# Multizone Airflow Models for Calculating Infiltration Rates in Commercial Reference Buildings


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## Abstract

Sixteen reference building models were created in the multizone airflow and contaminant transport program CONTAM in order to support physically-based airflow calculations, as well as indoor air quality analyses, that are not possible using the existing EnergyPlus input files of these buildings. The EnergyPlus models were created for assessing new technologies and supporting the development of energy codes in pursuing building energy efficiency improvements. These models employed an oversimplified approach to infiltration in which infiltration rates were input as constant values. A number of additional inputs had to be defined for the CONTAM models to realistically account for airflow, including the addition of several building zones. Annual airflow simulations were performed in CONTAM for six of the sixteen reference buildings. There are clear relationships between the infiltration rates calculated by CONTAM and weather, which are not exhibited in the EnergyPlus results. In addition, the building envelope airtightness values assumed in either approach have a major impact on calculated infiltration rates. The results of this study provide a baseline for subsequent use of these models to investigate design approaches and technologies that are intended to reduce building energy consumption, improve indoor air quality, or both.



Keywords: airflow, energy, CONTAM, EnergyPlus, reference buildings, ventilation

## 1. Introduction

Heating, ventilating, and air conditioning (HVAC) systems in buildings are designed to provide thermally comfortable conditions and to maintain acceptable indoor air quality (IAQ). At the same time, the operating costs of HVAC systems are often a large percentage of the total energy consumption of buildings, which constitutes 40 % of the primary energy consumed in the U.S. [1]. To address the need to reduce the building sector's contribution to the nation's energy consumption, the U. S. Department of Energy (DOE) Building Technologies Program (BTP) supports the development of the building energy simulation software EnergyPlus and its application in analyzing building energy efficiency opportunities. Under the BTP, 16 building models were created in EnergyPlus that characterize more than 60 % of the commercial building stock in the U.S. [2]. These "reference" buildings include 15 commercial buildings and one multi-family residential building. There are three versions (or vintages) of each reference building: new, post-1980, and pre-1980 construction. The three vintages differ in insulation values, infiltration rates, lighting levels, and HVAC system types. The new construction models were developed to comply with the minimum requirements of ANSI/ASHRAE/IESNA Standard 90.1-2004 [3], the post-1980 models to comply with the minimum requirements of ASHRAE/IES Standard 90.1-1989 [4], and the pre-1980 models to comply with requirements from previous standards and studies of construction practices.

The reference buildings were created to assess new technologies and support the development of energy codes and standards, and therefore their definitions are focused on capturing energy performance, not IAQ. As a result, simplified approaches to account for infiltration were used in the EnergyPlus models. A constant infiltration rate was calculated from an assumed building envelope airtightness, applied to the entire envelope at a constant pressure, and scheduled at 100 % when the HVAC system was off and at 25 % when the HVAC system was on [2]. Note that this approach does not account for the important effects of weather on infiltration.

A simplified approach for accounting for weather in the infiltration rate was developed by Gowri, et al. [5] for commercial buildings. The researchers reported on their determination of an average wind speed coefficient for a square office building and its use to calculate a base infiltration rate. This base infiltration rate can then be varied with wind speed using a capability already within EnergyPlus. Nevertheless, this approach is limited to square buildings and does not account for stack (temperature) effects on infiltration. No other approaches for accounting for infiltration in energy models of commercial buildings are available. However, an empirical formula for stack and wind driven infiltration in large buildings was developed in the 1970s, but it has not been widely applied [6]. More recently, Bernier and Hallé [7] proposed a method to determine the infiltration through windows for energy rating purposes.

Many discussions of building energy efficiency neglect potential impacts on IAQ or view acceptable IAQ as being in conflict with energy efficiency [8]. And saving energy at the expense of IAQ has the potential to negatively impact the health, comfort, and productivity of building occupants. However, there are many approaches to building design and operation that can improve both energy efficiency and IAQ, such as heat recovery ventilation (HRV), demand control ventilation (DCV), natural and hybrid ventilation, and building envelope airtightness [8]. One limitation in the implementation of certain energy efficiency technologies and the consideration of their impacts on IAQ is that current energy design and analysis tools are limited in their ability to model building airflow and IAQ in a physically reasonable fashion. Nevertheless, multizone airflow and contaminant transport models exist and have long been used to examine the energy and IAQ impacts of energy efficiency technologies. Adams et al. [9] used a coupled airflow-thermal model to show that the use of an HRV resulted in 20 % energy savings and reduced contaminant levels. Persily et al. [10] used CONTAM to show that the use of DCV resulted in 10 % to 80 % energy savings without necessarily compromising certain aspects of IAQ. Carpenter [11] used an airflow-thermal model to show that the use of DCV resulted in 20 % to 30 % energy savings, reduced $CO_2$ levels, and 50 % to 100 % reduction in formaldehyde concentrations. Emmerich et al. [12] used a coupled airflow-thermal model to show that building envelope airtightness tightening in commercial buildings resulted in 9 % to 36 % energy savings. Emmerich and Crum [13] used an airflow-thermal model to show that the use of a hybrid ventilation system in an office building in various climates resulted in significant energy savings and acceptable thermal comfort and IAQ.

