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Investigation of efficient air pollutant removal using active flow control

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A B S T R A C T

Efficiency in maintaining indoor air quality is central to the operation of high-performance buildings. The purpose of this work was to investigate the effect of airflow velocities generated by a low-power annular, multi-orifice synthetic jet actuator (SJA) on the degradation rate of a model air pollutant, nitrogen dioxide (NO_2), by a photocatalytic surface. In this study, the active flow fields generated by the SJA were first characterized, and the effect of SJA-to-wall distance was analyzed as the airflow impinged on a wall of varying surface textures. Second, the impact of flow characteristics, namely surface velocity and velocity distribution, on the removal rates of NO_2 by the photocatalytic surface was investigated in a closed chamber. Results showed that a SJA-to-wall (L) distance of 315 mm had the greatest reduction (dampening) on peak airflow velocities. Also, the surface with the highest roughness used in this study resulted in increased turbulence at the wall surface. The use of the SJA enhanced the removal rate of NO_2 compared to passive (control) conditions. Increases in air velocity, however, did not monotonically enhance the removal rate of NO_2. The highest removal rate (k = 0.0013 min^{-1}) was measured at L = 315 mm, where the highest velocity dampening was observed. It also corresponded to an average surface velocity of approximately 0.1 m/s across the photocatalytic surface.

1. Introduction

High performance buildings require greater air tightness and, thus, increased need for indoor ventilation, which can lead to an overall increase in heating and cooling loads [1–4] especially as climate change effects increase [5]. Some modern building materials and furnishings have also introduced a variety of pollutants, including volatile organic compounds (VOCs) as well as highly reactive molecules and radicals such as ozone, nitrous oxides, hydroxyl radicals, and sulfur dioxides [6,7] into the indoor environment. Reducing pollutant emissions from materials increases both actual and perceived indoor air quality [8,9]. Sick Building Syndrome (SBS) is a term used to diagnose buildings where occupant exposure to indoor pollutants has led to negative health effects [10,11] and productivity losses. Studies have shown that improving indoor air quality in U.S. buildings can save $30 billion annually by reducing occupant sick days [12].

Traditionally, indoor air quality has been improved by increasing ventilation using energy-intensive central Heating Ventilation and Air Conditioning (HVAC) systems. Thus, methods and means to achieve acceptable building air quality without costly energy usage have become increasingly attractive. Task/ambient conditioning (TAC) systems, such as individually controlled under-floor air distribution and desk-level supply air diffusers, have been proposed as alternatives for improving indoor air quality in buildings [13–17]. Sorptive and photocatalytic building materials have also been proposed as pollutant sinks that can alleviate energy demand on large-scale central systems particularly in geometrically complex interiors [14,18]. The use of low-energy devices like synthetic jet actuators for indoor air quality applications have also been proposed in the past [19,20].

1.1. Synthetic jet actuators

Considered zero net mass flux devices, synthetic jet actuators (SJAs) are mechanical devices used to generate air flows that require zero mass input and produce non-zero momentum output [21]. Additional advantages of SJAs over conventional fans are that they can be mounted to surfaces, require less space, and provide

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greater heat transfer rates [22]. These characteristics make SJAs desirable for electronic applications. The oscillating motion of a diaphragm (driven by piezoelectric, mechanical, or magnetic means) in the SJA cavity alternates between suction and ejection of fluid through the orifice. This process creates a continuous synthetic jet where the vortices are comprised entirely of ambient air. When a vortex is ejected through the orifice, it is propagated downstream and new ambient air is entrained in the cavity.

Synthetic jets have been used to enhance natural convection [23–25], to vector air streams, and to manipulate fluid [20,26–28] and aerosols [19,29,30]. In addition, synthetic jets have been used extensively in heat transfer research [22,23,31,32]. Pavlova and Amitay [32], for example, found that, at the same Reynolds numbers, synthetic jets provided up to three times more cooling from surfaces than continuous jets due to the enhanced mixing generated by the coherent vortex rings formed by the synthetic jets. Chaudhari et al. [23], investigated multi-orifice synthetic jets (with a center orifice surrounded by satellite orifices) and found that heat transfer coefficients using this device were 12 times those of natural convection and up to 30% larger than those of traditional single orifice synthetic jets. Travnicek and Tesar [33] experimented with annular synthetic jets for impinging flow mass transfer and found that annular synthetic jets operating at low frequencies retained their individual vortices for a longer distance compared to high-frequency jets. There are no known studies that have investigated the use of SJAs for gaseous pollutant removal applications; however, one study investigated the use of SJA to control aerosols in a room [19].

