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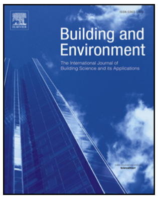

Experimental and numerical investigations of a new ventilation supply device based on confluent jets

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ABSTRACT

In developed countries, heating, ventilation, air conditioning (HVAC) systems account for more than 10% of national energy use. The primary function of a HVAC system is to create proper indoor environment. A number of ventilation strategies have been developed to minimize HVAC systems' energy use whilst still maintaining a good indoor environment. Among these strategies are confluent jet ventilation and variable air volume. In this study, an air supply device with a novel nozzle design that uses both of the above-mentioned strategies was investigated both experimentally and numerically at three different airflow rates. The results from the numerical investigation using the SST k - ω turbulence model regarding velocities and flow patterns are validated by experimental data carried out by Laser Doppler Anemometry. The results from both studies show that the flow pattern and velocity in each nozzle is directly dependent on the total airflow rate. However, the flow pattern does not vary between the three different airflow rates. The numerical investigation shows that velocity profiles for each nozzle have the same pattern regardless of the airflow rate, but the magnitude of the velocity profile increases as the airflow increases. Thus, a supply device of this kind could be used for variable air volume and produce confluent jets for the airflow rates investigated.

1. Introduction

Buildings generate about one-third of global greenhouse gases, utilizes about 40% of the world's energy, and consume 57% of all electricity [1]. In developed countries, HVAC systems are responsible for about 50% of the buildings' energy use and between 10 and 20% of a nation's total energy use [2]. Many measures are being taken to reduce energy usage in the building sector, such as new and stricter building codes, green building schemes and energy efficient renovations. The EU has set a target to reduce greenhouse gas emissions by at least 80% by 2050 from the 1990s level [3]. Of all the buildings that will be in use in 2050 in the European Union, 60% of them have already been built [4]. Therefore, the EU has identified the existing building stock as the "single biggest potential sector for energy savings" [3].

Renovation of buildings tend to focus on improving the thermal performance of building envelope using different energy efficiency measures (EEMs) such as additional insulation, well-insulated windows [5]. While these EEMs reduce the heat losses they may also lower the infiltration rate, e.g. changing the windows can lower a building's air exchange by as much as 0.25 ACH [6]. This may have the adverse effect of lowering the indoor air quality (IAQ) [7]. When buildings are being renovated green building schemes are often used to evaluate the building. On average the IAQ only makes up 7.5% of the total score in these schemes [8].

Numerous studies have shown the importance of IAQ and adequate ventilation rates in public buildings regarding health [9–11], cognitive abilities [11,12], academic performance [12–15], work and economic productivity [10,16–18]. Therefore, more standards and recommendations are being set to increase the airflow rates in public buildings such as schools, hospitals and office buildings [19]. A survey by the Swedish Energy Agency showed that electricity use in Swedish schools increased between 1990 and 2006 despite a national effort to decrease the electricity use [20]. The survey concludes that the increase is because the electricity use by ventilation fans doubled during the same time span, in order to satisfy demands for higher airflow rates and IAQ. The same survey showed that 87% of Swedish schools still use constant air volume (CAV) systems and that the switch to variable air volume (VAV) systems could save between 0.12 and 0.33 TWh annually.

A number of recent studies have been made on the implementation of VAV in buildings [21–25]. VAV have the potential for improving the IAQ [21], greatly reducing the energy use [21,22] and therefore reduce cost [22,23]. Two recent studies have showed that a scenario where

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Nomenclature

d	Inside diameter of nozzle [m]
D	Inside diameter of nozzle duct [m]
h	Distance from nozzle [m]
k	Turbulent kinetic energy [m^2/s^2]
P_k	Production term of k [kg/ms^3]
Sij	Strain rate tensor [1/s]
TI	Turbulence intensity [-]
U	Streamwise velocity [m/s]
U_{avg}	Average streamwise velocity [m/s]
U_{max}	Maximum streamwise velocity [m/s]
$U_{measured}$	Streamwise velocity measured by LDA [m/s]
$U_{predicted}$	Streamwise velocity predicted by CFD [m/s]
V	Spanwise velocity [m/s]
y^+	Dimensionless wall distance [-]

Abbreviations

CAV	Constant Air Volume
CFD	Computational Fluid Dynamics
CJ	Confluent Jet
CJV	Confluent Jet Ventilation
CJSD	Confluent Jets Supply Device
DV	Displacement Ventilation
EEM	Energy Efficiency Measures
IAQ	Indoor Air Quality
LDA	Laser Doppler Anemometry
MV	Mixning Ventilation
SMP	Selected Measurement Point
VAV	Variable Air Volume

