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Integrated analysis of whole building heat, air and moisture transfer

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ABSTRACT

There is a continuous dynamic heat, air and moisture (HAM) interaction between the indoor environment, building envelope and mechanical systems. In spite of these interdependences, the current indoor, building envelope and energy analysis tools are used independently. In this paper a holistic HAM model that integrates building envelope enclosures, indoor environment, HVAC systems, and indoor heat and moisture generation mechanisms, and solves simultaneously for the respective design parameters is developed. The model is benchmarked with internationally published test cases that require simultaneous prediction of indoor environmental conditions, building envelope moisture performance and energy efficiency of a building.

1. Introduction

Buildings are designed to create an isolated space from the surrounding environment and provide the desired interior environmental conditions for the occupants. In addition to fulfilling the function of creating favorable indoor environmental conditions, buildings are expected to be durable and energy efficient. These three functional requirements of the building should be optimized for a given climatic condition. This optimization process is necessary: (1) to provide a comfortable indoor environment to occupants since people spend most of their time indoors and their productivity is also dependent on how they perceive their indoor environment; (2) due to the high level of investment and maintenance costs[1] involved in the construction of new buildings and repair of building failures; (3) due to high energy consumption of buildings that results in high energy bills to maintain the desired building operating conditions.

Of course, exclusively dealing with one aspect of the building might lead to problems or yield less efficiency in the other aspects. For example, in early 1970s as a means of reducing energy consumption buildings were constructed and retrofitted to be more airtight and more highly insulated. Although the energy efficiency of the buildings improved, this new strategy created more problems in respect to durability of the building envelope due to high moisture accumulation in the building structure. The indoor humidity levels were also elevated due to the reduced air exchange, which resulted in low occupant comfort and health problems [1,2].

To maintain the indoor humidity level within the design range, the building engineer needs to use an indoor model to evaluate different ventilation strategies and/or moisture buffering materials, and decide on the appropriate material and equipment size for ventilation, humidification and dehumidification. However, the success of the strategy might depend on the robustness of the indoor model used to predict the indoor conditions. Most of the humidity models [3–6] ignore or lack comprehensive analysis of moisture exchange between the various building envelope components and the indoor air, despite the fact that approximately one-third of the moisture generated inside a room may be absorbed by moisture buffering materials [7,8]. In a reverse moisture exchange process, a significant amount of moisture is released to the indoor air from the building enclosure (e.g. initial moisture content of concrete) or/and surroundings through foundation walls, floor and above ground components [9]. This direct interaction of indoor air and building enclosure implies that to predict the indoor air condition more accurately, the indoor model needs to be dynamically coupled with the building envelope model to capture the dynamic moisture and heat exchange between the construction and indoor air. Conversely, to realistically assess the hygrothermal performance of building envelope components the indoor boundary conditions need to be well known, contrary to the current practice of using predetermined simplistic or empirically generated condi-

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[1] According to Statistic Canada, over $82 billion is invested in new building construction and about $37 billion was spent for renovation in 2007 (http://www41.statcan.ca/2008/2162/ceb2162_000-eng.htm).

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Nomenclature

A_c	condensate surface area (m^2)
A_i	surface area of surface i (m^2)
A_e	evaporative surface area (m^2)
Cv_m	specific capacity of solid matrix (J/K kg)
Cp_a	specific capacity of air (J/K kg)
Cp_v	specific capacity of water vapor (J/K kg)
D_l	liquid conductivity (s)
f_{sa}	solar air factor (–)
$\vec{g}$	acceleration due to gravity (m/s^2)
h_i^m	mass transfer coefficient of surface i (kg/Pa s m^2)
h_i^h	heat transfer coefficient of surface i (W/K m^2)
h_c^m	mass transfer coefficient for condensate surface (kg/Pa s m^2)
h_e^m	mass transfer coefficient for evaporation surface (kg/Pa s m^2)
h_{fg}	latent heat of evaporation/condensation (J/kg)
h_o	outdoor surface heat transfer coefficient (W/K m^2)
I_o	incident solar radiation (W/m^2)
I_t	transmitted solar radiation (W/m^2)
k_a	air flow coefficient (s)
$\dot{m}$	mass flow rate of dry air (kg/s)
$\dot{m}_m$	mass flow rate of dry air (humidification/dehumidification systems) (kg/s)
$\dot{m}_h$	mass flow rate of dry air (heating/cooling systems) (kg/s)
M	molecular mass of water molecule (0.01806 kg/mol) p zone vapor pressure (Pa)
P_{atm}	atmospheric pressure (Pa)
P_v	vapor pressure (Pa)
$\widehat{P}$	saturated vapor pressure (Pa)
p_i^s	surface vapor pressure of surface i (Pa)
$\widehat{p}_e$	saturated vapor pressure of reservoir e (Pa)
$\widehat{p}_c$	saturated vapor pressure of condensate c (Pa)
$\dot{Q}_s$	heat source (W/m^3)
R	universal gas constant (8.314 J/mol)
T	temperature (°C)
T_e	outdoor air temperature (°C)
T_i^s	surface temperature of surface i (°C)
$\tilde{T}$	set point temperature (°C)
U	oveall heat transfer coefficient (W/K m^2)
$\vec{u}$	air velocity (m/s)
$\tilde{V}$	volume of the zone (m^3)
w	moisture content (kg/m^3)
Y_a	mass fraction of air (–)
Y_l	mass fraction of liquid water (–)

