EXPERIMENTAL AND NUMERICAL INVESTIGATIONS FOR EVALUATING CONTAMINANT REMOVAL EFFECTIVENESS IN A MIXING VENTILATED ROOM

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ABSTRACT
For occupants and facility managers of the buildings, assessment of risks related to indoor air quality (IAQ), has become a very complex and challenging issue. To meet the requirements of better indoor air quality, HVAC engineers, world-wide, are facing many challenges related to system design and operation because of development of variety of air distribution systems and innovative diffusers. The demand for appropriate ventilation systems which provide contaminant free healthy air to the occupants is constantly growing.
In this context detailed study related to different ventilation systems like displacement ventilation, mixing ventilation and UFAD ventilation systems has become inevitable. The performance of these ventilation systems is affected by variables like air changes per hour, contaminant particle sizes and contaminant source locations. In this paper, performance evaluation of mixing ventilation system based on contaminant removal effectiveness in occupied zone and breathing zone, is presented. For this, rigorous experimentation is carried out in a experimental test room using suitable instrumentation. CFD simulations are also carried out using RNG k-ε model and Drift-flux model. Encouraging results are obtained through both experimentations and simulations. The parametric variations in terms of effects of changes in ACH, contaminant particle size and contaminant source location help in evaluating the given ventilation method based on contaminant removal effectiveness. The results obtained will help in deciding appropriate parametric combinations at operational level which will help in providing cleaner and healthier indoor environment.

KEYWORDS: Mechanical Ventilation systems, Contaminant Removal Effectiveness, CFD, Occupied zone, Breathing zone.

1. INTRODUCTION
Many people spend 80% to 90% of their lifetime indoors, and indoor environment has important effects on human health and work efficiency[1]. Major factors affecting indoor environment include temperature, humidity, air exchange rate, air movement, ventilation, particle pollutants, biological pollutants, and gaseous pollutants [2]. Analysis of recent studies reveal that there is increase in prevalence of sick building syndrome (SBS) in buildings with mechanical ventilation systems compared to buildings with natural ventilation systems[3]. This paper will, however, focus on particulate contaminants and will not investigate gaseous and biological contaminants. Many recent studies have shown that increased concentration of environmental PM (Particulate Matter) is related to many respiratory diseases [4].
In this paper, influence of various air change rates, contaminant particle sizes and contaminant source locations on performance of mixing ventilation system, are studied and presented. Through Computational Fluid Dynamics (CFD) modeling it is possible to assess the indoor environment by virtually constructing a room and testing different system layouts to meet the predetermined design criteria. The CFD simulation could provide the field distributions of air velocity, air temperature, contaminants, etc. With a validated turbulence model, the CFD simulation would be more accurate and informative than the analytical models, empirical models, multi-zone models, and zonal models and much faster than the experimental measurements.

For bringing in fresh air from outside and to remove particulate contaminants out of the room ventilation is necessary. This paper is particularly interested in mechanical ventilation systems even though many houses and room have natural ventilation system. The transport pattern of contaminants and in turn value of ventilation effectiveness is affected by many factors[5]. The most important factor is the basic ventilation scheme. Mixing ventilation scheme, displacement ventilation scheme and under-floor air distribution scheme are the common schemes[6]. Out of these mixing and displacement schemes are popular and widely adopted by HVAC industries. Here, mixing ventilation scheme is analyzed to evaluate contaminant particle removal effectiveness.

2. LITERATURE REVIEW

A recent study by the Organization for Economic Co-Operation and Development (OCED) [7] related to India, has estimated US$ 0.5 trillion as the cost of air pollution to society in 2010. ISHRAE in its position paper on Indoor Environmental Quality, have pointed out that indoor air pollution is the second highest killer in India [7]. Therefore maintaining good Indoor Air Quality (IAQ) is a very important issue.

Paul, T. et al. [8] studied effect of mechanically induced ventilation on the indoor air quality.

Yuan, L.L. and Liu, B. [9] carried out research on indoor air quality under different ventilation modes.

Austin, J. et al. [10] conducted a synthetic literature survey of indoor air quality and summarized that indoor air quality could be affected by a number of pollutants such as second-hand smoke, volatile organic compounds (VOCs), asbestos fibers, biological particles, radon, carbon monoxide, etc.

In this work focus is on some particulate contaminants in mechanically ventilated indoor environment.

ASHRAE [11] has given detailed classification of particulate contaminants according to size and type (solid/liquid/gaseous), covering dusts, fumes, smokes, mists, fogs, smogs and bio-aerosols.

