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Internal Contaminant Source Dilution and Filtration in Dedicated Outdoor Air Systems

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Abstract

Heating, ventilation and air-conditioning (HVAC) systems account for more than 50% of energy use in residential buildings [1] and approximately three-quarter in healthcare environments [2]. Hence, HVAC systems are a favorable sector for sustainability with a great potential of energy savings. The engineering approach to this issue has led to the advent of newer and more sustainable technologies. Dedicated outdoor air systems (DOAS) are a case in point. By decoupling the sensible and latent loads, an enormous saving can be achieved in the amount of air to be conditioned. Ventilation systems are designed to satisfy three predominant requirements: (1) to deliver fresh air to occupants and dilute the indoor generated contaminants, (2) to control the temperature and humidity in indoor spaces, and (3) to pressurize the space.

There is ample evidence that the DOAS facilitates the last two requirements with more quality and less cost, which makes it more sustainable. This work, however, focused on the effect of using this system on the first requirement, particularly with regard to the indoor generated contaminants. The results showed that compared to the traditional ventilation systems, the DOAS system less effectively treats the indoor generated contaminants. Therefore, other mechanisms such as filtration must be properly implemented to limit the contaminants level below their standard threshold.

Keywords: Sustainable Design, Well-mixed condition, Ventilation, DOAS

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1. Introduction

The general purpose of building ventilation has evolved through the recent century. This evolution has undoubtedly altered the engineering approach toward ventilation design [3]. As a consequence, some traditional methods were no longer able to effectively address the new ventilation demands. To cope with this challenge engineers need to create new systems to best respond to the new objectives of a modern ventilation system. Ventilation systems are designed to satisfy two predominant requirements: (1) to deliver fresh air (replace the consumed oxygen) to occupants and dilute the indoor generated contaminants, (2) to control the temperature and humidity of the indoor space [4], and (3) to pressurize the space. Moreover, dealing with a multi-purpose system (e.g. building ventilation) could culminate in some conflicts as the system design has different purposes. Particularly, ventilation systems would not only solve the issues of thermal comfort, but they also should be able to maintain the indoor space’s relative humidity within the desired range. Thus, traditional ventilation, with a Variable-Air-Volume (VAV) system, does not always efficiently achieve a proper ventilation performance [5]. VAV systems mostly require higher airflow in order to maintain proper performance at all operational conditions [6].

Additionally, these two comfort elements (humidity and temperature) do not necessarily peak at the same time [7]. For example, in a hot outdoor condition the sensible load exceeds the latent load while on a rainy day these two operate inversely. The premise behind Dedicated Outdoor Air System (DOAS) ventilation is that it decouples the latent and sensible loads and makes each of them more manageable [8].

Essentially, the conditioning process is performed in two decoupled levels. Zone-level cooling provides the space with the circulated conditioned air with the desired temperature. Local coincidental dehumidification which occurs at this level is negligible. The main latent cooling takes place in the DOAS unit. This unit conditions outdoor air to the favorable humidity; given the dehumidification process, the outcome of this level is cool air (i.e. 11°C vs. 23°C) that can partly contribute to the sensible load control [9]. Generally, a DOAS system can be installed either in a series arrangement or in a parallel arrangement (Figure 1). In either case, a DOAS system is responsible for carrying the latent load (humidity control); however, the sensible load may be controlled by several mechanism such as using FCU (Fan Coil Units) or radiant-chilled beam [10]. In the case of series configuration, the outdoor air intake mixes with the return air prior to entering the room whereas for parallel configuration, the outdoor air intake is added to the supply pathway of recirculation process [11].

DOAS basically was developed to cover the traditional system’s pitfalls. Factors such as poor air distribution, poor humidity control, poor acoustical properties, poor resistance to the threat of biological and chemical contaminants and unpredicted ventilation performance are reported as the inherent problems of ventilation through a VAV system [11]. A proper implementation of DOAS system can mitigate the mentioned problems, and thus can be advantageous in many ways [8].

1.1. Efficient Ventilation

As opposed to the poor air distribution in the traditional VAV ventilation system, given the fact that the system will be designed based upon 100% outdoor air, the DOAS method can uniformly condition air in multi-space projects. Dieckmann [5] estimated the over-ventilation of VAV systems in the range of 20% up to 70% or more.

1.2. Ventilation performance

Unlike VAV systems which vary the flow rate to achieve thermal comfort, DOAS operates with a constant outdoor air flow rate which conditions based on satisfying the humidity set point. This variable flow of VAV systems exacerbates the ventilation performance prediction. Separating the sensible and latent loads would facilitate the system’s operational performance, which leads to energy conservation opportunities [11].

1.3. Architectural benefits

According to the DOAS energy consumption level, several architectural aspects of the building, such as ductwork could improve. Research on a government office tower reported an approximate 20% decrease in the overall
ductwork in addition to other benefits such as lower building floor to floor height, reduced shaft footprint and the elimination of a mechanical room on each tenant floor [12].