Greek letters

α	solar absorptance (–)
ϕ	relative humidity (–)
ρ_a	density of air (kg/m^3)
ρ_w	density of water (kg/m^3)
ρ_m	density of material (kg/m^3)
λ_{eff}	effective thermal conductivity (W/m K)
μ	air dynamic viscosity (kg/m s)
τ	solar transmittance (–)
ω	humidity ratio (kg/kg dry air)
ω_e	humidity ratio of outdoor air (kg/kg dry air)
ω_i^s	humidity ratio of surface i (kg/kg dry air)
$\tilde{\omega}$	set point humidity ratio (kg/kg dry air)
δ_v	vapor permeability (s)
Θ	sorption capacity (kg/m^3)

tions [10–14]. In reality the indoor conditions are determined by performing an integrated analysis of heat and mass balance of the external and internal loading as well as the mechanical systems' outputs. Energy models usually ignore the moisture effect on the thermal transport and storage properties of materials [15] as well as the local heating and cooling effects that are generated within the structure due to moisture phase changes (condensation and evaporation, respectively), which consequently affects the sensible and latent heat load calculations for the building. Incorrect prediction of the indoor air condition and ignoring moisture in the energy calculation might lead to an incorrect prediction of the required ventilation rate, energy demand for heating/cooling, as well as humidification/dehumidification needed to maintain the intended building operating conditions. To deal with these interrelated and coupled effects, an integrated and fully coupled modeling approach that integrates the dynamic HAM transfer of the building envelope with the indoor environment and its components (i.e. HVAC system, moisture and heat sources) is necessary. In this paper, the development and benchmarking of a whole building hygrothermal model is presented. The model can be used to simultaneously assess building enclosure durability, indoor conditions, occupant comfort, and also the energy efficiency of a building with the objective of attaining efficient building design. The development and benchmarking of a building envelop model, which is an essential building block to the holistic HAM model described in this paper, is presented in Tariku et al. [16] and Tariku [17].

2. Whole building hygrothermal model development

The holistic HAM model that is developed in this paper considers the building as an integrated system consisting of building enclosure, indoor environment, mechanical systems, and the possible hygrothermal loadings. Fig. 1 shows the schematic representations of the hygrothermal loadings that are expected in a typical building. The building is exposed to the local weather conditions including wind-driven rain and solar radiation on the outside, internal heat and moisture generations as well as solar gain on the inside. The building is also subjected to additional hygrothermal loadings related to mechanical systems for heating/cooling, de/humidification as well as ventilation.

Generally, the indoor environmental conditions, more specifically, temperature and relative humidity, are unknown quantities, and have to be determined from the heat and mass balance at the zone considering the three heat and moisture exchange mecha-

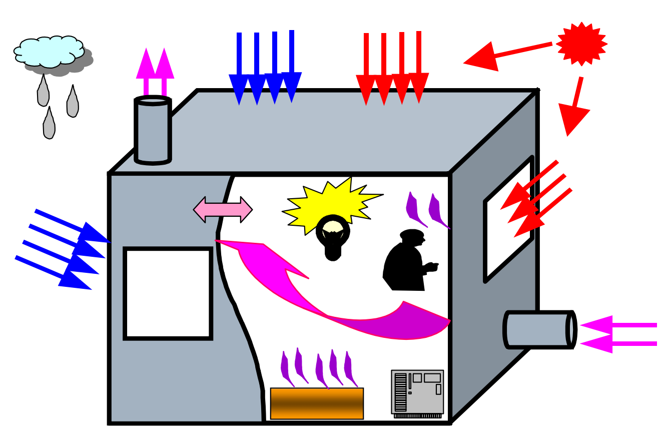

Fig. 1. Typical hygrothermal loadings on a building.