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A Workplan to Analyze the Energy Impacts of Envelope Airtightness in Office Buildings

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Abstract

US. office buildings consume approximately 1.2 EJ (1.1 Quadrillion BTUs or Quads) of energy, 0.72 EJ (0.68 Quads) of which is associated with space heating, cooling, and ventilation. These estimates, and other analyses of energy consumption in office buildings, are based on building energy analysis programs such as DOE-2. These analyses have been helpful in identifying opportunities for energy efficiency, developing building energy efficiency standards and predicting future energy consumption levels. Although these programs contain sophisticated models of heat transfer and HVAC system performance in buildings, they are acknowledged to have shortcomings in accounting for the energy associated with building airflows, particularly infiltration of outdoor air through leaks in the building envelope. These airflows, and their dependence on weather and ventilation system operation, are more complex than the models used in these programs. The simple models of infiltration, ventilation and interzone airflows that are used in these programs do not enable the analysis of the energy consumption associated with building airflow or the impact of options that may reduce this energy consumption, such as increased envelope airtightness or better control of ventilation system airflow rates. This report describes the impact of building airflows on energy consumption in multi-zone buildings and the analysis approaches that can be used to account for the energy associated with these airflows. Plans to link a multi-zone network airflow analysis program with a building energy analysis program are discussed. An initial estimate of the energy associated with infiltration in US. office buildings, based on a simplified analysis approach, is presented. This estimate reveals that infiltration in U.S. office buildings accounts for 0.074 EJ (0.07 Quads) of space heating energy use, which is 18% of the total heating energy use, and 0.0025 EJ (0.0024 Quads) for cooling, which is 2% of the total.

Key Words: airflow modeling, building energy simulation, building technology, commercial buildings, computer simulation, HVAC systems, infiltration, ventilation

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Introduction

US office buildings consume a large amount of energy each year, a substantial portion of which is used by building heating, ventilating, and air-conditioning systems. A study prepared by Pacific Northwest Laboratories (PNL) for the Gas Research Institute (Briggs et al. 1992 and Crawley and Schliesing 1992) estimates that US office buildings consume approximately 1.2 x 1018J, or 1.2 EJ, (1.1 Quadrillion BTUs or Quads) of energy, 0.72 EJ (0.68 Quads) or 60% of which is associated with space heating, cooling, and ventilation. The PNL study was conducted to characterize in detail the energy requirements of the office building sector for use in targeting research of new gas-fueled technologies. PNL performed a statistical categorization of the existing and future national office building stock which resulted in a total of 30 prototype buildings that are intended to represent construction through 1995. Energy simulations were then performed on these buildings using the DOE-2 program (Curtis et al. 1984) to calculate annual energy use. This estimate is supported by a report published by the U.S. Department of Energy which estimates that the actual energy consumed in US office buildings in 1989 was 1.3 EJ (1.2 Quads) of which 0.62 EJ (0.58 Quads) was associated with space heating, cooling, and ventilation (EIA 1994). The DOE estimate is based on a combination of an extensive commercial building energy consumption survey (EIA 1992) and energy simulations.

Many other analyses of energy consumption in commercial buildings are based on DOE-2 or similar building energy analysis programs. These analyses have been helpful in identifying opportunities for energy efficiency, developing building energy efficiency standards and predicting future energy consumption levels. Although these programs contain sophisticated models for the heat transfer in buildings, they are acknowledged to have shortcomings in accounting for the energy associated with building airflows, particularly infiltration of outdoor air through leaks in the building envelope. Several researchers have discussed the need for improved consideration of the combined problem of building airflow and heat transfer (Axley and Grot 1989, Clarke and Hensen 1990, Kendrick 1993, Klobut 1991, Lomas 1991, Pelletret and Khodr 1990, Schneider et al. 1995 and Tuomaala and Rahola 1995). The interactions of airflow into and within buildings with heat transfer and storage in buildings and with building HVAC system operation are complex. Building thermal analysis programs and multizone airflow programs have been extensively used to examine building energy use and airflow separately. However, calculation of the combined problem has received much less attention. To date, most of the efforts at analysis of the combined problem have been focussed on the simpler case of single-family residential buildings (Melo 1986, Pelletret 1987, Fischer 1993).

Better information on the actual energy impacts of building envelope leakage and poorly controlled ventilation system airflow rates is needed to determine the cost-effectiveness of improved airtightness and system control. Mechanically ventilated commercial buildings currently experience significant amounts of envelope air leakage and poor control of ventilation system airflows. The simple models of infiltration, ventilation and interzone airflows that are used in most existing building energy analysis programs do not enable the analysis of the energy consumption associated with building airflow or the impact of options that may reduce this energy consumption, such as increased envelope airtightness or better control of ventilation system airflow rates. Research is being performed with the objective of improving building airtightness and optimizing ventilation system control in order to reduce building energy use and improve indoor air quality. However, construction of tighter buildings and implementation of better controls involves increased costs for state-of-the-art technologies and materials, and an understanding of the energy impact of these impacts is needed to justify their additional first costs.

The National Institute of Standards and Technology (NIST) is conducting a study for the US. Department of Energy (DOE) to assess the energy impacts of building airtightness and ventilation system control. In this project, NIST will perform whole building airflow and thermal analysis simulations to quantify the energy costs of airflows associated with building leakage and poor ventilation system control in large, commercial buildings. The project has three primary objectives. The first objective is to determine the percent of total energy consumption in commercial buildings due to envelope infiltration and non-design ventilation system airflow rates. The second is to determine the energy savings potential of improving building airtightness and ventilation system control in existing buildings. The third objective is to determine the energy savings potential in new construction.

This report summarizes the efforts to develop the project and the method and results of the first phase of the project. It consists of four main sections titled: Airflow and Energy Use in Office Buildings, Approaches to Combined Thermal and Airflow Analysis, Project Plan, and Initial Estimate Based on PNL Infiltration Rates. The first section discusses the building physics involved in the interaction of building airflow dynamics and thermal loads and describes some shortcomings in the treatment of airflow in building energy use studies. The second section describes the selection of the analytical tool to be used in the project, and includes a review of available analytical tools. The next section outlines the research plan including a discussion of candidate buildings for simulation and a description of the project phases. This section also includes a discussion of other applications for the simulation tool that are not part of the current project plan. The final section presents an initial estimate of the national energy impact of infiltration in office buildings.

