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Research paper

Development of a simulation analysis environment for ventilated slab systems

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HIGHLIGHTS

- A new dynamic simulation environment has been developed for ventilated slabs.
- Thermal bridging effects for ventilated slabs have been evaluated.
- Impact of a wide range of design and operating parameters is determined.

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ABSTRACT

In this paper, a new simulation environment is presented to evaluate the energy performance of ventilated slab systems in multi-floor buildings. The simulation environment combines a transient two-dimensional finite difference solution of a ventilated slab system comprising slab-wall joints with thermal network model for indoor spaces and associated exterior walls. The developed simulation environment can assess the impact of thermal bridging effects on both heating and cooling building thermal loads. First, the predictions of the developed simulation environment are verified against those obtained from a detailed whole-building energy simulation tool when thermal bridging effects are neglected. Then, a series of parametric analyses are performed to determine the performance of ventilated slab systems under various design and operating conditions considering the thermal bridging effects. It is found that the energy performance of ventilated slab systems and thermal bridging impact depend on a wide range of factors including size of the slab, supply air inlet temperature, air mass flow rate, core diameter, core pitch, and depth of hollow cores. In particular, it is found that the thermal bridge affects significantly the energy performance of ventilated slab systems and can increase both heating and cooling energy consumptions by 17% and 11%, respectively.

1. Introduction

In most countries, approximately 20–40% of total energy consumption is due to building heating and cooling operations [1]. The use of building thermal mass is one of the effective techniques to reduce the building energy consumption. Recently, active cooling/heating systems integrated with building thermal mass, such as ventilated slab systems, have been considered to heat and cool residential and commercial buildings. Indeed, ventilated slab systems have been employed in northern Europe and Australia. Ventilated slab systems, utilize air channels within precast slabs to cool or heat thermal zones. The basic operation of ventilated slab systems is similar to hydronic radiant systems, but it uses air instead of water as the heat transfer fluid. The air is then supplied directly to condition various thermal spaces.

Compared to conventional air systems, hollow core slab systems have the potential to significantly reduce energy use to heat and/or cool buildings. In particular, it is reported that ventilated slab systems can serve as passive thermal storage media, and can effectively reduce the daytime cooling demand for several types of buildings. During the summer season, outside air can be used to cool down the temperature of the slab thermal mass specially at nighttime. During the winter season, the slab thermal mass can store heat generated by internal sources (such lighting and

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equipment) and then release it to the conditioned zone during the on-peak period. Barnaby et al. simulated the thermal performance of a hollow core slab system for a commercial building using an energy analysis program and concluded that the system could provide an energy reduction between 13% and 30% for the peak cooling load for dry US climates [2]. However, the energy analysis evaluation neglected thermal bridging effects at the floor-wall joints. Using an implicit finite difference model for a ventilated slab system serving a single zone office in Montreal, Canada, Zmeureanu and Fazio found that the daily cooling load could be reduced by over 35% compared to conventional HAVC system [3]. Similarly, Russell and Surendran investigated the ventilated slab system performance using a two-dimensional finite difference model. Assuming that air at 16.9 °C is continuously circulated through hollow cores for 14 h, they indicated that the cooling potential of the system increased by 335% compared to a traditional slab configuration with night ventilation [4]. Chae and Strand developed a heat balance model suitable for EnergyPlus for the ventilated slab using a modification of the conduction transfer function (CTF) formulation with heat sources/sinks. The authors have found that daily total demand savings of 23% and peak demand savings of 28% can be achieved by the ventilated slab system if outdoor air is circulated through the hollow cores during unoccupied hours [5].

Moreover, compared to all air HVAC systems, the benefits of ventilated slab systems include better thermal comfort. Better thermal comfort is associated to increased heat transfer by radiation. It is estimated that more than 50 percent of heat can be transferred from the controlled ventilated slab surface to other surfaces by radiation [6]. Indeed, Shaw et al. reported that ventilated slab systems can control slab surface temperatures and maintain comfortable environment for the occupants [7]. Corgnati and Kindinis investigated the thermal performance of active hollow core slabs under a Mediterranean climate. The authors concluded that the hollow core ventilated slab system reduces thermal cooling load and provides better thermal comfort to the occupants compared to the traditional ventilation system. However, no specific analysis was carried to estimate the level of thermal cooling load reduction and thermal comfort improvement compared to the traditional ventilation system [8].

