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Impact of aperture separation on wind-driven single-sided natural ventilation

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ABSTRACT

This paper presents a study of the impact of horizontal aperture separation in single-sided ventilation flows with two apertures (SS2). The study is based on wind tunnel measurements and dimensional analysis. The results show that the SS2 ventilation flow rate, scaled with incoming wind velocity and aperture area, depends on the incoming wind angle relative to the aperture façade, θ, and on the aperture separation scaled by building width, s'. For most wind angles, the ventilation flow increases as the square-root of s'. This study also identified a novel flow driving mechanism – vortex shedding: when the ventilation openings are on the leeward side of the building and the wind is nearly head-on, the flow is driven by a pumping mechanism due to vortex shedding.

1. Introduction

Reducing energy usage in the building stock is a desirable goal from the point of view of both lower running costs for owners or occupiers and fewer emissions of pollutants and greenhouse gases from fossil fuel-based energy generation. Natural ventilation can be an important potential source of energy savings for space conditioning (cooling and ventilation), particularly in the commercial building sector, either alone or supplemented with mechanical conditioning in a hybrid approach.

The primary agents harnessed in natural ventilation are twofold: the wind, impacting on the openings in the exterior of the building; and temperature differences, between the exterior and interior caused by internal sensible heat gains. In typical natural ventilation configurations one or more open windows ventilate the internal space. The case of two openings is the simplest multi-opening situation, and leads to four possible airflow regimes, depending on the relative opening position:

- Single-sided ventilation, SS
- Corner ventilation, CR
- Cross-ventilation, CV
- Displacement ventilation, DV

in which the two openings are in the same, adjacent, or opposite external façades, or at different heights, respectively (Fig. 1).

In the first three flow regimes, wind-generated flow will be dominant unless the wind is light enough and/or the temperature differences are sufficiently large. This paper will focus on wind-driven flows and, therefore, will not discuss displacement ventilation or interactions between buoyancy and wind.

Many studies of natural ventilation focus on cross-ventilation because of its potential to achieve large flow rates that maximise free-cooling capacity [1–3]. Unfortunately, the large cooling potential of CV is difficult to realise because in most cases the high flow rates are incompatible with office tasks and may result in draft-induced discomfort (particularly in the jet region of the flow [4]). Further, CV requires that the room must have opposing external walls, a characteristic that most rooms in the perimeter of a building do not have. The corner ventilation case is fairly similar in character to cross-ventilation [5,6] and furthermore is relevant to only a relatively small percentage of offices. On the other hand, in many perimeter office spaces, SS systems that induce lower, more

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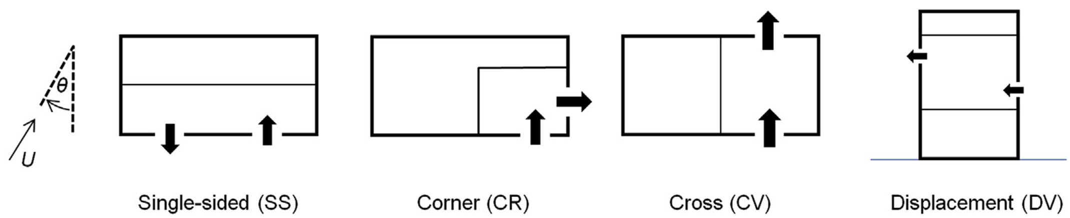

Fig. 1. Ventilation regimes with 2 apertures (DV shown in elevation, others in plan view).

manageable, ventilation rates can be a good option. Perimeter spaces often have limited room depth and therefore, for at least some parts of the year, the smaller cooling capacity of SS may be sufficient [7].

Single-sided ventilation systems can be divided into two types: single-opening (SS1) and multiple-opening (SSn). In terms of the physical picture of single-sided ventilation, there is a fundamental divide between one opening and more than one opening, since in the former case the external air entering and the internal air being removed must both pass through the same opening, while in the latter case there can be a clearer division between inlet and outlet openings. This difference means the single-opening case is somewhat limited in its ability to ventilate a room, whereas a room with two or more openings on the same façade can give a substantial supply of fresh air under many circumstances. Hence SS1 systems form the typical option for small offices, while systems with multiple openings in distinct zones of the façade are the choice for large rooms.

