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# Validating a new model for rapid multi-dimensional combined heat and air infiltration building energy simulation

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ABSTRACT

The relative accuracy of current thermal simulation algorithms is evaluated against an intricate multi-physics hygrothermal computational fluid dynamics (CFD) building envelope analysis that incorporates, in addition to real-life conditions, a meticulous representation of cracking in building envelopes. The study found that even the most advanced current algorithms have up to 96.13% relative error versus CFD analysis. A new model for combined heat and air infiltration simulation is developed and presented. The model resulted in up to 91.6% improvement in relative accuracy over current algorithms. It reduces error versus CFD analysis to less than 4.5% while requiring less than 1% of the time required for a complex hygrothermal analysis. The model used is demonstrated to be easy to integrate into other simulation engines as a standalone method for evaluating infiltration heat loads. This will vastly increase the accuracy of such simulation engines while maintaining their speed and ease of use characteristics that make them very widely used in building energy design.



## 1. Introduction and justification

The need for efficient, sustainable, and planned utilization of resources is ever more critical. In the U.S. alone, buildings consume 35.8 Quadrillion ($10^{15}$) BTU of energy annually at a cost of $503 Billion [1]. Of this energy 58% is utilized for heating and air conditioning [2]. This represents 20.75 Quadrillion BTU's a year. That, by proportion, stands for $291.56 Billion spent annually on heating and cooling of buildings. As a result, even minor factors influencing the heating/cooling loads of buildings become of significant importance, much less factors such as air infiltration that can contribute to more than a third of the heating/cooling load of a building.

Traditionally, the two primary reasons for performing building thermal performance calculations are to (1) size and select the required mechanical equipment, or to (2) obtain a prediction of the building's annual energy consumption and costs. Some models can handle either of these tasks while others can handle both [3].

A wealth of Building Energy Simulation software and analysis tools is available to assess energy demands and lifecycle energy costs in buildings. The United States Department of Energy Building Technologies Program lists under its "Building Energy Software Tools Directory" three hundred and eighty nine building software and tools. These software and tools range between databases, component and system analysis tools, spreadsheets, and whole-building energy performance simulation programs [4]. DOE-2 is among the most widely known full building energy analysis models. It also constitutes the major simulation engine of other prominent software such as eQUEST, EnergyPro, PowerDOE. Therefore, it is essential that DOE-2 energy simulations be characterized by high accuracy. However, some major energy demand components are treated by the software with less complexity and are accounted for using overly simplified algorithms. Studies have found that the methods used by such software for building leakage do not account for the infiltration driving mechanisms and other building characteristics. Consequently, the assumed infiltration rates in such leading building energy simulation software do not reflect the direct impacts of outdoor weather conditions [5].

In this work, transient hourly analysis on an intricate multi-physics hygrothermal computational fluid dynamics (CFD) building envelope model that incorporates, in addition to real-life conditions, a meticulous representation of cracking in building envelopes is conducted and compared to prominent energy software analyses. Results revealed large inaccuracies in these simulation algorithms that could underestimate infiltration heat loading by up to 96.13%.

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An infiltration load calculation algorithm was therefore developed and validated. The algorithm combines conduction, air infiltration, and solar radiation, and is easy to integrate into other simulation engines as a standalone method. The validation of the developed Enhanced Model shows that it improves infiltration heat loading calculations relative accuracy by up to 91.63% and reduces the relative error to below 4.5% when compared to CFD analyses results. The validation of the Enhanced Model also shows that it maintains the speed and ease of use advantage of current methods by requiring less than 1% of the time necessary to run a complex multiphysics hygrothermal CFD analysis.

## 2. Background

Infiltration is an uncontrolled process through which outside air leaks into a building affecting the indoor air quality, indoor human comfort, and the building's energy consumption. Studies have shown infiltration to account for as much as 50% of a building's energy demand [6,7]. Caffey [8] attributed 40% of the heating/cooling load in houses to infiltration. Similarly, Persily [9] concluded that one third of the heating and cooling loads in a building are due to infiltration. A similar conclusion was also affirmed by Sherman and Matson [10]. This, considered alongside the annual cost of buildings energy consumption, reveals the heavy energy costs of air infiltration and stresses the need that prominent building energy simulation software accurately account for its impact.

In Younes et al. [11] the aspects and significance of this loading and its substantial energy impacts on the building performance were reviewed in details. The authors also presented a comprehensive discussion of the various methods and techniques available for modeling and simulating this energy impact, ranging from the basic air change models to the complex multi-zone models and coupled multi-zone models. The advantages, disadvantages and shortcoming of each method were also discussed and highlighted. It was shown that such classical method for evaluating the infiltration energy load and considering it to act independently from conduction and other phenomena in the building envelope result in significant errors in building energy loads estimation [11]. The study found it necessary to develop an enhanced algorithm that better evaluates and accounts for the heat loading and energy impact of air infiltration.