The discussion above supports the need for more physically-based infiltration in energy models and the application of multizone airflow, and coupled airflow-thermal, analyses in evaluating the performance of energy efficient technologies and retrofits. To provide the ability for more complete airflow, infiltration, and IAQ analyses of the reference buildings, models of the 16 buildings were created (including new, post-1980, and pre-1980 versions) in CONTAM (version 3.0). When using CONTAM, a building is represented as a series of interconnected zones (e.g. rooms), with the airflow paths (e.g. leakage sites and open doors) between the zones and the outdoors defined as mathematical relationships between the airflow through the path and the pressure difference across it. The inputs (weather, systems airflow rates, leakage paths) are used to define mass balances of air into and out of each zone, which are solved simultaneously to determine the interzone pressures relationships and resulting airflow rates between each zone, including the outdoors. A similar effort to develop multizone airflow models for a representative collection of residential buildings was conducted by Persily et al. [14]. Over 200 residential building models were created in CONTAM to represent 80 % of the U. S. housing stock. These residential models have been used to characterize the distribution of ventilation rates in U. S. homes [15].

The EnergyPlus and CONTAM models in combination allow more physically realistic analyses of the energy and IAQ impacts of airflow-related design options and retrofit strategies, such as increased building envelope airtightness. The availability of the CONTAM models specifically supports the study of technologies and approaches that can simultaneously reduce building energy consumption while maintaining or improving IAQ. This paper describes the CONTAM building models and the airflow simulations performed to demonstrate their usefulness in characterizing infiltration. The airflow results calculated by CONTAM and EnergyPlus, and their impact on energy, are also discussed.

## 2. Building descriptions

This section describes how the 16 reference buildings are represented in CONTAM. For more detailed building descriptions, see Deru et al. [2] and Ng et al. [16]. Table 1 lists the 16 reference buildings along with their floor area, number of floors, and the number of zones in the EnergyPlus and CONTAM models. The number of zones was different in buildings where the CONTAM models needed additional zones to support more realistic airflow and IAQ analyses. Zones that were added to the CONTAM models include restrooms, stairwells, elevator shafts, and storage rooms. Modeling all building zones, or at least more of the zones than are typically needed for energy analyses, is often important for airflow and IAQ analyses in order to properly capture pressure relationships and airflow patterns in buildings. Though the number of zones and some zone areas are different between the EnergyPlus and CONTAM models, the total building areas are consistent. The CONTAM models employ the same occupancy and outdoor air ventilation requirements that were modeled in EnergyPlus. Details on occupancy schedules and ventilation requirements can be found in Ng et al. [16].

## 3. Analysis approach

The manner in which building envelope airtightness and mechanical ventilation were modeled for the 16 reference buildings is described in this section. Airflow simulations were performed for six of the 16 reference building models, representing each type of occupancy covered by the 16 reference buildings. The buildings simulated were: Full Service Restaurant, Hospital, Medium Office, Primary School, Small Hotel, and Stand-Alone Retail. Annual simulations with a one-hour timestep in CONTAM, and a 10 minute or 20 minute timestep in EnergyPlus for the "new" buildings. Simulations were performed using typical meteorological year version 2 (TMY2) weather data for Chicago, IL [17].

Building exterior envelope leakage was modeled in CONTAM using an effective leakage area ($A_L$) of 5.27 $cm^2/m^2$ at a reference pressure difference ($\Delta P_r$) of 4 Pa, a discharge coefficient ($C_D$) of 1.0, and a pressure exponent ($n$) of 0.65 for all three vintages of the reference buildings [18]. This leakage value was based on consideration of all available building envelope airtightness data in U.S. commercial buildings [19], which does not support the use of different values for the different building vintages. This envelope leakage was applied to all above-grade exterior walls, ceilings, roofs, and floors. Basement walls were modeled with half of the leakage specified for above grade walls, and ground-contact floors were modeled with no leakage. The effective leakage area of partitions between floors and between zones was modeled using the same value as the exterior wall leakage. The connections between zones that are not separated by a physical partition, such as within an open office or large retail space, were modeled as large openings with discharge coefficient $C_D = 0.6$ and $n = 0.5$. Transfer grilles and door undercuts were included as connections between restrooms and adjacent zones.

To better capture the stack effect, exterior wall leakage on individual floors was divided into three portions on each wall, representing the lower third, middle third, and upper third of each wall. Wind effects were calculated using a wind pressure profile calculated using wind pressure coefficient ($C_P$) relationships found in Swami and Chandra [20]. A wind speed modifier of 0.36, which corresponds to “suburban” terrain [21], was applied to all exterior leakage paths. This parameter is used in CONTAM to account for the effects of local terrain on the variation of wind speed with height above ground level. For openings on roofs, $C_P$ was -0.5 for all wind directions, which is an average value for roofs with less than a 15 degree slope given in the ASHRAE Fundamentals Handbook, Chapter 24 [22]. For buildings with attics, leakage from the attic roof was modeled with venting equal to 1/150 of the floor area [23].

