Impact of Infiltration on Heating and Cooling Loads in U.S. Office Buildings

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ABSTRACT

The energy use in commercial buildings due to infiltration has received little attention in the United States. However, as improvements have been made in insulation, windows, etc., the relative importance of these airflows has increased. Previous work at NIST described a research plan to quantify and assess opportunities to reduce the energy and indoor air quality impacts of building envelope leakage and poor ventilation system control in office buildings (Emmerich et al. 1995). It included an initial estimate,of the energy impacts but also concluded that improved estimates would require the development of a simulation approach that couples a multizone airflow model with a building thermal analysis program.

McDowell et al. (2003) describes the incorporation of the AIRNET airflow model (the airflow simulation portion of the CONTAM multizone indoor air quality (IAQ) modeling program) into the TRNSYS energy simulation program as an approach to meet this need. The resulting integrated simulation tool was used to estimate the energy usage of 25 buildings representing the U.S. office building stock over a range of infiltration and ventilation conditions. This paper presents simulation results including infiltration rates and their associated heating and cooling loads with an emphasis on the results for the buildings representing recent construction. The new method has resulted in estimates that that infiltration is responsible for 33 % of the total heating energy use but saves 3.3 % of the total cooling energy use in U. S. office buildings.

KEYWORDS

Airtightness, commercial buildings, energy efficiency, infiltration, ventilation

INTRODUCTION

Despite common assumptions that envelope air leakage is not significant in office and other commercial buildings, measurements have shown that these buildings are leakier than commonly believed (Persily 1998). Infiltration in commercial buildings can have many negative consequences, including reduced thermal comfort, interference with the proper operation of mechanical ventilation systems, degraded indoor air quality (IAQ), moisture damage of building envelope components and increased energy consumption. Emmerich and Persily (1998) estimated the energy impact of infiltration and ventilation using a non-coupled method of multi-zone airflow modeling and a bin method of energy calculation. However, based on the need for a better estimate to evaluate the cost effectiveness of such measures and to justify envelope airtightness requirements, a coupled multi-zone airflow and thermal simulation method was developed to determine these improved estimates. In this method the multizone airflow model CONTAM was coupled with the building energy model TRNSYS. To study the national impacts of infiltration and ventilation rates on the energy usage of buildings, it was necessary to conduct simulations of airflow and energy usage for a set of different building types and locations. The sources for the building set were two studies completed by the Pacific Northwest Laboratory (PNL) describing 25 buildings representing the commercial office building stock of the United States (Briggs et al. 1987 and Crawley et al. 1992).

METHOD

Simulation Tool

McDowell et al. (2003) describes the details of the coupling of the CONTAM and TRNSYS simulation tools used for this study. CONTAM is a multi-zone airflow and contaminant dispersal program that contains an updated version of the AIRNET model (Walton 1989) and a graphical interface for data input and display. The latest publicly available version of CONTAM is CONTAMW 2.4 (Walton and Dols 2005). The multi-zone approach is implemented by constructing a network of elements describing the flow paths (ducts, doors, windows, cracks, etc.) between the zones of a building. The network nodes represent the zones, each of which are modeled at a uniform temperature and pollutant concentration. The pressures vary hydrostatically, so the zone pressure values are a function of the elevation within the zone. The network of equations is then solved at each time step of the simulation.

TRNSYS (Klein 2000) is a transient system simulation program with a modular structure that is a collection of energy system component models grouped around a simulation engine. The simulation engine provides the capability of interconnecting system components in any desired manner, solving differential equations, and facilitating inputs and outputs. The TRNSYS multi-zone building thermal model (called Type 56) includes heat transfer by conduction, convection and radiation, heat gains due to the presence of occupants and equipment, and the storage of heat in the room air and building mass.

Buildings

PNL categorized the U.S. office building stock using a statistically valid sample of the nation’s office building sector known as the Commercial Building Energy Consumption Survey (CBECS) [EIA 1986, 1989]. The categories were developed using a statistical technique known as cluster analysis based on attributes such as size, age and location. Twenty buildings representing the existing building stock as of 1979 were described by Briggs et al. (1987) and five buildings representing expected construction between 1980 and 1995 were described by Crawley et al. (1992). Emmerich and Persily (1998) examined the 1995 CBECS data (EIA 1997) and found that the projected construction was highly accurate in terms of geographic representation although total new floor space was about 14 % less than expected. PNL used the DOE2 program to simulate the energy use of the buildings (Curtis et al. 1984). The assumptions used in determining the DOE2 input parameters are discussed in detail in the PNL project report. A summary of the buildings with some key modeling parameters is shown in Table 1. Other simulation details are discussed in McDowell et al. (2003).

