

# Assessment of the Effects of Environmental Factors on Air Flow In and Around Buildings

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**ABSTRACT:** This paper assesses air flow characteristics in and around buildings under different environmental conditions using computational fluid dynamics modeling techniques. It argues that any “generic” representation of air flow without explicitly stating the quantification of the parameters assumed in deriving those representations (as commonly encountered in architectural design guides or similar publications), may be erroneous and should be used with caution.

To illustrate this point, an experimental approach is adopted to select certain air flow phenomena or design guidelines offered in some “representative” publications where the environmental context may not have been explicitly communicated in qualitative and quantitative terms. Demonstrative sets of quantitative values are then applied to the relevant design input parameters within certain assumed environmental context to simulate the air flow performance using an air flow modeling tool CFD-ACE+ (2000).

The results from the parametric experimental set-ups demonstrate that any change in the environmental factors can significantly affect the boundary conditions and consequently the indoor air flow in both velocity and distribution pattern. It reinforces the main assertion of this work that it is critical for the building design team to clearly define the performance goals of the project as well as the contextual conditions, covering both the qualitative and the quantitative aspects as comprehensively as possible. This will facilitate a productive design process that will yield clear and accountable solutions accordingly.

**Keywords:** wind, natural ventilation, computer simulation, building performance

## 1. INTRODUCTION

Natural ventilation remains an important passive design feature in our efforts to promote energy efficient and sustainable building design in a variety of contexts (Schwarz 2003). It requires complicated interrelated considerations such as terrain, climate, building design and thermal comfort, which should be well-understood by architects from the early conceptual phase of the design process (Jones 1997). Unfortunately, many readily available references are given in highly simplified diagrams without sufficient information on their context and details. Considering that air flow in and around a building is unique every building, using simplified diagrams can be erroneous or misleading. Thus, basically, architects are supposed to conduct simulation for their building.

Many tools are available for architects to model natural ventilation performance. They can use a wind tunnel to conduct physical simulation, or computer software (such as nodal network and computational fluid dynamics software) to perform computational simulations (Alexander, et al. 1997) Among them, computational fluid dynamics (CFD) programs are becoming more readily available. They can produce graphical results which make it easier for architects to

visualize and understand the “real” phenomena by including information on flow vectors, particle tracking, air velocity and temperature profiles.

This research project deals with transferring simplified design diagrams into computer models, testing them under different scenarios (climate, terrain, building configurations and dimensions) and comparing the resulting air flow velocity, distribution pattern and indoor air temperature.

## 2. THE SIMULATIONS

### 2.1 Experimental set-up

A general purpose CFD program is used to simulate air flow around and inside a building at the early building design phase. The purposes are:

- To demonstrate that there can be different outdoor and indoor air flow characteristics depending on surrounding conditions, which may not be adequately represented by generic diagrams of air flow in and around a building commonly found in architectural design guides or similar references;
- To illustrate indoor air flow (distribution pattern, air velocity) under different atmospheric conditions (i.e., different boundary layers);

- To demonstrate the ability of a CFD program to simulate natural ventilation generated by wind and stack effect.

To reduce the complexity of the computation (thus considerably reducing the time to construct and execute the models and analyze the result as required during the early design phase), only two dimensional (2D) models were made. It should be noted, however, that three dimensional (3D) model will give more accurate results since air flow is three dimensional.

A demo version of a commercial general purpose CFD program, called CFD-ACE+ (2000), was used. This program comes in three modules: (1) CFD-GEOM version 6.2.03, the pre-processor, (2) CFD-GUI version 6.2.3, the solver, and (3) CFD-VIEW version 6.2.75, the post-processor. The program ran under Microsoft Windows XP Professional 2002 operating system, Intel Pentium III processor 598 MHz and 384 MB of RAM.

## 2.2 Scenarios

Two diagrammatic models found in the publication "Natural Ventilation in Northwest Buildings" by Brown (2004) are used for this CFD simulation study. No detail of any assumed climate, terrain or applicable range of building dimension information is provided. In this experiment, Fig. 1 is modeled as a 7 m high gable-roof building model (Fig. 3) to simulate the horizontal air flow phenomenon. Fig. 2 is modeled as a 12 m high chimney-roof building model (Fig. 5) to simulate the vertical air flow, which combines wind-driven and buoyancy-driven flow. This experiment aims to test whether air flow representations in these diagrammatic models are always valid under different environmental conditions.



