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History recovery and source identification of multiple gaseous contaminants releasing with thermal effects in an indoor environment

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ABSTRACT

Thermal transport and transient dispersion of pollutants emitted from two discrete strips within the displacement ventilation enclosure have been modeled numerically. Following the full numerical simulation of turbulent air flows, the inverse determinations of multiple pollutant sources were conducted by the use of quasi reversibility methodology. Direct simulation together with the turbulent streamlines and turbulent heatlines demonstrate that the enclosure flow pattern, enclosure air thermal level and heat transfer potential will depend on the interactions of external forced flow and thermal buoyancy driven flows, i.e., Reynolds number ($2 \times 10^3 \leqslant Re \leqslant 10^4$) and Grashof number ($10^6 \leqslant Gr \leqslant 10^{10}$). In subsequent forward time and backward time modeling of airborne pollutant transports, temporal evolutions of enclosure average concentration and pollutant exhaust are shown to depend on the supplying velocity (Re), thermal plume (Gr), pollutant diffusivity ($0.1 \leqslant Sc \leqslant 2$), and the pitch between both sources ($0.2H \leqslant d_{PSL} = d_{PSR} \leqslant 0.7H$). Reverse time modeling of airborne spread has demonstrated that increasing the spread rate and the concentration sensitivity of airborne pollutants will facilitate the identification of pollutant sources.

1. Introduction

Knowledge of the contaminant distributions is vital important for industrial pollutant control, deep water protection, and indoor occupancy health. Usually, the contaminant can easily diffuse into the fluid flow, and which can disseminate the pollutants quickly and extensively [1,2]. The process of fluid flow, together with the dispersion of the pollutants, can be numerically predicted well with the known releasing rate and position of the pollutant sources. In other words, the temporal and spatial distributions of pollutant dispersion can be obtained directly through solving the equations of fluid flows and pollutant transport with the known boundary and initial conditions [3–5]. However, the initial and boundary conditions of airborne pollutants cannot be easily measured or obtained as a prior, such as poisonous gases released by terrorists, smoke flow caused by the sudden building fire, and pollutant dissemination into ground water. At this moment, the initial or boundary conditions should be determined depending on other information, such as temporal episode of temperature and gaseous concentration or downward flows. Here, it poses an inverse problem. Some representative researches, including identifying the inflow velocity, wall temperatures and heat fluxes, and temporal history of heating source have been conducted in heat transfer community [6–9], where adjoint methods have been applied.

Whereas, for inversely determining pollutant sources, time reverse method should be adopted to identify these pollutant sources, and this method can compute the various choices of source distribution from a transport model and some range of possible source scenarios thus determined to be consistent with observed concentrations [10–16]. Past applications of time reverse methods mostly focused on the fluid flow of diffusion dominated mode, such as ground water flow; concerning indoor air environment, convection of room air will be comparable with that diffusion. Recently, some authors have presented the backward time simulations of airborne pollutants in the airplane cabinet, where convection played the dominant role and thermal buoyancy was almost neglected [15,16]. Further references of these relevant researches can be tracked, such as probability based inverse multi-zone modeling, integration of sensor network or optimal algorithm with fluid flow simulations [17–19]. In the present work, reverse time methodology covering both advection and diffusion effects will be implemented to identify the pollutant sources within a slot vented enclosure, where discrete heat source will give rise to thermal plumes interacting with the pumping vent flows.

Concerning the turbulent flows in the slot-vented enclosure, the interactions of vent flow and thermal buoyant plumes have been

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Nomenclature

Ar	Archimedes number (Gr/Re^2)
AC	pollutant flow rates (Eqs. (14) and (15))
C	dimensionless concentration
d	size of ports and sources (m)
d_{LR}	dimensionless pitch (($d_{PSL} + d_{PSR}$)/H)
DT ($\Delta\tau$)	temporal internal (s)
E	dissipation rate of kinetic energy ($\varepsilon H/u_{in}^3$)
g	gravitational acceleration (m/s^2)
Gr	Grashof number ($\beta g H^3(t_{HS} - t_{in})/\nu^2$)
H	enclosure height (m)
K	turbulence kinetic energy (k/u_{in}^2)
P	dimensionless pressure (($p + \rho gy$)/(ρu_{in}^2))
Pr	Prandtl number (ν/α)
Re	Reynolds number ($\rho u_{in} H/\mu$)
Sc	Schmidt number (ν/D)
T	dimensionless temperature
U, V	dimensionless velocities
W	enclosure width (m)
X, Y	Cartesian coordinates (x, y)/H

