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Novel cylindrical induction controller and its application in VAV air conditioning system in an office building

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ABSTRACT

High performance variable air volume (VAV) air-conditioning systems can be as energy efficient as systems based on water or refrigerant, while first and life-cycle costs of such systems are significantly lower. The paper presents experimental test results of a novel cylindrical induction VAV controller and simulation results of energy consumption and thermal comfort in an office building with such controllers. A method for estimation of the minimum induced airflow required to avoid cold air dumping and a method for induction controllers and diffusers selection and sizing are proposed. To compare the VAV system with induction controllers and two other popular air conditioning systems, in terms of energy consumption and thermal comfort in an office building, the IDA Indoor Climate and Energy simulation tool was applied. The comparison was made for moderate climate conditions of Krakow, Poland, typical of Central and East Europe. The results showed that the total consumption of the electric energy used in cooling season for cooling and media transportation was similar when using a VAV system with induction controllers, a system with air chilled beams or a fan coils system. Similar thermal conditions were also observed.

1. Introduction

To fulfil high requirements regarding indoor environment quality (IEQ), modern office buildings need to be equipped with air conditioning systems (AC) that consume high amount of energy. The choice and optimization of AC systems, taking into account both energy consumption and IEQ, is still an actual and important issue [1–4]. When selecting an AC system, many factors, e.g., the building type and exploitation, local climate, first and operating costs on the local market, local regulations and practices, reliability of the system, control strategies and others should be taken into account [5–8]. Many researchers have recently found that the control strategies have significant impact on the energy consumption and IEQ [8–13]. According to many reports, high-performance variable air volume systems (VAV) can be as energy efficient as outdoor air systems (DOAS) with active chilled beams and that they can be superior regarding to first and life-cycle cost [14–17]. High-performance VAV systems can be achieved when advanced design and control strategies regarding ducts sizing, fan selection, fan-pressure optimization, optimal start/stop, supply air temperature reset, demand controlled ventilation and others are applied. The most important features of high performance VAV systems are listed in [14,17]. In the report [14] and in a few other recent papers [18,19] it was concluded that to ensure high energy efficiency during low heat load periods the airflow should be reduced as low as possible, approximately to 20% of its nominal value (five times). The minimum airflow rate supplied to the air-conditioned zone is the main factor affecting the indoor environment quality and the energy consumption.

Significant decrease in the supply airflow in cooling mode may cause cold air dumping. The reason is that the ratio of buoyancy and momentum forces (the Archimedes number) increases significantly, approximately 25 times when the airflow is reduced to 20% of its nominal value. Additionally, the throw length of the jets, which is typically proportional to the airflow, decreases significantly. Then, there is a risk of the jet detachment from the ceiling and the cold air will flow directly to the occupied zone which will result in a risk of the local thermal discomfort caused by draft. The decrease in the supply airflow in heating mode deteriorates the air mixing in the room and, in result, it decreases the air change effectiveness and increases the temperature stratification. The weak supplied jets can be easily affected by convective plumes above different heat sources in the room, e.g. interaction of the supplied cold air jet with thermal plumes generated by a hot window, an occupant and a computer can result in cold air dumping and local thermal discomfort caused by draft sensation at the adjacent workplace [20].

If high quality of indoor environment in the whole occupied zone, during the whole occupancy time is required the phenomena of cold air dumping and stratification should be avoided. In

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high performance VAV systems the risk of cold air dumping can be eliminated when using:

- variable-geometry VAV diffusers, in which the supply slot size is controlled by the actuator depending on the supply air volume,
- fan assisted VAV terminal boxes which take the primary (air conditioned) and plenum (room) air, mix the two and provide the approximately constant airflow to the zone,
- induction controllers instead of traditional controllers.

Induction controller induces room (plenum) air and mixes it with primary (conditioned) air. The airflow delivered through the induction controller to the zone is the sum of the primary airflow and the plenum airflow. Due to mixing the air supplied by diffusers to the room has higher temperature and higher flow rate than primary air. The use of induction VAV controllers reduces both the range of changes in the velocity of the air supplied to the zones and the difference between the air temperature in the room and the supplied air temperature. The operation principle of the induction VAV controller is described in detail in [21]. Using VAV induction controllers it is possible to change the primary air flow rate within a wide range without the risk of cold air dumping. Consequently, lower energy consumption for the air transportation can be expected. However, the results of the energy performance for the VAV system with induction controllers have not been described in the literature yet.

