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Real-time thermal load calculation by automatic estimation of convection coefficients

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ABSTRACT

A significant step in the design of Heating, Ventilating, Air Conditioning, and Refrigeration (HVAC-R) systems is to calculate the room thermal loads which often vary dynamically. A self-adjusting method is proposed for real-time calculation of heating/cooling loads in HVAC-R applications. In this method, the heat balance calculations are improved by real-time temperature data to achieve more accurate load estimations. An iterative mathematical algorithm is developed to adjust the heat transfer coefficients according to live measurements.

Accepted analytical correlations are also used to estimate the heat transfer coefficients for comparison with the present model. The adjusted coefficients and the analytical correlations are separately used to estimate the thermal loads in an experimental setup. It is shown that the utilization of the adjusted coefficients yields to higher accuracy of thermal load estimations compared to the conventional analytical correlations. Since the proposed method requires less engineering information of the room, it can be adopted as a simplified yet accurate method for the design and retrofit of new and existing HVAC-R systems.

Calcul de charge thermique en temps réel par une estimation automatique des coefficients de convection

Mots clés : CVC-R ; Calcul de charge thermique ; Coefficient de convection ; Méthode d'auto-réglage ; Méthode du bilan thermique

1. Introduction

Heating, Ventilating, Air Conditioning, and Refrigeration (HVAC-R) consume a remarkable portion of the worldwide energy. Half of the total energy usage in buildings as well as 20% of the total national energy usage in European and American countries is consumed by HVAC-R systems (Pérez-Lombard et al., 2008). HVAC-R energy can even exceed half of the total energy usage of a building located in tropical

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Nomenclature

a	Sigmoid function parameter
$A[m^2]$	Wall surface area
$c_p[J\ kg^{-1}\ K^{-1}]$	Air specific heat
$c_1, c_2[°C]$	Correlation coefficients
$c_3[s^{-1}]$	Correlation coefficient
C	Correlation coefficient
D	Desired neuron output
f	Sigmoid function
$g[m\ s^{-2}]$	Gravitational constant
$h[W\ m^{-2}\ K^{-1}]$	Convection coefficient
$H[m]$	Wall height
$k[W\ m^{-1}\ K^{-1}]$	Air thermal conductivity
n	Number of walls
O	Calculated neuron output
$P[m]$	Surface perimeter
$\dot{q}[W]$	Heat transfer rate across one wall
$\dot{Q}[W]$	Heat transfer rate
R^2	Coefficient of determination
$t[s]$	Time
$T[°C]$	Temperature
$w_0[W]$	Bias weight factor
$w_j[W\ K^{-1}]$	Input weight factors ($j = 1, \ldots, n$)
$x, y, z[cm]$	Coordinates

Greek letters

$\beta[K^{-1}]$	Volumetric coefficient of thermal expansion
ε	Convergence criterion threshold
η	Learning rate
$\mu[N\ s\ m^{-2}]$	Air dynamic viscosity
$\rho[kg\ m^{-3}]$	Air density

Subscripts and superscripts

a	Air
I	Internal sources
j	Wall number
m	Training step number
V	Ventilation and infiltration
w	Wall surface
W	Walls

climates (Chua et al., 2013). Refrigeration systems also consume a substantial amount of energy. They may use 80% of the total energy in supermarkets (Hovgaard et al., 2011). Moreover, air conditioning is a significant energy-consuming unit in vehicles (Farrington et al., 1999). The air conditioning energy in vehicles outweighs the energy loss to aerodynamic drag, rolling resistance, and driveline losses for a typical vehicle. Air conditioning can reduce the fuel economy of mid-size vehicles by more than 20%. It can also increase vehicle NOx and CO emissions by approximately 80% and 70%, respectively (Farrington and Rugh, 2000). Air conditioning systems of light-duty vehicles consume 7 billion gallons of fuel per year in the United States (Johnson, 2002). Improved design and performance of HVAC-R systems can lead to considerable reductions in the associated energy consumption and gas emissions worldwide.

Thermal load calculation is the primary step in HVAC-R design. It often involves the study of the room characteristics such as wall properties, fenestration, openings, and air distribution. Occupancy level, geographical location, and ambient weather conditions are other necessary data that need to be investigated for thermal load calculations. Considerable engineering effort and time are required for collecting these data. Such detailed information is prone to inaccuracy and may even be unavailable. Therefore, it is promising to develop innovative methods for estimating the thermal loads accurately and with minimum data requirement.

The heat balance method is an effective thermal load calculation technique recognized by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). The heat balance method is based on the fundamentals of heat transfer and energy balance (ASHRAE, 2009). It is a well-recognized method widely used for calculations in both residential and non-residential applications (Pedersen et al., 1997; Fayazbakhsh and Bahrami, 2013). According to this method, the temperature variation inside a room is the result of the heat transfer through various mechanisms including radiation, convection, and conduction. Among these mechanisms, convection heat transfer has a sophisticated nature and its calculation tends to be complicated and inaccurate.

The convection heat transfer over a wall depends on the velocity and temperature of the air as well as the surface temperature. A common practice for the calculation of the convection heat transfer is to evaluate the coefficients using analytical correlations. ASHRAE Standard 90.1 (ASHRAE, 2013) offers comprehensive tables for the estimation of U-Factors. The U-Factor, or thermal transmittance, is defined as the "heat transmission in unit time through unit area of a material or construction and the boundary air films, induced by unit temperature difference between the environments on each side" (ASHRAE, 2013). However, finding the proper U-Factor requires extensive information to be gathered by the designer. Moreover, the estimated U-Factor may be inaccurate for varying air patterns and thermal conditions.

Besides ASHRAE, other attempts are made to provide reliable estimations of the convection coefficient. A broad range of experimental, computational, and analytical methods is utilized in the literature for estimation of the coefficients. Loveday and Taki (1996) used an experimental arrangement to find correlations for the external convection coefficient as a function of wind speed for a building wall. Kurazumi et al. (2014) experimentally found the convection heat transfer coefficients of human seated body during forced convection by downward flow from the ceiling using a thermal mannequin. Lei et al. (2014) presented an inverse modeling strategy to determine the required wall boundary convection heat fluxes required in computational simulations. In several studies by Zhai et al. (2001), Zhai and Chen (2003b), Zhai and (Yan) Chen (2004), Zhai and Chen (2005), Khalifa (2001a,b), Zhai et al. (2002), Zhai and Chen (2003a), they developed a methodology to couple Computational Fluid Dynamics (CFD) simulations