Towards Improved Energy Simulation Tools for Buildings
Improving airflow parameterizations within energy simulation using CFD and building measurements

Gianluca Iaccarino
Assistant Professor of Mechanical Engineering
Lead Principal Investigator

Martin Fischer
Professor of Civil Engineering
Co-Principal Investigator

Erin Hult
Postdoctoral scholar

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Summary

Improving the energy efficiency of buildings in California and beyond has great potential for reducing carbon emissions at low cost. Building energy simulation (ES) tools such as EQuest and EnergyPlus that are used in the design of new and retrofitted energy efficient buildings often fail to accurately predict the energy use in buildings (Turner and Frankel 2008). The more confidence there is that energy simulation tools can accurately model energy use, the more these tools will be utilized in energy efficient design and the more effective performance-based building codes on energy efficiency will be. Building ES tools do not explicitly model the air circulation through the space. As a result, the energy use can be quite challenging to model in buildings with thermal stratification or high airflow velocities, which are particularly common with energy efficient strategies such as displacement ventilation, passive ventilation or mixed-mode ventilation. Moreover, comfort in a building is assessed and controlled at room level, and existing ES methods are particularly poor in characterizing these detailed conditions, leading to inaccurate predictions of the energy use. While sophisticated computational fluid dynamics (CFD) tools exist to model airflow and heat transfer in complex spaces, the application of these tools to building-energy problems is limited, given the cost of implementation and simulation. We propose to develop a building energy model using the current best practices in CFD, coupled with heat transfer information from existing an existing energy simulation tool. The intention is not to develop a replacement for existing ES tools, but instead to use an integrated CFD-ES model to identify conditions where discrepancies occur between standard ES predictions and actual energy use in buildings. The extensive building monitoring data from the Yang and Yamazaki Environment and Energy (Y2E2) building and the Santa Clara County Jail building offer a unique opportunity to validate this coupled model. Identifying conditions under which energy models are underperforming would help to focus the future development of building energy modeling.

Part I: Problem Statement

Background

Improving energy efficiency in buildings has the potential to reduce carbon emissions at low cost (McKinsey 2007). Energy simulation tools used in the design of proposed new or retrofitted green buildings often fail to predict actual energy use in these spaces. In a study of 121 buildings, Turner and Frankel (2008) report that while LEED certified buildings did use an average of 25% less energy than a code baseline design, there was significant variation between predicted energy savings and measured energy savings, with some buildings not even meeting the code baseline performance reported by Turner and Frankel (2008) for 121 LEED certified buildings in 2007.

Figure 1: Proposed versus measured energy savings
While some of this discrepancy may be due to changes in building design or operation from the original model used to estimate energy use, there is still significant room for improvement in energy simulation tools. Monitoring and verification of energy efficient buildings is critical in order to use experience to improve simulation tools and inform future design. Energy modeling tools were designed for the conventional, mechanically ventilated buildings, and as a result, it can be very difficult to model passive and mixed-mode ventilation methods. Because energy simulation tools are used to verify that buildings meet energy efficiency regulations, the accuracy of ES tools is critical in order for these regulations to be effective.

**Previous work**

Energy simulation and computational fluid dynamics can provide complementary information about building performance. The coupling of ES and CFD simulations has been used to improve energy modeling performance (Zhai and Chen 2005). ES can be used to estimate heating and cooling loads, and overall energy use on the building zone. In order to simulate the annual energy use of an entire building in a short period of time, standard ES tools rely on the simplifying assumptions that zones within the building are well mixed. Flow dependent quantities such as the convective heat transfer coefficients for interior surfaces are calculated using empirical correlations. On the other hand, CFD provides airflow paths and velocities throughout a zone. In a coupled simulation, CFD can be used to evaluate the convective heat transfer coefficient directly, using heat transfer information from the ES tool.