Airflow and Energy Use in Office Buildings

The impact of building airflows on energy use in office and other commercial buildings has received only limited attention. As discussed later in this report, the consideration of the energy impacts of airflow has generally been restricted to intentional outdoor air intake through mechanical ventilation systems. Little attention has been given to unintentional infiltration through envelope leaks or to detailed representations of mechanical ventilation system airflows. The analysis of the energy impacts of building airflow has been limited, in part, because of the complexities of airflow in office buildings, which are usually mechanically ventilated and almost always must be considered as multizone systems. This section presents some background information on airflow in office buildings, how these airflows impact thermal loads, and how the interaction of airflow and energy has been addressed in previous studies of energy use in office buildings.

Airflow in office buildings

Airflow into, within, and out of office buildings is a complex phenomena. These buildings almost always behave as multizone airflow systems, meaning that the resistances to airflow between different building zones are significant relative to the resistance across the exterior envelope and that significant airflows exist between different portions of a building. In addition, most office buildings have mechanical ventilation systems that supply and remove air from these zones, adding complexity to the problem. Airflow rates in multizone systems are determined by weather conditions (air temperature, wind speed and wind direction), effects of surroundings on the exposure of the building to the wind, the temperature distribution within the building, the airflow rates to and from each zone from mechanical ventilation systems, and the airtightness of the exterior envelope and of the interior partitions between zones. The physical mechanisms that determine these airflow rates are well understood and include temperature and wind-induced pressure differences as well as the operation of mechanical ventilation equipment, however the complexity of the airflow patterns in any given building can be overwhelming.

It is generally assumed that the envelopes of modern office buildings are relatively airtight. In addition, the ventilation systems of these buildings are generally designed to operate with an excess of outdoor air intake over exhaust airflow out of the building such that the building is at a higher pressure than outdoors and the infiltration of outdoor air into the building through leaks in the building envelope is minimized or eliminated. When performing analyses of energy use in office buildings, these assumptions often translate into infiltration rates of zero. However, field studies of office buildings have shown that these assumptions are not necessarily valid. While the exterior envelopes of office buildings have generally been assumed to be fairly airtight, the results of pressurization testing of the exterior envelopes have shown that the envelope airtightness of these buildings is similar to that of leaky residential buildings in terms of leakage area per unit wall area (Persily and Grot 1986, Shaw and Reardon 1995, Tamura and Shaw 1976). In addition, ventilation system airflow rates do not necessarily correspond to their design values, which can alter the intended pressurization of these buildings (Persily and Norford 1987). Schliesing et al. (1993) summarizes literature reports that describe problems with HVAC system maintenance and operation such as stuck dampers, blocked return vents, and disconnected controls. Leaky buildings and imperfect control of ventilation system airflow rates can combine to yield significant air infiltration rates, on the order of one-half to one air change per hour as opposed to rates of about one-tenth as are often assumed to exist in the buildings. In addition to increased infiltration rates, ventilation system airflow rates that differ significantly from their design values can result in unintended airflows between different zones of a building. These airflows can be undesirable from the perspectives of energy, thermal comfort and indoor air quality.

Tracer gas measurements of air infiltration rates in office buildings have shown that the assumption of low infiltration rates, upon which the design, operation, and energy analysis of such buildings are based. are often false. Grot and Persily (1986) reported air infiltration rates in eight federal office buildings constructed since 1976 that varied from about 0.2 to 0.7 ach. Persily and Norford (1987) reported measurements of total air change, infiltration and outdoor air intake under a range of weather conditions in a three-story office building constructed in 1984. The infiltration rates in this building were generally on the same order of magnitude as the intentional outdoor air intake rates and were strongly dependent on the mode of outdoor air intake control.

The existence of significant air infiltration rates in office buildings can have a number of negative consequences. These include increased energy consumption, thermal comfort problems, the degradation of indoor air quality because the infiltrating air in not filtered, the increased potential for moisture damage, and the degradation of envelope materials and interior furnishings. While an assumption that infiltration does not exist, or the rates are very low, in office buildings is not necessarily correct, it is not clear whether the associated assumption of negligible energy consumption due to infiltration is appropriate or not. In order to answer this question, the energy use associated with heating or cooling this infiltrating air must be determined.

Interaction of building airflow and thermal loads

Building heating and cooling loads depend on the heat gains and losses through the building envelope, heat and moisture gains due to internal sources such as people and equipment, storage of heat within the building, and the transfer of heat between the zones of the building. The physical phenomena involved include transient conduction, radiative exchange (both longwave and shortwave), convection from surfaces (both internal and external), and bulk convection (due to infiltration and interzone airflows in a multizone building). Most of these phenomena can be modeled with available simulation packages such as DOE-2 (Curtis 1984), TRNSYS (Klein 1992), and HVACSIM+ (Park 1986).

Assessing the energy impacts of building airflows requires consideration of the mechanisms and factors that induce these airflows and of the interactions of building airflows with other heat transfer processes. First, there is the energy required to heat or cool the infiltrating air. However, the energy liability associated with infiltration is not always straightforward; it can depend strongly on the type of HVAC system and the strategy employed to control this system. For very low and very high outdoor air temperatures, infiltrating outdoor air will add to the space conditioning load by an amount proportional to the indoor-outdoor air temperature difference and to the air infiltration rate. During mild weather conditions, infiltration can cool the building, thereby decreasing the cooling load. If the infiltrating airflow is induced by building depressurization caused by inadequate outdoor air intake, then the infiltration air is simply replacing ventilation air and does not necessarily entail an energy liability. However, ventilating a building through infiltration as opposed to mechanical ventilation may involve negative consequences in terms of indoor air quality.

Additional interactions between airflow and thermal loads are associated with the indoor air temperature. Indoor air temperatures are important factors in determining air infiltration rates due to the stack effect. In addition, the indoor temperature impacts the operation of the HVAC system, for example through the modulation of supply airflow rates in VAV systems, which in turn affect building pressures and therefore infiltration rates. The resultant infiltration rates are important determinants of thermal loads, and therefore impact the interior air temperatures themselves.

