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SIMPLIFIED METHODS FOR COMBINING MECHANICAL VENTILATION AND NATURAL INFILTRATION

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ABSTRACT

During the past ten years, the means of ventilating single-family residences has received considerable attention. In many areas, the use of natural ventilation for infiltration has either come under close scrutiny, or has already been supplanted by mechanical ventilation systems. To evaluate the energy efficiency and ventilation effectiveness of both mechanical and natural ventilation strategies, both complex and simplified infiltration models are used. This paper examines the inaccuracies associated with using simplified models to compare ventilation strategies. Two simplified techniques for combining mechanical ventilation flows to the flows caused by wind and stack effects are examined. The simplified combination techniques are compared with the results obtained with an iterative flow-balance simulation. The flow-balance simulation determines the ventilation by balancing the incoming and outgoing flows under the pressure conditions resulting from the combination of wind effect, stack effect and mechanical ventilation. These comparisons result in three major conclusions: 1) the commonly used flow superposition technique (flow combination in quadrature) provides better estimates of the total flow than does a technique that takes into account measured flow exponents, 2) although flow combination in quadrature overpredicts ventilation when combining wind-induced and stack-induced flows, this is not the case when mechanical ventilation is added to the picture, and 3) a simple correction for the errors caused by the simplified flow superposition technique is not easy to achieve due to the large variations in error that occur with changes in wind direction and individual flow ratios.

INTRODUCTION

An important part of building design and operation is to provide the occupants with fresh air, commonly known as ventilation. The means by which a building is ventilated varies with the type of building, as well as with the accepted practices at the time of construction. During the past ten years, the means of ventilating single-family residences has received considerable attention. The traditional means of ventilation for single-family residences in the United States, natural infiltration, has come under close scrutiny due to energy conservation and indoor air quality concerns. Natural infiltration is difficult to control, providing excessive ventilation at times (and thus unnecessary energy losses), and inadequate ventilation at other times, contributing to indoor air quality problems. Because of these difficulties, it has been suggested that buildings should be tightened and mechanical ventilation systems installed; this is the current practice in some countries, such as Sweden.

As a means of determining the natural infiltration (or ventilation) rate of single-family residences, mathematical models (including simplified models) of weather-induced infiltration have been developed.[1] Because the simplified models can be used to examine expected ventilation rates for many different cases without making expensive measurements, there is significant interest in using such models to explore the use of mechanical ventilation systems. In this report, we shall examine some proposed methods for adding mechanical ventilation systems into simplified infiltration models, as well as evaluate the present technique for combining infiltration flows due to different driving forces.

INFILTRATION MODELING

Most natural infiltration in buildings is caused by two separately identifiable driving forces: the wind effect and the stack effect. The wind effect consists of differential pressures across the building envelope caused by over-pressure on the windward side(s) and under-pressure on the leeward side(s) of a building. These pressure differences cause infiltration on the windward side(s) and exfiltration on the leeward side(s). The stack effect is caused by the temperature difference between indoor and outdoor air. During winter, indoor air is warmer and therefore lighter than outdoor air, thereby creating pressure differences across the building envelope. The building acts like a chimney, exhausting warm air in the upper part of the building, and drawing in cool outdoor air in the lower part of the building. During the cooling season, the flow direction is reversed.

For both wind-induced and stack-induced infiltration, the ventilation rate for a given windspeed or temperature difference can be determined by computing the flowrate through each hole in the building envelope and adjusting the internal pressure so as to balance infiltration and exfiltration. For both effects, the balancing internal pressure depends on the distribution of holes in the building envelope. However, for the wind effect, the internal pressure also depends on the wind direction. To compute the infiltration when both stack and wind effects are present, the flow balance must be performed with both pressure distributions present.

As with wind-induced and stack-induced infiltration, mechanical ventilation systems affect the internal pressure of a building. To determine the total flow through a building due to mechanical ventilation and natural infiltration acting simultaneously, a flow balance should be performed with all three pressure distributions present. Because flow balances are rather time-consuming and require considerable computational capability, and because such simulations require an excessive amount of input data to describe the building, simplified models for predicting infiltration have been developed.[2,3] These simplified models often treat infiltration due to different driving forces separately, and combine the individually computed infiltration rates.