VAV induction controllers are available on the market (induction VAV air volume control terminals NV series, induction terminal unit IPV, IDV series). They are produced as rectangular boxes 2–3 times wider and 1.5–2 times higher than the controller inlet spigot diameter. The primary air flowing through a narrow slot into the rectangular induction chamber generates a plane wall jet or a plane free jet that induces the plenum air. The primary airflow is controlled by changing the height of the supply slot, i.e., by changing the angular position of one or two damper blades. In the author's previous study [21] the rectangular controller with two damper blades was tested experimentally and numerically (using the CFD) and a satisfactory agreement between the CFD and the measurement results was found. The tested construction of the controller with two damper blades fulfilled the most important requirement for VAV induction controllers, i.e., high induction of the plenum air at the minimum flow rate of the primary air. Despite the fact that the previous test results were positive, other constructions of the induction VAV controller were considered as well. In result, a new cylindrical construction of the induction controller was invented (patent pending, P.412626 Polish Patent Office).

There is a lack of research results of the induction VAV controllers and their performance in the VAV system. The paper presents:

- the construction and tests of the novel cylindrical induction VAV controller,
- the method for estimation of the required minimum induced airflow to avoid cold air dumping,
- the method for induction controllers and diffusers selection and sizing,
- comparison of the VAV system with induction controllers, air chilled beams system and fan coils system, in terms of energy consumption and thermal comfort, in an office building for moderate climate conditions of Krakow, Poland, typical of Central and East Europe.

2. Tests of the cylindrical induction VAV controller

The novel cylindrical induction VAV controller, as shown in Fig. 1, consists of standard cylindrical ventilation elements such as: inlet, IRIS damper and outlet. The outlet diameter may be the same as the inlet diameter or it may be one size larger. The circular orifice of the IRIS damper forms the axisymmetric air jet which is discharged into the outlet element. The jet induces plenum air through the open space between the two parts of the controller. The IRIS damper is adjusted by an electric actuator which receives a signal from the control system. The invented controller construction is simple and compact, the controller can be easily connected to ventilation cylindrical ducts. Such the construction minimizes the local pressure losses at the inlet and outlet of the controller.

The induced airflow depends on the controller construction and the overpressure at the inlet of the controller P_1. This airflow is characterised by the induction ratio:

$$\mathrm{N_V} = \dot{V}_3/\dot{V}_1 \tag{1}$$

For constant P_1 the induction ratio depends on the primary airflow $\dot{V}_1$ and the flow resistance of the terminating elements characterised by the coefficient ζ [22]:

$$\zeta = 1 + \frac{P_2}{0.5 \cdot \rho \cdot W_2^2} = 1 + \frac{2 \cdot A_2^2 \cdot P_2}{\rho \cdot \dot{V}_2^2} \tag{2}$$

To evaluate the performance of induction controllers it is necessary to know the amount of the air induced from the plenum $\dot{V}_3$, that would ensure (when it mixes with the primary air) sufficiently high airflow $\dot{V}_2$ and sufficiently low temperature difference of the air in the room and the air supplied by the diffuser $\Delta t_2 = t_r - t_2$ to guarantee low buoyancy and inertia forces ratio of the jet discharged into the room. The aim of the below analyses is to determine the minimum value of the induced air $\dot{V}_{3\,\mathrm{min}}$.

2.1. Required minimum induced airflow of VAV induction controllers

A decrease in the supply airflow causes the inertia forces decrease. Thus, the absolute value of the buoyancy and inertia forces ratio (the Archimedes number) increases significantly. The Archimedes number can be calculated from the equation:

$$Ar = \frac{\beta\, g\, A_{eff}^{0.5}\, \Delta t_2}{W_{eff}^2} = \frac{\beta\, g\, A_{eff}^{2.5}\, \Delta t_2}{\dot{V}_2^2} \tag{3}$$

where Δt_2 is temperature difference of the air in the room and the air supplied by the diffuser, A_{eff} is the diffuser outlet opening effective area, W_{eff} is effective air velocity at the diffuser outlet, β is the air volumetric expansion coefficient and g is acceleration due to gravity.

For the induction controller the air volume flux at the inlet of the diffuser $\dot{V}_2$ (as shown in Fig. 1) is a sum of the primary (air conditioned) airflow and the induced airflow $\dot{V}_2 = \dot{V}_1 + \dot{V}_3$. Owing to the induced air and primary air mixing the temperature difference of the air discharged by the diffuser is equal to:

$$\Delta t_2 = \Delta t_1 \frac{\dot{V}_1}{\dot{V}_1 + \dot{V}_3} \tag{4}$$

where Δt_1 is temperature difference of the induced room air and the primary air $\Delta t_2 = t_r - t_1$.