Moisture Transfer in Commercial Buildings Due to Air Leakage: A New Feature in the Online Airtightness Savings Calculator

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ABSTRACT

Air leakage through the building envelopes is responsible for a large amount of energy use. The US Department of Energy Windows and Building Envelope Research and Development Roadmap for Emerging Technologies states that, in 2010, air infiltration was responsible for 20% of primary energy consumption attributable to the fenestration and building envelopes of commercial buildings. Despite this fact, improving airtightness is not always recognized by commercial building owners, as they have been slow in acknowledging and diminishing the detrimental effects of air leakage on energy use, comfort, indoor air quality, and building material durability.

The design and construction industry would benefit from a credible, easy-to-use tool that estimates potential energy and financial savings in a standardized manner so designers and contractors can give building owners compelling reasons to invest in reducing air leakage. In 2016–2017, Oak Ridge National Laboratory, the National Institute of Standards and Technology, the Air Barrier Association of America, and the US-China Clean Energy Research Center for Building Energy Efficiency collaborated to develop an online calculator. This user-friendly calculator is free to the public and uses the simulation results of the whole building energy simulation tool EnergyPlus and the airflow simulation tool CONTAM. In 2018–2019, the calculator was expanded to add moisture transfer calculations given that air leakage through the building envelope can have a significant impact on moisture transfer and associated impacts. Four more commercial building types were also added to the existing database of three building types as part of this update. This paper describes the procedure used to calculate moisture transfer due to air leakage and provides examples that demonstrate the moisture transfer for each of the seven commercial building types that are currently part of the calculator.

INTRODUCTION

Envelope air leakage in commercial buildings in the United States accounts for about one quad (1 EJ) of primary energy annually (US Department of Energy [DOE] *Windows and Building Envelope Research and Development Roadmap for Emerging Technologies*), costing approximately $10 billion/year. The roadmap also states that computational tools are critically important for the design of commercial buildings with energy-efficient envelope technologies. As the thermal resistance of commercial building envelopes continues to improve, the relative contribution of air leakage to heating and cooling loads is increasing. As new technologies are developed, models and simulation tools must be updated to account for their performance. One impediment to the broader adoption of continuous air barrier systems into buildings is the lack of a simple, credible tool that can be employed by building architects, designers, and owners to accurately estimate the energy savings that can be expected if building envelope airtightness is improved.

Advances are needed in easy-to-use tools for determining the impact of air leakage to promote more energy-efficient and durable building envelope design. Oak Ridge National Laboratory (ORNL), the National Institute of Standards and Technology (NIST), the Air Barrier Association of America (ABAA), and the US-China Clean Energy Research Center for Building Energy Efficiency (CERC BEE) partnered to develop an online energy savings calculator[1], hereinafter referred to as "the calculator" (Shrestha et al. 2016), which calculated the potential energy and costs savings estimates from building envelope air tightening for three building types in 62 cities. The updated calculator now also calculates the reduction in moisture transport from improvements in airtightness, based on pre-and post-retrofit air leakage rates for commercial buildings. The updated calculator also includes four more building types than the original calculator. This article describes the need to add moisture transfer to the calculator, the buildings included in the calculator, the calculator itself, and the procedure used to calculate moisture transfer due to air leakage that is included in the updated calculator.

PREVIOUS STUDIES

Although air leakage through building envelopes has long been recognized as a major contributor to heating and cooling loads, methods that estimate the effects of air leakage on energy consumption vary (Crawley et al. 2008; Goel et al. 2014; Gowri et al. 2009; Ng et al. 2012). Air leakage has also been identified as a significant cause of moisture damage in lightweight constructions as demonstrated by the following studies. Belleudy et al. (2015) state that airtightness has become a considerable challenge over the past few decades in creating low-energy and durable buildings. The study assesses the impact of an airtightness defect on the hygrothermal field in a ceiling section insulated with loose-fill cellulose and separating a heated indoor space from an unheated attic. The experimental and simulation studies were conducted with and without air leakage, and the results show unambiguously that even relatively limited airflow through construction elements has a substantial impact on hygrothermal fields within the building envelope. Janssen and Hens (2003) identify air leakage as a significant cause of condensation problems in lightweight roof systems in cold climates. The study points out a need to incorporate airtightness requirements in building codes and to develop and certify adequate air barrier systems. Tenwolde and Rose (1996) conclude air leakage is one of the primary moisture sources that may increase the risk of moisture problems in wood frame walls. Similarly, Armstrong et al. (2010) identify air leakage as a potential cause of moisture damage in conventional light wood frame walls with exterior insulation that has low water vapor permeability.