THE LBL INFILTRATION MODEL

A simplified model that is used extensively is the Lawrence Berkeley Laboratory (LBL) model (see Reference 3). This model was derived from separate flow balances for wind-induced and stack- induced infiltration, assuming a semi-uniform distribution of leakage in the building. By making separate flow balances for wind-induced and stack-induced infiltration, simple expressions for wind-induced infiltration as a function of windspeed and stack-induced infiltration as a function of indoor-outdoor temperature difference were derived. One disadvantage of this simplification is that the total infiltration due to stack and wind effects acting simultaneously must be approximated. The method chosen for combining stack and wind induced flows in the LBL model is:

$$Q_{total} = \sqrt{Q_{wind}^2 + Q_{stack}^2} \tag{1}$$

The errors in predicting the total infiltration using this method of estimation were examined in a paper that describes the simplifying assumptions on which the LBL model was based.[4] Figure 1, reproduced from that paper, is a plot of the expected errors in total flow prediction caused by this estimation method. These errors were determined by computing the actual flow using a flow-balance program and comparing the results with those obtained with the estimation method. The plotted errors represent average values for nineteen wind directions and three different building shapes. The figure shows that the estimation method always overpredicts the total infiltration. The maximum error occurs when the stack and wind induced flows are equal, and the error decreases to zero as one type of infiltration begins to dominate the other. Because this error is always in the same direction, it appears that the model will systematically overpredict infiltration.

Because the above estimation technique (Equation 1) appears to consistently overpredict infiltration, and a similar technique has been proposed for combining mechanical ventilation flows with natural infiltration, improvements to this flow estimation method could prove useful. Possible corrections for the overprediction can take many forms, including alternate methods for combining the different types of infiltration. A simple correction to this technique for combining stack-induced and wind-induced infiltration would be to assume that the ratio of stack-induced to wind-induced infiltration will be evenly distributed over the entire curve and therefore use the average correction indicated by the curve. If we assume that the overprediction errors only depend on the ratio of the individual infiltration rates, we could also construct a more precise correction scheme using a function that exactly compensates for the error at each infiltration ratio.

COMBINED STACK, WIND AND MECHANICAL VENTILATION

As we are interested in the effect of mechanical ventilation on the total ventilation rate of a building, as well as the interaction of different types of natural ventilation (infiltration), we have constructed some simple flow-balance simulations for different combinations of the three types of ventilation. These models calculate the total flow by balancing infiltration and exfiltration under the combined pressure conditions resulting from the different ventilation driving forces.

They were designed to provide accurate flows for simple representative cases, thereby allowing us to compare different strategies for combining the individual flows. On the other hand, the models were not designed to provide infiltration predictions from measured temperatures and windspeeds. Such predictions would require a more detailed input-output procedure, and an efficient iterative procedure for determining the flow under specified conditions.

All of the flow-balance simulations in this paper use a simplified building to examine the trends to be expected when using different flow superposition techniques. The building was designed to reduce pressure and flow subtleties as much as possible, allowing us to focus on the flow superposition techniques. It has four walls with a uniform leakage distribution, and has no leakage in the ceiling or floor. The wind pressure coefficients used are average surface values, and the internal temperature is assumed to be uniform. In addition, the fan operation is assumed to be independent of any wind-induced or stack-induced pressure differences imposed across it. Using this building, the actual and estimated flows were calculated for combined fan and wind effect pressure distributions, combined fan and stack effect pressure distributions, and combined wind effect, stack effect, and fan pressures.

RESULTS

As a means of examining the expected errors associated with different flow superposition techniques, the errors in the estimated ventilation rates relative to the ventilation rates computed with the flow-balance simulations are plotted in Figures 2 through 6. As in Figure 1, the errors are plotted against the ratio of the flows being superimposed. Two different flow superposition techniques are examined in these figures. The first is that used in the LBL infiltration model (Equation 1), and the second is a variation of this technique in which the actual flow exponent of the building is used to modify the superposition equation:

$$Q_{total} = \left(Q_1^{\frac{1}{n}} + Q_2^{\frac{1}{n}} \right)^n \qquad (2)$$

If, as previously supposed, Equation 1 can be interpreted as a means of adding effective pressure drops across the entire flow resistance of the building, Equation 2 can be seen as a generalization of Equation 1, using the actual flow exponent to calculate the flow from the combined pressure drops. The rationale behind Equation 2 is that, although the LBL model assumes that infiltration is similar to orifice flow (i.e., n=1/2), it has been found experimentally that the flow through most buildings is more closely approximated by a power-law function with an exponent (n) of approximately 2/3.[5] Using the measured exponent should thus improve the prediction.

Figure 2 is a plot of the errors that occur when Equation 1 is used to estimate the total ventilation for a building being ventilated by stack effect and an exhaust fan. The estimates are compared with flowrates computed with a flow-balance simulation. Examining this figure, we immediately see that it does not resemble Figure 1. Unlike Figure 1, the error is not always positive, and there is no error peak at a flow ratio of 1. This suggests that the errors caused by combining flows using Equation 1 are not independent of the type of flows being combined, possibly indicating that a simple correction as a function of flow ratio may not be generally valid.

