



Dynamic optimization based integrated operation strategy design for passive cooling ventilation and active building air conditioning



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ABSTRACT

As one form of passive cooling, night ventilation (NV) has been proven effective to improve the building energy performance. In previous studies, however, fixed NV operating strategies were usually pre-defined, ignoring the weather condition variations over the whole operation process, the influence of outdoor humidity on NV's efficiency, and NV's integrated performance with active air conditioning systems. Such strategies may have potentials for further improvements. This paper presents a systematic approach to address the dynamic optimization of integrated operation of NV and active building air conditioning using typical variable-air-volume (VAV) systems as the case. In the optimization scheme, the physical model is developed per differential algebraic equations (DAEs). The simultaneous collocation method is introduced to translate the dynamic optimization into a nonlinear program, which is then implemented in the GAMS platform and handled by IPOPT solver. The study results indicate that the optimized strategies lead to a remarkable energy saving of 23.19–49.31% in different climate conditions compared to the traditional local control scheme without NV, and a saving of 14.97–39.70% compared to that with pre-defined NV.

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1. Introduction

The hygrothermal response properties of building materials are at the heart of the management of building energy systems. Excitations from surrounding environment and building equipment may take hours to cause changes in the building energy system, due to the thermal storage effect and moisture buffering effect inherent in massive building materials [1,2]. This raises several challenges to the operation design of building heating, ventilation and air conditioning systems (HVAC), the purpose of which is to provide good thermal comfort and acceptable air quality in the indoor environment. First, the lag and decrement between various excitations and responses caused by building materials need to be quantified to facilitate the HVAC operation design. Second, the variations of the affecting parameters, such as the outdoor air temperature and relative humidity, over the whole process should be taken into account. In addition, investigating the synergistic influence of the variations of numerous affecting parameters is essential. This is even more challenging when the number of affecting parameters is large and their variations are diverse [3–5].

Furthermore, both temperature and humidity play critical roles in creating acceptable thermal environment, hence both heat and moisture transfers in the building system need to be concurrently considered in the design of HVAC operations [6–8]. Maintaining an appropriate indoor humidity level for thermal comfort, either by mechanical or chemical methods, adds more burdens to HVAC systems and consequently causes more energy consumptions. According to previous research on the impact of air humidity in building energy systems in different climatic areas, the energy consumption in the temperature–humidity control (THC) mode is typically 10–45% higher than that in the temperature control (TC) mode [9,10].

A variety of energy saving techniques have been developed in the past two decades to improve the performance of building energy systems. Among these techniques, night ventilation (NV) has been proven effective and energy efficient to transfer heat from buildings to natural heat sinks. It makes use of the building thermal mass, both internal and external, to store heat during a warm period and release it later during the day. NV not only leads to significant potential to reduce building cooling loads and HVAC energy consumptions, but also offers good indoor air quality and thermal comfort as an indirect positive product [11]. Note that NV is a passive cooling approach in terms of cooling sources, because it doesn't operate refrigeration cycles to generate heat sinks; but it is not

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Nomenclature

A_m	surface area of thermal mass (m^2)
c_m	heat capacity of thermal mass ($\text{J/kg}^\circ\text{C}$)
c_p	heat capacity of air ($\text{J/kg}^\circ\text{C}$)
h	convective heat transfer coefficient ($\text{W/m}^2^\circ\text{C}$)
h_m	convective mass transfer coefficient ($\text{kg/m}^2 \text{ s}$)
M_a	mass of zone air (kg)
M_m	mass of thermal mass (kg)
Q_{coil}	energy consumption rate of the coil (kW)
Q_{fan}	energy consumption rate of the fans (kW)
R_m	thermal resistance of thermal mass ($\text{m}^2^\circ\text{C/W}$)
RH	relative humidity (%)
T	temperature ($^\circ\text{C}$)
W	humidity ratio (kg/kg_a)

Subscripts

i	indoor air
inf	infiltration
me	external thermal mass
meo	outside part of external thermal mass
mei	inside part of external thermal mass
mi	internal thermal mass
o	outdoor air
s	supply air
sys	air conditioning system
$vent$	ventilation

passive in terms of driven forces, because mechanical fans can be conducted when necessary which consumes electricity. Therefore, NV can be considered a passive cooling method but not complete passive approach.