Consideration of airflow in building energy use studies

Past efforts analyzing the annual energy use in large buildings have suffered from two main shortcomings regarding the impacts of building airflows. The first is the use of simplified mathematical models of airflow in buildings. For example, an analysis of the energy impact of a demand-controlled ventilation system used a multizone building but assumed values for infiltration and interzone flows that depended only on operation of the HVAC system (Emmerich 1993). Several studies on the energy impacts of increasing outdoor air intake in commercial buildings have used a simulation program which, at best, uses a simple single-zone infiltration model considering wind-dependence (Eto 1990, Eto and Meyer 1988, Steele and Brown 1990, and Zmeureanu et al. 1992). A detailed analysis of the energy use in a modern office building assumed constant values for building infiltration that depended only on whether the building was occupied (Norford 1984). These are just a few examples of the consideration of airflow in building energy use studies in the past. Numerous examples of building energy use studies with simplified airflow models may be found in the literature.

Another shortcoming has been in the assumed values of infiltration and ventilation rates in large modern office buildings. Past analyses of energy use in such buildings have generally assumed that only small amounts of air infiltrate the building through the envelope due to a combination of tight construction and a positive pressure maintained inside the building by the mechanical ventilation system(s). Since low infiltration rates are assumed, the total building air exchange rate is assumed to be dominated by outdoor air intake through the mechanical ventilation system. The mechanical ventilation systems are assumed to provide a minimum level of outdoor air intake, keep the supply fan airflow rate sufficiently above the return airflow rate to pressurize the building, and properly adjust the positions of system dampers for economizer cycle operation.

The modeling of airflow in building energy use studies in the past has neglected important factors and has ignored the reality of infiltration and ventilation system operation in office buildings. The current state-of-the-art in whole building airflow modeling requires the use of multizone airflow models. These models are discussed further in the next section.

No reports have been found in the literature of studies analyzing either the energy impacts of poor building airtightness and ventilation system control or the energy savings potential of measures to correct these conditions. Therefore, the expenses which can be justified for reducing infiltration and improving ventilation system control are not known.

Approaches to Combined Thermal and Airflow Analysis

This section describes existing approaches for analyzing the energy impact of infiltration and ventilation system airflows, discusses shortcomings of these approaches, and discusses better ways to account for the complexity of airflow-related energy in multizone buildings.

The discussion is divided into modeling and simulation tools as the selection of an analysis approach requires consideration of both. The distinction between modeling and simulation is described by Jeandel and Palero (1991). Modeling includes the choice, creation, and validation of models, where the term model is used to describe a mathematical representation of the physical phenomena involved. The mathematical representation must be adequate to yield results that will achieve the project objectives, and therefore, the choice of a model follows directly from the definition of the problem. Simulation includes choice or creation of the simulation tool and the simulations to be performed. Beyond incorporation of the previously selected model(s), the selection of the simulation tool will depend on less scientific reasoning. Reasons for choosing a specific simulation tool may include familiarity or previous experience, ease of use, input/output processing capabilities or other special features, and availability of support.

Modelling

The objective of the project is to examine, on a national scale, the energy impacts of the airflows associated with building envelope leakage and poor ventilation system control. The criteria by which the results will be measured is the annual energy use to operate a building. The energy use due to these problems must be calculated accurately enough to evaluate the difference between different levels of building airtightness and ventilation system control.

The intent of this project is to apply available models rather than create new models. The choices of available models range in level of detail from simple regression equations to detailed room airflow modelling and include the following;

1. Regression equation models
2. Room airflow models
3. Building energy balance (with multizone airflow) models
4. Integrated airflow and thermal element models

The first two types of available models can be readily dismissed from consideration for the analysis approach. Regression equation models are often the results of multiple parametric runs of a more powerful model which have been reduced to simple relationships (Clarke 1985). Available regression equation models (such as degree day methods) do not incorporate the level of detail necessary to provide results capable of accurately determining the difference in building energy use due to building airflows.

Even as regression equation models are not detailed enough, room airflow models are too detailed. Room airflow modelling applies the principles of conservation of momentum, mass, and energy through the use of a computational fluid dynamics (CFD) program. This type of model could provide a detailed analysis of the coupled airflow and heat transfer processes that occur in a building. A recent review of the application of CFD programs to room airflow modeling by the International Energy Agency is reported by Moser (1992). However, modeling an entire building is beyond the capability of current computers for even a steady state condition and would require a massive effort for data input and results analysis.

In general, building energy balance models provide a level of detail between that of the regression and CFD models. As the name implies, this type of model involves applying an energy balance to the building. This category of models can be further broken down depending on the numerical implementation of the energy balance. Two different implementations include the response function model and the finite difference model.

Response function models divide a building into large thermal zones. For a given zone, energy balance equations are written for the entire energy field. The solution of this set of equations when subjected to a unit excitation function gives the corresponding unit response function (URF). The complete URF set is determined by repeating for each possible excitation. This method provides a specific analytical solution to the zonal energy balances. The transfer function method is the baseline procedure adopted by the American Society of Heating, Refrigerating and Air-Conditioning Engineers and is considered one of the most accurate methods of calculating building heating and cooling loads (McQuiston and Spitler 1992). A thorough description of this type of model may be found in Clarke (1985) and McQuiston and Spitler (1992).

Clarke (1985) also describes the finite difference method of building energy calculation. In this method, a building is divided into many small volumes and energy balance equations are written for each volume. Numerical solution techniques are used to solve these equations. Clarke describes this method as general in concept with better physical insight, however, he states that the quality of the results depends on the care taken in implementing the model.

These energy balance models do not directly incorporate the consideration of the interactions of the airflows and thermal processes discussed in the definition of the problem. Accurately modeling the airflow in large commercial buildings requires use of a multizone airflow model. A multizone airflow model applies a mass balance to a network of elements describing the flow paths (HVAC ducts, doors, windows, cracks, etc.) between the zones of a building. The network nodes represent the zones which are modeled at a uniform temperature. Walton (1989) discusses multizone airflow modeling in detail.

The fourth method, integrated airflow and thermal element modeling, involves a direct coupling of the airflow and thermal modeling equations. Axley (1988) develops a modeling approach to the thermal analysis of buildings that is analogous to the method of multizone airflow modeling described above. In this method, the building is defined as discrete thermal elements for which equations describing the thermal transport processes are written. These elemental equations are then assembled into a matrix which is solved by finite element techniques. Axley (1989) describes the integrated coupling of this element based thermal analysis model with the airflow analysis model. This integrated model is described as quasi-dynamic as it combines a dynamic thermal solution procedure and a steady airflow solution procedure.