Greek letters

$u_i' u_j'$	Reynolds stresses [m^2/s^2]
Δij	Kronecker delta [-]
ε	Rate of dissipation of turbulent kinetic energy [m^2/s^3]
ρ	Density [kg/m^3]
μ	Dynamic viscosity [(kg/ms]
μt	Eddy viscosity [kg/ms]
ω	Specific dissipation rate [1/s]

VAV was implemented in small, medium and large offices in the U.S. (~75% of US office floor space) could save \$28 billion annually with a VAV-strategy optimized for energy savings [23] and \$55 billion for a VAV-strategy for the improving work performance [21]. The VAV-strategy for optimized for energy savings could save 53 TWh annually [22]. Research into VAV has showed that both the minimum and maximum airflow for a VAV-system has high impact on the HVAC-system overall energy demand [22–28]. It is therefore important if VAV is implemented that the supply devises can handle the minimum/maximum airflow and that the ventilation strategy works in both cases.

There is a potential conflict between IAQ and the energy performance of buildings [5]. Since improving the building envelope minimizes heat losses and improves indoor thermal climate, it sometimes has the adverse effect of lowering IAQ [6]. At the same time, the increases in ventilation rates in service buildings to improve IAQ will increase the power demand of the HVAC systems, which will affect the building's energy performance [20].

The main objectives of any ventilation system with regards to IAQ, comfort and energy performance are providing fresh air, removal of indoor contaminants and the removal of heat [29]. Mixing ventilation (MV) is the most common ventilation system, designed to dilute the polluted and cool/warm room air with supply air to lower the contaminant concentration and regulate the temperature [30]. The air is often supplied with high momentum mainly from ceiling and can be used for both heating and cooling of the room. MV systems are quite versatile and can have a larger occupied zone than other systems, which frees up valuable floor space. MV often have very good thermal comfort, however, MV systems have lower air exchange effectiveness and lower heat removal effectiveness compared to stratified systems and therefore a lower energy efficiency [29,31]. Another common ventilation principle is displacement ventilation (DV) which supplies air below room temperature at floor level in order to create vertical gradients of temperature and air contamination [30]. DV has a high heat removal effectiveness and high air exchange effectiveness [29,32]. DV can only be used for cooling and is therefore not as versatile as MV and there may be issues with thermal comfort and draft complaints [29,33].

Some research has been done on a hybrid system between displacement ventilation and mixing ventilation based on confluent jets (CJ). Confluent jets occur when jets issue from different apertures in the same plane in parallel directions, and at a certain distance downstream they coalesce and move as a single jet [21]. Some studies show that the velocity of confluent jets decays more slowly than other forms of jets because of lower entrainment of surrounding air. The momentum is therefore conserved better and ventilation based on CJ has better penetration of the occupied zone than other ventilation strategies [34–37]. In a series of studies, the dynamics of CJ were investigated and it was found that the spacing between jets, the diameter of jets and the velocity of the jets have the highest influence on the characteristics of the CJ flow [39–43]. Several studies report good energy efficiency and IAQ for different air distribution systems based on confluent jet ventilation (CJV) [34–38]. In both lab studies [34,35] and field studies [38], CJV in a classroom environment has been investigated with various heat loads and airflow rates. All three studies showed that CJV was able to sustain a good thermal comfort and high IAQ. All three studies also showed a higher thermal comfort when compared to DV.

This paper is a part of a series of studies with the aim to investigate the possibility of optimizing an air supply device based on confluent jets (confluent jets supply device CJSD) for a classroom environment with regards to IAQ, thermal comfort and energy efficiency. The aim of this study is to investigate the outlet flow feature of a CJSD. The supply device has a novel nozzle design, the effects of which will be investigated both experimentally and numerically. The object of this study is to reveal that if a supply device with this kind of nozzle is suitable for VAV, if a variation in airflow rate will influence the air distribution from the supply device's outlets. The experimental study is used to test and validate the predicted internal airflow pattern and velocity profiles for the CJSD using computational fluid dynamics (CFD). These results will be used to access the characteristics for the jets produced by the supply device and how those characteristics may depend on the supplied airflow rate and configuration of the supply device.

2. Experimental set-up

The experimental study was carried out in a well-insulated test room with the dimensions 8.4 × 7.2 × 3.0 m, located in the Laboratory of Ventilation and Air quality at the University of Gävle, Sweden. The door and air vents were closed as well as the indoor air temperature was regulated during the experiment (except for the centrifugal fan and the measurement equipment) in order to provide an isothermal condition.

The airflow was supplied by a centrifugal fan controlled by a frequency regulator, see Fig. 1. The airflow rate was measured by an orifice flowmeter. The pressure drop over the flowmeter was measured and registered frequently with a SwemaMan 80 micro manometer,