Diociaiuti, M. et al.[12] studied major characteristics of particles like mass, size number distribution, settling velocity, aerodynamic diameter and their behavior in air.

3. METHODOLOGY

3.1. Experimental and numerical studies

3.1.1 Details of experimental studies

The experimental study for all the measurement of distribution of room air and particle concentration measurements was carried out in Experimental Test Room (ETR). This Experimental Test Room had the dimension of (4.4m(L) x 4.0m(W) x 3.2m(H)). The HVAC system and the Experimental Test Room are as shown in the figure 3.1. The air supply unit has High Efficiency Particulate Air (HEPA) filters at the inlet, the fan unit, cooling grid, heating grid, moisture supply unit and particles supply unit.

The inlet contaminant particle mass concentration was maintained at 450 µg/m^3. The contaminant particle mass concentration was measured at inlet, exhaust and 54 measurement points in the Experimental Test Room. The measured contaminant particle concentration was normalized with exhaust concentration.

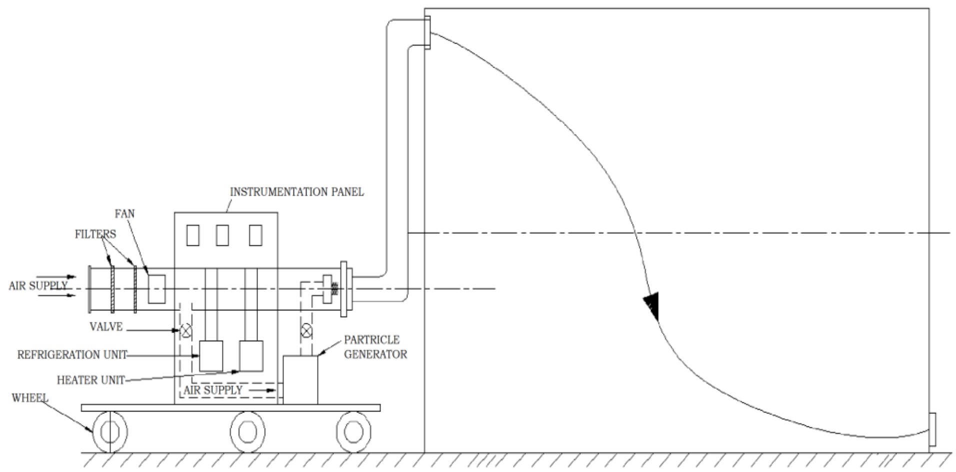

Figure 3.1 Schematic Diagram of Mixing Ventilated Experimental Test Room and HVAC System

Air velocity measurements at various measurement points in the Experimental Test Room were carried out using constant temperature hot wire anemometer and particle concentration measurements were carried out using Beckman Coulter Air Particle Counter (AEROCET 531S, Met One, Beckman-Coulter). Experimental set-up is shown in figure 3.2.

In these investigations various parametric variations like effects of ACH changes, particle size and source location were used to evaluate contaminant removal effectiveness in occupied zone (ε_{oz}) and contaminant particle removal effectiveness in breathing zone (ε_{bz}) for a mixing ventilated room.

3.1.2 Numerical Study Details

A numerical model was based on the geometrical details of experimental test room. Grid independence check and validation of the model was carried out.