Three of the modelling options discussed above (multizone airflow modelling combined with response function, finite difference or element assembly thermal modelling) adequately describe the physical phenomena involved and could provide results to meet the problem objective. The specific model and implementation chosen are discussed below.

In general, models need to be validated to determine the quality of the model. Jeandel and Palero (1991) describes four types of model validation including: numerical validation, analytical simulation, quantitative validation, and experimental validation. These types of validation apply to individual models as well as coupled systems of models. No new models will be created in this project and the individual models to be used have been subjected to various types of validation in the past. However, new combinations of the models may be used and these combinations should be subjected to some level of validation.

Simulation

The multizone airflow models discussed above have been implemented in many forms. Walton (1989) described one of the first widely available multizone airflow simulation programs called AIRNET. Many other multizone airflow programs have been written since AIRNET, and Feustel (1991) describes a survey of multizone airflow programs. One particular multizone airflow program which deserves specific mention is COMIS (Feustel 1990). COMIS was written as part of an international effort of airflow modelling specialists sponsored by the International Energy Agency. It is based on the same multizone airflow model as AIRNET and shares many of the same simulating capabilities. The latest available version of the AIRNET is included in the multizone airflow and contaminant dispersal program CONTAM94 (Walton and Emmerich 1994). CONTAM94 combines the best available algorithms for modeling the airflow and contaminant dispersal in multizone buildings with a unique graphic interface for data input and display.

Response function building energy models have been implemented within many available simulation tools including TRNSYS (Klein 1992), HVACSIM+ (Park 1986), and DOE-2 (Curtis 1984). None of these tools incorporates a multizone airflow model at this time. Although these simulation tools implement the same basic model, there are some important differences between these tools to consider.

TRNSYS and HVACSIM+ are both modular simulation tools which include a central simulation 'engine' which provides solution routines and performs various output and input data processing tasks and modules which are implementations of equipment and building energy models. Both of these tools are very flexible, allowing the user to select the needed modules from the provided ones and to add needed capabilities by writing new modules. One significant difference is the time scale for which they were intended to operate. HVACSIM+ was intended to be used for detailed and accurate simulation of the control systems of building HVAC equipment which may require time steps on the order of seconds or minutes. As a result, performing a yearlong simulation becomes a large computing effort. TRNSYS was originally intended for simulating solar energy systems, many of which can be accurately simulated with time steps on the order of hours with year-long simulations being routine. It is anticipated that such time steps will be appropriate for this project.

While employing an implementation of the same model, DOE-2 was not designed as a modular program. As such, DOE-2 is not easily modified by the user and is generally limited to the currently available capabilities. No multizone airflow model is incorporated within DOE-2 and adding one would require significant effort. Modera (1992) reports on a study which considered the interactions between multizone airflow and building thermal processes by combining DOE-2 with COMIS (Feustel 1990) via a third program called DUCTSIM. This program was written to pass information between DOE-2 and COMIS but is not a general coupling and would need to be rewritten for each building simulated.

One available implementation of the finite difference building energy model is the simulation tool ESP (Clarke 1988). ESP is a modular simulation tool similar in some respects to TRNSYS and HVACSIM+. ESPmfs, an implementation of a multizone airflow model based on AIRNET, was added as an ESP module by Hensen (1990).

An available implementation of the integrated element (or element assembly) models is the program TFCD (Klobut 1991). TFCD is capable of simultaneously calculating airflows, air temperatures, and contaminant concentrations in a multizone building. However, this simulation tool has a limited number of elements and does not yet have the needed capability of modeling the HVAC system equipment and is not yet intended to be used for annual energy use calculations. Tuomaala and Rahola (1995) reported the development of a program called BUS with similar limitations.

One additional simulation program that combines a building thermal analysis model with a multizone airflow modelling capabilities should be mentioned. The HOUSE-II model (Fischer 1993) incorporates the appropriate models to study the physical phenomena discussed above. However, this program was designed specifically for residential applications and as such is not appropriate for the project objective.

The two most promising alternatives for simulation tools for this project are (i) TRNSYS with a new module based on AIRNET and (ii) ESP. Both of these tools would provide the capabilities needed to achieve the project objective. ESP has the advantage of not requiring any simulation tool development but would require learning to use the simulation environment and the finite difference energy model. Selection of TRNSYS requires developing a new module. While not trivial, this task is made easier due to familiarity within NIST with the TRNSYS simulation environment and response function building model and with the AIRNET multizone airflow model. Selection of this option also has the advantages of making a multizone airflow module available to TRNSYS users and of taking advantage of the convenient graphic interface of CONTAM94 for preparing data input to the airflow module. Dorer and Weber (1994) recently reported the results of a similar effort in which TRNSYS and COMIS were combined to study passive cooling and natural facade driven ventilation in a school building. Due to the similarities between AIRNET and COMIS, discussed above, this effort indicates the feasibility of the proposed option of creating a TRNSYS module based on AIRNET.

Project Plan

This section outlines the research plan developed to examine the national energy impacts of infiltration and ventilation airflows in office buildings. It includes a discussion of candidate buildings for simulation and a description of the project phases. This section also includes a discussion of other applications for the simulation tool that are not part of the current project.

Candidate Buildings

The commercial building stock in the United States contains a great variety of buildings in terms of size, location, design features, and operation. To estimate the energy impacts on this population requires selecting some representative set of buildings to simulate and then extrapolating the results to the population as a whole. To save the effort required to define a set of buildings for the study, the literature was reviewed for reports of sets of prototypical commercial buildings which could be used.

Briggs et al. (1987) describes a categorization of the office building stock derived from a statistically valid sample of the nation's office building sector. This effort developed 20 office building categories based on a statistical technique known as cluster analysis. Categories or clusters were defined on the basis of physical attributes such as size, age, location, and building energy loads. Crawley 1992 added to the categorization of the building stock by specifying 10 additional buildings representing recent and future construction. However, the 10 buildings defined to represent recent (circa 1986) and future (circa 1995) construction are essentially only 5 buildings with minor differences between the recent and future prototypes. Therefore, the building set could be condensed to 25 buildings. These prototype descriptions will be reviewed further to determine their appropriateness for use in this study. It may be necessary to further restrict the cases considered based on the available project resources.

