NATURAL VENTILATION

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Keywords: wind data, climatic conditions, pressure difference, temperature difference, simulation tools, empirical models, network models, CFD Models, experimental work, single-side ventilation, cross ventilation.

Contents

Summary

Ventilation is necessary for maintaining acceptable indoor air quality and can also be used to improve indoor thermal conditions. With natural ventilation the outdoor air moves in and the indoor air moves out of a space as a result of physical driving forces without the assistance of any mechanical means. Natural ventilation can be used as a passive cooling technique to reduce the building's energy consumption. The driving forces for single-side and cross natural ventilation is a combination of inertia forces caused by the wind and buoyancy forces which are caused by the temperature difference in the airflow direction. Modeling the complex phenomena and accounting for all the parameters involved in natural ventilation is a demanding process. The available simulation tools and models range from simple to more complex methodologies, including empirical models, network models, and Computational Fluid Dynamics (CFD). Experimental work for single-side and cross flow ventilation provides useful data and a better understanding of the phenomena. As a result of this work, a methodology has been developed to improve the accuracy of network models for airflow prediction in single-side ventilation. Network models have a weakness in modeling cases of wind dominated airflow processes because of the way the inertia forces are accounted for. The correction factor is calculated as a function of the

Archimedes number and can improve the accuracy of network model predictions, by taking into account the relative importance of the inertia and buoyancy forces.

1. Introduction

The term "ventilation" includes all the processes by which the indoor air is replaced with the equivalent air masses of outdoor air. Ventilation is necessary for maintaining acceptable indoor air quality and can also be used to improve the indoor thermal conditions. Proper ventilation can also contribute in reducing energy consumption in the building. Depending on the drive mechanisms of ventilation, there are two primary means for ventilating a space, namely:

- **Mechanical ventilation**. The outdoor air is conditioned before entering into a space in order to reach the acceptable conditions and is distributed by mechanical means (i.e., fans). Indoor air may be extracted in a similar way. The outdoor air can be filtered (for example in areas where the outdoor air is polluted) and conditioned (i.e., heated, cooled, humidified, or dehumidified) in order to reach the specific indoor thermal conditions. The air supply and exhaust conditions (i.e., flow rates, air exchanges, air quality, and thermal conditions) can be optimized for any kind of conditions and indoor requirements. However, central mechanical ventilation systems increase the building's energy consumption and operating cost. Relevant topics on mechanical ventilation are presented in chapter *Mechanical Ventilation and Equipment*.
- **Natural Ventilation**. The outdoor air moves in and the indoor air moves out of a space as a result of physical driving forces without the assistance of any mechanical means.

Natural ventilation has long been recognized as an effective technique for cooling in buildings, by extending the human thermal comfort zone as a result of higher indoor velocities. Higher indoor air velocities, up to a certain limit so that they do not disturb the occupants, are acceptable and sometimes desirable in summer. Natural ventilation through large openings, depending on the outdoor air conditions (i.e., wind speed, wind direction, temperature, and humidity) and space geometry (i.e., space layout) can maintain sufficient airflow to reach the desirable indoor air velocity and improve the indoor air quality (given suitable outdoor air quality conditions).

Natural ventilation is driven by the outdoor airflow into a space through:

- Cracks: very small openings with one dimension less than 1 cm. For example, the number of air changes per hour (ACH), that is the number of times the indoor air volume is replaced, varies according to the building construction. For airtight good building constructions, the airflow through cracks can be of the order of 0.1–0.2 ACH, while for old building constructions the infiltration rate can be up to 3 ACH.
- Large openings: open windows and doors. This is the primary means for effective natural ventilation. The number of air changes and the effectiveness of natural ventilation depend on the outdoor wind conditions, the number and size of openings, and the space geometry.

Natural ventilation through cracks or large openings is driven by the combination of two physical phenomena, namely:

- Wind driven flows, and
- Temperature difference flows (temperature difference between the indoor and outdoor environment).

Natural ventilation through large openings is distinguished in:

- Single-side ventilation: refers to applications when all space openings are located on the same wall or there is only one opening in the space (Figure 1). In this case, thermal buoyancy and wind-induced pressures are the driving forces of ventilation.