To further examine the interaction of different ventilation driving forces, estimations made with Equation 1 were compared with balance-equation flows for houses subjected to wind-induced and fan-induced ventilation. These comparisons for two different wind directions are shown in Figure 3. This figure shows that the estimation errors are once again different from those shown in Figure 1, and that the errors depend on the wind direction. We should note that the errors plotted in Figure 1 are average values for different wind directions and building shapes, and are thus not directly comparable. However, Figure 3 does demonstrate that a correction equation devised to improve Equation 1 may or may not improve the predictions, depending on the wind direction.

As mentioned above, it has been proposed that Equation 1 can be extended to combine wind-induced, stack-induced, and mechanical ventilation flows. This extended equation has the form:

$$Q_{total} = \sqrt{Q_{wind}^2 + Q_{stack}^2 + Q_{unbalanced}^2} + Q_{balanced} \qquad (3)$$

In Equation 3, the balanced flow represents the flow rate through a fan that is balanced exactly by an equal and opposite flow through another fan (e.g., an air-to-air heat exchanger). The unbalanced flow is any fan-induced flow that either pressurizes or depressurizes the house, such as an exhaust fan or a maladjusted air-to-air heat exchanger.

To examine the validity of Equation 3, another flow-balance simulation that includes stack, wind and fan-induced flows was constructed. The flows calculated with this simulation were compared with estimates made with Equation 3 for $Q_{balanced} = 0$, the results of which are plotted in Figures 4 and 5. Although Figures 4 and 5 are similar to the previous figures, they differ in two respects. The first difference is that the x-axis is not the ratio of two individual flows, as three flows are being superimposed in this case. The x-axis in these figures is the ratio of the fan-induced flow to the combination of naturally induced flows (stack and wind) estimated with Equation 1. The second difference is that, because we are combining three flows in this case, the ratio of estimated flow to actual flow is not a single-valued function at each point on the x-axis. For each x value, or ratio of fan to wind plus stack, there can be infinitely many combinations of wind and stack induced flows that do not give the same estimation errors. The data points in Figures 4 and 5 thus represent a range of different wind to stack ratios, thereby describing the estimation errors to be expected over a wide range of flow combinations.

Upon examining Figures 4 and 5 (which differ only in wind direction), there does not seem to be any apparent trends in the errors, except that they increase as the fan flow approaches zero. This error increase at very low fan flow can be explained by the choice of wind and stack flows (stack-wind ratio). The effect of stack-wind ratio can be seen in Figure 5, which has different symbols for different stack-wind ratios. Because Equation 3 reduces to Equation 1 at low fan flows, the choice of stack-wind ratio determines the error at low fan flows. Figures 4 and 5 also demonstrate that the errors do not increase when the fan flow is similar to the natural infiltration flow, and more importantly, that the estimation errors remain within a rather small range distributed on either side of zero. This result is encouraging, indicating that Equation 3 can provide reasonable estimations of the total ventilation rate over a wide range of fan flows without any apparent bias in the errors. Figures 4 and 5 thus provide an estimate of the scatter in ventilation predictions to be expected when using Equation 3 to superimpose the flows.

The flow-balance simulations have also been used to examine the possibility of using Equation 2 to estimate total ventilation rates. The results of these examinations are shown in Figure 6, which compares the estimation errors obtained when using Equation 1 and Equation 2 for combining wind-induced infiltration and fan flow. The estimation errors, shown for a building with a flow exponent of 2/3, demonstrate that estimations made with Equation 2 are far worse than those obtained with Equation 1. Although these results are only strictly valid for the combination of fan-induced flow and wind-induced flow for a single wind direction, similar results were obtained at other wind directions, and when combining fan-induced flows with stack-induced flows. This apparent failure of Equation 2 suggests that the major source of error in Equation 1 is not the choice of exponent, but rather the assumption that the individual flows can be treated as additive effective pressure drops.

CONCLUSIONS

Our first and most important conclusion is that the systematic error previously associated with using quadrature to combine stack-induced and wind-induced flows is not generally valid for flow combination by quadrature. The earlier findings are particular to the combination of these flows under the particular assumed conditions. We found that the errors caused by combining stack-induced flows with fan-induced flows by quadrature were significantly different from those caused by combining stack-induced with wind- induced flows (see Figure 2). We also saw that when combining wind-induced and fan-induced flows, the errors depended on wind direction.