Several studies have found that thermal bridging effects especially at the wall-floor joints can be significant and can increase building thermal loads [9–11]. In particular, Theodosiou and Papadopoulos reported that actual heating loads can be up to 30% higher when thermal bridging effects are considered [10]. Most of the simulation models developed for ventilated slab systems do not take account for thermal bridge effects which can be magnified due to the controlled slab temperatures. Indeed, higher slab surface temperature for hollow core ventilated slab system could increase heat losses through slab edges during the heating operation. Existing detailed whole-building simulation tools including, eQUEST and EnergyPlus which are the most widely used building energy analysis tools in the US, are not suitable for estimating of thermal bridging effects on the energy performance of ventilated slabs. Indeed, eQUEST has no capabilities to perform any 2D heat transfer analysis (i.e., analysis of thermal bridging in building envelope including joints between floors and walls). Moreover, while the current version of EnergyPlus has some capabilities to perform 2-D heat transfer analysis for slab floors, the boundary conditions along the joints between the floor and the walls have to be set as adiabatic. Thus, EnergyPlus is also not capable to evaluate the thermal bridging effects for the ventilated slab due to the wall-floor joints. In paper, the impact of thermal bridges on the performance of ventilated slab systems is estimated under various design and operating conditions using a simulation analysis environment for multi-floor buildings.

2. Development of the simulation analysis environment

A simulation environment that combines finite difference model and thermal network technique is developed to evaluate the performance of ventilated slab systems and assess the impact of thermal bridging effects associated with floor-wall joints. Specifically, 3R2C thermal network model is used to estimate heating and cooling loads for the thermal zones. A 2-dimensional FDM ventilated slab model is employed to accurately address the heat transfer through slab-wall joint. Fig. 1 illustrates the schematic of the simulation environment using both an RC thermal network model and a finite difference method (FDM) ventilated slab system model.

2.1. FDM ventilated slab model

A control volume approach and pure implicit finite difference technique is used to model hollow core ventilated slab system by solving the two dimensional heat conduction equation within the building envelope components that include embedded heat source/sink (i.e. floor and ceiling) [12]:

$$k\frac{\partial^2 T}{\partial x^2} + k\frac{\partial^2 T}{\partial y^2} + Q = \rho c_p \frac{\partial T}{\partial t} \tag{1}$$

The actual heat transfer between the building envelope elements (i.e. slab floor and walls) and the ventilated slab system depends on the fluid inlet temperature and mass flow rate. To model the ventilated slab system using Eq. (1), it is assumed that the air inlet temperature and the mass flow rate are known while the remaining parameters are to be calculated [13]. Specifically, air flows through hollow cores of the ventilated slab system are supplied to heat and cool the indoor space. A ventilated slab system can be thought of as a heat exchanger between air flowing through the hollow cores and the slab floor. The effectiveness-NTU heat exchanger method has been shown to be convenient to utilize when the air outlet temperature is not known [14]. Specifically, heat released or absorbed from the air flowing in the hollow cores can be estimated using Eq. (2):

$$Q = (\dot{m}c_p)_{\text{air}}(T_{\text{air, in}} - T_{\text{air, out}}) \tag{2}$$

The maximum heat transfer potential between the air and the slab is estimated based on the temperature of heat source or sink, T_{src}:

$$q_{\max} = (\dot{m}c_p)_{\text{air}}(T_{\text{air, in}} - T_{\text{src}}) \tag{3}$$

The effectiveness of the heat exchanger, ε, is defined as the ratio of the actual energy transfer to the maximum amount of energy transfer. When one fluid is stationary for a heat exchanger, the effectiveness can be related to the number of transfer units (NTU) [15]:

$$\varepsilon \equiv \frac{Q}{Q_{\max}} = 1 - e^{-\text{NTU}} \tag{4}$$

where NTU is defined by:

$$\text{NTU} \equiv \frac{\text{UA}}{(\dot{m}c_p)_{\text{air}}} \tag{5}$$

The heat transfer coefficient, UA, is can be estimated using the convection heat transfer along the contact surface area of the cores:

$$\text{UA} = h_{\text{air}}\,(\pi \text{DL}) \tag{6}$$