Figure 1: Gable-roof model.

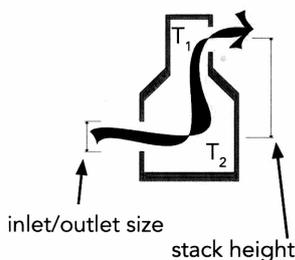


Figure 2: Chimney-roof model.

The gable-roof model is tested under the following scenarios:

- As a stand-alone building and in a complex with surrounding buildings;
- Four outdoor wind speeds 3.3, 9.8, 16.4, 32.8 fps (1, 3, 5 and 10 m/s), all are measured at flat

terrain at 32.8 ft (10 m) high, boundary layer profile;

- Three seasons: summer, swing (autumn/spring) and winter;
- Surface temperature assumptions (Table 1);
- Three variations of openings (inlet = outlet, inlet > outlet, inlet < outlet), in summer only.

The chimney-roof model is tested under the following scenarios:

- Located within a complex of buildings;
- Four outdoor wind speeds 3.3, 9.8, 16.4, 32.8 fps (1, 3, 5 and 10 m/s), all are measured at flat terrain at 32.8 fps (10 m) high, boundary layer profile;
- Three seasons: summer, swing (autumn/spring) and winter;
- Surface temperature assumptions (Table 1) ;
- Only one variation of opening (inlet = outlet).

Since this study focuses on natural ventilation, evaluations are based on the relevant thermal comfort zone limits:

- Indoor air velocity ~3 fps (~1 m/s), velocity recommended for residential building;
- Indoor air temperature 68 – 80.6°F (20 – 27°C);
- Indoor air pattern (the uniformity of air distribution);
- Indoor air humidity (30 -60%).

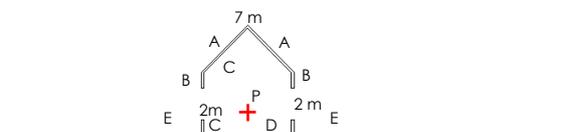


Figure 3: Stand alone gable-roof building.

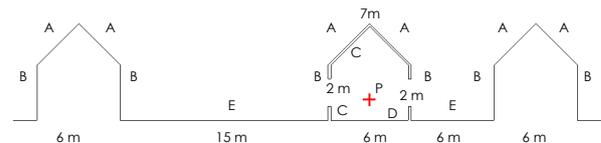


Figure 4: Gable-roof model in a complex.

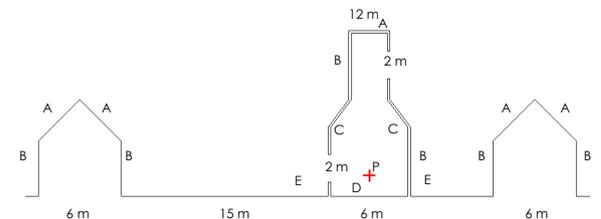
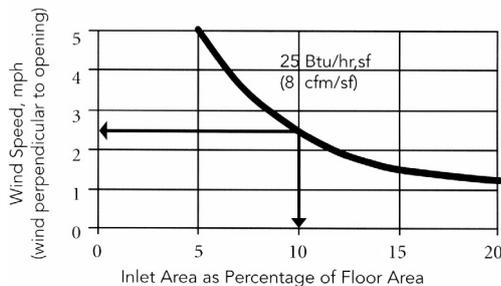


Figure 5: Chimney-roof model in a complex.

**Table 1:** Assumed building surface temperatures.

Seasons	Wind Temperature °F (°C)	A °F (°C)	B °F (°C)	C °F (°C)	D °F (°C)	E °F (°C)
Summer	68 (20)	122 (50)	104 (40)	75.2 (24)	71.6 (22)	104 (40)
Swing	50 (10)	77 (25)	71.6 (22)	69.8 (21)	66.2 (19)	68 (20)
Winter	32 (0)	32 (0)	41 (5)	64.4 (18)	60.8 (16)	32 (0)

Additional study is conducted to check the air flow rate (or cross ventilation efficiency) in the gable-roof stand alone building and reference it to the graph in Brown (2004,) (Fig. 6). According to Brown, the cross ventilation rate is sensitive to wind at low speeds and opening sizes at high wind speeds. No mention is made where the wind speed is measured relative to the building. This is important since the wind speed fluctuates when it approaches any obstruction (in this case, a building.) Moreover, the roughness of the ground will also affect the wind speed. In this study, the wind speed is measured at 1 m from the building.



