Building and Environment 71 (2014) 212–222

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

Influence of spatial layout on airflow field and particle distribution on the workspace of a factory

Chih-Hong Huang*, Pei-Yin Lin

Department of Architecture, National Taipei University of Technology, No. 1, Sec. 3, Chung-Hsiao E. Rd., Taipei 10608, Taiwan

ARTICLE INFO

Article history:
Received 27 May 2013
Received in revised form
5 September 2013
Accepted 22 September 2013

Keywords:
Architectural design
Indoor air quality
Computational fluid dynamics
Particle emission
Enzyme factory

ABSTRACT

The transport of raw materials within factories can lead to contamination in the form of suspended particles. This study used airflow velocity distribution and pollutant distribution to develop a reliable fluid mechanics model for the calculation of dispersion values. We then modified conventional air inlet models with the precondition of maintaining the same inlet volume and proposed a model to optimize airflow based on simulations of particle dispersion and accumulation. Finally, we altered the spatial layout of the building and compared the effects of various factors on the distribution of particulate pollution. Our results demonstrate that the spatial design of the factory significantly influences airflow and therefore the effectiveness of efforts to eliminate particulate matter. When designing factories, one must consider the operations of personnel and in-feed materials and configure air-conditioning systems within the overall layout of the space. To ensure a healthy work environment, airflow field control should be used to plan models for the discharge of harmful substances, according to their source and dispersion paths.

1. Introduction

The activities of individuals can lead to the dispersal of pollutants within buildings. In conventional enzyme factories, for instance, it is extremely easy for enzyme particles to drift into the air from raw materials, thereby jeopardizing indoor air quality. Enzyme particles can enter the human body through the skin or the respiratory tract, triggering allergies and discomfort in the skin and eyes. Although many factories have instituted protection measures, the air in a large proportion of factories is still considered unhealthy.

Suspended particles can exert irreversible effects on human health and they can be found throughout an indoor environment [1]. The harm caused by suspended particles is closely related to the location in which they are deposited within the respiratory system. Thus, suspended particles are a serious workplace safety issue, particularly in factories forced to deal with the dispersion of dust.

In an investigation of the transport behavior of particles and gaseous pollutants, Rim and Novoselac [2] simulated the circumstances in which pollutants uniformly distributed in an indoor environment enter the breathing zone of a human being. They discovered that when the source of the pollutants is located near floor level within the vicinity of the human body, the concentration of inhaled particles was four times higher than that of pollutants in ambient concentrations. The trajectories of the particles were established according to the field airflow using equations related to the momentum of particles. That study discussed differences in the transport of particles of various sizes (0.03 μm, 0.77 μm, and 3.2 μm) and found that while particle size influenced the method of diffusion, the direction of transport was roughly the same as what would be expected in the indoor airflow field model. Nevertheless, it is worth noting that coarse particles presented the highest concentration of inhaled particulate matter.

Air pollution standards around the world are becoming increasingly stringent. Nevertheless, individuals that remain in such workplaces for long periods of time require an understanding of the potential effects of particles drifting in the air and the paths traversed throughout the human body.

Within the spaces produced in modern urban architecture, complex hybrid ventilation systems are influenced by many factors, such as the velocity of supplied air, air temperature, room height, and cooling load. Lin et al. [3] applied a simplified fluid mechanics model to verify the heat flux and mass flow rate of inlets and outlets in cubicles and large offices using the pollutants toluene, formaldehyde, and carbon dioxide. Their results demonstrated that providing a gap between the top of partitions and the ceiling can

* Corresponding author. Tel.: +886 2 27712171x2915; fax: +886 2 27765102.
E-mail addresses: huangch@ntut.edu.tw, joseff299@gmail.com (C.-H. Huang).

0360-1323/$ – see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.buildenv.2013.09.014

improve airflow distribution, and under floor air supply ventilation favorably complemented the airflow fields within partitioned indoor spaces. In contrast, displacement floor ventilation was less than ideal when dealing with pollutant sources near floor level.

Regarding the elimination of particulate pollutants, Kao et al. [4] focused on multi-room reinforced concrete buildings commonly seen in Asia and analyzed the influence of various ventilation models on airflow patterns and particle transport behavior. Time-averaged ventilation rates were set for each opening in the building and various outlet-to-inlet opening size ratios were tested (1.67, 1.00, 0.50, and 0.17). In factory workspaces, cleanrooms, and isolation wards, the elimination of pollutants and flow field control systems are closely associated with the efficiency of energy consumption [5,6].

Chanteloup and Mirade [7] evaluated the efficiency of forced-ventilation food plants (a cheese ripening room and a sausage dryer). Verifications were completed using steady-state and transient-state models based on data from the literature. The steady-state method was used to strike an optimal compromise between computation time and accuracy. The integration of computational fluid dynamics and building simulation revealed that in terms of emphasizing regions with inadequate ventilation, the concept of local "mean age of air" served as a better and more sensitive parameter than mean air velocity and was thus suitable for the assessment of ventilation efficiency in industrial food plants.