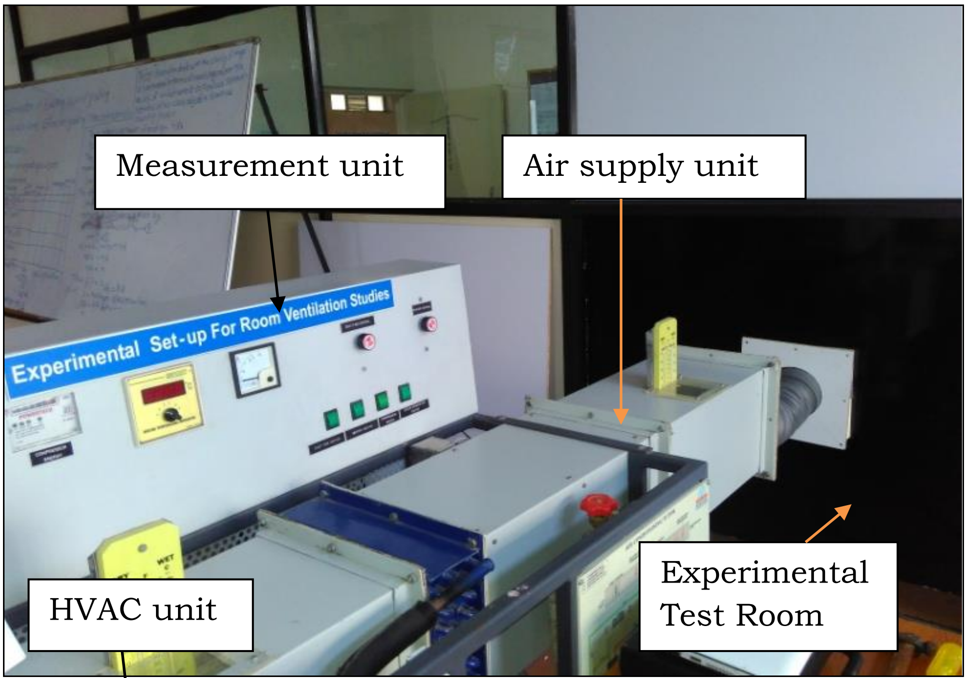

Figure 3.2 Experimental Set-up for Room Ventilation Studies

In the numerical study related to air flow, the Reynold's Averaged Navier Stokes (RANS) equation along with the RNG k-ε turbulence model are used to predict the incompressible turbulent airflow in the test room.

The generalized form of the governing equations are,

The Continuity Equation,

$$\frac{\partial \rho}{\partial t} + \nabla.(\rho.u) = 0 \qquad (1)$$

The Momentum Equation,

$$\frac{\partial(\rho U)}{\partial t} + \nabla.(\rho U \otimes U) = -\nabla.p + \nabla\tau + S_m \qquad (2)$$

The Thermal Energy Equation,

A simplified energy equation form which is suitable for low velocity flows, is called as thermal energy equation which is given as follows:

$$\frac{\partial(\rho.e)}{\partial t} + \nabla.(\rho.Ue) = \nabla.(\lambda T) + p\nabla.U + \tau:\nabla U + S_E \qquad (3)$$

In the numerical study related to particle concentration, the traditional transport model of contaminant concentration is modified by adding the drift-flux term, $\nabla\,(\rho\,\vec{v_s}\,c)$ in the concentration equation. For dispersion of particles, the drift-flux model is given as,

$$\nabla.(\rho\,(\vec{u}_a+\vec{v_s})c) = \nabla.\left(\frac{M_{eff}}{\rho_c}\,\nabla\,c\right) + s_c \qquad (4)$$

The mixture multiphase model with single fluid approach is used. Using the concept of slip velocity which is often called as drift flux velocity, this model permits the movement of phases at different velocities.

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Contaminant particle removal effectiveness is used as a performance parameter for evaluation of mixing ventilation configuration. The breathing zone quality of air is expressed through contaminant removal effectiveness at breathing zone (ε_{bz}). This gives relation between breathing zone and exhaust outlet concentration of particles. Under steady state conditions, the breathing zone particle removal effectiveness can be defined as,

$$\varepsilon_{bz} = \frac{C_{exhaust}}{C_{bz}} \quad (5)$$

Similarly, contaminant removal effectiveness in occupied zone (ε_{oz}) can be calculated as,

$$\varepsilon_{oz} = \frac{C_{exhaust}}{C_{oz}} \quad (6)$$

4. RESULTS AND DISCUSSIONS

Some representative results are discussed here because of space limitations. Results from various parametric variations like effect of changes in ACH, changes in particle size and particle source location on $\boldsymbol{\varepsilon_{oz}}$ for mixing ventilation system are shown in figure 4.1, figure 4.2 and figure 4.3 and important findings are highlighted here.

