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Technical note

# A technical note on simplified modeling of turbulent mixing in wind-driven single sided ventilation

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## ABSTRACT

Single sided ventilation is a commonly used room natural ventilation strategy. Small, single occupant offices, often use single sided ventilation through a single opening (SS1). In most multistory buildings, the ratio between building façade and SS1 window opening area is 0.1% or less. In these cases, wind driven SS1 flows are caused by entrainment of room air that contacts outdoor airflow along the building opening plane. The turbulent mixing layer that develops in this region is central to the room airflow development process. The existing theoretical analysis of these flows was developed in 1977 and preceded several experimental studies of turbulent mixing layers that revealed new flow features that impact the resulting airflow estimate. This technical note presents a simple analytic calculation of turbulent mixing in SS1 flows that incorporates these developments. The proposed approach can predict the bulk ventilation flow rates measured in wind tunnel studies with an over prediction of 21%, a significant improvement over the existing analysis that resulted in an average under-prediction of 70%.

## 1. Introduction

Natural ventilation (NV) through openings in a single façade is known as single sided ventilation (SS). Since most rooms in medium and large buildings only have access to a single building façade, SS systems are the most commonly used NV strategy. In small, single occupant offices, it is common to use SS ventilation systems with a single opening (SS1).

Due to size constraints and flow scaling limitations, many existing experimental and numerical studies of SS1 ventilation are based on single zone models with a relatively large ratio of opening to building façade area ($A/A_F$, 17% [1], 7% [2], 6% [3]). These geometries are representative of small single zone pavilions but are far from what occurs in typical multistory buildings whose ratios between opening and building façade areas are one to two orders of magnitude lower than these experimental models (typically less than 0.1% [4–6]). These geometry differences have a significant impact in the driving mechanism of wind driven SS1 flows. A recently completed wind tunnel study of SS ventilation [7] showed that the wind generated pressure difference between two points in a façade is proportional to the distance between the points divided by the façade length scale ($\sqrt{A_F}$). This proportionality implies that a 1 $m^2$ opening in a 10 $m^2$ facade is subjected to a static pressure variation that is one order of magnitude larger than the same opening in a building with a 1000 $m^2$ façade (a 30 m wide ten-story building facade). As a result, wind driven SS1 flows in small single zone buildings may be driven by static pressure variations along the opening area, whereas the same opening in a larger building is subjected to negligible static pressure variations that do not drive the flow. In these latter cases the flow is driven by entrainment caused by external airflow parallel to the building façade. Observation of the airflow in the window plane in these two types of SS1 flows reveals significant differences. Static pressure driven flows have clearly defined regions of inflow and outflow perpendicular to the window plane, whereas in entrainment driven flows the flow is predominately parallel to the opening.

Fig. 1 shows wind tunnel [8] and numerical [9] simulations of SS1 flows in infinitely large facades. The left side of this figure shows outdoor air flowing parallel to a rectangular opening and entraining outdoor and room air into a turbulent mixing layer that expands into the room towards the trailing edge of the opening (where it reaches its maximum thickness). This technical note presents a simplified analytical model of this turbulent mixing layer. The transition between a static pressure or entrainment driven SS airflow is likely to depend on opening geometry and position in the building façade. This technical note does not focus on this transition, yet, it is important to define the limits of application of the model that will be presented. In Ref. [7], entrainment driven flow was observed with an area ratio of 2% ($A/A_F$). In this context the proposed model can be applied to SS1 wind driven ventilation systems in building facades with an area that is at least two orders of magnitude larger than the ventilation opening area ($A/A_F < 1\%$). The next section presents a simplified model for turbulent mixing in wind-driven SS1 flows. This section is followed by a

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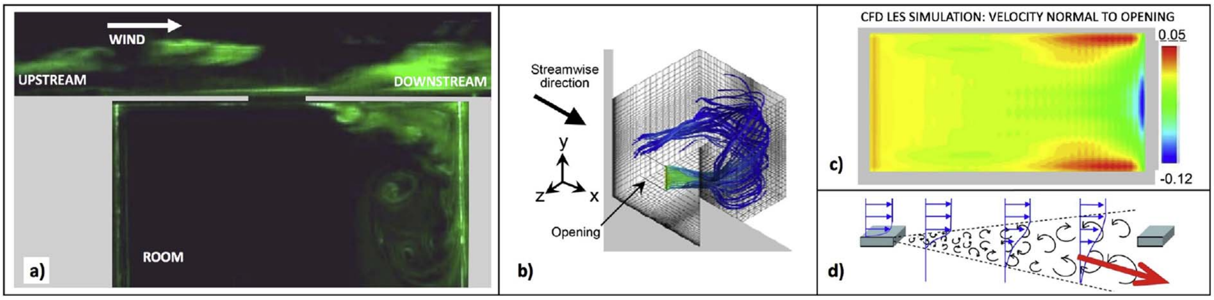

**Fig. 1.** a) Top view of the turbulent mixing layer expanding along an opening in SS1 ventilation (room mounted on the side wall of a wind tunnel [8]). b) streamlines showing inflow in the downstream side of an SS1 opening (LES simulation [9], same configuration as in a)). c) average air velocity perpendicular to the opening plane, showing inflow near the downstream edge and outflow along the upper and lower edges (LES simulation [9]). d) two dimensional schematics of the mixing layer exchange [9].

comparison of the model predictions with existing experimental measurements.