Two approaches exist for coupled ES-CFD simulations. The first approach, the conjugate heat transfer method, involves modeling the temperature distributions in both the walls and air portions of the space, as well as the airflow in the zone. This approach captures the spatial variability in flow and heat transfer processes. While conjugate heat transfer schemes have been implemented for a range of applications, this approach has been considered to be prohibitively expensive for building applications (e.g., Djuneady et al. 2003). The second approach involves running an ES simulation, while using intermittent CFD results to obtain more accurate estimates of flow dependent parameters. This is the approach that will be used in this study. The ES tool provides wall temperatures and internal loads for the CFD simulation.

In the cases where ES-CFD coupling has been attempted, the thermal loads and overall energy use predicted by the coupled simulation can vary from standard ES results, although the magnitude of this difference is depends on the nature of the flow. One case in which ES-CFD coupling resulted in a substantial change was the simulation of an indoor racetrack (Zhai et al. 2002). Large convective velocities induced by the race cars greatly enhanced the heat transfer within the interior of the facility, such that the heat transfer coefficients in the coupled model were up to 50 times higher than predicted by the standard ES model. As a result, the cooling load from the coupled simulation increased 10% from the standard ES prediction. This difference corresponds to thousands of dollars per week in power costs for the facility.

A coupled ES-CFD simulation could be particularly helpful in improving ES analysis in buildings with mixed-mode and passively ventilated spaces. Mixed-mode buildings, such as the Y2E2 building, use both passive and mechanical ventilation strategies. Although mixed-mode ventilation, can allow for significant reduction in cooling and ventilation costs in a broad range of
building types and climates, there remains some hesitancy towards mixed-mode strategies. Brager, Ring and Powell (2000) argue that building design professionals are wary of how passive and active ventilation systems will perform in conjunction. With limited case studies available, the concern is that such mixed-mode systems could be, in practice, less efficient than a purely mechanical system. It is not easy to dispel such concerns, particularly given that standard energy simulation tools have limited capability to incorporate passive ventilation. Coupled simulation allows for direct calculation of convective heat transfer at the walls, as well as heat fluxes through open windows and vents. A fully coupled ES-CFD simulation could help evaluate the performance of mixed-mode designs under both optimal and sub-optimal building operations. Despite the potential, to date there are no studies applying coupled ES-CFD to mixed-mode or passively ventilated systems, as existing cases are limited to mechanical ventilation or no ventilation scenarios (e.g., Zhai and Chen 2005). Zhai and Chen (2006) suggest that coupled ES-CFD simulations are most valuable when the air in a space is stratified or when air velocities are high. In these circumstances, the convective heat transfer coefficients at the interior boundaries and the airflow rates are most likely to differ from the predictions of a standard energy simulation tool. In sensitivity analyses, heating and cooling loads as well as overall energy use have been shown to be sensitive to the convective heat transfer coefficient and the airflow rate (Negrao 1995). Thus, coupled ES-CFD simulations are expected to improve the prediction of heating and cooling loads for mixed-mode and passively ventilated spaces where stratification and higher air velocities are common.

Project objectives

The overall objective of this project is to improve the ability of building energy simulation tools to predict energy use by improving the modeling of airflow and heat transfer processes within the simulation tools. Specifically, the project objectives include:

- Implementation of a coupled energy simulation-CFD model to highlight the effect of simplifications in the energy simulation tool. The coupled model will be used to directly evaluate key parameters for energy use such as convective heat transfer coefficients and airflow rates within the space.
- Model validation using simple flows with analytical and lab results as well as actual monitoring data extracted from the Y2E2 building.
- Investigation of accuracy gains resulting from the use of customized computational tools developed in the ME Department at Stanford, namely the Immersed Boundary and Large Eddy Simulation.
- Identification of the most sensitive design parameters on which to focus further analysis.
• Identification of operational conditions under which heating and cooling loads vary most greatly from ES predictions.

Building on these objectives for the first year of the project, the longer-term goal is to use this coupled model to improve the parameterization schemes within standard energy simulation tools. Once the model is validated, it could also be used to improve design guidelines as well as to improve building control algorithms to reduce energy use, for example with respect to when to open and close vents for night flushing in the Y2E2 building.

