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Sub-additivity in combining infiltration with mechanical ventilation for single zone buildings

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ABSTRACT

In determining ventilation rates, it is often necessary to combine naturally-driven infiltration, with air flows from mechanical systems. When there are balanced mechanical systems, the solution is simple additivity, because a balanced system does not impact the internal pressure of the space or the air flows through the building envelope. Unbalanced systems, however, change internal pressures and therefore can impact natural ventilation non-linearly in such a way as to make it sub-additive. Several sub-additive approaches are found in the literature, but they are not robust across the full spectrum from tight to leaky buildings and ranges of mechanical ventilation air flow rates. There are two approaches for combining natural infiltration with mechanical ventilation that require different solutions. The *forward* problem is to find the total air flow when adding mechanical ventilation to natural infiltration, and this application has been investigated in previous studies. The *inverse* problem finds the required mechanical ventilation in order to meet a total ventilation rate given a known amount of natural infiltration. This article presents the results of millions of hours of simulations of the physically correct solution, which span a broad range of climates, air leakage and structural conditions. This large dataset allows for the comparison with three literature models and the development of new robust sub-additivity models. These improved models are for use with unbalanced systems appropriate for consensus standards and guidelines for both the forward and inverse problem. They reduce errors to 1% or less and work across the air tightness spectrum.

1. Introduction

Most homes (and other single zone spaces) are ventilated by infiltration through leaks in the building envelope that are driven by wind and indoor–outdoor temperature differences. In order to decrease energy consumption, building envelopes are getting tighter. Combined with potential increases in pollutant sources in indoor living environments, this raises concerns for indoor air quality (IAQ) [1]. As a result, more houses are using a mechanical ventilation system to maintain a good air quality. There are standards for estimating the minimum total air exchange requirements for maintaining acceptable IAQ in homes. Some of these, e.g., ASHRAE 62.2–2013 give credit for infiltration towards the total air flow.

If a balanced ventilation system is installed, the impact on infiltration will not be significant, because the balanced system does not change the pressures across the building leaks. As a result, the total ventilation rate (Q_t) is simply the addition of the balanced fan flow and the natural infiltration.

Unbalanced mechanical ventilation systems modify the indoor pressure of the building, which interacts with the wind and stack induced flows, making the combination of the flows sub-additive. Exhaust fans depressurize the building, which increases the airflow in through the building envelope. The greater the fan flow, the higher proportion of the building envelope experiences inflow. The opposite effect occurs with supply-only systems.

The problem this article addresses is how to combine infiltration with mechanical ventilation in a single zone. This can be done using detailed mass balance physical and mathematical models to find the internal pressure that balances the incoming and outgoing mass flows. Such an approach is powerful, but requires many computational inputs and can be too time consuming for some purposes such as ventilation standards or simplified parametric modeling. Or it may be that the details of the mechanical side and

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the infiltration side are not available at the same time. An alternative is to use a simple empirical combinational model when the infiltration is determined using simplified approaches and use other methods to combine infiltration with mechanical ventilation.

A few models for combining infiltration and unbalanced mechanical ventilation were suggested and tested a few decades ago, but the results were sometimes contradictory. In this article we develop a new sub-additive approach for improving on previous relationships.

2. Superposition background

2.1. Superposition issue

The approach of combining a pre-calculated infiltration rate with a fixed mechanical ventilation rate to find the total air change (or ventilation) rate is called *superposition*. This is the *forward* problem of finding totals from individual pieces. The opposite problem of sizing a mechanical ventilation system given infiltration is the *inverse* problem. Analysis of the physical pressure–flow relationship (supported by measurements) shows that the totals will come out smaller than additivity because the unbalanced fan will impact the internal pressure which effectively reduces the amount infiltration contributes to the total.

The fundamental physics of air flow through leaks shows that these leaks have non-linear pressure–flow relationships, but the addition of pressures themselves is a simple linear phenomenon. Both individual leaks and the combinations of leaks found in building envelopes can be represented by a power law function [2], but the details of that are not important here except to realize there is nonlinear relationship between pressure and flow. The pressure difference depends on wind and indoor–outdoor temperature difference and an internal pressure shift that acts to balance the air flow in and out of the building. The operation of an unbalanced mechanical ventilation system changes this internal pressure and therefore the flow through each leak, and does so in a nonlinear way.