PROTOTYPE BUILDING MODELS USED IN THE CALCULATOR

The calculator (described in the next section) uses DOE commercial prototype building models (DOE 2019) developed by DOE in EnergyPlus[2] (Deru et al. 2011) as a standardized baseline for energy savings calculations, and in part to support the development of ANSI/ASHRAE/IES Standard 90.1, *Energy Standard for Buildings except Low-Rise Residential Buildings*. The envelope assembly and heating, ventilating, and air conditioning (HVAC) units for each of the prototypes vary based on geographical location and the version of ASHRAE Standard 90.1 with which the prototype building was modeled to comply. A scorecard of each prototype building model, provided by DOE (DOE 2019), summarizes the building descriptions, thermal zone internal loads, schedules, and other key modeling input information.

The prototype models cover 16 commercial building types that represent about 80% of commercial

[1] https://airleakage-calc.ornl.gov/#/

[2] https://energyplus.net/

buildings in the United States in 17 climate locations defined in ASHRAE/IES Standard 90.1-2013 (ASHRAE 2013). Figure 1 shows the prototype buildings as a percentage of total US commercial building floor space. These are depicted in Figure 1 by a solid green-colored bar and represent over 55% of US commercial floor space. Figure 2 shows the renderings of the seven commercial prototype building models available in the calculator. Table 1 shows the floor area, number of floors, five-sided envelope area (exposed to ambient conditions), and six-sided envelope area of the 16 commercial prototype building models.

The variables defined in these models include building envelope components, HVAC equipment types and efficiency, and occupancy schedules. As ASHRAE Standard 90.1 evolves, Pacific Northwest National Laboratory modifies these models with input from ASHRAE Standing Standard Project Committee 90.1 members and other building industry experts. Features of the building models and a detailed description of their development are provided by Goel et al. (2014) and the Building Energy Codes Program website (DOE 2019).

The selection of the included cities was based on consideration of the major metropolitan areas throughout the United States; therefore, not every state or province is represented. If a specific city of interest does not appear on the list, it is recommended that the user select a city that has similar meteorological conditions (wind, temperature, solar radiation, and rain). This is not always the city geographically closest to the target city. For example, Minneapolis (MN) is in climate zone 6A and commercial prototype building models are not available for Minneapolis; so, the models for Burlington (the representative city for climate zone 6A), along with the weather file for Minneapolis, were used to run simulations for Minneapolis. Models that represent typical commercial buildings in Canada and China are not available in the public domain; therefore, the DOE prototype building models were used in these two countries. US cities where the commercial prototype building models were available, and where the climate matched the five cities in Canada and China, were used to model the buildings in those countries.