Our second conclusion relates to the computation of the total ventilation rate when the wind effect, the stack effect, and a fan are present. We found that under these circumstances, the quadrature equation (Equation 3) seemed to provide good estimates of the total ventilation rate of a building. At least for the simplified building that we simulated, the ratios of estimated to actual flow seemed to be distributed around a ratio of 1, implying that there should not be any systematic error caused by this means of flow estimation. We also found that the estimation errors were rather small, always within 10% of the actual ventilation except at very low fan flows. The success of this initial investigation suggests that a more detailed examination of this type of flow combination be undertaken.

A third conclusion that can be drawn from our examination of flow superposition is that combining the flows in quadrature provides better results than treating the flows as effective pressure drops and combining them using the true exponent. Our results indicated that combining the flows using the proper exponent can cause extremely large errors, especially at flow exponents close to one. As suggested above, the major source of error associated with adding flows in quadrature is probably not the choice of exponent. These results also suggest that the combination of flows by quadrature may have purely mathematical reasons for its success, and that its physical interpretation is not clear.

ACKNOWLEDGEMENT

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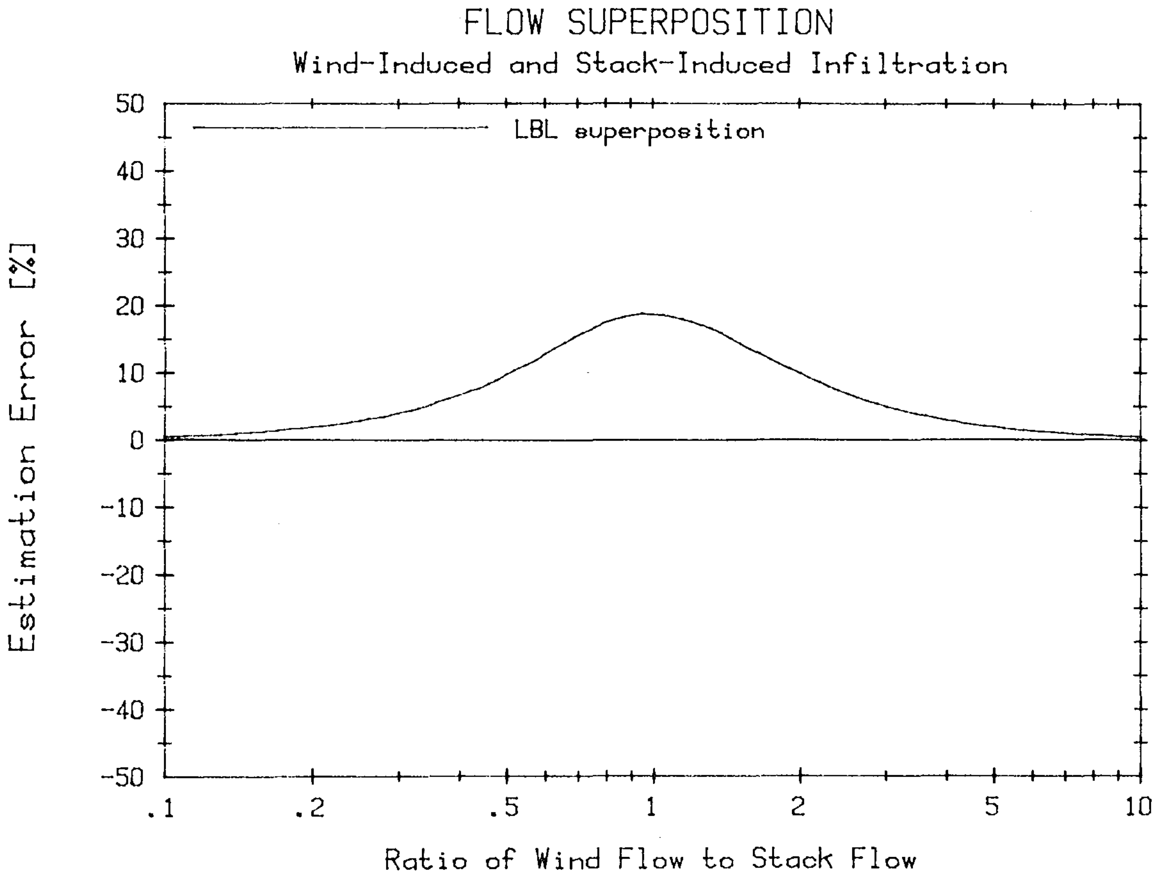


XBL 855-2526

Figure 1. Errors in total infiltration prediction resulting from flow combination by quadrature (Equation 1) vs. Ratio of wind-induced flow to stack-induced flow.