Greek symbols

α	thermal diffusivity (m^2/s)
β	volumetric expansion coefficient (1/K)
ε	Stabilization
ν	kinematics viscosity (m^2/s)
ρ	density (kg/m^3)
λ	thermal conductivity (W/m k)
χ	effective diffusion coefficients
Ψ	dimensionless streamfunction
Θ	dimensionless heatfunction
Ω	dimensionless massfunction

Subscripts

HS	heat sources
in	inlet
PS	pollutant sources

drawn many attentions [20–23]. The stable spread and transient removal of pollutants from the slot vented enclosures, considering the effects of internal partition, ventilation strategies and source locations, have been investigated, although thermal effects have not been taken into consideration [24–27]. Recently, spread of airborne pollutants within a slot vented enclosure containing thermal sources have been modeled numerically [28], where each port located on the same side.

In the present work, interactions of thermal plumes and vent flows within a slot vented enclosure concurrently containing thermal and airborne pollutant sources will be investigated. Effects of supplying air velocity, thermal source intensity, pollutant property and source locations on the air flow patterns and pollutant spread will be discussed on the basis of forward time simulation methodology; following that, reverse time simulations of pollutant dispersions will be implemented to identify the spatial locations of pollutants within this enclosure.

2. Forward pollutant dispersion within the slot vented room

2.1. Physical model

As shown in Fig. 1, a slot-ventilated enclosure is attached with the bottom supplying vent and top exhaust port of same size d_{port} respectively on the left and right sides. The rectangular enclosure is of width W and height H, and the Cartesian coordinates (x,y), with the corresponding velocity components (u, v), are indicated herein. It is assumed that the third dimension of the enclosure is large enough such that room air and heat transports are two dimensional. A discrete heat source, size of d_{HS}, is centrally positioned on the floor. With the upward thermal buoyancy effect, the external forced convection will expectedly be aided with the thermal buoyant flows, where the displacement ventilation mode will be established. In addition, two strip pollutant sources of same size d_{PS} were located on the floor respectively on the right and left hand sides of the central heat source (separately with pitch distances d_{PSR} and d_{PSL} from the central point).

The radiation heat transfer, viscous heat dissipation and compressibility effects are considered to be negligible. The fluid mixture (base fluid and contaminant) is modeled as a Newtonian fluid with constant density and viscosity. The effect of the density variation causing the thermal buoyancy force is taken into account through the Boussinesq approximation. Other thermo-physical properties of the fluid mixture are assumed to be independent of temperature. The mass diffusivity for the diffusion of contaminant through the mixture is also treated as constant. In the present work, fluid convection driven by the pollutant concentration difference has been omitted; that is to say, the gaseous pollutant will be

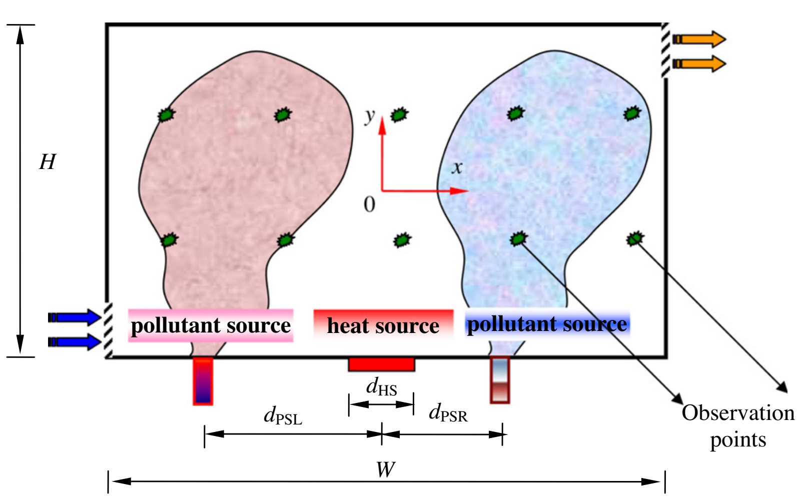

Fig. 1. Schematic diagram of the slot-ventilated room with discrete heat strip and pollutant point source of unknown positions. All geometric units are meter.