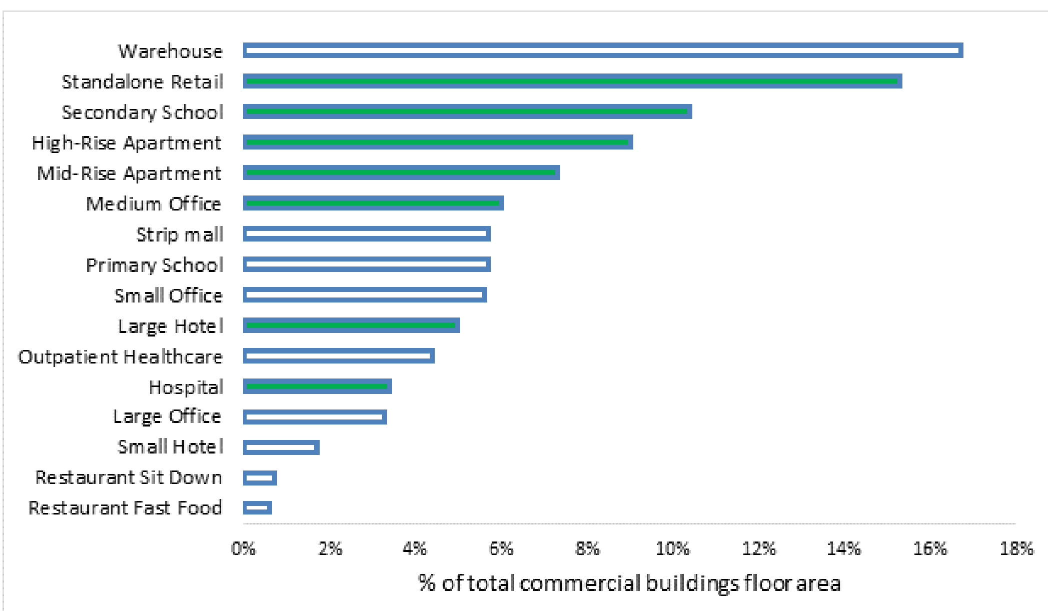

Figure 1. Prototype buildings as a percentage of total US commercial building floor space.

Table 1. Some Details of the Prototype Building Models

Building	Floor Area, m^2	Number of floors	5-sided envelope area, m^2	6-sided envelope area, m^2
Standalone Retail	2,294	1	3,471	5,765
Mid-Rise Apartment	3,131	4	2,326	3,109
Medium Office	4,980	3	3,640	5,301
High-Rise Apartment	7,837	10	4,639	5,422
Hospital	22,428	5	9,089	12,827
Large Hotel	11,346	6 + basement	6,005	7,984
Secondary School	19,593	2	17,871	29,774
Small Hotel	4,013	4	2,697	3,701
Large Office	46,321	12 + basement	15,158	18,726
Small Office	511	1	880	1,392
Outpatient Healthcare	3,804	3	2,938	4,322
Restaurant Fast Food	232	1	445	677
Restaurant Sit Down	511	1	845	1,356
Strip Mall	2,090	1	3,274	5,365
Primary School	6,871	1	9,384	16,256
Warehouse	4,598	1	7,095	11,694

Note: 1 m^2 = 10.76 ft^2

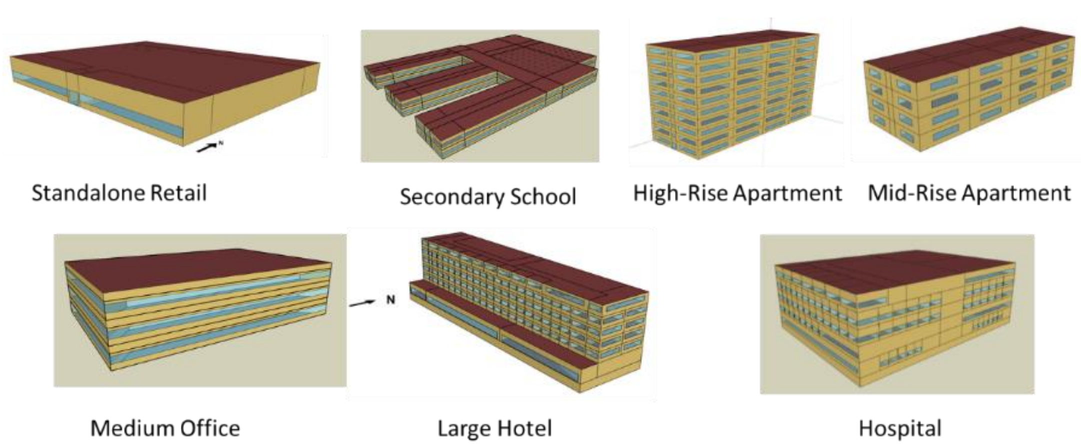

Figure 2. Renderings of the seven commercial prototype building models available in the calculator.

THE CALCULATOR

The calculator uses a database of pre-run simulation results from DOE's whole-building energy simulation software EnergyPlus for the DOE commercial prototype buildings. The main difference between the online calculator and the procedure followed in the DOE prototypes to account for infiltration (or "air leakage") is that the calculator uses CONTAM-calculated air leakage rates as inputs into EnergyPlus, whereas the prototype models make more simplified assumptions regarding air leakage. CONTAM (Dols and Polidoro 2016) is a multizone airflow and contaminant transport analysis software developed at NIST. This software considers multiple factors, such as weather conditions, envelope airtightness, and HVAC system operation, to calculate air leakage rates through building envelopes. The CONTAM-calculated hourly air leakage rates are converted into the format required by EnergyPlus using the CONTAM Results Export Tool (Polidoro 2016). EnergyPlus is then used to calculate the effects of air leakage on energy consumption and moisture transport.