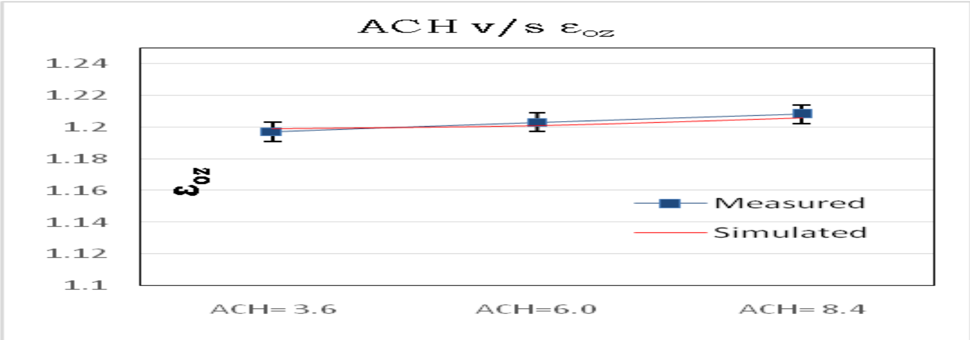

Figure 4.1 Effect of ACH changes on $\boldsymbol{\varepsilon_{oz}}$

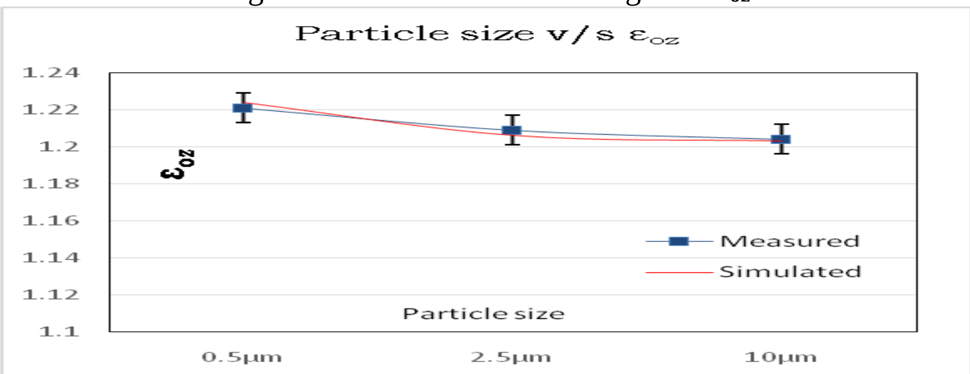

Figure 4.2 Effect of particle size on $\boldsymbol{\varepsilon_{oz}}$

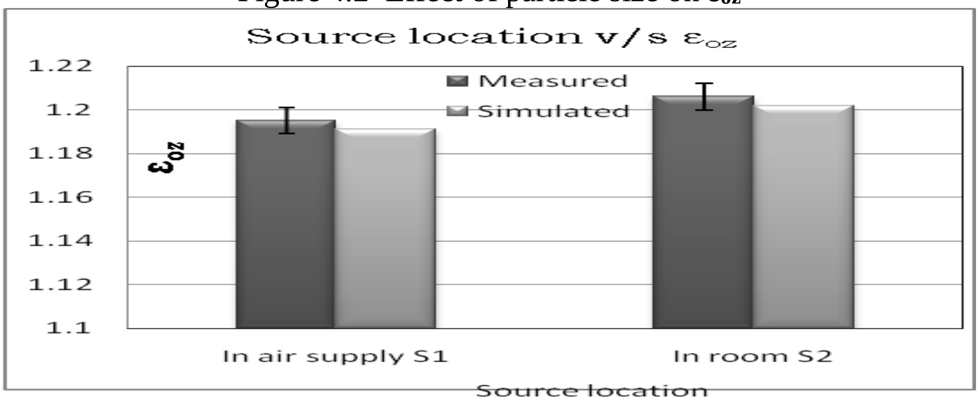

Figure 4.3 Effect of particle source location on $\boldsymbol{\varepsilon_{oz}}$

It is observed that the average contaminant concentration in occupied zone decreases with increase in ACH and the average contaminant concentration in breathing zone increases with increase in ACH. The average contaminant concentration in lower zone decreases with increase in ACH and the average contaminant concentration in upper zone also decreases with increase in ACH.

It is observed that the average contaminant concentration in occupied zone increases with the increase in particle size and the average contaminant concentration in breathing zone also increases with increase in particle size. The average contaminant concentration in lower zone increases with the increase in particle size and the average contaminant concentration in upper zone also increases with increase in particle size.

It is observed that the contaminant removal effectiveness in occupied zone (ε_{oz}) for particle source location (S2) is higher than for particle source location (S1) and the contaminant removal effectiveness in breathing zone (ε_{bz}) for particle source location (S1) is higher than particle source location (S2).

5. CONCLUSIONS

From these experimental and numerical simulation studies using mixing ventilation strategy, following conclusions can be drawn-

(1) There is good agreement between experimental and simulation results indicating that CFD simulations can be effectively used for carrying out room ventilation studies.
(2) The average contaminant concentration in occupied zone decreases with increase in ACH and the average contaminant concentration in breathing zone increases with increase in ACH.
(3) The average contaminant concentration in occupied zone increases with increase in particle size and the average contaminant concentration in breathing zone also increases with increase in particle size.
(4) The average contaminant concentration in occupied zone is higher for the contaminant source location in the supply air as compared to contaminant source location in the room.
(5) The average contaminant concentration in breathing zone is higher if the contaminant source location is in the room as compared to contaminant source location in the supply air.

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