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Research paper

Operating characteristics and efficiencies of an active chilled beam terminal unit under variable air volume mode

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HIGHLIGHTS

- The operating characteristics and efficiencies of an active chilled beam terminal unit were revealed.
- The performance indexes were correlated and mutually constrained with a colorful trapezoid.
- The sensitivity of the performance indexes to actual primary air and space conditions were evaluated.
- Application range of the active chilled beam terminal unit can be enlarged at a low primary air relative humidity.

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ABSTRACT

Appropriately designing and maintaining temperature and relative humidity in a given space is essential for active chilled beam systems, where condensation should be strictly prevented. As a consequence, the Total Cooling Output Capacity (TCOC) of an active chilled beam system should be matched with the total cooling load of the applied space, as well as the Sensible Heat Ratio (SHR) of the system with the SHR of the space. From such a perspective, this paper for the first time explored the operating characteristics of a 2-way discharge active chilled beam terminal unit. Based on an experimentally verified model of the unit, a series of realistic simulations were carried out under various primary air volume flow rates and various chilled water volume flow rates. Inherent correlations between the TCOC and SHR were revealed. In the meanwhile, the operating efficiencies of the unit were also measured by an energy saving potential index ε, which is defined as the ratio of chilled water sensible cooling output capacity to the total sensible cooling output capacity. In addition, influences of different primary air and space conditions on the operating characteristics and efficiencies were studied. The results obtained in this study are expected to facilitate a better understanding of the active chilled beam terminal unit, so as to the designs, the operating principles, and the control strategies of active chilled beam systems for an improved indoor thermal environment.

1. Introduction

Over the past few years, active chilled beam systems have become a popular alternative to all-air HVAC systems. Their adoption has been significantly fueled because of the space saving, energy conservation, indoor thermal comfort improvement, etc. [1–4]. However, these benefits are quite easy to be diminished even eliminated due to over-conservative, non-optimized system designs and/or operations. For example, in the design phase, system designers may attempt to increase primary air exceeding the space latent load and ventilation requirement considering transient infiltration, purge demand, tendency to put a safety margin, etc. It then leads to such application where the primary air provides sufficient cooling while all the chilled water control valves are closed throughout the entire summer [5]. In this case, active chilled beam terminal units become expensive and the inherited benefits are essentially declined. In the operating phase, most active chilled beam systems have the ability to turn down the primary air, but they may be set at constant air volume mode. That means the primary air is inevitably oversized at part-load conditions and

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Nomenclature

A	constant coefficient
A_a	constant coefficient
A_w	constant coefficient
B	constant coefficient
C	constant coefficient
C_a	air specific heat (J/(kg °C))
C_w	water specific heat (J/(kg °C))
ER	entrainment ratio
e	constant coefficient
k	constant coefficient
m	constant coefficient
n	constant coefficient
P	pressure (hPa)
Q	cooling output capacity (W)
R	constant coefficient
RH	relative humidity
T	temperature (°C)
T_n	constant coefficient
$\dot{V}_a$	air volume flow rate (m^3/s)
$\dot{V}_w$	water volume flow rate (L/s)
W	moisture content (g/kg)
ε	energy saving potential index
ρ	density (kg/m^3)

Subscripts

a	air
am	ambient
d	dew point
in	inlet
lat	latent
offc	off coil
pri	primary
s	space
sec	secondary
sen	sensible
tot	total
w	water

above declination could be further exacerbated. As a consequence, problematic or even erroneous deployments of active chilled beam systems do happen in practice and the perception of those benefits is sometimes just that, a perception, albeit misguided. For instance, Stein and Taylor [6] held a head to head competition between an active chilled beam plus dedicated outdoor air system and a variable air volume reheat system in California and concluded that the latter had much lower first cost and energy consumption but similar floor to floor height. This debatable conclusion then led to a series of heated discussions and arguments [7,8]. Kosonen and Tan [9] presented a case study to investigate the feasibility of active chilled beam systems in Singapore. It was shown that condensation is possible to be prevented if the infiltration is minimized, the primary air is sufficient to extract the humidity of people, and tuning of the automation system is conducted probably. However, four 2.1 m active chilled beam terminal units were installed in a 20 m^2 office room. Cost/benefit of such an application was questionable.

In reality, the community is still constantly seeking effective methodologies to utilize active chilled beam systems in different climates. An optimum system generally requires some specific parameters and ends up in many cases to be an iterative selection and design process. It is also urged to weight cost/benefit of various solutions on a project by project basis. Before that, appropriately knowing the operating characteristics and efficiencies of a system is definitely necessary, particularly on latent cooling output capacity [10]. Different from all-air HVAC systems, where space dehumidification is only a by-product of space cooling, it is a critical concern in active chilled beam systems. If the latent cooling output capacity of a system is oversized, the space humidity level becomes unnecessarily low, which results in a lot of energy wasted on treating and transporting the primary air. On the contrary, without sufficient latent cooling output capacity or designing a high humidity level may lead to some condensation issues, which conversely decreases the sensible cooling output capacity of the system due to the condensation avoidance actions. In addition, an exorbitant humidity level may cause growth of fungus and bacteria. Only when the system is perfectly matched with the conditioned space in terms of both sensible and latent cooling output capacities can indoor temperature and relative humidity be simultaneously and accurately controlled. Taking direct expansion air conditioning systems as an example, which has the same concern, Li and Deng [11] studied the TCOC and SHR of an experimental direct expansion air conditioning system under different combinations of compressor and supply fan speed, but only at a fixed space condition. Xu et al. [12] extended the study to various space conditions and depicted the system operating characteristics in a more intuitive form. Li et al. [13] carried out a further study to model and predict the system for humidity control purpose. These research results were indeed utilized in developing proper control algorithms [14]. As for active chilled beam systems, there exist a few proactive studies from the point view of latent cooling output capacity. For example, Loudermilk et al. [15,16] explored the humidity behaviors of spaces served by active chilled beam systems and forth brought some discussions on the system design and operation, but the studies were just in the form of case studies with some prescribed settings. Darren Alexander and O'Rourle [17] and Setty [18] listed some application issues for active chilled beam systems, also including the humidity related ones. It was suggested that using energy wheels and wraparound style heat pipes can enhance the system dehumidification ability in humid climates. Additionally, Wahed et al. [19] integrated a thermally regenerated desiccant dehumidification system with an active chilled beam system in Singapore.

Beyond that, it should be noted that in active chilled beam systems the ventilation requirement and latent load of a space can only be satisfied by the primary air, while the sensible load can be accommodated via either the primary air or the chilled water. Since using the chilled water to handle the sensible load is much more energy efficient, quantity of the sensible load shared by the chilled water can be an indirect measurement of the system efficiency. Livchak and Lowell [5] defined a parameter that represents this kind of important performance of active chilled beam terminal units and called it coil output to primary airflow ratio. As implied by the name, it is the amount of cooling output capacity produced by the chilled water per volume of the primary air used. The parameter can be a measurement of the efficiency of active chilled beam terminal units' design rather than of the systems' operation. In practice, coefficient of performance is the worldwide acknowledged measurement of HVAC components and systems, which is directly related to cooling output capacity instand of fluid volume flow rate. As a result, efficiencies of active chilled beam systems are