Typical energy simulations tend to simplify their analyses by assuming constant air leakage rates or using simplified algorithms that can lead to less accurate energy usage estimates. Ng et al. 2018 estimate that these simplifications in the EnergyPlus models for the prototype commercial buildings lead to underestimations of average electrical and gas use for heating and cooling. Shrestha et al. 2016 show that the discrepancy in the predicted cost savings could be as high as 40%.

The moisture transport calculation in the calculator (as described below) computes the total amount of moisture that could be transported through the building envelope as a result of air leakage, assuming no loss or gain while traveling through the building envelope. It is a measure of the potential moisture source but does not quantify how much moisture is accumulating in the wall assembly. The hypothesis is that more moisture transported through the wall, the higher the likelihood it will create a durability issue and other moisture-related problems such as mold growth.

Figure 3 shows the input page of the calculator. The user input parameters are location (country, state, city), building type (one of the seven building types from the drop-down menu), floor area, building envelope leakage rate at 75 Pa (0.3-inch water column), "base case", and reduced air leakage after improving envelope airtightness, the "retrofitted building", and unit energy cost (electricity and natural gas). Location can be selected either by using drop-down menus or by using the map. Cities available in the database are highlighted with red flags on the map. Once the building type is selected, the default footprint of the corresponding prototype building is displayed. However, the user can change the floor area to their building footprint. The calculator prorates the energy savings and moisture transport results based on the floor area input by the user. Descriptions of each input variable and recommendations can be obtained by pressing the help button. The calculator allows data input in either SI or imperial units.