Huang et al. (1991) describes a set of 481 prototypical buildings used to develop a building loads database for assessing cogeneration market potential. The buildings simulated included offices, hospitals, schools, prisons, hotels, restaurants, supermarkets, apartments, and retail stores specified to characterize the commercial building stock in 20 urban market areas. This building set is more elaborate than required for this study, however, some subset of the buildings may be appropriate. In addition to developing a prototypical building set, Huang conducted an extensive review of other studies that either defined average building conditions or developed prototype buildings. Many of these studies developed prototypical buildings specific for one region of the country and were not intended to be representative of the national building stock.

Another study describing a set of prototypical buildings for a specific region but not included in Huang's review is reported by UIC (1989). This study develops 10 commercial building prototypes representative of typical characteristics of the building stock in the Bonneville Power Administration's service area.

Included in Huang's review but worthy of separate mention is a set of prototypical buildings developed by Pacific Northwest Laboratories to support commercial building energy standard research (PNL 1983). The building prototypes included offices (small, medium, and large), retail stores (small and large), an apartment, a hotel, a warehouse, a church, and a school based on real buildings judged to be typical for their type. Although the buildings have been simulated in many locations, no statistical representation of the building stock was made.

Friedrich (1994) described another methodology to characterize energy use in the national commercial building stock. The method uses a three-story building prototype with characteristics for each US. census region based on Commercial Building Energy Consumption Survey (CBECS) data (EIA 1992) and using loads specific for the building type (e.g. office). Simulations are then performed for representative climate zones identified by Hadley and Jarnigan (1993) to find the annual energy use intensity (EUI) for each building thermal zone. The energy use estimates are then scaled based on CBECS data on building construction, size, and fuel type distribution. However, there is no simple way to correlate the identified climate zones with the CBECS data and some type of averaging across census regions is necessary.

Project Phases

Phase 1. Initial estimate based on PNL infiltration rates

The objective of this phase is to make a rough estimate of the national impact of infiltration loads. This estimate is not intended to be very reliable but simply to indicate the magnitude of the energy used, in order to demonstrate the importance of investigating the problem. This phase has been completed and a summary of the method and the results are described in this report in the section called Initial Estimate Based on PNL Infiltration Rates. A detailed description of the initial estimate is included in Appendix A.

Phase 2. Improved estimate based on AIRNET infiltration rates

This project phase will improve on the initial estimate by using airflows from multizone airflow simulations. Airflow simulations will be performed for each of the prototype buildings under a range of indoor - outdoor temperature differences and wind speeds to determine whole building air change rates under these weather conditions. These simulations will be performed both with the HVAC systems off and on. Then, infiltration heating and cooling loads will be calculated as in Phase 1 except the calculated air change rates will be used in place of the PNL infiltration rates. The building set may also be expanded to include other prototypes of other commercial building market segments (possibly retail, assembly, education, and/or warehouse).

Phase 3. TRNSYS/AIRNET approach

This phase involves use of the TRNSYS/AIRNET approach described in the previous section. The first step is developing a TRNSYS module based on the AIRNET program. After the TRNSYS/AIRNET coupling is complete, a prototype building will be modeled as a trial case to verify the viability of the simulation method. It will be useful to simulate a building which has been simulated previously to provide an inter-model comparison of the energy use predictions. Many questions on the details of the building simulation will be answered at this point.

After the trial simulations have been successfully performed, the complete set of prototypical buildings will be simulated to estimate the total energy consumption due to envelope infiltration and non-design ventilation system airflow rates. Separate simulations will also be performed to determine the energy savings potential in both existing buildings and new construction.

Estimating the energy impacts of poor building airtightness and ventilation system control will also require defining both poor and good building airtightness and ventilation system control for each of the representative buildings. The published literature on building airtightness and ventilation system control will be reviewed to assist in making these determinations.

Phase 4. Solution technologies for reducing energy impact

The objective of this project phase is to develop guidance on reducing the energy impacts. This will begin with identifying technologies for solving problems including envelope design and construction and ventilation system controls. Experimental work may be performed to evaluate solution technologies.

Other Applications of Simulation Tool

The simulation tool described above would have many possible applications that take advantage of the combined building thermal and multizone airflow modeling capabilities. One application would be analysis of the energy impact of increasing the required ventilation rates in buildings. The energy impacts of increasing outdoor air intake in commercial buildings have been reported by several researchers including Eto (1990), Eto and Meyer (1988), Steele and Brown (1990), Ventresca (1991), and Zmeureanu (1992). As discussed earlier, these studies used simplified approaches that do not account for the complexities of airflow in multizone buildings. Consideration of the multizone nature of airflow in large buildings and of the airflow and heat transfer interactions would result in better estimates of these and other related energy impacts.

Another application would be a parametric study of the interactions of building airflow with various building thermal features. For example, the effectiveness of energy conservation strategies such as adding insulation or increasing thermal mass may depend on the airtightness of the building. Although many studies of this type have been performed in the past, the combined thermal and airflow modelling described here may affect the results of such studies.

A third and very important application would be evaluating indoor air quality. This application would require further simulation tool development of a TRNSYS module based on the NIST program CONTAM94 (Walton 1994, Walton and Emmerich 1994) although a less capable multizone pollutant dispersal module currently exists (Emmerich 1993) and could be used. Such a tool could be used to evaluate both the indoor air quality and energy impacts of indoor air quality control strategies.

Initial Estimate Based on PNL Infiltration Rates

The first phase of the project involved making an initial estimate of the national impact of infiltration loads. This estimate is not intended to be very reliable but simply to indicate the magnitude of the energy use. The initial estimate method uses information from a previous study by Pacific Northwest Laboratory (PNL) on energy use in office buildings (Briggs et al. 1992, Crawley and Schliesing 1992). The PNL study was conducted to characterize in detail the energy requirements of the office building sector for use in targeting research of new gas-fueled technologies. PNL performed a statistical categorization of the existing and future national office building stock which resulted in a total of 30 prototype buildings. Energy simulations were then performed on these buildings using DOE-2 program to calculate annual energy use.