Table 1
Summary of Modeled Office Building Characteristics

No.	Floor Area (m^2)	Floors	Year	Location	Lighting load (W/m^2)	Receptacle Load (W/m^2)	Weekly Operating Hours (h)	Effective Leakage Area at 10 Pa (cm^2/m^2)
1	576	1	1939	Indianapolis, IN	22.2	7.1	83	15
2	604	3	1920	Toledo, OH	18.0	6.2	83	15
3	743	1	1954	El Paso, TX	22.5	6.9	83	10
4	929	2	1970	Washington, DC	25.4	7.5	83	7.5
5	1486	2	1969	Madison, WI	28.2	7.5	83	5
6	2044	2	1953	Lake Charles, LA	20.3	6.7	77	10
7	2601	4	1925	Des Moines, IA	18.0	6.2	77	10
8	3716	5	1908	St. Louis, MO	21.1	7.2	77	10
9	3902	2	1967	Las Vegas, NV	23.5	5.5	84	7.5
10	4274	3	1967	Salt Lake City, UT	28.0	7.6	86	5
11	13 935	6	1968	Cheyenne, WY	23.6	6.7	84	5
12	16 723	6	1918	Portland, OR	19.1	5.0	105	10
13	26 942	11	1929	Pittsburgh, PA	18.0	7.1	168	10
14	26 942	6	1948	Amarillo, TX	19.7	6.5	77	10
15	27 871	12	1966	Raleigh, NC	21.8	7.3	168	5
16	28 800	10	1964	Fort Worth, TX	23.1	6.6	105	5
17	53 884	19	1965	Minneapolis, MN	24.8	6.8	105	3.33
18	67 819	10	1957	Boston, MA	29.7	9.6	86	5
19	68 748	28	1967	New York, NY	26.5	8.1	102	3.33
20	230 399	45	1971	Los Angeles, CA	25.5	8.4	102	3.33
21	1022	2	1986	Greensboro, NC	18.5	7.5	77	5
22	1208	2	1986	Tucson, AZ	18.5	6.2	84	5
23	1579	2	1986	Scranton, PA	18.5	7.5	77	5
24	38 090	9	1986	Pittsburgh, PA	16.1	8.3	102	3.33
25	46 452	14	1986	Savannah, GA	16.1	5.8	102	3.33

Envelope Airtightness

The envelope airtightness values were based on an examination of the limited data that exist for U.S. office buildings from fan pressurization tests (Persily 1998). The airtightness values in the Persily paper ranged from about 1 cm^2 of effective leakage area per m^2 of wall area at 10 Pa to about 40 cm^2/m^2. The mean value for all 25 U.S. office buildings in that dataset is about 9 cm^2/m^2. These data were analyzed for relationships of airtightness to building age and wall construction, but essentially no correlation was seen. The only relationship that was observed was that taller buildings (more than 15 stories), tended to have tighter envelopes, while shorter buildings ranged from tight to loose.

Based on this data set and engineering judgment, the airtightness values for the 25 simulated buildings were determined along the following guidelines. While the published airtightness data do not necessarily support these assumptions, it was determined that some credit needed to be given for newer buildings, modern double-glazed windows, and tall buildings. Therefore, buildings constructed prior to about 1965, with single-glazed windows (often wood framed), were assumed to have a leakage value of 10 cm^2/m^2. Buildings built around 1965 or later, still with single-glazed windows, were set at 7.5 cm^2/m^2. Buildings of the same vintage with double-glazed windows were assumed to have a leakage value of 5 cm^2/m^2. Recent buildings of about 10 stories or more, with double-glazed windows, were assumed to have a leakage value of 3.33 cm^2/m^2. Table 1 includes the envelope leakage values for all 25 buildings. The wall leakage was distributed vertically on each building level, rather than represented by a single opening on each wall.

