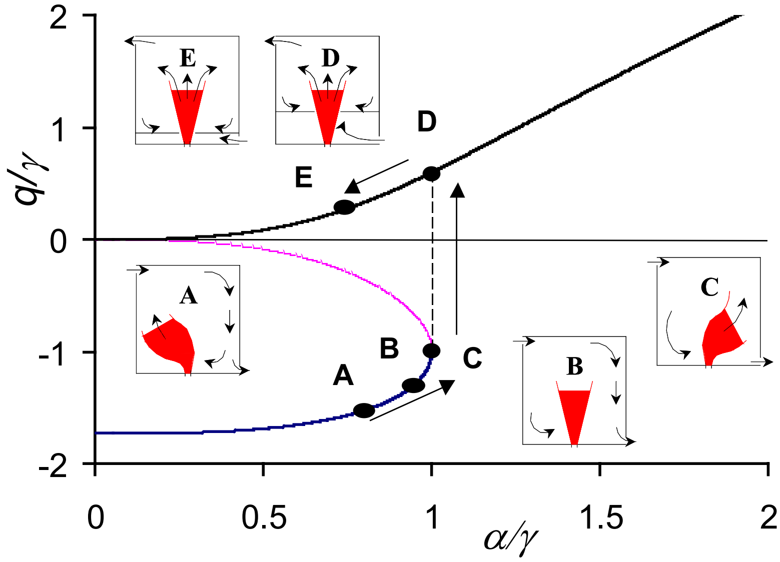

Figure 3 Sketch of the flow patterns during different stages of a small-scale experiment.

The basic solution behaviour in Figure 2 can be further explained using Figure 3. Imagining an experiment beginning with a wind-dominated ventilation mode without any heat source, the 'heat' source is gradually increased into the building, i.e. stages *A*, *B* and *C* in Figure 3, until the flow reaches the turning point and becomes buoyancy-dominated, i.e. stage *D*. Then the supply of 'heat source' is decreased, and the flow remains buoyancy-dominated following the curve DO, reaching the stage *E* in Figure 3. The fact that the flow does not return from D to C suggests the existence of two stable steady solutions. The solutions between O and C are not stable. Figure 3 is actually what was observed in a small-scale experiment; see Heiselberg *et al.* (2003). As shown in Figure 3, stages *A–C* are the wind-dominated flow and the air in the building is well mixed. Stages *D–E* are the buoyancy-dominated ventilation and the air in the building is stratified. The effect of stratification is included in a recent analysis by Heiselberg *et al.* (2003).