1.4. Building pressurization

Slight positive pressurization can improve the indoor air quality and consequently occupant’s comfort by impeding infiltration through the envelope. Mumma [13] studied the building pressurization and recommended a new package including a DOAS unit and a Total Energy Recovery (TER) wheel (enthalpy wheel) to effectively provide the interior space with sufficient pressurization. Pressurization, on the other hand, implicitly correlated to IAQ in terms of some particular purposes like radon leakage confinement through the building foundation.

1.5. Humidity control

Although humidity seems to be considered as a part of the system efficiency (i.e., non-IAQ) scope, there are serious aspects of IAQ related parameters regarding this issue. In fact, inadequate humidity control has been linked to discomfort, mold growth and various respiratory illnesses [13]. In their study, Fischer and Bayer [14] investigated the effect of relative humidity control in several school facilities. Conducting a study of 10 schools in Georgia, they observed a decrease on absenteeism (9% lower on average) in addition to an increase in ventilation effectiveness using a DOAS ventilation system.

1.6. Contaminant transport minimization

Contaminant containment is of enormous importance in IAQ management. Providing 100% outdoor air at supply on one hand, and removing 100% of exhaust air on the other hand would definitely help DOAS to hinder the contaminant transport from one zone to another in multi-zone spaces.

DOAS has some advantages over other systems while it is also accompanied by few disadvantages. For instance, given the fact that in many DOAS configurations (Figure 1) the circulation and outdoor air pathways are totally separated, one can challenge the assumption of a well-mixed condition. Another discrepancy regarding DOAS is that once a designer decouples the sensible and latent loads, the outdoor air intake would be estimated based upon the latent capacity of system, thus the fresh air intake in DOAS is significantly smaller than those of traditional systems. Hence, this phenomenon can culminate in a less effective contaminant decay process. Although DOAS effectively impedes contaminants from travelling from one space to another, this system is fragile toward diluting the internal contaminant sources. Therefore, designers should vigilantly consider the use of other contaminant decay mechanisms, such as filtration, to achieve the desirable air quality in the building.

Figure 1. DOAS ventilation system arrangement series (left), and parallel the correct paradigm (right) [11]
2. Research problem

Although vast efforts have been invested in DOAS development and its recent widespread use, less attention was paid to the contaminant transport behavior of DOAS. In his inspiring study, Mumma compared the contamination transport and filtration issues with DOAS versus VAV system [15]. He concluded that to obtain the same contaminant exposure rate for both systems, a high equivalent filter efficiency is required for DOAS. In fact, these systems do not resemble in terms of contaminant dilution, and in order to equalize the level of contamination higher efficiency filters should be installed on DOAS. For example, a 50% VAV filter is equivalent to 88% DOAS filter efficiency for one hour exposure. However, the entire model was constructed with the assumption of no internal contamination source. The only source of contamination was that entering with the outdoor air intake. Other studies have mostly mentioned the system performance with respect to IAQ issues in passing [16]–[18].

The purpose of this study is to address the contaminant’s spatial distribution in multi-zone space with a DOAS ventilation system in which both the internal source of contamination and outdoor contamination exist and compare it to the same condition with a VAV system. The correlation between equivalent filter efficiency in both conditions will be analyzed, and eventually the risk of contamination under different exposure circumstances will be calculated.

Spatial arrangements, ventilation rates, and basic information was extracted from Mumma’s study [15] to extend his findings. In fact, this study will scrutinize the existence of an internal source of contamination in addition to the other assumptions made by Mumma in the original paper.

3. Methodology

A facility with the total floor area of 20,000 ft² (1,858 m²) and 10 ft. (3 m) high ceilings was used, consisting of a two-zone perimeter region: 1,000 ft² (93 m²) zone 1 and 9,000 ft² (836 m²) zone2 respectively. The facility also has a large interior 10,000 ft² (929 m²) zone 3 (Figure 2). Airflow described below was used for this study:

- **VAV system:** Supply air (SA) flow rate, 16,000 cfm (7,550 l/s), of which 4,000 cfm (1,888 l/s) is outdoor air. Perimeter zones 1 and 2, each receives 1 cfm/ft² (5 l/s-m²) of supply air. Interior zone 3 receives 0.6 cfm/ft² (3 l/s-m²) of supply air via a VAV system. 25% of all above flow rates are outdoor air intake.
- **DOAS:** outdoor airflow for the facility, 4,000 cfm (1,888 l/s) uniformly distributed in each zone which equals to 0.2 cfm/ft² (1 l/s-m²).