1.2. Air velocity and pollutant removal

Several previous studies have investigated the impact of air velocity on the removal of volatile organic compounds (VOC) [34–36] and ozone [37] by building materials; however, no clear consensus has emerged. Jorgensen et al. [34] reported negligible effects of velocity on alpha-pinene and toluene sorption by wool carpet. Zhang et al. [35] also found that increased air velocity had an insignificant effect on the sorption of most test compounds and material combinations except for dodecane on carpet, where increased air velocity led to increased sorption. Kjaer and Tirkkonene [36], however, found that, for gypsum board, the desorption rate of a mixture of 17 compounds increased with velocity.

Previous work using ultraviolet (UV) light-induced photocatalytic degradation of nitrogen dioxide (NO_2) by titanium dioxide (TiO_2) found that the efficiency of NO_2 reduction (%) increases with pollutant contact time. In general, larger surfaces, lower air velocities (<2 m s^{-1}), lower relative humidity, higher turbulence, and higher incident light angle all enhanced NO_2 pollutant reduction [38–40]. Maggos et al. [39] studied the photocatalytic removal rate of NO_2 by commercial paints containing TiO_2. Their pollutant removal rate was measured as photocatalytic oxidation rate (PR), in μg m^{-2} s^{-1}. In the case of water-based styrene acrylic paint treated with 10% TiO_2 exposed to 1 h of UV irradiation and exposed to an initial concentration of 220 ppb NO_2, the researchers reported a PR of 0.11 μg m^{-2} s^{-1} [39].

The objective of the present study was to analyze the flow-field characteristics generated by a commercial SJA and their effect on the removal rates of NO_2 by a photocatalytic surface. This study focused on a single model pollutant (NO_2) to demonstrate this novel application of synthetic jet actuators (SJA). The NO_2 photocatalytic process was selected because it is well understood; therefore, the novelty of this work lies in the characterization of the SJA flows and their effect on the NO_2 removal – not in proving the NO_2 reduction. In a first set of experiments, the flow fields generated by the SJA were studied in the absence and the presence of an impinging wall of varying texture, located at different distances from the SJA. A second set of experiments, conducted in a closed chamber, studied the impact of air velocities generated by the SJA on the removal rate of NO_2 by a photocatalytic surface.

The ultimate goal of this work is to demonstrate that these devices can be used in targeted (i.e. directed) flow control applications in buildings, such as localized ventilation and/or improved/controlled flow in HVAC systems. Understanding the performance of the SJAs in such larger-scale studies first necessitates more fundamental studies on the SJA performance, as in this study.

2. Materials

2.1. Synthetic jet actuator (SJA)

A low-frequency, annular, multi-orifice synthetic jet (SynJet ZFlow 87 LED Cooler) was purchased from Nuventix Inc. (Austin, TX). The flow range and field of this synthetic jet were characterized in previous work [41]. That was the first published characterization study for this commercial SJA and it does not overlap with the work reported here. The device is comprised of 8 annular slots, each 2 mm wide and evenly spaced around the perimeter of the SJA face. The power consumption of the device is 0.46 W, with a current draw of 38 mA. A 12 V DC power supply provides a sine wave current load that is two times the actuator displacement to account for both positive and negative directions of the diaphragm. The frequency is estimated between 100 and 120 Hz. While synthetic jets can be noisy and, according to Arik and Setlur [24], can reach 65 dB, the SJA model used in this study has a maximum noise level of 27 dBA and a silent performance mode of 19 dBA. Abarr et al. [41], described these and other advantages in more detail. For example, this SJA was determined to be axisymmetric, which simplifies its deployment. In addition, this SJA has a higher average dynamic pressure per power input compared to the ACF, leading to a mass flow confined to a smaller cross-sectional area and higher peak velocities. This feature could prove valuable for directing and confining flows.

2.2. Axial computer fan (ACF)

A 12 V DC, 40 mm ACF (model 70-4128, LKG Industries, Rockford, IL) was used in this study as a reference point and for limited comparison. The ACF power consumption was 0.96 W, with a current draw of 0.80 mA at 12 V. The fan had seven blades, each 10 mm wide with a blade pitch of 44.3°. Additional characterization of this fan is provided by Ref. [41].

2.3. Anemometer

A hot wire anemometer (Climomaster Model 6531, Kanomax, Andover, NJ) with an accuracy of 0.1 m s^{-1} was used to measure air velocity in the first set of experiments. The anemometer recorded 40, 1-s measurements at each location. The instrument reported average velocity and standard deviation.

2.4. Impingement wall surfaces

Three wall surface textures were studied to determine their effect on the peak velocity (at the center line) generated by the SJA: 1) a smooth, polished stainless steel sheet (900 × 900 mm), 2) a medium-grade 3M-brand sandpaper sheet (150 grit, 228 × 279 mm), and 3) a coarse sandpaper sheet (100 grit, 228 × 279 mm). The sheets were attached flush to the wall using an adhesive and placed perpendicular to the impinging airflow. The stainless steel sheet served as the smooth (control) wall surface.