A simplified approach for modeling infiltration was used in the EnergyPlus models of the reference buildings [2]. For the EnergyPlus models of the "new" buildings, building envelope leakage was assumed to be 1.18 $cm^2/m^2$ with a constant indoor-outdoor pressure difference of 4 Pa assumed to be acting across the entire envelope [2]. This leakage value is based on building assembly tightness requirements in ANSI/ASHRAE/IESNA 90.1-2010 [24], but is not consistent with existing building envelope airtightness data on commercial buildings [19]. Thus, a CONTAM-equivalent building envelope leakage was also input into EnergyPlus in this analysis. The building envelope leakage assumed by Deru et al. [2] is equivalent to an airflow rate of $3.02\times10^{-4}$ $m^3/s{\bullet}m^2$ of exterior surface area, which is input into each zone of the EnergyPlus models as a scheduled infiltration rate. The CONTAM-equivalent leakage is equal to an airflow rate of $1.37\times10^{-4}$ $m^3/s{\bullet}m^2$ of exterior surface area. A summary of the infiltration rates assumed in

EnergyPlus and the building envelope airtightness modeled in CONTAM are given in Table 2 for the six simulated buildings. Conversion to other leakage units can be done using the equations in ASHRAE Fundamentals [22]. Infiltration was scheduled at 100 % of the input value when the HVAC system was scheduled to be off and reduced to 25 % or 50 % when the HVAC system was on [2]. Therefore, unlike CONTAM, the infiltration rates in the EnergyPlus models do not exhibit any dependence on weather.

The minimum amount of outdoor ventilation air for each zone (or HVAC system) was specified in EnergyPlus using ASHRAE 62-1999 for all vintages [25], and these same values were included in the CONTAM models. These ventilation rates are summarized in Table 2 as outdoor air intake per person and per floor area for the six simulated buildings. The common design goal of pressurizing commercial buildings was accounted for in the CONTAM models by returning 90 % of the supply airflow rate to the HVAC system. For buildings with large exhaust flows, i.e., the two restaurants, the total outdoor air intake was approximately equal to the total exhaust. A brief description of the HVAC systems and the net system flow (supply minus return minus exhaust) for the six buildings are also listed in Table 2. This table shows that the Full Service Restaurant is the only building with net negative system flow, and the Hospital has the largest net positive system flow. In contrast, HVAC systems were modeled in EnergyPlus models with the supply airflow rate equal to the return airflow rate, reflecting no net pressurization or depressurization of the building. Details on the supply, return, and outdoor ventilation rates modeled in CONTAM can be found in Ng et al. [16]. The CONTAM simulations in this study were performed assuming a single building envelope airtightness value and a single set of HVAC system flows. Future work is being considered to could include studying the effects of building envelope airtightness and HVAC system flows on infiltration.

The indoor temperature setpoints for the EnergyPlus simulations varied between buildings but were on average 23 °C in the cooling months and 19 °C in the heating months during system-on hours. During system-off hours, the cooling and heating setbacks were 27 °C and 17 °C, respectively. In CONTAM, a constant indoor temperature of 20 °C was assumed for the entire year.

## 4. Simulation results

This section presents the results of the simulations, beginning with the distribution of outdoor air change rates due to infiltration, or "infiltration rates", calculated by CONTAM and EnergyPlus for the six buildings. The relationship between the infiltration rates and weather are also discussed, as well as the impact of the infiltration rates on energy consumption. A comparison of total outdoor air change rates, i.e., including both infiltration and outdoor air intake via the mechanical ventilation system. Total outdoor air change rates calculated by the CONTAM and EnergyPlus models are presented and discussed in Ng et al. [16].

### 4.1. Infiltration rates and HVAC system operation

Infiltration rates were calculated as the total air flow entering the building through the exterior envelope divided by the building volume. Attics were not included in the building volume in this calculation. Table 3 lists the number of hours under each system condition, as well as the corresponding minimum, maximum, mean, and standard deviation (SD) of the infiltration rates calculated by CONTAM and EnergyPlus. Differences in system-off hours between CONTAM and EnergyPlus results are attributed to the manner in which economizers are modeled in EnergyPlus and the fact that they were not included in the CONTAM models. The EnergyPlus results are presented using two assumed building envelope airtightness values. The results using the value assumed by Deru et al. [2] are referred to as "EnergyPlus (tight)." The results using the leakage values assumed in the CONTAM models are referred to as "EnergyPlus (CONTAM-equivalent)." Figure 1 shows the frequency distribution of system-on and system-off infiltration rates for the Full Service Restaurant and Medium Office for an entire year as calculated by CONTAM and EnergyPlus. Infiltrations rates are plotted against indoor-outdoor temperature difference and against wind speed in Figure 2 for the Full Service Restaurant. Similar plots for the other simulated buildings can be found in Ng et al. [16].

Table 3 shows that the mean system-on and system-off infiltration rates calculated using CONTAM were 20 % to six times higher than the assumed inputs in the EnergyPlus (tight) models for all of the buildings except the Stand-Alone Retail. In the Stand Alone-Retail building, the mean system-off infiltration rates calculated by CONTAM and EnergyPlus (tight) are similar. The frequency distributions in Figure 1 show that for the Full Service Restaurant and Medium Office, the EnergyPlus (tight) results tend to be well below the CONTAM results. For large temperature differences and high wind speeds, the infiltration rates calculated using CONTAM were as much as nine times higher than the EnergyPlus (tight) inputs.