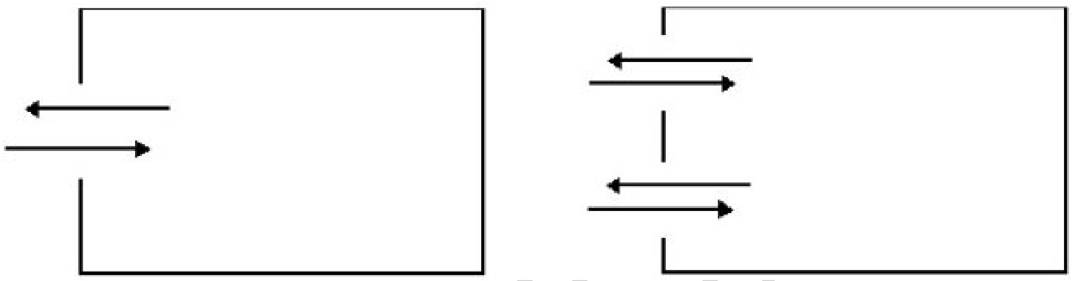

Figure 1. Opening arrangements for single-side ventilation.

- Cross ventilation: refers to applications when the openings are located on different wall sides of the space (Figure 2). In this case, the indoor airflow is strongly influenced by the wind characteristics and by the location of the openings and it directly depends on the pressure differences at the various openings.

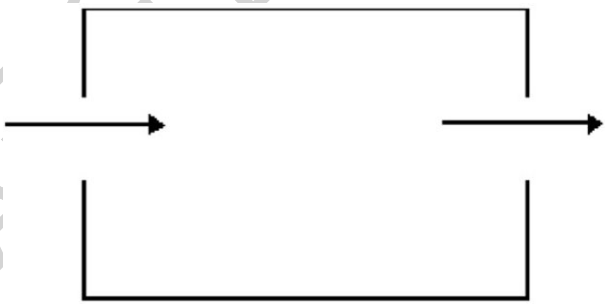

Figure 2. Opening arrangement for cross ventilation.

In all cases, the amount of air coming in to the space must be equal with the amount of air going out of the space, in accordance with the fundamental mass conservation law.

The airflow mechanisms of wind approaching a building are illustrated in Figure 3. The wind speed is U and the airflow is directed towards a building, creating a positive and negative pressure on the building's external surfaces (left illustration in Figure 3). A pressure increase is identified with a (+) sign on the wind-exposed surfaces and a pressure decrease is identified with (-) sign on the non-exposed surfaces (in the wind shade). The result is the development of a negative pressure inside the space that is sufficient for creating an airflow through the openings (right illustration in Figure 3).

In general, the air enters from the openings on the wind-exposed side of the building and the air exits through the openings on the wind-shaded side of the building (the side not exposed to the wind direction). Vortices are created on the wind-shaded side of the building (Figure 3) and in certain areas inside the building depending on the location of the windows and the airflow path.

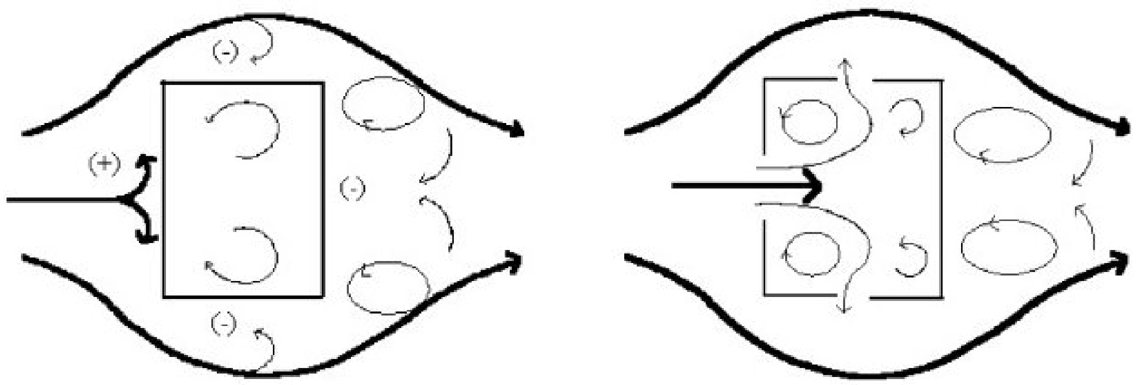

Figure 3. Wind airflow around and inside buildings for different opening arrangements.