Other Issues

To study the effects of building pressurization on infiltration and energy use, the models were simulated with positive, negative, and neutral building pressures. The positive and negative building pressures were created by setting the return airflow rate 10 % lower and higher, respectively, than the supply airflow rate. For all buildings, the outdoor ventilation rate modeled was 5 L/s per person. As a baseline case for comparison, all buildings were also simulated with zero infiltration.

The simulation models did not include detailed equipment models so all results are presented in terms of the zone heating and cooling loads that must be met to maintain the thermostat setting. Since equipment was not modeled, the true impact of economizers could not be calculated. However to estimate the potential impact of economizers, an “ideal” economizer component was created which examines the zone load, the required outdoor airflow portion of the ventilation flow, and the maximum amount of supply air available to the zone and determines the maximum amount of the load, based on enthalpy, that could be met by increasing the amount of outdoor air. The PNL descriptions stated whether individual buildings had either economizer cycles or operable windows.

RESULTS

Infiltration

The simulated hourly infiltration rates for the entire year for buildings 23 and 24 are shown in Figure 1, including the pressurized, neutral, and depressurized cases for each building. Figure 1 shows substantially larger infiltration rates for the leakier, shorter building 23 (leakage of 5 cm^2/m^2) compared to the tighter, taller building 24 (leakage of 3.33 cm^2/m^2). The figure also highlights the importance of proper control of heating, ventilating, and air-conditioning (HVAC) system flows as seen in the significant differences in infiltration rates depending on pressurization. For the pressurized cases, the infiltration rates are at or near zero during most hours of system operation. The infiltration rates are moderately higher for the neutral pressure case but extremely high for the depressurized case as the rates are driven by the excess HVAC system return flow.

Table 2 summarizes the calculated annual average infiltration rates for all 25 buildings including all three pressurization cases and the averages when the systems are on and off. The overall annual average infiltration for positive pressurization cases ranges from 0.025 h^{-1} to 0.55 h^{-1} with an average of 0.12 h^{-1}. For negative pressurization cases, the average infiltration rates increase and range from 0.18 h^{-1} to 0.74 h^{-1} with an average of 0.35 h^{-1}. The neutral pressure cases fall in between.