A steady-state method was used to obtain a rough estimate of the annual energy impact of air infiltration for the PNL building set. For each building, the thermal loads due to infiltration were estimated for each hour of a typical year using the equation $Q_s = q*\rho*C_p*\Delta T$, where Q_s is the sensible load, ΔT is the indoor-outdoor temperature difference, ρ is the density of the air, C_p is the specific heat of the air, and q is the flow rate of infiltrating air. The sensible load is the rate at which heat must be added to (or removed from) the incoming air in order to raise (or lower) its temperature by an amount ΔT. A similar equation describes the latent load due to removal of moisture during cooling.

Many simplifying assumptions were made in performing these calculations. No transient effects (i.e. thermal storage) were considered. Balance point temperatures, above which heating loads were not calculated, were used. Density and specific heat of air were assumed to be constant. Infiltration flow rates were derived from the air infiltration rates specified for each building by Briggs et al. (1992), which were adjusted hourly for wind speed but not for temperature. It was assumed that the infiltrating air would be heated (or cooled) to the current thermostat setpoint of the building. Briggs et al. (1992) contains detailed operating schedules for each building, including the thermostat settings for every hour of the day. The assumption of constant infiltration flow rate and temperature difference during an hour allowed a straightforward calculation of the total amount of heat added to (or removed from) the building space for that hour. By neglecting losses in the air ducts, the space heating (or cooling) load becomes equivalent to the coil load on the HVAC system equipment. Estimates of annual heating and cooling coil loads were made by summing the hourly loads over the span of a year. The loads were then converted to energy-use values by applying the overall conversion efficiencies that were used for the buildings in the PNL study. The details and assumptions involved in this method are described in Appendix A.

Results

Table 1 shows the results of the calculations, in which the heating and cooling loads are normalized with respect to the floor area that each building represents. For each building, the associated loads due to air infiltration are shown, along with the total annual heating or cooling load as predicted by DOE-2, and the percentage of this total accounted for by the infiltration loads. The last row of the table contains these values for all the buildings together, based on the individual building values weighted by floor area. Note that these values are the loads on the heating and cooling coils, not energy consumption, so are independent of the source of energy.

BUILDING	LOCATION	HEATING LOADS (MJ/m^2)			COOLING LOADS (MJ/m^2)		
		Infiltration	Total	% Inf	Infiltration	Total	% Inf
1	Indianapolis, IN	105	656	16%	5	234	2%
2	Cleveland, OH	346	2127	16%	14	355	4%
3	El Paso, TX	26	162	16%	4	429	1%
4	Washington, DC	34	341	10%	4	355	1%
5	Madison, WI	45	313	14%	2	254	1%
6	Lake Charles, LA	20	120	17%	13	621	2%
7	Des Moines, IA	151	1087	14%	7	401	2%
8	St. Louis, MO	104	745	14%	24	764	3%
9	Las Vegas, NV	16	133	12%	4	420	1%
10	Salt Lake City, UT	25	226	11%	2	547	0%
11	Cheyenne, WY	65	382	17%	1	535	0%
12	Portland, OR	70	724	10%	1	199	1%
13	Pittsburgh, PA	78	1357	6%	5	615	1%
14	Amarillo, TX	73	191	38%	6	516	1%
15	Raleigh, NC	15	639	2%	6	1209	0%
16	Dallas, TX	20	185	11%	11	1087	1%
17	Minneapolis, MN	70	651	11%	3	479	1%
18	Boston, MA	46	991	5%	1	990	0%
19	New York, NY	84	233	36%	4	292	2%
20	Los Angeles, CA	6	66	9%	0	1000	0%
21	Raleigh, NC	43	98	44%	9	565	2%
22	Phoenix, AZ	13	49	26%	12	363	3%
23	Pittsburgh, PA	72	155	46%	3	184	1%
24	Pittsburgh, PA	42	49	86%	2	246	1%
25	Charleston, SC	17	64	27%	14	444	3%
	All Buildings	59	380	16%	6	494	1%

Table 2: Summary of Annual Heating and Cooling Loads

The results indicate that, nationwide, air infiltration is responsible for about 16% of the total annual heating load of the office building stock, but only 1% of the cooling load. One reason for the disparity between heating and cooling percentages is clear from Equation (a) of Appendix A, which shows that sensible loads are directly proportional to the inside-outside temperature difference, ΔT. Therefore, it is to be expected that heating loads due to infiltration are far greater than cooling loads, due to the larger values of ΔT that occur during the heating season. Furthermore, cooling loads are strongly dependent on the heat generated by internal sources, and these sources tend to increase the amount of cooling necessary, but decrease the amount of heating. The end result is that a significantly greater portion of the heating load arises from air infiltration than of the cooling load.

A closer look at the results for individual building categories reveals that the percentage of the heating load due to air infiltration varies widely from building to building. Much of the variability of the percentage due to air infiltration was due to variability of the total heating load not the infiltration heating load. For example, despite three of the buildings sharing a common climate (Pittsburgh), the heating load due to infiltration for buildings 13, 23, and 24 varied from 6% to 86% of the total heating load. For these buildings, the infiltration heating load varied only from 42 to 78 MJ/m^2 but the total load varied from 49 to 1357 MJ/m^2. The estimated percentage for all five of the recent and future building classes (21 through 25) are significantly above the mean of 16%. In the PNL analysis, these buildings were assumed to meet the building energy efficiency guidelines of ASHRAE Standard 90.1-1989 (ASHRAE 1989). The more stringent envelope insulation values prescribed therein decrease conductive losses, making infiltration loads a higher percentage of the total. In buildings 13 and 15, infiltration is a far smaller percentage of the heating load than the average, partly because the HVAC systems of these buildings operate for 24 hours per day. This had the dual effect of eliminating thermostat setbacks, thus increasing the total heating load, and reducing the infiltration loads because the building is pressurized day and night.

The estimated annual energy use for heating infiltration air in US. office buildings is 0.074 EJ (0.070 quadrillion BTU) which is about 18% of the total heating energy use calculated by PNL. The estimated annual energy use for cooling infiltration air in US. office buildings is 0.0025 EJ (0.0024 quads) which is 2% of the total cooling energy use calculated by PNL. Among the buildings representing recent and future construction (between 1980 and 1995), air infiltration accounted for 45% of the heating energy use, showing the increasing relative cost of air infiltration in newer, better insulated buildings. This method yielded an estimate of the infiltration heating and cooling loads for the office building stock only. However, this is one of the largest commercial building market segments and gives an indication of the magnitude of energy involved in the issue of building airtightness and ventilation system control.