Table 3 shows that, for all buildings except the Full Service Restaurant and Primary School, the mean system-on and system-off infiltration rates calculated using CONTAM were 20 % to 80 % lower than the assumed inputs in the EnergyPlus (CONTAM-equiv.) models. Figure 1(b) shows that for the Medium Office, the EnergyPlus (CONTAM-equiv.) infiltration rates are significantly higher than the CONTAM rates. In contrast, for the Full Service Restaurant (Figure 1(a)), Hospital, and Primary School (not shown), the mean system-on infiltration rates calculated by CONTAM are 20 % to 30 % higher than the EnergyPlus (CONTAM-equiv.) results. Some of the differences between the CONTAM, EnergyPlus (tight), and EnergyPlus (CONTAM-equiv.) results can be attributed to how weather impacts, or does not impact, the predicted infiltration rates. Differences also arise due to the building envelope airtightness values used in the simulation models, which is a critical but challenging value to select based on the limited building envelope airtightness data available as discussed in Section 5.

### 4.2. Infiltration rates vs. weather conditions

Independent of the difference in the mean infiltration rates calculated by CONTAM EnergyPlus, the infiltration rates calculated using EnergyPlus do not reflect any dependency on weather. This is clearly seen by comparing the standard deviations in Table 3, as well as the distribution of infiltration rates in Figure 1. The standard deviation of infiltration rates is non-zero for all of the CONTAM cases, and is zero for most of the EnergyPlus cases. Figure 1 shows the variability in infiltration rates as calculated using CONTAM, whereas there is no variability in the infiltration rates calculated using EnergyPlus.

Infiltration rates are plotted against indoor-outdoor temperature difference, $\Delta T$, and against wind speed, $W_s$, in Figure 2 for the Full Service Restaurant. Similar plots for the other five simulated buildings can be found in Ng et al. [16]. The plot of infiltration rates versus indoor-outdoor temperature difference only includes values of $W_s$ less than 2 m/s. The plot of infiltration rates versus wind speed are shown for $\Delta T$ with absolute values less than 10 °C. Limiting the plots to low $W_s$ and low $|\Delta T|$ makes the effects of $\Delta T$ and $W_s$ more evident. Results are plotted for system-on and system-off hours.

Generally, there is a nearly linear relationship between infiltrations rates calculated using CONTAM and $\Delta T$, with the dependence being symmetrical about $\Delta T = 0$ for both system-on and system-off conditions. Figure 2(a) demonstrates this relationship for the Full Service Restaurant, which is similar to the trends found in the other buildings. Figure 2(b) shows that generally there is a non-linear relationship between infiltrations rates calculated using CONTAM and $W_s$ for both system-on and system-off conditions. This non-linear dependence is expected since indoor-outdoor pressure differences due to wind are related to the square of the wind speed [22]. Figure 2 shows that the infiltration rates calculated using EnergyPlus are constant for both system-on and system-off conditions, which is expected since infiltration is a scheduled input. It should also be noted that while the system-on infiltration in EnergyPlus is assumed to be reduced to 25 % or 50 % of the system-off value, the system-on and system-off infiltration rates calculated by CONTAM are similar in most buildings except the Medium Office.

### 4.3. Impacts of infiltration on sensible load

Sensible loads were calculated to examine the impact of differences in calculated infiltration rates on heating and cooling loads in the six simulated buildings. Details can be found in Ng et al. [16]. Table 4 lists the total heating and cooling sensible loads due to infiltration in each building for one year in Chicago. These estimates do not account for any other loads, internal or external, or HVAC system effects and efficiencies in meeting these loads. The columns in Table 4 contain the sensible load due to infiltration using the EnergyPlus (tight and CONTAM-equiv.) models, the sensible load using the CONTAM models, and the ratios of the CONTAM infiltration sensible load to the EnergyPlus (tight and CONTAM-equiv.) load.

In general, Table 4 shows that the infiltration loads calculated using CONTAM are higher than the EnergyPlus tight and CONTAM-equiv. results. Only for the Hospital, Medium Office, Small Hotel, and Stand-Alone Retail are the infiltration loads calculated using CONTAM lower than the EnergyPlus (CONTAM-equiv.) results. This is because in these buildings, the infiltration rates calculated by CONTAM are similar to or lower than rates in the EnergyPlus (CONTAM-equiv.) models (see Table 3).

For all of the simulated buildings, except the Hospital, the differences in calculated infiltration load between the CONTAM and EnergyPlus tight and CONTAM-equiv. models were 10 % to 60 % of the total energy consumption. For the Hospital, the differences in calculated infiltration load were only 1 % to 5 % of the total energy consumption because the energy consumption for the Hospital is very high compared to the other simulated buildings. Although the infiltration loads calculated using the EnergyPlus (CONTAM-equiv.) models were closer to the CONTAM values, there were still 10 % to 50 % differences between CONTAM and EnergyPlus (CONTAM-equiv.) results. Note that the values in Table 4 are total loads over one year and that the differences between the CONTAM and EnergyPlus loads are more significant for individual hours when the weather conditions lead to higher infiltration rates in the CONTAM models. Nevertheless, differences between CONTAM and EnergyPlus results point out the importance of accounting for building airflow in energy simulation in a more physically reasonable fashion.