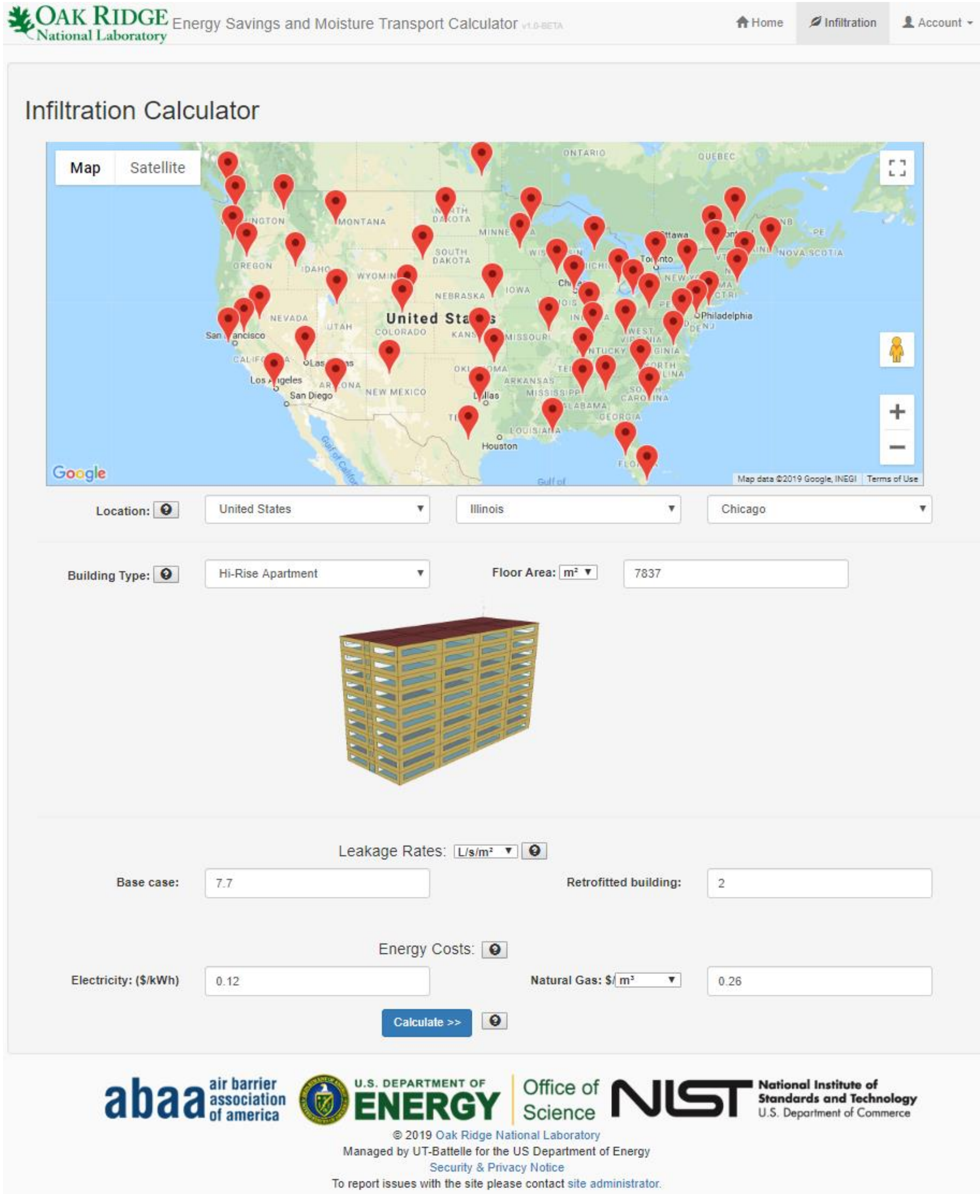

Figure 3. Input page for the Energy Savings and Moisture Transfer Calculator.

The output screen is shown in Figure 4. A summary of the user inputs is posted at the top of the page. The calculator determines the equivalent leakage area at 4 Pa (0.3-inch water column) (ELA) for the base case and the retrofitted building. This is calculated using Chapter 16 in the *ASHRAE Handbook—Fundamentals 2017*. When the ELA is calculated, all openings in the building shell are combined into an overall opening area and discharge coefficient for the building. The ELA of a building is, therefore, the area of an orifice with an assumed value of discharge coefficient that would produce the same amount of leakage as the building envelope at the reference pressure. The calculator also calculates the amount of energy saved (electricity and natural gas) and the cost savings in the currency of the country. Finally, the calculator computes the total amount of moisture that could be transported through the wall for both the base and retrofitted cases.

Table 2 compares the moisture transfer at an envelope leakage rate of 7.7 L/(s•m^2) (1.5 cubic feet per minute (CFM)/ft^2) and 1.25 L/(s•m^2) (0.25 CFM/ft^2) at 75 Pa (0.3-inch water column) for the seven building types in Chicago, including the percent reduction in the last column as a result of the increase in building envelope airtightness.

Table 2. Moisture Transfer for all Buildings at Two Different Airtightness levels at Chicago, IL

Building Type	Moisture Transfer, kg/(m^2•year)		Reduction in Moisture Transfer, kg/(m^2•year) (% reduction)
	At 7.7 L/(s•m^2)	At 1.25 L/(s•m^2)	
Standalone Retail	105.7	11.6	94.2 (89)
Mid-Rise Apartment	90.8	14.7	76.1 (84)
Medium Office	103.9	10.5	93.4 (90)
High-Rise Apartment	79.0	27.8	51.2 (65)
Hospital	73.1	12.1	61.0 (83)
Large Hotel	112.9	60.0	52.9 (47)
Secondary School	153.2	40.1	113.1 (74)

Note: 1 kg/(m^2•year) = 0.205 lb./(ft^2•year), 1 L/(s•m^2) = 0.2 CFM/ft^2.