Proposed research and methods

Three major challenges are present in this project: the detailed representation of the physical interaction between buoyant forces and turbulent motions, the complexity of the building geometry and the data exchange with energy simulation tools to acquire load and boundary condition information. With respect to the CFD simulations, one step will be to evaluate the ability of existing turbulence models (such as those implemented in Fluent) to capture buoyancy driven currents. In the longer term the objective is to investigate the accuracy gains resulting from the use of customized computational tools developed in the ME Department at Stanford (namely the Immersed Boundary and Large Eddy Simulation). We plan to perform highly resolved computations that capture the strong interplay between baroclinic production and the dynamics of vortical structures without resorting to semi-empirical models (Fluent). The advantage of this technique is its inherent ability to handle extremely complex geometries such as the entire building if necessary without requiring time-consuming grid generation activities.

For initial validation of the CFD model, a simple enclosed space with a single source of buoyancy with high and low openings will be simulated. Both analytical and laboratory results exist for the temperature profile evolution in this flow, making it an excellent case to verify that the CFD model is capturing the essential physics of buoyancy driven flows in a room (Linden 1999).

After initial validation cases, the CFD model will be applied to a realistic building case. A sample office space in the Y2E2 building will be used, to complement monitoring and energy modeling efforts already underway for this building. Coupling with the ES tool will provide the wall boundary conditions and internal loads, following the approach described by Zhai et al. (2002). Initially, the building domain will be restricted to a single exterior room of the Y2E2 building. Rooms on the south side of the building have no mechanical ventilation, and rely on operable windows and ceiling fans for ventilation and cooling, as well as radiant heating. North side offices have active chilled heated beams to provide mechanical heating, cooling, and ventilation in addition to operable windows. This design allows for a range of test cases of increasing complexity:

• No ventilation
• Ventilation via open window
• Ventilation via open window plus ceiling fan
• Mechanical cooling /ventilation via active chilled beam
• Mechanical cooling /ventilation via active chilled beam and ventilation via open window.
By simulating these cases, we can explore how parameters from the coupled ES-CFD model compare with parameters estimated by the ES tool. The ES-CFD coupling can be used to examine impacts on heating and cooling loads and overall energy use. CFD simulations will also be used to explore what conditions lead to the greatest violations of the assumptions built into the ES tool. The temperature evolution and heating/cooling loads can also be compared with building monitoring data for rooms under similar conditions. Monitoring data from the Santa Clara County Jail building provides another opportunity for simulation and comparison with actual building performance.

Rather than simulating an entire building on an annual basis, as is typical for building energy analysis, the coupled ES-CFD tool will be used to simulate a portion of a building on the time scale of several days. These shorter simulations will be used to look at how heat transfer and airflow parameters vary from the ES tool assumptions. By simulating the flow physics directly with the CFD tool, we can better assess when model assumptions are appropriate and where better parameterizations are needed.

**Significance**

There are broad implications for improving the parameterization of heat transfer and airflow physics in energy simulation tools. If building design professionals do not have confidence that energy simulation tools can accurately predict energy use, this degrades the ability to improve the energy efficiency of building projects. Energy simulation tools are used to demonstrate that projects satisfy building code requirements for energy efficiency such as California Title 24, and verification of actual energy use in the building is typically not required. Meaningful performance-based regulation requires accurate energy simulation tools that can handle a range of heating, ventilation and air conditioning strategies. For mixed-mode and passive ventilation strategies to be adapted more broadly, energy simulation strategies will need to become increasingly flexible. Energy simulation tools provide global information about the energy use and can be effective in aiding the designer to select different solutions. On the other hand, day-by-day energy use in the building is strongly affected by occupants’ comfort, which requires local evaluation of airflow and temperatures. The present approach of coupling ES tools and fluid dynamics simulations provides will greatly enhance the designer ability and confidence in estimating room-level air-quality indicators.