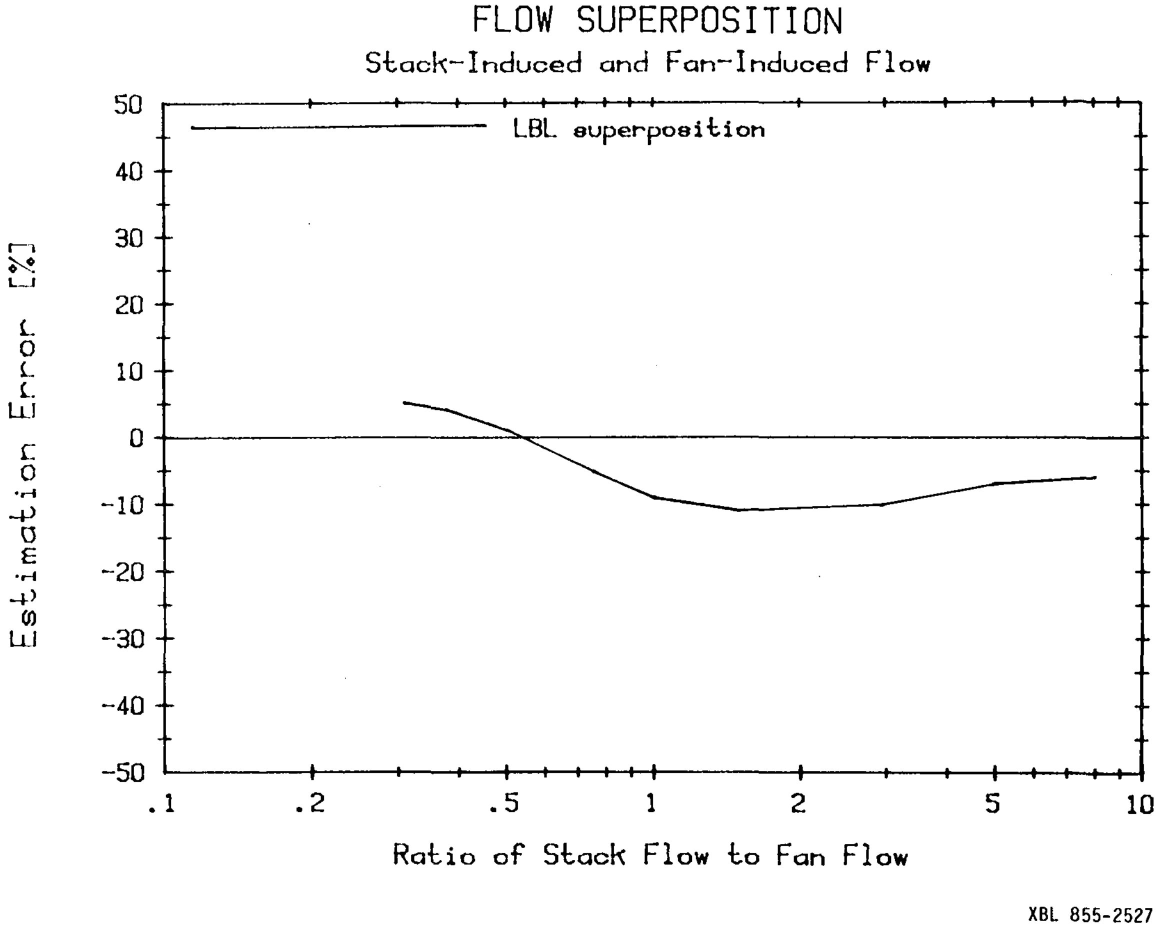
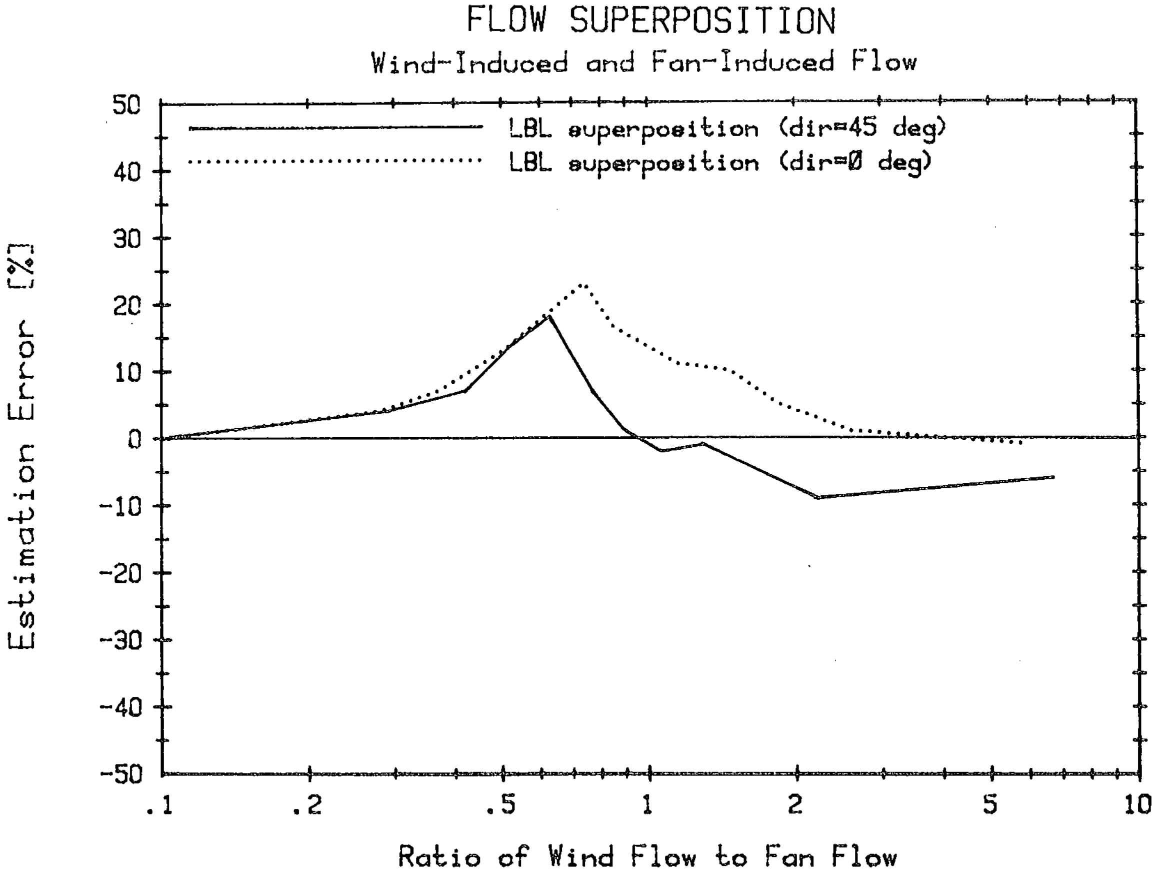