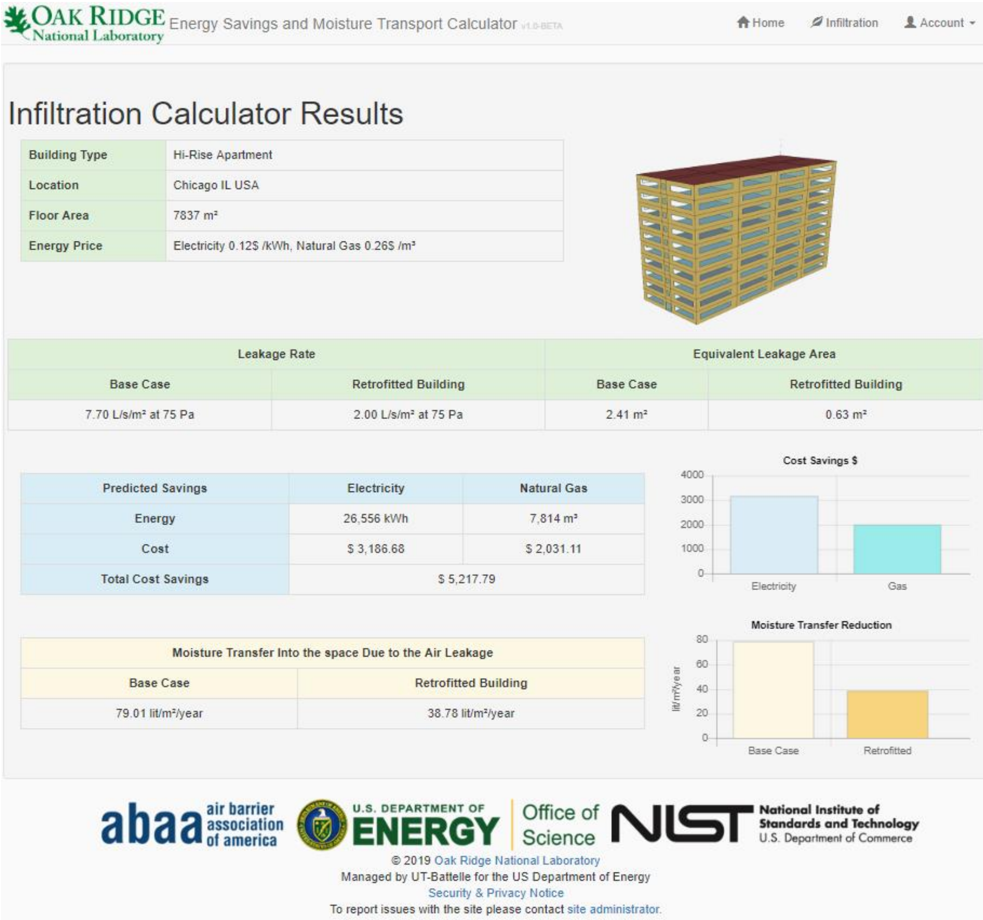

Figure 4. Output page for the Energy and Moisture Transfer Calculator.

EXAMPLE CALCULATIONS

This section presents example calculations for the DOE High-Rise Apartment prototype building model using the updated calculator. The relevant characteristics of this prototype model are based on ASHRAE 90.1-2013 and listed in Table 1. The scorecard for High-Rise Apartment building shows that this building was modeled with an air leakage rate of 1 L/(s•m^2) (0.2 CFM/ft^2) of exterior envelope area at 4.47 m/s (880 ft/min) wind speed. In the EnergyPlus model of this building, infiltration is modeled using the "ZoneInfiltration:DesignFlowRate" method that calculates infiltration using Eq. (1).

$$Infiltration = \left(I_{design}\right)\left(F_{Schedule}\right)\left[A + B\left|\left(T_{zone} - T_{odb}\right)\right| + C\left(WindSpeed\right) + D\left(WindSpeed^2\right)\right], \quad (1)$$

where

$I_{design} =$ design infiltration volume flow rate normalized by exterior surface area, m^3/(s•m^2)

$F_{schedule} =$ the schedule that modifies the design infiltration volume flow rate

T_{zone}, $T_{odb} =$ the indoor and outdoor air dry-bulb temperatures, °C

The EnergyPlus model of the High-Rise Apartment prototype building uses I_{design} = 0.57 L/(s•m^2) (0.11 CFM/ft^2), $F_{schedule}$ = always 1, coefficients *A*, *B*, and *D* = 0, and *C* = 0.224. This simplified approach to modeling infiltration in the prototype building models does not consider the effects of indoor-outdoor temperature differences, HVAC operation, or wind direction on air leakage. In contrast, the online calculator uses CONTAM to estimate air leakage rates, which considers all these factors mentioned while accounting for multizone building airflow physics.

