40 Years of Modeling Airflows

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SUMMARY

The modelling of air flows to investigate indoor air quality and energy issues has been a topic at the AIVC for all of its 40 years. Models have been developed that range in complexity from single-zone algebraic expressions that can be calculated by hand to complex multi-zone approaches that integrate contaminant transport and other functions. Key advancements have come in terms of increased computer speed and storage capabilities, (leading to more complex multi-zone approaches and smaller time-step/longer simulation periods), improved used interfaces, and better input data (e.g., wind pressure coefficients).

KEYWORDS

Infiltration, ventilation, modelling, energy, indoor air quality

1 INTRODUCTION

The ability to model infiltration using physics-based engineering calculations grew from the desire to know more about the energy associated with heating (and sometimes cooling) loads driven by the first “energy crisis” starting in about 1973. Researchers in Europe, Canada and the USA began investigating these air flows. Experiments showed that the air exchange increased with building envelope leakage and with harsher weather and efforts were begun to model the infiltration using the measured envelope leakage and weather conditions. Two types of ventilation model have emerged: simple models that use semi-analytical approaches and simplifying assumptions to allow for hand calculation and complex models that require computation to solve the non-linear mass balance equations.

2 CALCULATING BUILDING ENVELOPE AIR FLOWS

The nature of the relationship between flow through building cracks and the pressure difference across the crack and the crack geometry has been thoroughly debated in AIVC publications (e.g., Liddament (1987) and Etheridge (1987) published on both sides of the discussion in Air Infiltration Review). There are essentially two alternative viewpoints (Walker et al. (1997) give a more detailed summary in the Proceeding of the 17th AIVC Conference). The first assumes that we can combine fully developed laminar flow with entry and exit losses to describe the pressure-flow relationship. The other uses a semi-empirical approach based on measured characteristics and developing flow experiments called the power law. The two governing equations are:

Laminar + entry/exit (usually called a quadratic approach): $Q = A\Delta P + B\Delta P^2$ (1)

Power law: $Q = C\Delta P^n$ (2)

Where, A, B, C and n are parameters that are fitted to measured pressure and flow data. Over time the power law has been used more and is the basis of most infiltration modeling.. Some models use a special case of the power law and assume that the pressure exponent, n, is equal to 1/2 (e.g., the LBNL Model (Sherman and Grimsrud 1980).

3 SIMPLE MODELS

Simple models are single zone and calculate wind and stack effects separately, which are then combined using various semi-empirical approaches to account for their non-linear interactions. Many of the first ventilation models were purely empirical based on correlating measured ventilation rates to wind and temperature. However, most subsequent models have been more physics-based and follow the following general format. “Stack” flows (Q_s) are driven by the difference in air density between inside and outside a building that causes pressure differences across the building envelope. This depends on the indoor-outdoor temperature difference (T_{in}-T_{out}), air density (ρ_{out}), the gravitational constant (g), the building height H, and the location of building leaks (represented in this case by the stack factor, f_s) first introduced by Sherman and Grimsrud (1980).

$$= \quad (3)$$

$$\frac{|\quad\quad|}{\quad} \quad (4)$$

Wind flows have a similar functional form where the wind pressure depends on windspeed (U), a factor to account for shelter (S_w) and the location of building leaks (represented by f_w).

$$= \quad (5)$$

$$= \frac{(\quad)}{\quad} \quad (6)$$

Various approaches have been used to combine stack and wind effects to obtain the total natural infiltration. Quadrature (squaring, adding and square-rooting) has proved to be a reasonable approach for many buildings, although attempts at pressure addition and pressure addition with empirically determined correction factors have also been used (Walker and Wilson (1998)).

$$\text{Quadrature } Q_{total} = \sqrt{Q_s^2 + Q_w^2} \quad (7)$$

$$\text{Pressure addition with correction: } Q_{total} = \left(Q_s^{\frac{1}{n}} + Q_w^{\frac{1}{n}} + B(Q_s Q_w)^{\frac{1}{2n}} \right)^n \quad (8)$$

Similarly, various non-linear empirical approaches have been used to combine natural infiltration with mechanical ventilation (Li (1990), Modera and Peterson (1985) and Wilson and Walker (1990) summarize these approaches) For balanced systems, simple addition is adequate as the mechanical systems do not interact with the envelop pressures. For unbalanced mechanical ventilation several approaches have been suggested, such as the “half-fan” approach for stack-dominated buildings (Palmiter and Bond 1991) and quadrature. More recent work by Hurel et al. (2015) developed more sophisticated approaches that, while retaining simplicity, work well for large range of conditions.

4 COMPLEX AND MULTIZONE MODELS

More complex single-zone and all multizone models are based on developing an air flow network of envelope (and internal for multi-zone) air flow paths and combining this with inputs for mechanical system air flows, weather, and assumptions about leak locations and surface wind pressure coefficients. The air flow for each individual leak is calculated using the same principles as those for simplified models – with the exception that the pressure across each flow path is a function of the weather, operation of mechanical systems and pressure shifts that act to balance mass flows in and out of the building. The resulting set of equations are solved to perform a mass balance. AIVC Tech Note No. 11 (Liddament and Allen (1983)) was the first comprehensive attempt to compare several single and multi-zone model predictions of infiltration to measured data. Tech note No.11 found that all the models gave reasonable predictions (+/- 25%) compared to measured data and that the biggest source of uncertainty was estimating wind pressure changes due to shielding and different building shapes. The next major step for multizone modelling was the development of COMIS - Conjunction of Multizone Infiltration Specialists (Feustel and Raynor-Hoosen (1990)). COMIS included relatively sophisticated approaches for creating wind pressure coefficients, and introduced an inter-zonal pollutant transport model. Since then other multizone models have been developed including CONTAM, BREEZE and AIOLOS, together with single zone and simplified models. These newer models build on the basic principles discussed here and include things like more advanced wind pressure modling, improved user interfaces and integrated thermal modelling. These advances are summarized, together with an update for simplified models in AIVC Tech Note No. 51 Orme ((1999).

5 RECENT DEVELOPMENTS

Over the past 20 years infiltration modelling has seen small incremental improvements (such as better superposition techniques for simplified models) and integration of these models developed in the 80's and 90's into specific applications, such as building energy and IAQ regulations. The modelling of ventilation has successfully transitioned from a research tool to develop a better understanding of building physics into a well-accepted part of energy and IAQ regulation. Current ventilation modeling advancements are into highly specific applications, such as developing smart ventilation control strategies (e.g., Clark et al. 2019) and ventilation of semi-conditioned spaces (e.g., attics) that have unique goemetries or wind pressures.

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