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Numerical study on smoke movement driven by pure helium in atria

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ABSTRACT

The hot smoke test is often used for commissioning fire smoke management system in atrium buildings, in which liquid fuel is burnt to generate a buoyant plume mixed with artificial tracer smoke to model a fire smoke. The method is usually costly and often causes safety concerns. This paper studied an alternative method of using a cold smoke test, in which pure helium is used to create the buoyant plume. A method was developed to determine the supply rate of pure helium necessary to achieve the same buoyancy effect as that of the corresponding hot smoke test. Computational fluid dynamics (CFD) simulations of the helium smoke tests were conducted and compared to the measured hot smoke tests in a full-scale naturally ventilated atrium and a sub-scale atrium with mechanical ventilation. A new method was added in the CFD model to track the smoke layer height for the simulations of helium smoke based on the concentrations of smoke and helium. It is found that the predicted smoke layer heights based on the mass fractions of the tracer smoke are generally close to the measured ones in the hot smoke tests of different heat release rates. A non-dimensional temperature in the hot smoke test is also found closely related to the dimensionless helium concentrations in the helium smoke test for the atria modeled. Although the consumption of pure helium for a full-scale helium smoke test can be very high, it is promising to use the pure helium smoke test in the lab-scale experiments as the preliminary tests of full-scale and/or lab-scale testing of real fires.

1. Introduction

Atria seem one of the favorite features for modern buildings, e.g. large office buildings, shopping malls, banks and hotels. The design and commissioning of an atrium's fire smoke management system is challenging because the atrium building often has a heavier occupant load and a bigger dimension, especially the height, compared to other traditional building spaces. Among other considerations, the smoke filling process, especially the smoke layer height, is one of the major concerns when testing an atrium's smoke management system [1]. A conventional method is the so-called hot smoke test (HST), in which a small clean burning fire of liquid fuel, such as methylated spirit, is created in a tray to provide buoyant plume and artificial tracer smoke (hereafter tracer smoke or TS) is introduced into the plume to track the location of the smoke plume and hot gas layer [2]. The method is costly and often causes safety concerns. Using a real fire, a HST needs to be carefully controlled to avoid any potential damage to building structures. Besides the high expenditure of the test itself, the necessary risk assessment measures and insurance coverage increase the total cost. As a result, building owners are often not in favor of HST, which is also not mandatory by most of the building codes.

Given the fact that the use of fire in a HST is not to establish real fire conditions but to generate thermally buoyant smoke [2], fire is not the only means to create buoyancy. The use of light gases, e.g. helium, is also an option to conduct a cold smoke test, in which the generated plume is “cold” because of no fires needed. One of the early applications of the cold helium smoke test (HeST) was conducted by the U.S. Federal Aviation Administration (FAA), in which helium is diluted with air with a volumetric ratio of 1:1, and used as the supply flow into aircraft cargo compartment to certify the smoke detection system [3]. A helium smoke generator was also invented to mix helium, air and theatrical smoke [3]. Because there is no fire needed, HeST is safer, less expensive and expected to be more accessible than HST. The HeST has also been applied to the studies of road tunnel ventilations, for which a scaling law, centering around buoyancy flux of a plume, was developed for tunnel fires at laboratory scales [4,5]. The mixing ratio of helium and air necessary to maintain the same buoyancy flux as a hot smoke test was determined from the convective heat release rate, surrounding ambient temperature, and density difference of helium and air. In a test of a Particle Image Velocimetry (PIV) for the measurements of buoyancy induced flow through a doorway, the US National Institute of Standards and Technology (NIST) [6] used a HeST in a sub-scale model, which was found sufficient to test the PIV system and provided guidelines for conducting a successful test in a full-scale fire experiment later. Therefore, a HeST provides a reasonable option as an alternative or a preliminary test of a HST in the situations, where HST is not preferred either due to its high cost or safety concerns. Meanwhile, some limitations of the HeST have been reported. In the HeST of tunnel

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Nomenclature

B	buoyancy flux, m^4/s^3
B_h	buoyancy flux of helium gas, m^4/s^3
C^*	non-dimensional concentration
C_g	mass fraction of helium or the tracer smoke, kg/kg
C_m	coefficient, $m^{4/3}/(s\ kW^{1/3})$
C_p	specific heat capacity, kJ/(kg K)
C_s	Smagorinsky constant
D_b	thickness of emerging smoke layer, m
g	acceleration of gravity, m/s^2
H	total height of atrium, m
I	integral
M_b	emerging smoke layer mass flow rate, kg/s
M	smoke extraction rate, kg/s
N	number in N-percentage rule
Q	heat release rate, kW
Q_c	convective heat release rate, kW
q_h	required volumetric flow rate of helium, m^3/s
$q_{s,f}$	volumetric flow rate of the fire plume, m^3/s
$q_{s,h}$	volumetric flow rate of a helium smoke, m^3/s
T	temperature, K
T_a	temperature of air, K
T_s	temperature of smoke, K
T^*	non-dimensional temperature
W	width of the atrium, m
x	length, m
z	height above spill edge, m
z_0	virtual origin height of smoke plume, m
z_s	smoke layer height, m
ρ_0	ambient density, kg/m^3
ρ_a	surrounding air density, kg/m^3
ρ_s	smoke density, kg/m^3
χ_a	volumetric fraction of air
χ_h	volumetric fraction of helium