Summary

US office buildings consume a large amount of energy each year, a substantial portion of which is used by building heating, ventilating, and air-conditioning systems. These energy costs may be reduced through tighter building envelopes and improved ventilation system control. Better information on the actual energy impacts of building leakage and poorly controlled ventilation systems is needed to determine the cost-effectiveness of improved airtightness and system control. However, commonly used building energy analysis programs exhibit several shortcomings in modeling the airflow in multizone buildings which limit their usefulness in studying this problem.

NIST has developed a research plan to quantify, and assess opportunities to reduce, the energy and indoor air quality impacts of building airtightness and ventilation system control. The energy impacts of poor building airtightness and ventilation system control will be analyzed with the TRNSYS simulation program employing the existing building energy balance module and a new module based on the multizone airflow program AIRNET. The program will be used to model several prototypical large buildings in representative US climates. The simulation results will be extrapolated to the commercial building population as a whole based on available statistical information. The simulation tool will also be used to evaluate potential building envelope design changes and retrofits in combination with other building design and operation features through parametric analysis. This simulation tool will also be available to use for indoor air quality simulation studies including determining both the indoor air quality and energy impacts of modifications to building design and operation.

An initial estimate indicates that infiltration is responsible for 18% of the total heating energy use and 2% of the total cooling energy use in US office buildings.

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Appendix A: Description of Method for Initial Estimate

This appendix describes the method used to develop the initial estimate of the national energy use in US office buildings due to infiltration. The results of the initial estimate are included in the section of the report titled Initial Estimate Based on PNL Infiltration Rates.

Introduction

A simple approach was used to calculate the cumulative annual load due to heating and cooling of infiltrating air in office buildings nationwide. The leakage characteristics of a given building were used, in conjunction with hourly weather data from the WYEC tape for an appropriate climate, to estimate the volume of outdoor air that penetrates the building envelope during a given hour. The load associated with heating or cooling this air to the thermostat setpoint of the building was summed over every hour of the year in order to find annual loads for the building. Infiltration loads were calculated in this manner for a set of 25 buildings, each representing a certain percentage of the total building stock of the United States. Twenty of these buildings were developed by Briggs, Crawley, and Belzer (1987) to represent the existing office building stock as of 1979, and are summarized in the report "Energy Requirements for Office Buildings" (Briggs, Crawley, and Schliesing 1992). The other 5 buildings represent construction between 1980 and 1995, and are described in volume 2 of the same report (Crawley and Schliesing 1992). A summary of features of the 25 representative buildings are shown in Table A-1. The two volumes of this report include an estimate of the total heating and cooling coil loads experienced annually in each of the 25 buildings, obtained using the DOE-2 building energy simulation program. By matching the important parameters in the calculations of energy use due to infiltration as closely as possible with those used in the PNL analysis, it was possible to compare these results to the earlier predictions of total loads to estimate the percentage of the total annual load that is attributable to air infiltration.

Bldg. No.	Floor Area (m^2)	No. of Floors	Year Built	Location	Floor Area Represented - (10^6 m^2)	Air Change Rate w/ Fans Off (h^{-1})
1	576	1	1939	Indianapolis, IN	15.6	0.53
2	604	3	1920	Cleveland, OH	24.8	1.00
3	743	1	1954	El Paso, TX	21.5	0.43
4	929	2	1970	Washington, DC	26.5	0.33
5	1486	2	1969	Madison, WI	51.7	0.28
6	2044	2	1953	Lake Charles, LA	31	0.42
7	2601	4	1925	Des Moines, IA	68.2	0.65
8	3716	5	1908	St. Louis, MO	28.3	0.70
9	3902	2	1967	Las Vegas, NV	43.2	0.18
10	4273	3	1967	Salt Lake City, UT	35.5	0.21
11	13935	6	1968	Cheyenne, WY	28.6	0.19
12	16722	6	1918	Portland, OR	27.9	0.54
13	26941	11	1929	Pittsburgh, PA	58.5	0.62
14	26941	6	1948	Amarillo, TX	37.3	0.31
15	27870	12	1966	Raleigh, NC	32.7	0.22
16	28799	10	1964	Dallas, TX	22.9	0.18
17	53882	19	1965	Minneapolis, MN	27.6	0.26
18	67817	10	1957	Boston, MA	16.3	0.16
19	68746	28	1967	New York, NY	43.4	0.32
20	230392	45	1971	Los Angeles, CA	40.8	0.26
21	1022	2	1986	Raleigh, NC	117	0.62
22	1208	2	1986	Phoenix, AZ	92.2	0.58
23	1579	2	1986	Pittsburgh, PA	101	0.53
24	38089	9	1986	Pittsburgh, PA	64.5	0.21
25	46450	14	1986	Charleston, SC	54	0.23

Note: Each of buildings 21 - 25 represents a mix of building construction in 1986 and 1995.

Table A-1: Summary of Representative Building Set

Method

The algorithm for calculating infiltration loads for a given building consists of the following steps:

1. Obtain weather conditions for the current hour: outdoor temperature, humidity, and wind speed.
2. Determine the appropriate air infiltration rate, based on wind speed and HVAC system status.
3. Determine the appropriate thermostat setpoints of the HVAC system, depending on the building occupancy schedule.

4. Compare the temperature of the outdoor air with the thermostat setpoints to determine whether the infiltrating air needs to be heated or cooled.
5. If cooling is necessary, compare the humidity of the outdoor air to the desired humidity to determine whether latent cooling loads will be present.
6. Calculate the hourly loads using equations (a) and (b) (ASHRAE 1993).

$$\text{(a)} \qquad Q_s = \rho * C_p * \Delta T * ACH * V$$

$$\text{(b)} \qquad Q_l = \rho * h_{fg} * \Delta W * ACH * V$$

7. Add the hourly infiltration load to the cumulative total for either the heating or cooling load.

In equations (a) and (b), Q_s is the sensible heating or cooling load due to infiltration, Q_l is the latent cooling load, ρ is the density of the infiltrating air, C_p is the specific heat of the infiltrating air, ΔT is the indoor-outdoor temperature difference, ΔW is the indoor-outdoor humidity ratio difference, ACH is the infiltration rate in air changes per hour, and V is the total volume of the building. ACH * V, therefore, represents the volume of outdoor air that enters the building in one hour.