**Part II: Expected interest in the project**

**Costs and benefits**

Improving building energy modeling has potential economic benefits on both local and broad scales. Applying CFD to building flows can be computationally expensive, particularly on the scale of large buildings. The goal of this study, however, is to use CFD to improve, not replace, energy simulation tools. Studies comparing detailed building simulation with energy monitoring data are rare, in part because it can be so expensive to instrument buildings with monitoring equipment. Given that extensive data over multiple years are already available for the Y2E2 building and the Santa Clara County Jail building, these buildings are excellent sites for additional analysis with CFD. On a local scale, even small improvements of energy modeling and efficient operation of
Y2E2 and the other Stanford Engineering Quad 2 buildings could lead to substantial economic benefit over the lifetime of the buildings. On a more broad scale, improving the parameterization of heat transfer and airflow processes in energy simulation could have a huge impact, given the widespread use of these tools in both design and certification of energy efficient buildings.

**Feasibility**

This project is designed to take advantage of established computational tools as well as ongoing building monitoring and energy modeling projects at local sites. While there is significant potential to use CFD to improve the simulation of energy use in buildings, this project has been designed to have useful intermediate deliverables. Starting from simple validation cases will provide opportunities to examine how well the physics of the flow is captured by the numerical simulation. Once the CFD method is validated, we can begin to explore the validity of assumptions in energy simulation tools by applying the model to a portion of a building. In the longer term, these initial objectives will contribute to analysis on the full building scale.

**Scalability**

In this project, we are not aiming to replace traditional energy simulation tools, but instead to shine some light on where improvements may be needed. Energy simulation tools are widely used in the design and certification of energy efficient building stock. Thus, even slight improvements in predictive ability would have large implications for statewide energy use if the tool can then better guide users to efficient solutions. Because of the effort required to develop robust energy simulation tools, there are a limited number of products available. One of the more advanced tools, EnergyPlus, has been developed primarily through research at government laboratories (Crawley et al. 2001). The Simulation Research Group at Lawrence Berkeley National Laboratory is working to develop a collaboration platform for simulation-based building systems research and development. The platform would provide an interface for daylighting, building control, energy simulation, CFD, and other simulation software. One extension of this work would be to connect in with this collaboration platform, as the proposed interface with CFD is not currently under development at LBNL.

**Future investment needs**

This project is intended to be a starting point for collaboration between the CFD and building science research groups at Stanford. Future funding for this research could come from a multi-institution proposal for a Department of Energy funded Energy Regional Innovation Cluster or from a proposal for an NSF CAREER award. Depending on the project findings, it may be sensible to pursue more involved collaboration with Lawrence Berkeley National Lab to focus on the interfacing of CFD and Energy simulation tools.

**Part III: Project personnel and contributions**

The project will involve Lead Principal Investigator Gianluca Iaccarino, Assistant Professor of Mechanical Engineering; Co-Principal Investigator Martin Fischer, Professor of Civil and Environmental Engineering; postdoctoral scholar Erin Hult; as well as a graduate student research
assistant in Mechanical Engineering to be determined later. This project brings together CFD expertise in Mechanical Engineering and building science expertise in Civil Engineering, and is the first project in which the researchers above have worked together. Gianluca Iaccarino contributes significant experience working on numerical simulations of flows involving complex geometries including conjugate heat transfer. Iaccarino is also working to develop rigorous methods to quantify the effects of uncertainty in methods and inputs on results of interest. Martin Fischer brings extensive experience in the building sciences to the project. Fischer’s research group has been investigating the design and operation of energy efficient building design through building monitoring and energy simulation of the Santa Clara County Jail building and the Y2E2 building.

In the project, Iaccarino will be involved in applying existing CFD tools to this problem and will provide advising from the computational perspective. Fischer will advise on the use of energy simulation tools and the acquisition and interpretation of building monitoring data. Postdoc Erin Hult will perform the simulations as well as data analysis of model results and building monitoring data. The mechanical engineering graduate student will help with developing the building geometry grid and implementing the CFD model.

**Part V: Addendum**

**References**