Summarizing the above studies, we can see that the simulation of airflow field models within a space and predicting the effectiveness of efforts to eliminate pollutants require a complex design process based on case studies.

Unlike previous studies which focused mainly on airflow control, this study examined the design of interior spaces in buildings to identify the correlation between the spatial design of workshops and indoor flow field control. This empirical study analyzed existing airflow patterns and investigated how adjustments to air-conditioning configurations influence the accumulation of pollutants. Our aim was to enhance local ventilation and energy efficiency. This study adopted empirical data from previous studies [8] concerning the concentration of diffuse particulate matter originating from the feed-in equipment in enzyme factories (including raw feeding materials, feed-in equipment, and stocked materials).

The contribution of this study lies in its integration of spatial layout and air-conditioning duct configurations to optimize the airflow field within a given space. It is hoped that in the design of safe workplaces, designers will be able to make improvements to indoor air quality and ensure the safety of workers in factories coping with the issue of dust dispersion.

2. Methods

This study adopted two numerical models to simulate ventilation patterns. The first model was based on three-dimensional transient mass and momentum conservation equations to simulate the behavior of incompressible turbulent flow. For the other model, we adopted the semi-implicit method for pressure-linked equations consistent (SIMPLEC) to solve equations governing transient continuity and momentum and determine the characteristics of the indoor airflow field.

This study employed data from the elutriation dust column (EDC) experiments conducted by Liu et al. [8]. to verify the calculations obtained from the model used in this study. We then examined the ventilation patterns in this factory to devise improvements related to airflow control conditions. According to the areas in which pollutants were concentrated in the simulations, we further modified the spatial modeling of the airflow field, which involved altering the design of turbulent zones within the airflow field.

The factors influencing the suspension of particles in an indoor space include airflow patterns, particle characteristics, the geometric configuration of the space, internal partitions, ventilation rates, and the locations of inlets and outlets. This study employed an indoor turbulent flow model based on a three-dimensional Lagrangian particle tracking model as well as Navier–Stokes equations for numerical simulation [9]. We used continuous equation, momentum equation, and species concentration transport equations to determine the velocity of air moving throughout the airflow field as well as the concentrations of harmful gases in order to characterize the dispersion of air pollutants.

We first assumed that the turbulent flow model in the numerical simulation was steady, three-dimensional, and incompressible. We assumed atmospheric pressure in the entire computation area as well as near-isothermal conditions. We adopted the standard k-epsilon turbulence model to solve the turbulent flow.

For numerical analysis, we referred to the SIMPLEC algorithm proposed by Doormaal and Raithby [10] to solve the governing equations and calculate flow field distribution within the enzyme factory.

To achieve the stability required for numerical calculation, we integrated the original equation, the transient and convection terms of which were discretized using the first-order backward difference method and first-order upwind scheme, respectively. Following completion of the finite volume differential equation, we employed the SIMPLEC algorithm to correct the pressure values, which were used to obtain the velocity field.

The typical equations of motion for suspended particles include those for gravity, friction, Saffman's lift force, and Brownian motion. The primary transport mechanisms of suspended particles with a particle size distribution between 5 μm and 10 μm in a partitioned space are inertia and friction [1]. In the enzyme factory in this study, the particle size of the primary particulate was ca. 7.07 μm; therefore, we ignored Brownian motion and Saffman's lift force.

This study employed steady-state models to investigate the distribution of pollutants, (concentration range: $0 - 580$ ng/m^3), in which the airflow analysis assumed that the pollutant concentrations had reached a steady state. To observe the concentrations of pollutants in each of the five cases with different inlet locations, we established two line segments for monitoring the empty space at a height of $Z = 1.4$ m with no equipment in the factory building. Line Segment a, which was closer to the lower side of the space and further from the pollutant source ($Y = 1.4$ m, $X = 0 - 14$ m), and Line Segment b, which was closer to the upper side of the space and the pollutant source ($Y = 5$ m, $X = 0 - 6$ m).

3. Validation of the mathematical model

Before using the model, we had to validate its reliability. The validation process was divided into two stages. The first involved validating the velocity field and the second involved validating the concentration of pollutants under various release conditions.

For the three-dimensional turbulent flow model, we confirmed that the air velocity measurement data from the internal space of the factory building equaled that of the simulation. The same was true of the pollutant concentration data [11].

Particles in indoor ventilation are generally influenced by airflow patterns, particle characteristics, geometric configurations, ventilation rate, the location of inlets and outlets, internal partitions, and thermal buoyancy. Zhao et al. [12] employed numerical simulation to validate the measurement data in previous studies. They subsequently adopted two different indoor ventilation models (displacement and mixing), and simulated the deposition and concentrations of four different particle sizes: 1 μm, 2.5 μm, 5 μm, and 10 μm. They determined that although particle size influenced