Examining existing CFD models of air leakage reveals that they are few and have exclusively modeled small 2-D sections of a building envelope (wall) with a clearly defined single airflow path. Examples of such models include those developed by Chebil et al. [12], Boussa et al. [13] and Buchanan and Sherman [14]. Younes and Abi Shdid [15] developed a modeling methodology for performing 3D full envelope realistic multiphysics hygrothermal simulations for air leakage in buildings. The approach realistically depicts the various cracks common in an envelope in terms of shape, location, and quantity [15]. The methodology developed also accounts for the true multiphysics hygrothermal nature of the phenomenon and for various hourly weather variables. The methodology achieved higher accuracy that allows for a more accurate calculation of air leakage heat loading necessary for an efficient building energy design [15].

Several algorithms and models have been proposed to improve infiltration calculations and incorporate the effect of heat exchange due to heat storage in the thermal mass of the envelope wall into infiltration energy load calculations. Algorithms proposed by Anderlind [16], Kohonen [17], Kohonen and Virtanen [18] were based on a linear reduction factor, depend on steady temperatures and a steady inside/outside enthalpy difference, and ignored solar radiation. Solar radiation has been experimentally shown by Liu [19] to affect the intensity of heat exchange occurring between the walls of the envelope and infiltrating air. A later model proposed by Buchanan and Sherman [14] disregarded the experimentally proven role of incident solar energy, and CFD models they created to verify the method suffered from convergence issues. According to the authors, the model is not for incorporation into network codes and "doesn't capture the full physics of the problem" [14]. Subsequent experimental work by Brownell [2] revealed very little agreement with the Sherman and Buchanan [14] model results.

Kai and Fariborz [20] proposed an analytical model based on one-dimensional combined air infiltration and heat flux through a building wall. The analytical model was validated against a numerical finite difference model of the wall. The proposed model ignored outside environmental factors that have been shown to have a large influence on infiltration heat loads, such as: outside air velocity and direction, solar radiation, convection, and shading effects. The model was presented and validated as a stand-alone algorithm with no attempt to combine it with existing building energy simulation algorithms. One dimensional model further ignore the shape and height of the building, which influence such infiltration driving effects as the stack effect. Research studies on airflow rate calculations indicated that the underestimation and overestimation due to using such surface-averaged pressure coefficients are not negligible [21].

Infiltration rates could also be calculated according to numerical equations [22]. Brinks et al. [23] used experimental data obtained from test stands, which work like a blower door test, to develop a model for monthly infiltration heat loads in large industrial buildings. The proposed model provides monthly coefficients of infiltration that consider the seasonal cycle during the year as well as building properties and temperature [23]. The study provides easy to use infiltration coefficients that can be implemented in energy balance calculations. The coefficients are however generic for typical seasonal temperatures, and relevant only to industrial steel structures. The model thus falls short of being able to perform full transient simulation of air infiltration into buildings with varying external environmental conditions.

Han et al. [24] discussed and compared three different approaches of infiltration rate calculations in building energy simulations including coupled time-dependent infiltration calculations, AVIC database, and default calculations for leaky, medium and tight buildings. The study proposed and tested a framework of building energy simulations associated with time-dependent infiltration rates that integrates computational fluid dynamics and airflow multi-zone modeling approach with energy simulations. The results showed that the energy consumption due to air infiltration takes up approximately 12% of the total annual energy consumption of a building, and that the proposed model improves the accuracy over infiltration rates obtained from the database and default settings in energy simulation programs [24]. The study is however vague about the simulation time that the proposed model would take to simulate a typical building if compared to CFD or to generic energy simulation programs such as Energy Plus or eQUEST.

Younes and Abi Shdid [25] presented a methodology to perform hourly calculations for infiltration heat loading in an accurate, quick and efficient manner. The core principal adopted was to combine the effect of the various involved heat phenomena rather than treating them as to act independently, as commonly done. The algorithm proposed integrated: (1) the interaction between conduction, solar radiation and air infiltration and (2) an airflow/mass flow rate model. The airflow rate model proposed considers the impact of surface roughness, topography, wind speed, wind direction, building height and other factors that influence the infiltration flow rate [25].

Infiltration, as discussed in previously, is a major contributing factor to the heating/cooling load of a building. However, it is the component that most building energy simulation software struggle