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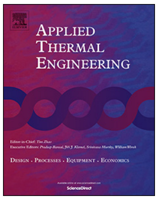

Research Paper

# Geometric optimization on active chilled beam terminal unit to achieve high entrainment efficiency

Zheming Guan *, Changyun Wen

*School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore 639798, Singapore*

## HIGHLIGHTS

- A terminal unit with novel geometry is proposed in this paper.
- The entrainment efficiency is increased by 30%, with the same ventilation ability.
- A new method of measuring entrainment ratio is proposed.
- The nozzle length used for the novel geometry is optimized.

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## ABSTRACT

In this paper, a novel structure of terminal unit is investigated to achieve high entrainment of room air. The energy efficiency of the whole system can thus be increased. Firstly, entrainment ratio of a commercial terminal unit is tested with a series of experiments. An innovative method of acquiring entrainment ratio is also proposed and validated throughout our experimental studies. Secondly, a computational fluid dynamics (CFD) model of this terminal unit is established for simulation study. It is verified that the model accords with the experimental data and is thus proved valid. Thirdly, the geometry of the terminal unit based on the CFD model is modified in CFD software to achieve higher entrainment ratio. It is found that, by changing the geometry of the mixing chamber and lengthening the nozzle, the modified structure can increase entrainment ratio by 30% with the same working condition and primary air volume flow rate. The height of the terminal unit is also suppressed to fit a tighter space. This study proves that the entrainment ratio of a terminal unit, as well as the efficiency of the whole air conditioning system, can be effectively increased by proper modification on its geometry. The findings about the nozzle can also guide the adjustment of other geometric characters of the terminal unit.

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## 1. Introduction

Heating, ventilation and air conditioning (HVAC) systems with active chilled beams (ACB) terminal units are attracting increasing attention in both theoretical research and practical application, due to their superior benefits compared with variable air volume (VAV) systems [1–5]. In conventional VAV systems, a large volume of recirculation air is distributed through ductwork by big exhaust and supply fans. The energy consumed by these fans is enormous. As water has a much higher heat capacity compared with air, the ACB system utilizes water instead as the media of heat exchange, saving energy from delivering less volume of air. The volume of water transferring the same cooling is much smaller than air. Therefore, ACB systems are more energy efficient, by taking advantage of using less energy in distributing the chilled water directly to the air-conditioned space [6].

Besides its superior performance in energy saving, ACB system may reduce the total construction cost of a building. In most office buildings, the space above the suspension ceiling is occupied by HVAC system ductwork and terminal unit, lighting facilities, cables, etc. If the space above the suspension ceiling can be suppressed, the floor-to-floor height can be reduced and so is the cost of construction. In most cases, the bottle neck of reducing this space is the size of the HVAC system ductwork and terminal units. The ductwork used in ACB system is smaller than the VAV system, as the volume rate of primary air needed for ACB system is smaller. The terminal unit of ACB system is usually smaller in height, but there is still room to improve. In fact, the great potential of the ACB system has been well recognized in the building industry. The ACB system has been accepted by building service industry, and it is promoted as a “green” HVAC system solution [4,7].

Although cooling is delivered mainly by chilled water, a small amount of air is still needed for circulation and dehumidification.

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* Corresponding author. Tel.: +6583574222; fax: +6567933318.
*E-mail addresses:* zhemingguan@gmail.com; guan0036@e.ntu.edu.sg (Z. Guan).

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The ACB system consists of two parts of air circulation: primary air and room air. Supplied by an outdoor air system, the primary air is cooled to partially handle the temperature-driven sensible loads, and more importantly, dehumidified to handle all the moisture-driven latent loads. The room air circulates from the room to the terminal unit, exchanges heat with the cooling coils and fins inside the terminal unit, and is discharged back to the room. The cooling coils and fins, more commonly known as the chilled beams, are the major supply of cooling. The entrainment ratio (ER), defined as the ratio of the mass flow rate of room air induced to the mass flow rate of primary air supplied, is a significant index for an ACB system that evaluates the efficiency of the terminal unit and thus the overall energy performance. Larger ER contributes to a more efficient terminal unit, and the system will eventually be more economical in the long run [8].

To efficiently use the primary air, attention has been paid on increasing ER in many aspects. In Reference 3, by focusing on minimizing the volume flow rate of primary air and maximizing the use of water coil, a fan-assisted or VAV beam is proposed, which uses a built-in fan to increase the circulation of room air. Although VAV beams can largely increase air circulation and heat exchange rate between room air and chilled beams, the cost of terminal unit will increase. Moreover, the moving parts like motor will also introduce noise and increase maintenance cost, which compromises the advantage of ACB system over VAV system. Some commercial companies, such as DADANCO, utilizes unique nozzles to provide high ER [9]. The results show that the use of unique nozzles can increase entrainment ratio, but the effects are limited. Nozzles with small diameters can increase ER effectively, but they also lessen primary air, which leads to conditioned room suffocating and also weaken the ability of handling latent load.