## 5. Discussion

The CONTAM models of the reference buildings described in this paper will be useful in supporting future studies of ventilation and IAQ. And while the development of CONTAM models of the DOE reference buildings furthers the ability to conduct simultaneous energy, airflow and contaminant transport simulations, it also revealed a number of issues and presented a number of challenges that merit discussion and should be addressed in the future.

One key issue identified in this effort is the impact of the selected building envelope airtightness value on calculated infiltration and impact on energy. Section 4 shows differences between CONTAM, EnergyPlus (tight), and EnergyPlus (CONTAM-equiv.) infiltration rates from 20 % to six orders of magnitude. Differences in infiltration rates then translate into differences in sensible loads from 10 % to nine orders of magnitude as shown in Section 4.3. Thus, the selection of an infiltration or envelope leakage rate to be used in building energy simulation needs to be carefully considered since it significantly impacts predicted airflows and energy use. However, given the very limited data on building envelope leakage, selecting these values is a significant challenge for both energy analysis and airflow simulation. Nevertheless, assuming constant infiltration airflow rates in energy simulation, no matter the value, cannot capture the important effects of weather on infiltration. Thus, a treatment of infiltration that is more physically-based should be applied to EnergyPlus models and building energy simulation in general. As an alternative to performing multizone analyses using tools like CONTAM, simple empirical relationships between infiltration rates, building envelope airtightness, system operation (ranges of supply and exhaust rates) and weather can be developed for use in energy simulation. Note that EnergyPlus currently has the capability to use such relationships. The challenge is to develop such algorithms that provide sufficiently accurate infiltration rates for various building sizes, designs and shapes and under various weather conditions. Furthermore, since building materials and construction practices will influence building envelope leakage, and thus energy consumption, it is important that buildings are designed and constructed for improved airtightness. This can be accomplished with the continued development of codes, standards, testing procedures, and construction practices for improved building envelope airtightness.

Another challenge in conducting simultaneous energy, airflow and contaminant transport simulations is that building models developed for performing airflow and IAQ analyses generally employ different building representations and require different data than those used for energy analyses. CONTAM, and other multizone airflow and IAQ models, consider buildings as networks of interconnected zones. Airflow rates are then calculated based on physical relationships between flow and pressure analogous to the relationship between heat transfer and temperature differences in energy models. Thus, it is important that multizone building airflow models capture the pressure relationships between building zones, which are a function of building geometry, exposure to the outdoors, interzone leakages, and HVAC system airflows. In contrast, building models for energy analysis are focused on accounting for thermal loads of different building zones, system efficiencies in meeting these loads, and selecting equipment types and sizes. While building geometry, exposure to the outdoors, and HVAC system flows are also important in energy calculations, the zones used in energy models are based on the similarity and differences between their thermal loads. Therefore, these thermal zones may not be the same as the zones needed for properly modeling building airflow, as was the case in this effort.

In addition to different approaches to building zoning, another key difference between airflow and energy models is how they manage airflow balances and interzone airflow. EnergyPlus generally maintains a balance between the airflows into (supply) and out of (return and exhaust) each zone. Interzone airflows are sometimes input, but a net airflow balance between entering and leaving air is maintained for each zone. Infiltration airflows are not part of this balance but are considered only as they impact the thermal loads of the zone. In contrast, CONTAM and other multizone airflow models use the mass balance of air for each zone to determine the amount of infiltration and exfiltration for each zone to the outdoors and/or adjacent zones. Therefore, the system flows are an input while temperature differences and wind pressures serve as boundary conditions, which in conjunction with leakage values of the zone boundaries are used determine infiltration and exfiltration flows. Thus, the differences in how the

HVAC system airflows and infiltration (or exfiltration) are managed in airflow and energy models needs to be reconciled before simultaneous energy, airflow and contaminant transport simulations can be conducted.

The CONTAM models of the reference buildings provide important tools to evaluate the ventilation and IAQ performance of various building and system design options in conjunction with EnergyPlus analyses. However, there are a number of limitations to the CONTAM models that need to be considered and addressed in the future. To simplify CONTAM modeling, the maximum supply airflow rates calculated by EnergyPlus were used in the CONTAM models. Therefore, variable-air volume (VAV) system effects were not included. Also, the CONTAM simulations maintained a constant indoor temperature and used the minimum amount of outdoor ventilation air specified in EnergyPlus for each zone (or HVAC system) with no economizer cycle. Thus, future applications of CONTAM to these models may consider varying supply airflow rates, varying indoor temperatures, and economizer operation.