The driving forces for natural ventilation is a combination of:

- Inertia forces caused by the wind;
- Buoyancy forces caused by the temperature difference (thus the air density difference) in the airflow direction.

The two mechanisms that cause the air masses to move during natural ventilation, that is the pressure changes (wind) and temperature difference between the indoor and outdoor environment, interact with each other resulting in pressure differences across the opening. These pressure differences move the air mass into and out of a space.

2. Wind Data and Climatic Conditions

Wind is a strongly and arbitrarily variant physical parameter. The variations of wind speed and direction are due to:

- turbulent phenomena which in the lower parts of the atmosphere are caused by obstacles along the flow path of air masses, and
- thermal imbalances created by temperature differences of air masses in the atmosphere.

The turbulent airflow is weakened in the vertical direction moving away from the ground,ultimately reaching a uniform fully developed flow (Figure 4).

The expressions available in the literature used to describe the vertical variation of the wind speed usually refer to the surface atmospheric layer. This is characterized by strong, small-scale turbulence that is caused by the ground surface roughness and heat transfer as a result of air streams. This layer starts practically from the ground surface and its thickness during the day can be up to 100 m while at night its thickness is only a few meters. The two most popular expressions are as follows:

$$\text{Exponential Law}: \quad \frac{U_1}{U_2} = \left(\frac{z_1}{z_2}\right)^a \qquad (1)$$

$$\text{Logarithmic Law}: \quad \frac{U}{u_*} = \frac{1}{k}\ln\left(\frac{z}{z_0}\right) \qquad (2)$$

where U, U_1, and U_2 are the horizontal components of the wind speed at heights z, z_1, and z_2 respectively, u_* is the friction velocity, k is the von Karman constant (=0.35), and z_0 is the surface roughness or roughness height. The power coefficient (a) depends only on the surface roughness and is calculated from empirical expressions for different surface types.

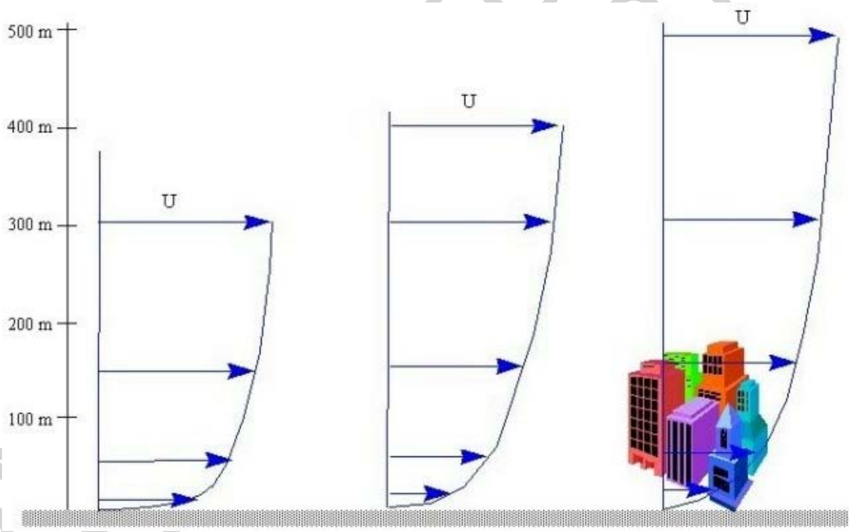

Figure 4. Variation of the horizontal component of the wind speed profile, moving from open flat country, to rural with some wind brakes (i.e. trees), to an urban environment.

2.1. Pressure Difference

The dynamic pressure (P_W) exerted by airflow moving with a speed U incident on a surface is given by the following expression:

$$P_W = 0.5 \cdot \rho \cdot C_p \cdot U^2 \quad [\text{Pa}] \qquad (3)$$

where ρ is the air density (kg/m^3), C_p is the pressure coefficient, and U is the wind speed (m/s).