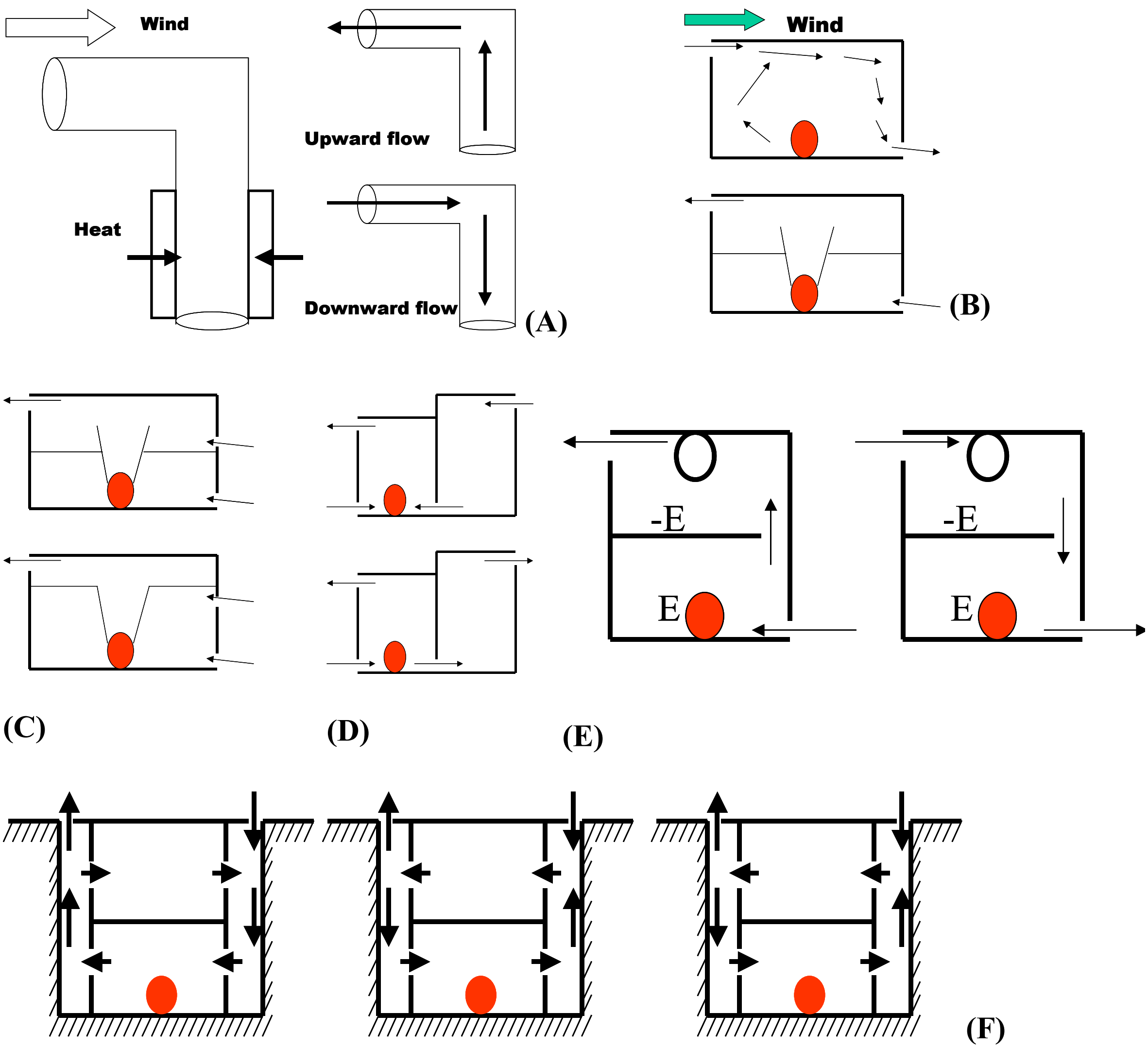

Figure 4 Examples of natural ventilation problems in which multiple solutions exist: (A) a chimney (Whitehead, 2001); (B) a building with opposing wind (Li and Delsante, 1998); (C) two smoke layers in a building with three openings (Chen and Li, 2002); (D) two-zone building with a fire; (E) 'arm wrestling' flow (Li, 2003) and (F) a symmetrical underground building (Nitta, 1999).

OTHER EXAMPLES OF MULTIPLE SOLUTIONS

It may be seen from the above discussion that the multiple states that we consider here are very different from the dynamical phenomena of turbulence flows. There are some 'big' changes in the overall flow pattern, e.g. the overturning of the global flows, a complete change of flow direction through an opening, existence of two smoke layers, different smoke paths, etc. Figure 4 summarizes some other examples of natural ventilation problems where more than one solution exists for the same set of parameters.

1. The Whitehead chimney with opposing winds (Figure 4A). Heat gain in a solar chimney produces an upward flow, while a positive pressure due to winds produces a downward flow. Whitehead *et al.* (2001) shows that both up and down flows are possible for some parameters. This chimney model is also valid for slopping tunnel ventilation problems; see Li *et al.* (2001).
2. A building with combined thermal force and opposing winds (Figure 4B). Competing winds and buoyancy effect can introduce two stable solutions (Li and Delsante, 1998). Experimental evidences for the existence of two solutions for this flow were provided by Hunt and Linden (2000) and Andersen *et al.* (2000).
3. Two smoke layers in a building with three openings driven by stack force alone (Figure 4C); see Chen and Li (2002). For a certain range of parameters, both a low and a high smoke layer is possible, suggesting the risk in fire safety design when similar geometries are encountered, e.g. in an atrium.
4. Nitta's two-zone problem (Nitta, 1997) (Figure 4D). The fire occurs in the left room and the question is whether the smoke will spread to the right room or be contained in the origin room. Analyses have shown that both possibilities are possible.
5. The 'arm wrestling' room shows that the two buoyancy forces collide and produce an interesting dynamical phenomenon (Figure 4E). Both upward and downward flows are possible; see Li (2002).
6. Multiple smoke route problem (Nitta, 1996). Nitta (1996) analysed a number of multi-room buildings and suggested the existence of 'variety modes' in natural ventilation and smoke venting. The smoke can choose different routes depending on the initial conditions.

PRACTICAL RECOMMENDATIONS

The following practical recommendations are based on our current understandings on the dynamical phenomena with ventilation flows, including those not presented in this paper:

- Avoid colliding of two or more driving forces in building airflow design. For example, wind and stack forces should be designed to work together, rather than be made to against each other in natural ventilation design.
- Try different initial conditions or initialisations in the multi-zone or CFD programs if the design problem is suspected to have more than one solution. One way to determine the possible existence of multiple solutions is to see whether there are any potential opposing forces in the flow. For most design problems, it may become impossible to test different combinations of initial conditions. It is hoped that such a computer analysis tool of dynamical nonlinear phenomena of ventilation will become available soon.
- If possible, do not use symmetrical boundary conditions, and always simulate the building as a whole. Symmetrical boundary conditions are often recommended in CFD simulations to save CPU time. Limited experimental information in the literature suggests that this may not be suitable and the flow in a symmetrical setup can also be asymmetrical; see Zhang *et al.* (2000). Before more information become available, it is safe to carry out a full CFD simulation if possible.

CONCLUSIONS

The examples reviewed in this paper suggest that multiple solutions exist in building ventilation flows. Care should be taken when using almost all existing analysis methods for building ventilation airflows such as the multi-zone or zonal methods and computational fluid dynamics, which give only one unique solution for one set of identical input parameters when started with zero initialization or zero initial conditions. Three practical recommendations in terms of design and analysis are suggested based upon the current understanding of dynamical phenomena.

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