It is also important to note that coupled airflow-thermal interaction cannot be captured by performing independent airflow and thermal simulations, which is especially important for modeling natural or hybrid ventilation approaches. Current methods of coupling airflow-thermal simulations include ping-pong, onion, or fully-integrated [26]. Ping-pong coupling passes airflow and temperature values between two separate simulations at each time step. Onion coupling passes airflow and temperature values between two separate simulations within each time step until convergence is reached. Lastly, fully-integrated coupling simultaneously solves the airflow and energy equations within a single simulation. Fully-integrated coupling is the most computationally intensive of the three coupling methods, but may be more accurate. The most appropriate coupling method depends in part to the degree of coupling of the airflow-thermal problem. The more highly coupled the interaction, such as in naturally ventilated buildings where large temperature gradients may exist and are important drivers of airflow, the more sophisticated the coupling method will need to be. Other important factors in selecting an appropriate airflow-thermal coupling method include the achievable convergence of airflow and thermal values and differences in time scales between the airflow (on the order of minutes or hours) and thermal (on the order of seconds to hours) problem. Wang et al. [27] developed a fully-integrated coupling method and compared its performance to an onion-coupled simulation for a buoyancy-driven problem. The study found numerical instabilities with the onion-coupled method. The fully-integrated coupling method was not subject to these instabilities and predicted airflow rates and temperatures comparable to the results of a CFD simulation with significantly reduced computational cost. Nevertheless, more development and testing of coupling techniques for a variety of airflow-thermal problems are still needed.

## 6. Conclusion

Sixteen reference buildings were created in the multizone airflow and contaminant transport program CONTAM in order to support physically-based airflow calculations, as well as IAQ analyses, that are not possible using the existing EnergyPlus input files. Six of the 16 reference buildings, representing each type of occupancy covered by the reference buildings, were selected for annual airflow simulations.

The infiltration rates calculated by CONTAM were two to six times greater than the assumed inputs in the EnergyPlus (tight) models. The infiltration rates calculated by the EnergyPlus (CONTAM-equiv.) models were closer to the CONTAM predictions. Nevertheless, the assumed infiltration rates in EnergyPlus did not reflect the impacts of outdoor weather conditions, which were captured by CONTAM. This inability of the EnergyPlus models to account for weather, and the building envelope airtightness values assumed in these models, resulted in substantial differences in the infiltration rates and associated energy impacts.

The EnergyPlus and CONTAM models of the reference buildings serve as baseline cases, which will be useful in future analyses to support the design and implementation of ventilation and IAQ control approaches that can simultaneously reduce building energy use while maintaining or improving IAQ.

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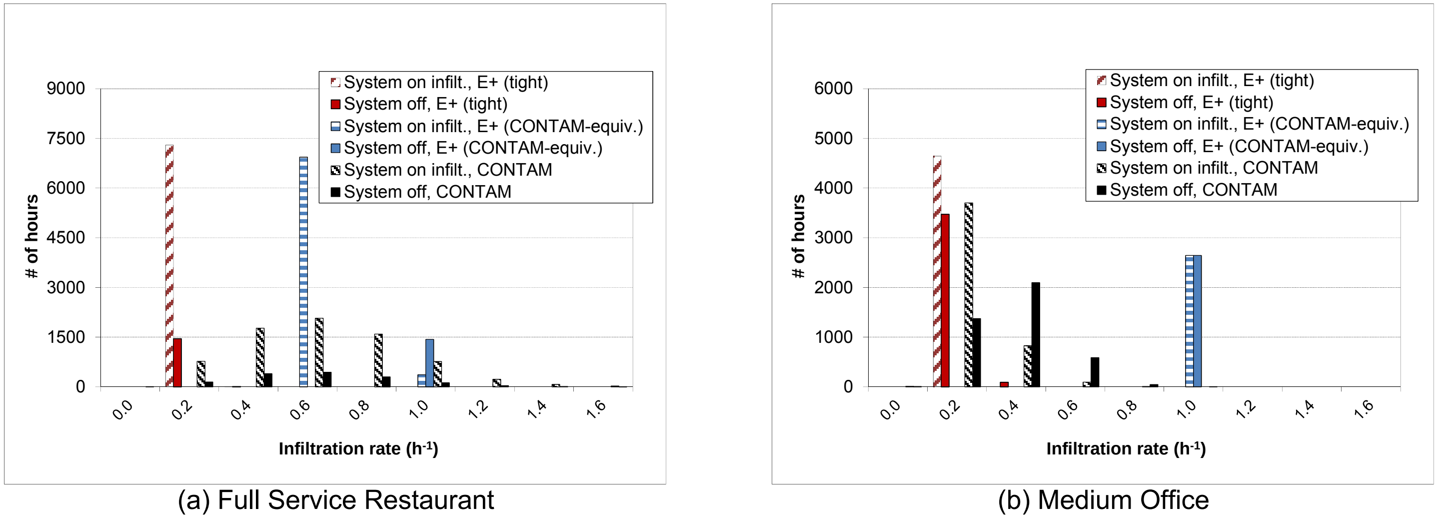
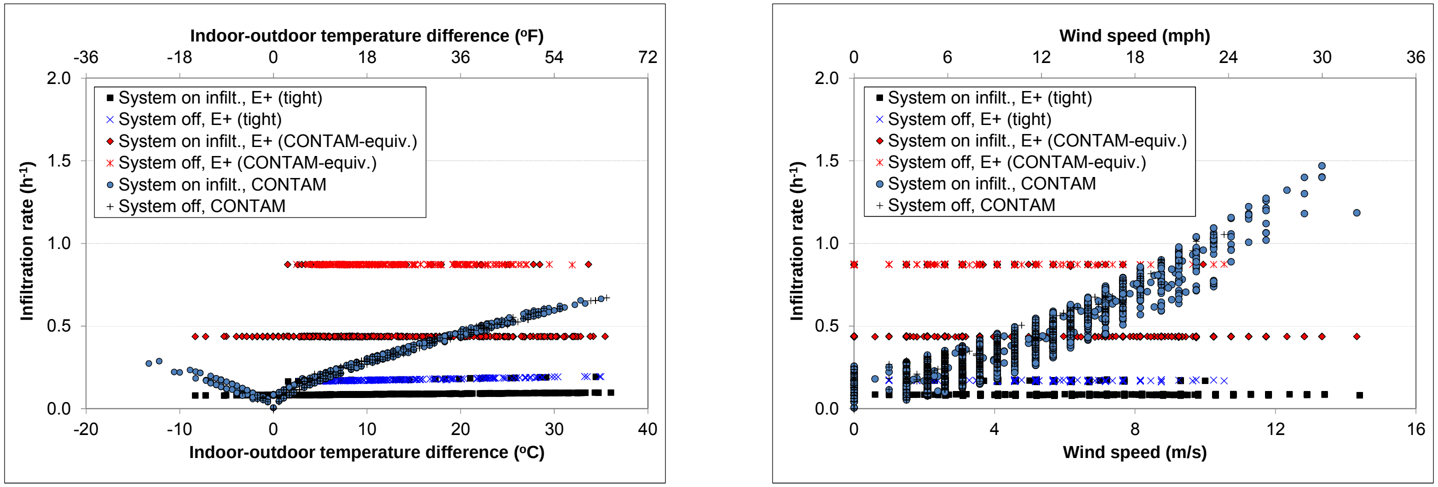