The SS1 case has been much studied [8–11] and explained in terms of unsteady static pressure variations across the opening, a growing shear layer generated by the flow along the building façade, or a combination of both. Recently, Ai and Mak [12] measured instantaneous flow rates in a single-room small building in a boundary layer wind tunnel and concluded that the fluctuating part of the flow contributed between 15 and 64% to the ventilation rate (depending on wind direction). Simple scalings for the SS1 ventilation rate were proposed and validated by Warren and Parkins [8]. This pioneer study was also one of the first to address the effect of window geometry. Subsequently several authors, including Heiselberg et al. [13], Caciolo et al. [14] and Wang et al. [15], have worked on this important effect, which is difficult to model accurately in typical small-scale wind tunnel studies.

The two-aperture single-sided case (SS2), on the other hand, is potentially a common practical situation and yet is not well-represented in the literature. Warren and Parkins [8] measured single-sided ventilation driven by multiple openings in a single façade in a full-scale building, but the study was inconclusive and did not result in a model. Cóstola et al. [16] showed that wind-generated pressure variations along the façade can be significant with, therefore, the potential to generate useful flow rates. Teppner et al. [17] tested a 3-storey section of a 10-storey building (14 m × 21 m × 30 m) at 1:25 scale in an aerodynamic wind tunnel. This study revealed significant pressure variations Δp along the façade at a given height: $\Delta p/(1/2\rho U^2) \sim 0.5$, where U is the approach flow velocity scale. Chu et al. [18] studied a small single-storey building with two openings in the same façade and proposed a simple model to predict ventilation flow rates. The study used openings a fixed distance apart and, therefore, the proposed model does not include aperture separation effects. The model distinguishes two ranges for the incoming wind angle θ where different mechanisms drive the flow: for wind directions in the range 22.5–45° region the flow is driven by pressure difference between the two openings, while for the remaining angles the flow is driven by pressure fluctuations and (for 90° wind) by shear.

SS2 flows are primarily the result of differences in static pressure between the openings: inflow occurs at the openings with higher pressure and outflow occurs at the openings with the lower pressure. This pressure difference is driven by the external flow and comprises a combination of steady and unsteady components whose relative contributions depend primarily on wind angle and aperture separation.

Turbulent external flow leads to unsteadiness in the pressure field, which means the pressure difference changes with time in both magnitude and sign. This leads to a contribution to the ventilation rate provided the frequency is low enough: if the pressure difference fluctuates too rapidly then it drives fluid in and out again before it has been able to mix with the internal air. The unsteady contribution is present in all cases but is particularly important when the mean pressure difference is approximately zero. One extreme but interesting manifestation of this unsteady contribution occurs when the openings are on the leeward side of the building. In this case, discussed in Section 3.1, the flow is driven primarily by the low-frequency periodic effect associated with Strouhal vortex shedding [19].

The objective of this paper is to examine in more detail the effect of aperture separation in SS2 flows and to use a combination of wind tunnel measurements and dimensional analysis to develop simple formulae to predict the ventilation rate in terms of basic parameters describing both the incoming wind and the building. These formulae should be simple enough to allow their straightforward integration in simplified simulation tools such as EnergyPlus [20].

The rest of this paper proceeds as follows. Section 2 presents the wind tunnel experimental set-up. Section 3 gives an overview of the results used in the subsequent modelling work – the characteristics of the pressure difference between the two apertures and the associated ventilation rates – and concludes by deriving a formula connecting the measured ventilation rate with the magnitude and characteristics of the driving pressure difference at the two openings. Section 4 then takes this a stage further by proposing a simple expression for the driving pressure difference in terms of the characteristics of the incoming wind and the opening separation scaled by the characteristic length of the building façade, which can then be combined with the previous result to relate the ventilation rate to the parameters describing the set-up. Thus the paper offers two levels of use, depending on the type of data available: when pressure (difference) data are available, the results in Section 3 may be used; while if only basic set-up parameters are known, the formulation in Section 4 is appropriate. The latter offers a more accessible model, but with increased uncertainty in some circumstances due to additional assumptions.

2. Wind tunnel measurements

The wind tunnel used in this study is located in Fort Collins, Colorado, USA and operated by CPP Wind Engineering, Inc. The