ventilations [4,5], it was found that the required total supply of helium and air mixture is impractically high for full-scale facilities so the method was limited to laboratory-scale tests. It was also found that the helium plume tends to mix poorly with the surrounding air downstream of a plume due to loss of momentum so the helium concentration becomes constant, which results in a stable buoyancy effect. This is inconsistent with an actual fire, where smoke temperature decreases downstream due to the loss of heat to the surrounding environment [7].

Limited studies were found in the literature about using HeST in buildings. Compared to tunnels or aircraft compartments, which are characterized by longitudinal and/or horizontal spaces, buildings are comprised of multiple spaces with various sizes and complicated ventilation systems. In particular, large vertical spaces, e.g. atria, represent one of the many cases that distinguish building environment from aircrafts or tunnels. In an atrium, the size of smoke plume is much bigger than aircraft and tunnel configurations. The application of HeST in these spaces, e.g. atria, is therefore more challenging and needs to be examined. It is also important to identify the limitations and accuracy of a HeST when it is applied to smoke movement studies in atrium buildings as an alternative of a HST.

In this paper, we studied the atrium smoke filling process by HeST based on the measured data in a sub-scale atrium model [8,9] and an full-scale atrium [10,11]. Instead of helium and air mixture used in longitudinal tunnel and flight cabins in the previous studies, pure helium is used as the supply flow, the amount of which is determined from an analysis of atrium smoke filling based on the buoyancy flux. Numerical simulations are then conducted to model the smoke movement in the naturally ventilated full-scale atrium and the mechanically ventilated sub-scale atrium model with a large eddy simulation (LES) computational fluid dynamics (CFD) model, fire dynamics simulator (FDS) [12]. The predicted smoke layer heights are compared for the HST and HeST. The relations are also investigated among gas temperatures and helium concentrations during the smoke filling process for both atrium buildings.

2. Principles of helium smoke test

2.1. Determination of required pure helium in the supply flow

The determination of the amount of pure helium necessary to create a similar plume as in a HST is based on the goal of reproducing the buoyancy flux. Fig. 1 shows the schematics of the plumes in HST and HeST. For a fire plume, the convective heat release rate (HRR), Q_c is calculated by

$$Q_c = \rho_s C_p q_{s,f}(T_s - T_a) \tag{1}$$

The buoyancy flux of a buoyant plume, B is defined by

$$B = g q_{s,f}\left(\frac{\rho_a - \rho_s}{\rho_a}\right) \tag{2}$$

The buoyancy flux remains constant at all heights of the plume [13].

Using the ideal gas law and combining Eqs. (1) and (2),

$$Q_C = \left(\frac{\rho_a C_p T_a}{g}\right) B \tag{3}$$

Eq. (3) shows a relation of convective heat release rate and buoyancy flux for a given ambient condition.

In the HeST with pure helium, the same buoyant plume and smoke filling process as that of the HST are considered to be created when

$$B_h = B_f \tag{4a}$$

$$q_{s,h} = q_{s,f} \tag{4b}$$

As shown in Fig. 1(b), the pure helium is supplied at a rate of q_h, and mixed with the entrained air at a rate of q_a. The resultant volumetric plume flow rate is therefore

$$q_{s,h} = q_h + q_a \tag{5}$$

The mixture density is then calculated by

$$\rho_s = \chi_a \rho_a + \chi_h \rho_h \tag{6}$$

where χ_a and χ_h are the volumetric fractions at a specific plume height of air and helium, respectively.

So the required volumetric flow rate of helium, q_h can be obtained from Eqs. (3), (4a) and (6)

$$q_h = \frac{Q_c}{C_p T_a(\rho_a - \rho_h)} \tag{7}$$

Eq. (7) shows that the amount of helium required is only a function of convective heat release rate for a given ambient condition. The total volumetric flow rate of the helium and air mixture at the same plume height, $q_{s,h}$ can be calculated from Eqs. (1) and (4b)

$$q_{s,h} = q_{s,f} = \frac{Q_c}{\rho_s C_p(T_s - T_a)} \tag{8}$$