Table 3 lists the four levels of air leakage rates that were used in the simulations of the High-Rise Apartment building. These calculations assume the air leakage is equally distributed over all exterior surfaces and include the slab and below-grade envelope area in the normalization of the air leakage rate, which is why they are referred to as 6-sided leakage values. The 6-sided value is used as the requirement in many building codes and standards; however, the CONTAM and EnergyPlus models assume no air leakage through any part of the exterior envelope that is not exposed to ambient air. The baseline value in Table 3 was calculated using the average building envelope airtightness for commercial buildings reported by Emmerich et al. 2005, 9 L/(s•m^2) (1.8 CFM/ft^2) at 75 Pa (0.3-inch water column) for a 5-sided envelope. The baseline of 7.7 L/(s•m^2) (1.5 CFM/ft^2) at 75 Pa (0.3-inch water column) was obtained by multiplying the 5-sided value by the 5-sided-to-6-sided envelope area ratio of the High-Rise Apartment building prototype. Table 3 also lists three target levels for improved airtightness at 75 Pa (0.3-inch water column): 2 L/(s•m^2) (0.4 CFM/ft^2) is the most stringent of three options and is found in the 2015 International Energy Conservation Code (IECC 2015) because it involves a blower door test, whereas the other two options are based on laboratory tests using ASTM E2357 and ASTM E2178. The airtightness required by the US Army Corps of Engineers is 1.25 L/(s•m^2) (0.25 CFM/ft^2) (USACE 2012); and 0.25 L/(s•m^2) (0.05 CFM/ft^2) is used to estimate performance at lower leakage rates. Emmerich and Persily (2014) analyzed the NIST US commercial building air leakage database and found that the 79 buildings categorized as having air barriers had an average 6-sided leakage of 1.39 L/(s•m^2) (0.27 CFM/ft^2) at 75 Pa (0.3-inch water column), which was 70% below the average leakage rate of the 290 buildings without air barriers (i.e., 4.33 L/(s•m^2) (0.85 CFM/ft^2) at 75 Pa (0.3-inch water column)); the former rate is similar to the second target level above. Zhivov (2013) reported the average 6-sided leakage for a set of 285 new and retrofitted military buildings constructed to the USACE specifications to be 0.9 L/(s•m^2) (0.18 CFM/ft^2).

Table 3. Assumed 6-Sided Building Envelope Airtightness Levels for the High-Rise Apartment

Case	Air Leakage Rate at 75 Pa (0.3-inch water column), L/(s•m^2) (CFM/ft^2)	Source
Baseline	7.7 (1.5)	Emmerich et al (2005)
1	2.0 (0.39)	IECC (2015)
2	1.25 (0.25)	USACE (2012)
3	0.25 (0.05)	

The annual total amount of moisture that is transported through the building envelope due to air leakage (M_W) is calculated using Eq. (2).

$$M_W = \sum_{i=1}^{n}\sum_{h=1}^{8760} \dot{m}_{a_{i,h}} W_h \,, \tag{2}$$

where

$\dot{m}_{a_{i,h}}$ = hourly mass flow rate due to air leakage for each zone

W_h = hourly humidity ratio of the outdoor air

i = zone number

h = hour of the year

n = number of zones (e.g., the High-Rise Apartment building model has 90 zones)

Figure 5 shows the annual moisture transfer through the building envelope due to air leakage at four envelope airtightness levels for four cities (Miami, FL; Chicago, IL; Phoenix, AZ; and Winnipeg, Canada) for the High-Rise Apartment building. These cities cover the range in annual moisture transfer for all cities included in the calculator. Figure 5 also shows the quadratic regression equations for each city and the coefficients of determination for the regression equation. Similar equations were derived for each city and used to calculate the moisture transfer as a function of building envelope airtightness for each building type. For the High-Rise Apartment building, the annual moisture transfer at a building envelope leakage rate of 7.7 L/(s•m^2) (1.5 CFM/ft^2) is 546, 367, 288, and 175 metric tons (1.2e+6, 8.1e+5, 6.3e+5, and 3.9e+5 lbs.) (118, 79, 62, and 38 kg/m^2 (24.2, 16.2, 12.7, and 7.8 lbs./ft^2) of exterior envelope area) for Miami, Chicago, Winnipeg, and Albuquerque, respectively.