## 2. Simplified calculation of turbulent mixing in wind-driven SS1 flows

The most widely used simplified model for SS1 flows was developed by Warren, in 1977 [10]. This model uses the entrainment hypothesis [11] to estimate airflow in wind driven SS1 ventilation. According to the entrainment hypothesis the magnitude of the flow entrained into the mixing layer that develops along the window opening is proportional to the flow driving external airflow velocity ($U_L$) multiplied by the opening area ($A_{OP}$). The flow driving external airflow velocity ($U_L$) is the wind velocity near the façade, immediately outside the mixing layer that develops along the window plane shown in Fig. 2. These two concepts led to the simplest form of bulk airflow model for this ventilation process:

$$Q_{bulk} = F_{LB}.\, A_{OP}.\, U_L \tag{1}$$

where $Q_{bulk}$ is the bulk airflow into the room (m$^3$/s). The non-dimensional coefficient $F_{LB}$ models the effect of the turbulent mixing process. The value of this coefficient has been measured indirectly in several wind tunnel studies and in full scale wind-driven single opening ventilation (listed in Table 1).

Calculating $F_{LB}$ is the main challenge of this simple and elegant model. The existing theoretical calculation of $F_{LB}$, proposed by Warren, in 1977 [10], is based on a plane mixing layer developing along the window plane (Fig. 1, d) and entraining similar amounts of air from the room and outdoor sides. The $F_{LB}$ value obtained in the 1977 analysis, 0.013 [10], is 70% lower than the average of the available experimental measurements of this coefficient (0.042, presented in the next section, Table 1).

**Table 1**
Experimentally measured $F_L$ values for bulk (B, $F_{LB}$) and effective flow (E, $F_{LE}$). All measurements were performed in wind tunnels. Turb. (%) is the turbulence intensity in the external flow, defined as the ratio between the root-mean-square of the turbulent velocity fluctuations and $U_L$.

| Measurement | $F_L$ | Turb. (%) |
|---|---|---|
| Bulk flow (fan induced mixing) [19] | 0.036 (B) | 11.5 |
| Bulk flow (mixing induced by a rotating plate) [20] | 0.06 (B) | – |
| Bulk flow (mixing induced by a rotating plate) [8] | 0.028 (B) | 11.5 |
| Bulk flow (mixing induced by a rotating plate) [8] | 0.045 (B) | 11.5 |
| Average Effective flow (measured in multiple points) [21] | 0.025 (E) | 0.8 |
| Average Effective flow (measured in multiple points) [21] | 0.035 (E) | 9 |

Existing experimental analysis and simplified solutions of plane mixing layers use the 2D coordinate system (shown in Fig. 2) to describe a flow that has 3D mixing effects but is not affected by any boundaries along the z coordinate. The plane mixing layer that occurs in SS flows forms in the upstream edge and breaks up in the other three opening edges (the downstream and the two side edges). In addition, in SS flows there are regions of outflow that occupy a small portion of the opening plane (a manifestation of mass conservation effects, shown in Fig. 1c). SS flows are 3D and using a plane mixing layer to model this flow is an approximation whose validity will be tested in the analysis presented in this technical note.

There are several features of the mixing layer flow that occurs in SS1 openings that impact the value of $F_{LB}$ that were not included in the initial model [10]. We begin by defining the mixing layer width, δ, as the distance along the y coordinate between the points where the x-velocity is between 10 and 95% of the free stream velocity (δ ≈ 0.3x [13], see Fig. 2). Based on this mixing layer width we define a Reynolds

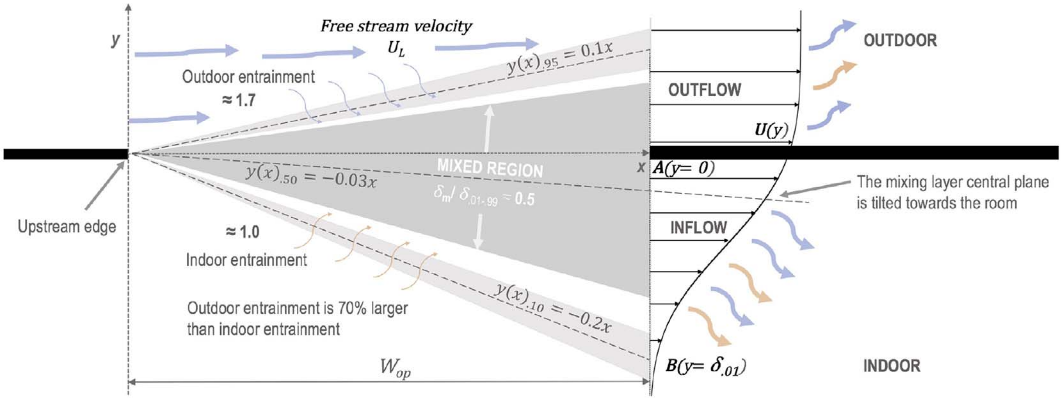

**Fig. 2.** Top view of a turbulent mixing layer expanding along an opening. The limits of the mixing layer are defined by the local ration between the x component of the velocity and the free stream velocity: $U_x(x)/U_L$. The subscripts in the y(x) lines refer to the value of this ratio (0.10, 0.50 and 0.95). The two triangles in light grey are the visual limits of the mixing layer that are used in experimental studies.