The analysis was performed based upon the following simplifying assumptions:

- Well-mixed condition

![Figure 2. Zone arrangement plan](image-url)
There is no inter-zonal contaminant transfer (e.g. leakage)

There is no deposition onto the vertical and horizontal surfaces (e.g. walls and ceilings)

Under the well-mixed condition the conservation of mass differential equations were solved to obtain the concentration of contaminants for the VAV system.

\[
V_i \frac{dC_i}{dt} = Q_i (C_m - C_i) + S_i \rightarrow i = 1, 2, 3
\]

(1)

\[
C_m = \frac{Q_1 C_1 + Q_2 C_2 + Q_3 C_3}{Q_{total}}
\]

(2)

\[
C_{exh} = (1 - \eta_{VAV}) \frac{Q_{OA} C_{OA} + Q_{rec} C_{exh}}{Q_{total}}
\]

Where \( C_{exh} \) is the concentration experienced by the DOAS system with zero percent filtration efficiency (C_{peak}). Furthermore, S was defined as the internal contaminant source strength. For each zone, the standard source strength (S_s) was equivalent to the outdoor contaminant concentration, multiplying the outdoor concentration by the zone air flow (S_s = Q_{zone} × C_{peak}). Various rates of source strength from 0.1 S_s to 2S_s was used to explore the relationship between source strength and required filter efficiency. After revealing each zone’s contamination trend, the effective exposure was introduced as the amount of contaminant concentration over time which can be identified by the surface under the concentration diagram (\( \int C(t) \, dt \)). For each case, calculations were performed for a three hour period. This time interval was sufficiently prolonged after the steady state condition to ensure that no significant change would occur afterwards. The total effective exposure was computed by adding each zone’s effective exposure (\( EE = \sum \int C(t) \, dt \)). The total effective exposure was calculated for both the VAV and DOAS cases. Ultimately, the equivalent filter efficiency for DOAS was calculated by equalizing total effective exposure of the two systems. It was also assumed that the internal source can exist exclusively in one zone at a time. In other words, there was no simultaneous active internal source of contamination.

4. Results
An exponential asymptotic trend was observed for all zones under the VAV and DOAS ventilation strategies (Figure 3). However, the concentration was higher under the DOAS mode which suggested that this ventilation system is more susceptible to an internal source compared to the VAV system. The total concentration was higher for the smaller zone (zone 1). Intuitively, when the contaminant was released in a larger zone, the same magnitude of contaminant distributed in a larger space. Thus, the steady state concentration declined. On the contrary, the contaminant was circumvented within the room where it was initially generated in DOAS ventilation system. Also, steady state condition reached later for the DOAS compared to the VAV system indicating the tardiness of the system in diluting the contaminants.

Relying solely on contaminant dilution via ventilation did not seem to be a sufficient solution to decay the internal source concentration. Therefore, the existence of other mechanisms such as filtration were deemed to be necessary. The analysis suggest that more efficient filtration was needed for the DOAS system as the contaminant source strengthened. In fact, stronger internal source inversely affected the decay rate for both systems, although this behavior was more salient for DOAS rather than VAV system (Table 1). Since the filter was placed on the outside air entrance, it practically had no effects on reducing the concentration of the internal source for the DOAS case. This means that to gain a comparable result in terms of contaminant concentration, not only should the filters be installed for the outside air, but each space must also be filtered separately.

Table 1. Filter efficiency- VAV vs. DOAS equivalency. Internal source in zone 1

| VAV filter Efficiency | 10%  | 20%  | 30%  | 40%  | 50%  | 60%  | 70%  |
|----------------------|------|------|------|------|------|------|------|
| Source strength % of Ss | DOAS equivalent filter efficiency |
| 10%                  | 36.1%| 54.6%| 68.4%| 79.1%| 87.6%| 94.4%| ---- |
| 20%                  | 47.2%| 66.0%| 80.0%| 90.9%| 99.5%| ---- | ---- |
| 30%                  | 58.2%| 77.3%| 91.6%| ---- | ---- | ---- | ---- |
| 40%                  | 69.3%| 88.7%| ---- | ---- | ---- | ---- | ---- |
| 50%                  | 80.3%| ---- | ---- | ---- | ---- | ---- | ---- |
| 60%                  | 91.4%| ---- | ---- | ---- | ---- | ---- | ---- |

Figure 3. Contaminant concentration versus time for VAV and DOAS; internal source in zone 1 (left), internal source in zone 2 (right)
5. Conclusion and Limitations

The advent of DOAS technology has been a major development in the HVAC design industry. Despite numerous undeniable advantages, some disadvantages accompany this system that requires further research. Of those disadvantages, inefficient contaminant dilution is of the greatest concern. Although Mumma tried to confine this deficiency to the notion of equivalent filtration, utilizing filtration as a supplemental process on top of the ventilation dilution does not necessarily resolve the problem. In fact, filtration is necessary but not sufficient. Other than installing an equivalent filter, in-space filtration might be also needed to maintain the contaminant level under the standard limits. It should be remarked that more filtration requires more energy to run the system and demand larger capital investment in the HVAC system. DOAS systems are tremendously efficient in containing the contaminant within the release zone, however the dilution level decreases due to lower ventilation rates. Thus, depending on the type of building (residential, office, hospital, etc.) using a dedicated outdoor air system might not be the best choice, or sometimes, the only choice.

Establishing a real time test can confirm or, perhaps, amend the outcomes of this study. Hence, the most important limitation regarding this research would be the lack of an experimental compliment to the model. By means of experimental tests, some other correlation such as the effect of temperature and humidity on contaminant concentration and the portion of particle deposition onto the existing surfaces can be profoundly analyzed.

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