Figure 2. Errors in total infiltration prediction resulting from flow combination by quadrature (Equation 1) vs. Ratio of stack-induced flow to fan-induced flow.



XBL 855-2528

Figure 3. Errors in total infiltration prediction resulting from flow combination by quadrature (Equation 1) vs. Ratio of wind-induced flow to fan-induced flow.

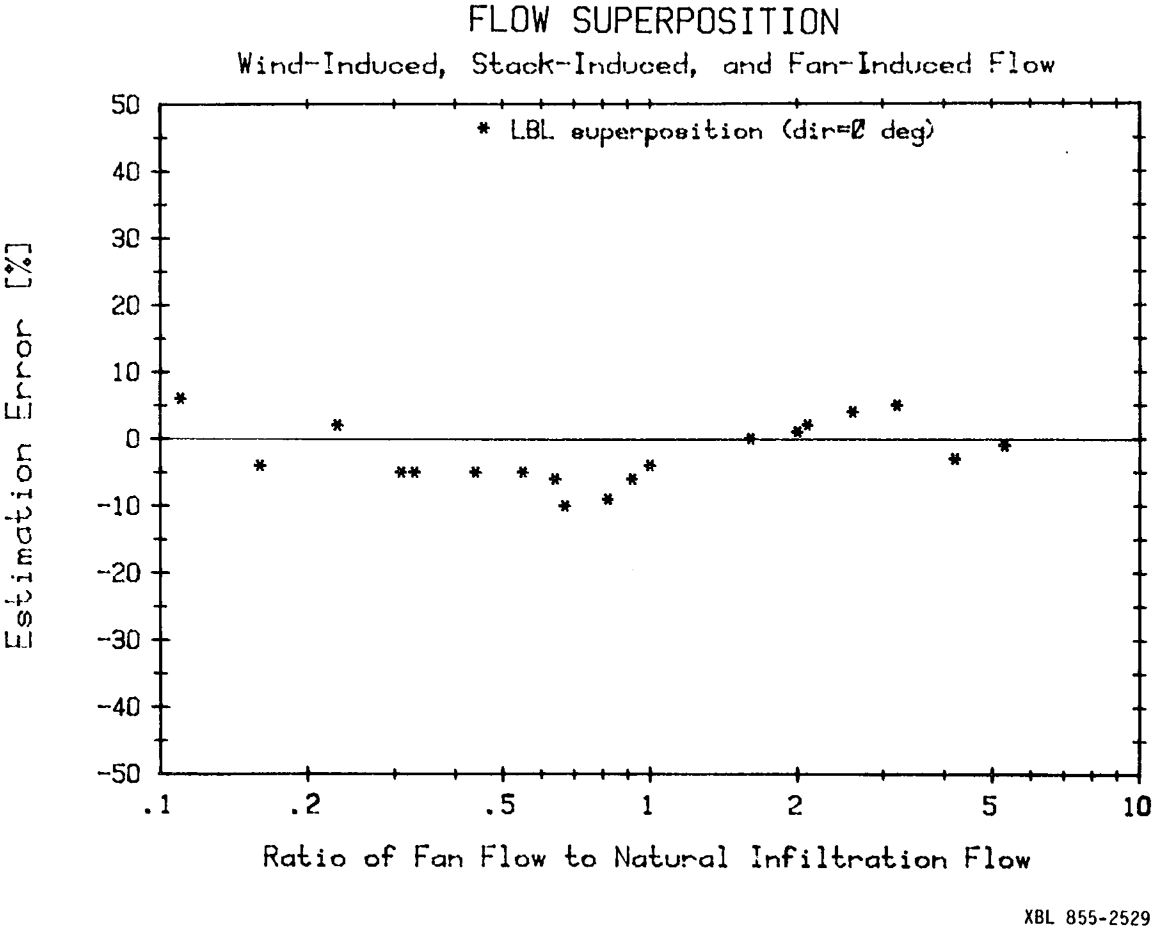


Figure 4. Errors in total infiltration prediction resulting from flow combination by quadrature (Equation 3) vs. Ratio of fan-induced flow to naturally-induced flow (wind and stack). Wind blowing parallel to the sides of the building.

