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The impact of atrium shape on natural smoke ventilation

R.M. Doheim [a,*], Y.G. Yohanis [a], A. Nadjai [a], H. Elkadi [b]

[a] School of the Built Environment, Faculty of Art, Design and the Built Environment, University of Ulster, Shore Road, Belfast, BT37 0QB. UK
[b] School of Architecture and Built Environment, Faculty of Science, Engineering and Built Environment, Deakin University, Melbourne, VIC, Australia

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ABSTRACT

The performance efficiency of natural smoke ventilation in atria spaces are influenced greatly by several design decisions such as atrium shape, height, size and openings location. This paper investigates the impact of atrium shape (horizontal profile) on smoke ventilation performance in naturally ventilated atria. Three different configurations (square, rectangular and triangular prism) with the same area, height, and hence, volume were tested. The smoke ventilation performance is being assessed in terms of smoke filling time using a computational fire dynamic simulator (FDS). FDS is used to simulate the natural smoke filling resulting from atrium fire in the three configurations. The smoke layer interface height as a function of time and soot mass fraction and temperature as a function of height have been registered during the simulation. The predicted transport lag time for initial formation of the smoke layer beneath the ceiling (ceiling jet) was compared for the three tests. In order to test sensitivity of the shapes, all other parameters were designed to be similar in the three tests, and the same fire scenario was applied including inlet and outlet area, and fire size and location. The results showed that the rectangular configuration contributes better to smoke ventilation, and that the triangular configuration is the most critical in terms of smoke filling time, followed by the square configuration.

1. Introduction

Atrium design is very challenging and requires careful considerations, especially with regard to fire safety design. The criticality of fire safety designs in atria spaces is due to the fact that there is no physical separation, which allows smoke and heat to travel throughout all floors of a building. There are many parameters that contribute to the impact of atrium design on smoke movement such as complexity of the atrium configuration, shape of the atrium plan (horizontal profile), shape of the atrium cross sections (vertical profile), height, size and communicating spaces. There are several shapes for the horizontal profile of the atrium space such as one-sided, two-sided, three-sided, four-sided, linear, bridging, multiple lateral, multiple vertical atria [1].

Natural smoke ventilation in atria spaces has been investigated widely using numerical and experimental work. It has been studied for both fire origins: shop fires and atrium fires. The smoke filling approach has been used extensively in investigating smoke ventilation performance in large atria [2–27]. Capote et al. [2] confirmed the use of the smoke filling approach numerically and experimentally for smoke ventilation investigations in large atria. In Chow et al. [3,4], natural smoke filling process in atrium was used to study atrium fire and evaluate the smoke ventilation performance. Jones and Quintiere [5] used the smoke filling approach numerically and experimentally to investigate the impact of smoke travelling from adjacent space in which fire origin is smoke filling time in an adjacent room to the fire origin room via comparing a zone model with experimental work.

There are several atrium design parameters that have been investigated with regard to smoke ventilation performance. Milke and Mowrer [6] investigated the impact of the vertical cross-sections of atria, where roof shape changes, on the smoke layer depth using the smoke filling approach. The area of the vertical cross-section of the atrium could be considered as a function of smoke layer depth depends on the roof shape (e.g. flat, peaked, parabolic, stepped, trapezoidal). Qin et al. [7] investigated the impact of fire location in atrium space on smoke filling speed. It was found that the smoke filling speed is slower when the fire origin at the corner of the atrium than when it is at the centre or near a side wall.

With regard to shop fires, the ventilation factor is very critical. Hu et al. [8] investigated the impact of ventilation factor on smoke filling speed. It was found that shops with larger ventilation factor would result in higher smoke quantity to the atrium. In Shi et al. [9], the authors investigated numerically and experimentally the natural smoke filling process and temperature rise in atrium due to shop fire. The time for smoke to transport from fire source to the ceiling and spread to form smoke layer (transport lag time) in the

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[*] Corresponding author. Tel.: +44 28 90368025.
E-mail address: mdoheim@yahoo.com (R.M. Doheim).

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atrium was considered with the plume model to get better predictions. The authors emphasized the importance of considering transport lag time in atrium fires especially for big heights. Chow [10] examined the smoke filling time in atrium space with different volumes and heights using zone modelling. In Kaye and Hunt [11], smoke filling time in a room was investigated in relation to the room height-to-width ratio. The authors tested experimentally their theoretical argument that the mixing between the upper smoke layer and the air below affect significantly the smoke filling time in a room. The authors highlighted the impact of the smoke outflow overturning when reaches the room side walls. Kerber and Milke [12] investigated numerically the smoke layer interface height in relation to different configuration of air supply vent in a simple 30.5 m cube atrium with different velocities. The authors tested 4 air supply vent configurations including symmetric, asymmetric (vents are only at the ground floor), centre, and corner (vents are one per floor). Results show the scenarios that were capable of maintaining the design smoke layer interface height are the symmetric and the centre air supply vent at particular velocity.

This paper aims to investigate the impact of atrium shape on natural smoke ventilation, and contributes to the smoke ventilation knowledge by testing if any of the studied configurations allows better smoke ventilation performance.