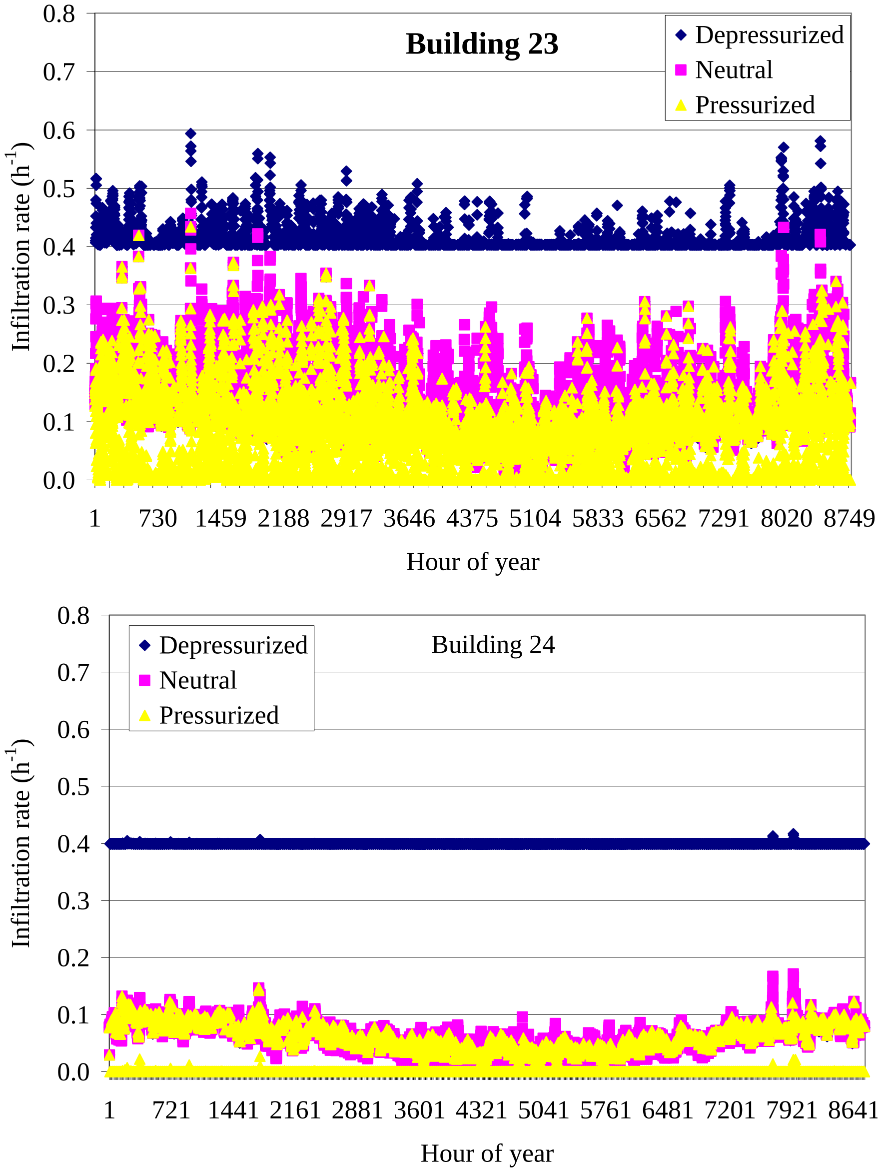

Figure 1 Hourly infiltration rates for Buildings 23 and 24

TABLE 2
Summary of Annual Infiltration Results (h^{-1})

Building No.	Average when system is off	Average during system operation			Average for all hours		
		Negative	Neutral	Positive	Negative	Neutral	Positive
1	0.27	0.54	0.31	0.15	0.40	0.29	0.21
2	0.57	0.91	0.70	0.52	0.74	0.64	0.55
3	0.14	0.56	0.16	0.026	0.35	0.15	0.086
4	0.14	0.45	0.12	0.013	0.29	0.13	0.076
5	0.12	0.45	0.13	0.015	0.28	0.12	0.066
6	0.16	0.48	0.20	0.066	0.31	0.18	0.12
7	0.29	0.64	0.40	0.23	0.45	0.34	0.26
8	0.22	0.47	0.22	0.085	0.34	0.22	0.16
9	0.12	0.42	0.12	0.026	0.27	0.12	0.070
10	0.10	0.40	0.10	0.015	0.25	0.10	0.057
11	0.13	0.41	0.15	0.044	0.27	0.14	0.088

Building No.	Average when system is off	Average during system operation			Average for all hours		
		Negative	Neutral	Positive	Negative	Neutral	Positive
12	0.25	0.62	0.26	0.089	0.48	0.26	0.15
13	NA	0.40	0.20	0.087	0.40	0.20	0.087
14	0.28	0.58	0.35	0.19	0.42	0.31	0.24
15	NA	0.61	0.19	0.031	0.61	0.19	0.031
16	0.2	0.56	0.22	0.05	0.42	0.21	0.11
17	0.14	0.37	0.13	0.023	0.28	0.13	0.067
18	0.12	0.39	0.12	0.071	0.26	0.12	0.095
19	0.19	0.44	0.19	0.057	0.34	0.19	0.11
20	0.13	0.40	0.12	0.006	0.29	0.12	0.056
21	0.11	0.42	0.14	0.027	0.25	0.12	0.074
22	0.10	0.26	0.10	0.033	0.18	0.10	0.067
23	0.12	0.41	0.14	0.025	0.25	0.13	0.076
24	0.063	0.40	0.058	0	0.27	0.061	0.025
25	0.075	0.40	0.081	0.003	0.27	0.079	0.031

Heating and Cooling Loads

Table 3 summarizes the predicted annual heating and cooling loads per unit floor area for all 25 buildings including both the zero infiltration case and one of the three infiltration conditions. For buildings 1, 2, 3, 6, 7, 8, 9, and 12, the infiltration case included in Table 3 is the neutral pressure case, since the system types were such that pressurization of the building would not be expected. For the remaining buildings, the case shown is the positive pressurization case. To be conservative in the estimate, the negative pressurization cases were not used for calculating the loads. Additionally, the cooling loads presented for buildings 1, 2, 3, 5, 8, 9, 11, 12, 18, 20, 23, 24, and 25 are net cooling loads obtained by subtracting the portion of the cooling that may be met by an economizer (either mechanical or operable windows) from the total cooling load.