**Figure 1** Frequency distribution of infiltration rates for selected buildings




(a) Function of $\Delta T$ ($W_s$ < 2m/s) (b) Function of $W_s$ ($|\Delta T|$ < 10 °C)

**Figure 2** Infiltration rates as a function of weather for Full Service Restaurant

**Table 1** Summary of reference buildings

| Building | Floor area ($m^2$) | No. of floors | No. of EnergyPlus zones | No. of CONTAM zones |
|---|---|---|---|---|
| Quick service restaurant | 232 | 1 | 2 | 3 |
| Full service restaurant | 511 | 1 | 2 | 3 |
| Small Office | 511 | 1 | 5 | 6 |
| Strip mall | 2090 | 1 | 10 | 30 |
| Stand-alone retail | 2294 | 1 | 5 | 6 |
| Midrise apartment | 3135 | 4 | 36 | 38 |
| Outpatient health center | 3804 | 3 | 118 | 118 |
| Small Hotel | 4013 | 4 | 67 | 67 |
| Supermarket | 4181 | 1 | 6 | 6 |
| Warehouse | 4835 | 1 | 3 | 4 |
| Medium Office | 4982 | 3 | 18 | 23 |
| Primary School | 6871 | 1 | 25 | 25 |
| Large Hotel | 11345 | 6 | 43 | 49 |
| Secondary School | 19592 | 2 | 46 | 46 |
| Hospital | 22422 | 6 | 55 | 64 |
| Large Office | 46320 | 13 | 73 | 87 |

**Table 2** Characteristics of six simulated reference buildings

| Building | EnergyPlus (tight) infiltration, $m^3/s/m^2$ | EnergyPlus (CONTAM-equiv.) infiltration, $m^3/s/m^2$ | CONTAM airtightness, $m^3/s/m^2$ at 4 Pa[1] | Average outdoor air intake, L/s•person (L/s•$m^2$) | HVAC system description | Net system flow in CONTAM[2], $m^3/s$ |
|---|---|---|---|---|---|---|
| Full service restaurant | $3.02\times 10^{-4}$ | $1.37\times 10^{-4}$ | $1.37\times 10^{-4}$ | 10.0 (5.5) | Packaged air handlers with kitchen exhaust | -0.7 |
| Hospital | | | | 27.1 (1.14) | VAV and CAV systems | 9.6 |
| Medium Office | | | | 11.9 (0.73) | VAV systems | 2.0 |
| Primary School | | | | 9.4 (2.71) | Packaged air handlers and VAV systems with kitchen and cafeteria exhaust | 0.2 |
| Small Hotel | | | | 9.2 (1.17) | Packaged air handlers and individual guestroom units | 1.4 |
| Stand-alone retail | | | | 9.8 (1.39) | Packaged air handlers | 0.7 |

Note 1: The building envelope airtightness assumed in CONTAM has a reference pressure of 4 Pa. It is used to calculate infiltration based on indoor-outdoor pressure differences caused by weather and HVAC operation. In contrast, the infiltration rates assumed in EnergyPlus are calculated assuming a constant 4 Pa pressure difference.
Note 2: Net system flow is equal to the supply minus return minus exhaust. In the EnergyPlus models, net system flow is zero for all buildings.