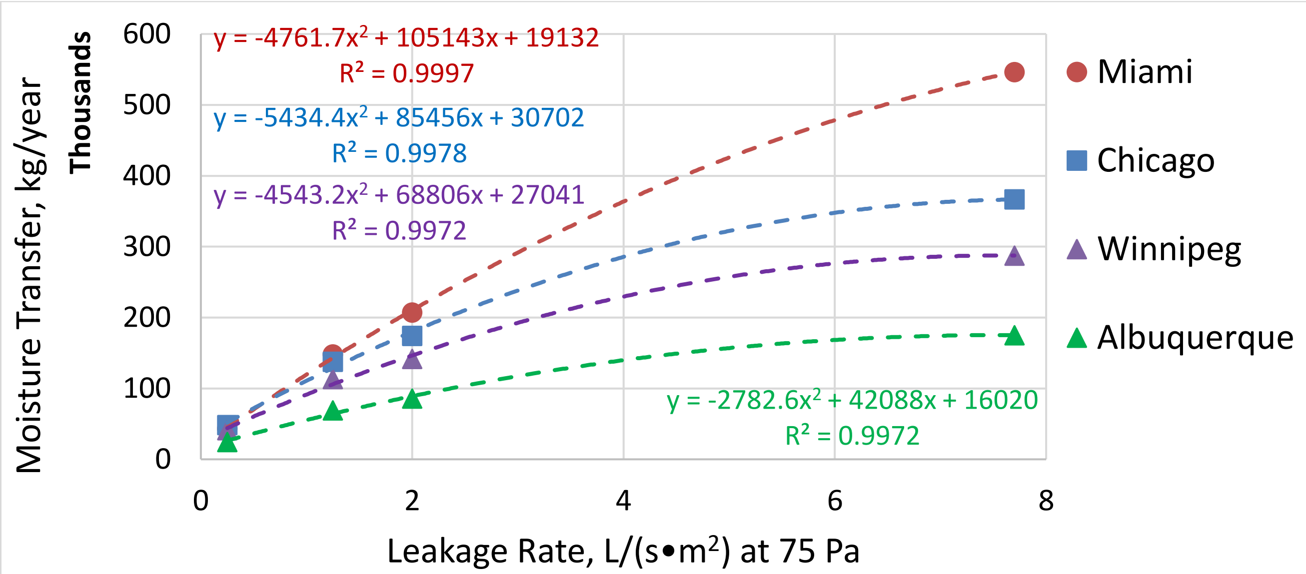

Figure 5. Annual moisture transfer through the building envelope due to air leakage at various envelope airtightness and locations. Note: 1 kg = 2.2 lb., 1 L/(s•m^2) = 0.2 CFM/ft^2, 75 Pa = 0.3-inch water column.

SUMMARY

In 2016–2017, ORNL, NIST, the ABAA, and the CERC BEE collaborated to develop an online calculator that uses the simulation results of the whole building energy simulation tool EnergyPlus and the multizone airflow simulation tool CONTAM. In 2018–2019, the calculator was expanded to add moisture transfer calculations because air leakage through the building envelope can have a significant impact on the amount of moisture transfer. Four more commercial building types were also added to the existing database of three building types. This paper describes the procedure used to calculate moisture transfer due to air leakage. This paper supplements Shrestha et al. 2016, which describes the calculation of energy savings due to the increase in envelope airtightness.

The procedure used in the online energy savings and moisture transfer calculator is different from other methods commonly used in energy analysis in that it uses hourly air leakage rates that are estimated by considering key variables such as building leakage rate, weather conditions, and HVAC operation. The calculator provides energy and costs savings and reduction in moisture transfer as a function of building envelope airtightness for the DOE commercial prototype buildings in 52 cities in the United States, five cities in Canada, and five cities in China. To demonstrate the moisture transfer calculations, the paper presents an example of how annual moisture transfer at an envelope leakage rate of 7.7 L/(s•m^2) (1.5 CFM/ft^2) at 75 Pa (0.3-inch water column) could be reduced by between 47% and 90% if the envelope leakage rate were reduced to 1.25 L/(s•m^2) (0.25 CFM/ft^2) at 75 Pa (0.3-inch water column) in the seven building types in Chicago.

The calculator is a powerful, credible, and easy-to-use tool that designers and contractors can utilize to estimate the benefits of reducing air leakage. These benefits include energy and cost savings in addition to a reduction in moisture transfer through the building envelope, as well as indoor air quality benefits not analyzed in this paper.

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