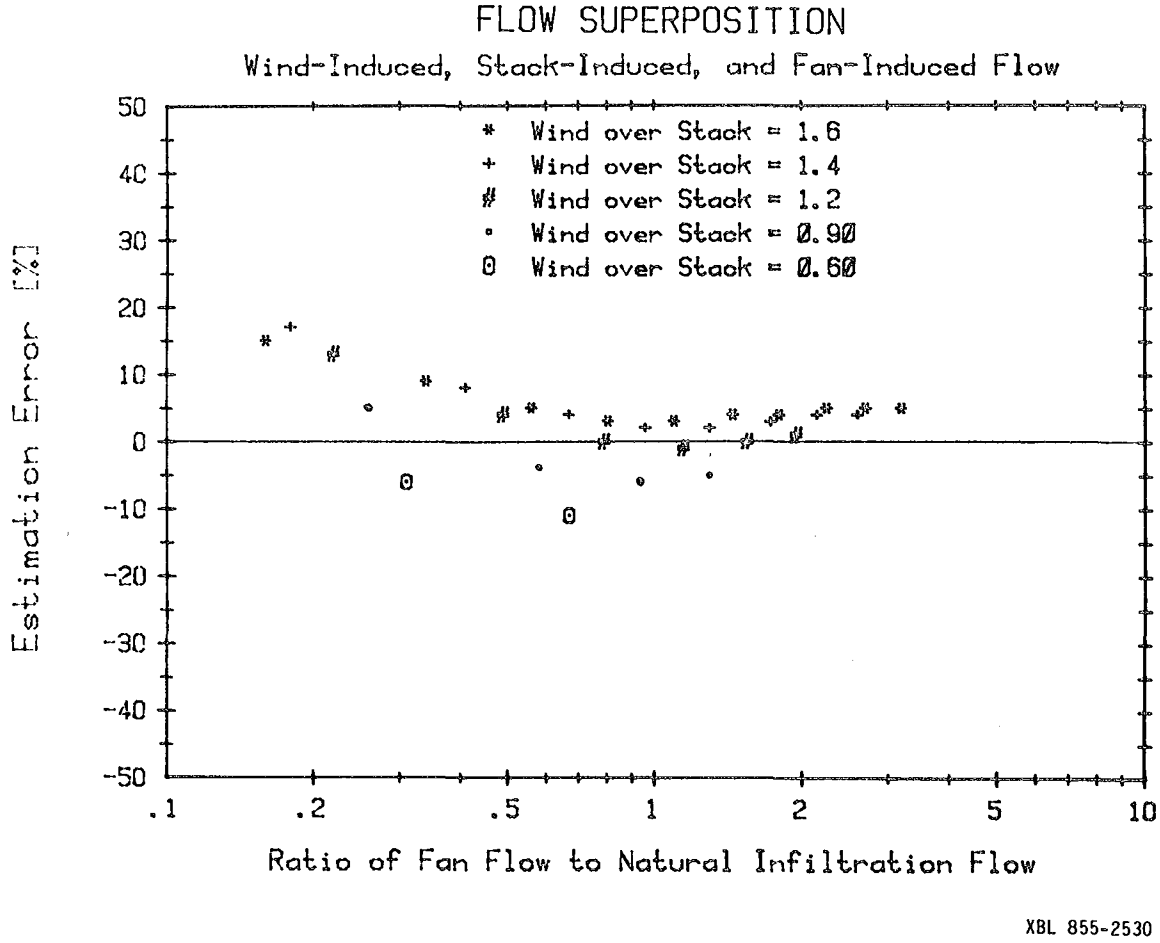


Figure 5. Errors in total infiltration prediction resulting from flow combination by quadrature (Equation 3) vs. Ratio of fan-induced flow to naturally-induced flow (wind and stack). Wind blowing directly onto one corner of the building.

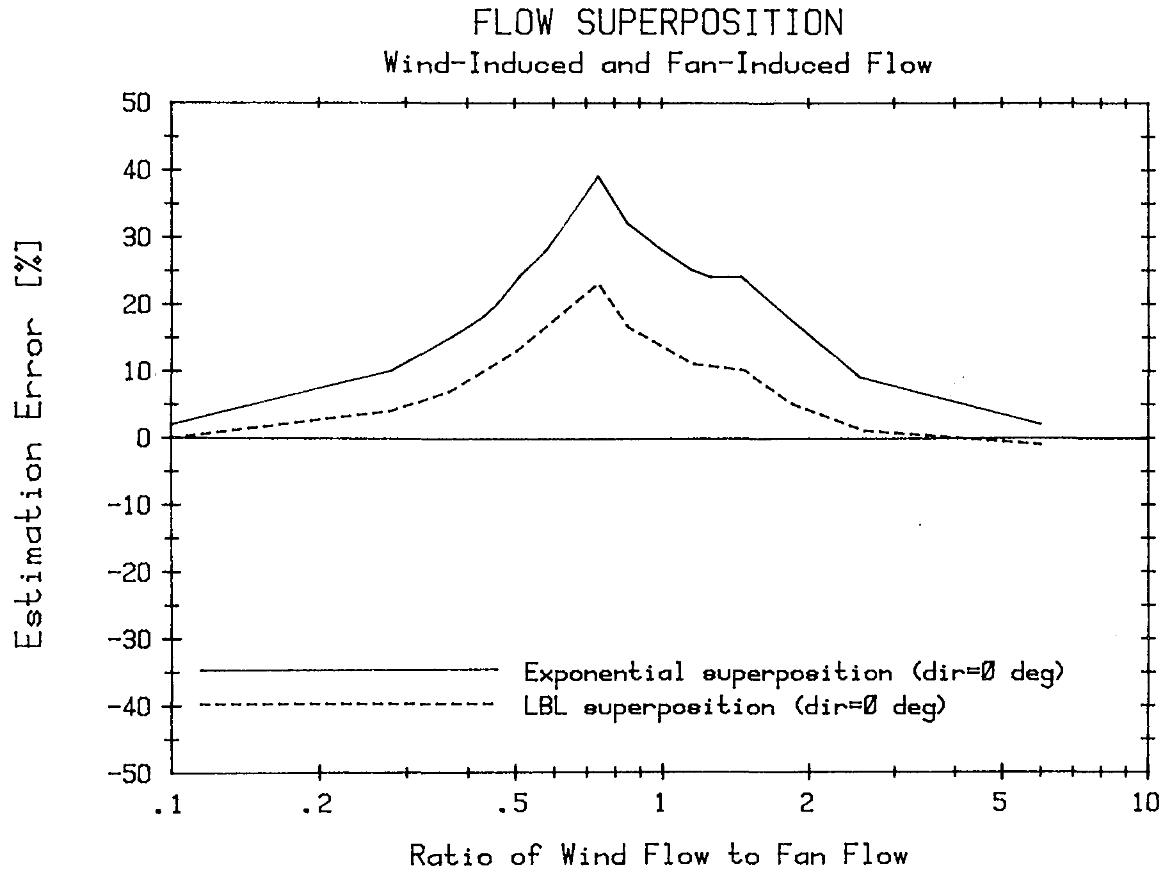


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Figure 6. Errors in total infiltration prediction resulting from flow combination by quadrature (Equation 1) and by flow combination using the measured flow exponent (n=0.67 in Equation 2) vs. Ratio of wind-induced flow to fan-induced flow.