The pressure coefficient C_p is a dimensionless, empirically defined parameter. It is used to describe the air pressure changes experienced by the airflow from its free flow condition to the exerted pressure by the wind on external building facades or any other obstacle in its flow path in the surrounding spaces. The numerical value of the pressure coefficient depends on the wind direction, the orientation of the building's surface, the topography of the surrounding environment, and the surface friction of the ground in the wind direction. Values of the C_p coefficient are available in the literature for different conditions. In general, positive values correspond to wind exposed surfaces, while negative values appear in the wind shaded surfaces. However, the pressure coefficient values correspond to an average value for the entire building facade and not specific locations on the surface. There are also some methodologies available in the literature which are based on parametric analysis from experiments performed in wind tunnels that provide data at specific conditions.

Wind speed and direction is usually measured at meteorological stations at a height of 10 m. However, meteorological stations (for example, at airports or other open terrain locations) are usually in areas where the terrain morphology and building density are not similar to where the buildings are usually located (distinctively different urban densities). Accordingly, in order to be able to use this data, it is necessary to modify them according to the specific characteristics of a given application.

Three models are commonly used to modify the measured data from meteorological stations, so that they correspond to the specific requirements for a given application, including the desirable height (other than the measured 10 m) and the characteristics of the surrounding environment. The three models are the exponential model, the logarithmic model, and the Lawrence Berkeley Laboratory (LBL) model.

The most simple model is the exponential one, where the local wind speed U_l at a height z_l from the ground is calculated as a function of the wind speed at 10m (U_{10}) by the following expression:

$$\frac{U_1}{U_{10}} = K \cdot z_1^{\ a} \qquad (4)$$

where the constants K and a depend on the ground roughness. Typical values are: for open flat country, K = 0.68, a = 0.17; flat country with scattered wind brakes, K = 0.52, a = 0.20; urban areas K = 0.35, a = 0.25; and downtown areas, K = 0.21, a = 0.33.

2.2. Temperature Difference

The temperature difference on either side of an opening (that is, indoor and outdoor temperature) is another key parameter in natural ventilation processes. The pressure difference caused by buoyancy forces is the main mechanism for the air mass movement from and to a space when there is no wind or very low wind speeds.

The air density changes as a function of the air temperature and results in a density gradient for the indoor and outdoor air. When the indoor air temperature is higher than the outdoor air temperature, cool airflows through the lower parts of the opening while at the same time warm air exits from the upper part of the opening (Figure 5). The directions are reversed in the case that the outdoor air is at a higher temperature than the indoor air. The height where there is a change in the flow direction is called the neutral level, where the indoor and outdoor pressure difference is zero, so there is no flow. The height of the neutral level depends on the location and the characteristics of the opening.

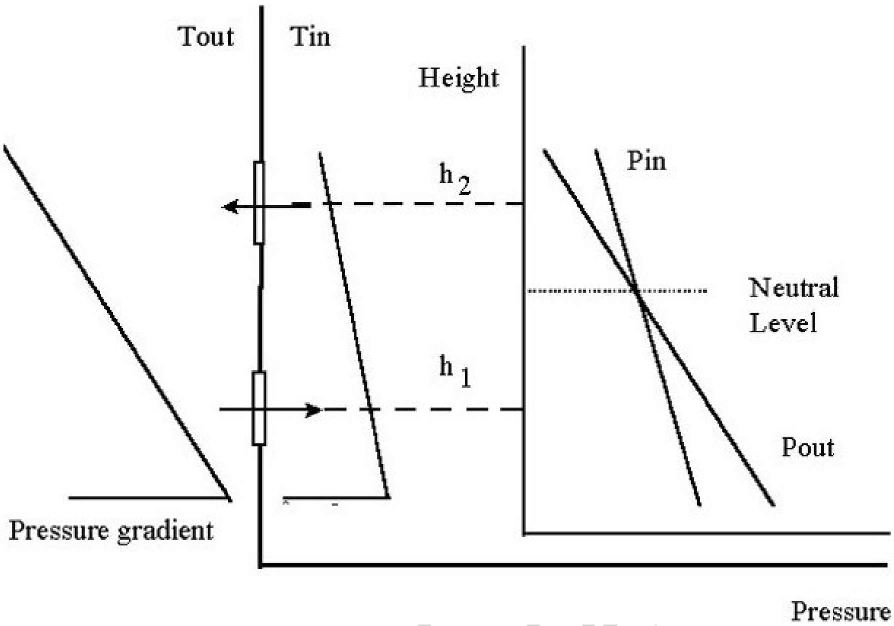

Figure 5. Pressure difference resulting from temperature difference between the indoor and outdoor conditions.