**Table 3** Summary of calculated infiltration rates

| **Full Service Restaurant** | **System-on infiltration rates, $h^{-1}$** | | | | | **System-off infiltration rates, $h^{-1}$** | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Hours | Mean | Min. | Max. | SD | Hours | Mean | Min. | Max. | SD |
| CONTAM | 7300 | 0.53 | 0.01 | 1.86 | 0.27 | 1460 | 0.50 | 0.00 | 1.87 | 0.25 |
| EnergyPlus (T*) | | 0.10 | 0.09 | 0.19 | 0.02 | 1460 | 0.19 | 0.19 | 0.19 | 0.00 |
| EnergyPlus (CE*) | | 0.46 | 0.43 | 0.88 | 0.09 | 1435 | 0.87 | 0.87 | 0.88 | 0.00 |
| **Hospital** | | | | | | | | | | |
| CONTAM | 8760 | 0.05 | 0.00 | 0.37 | 0.05 | 0 | NA | NA | NA | NA |
| EnergyPlus (T) | | 0.01 | 0.01 | 0.01 | 0.00 | | | | | |
| EnergyPlus (CE) | | 0.04 | 0.04 | 0.04 | 0.00 | | | | | |
| **Medium Office** | | | | | | | | | | |
| CONTAM | 4644 | 0.12 | 0.00 | 0.75 | 0.11 | 4116 | 0.28 | 0.00 | 0.86 | 0.13 |
| EnergyPlus (T) | | 0.05 | 0.05 | 0.05 | 0.00 | 3564 | 0.20 | 0.20 | 0.21 | 0.00 |
| EnergyPlus (CE) | | 0.23 | 0.22 | 0.23 | 0.00 | 2644 | 0.91 | 0.90 | 0.92 | 0.00 |
| **Primary School** | | | | | | | | | | |
| CONTAM | 3780 | 0.32 | 0.09 | 1.17 | 0.14 | 4980 | 0.29 | 0.01 | 0.97 | 0.14 |
| EnergyPlus (T) | | 0.05 | 0.05 | 0.10 | 0.01 | 4032 | 0.08 | 0.05 | 0.10 | 0.02 |
| EnergyPlus (CE) | | 0.24 | 0.22 | 0.45 | 0.06 | 3034 | 0.38 | 0.22 | 0.45 | 0.11 |
| **Small Hotel** | | | | | | | | | | |
| CONTAM | 8760 | 0.26 | 0.00 | 1.19 | 0.15 | 0 | NA | NA | NA | NA |
| EnergyPlus (T) | | 0.14 | 0.14 | 0.14 | 0.00 | | | | | |
| EnergyPlus (CE) | | 0.63 | 0.62 | 0.64 | 0.00 | | | | | |
| **Stand-Alone Retail** | | | | | | | | | | |
| CONTAM | 5278 | 0.23 | 0.00 | 0.82 | 0.14 | 3482 | 0.26 | 0.00 | 0.88 | 0.13 |
| EnergyPlus (T) | | 0.14 | 0.14 | 0.27 | 0.02 | 3482 | 0.27 | 0.26 | 0.27 | 0.00 |
| EnergyPlus (CE) | | 0.63 | 0.60 | 1.22 | 0.09 | 3482 | 1.21 | 1.20 | 1.23 | 0.00 |

* T corresponds to EnergyPlus (tight) case, and CE corresponds to EnergyPlus (CONTAM-equiv.) case.
Note: The calculated air change rates of 0.00 $h^{-1}$ using CONTAM correspond to very small indoor-outdoor temperature differences and/or wind speeds. The values are not exactly zero but are less than 0.005 $h^{-1}$.

**Table 4** Sensible loads due to infiltration

| Building | Load | EnergyPlus (tight) (GJ) | EnergyPlus (CONTAM -equiv.) (GJ) | CONTAM (GJ) | Ratio of CONTAM to EnergyPlus (tight) | Ratio of CONTAM to EnergyPlus (CONTAM-equiv.) |
|---|---|---|---|---|---|---|
| Full Service Restaurant | Heating | 27 | 115 | 128 | 4.8 | 1.1 |
| | Cooling | 0.4 | 2 | 6 | 13.6 | 3.0 |
| Hospital | Heating | 100 | 454 | 898 | 9.0 | 2.0 |
| | Cooling | 8 | 36 | 22 | 2.7 | 0.6 |
| Medium Office | Heating | 310 | 1178 | 611 | 2.0 | 0.5 |
| | Cooling | 4 | 16 | 23 | 6.6 | 1.4 |
| Primary School | Heating | 221 | 1083 | 1248 | 5.7 | 1.2 |
| | Cooling | 19 | 18 | 62 | 3.2 | 3.4 |
| Small Hotel | Heating | 230 | 1010 | 479 | 2.1 | 0.5 |
| | Cooling | 6 | 27 | 22 | 3.7 | 0.8 |
| Stand-Alone Retail | Heating | 333 | 1379 | 559 | 1.7 | 0.4 |
| | Cooling | 7 | 32 | 20 | 2.6 | 0.6 |