We have performed numerical investigations on the geometry parameters for designing efficient terminal units in Reference 10. The results clearly show that ER can be affected by nozzle radius and distance between nozzles, but the geometry of the terminal unit is not finalized. Despite these valuable results, there is still a lot of work to do. In a nutshell, it is an interesting and promising research topic to design a terminal unit with better performance by examining the geometrical shape and nozzle length, which is the focus of this paper.

We firstly investigate the ER of a commercial terminal unit, referred as Type I structure. In acquiring ER, primary air mass flow rate and room air mass flow rate are needed for calculation. In Reference 11, the room air flow rate is measured with a polyester fibers hood. The hood has a smaller air inlet than the room air inlet of terminal unit. As a result, the room airflow is restrained. Besides, as the polyester fibers are soft and easily deformed, the room airflow may be interfered by the hood. To enhance the accuracy, we propose a new method of acquiring ER, which is validated by experimental tests.

In fluid dynamics analysis, the Navier–Strokes equations, which are the most fundamental equations, are nonlinear and difficult to solve. It is still a challenge to analytically model the fluid pattern. A common practice in fluid analysis is to implement a geometric model in computational fluid dynamics (CFD) software. CFD technique solves and analyzes the fluid flow inside the terminal unit in a numerical way. The velocity and pressure of air flow can be solved with minimum error with proper mesh and boundary conditions. Thus, a CFD model of Type I terminal unit is built according to the experimental set. The mesh and boundary conditions of the model are fine tuned. The CFD model can be proved to be valid if it gives solutions that are consistent with the experimental data. After validation, we aim to enhance the ER by revising the geometry of the model. After a number of tests, we propose a new structure for the terminal unit, referred as Type II structure. Then we implement a CFD model of Type II structure in the same way as we implement Type I. The ERs of Type II structure under different working conditions are obtained through a batch of simulations on its CFD model. The performances of Type I and Type II are compared in terms of ER and primary air mass flow rate. In addition, the CFD software allows us to further investigate the optimal length of nozzles of the Type II structure. The results show that the Type II structure is superior to the Type I structure. Firstly, the ER is increased by 30% with the same primary air mass flow rate. The efficiency of the terminal unit is increased without sacrificing the ventilation ability. Secondly, the height of the mixing chamber is suppressed by 56 mm, which allows the Type II structure to be able to fit tighter spaces.

The remainder of this paper is organized as follows. Section 2 describes the principles of ACB terminal units. Section 3 presents the experiment setup and results of Type I terminal unit. The geometric modeling of Type I structure in CFD software follows in Section 4. Section 5 presents the CFD model of Type II terminal unit with some analyses and investigates how the length of its nozzles affects the ER. Section 6 compares the Type II terminal unit with a commercial product. Section 7 concludes this paper.

## 2. System description

Fig. 1 shows the Type I terminal unit schematics in the market. This terminal unit originates from a commercial product of DADANCO [9]. It consists of a primary chamber for primary air supply, a series of nozzles for primary air ejection, a mixing chamber where ejected primary air mixes with induced room air, and cooling coils and fins, i.e. chilled beams.

The airflow inside the terminal unit is illustrated in Fig. 2. The sufficiently cooled and dehumidified primary air is delivered to the primary chamber through ductwork by around 100 Pa pressure. The actual pressure may vary with ductwork shape and the distance to the air handling unit (AHU). The primary air is then ejected to the mixing chamber through the nozzles. The high speed ejected air forms a low pressure kernel near the nozzle exits, which induces room air into the mixing chamber. The warm room air, under the effect of suction and convection, will rise from room to terminal unit. The warm room air traverses and exchanges heat with the chilled beams. The cooled room air mixes with the ejected primary air and then is discharged to the air circulation in the room.

In this HVAC system, only the primary air is dehumidified and therefore all the latent load is handled by the primary air. Most of sensible load is handled by chilled beam. The more heat taken away

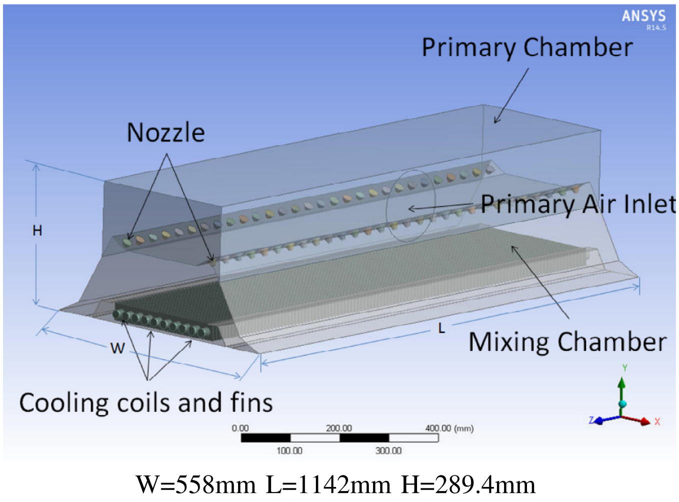

**Fig. 1.** Structure of a commercial terminal unit.

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