**Figure 6:** Relation between wind speed and inlet area with respect to air flow rate. (Brown, 2004).

### 3. FINDINGS

#### 3.1 Stand alone gable-roof building

The stand alone building was tested under summer condition, four different wind speeds, and three different (I)nlet and (O)utlet configurations. Using point P as the reference some findings are as follows:

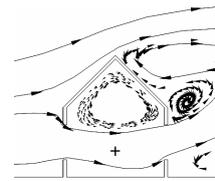
- There is no significant indoor air temperature difference between building with I = O, I > O and I < O; the higher the wind speed, the less obvious is the difference. For very low wind speed, < 1 m/s, the indoor air temperature of building with I = O is 0.6°C below other buildings, which is insignificant. In general, low wind speed, < 3.28 ft (< 1 m/s), results in higher indoor air temperature. In the summer, with wind temperature of 68°F (20°C), the indoor air temperature can reach 72.14°F (22.3°C).
- Air flow tends to follow a direct path from inlet to outlet, leaving air at other locations inside the building swirling. This means that air at those locations cannot ventilate well, though the swirling itself is useful for diluting any instantaneous pollutant source.

- There is very strong correlation ( $R^2 = 1$ ) between wind speed and indoor air velocity, i.e, the higher the wind speed, the higher the indoor air velocity.
- Building with I = O creates higher indoor air velocity, followed by those with I < O and I > O (see Fig. 8).

Since it is numerically based, the CFD program can produce very definite smoke tracing even though the wind and indoor air speeds are very low, under the order of one thousandth meter per second.

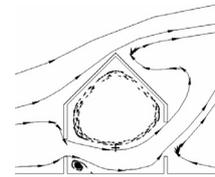
Inlet = Outlet

$V_p = 1.57$  fps (0.48 m/s)  
 $T_p = 71.06^\circ\text{F}$  (21.7 °C)  
 Rotating air flow under the roof, which brings heat from the warm roof, is above the occupants' zone.



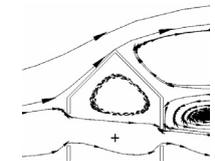
Inlet < Outlet

$V_p = 1.18$  fps (0.36 m/s)  
 $T_p = 72.14^\circ\text{F}$  (22.3 °C)  
 Rotating air flow under the roof, which brings heat from the warm roof, reaches upper part of the occupants' zone. Occupants will experience warm air flow on their head.



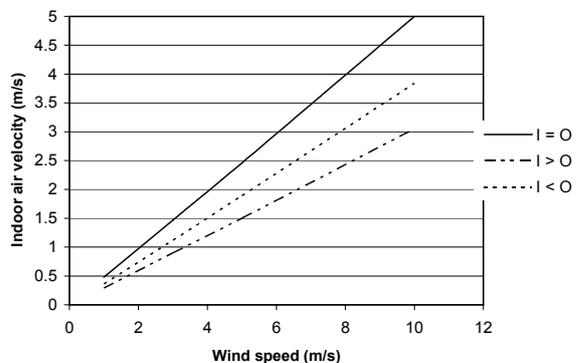
Inlet > Outlet

$V_p = 0.95$  fps (0.29 m/s)  
 $T_p = 71.96^\circ\text{F}$  (22.2 °C)



**Figure 7:** Comparison of different Inlet/Outlet configurations.

P is the measuring point, at the center of the room, 4.92 ft (1.5 m) above the floor; power law boundary layer equation for urban condition is applied, in summer, with wind speed of 3.28 fps (1 m/s) measured at flat area.



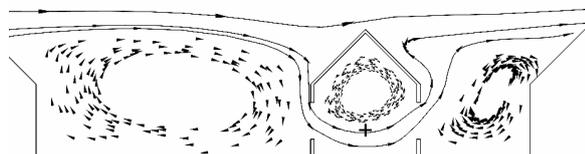
**Figure 8:** Correlation between indoor air velocity and wind speed (measured at open terrain.)