Sherman [3] has shown for some configurations of driving forces and air leakage, superposition will not be symmetric with respect to supply and exhaust flows. Since we are not going to take leakage distribution into account in our modeling, we will ignore that potential asymmetry, in which case we can recast our modeling in terms of balanced and unbalanced flows:

$$\begin{cases} Q_m = Maximum\left(Q_{supply},\ Q_{exhaust}\right) \\ Q_b = Minimum\left(Q_{supply},\ Q_{\mathrm{exhaust}}\right) \\ Q_u = Q_m - Q_b \end{cases} \tag{1}$$

Where the “m” subscript denotes the total mechanical flow, the “b” subscript denotes the balanced portion, the “u” subscript the unbalanced portion and all flow rates are positive numbers. The supply and exhaust flows represent the total of all the individual supply and exhaust systems operating at that time.

Throughout this article we will refer to volumetric air flows rather than mass flows. This is for convenience because most, if not all, applications are in terms of volumetric air flow at standard density. In addition, volumetric air flow is related to mass flows by the indoor air density that varies very little (about 1%) over typical ranges of indoor air temperature.

2.2. Prior work

Some previous approaches used empirical correlations to measured data but did not attempt to find methods for estimating the interactions between natural and mechanical ventilation. Measured air change rates in a home were used to compare balanced and unbalanced ventilation combined with natural infiltration in a test house by Etheridge et al. [4]. The effects of mechanical ventilation systems on building pressures have previously been studied in terms of shifting the neutral pressure plane of a building [5]. In addition to the deliberate use of mechanical ventilation, leakage in forced air space conditioning systems can also act to increase ventilation [6,7]. Although this paper discusses single zone modeling of homes, some preliminary studies in the past (e.g. from Li & Peterson [8] and, more recently, Laverge & Janssens [9]) have examined the effect of multizone approaches (for example homes with all interior doors closed.

Of more specific interest are approaches to modeling the interactions between natural and mechanical ventilation. Researchers have used both simplified physical and empirical approaches to develop superposition models since the late 70 s, and many were reviewed by Li [10]. However, many of these are optimized for limited situations, such as the Palmiter and Bond [11] method, referred to here as the half-fan model, which was developed for stack-only natural infiltration.

Li tested ten models by comparing them with a flow model over a range of wind speeds (0–8 m/s) and temperature differences (−20 to 20 °C) with open and closed exterior doors and two different exhaust fan speeds. His conclusion was that the quadrature combination of natural and mechanical ventilation worked best. This result is in agreement with the earlier work of Modera and Peterson [12], who also used a mass balance ventilation model.

Field tests with tracer gas measurements by Kiel and Wilson [13] found that for strong exhaust mechanical ventilation (four times the natural rate), simple linear addition was the most acceptable method, but that from a theoretical point of view, a half-pressure addition and half-linear addition model had more appeal with similar results to the linear addition. (See Table 1 for model definitions.) Continuing this work, Wilson and Walker [14] looked at a reduced fan flow rate that was approximately equal to the natural rate. The result was the same as Kiel and Wilson, where linear and half-linear/half-pressure addition were the closest to the measured and modeled combined rates. The above two studies looked at exhaust fans only, but over a wide range of natural infiltration driven by both wind and stack effects. Unlike Li, these studies showed large underpredictions using quadrature. This could be due to different building envelope leakage, weather conditions, leakage distributions and strengths of mechanical ventilation, but it mainly underlines the necessity of additional study.

Table 1 is a summary from the literature of published superposition models with some observations on their performance. The table gives the model functional form, the range over which it was evaluated, and if the comparisons were made to simulations (sim.) or experimental (exp.) data.

The most generally accepted of these models is quadrature. It is currently used in the ASHRAE Handbook of fundamentals [15]. Previous versions of the Handbook used the half-fan model. Sherman [3] reviewed the state of the art of superposition at the time and developed a model of quadrature, deriving some coefficient values based on leakage distribution properties, but this advanced quadrature is not typically used. In this study, our further investigation of previous models will be restricted to quadrature and half-fan as these are historically the most used.

3. Cases of interest

When selecting superposition models it can be important to consider the difference between short-term (typically hourly) flows and long-term (typically annual average flows.) Even if the