TABLE 3

Summary of Heating and Cooling Load Results

	Annual Loads with No Infiltration (MJ/m^2)		Annual Loads with Infiltration (MJ/m^2)	
No.	Heating	Net Cooling	Heating	Net Cooling
1	398	186	530	202
2	593	134	922	146
3	80	226	100	228
4	150	311	173	301
5	112	167	135	163
6	39	353	62	377
7	236	178	388	175
8	183	213	266	221
9	25	190	34	200
10	27	283	34	264
11	24	26	45	25
12	138	30	236	29
13	179	246	229	234
14	49	205	158	160
15	33	617	32	599
16	16	431	18	417
17	33	286	67	257
18	8.8	117	15	116
19	63	311	91	284

	Annual Loads with No Infiltration (MJ/m^2)		Annual Loads with Infiltration (MJ/m^2)	
20	1.3	110	2.2	107
21	21	278	36	263
22	12	394	16	378
23	40	109	64	106
24	3.4	141	6.0	139
25	8.9	305	8.8	299

Figure 2 shows the impact of infiltration on individual building space loads as a percent of total load relative to the no infiltration case. Weighted by the floorspace represented by the buildings, infiltration is responsible for an average of 33 % of the heating load in U.S. office buildings. For cooling, infiltration can either increase or decrease the load depending on the climate, presence of economizer capability and other building factors. On average, infiltration was responsible for a 3.3 % decrease in cooling load.

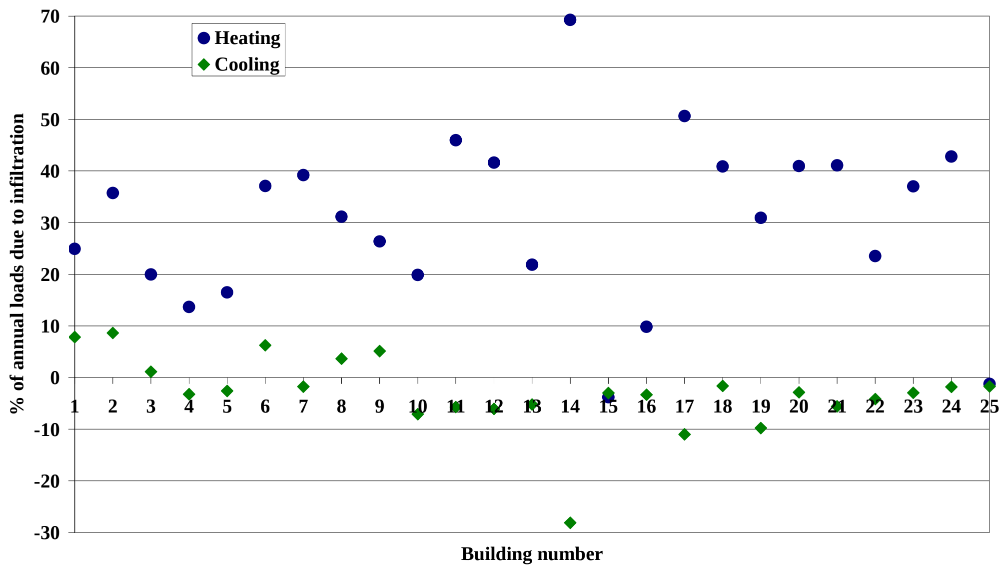

Figure 2 Percent of space loads due to infiltration

SUMMARY

A simulation study using a coupled multizone airflow and building thermal modeling tool was completed to estimate the impact of infiltration on heating and cooling loads in U.S. office buildings. These simulations did not include heating and cooling equipment models and thus represent zone loads, as opposed to energy use, and do not include fan loads. On average, the simulations found that infiltration was responsible for 33 % of the heating loads but reduced cooling loads by 3.3 %. Infiltration can either increase or decrease cooling loads depending on climate, the presence of an economizer and other building factors.

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DISCLAIMER

Certain software is identified in this paper in order to specify the procedure adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the software identified is necessarily the best available for the purpose.

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