2. Smoke interface height

Fire that occurs in the centre of space forms a uniform conical axisymmetric plume. This smoke plume and hot gases rise impinge on the ceiling. Once the plume and the gases impinge on the ceiling, smoke flows radially and horizontally immediately below the ceiling forming smoke layer [13,14]. The more entrained air in the space the thicker the layer gets, and the faster the interface descends. However, if the ceiling-jet flow gets vented through openings in the ceiling, this can slow the descent of the smoke layer interface [15]. The smoke layer stops descending when an equilibrium state occurs between the smoke mass exhaust rate and the air entrainment mass rate by the plume [16].

The smoke transport lag time is the time of the smoke-flow, released from the fire flame, to transport to the ceiling filling between the plume and all side walls, where smoke layer interface starts to descend. The transport lag time consist of two time components: ‘plume’ transport lag, which is the time for vertical transport, and ‘ceiling-jet’ transport lag, which is the time for horizontal transport from the plume centre line to walls [6,16]. The ‘plume’ transport lag is out of the scope because the fire scenarios in this study were designed with the same height for the three atria configurations. Therefore, only ‘ceiling-jet’ transport lag is considered, and it can be calculated for a fire with a constant heat release rate as in the following equation [17,18]

$$t_{cj} = \frac{r^{11/6}}{1.2\dot{Q}^{1/3}H_{1/2}} \tag{1}$$

where t_{cj} (s) is the ceiling jet transport lag time, r (m) is the horizontal distance from plume centre line, H (m) is the height of the ceiling above top of the fuel surface, and $\dot{Q}$ (kW) is the heat release rate of fire. In order to predict the position of the descending smoke layer interface, two principles are used: empirical, and theoretical. The empirical approach is based on measuring temperature rise or visual changes, and the theoretical one is based on defining the fire zone as upper and lower zones [19]. In this study, the FDS modelling is used to get predictions of smoke transport lag time based on visualisation of the fire simulation, and to get predictions of smoke interface height based on a continuous vertical profile of temperature and soot mass fraction.

3. Computational modelling

The fire dynamic simulator (FDS) is a model of computational fluid dynamics (CFD) developed by the National Institute of Standards and Technology [20]. The FDS modelling is one of the effective tools in fire protection engineering that facilitates fire design through the flexibility in changing the parameters for the same compartment. It allows testing of all potential risks in fire scenarios, and helps to predict the development and behaviour of fire [19]. FDS allows computing fire growth and spread, and predicting smoke and heat transport generated from fires. The version used in this study is version 5. This study examines three configurations (square prism, rectangular prism, and triangular prism), as shown in Fig. 1, which are the most common shapes for atria design: two-sided, three-sided, four-sided, and linear.

Three fire models were designed to simulate natural smoke ventilation in the three configurations. The FDS settings to study the impact of atrium shape on natural smoke ventilation are described in the following.

3.1. Settings of the tests

In order to test sensitivity of the atria shapes, the same fire scenario was used for the three tests. The same area was specified for the three cases (225 m²), the same height (18 m), and hence the same volume. The mesh/grid size parameter is an important one that affects the accuracy and validity of numerical results. In the literature, the mesh size varies between 0.3 m and 0.1 m for smoke investigations, depending on the convective heat release rate and the purpose of the simulation [7,12,21–25]. A sensitivity study suggests an appropriate mesh size of 0.2 m after using a simple sensitivity analysis with different sizes (0.5 m, 0.3 m, 0.2 m), as shown in Fig. 2. The same boundary conditions were designed for the three models. Open boundaries of minimum 5 m were specified in front of the atrium door, and 2 m above the exhaust vent in the ceiling. An additional simulation for an extended domain was carried out to test if different domains lead to different results. The results showed that there is no significant change between the designed domain and the extended domain, as shown in Fig. 3, which proves that differences in the domain will not affect the results.

Schematic diagrams of the three atria configurations are illustrated in Fig. 4. The atrium height was specified in the designed scenarios to be 18 m based on the average height (2–4 stories) of the majority of shopping malls in the UK. The ambient temperature in the atrium space is assumed to be 20 °C. In each case, the inlet opening (atrium door) located in the ground floor (10 m width × 3 m height), and the outlet opening located at the centre of the roof (10 m length × 3.5 m width).

3.2. Fire specifications and scenarios

Smoke was simulated for 300 s (5 min) to test the impact of different atrium profiles on natural smoke ventilation performance. This period was specified based on the time it takes to

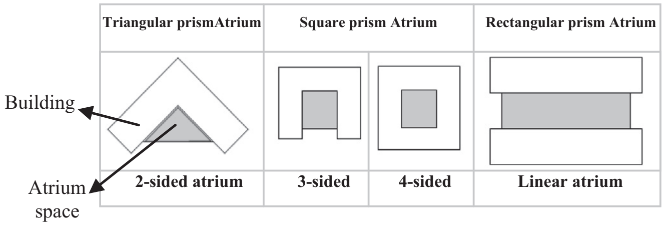

Fig. 1. Atrium configurations (atria space in grey).