### 3.2 Gable-roof within a complex of buildings

The stand alone gable-end building is placed within a complex of surrounding buildings and is tested under three seasons (summer, swing (autumn/spring) and winter), with surface temperature assumptions (Table 1), and four wind speeds. The results are as follows:

- Under corresponding wind speeds, seasons do not have any significant effect on indoor air velocity. Surrounding objects prove to significantly reduce the indoor air velocity. The stand alone building and the building in the complex had indoor air velocity of, respectively, 1.57 and 0.32 fps (0.48 and 0.1 m/s), when tested under summer condition with wind speed of 3.2 fps (1 m/s). For wind speed 9.84 fps (3 m/s) the indoor air velocity becomes, respectively, 4.82 and 0.98 fps (1.47 and 0.3 m/s). In terms of CFD program application, this highlights the caution that even though the same power law equation is used to create atmospheric boundary layer profile, the results can be significantly different with the absence or presence of surrounding objects.
- There is swirling wind between the buildings, which pushed the indoor air flow slightly downward (Fig. 9).

It is also demonstrated that surrounding buildings, with assumed surface temperatures, increase the indoor air temperature, though insignificantly (0.33 °C).



At wind speed 3.28 fps (1 m/s): VP = 0.33 fps (0.1 m/s), T<sub>P</sub> = 71.65 °F (22.03 °C)  
 At wind speed 9.84 fps (3 m/s): VP = 0.98 fps (0.3 m/s), T<sub>P</sub> = 70.7 °F (21.5 °C)  
 At wind speed 32.8 fps (10 m/s): VP = 3.28 fps (1.0 m/s), T<sub>P</sub> = 70.29 °F (21.27 °C)

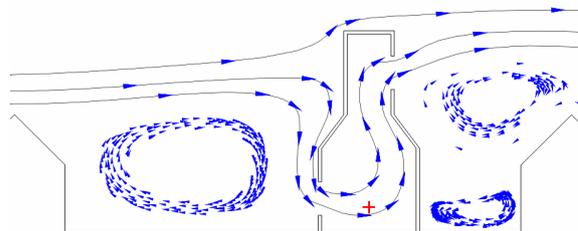
**Figure 9:** Air flow pattern in and around a gable-roof building located within a complex of buildings.

### 3.3 Chimney-roof building in a complex

A building with a chimney-like roof is placed within a complex of buildings (Fig. 10). As in the previous gable-roof building case, this is tested under three seasons and four wind speeds. The results are as follows:

- Wind easily entered through the lower opening and exited through the upper opening. The indoor air velocity is slightly higher than that of the gable-roof building. For wind speed of 3.28 fps (1 m/s), the indoor air velocities are respectively, 0.62 and 0.33 fps (0.19 and 0.1 m/s). For wind speed of 9.84 fps (3 m/s), they are respectively, 1.90 and 0.98 fps (0.58 and 0.3 m/s).
- There is swirling wind between buildings.
- In summer, the chimney-roof building has higher indoor air temperature than the gable-roof

building [73.27 °F (22.93 °C) compare to 71.65 °F (22.03 °C) at 3.28 fps (1 m/s) and 70.93 °F (21.63 °C) compared to 70.29 °F (21.27 °C) at 32.8 fps (10 m/s)]; whereas in winter it has lower indoor air temperature [34.36 °F (1.31 °C) compared to 31.98 °F (-0.01 °C) at 3.28 fps (1 m/s)].



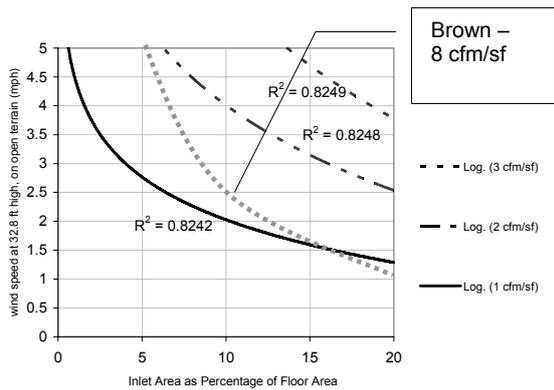
At wind speed 3.28 fps (1 m/s): VP = 0.62 fps (0.19 m/s), T<sub>P</sub> = 72.27 °F (22.93 °C)  
 At wind speed 9.84 fps (3 m/s): VP = 1.90 fps (0.58 m/s), T<sub>P</sub> = 72.18 °F (22.32 °C)  
 At wind speed 32.8 fps (10 m/s): VP = 6.33 fps (1.93 m/s), T<sub>P</sub> = 70.93 °F (21.63 °C)