The pressure difference between two vertical openings at a height h_2 and h_1 respectively, that are at a distance h (= h_2–h_1) from each other, is given by:

$$p = -\rho_o g T_o h \left[\frac{1}{Tout} - \frac{1}{Tin} \right] \quad (5)$$

where ρ_o is the air density at 273.15 K ($\rho_o \approx 1.29$ kg/m^3) and T is the absolute temperature [K].

2.3. Combined Wind and Temperature Effects

Airflow through openings during natural ventilation is the end result of the combined effect of wind and temperature differences. In general, this pressure difference at a height z above ground level can be estimated by the following expression:

$$\Delta P_{i,j}(z) = \Delta P_{wind} + \Delta P_{temp.\ dif.} = (PW_i - PW_j) - (\rho_i - \rho_j) g z + (P_{i0} - P_{j0}) \quad (6)$$

where PW_i, PW_j is the dynamic pressure caused by the wind, P_{i0}, P_{j0} is the reference pressure at both sides of the opening [Pa], and ρ_i, ρ_j is the air density at both sides of the opening [kg/m^3].

The (*i*) and (*j*) symbols correspond to the two spaces that communicate through the opening (for example, for an external-opening window, indoor space and outdoor environment). Since the wind effects are only applicable to external openings, this relation can be simplified for internal openings (for example, for an internal-opening door, space 1 and space 2) to read:

$$\Delta P_{in}(z) = -(\rho_i - \rho_j)gz + (P_{i0} - P_{j0}) \qquad (7)$$

For external openings, since the indoor air velocity is negligible compared against the outdoor wind velocity, the corresponding relation can be expressed as follows:

$$\Delta P_{out}(z) = \frac{1}{2}\rho_a C_p U^2 - (\rho_i - \rho_a)gz + (P_{i0} - P_{a0}) \qquad (8)$$

where ρ_a is the outdoor air density (kg/m^3) and U is the wind velocity (m/s) at the height of the opening.

3. Simulation Tools

Modeling of natural ventilation phenomena is rather demanding. Accordingly, there have been various methodologies that are available in the literature, ranging from simple to more complex. All together, they can be grouped into three main categories that differ in their level of complexity, namely:

- Empirical models
- Network models
- Computational Fluid Dynamics (CFD) models

A brief overview of each category is presented in the following sections.

3.1. Empirical Models

Empirical models are based on a simplified correlation that can be used for calculating the airflow or the average wind speed inside a space.

The correlation relates the airflow with the temperature difference and the wind speed to estimate the number of air changes and the indoor air velocity.

The empirical models are easy to use and they provide a quick and easy first estimate of the order of magnitude for the amount of airflow and air velocity.

However, they are not suitable for detailed calculations and they have a limited applicability since they are only applicable for simple space geometries.

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Biographical Sketch

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Institute of Technology, Hellenic Shipyards Co., Georgia Power Co. Participated in various European and national research projects, as a project manager and scientist in charge, including projects on energy renovation of office and apartment buildings, HVAC systems in hospital operating rooms, solar absorption heat pump, solar control, passive cooling, and regional development of renewable energy sources. Private practice includes electromechanical design and installation projects for new constructions and renovations of residential and office buildings, and a small size industrial building. Member of the Hellenic Technical Chamber (Chartered Mechanical Engineer), EUR ING, Hellenic Society of Mechanical— - Electrical Engineers, Hellenic Society of Heat and Power Cogeneration, Hellenic Forum for the Dissemination of Renewable Energy Sources (ELFORES), ASHRAE (Initiating representative and president of Hellenic Chapter 1999-2000), and ASME (Member of the Governing Board ASME Greek Section), ISES. Author and co-author of over 35 papers in international Journals and 50 papers in at conferences, chapter contributions in 9 scientific books and numerous technical project reports. Guest editor for a special issue of the Journal *Energy and Buildings*; Invited Reviewer of papers for the *Journal of Solar Energy*; Invited Technical Assessor for the European Architectural Competition Living in the City and Working in the City (under the auspices of the European Commission); Member of The Scientific Research Society; Pi-Tau-Sigma, Honorary Mechanical Engineering Fraternity.