Application of this algorithm required some assumptions regarding the leakage characteristics of the building and the HVAC system parameters, most notably the operating schedule and temperature and humidity setpoints. Whenever possible, the values of these parameters were taken directly from the input files for the PNL analysis (Briggs et al. 1992). However, in the cases of indoor humidity levels and HVAC system balance temperatures, no specific information was available, so additional assumptions were necessary.

Air Infiltration Rates

Air infiltration rates for each of the representative buildings were generated by Briggs et al. for a wind speed of 10 miles per hour (4.47 m/s), using a model that takes into account building age and height and an average annual indoor-outdoor temperature difference. For the infiltration load calculations, these values were scaled linearly with wind speed to generate a table of infiltration rates for each building for wind speeds between 0 and 20 m/s. Because the PNL analysis did not account for the dependence of the air infiltration rate on the indoor-outdoor temperature difference, this dependency was not included in the present analysis. The values in Table 1 represent air infiltration rates that were used when the HVAC system fans are off. During hours of fan operation, the resulting pressurization of the building may act to reduce the rate of air infiltration to some degree. Following Briggs et al. (1992), the amount of this reduction was based on the height of the building: for buildings of 5 stories or fewer, air infiltration was reduced to 25% of the fans-off rate, and in taller buildings it was reduced to 50% of the fans-off rate. Building number 2 has no mechanical ventilation so the infiltration rate was not reduced.

HVAC System Parameters

Due to the assumed effect of building pressurization on the air infiltration rate, it was necessary to know whether or not the HVAC system fans were running during any given hour of the day. The PNL descriptions of the representative office buildings include the average number of hours per day that the HVAC systems operate, which ranges between 9.2 and 21. For each value of this parameter, a detailed schedule is provided, indicating which hours the fans are considered to be running. When calculating the loads during such an hour, the infiltration rate was reduced as detailed earlier to account for building pressurization. Different schedules were utilized for weekdays and weekends.

The temperature setpoints were designed to reflect the common practice of changing thermostat settings in order to conserve energy at times when the building is expected to be unoccupied. Heating setbacks were 2.8 °C (5 °F) below the corresponding occupied-hours heating setpoints, which ranged from 21.1 °C (70 °F) to 22.2 °C (72 °F). Setpoints for cooling fell between 23.3 °C (74 °F) and 25.0 °C (77 °F). Cooling setups were fixed at 37 °C (99 °F) for every building, essentially ensuring that no cooling would occur during unoccupied hours. All of these values were taken directly from the corresponding DOE-2 input parameters. Schedules similar to those describing the hours of HVAC system operation were used to determine whether the high or low setpoint should be used for each hour's calculations. In general, setbacks and setups were in effect from the time the HVAC system fans cut off in the evening until one hour before they restarted in the morning. The existing building descriptions do not include a setpoint, per se, for the humidity of the indoor air. However, the input files for the system subprogram of DOE-2 include a listing for the maximum humidity of the system air. When calculating latent cooling loads, it was assumed that all infiltrating air that needed to be cooled was also dehumidified to the maximum level indicated for that building. The maximum level was 70% relative humidity for the 20 original buildings, and 60% for the 5 buildings representing recent and future construction.

Balance Points

Another building parameter was introduced to account for the presence of internal heat sources, such as occupants, lighting, and electrical equipment. At times when the outdoor temperature is below the thermostat setpoint by a small amount, infiltrating air may not need to be mechanically heated due to the heat generated by internal sources. The temperature above which this is true is called the balance temperature, or balance point, of the building. In order to include the 'free' heating effect of a building's internal heat sources, a balance temperature was assigned to each of the representative buildings. If the temperature of infiltrating air fell between the balance temperature and the heating setpoint, no heating load was assessed during that hour. A balance temperature was estimated for each building based on properties provided in the PNL input files, using the following equation (ASHRAE 1993):

$$t_{bal} = t_i - \frac{q_{gain}}{K_{tot}}$$

The total rate of heat gain, q_{gain}, includes internal sources such as occupants, lighting, and equipment, solar gains through fenestration, and radiative gains through the walls and roof. K_{tot} is the total heat loss coefficient of the building (in W/K) due to infiltration, ventilation, and conduction. If one assumes that heat transfer among the zones of a building is negligible (PNL divided the buildings into thermal zones for DOE-2), then each zone will exhibit its own characteristic balance temperature. Since most heat loss occurs across the building envelope, the limiting balance temperature (the highest) will be that of the zones having exterior walls. For this reason only the internal heat sources in the perimeter zones were included in the heat gain term when calculating the balance point for multizone buildings. For each building, a separate balance point was calculated for unoccupied hours. These estimates assumed no solar or radiative heat gains since unoccupied hours generally occur at night. Receptacle loads were assumed to be 50% of their occupied-hours level and lighting loads 25%, while occupancy was at 5% of the maximum, based on the sample schedules created by PNL. At both times, the interior temperature t_i was assumed to be equal to the current thermostat setpoint. Balance point temperatures for the 25 prototypical buildings ranged from -5.5 to 15 °C (22 to 60 °F) during the day, and from 10 to 17 °C (50 to 62 °F) at night, with averages of 4.5 °C (40 °F) and 14 °C (57 °F), respectively. These temperatures are in the same range as balance points calculated for a modern office building of 1.1 °C (34 °F) for weekday hours, 2.8 °C (37 °F) for weekend day hours, and 11.1 °C (52 °F) for night hours (Norford 1984).

Conversion of Coil Loads to Energy Use

The PNL results (Briggs et al. 1992) include an analysis of cumulative annual energy use, accounting for conversion efficiencies of HVAC system components and the source of energy (electricity or gas). By comparing these values of energy use to the corresponding coil loads, a single number was obtained to represent the system's overall conversion efficiency for heating, and one for cooling. These energy use-to-coil load ratios were then applied to the infiltration loads, yielding an estimate of the annual energy cost of air infiltration.

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