**Figure 10:** Air flow pattern in and around a chimney-roof building located within a complex of buildings.

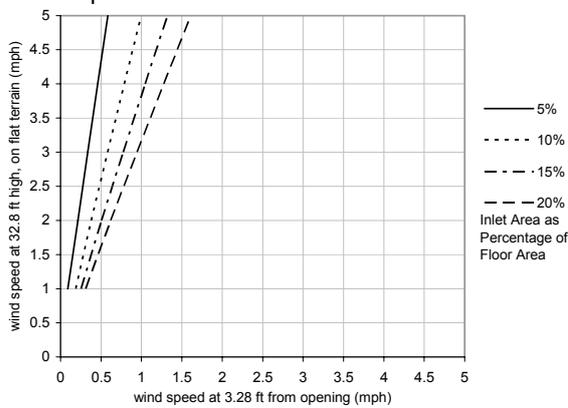
Table 2 provides descriptive characteristics of various wind speeds as a quick reference guide, according to Boutet (1987).

### 3.4 Cross-ventilation efficiency

Simulations using the CFD program produced different results compared to data found in Brown (2004). Computational results show far lower air flow rates (Fig. 11). Such variations may be attributed to several factors. Brown did not indicate any assumed boundary condition. Wind speed data from meteorological weather stations, which are usually based on measurement at 32.8 ft (10 m) above the ground, should not be used directly for predicting air flow rate through openings in this instance. Wind speed stratification caused by terrain condition (boundary layer profile) should be taken into account (see Fig. 12). Furthermore, the speed of wind approaching any object will also be reduced. It is demonstrated that air flow representation in the diagrammatic models as well as the correlation between wind speed and inlet size with respect to air flow rate found in Brown's book require more detailed contextual descriptions. Otherwise, the information can be misinterpreted.



**Figure 11:** Comparison between wind speed and inlet size with respect to air flow rate



**Figure 12:** Correlation between wind speeds measured at open terrain and 1 m from openings.

**5. CONCLUSION**

The primary goal of designing natural ventilated buildings is to create adequate and well-distributed indoor air flow. The performance outcome is affected by the environment, including terrain, climate, surrounding objects, and building design in terms of the building massing (formal configuration, dimensional proportion) and openings (formal configuration, dimensional proportion and location).

Outdoor and indoor air flows are unique under different environmental conditions and building design configurations. Any “generic” representation of air flow without explicitly stating the quantification of the parameters assumed in deriving those representations (as commonly encountered in architectural design guides or similar publications), should be used with caution.

The results from the parametric experimental setups reported in this research project demonstrate that any change in the environmental factors as well as the building design can significantly affect the indoor air flow in both velocity and distribution pattern. It reinforces the main assertion of this work that it is critical for the building design team to clearly define the performance goals of the project as well as the contextual conditions, covering both the qualitative and the quantitative aspects as comprehensively as possible. This will facilitate a productive design process that will yield clear and “accountable” solutions accordingly.

**Table 2:** Descriptive characteristics of various wind speeds.

mph (m/s)	General description	Specifications
< 1 (<0.45)	Calm	Smoke rises vertically.
1 – 3 (0.45 – 1.34)	Light air	Wind direction shown by smoke drift but not by vanes
4 – 7 (1.79 – 3.13)	Slight breeze	Wind felt on face; leaves rustle; ordinary vane moved by wind.
8 – 11 (3.58 – 4.92)	Gentle breeze	Leaves and twigs in constant motion; wind extends light flags.
12 – 16 (5.36 – 7.15)	Moderate breeze	Dust and loose paper moved; small branches are moved.
17 – 22 (7.60 – 9.83)	Fresh breeze	Small trees with leaves begin to sway.
23 – 27 (10.28 – 12.07)	Strong breeze	Large branches in motion; whistling in telephone wires.
28 – 34 (12.52 – 15.20)	Moderate gale	Whole trees in motion.
35 – 41 (15.65 – 18.33)	Fresh gale	Twigs broken off trees; progress generally impeded.
42 – 48 (18.78 – 21.46)	Strong gale	Slight structural damage occurred; chimney pots removed.
49 – 56 (21.90 – 25.03)	Whole gale	Trees uprooted; considerable structural damage.
57 – 67 (25.48 – 29.95)	Storm	Very rarely experienced; widespread damage.
> 68 (> 30.40)	Hurricane	Extremely rare; extensive damage common.

Wind measured at 20 ft above the ground. (Source: Boutet, 1987)

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