NV has been extensively investigated in the past. Yang et al. and Zhou et al. built the heat transfer model coupling thermal mass and natural ventilation, and estimated the impact of external and internal thermal mass on the cooling load reduction [12,13]; Blondeau et al. listed and categorized the key parameters related to the efficiency of NV [14]; Geros et al. investigated the influence of the urban environment on the efficiency of NV [15]. The feasibility of NV in different climate regions has also been investigated [16].

In the above studies, however, most of the researchers used the outdoor air temperature as the only index to evaluate the climatic potential for NV without considering the influence of outdoor humidity, and the humidity transfer process was not included in the ventilation model. In these studies, fixed operating strategies were usually pre-defined to study NV's performance from the building physics perspective, and the strategies may have potentials for further improvements. Moreover, it is commonly necessary for NV to cooperate with other active building air conditioning approaches such as VAV systems. As a result, the design of integrated operation strategies, which needs to account for the performance of all the involved systems, is even more complex.

Optimization based decision-making methods can be a powerful tool in dealing with such complex problems. For example, Zavala et al. established an on-line optimization framework to exploit disturbances of weather conditions for the operation design of a simplified building energy system, and found that more proactive and cost-effective operations can be obtained [17]. Sheikhi et al. proposed an optimization model to find the optimal size and operation for combined cooling, heat and power systems, in order to reduce power loss and enhance service reliability of the system [18].

This paper aims to analyze and optimize the integrated operation of NV and active building air conditioning approaches using

VAV systems as the case study. The study is carried out in two successive steps. First, the building and system physical model is developed on the basis of first principles. Thereafter, a dynamic optimization formulation is introduced to determine the optimal operation strategy. In the optimization algorithm, the simultaneous collocation method is employed to translate the dynamic optimization problem to continuous nonlinear programs (NLPs), which are further solved by interior point optimizer (IPOPT) that adopts the filter-based interior point algorithm. This method has been successfully applied to many real-world optimization problems in various research areas such as Chemical Engineering [19,20] and Economics [21,22].

2. Physical model development

A physical model simulating the operational performance of the building and system is essential for the optimization task. In this section, a first-principle based lumped single-zone building model including both external and internal thermal mass is built to describe the dynamic process of heat and moisture transfer in the building system, and a moist air thermodynamic property and process model is applied to describe the operation behavior of the air conditioning system.

2.1. Building model configuration

In this study, the configurations of the building model are adapted from relevant literatures [12,23]. The size of the zone is $8 \text{ m} \times 6 \text{ m} \times 3 \text{ m}$. The external thermal mass is composed of 150 mm R-0.15 concrete block and 25 mm R-0.80 extruded polystyrene insulation, with the total surface density of 205.0 kg/m^2 and heat capacity of $183.6 \text{ kJ/(m}^2 \text{ K)}$. The internal thermal mass is composed of wood and plasterboard, with the total surface density of 36.0 kg/m^2 and heat capacity of $43.2 \text{ kJ/(m}^2 \text{ K)}$. The convective heat transfer coefficient is $15 \text{ W/(m}^2 \text{ K)}$ for the surfaces exposing to the outdoor environment, and $2.5 \text{ W/(m}^2 \text{ K)}$ for the surfaces exposing to the indoor environment. The convective mass transfer coefficients of these surfaces are obtained via the Lewis equation in which the Lewis number is assumed to be 1 [24].

The operation time horizon of interest is set to 24 h. Steady periodic outdoor conditions are assumed, that is, both the outdoor temperature and relative humidity are sinusoidal harmonic functions with an angular frequency of $\pi/12 \text{ h}^{-1}$. For the temperature, the average is 28°C , the amplitude is 6°C and the phase shift is π . For the relative humidity, the average is 75%, the amplitude is 15% and the phase shift is 0. Such weather condition corresponds to the warm and humid climate [25]. The solar radiation defined for a typical design day is adapted for the solar temperature calculation [26]. The office hours are 8:00–18:00 h, during which the indoor thermal comfort and air quality have to be well maintained by the VAV system and ventilation.

2.2. Heat transfer and storage

A standard three resistances and two capacitances (3R2C) model is introduced to describe the heat transfer in the external thermal mass. It has been successfully implemented in several transient building load studies [27,28]. More specifically, external thermal mass is considered as two separate parts and the heat balance equations for both are developed independently.

Taking the inside part of external thermal mass for example, the heat balance equation is:

$$M_{mei} c_{mei} \frac{dT_{mei}}{dt} + h_{ei} A_{me} (T_{mei} - T_i) + \frac{A_{me} (T_{mei} - T_{meo})}{R_{me}} = 0 \quad (1)$$

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