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Experimental study based on large-scale smoke propagation fire tests through a horizontal opening connecting two mechanically ventilated compartments

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ABSTRACT

This work describes an experimental study of the flow through a horizontal opening (also referred to as a vent), applicable to specific situations typically encountered in nuclear installations. The configuration consisted of two rooms, which were mechanically ventilated and connected to each other by a horizontal opening, the fire being located in the lower room. The flow was governed by buoyancy due to the heat release from the fire, inertia resulting from the mechanical ventilation, and local momentum from the ceiling jet. Two flow regimes (bi-directional and uni-directional) were encountered depending on the fire power and the ventilation set-up. This study presents 17 large-scale fire tests, investigating the behaviour of the flow at the horizontal opening according to several fire scenario parameters: the fire heat release rate, the fire location, the ventilation configuration and the ventilation flow rate. This range of parameters enabled us to focus on different flow regimes, from pure natural convection (bi-directional) to forced convection (uni-directional). The new set of data obtained, based on detailed flow measurements, offers new insights for understanding the flow and developing sub-models to be used in zone codes.

1. Introduction

Smoke movement remains a key issue for safety assessments in nuclear installations. Smoke is responsible for the transport of heat and soot particles and may significantly impair safety systems (i.e. EIS: Equipment Important for Safety). The clogging of high-efficiency (HEPA) filters located in a ventilation network or the failure of electrical or electronic devices are typical events that can be prevented. Particular smoke flows occur through openings such as doorways or horizontal openings (also referred to as vents) that control the transfer between compartments [1]. These transfer flows are governed by mixed convection (buoyancy and inertia). They are often multi-directional (or at least bi-directional) and turbulent, with a density that varies across space and time. When the opening is directly connected to the enclosure where the fire takes place, the flow may also have a substantial influence on the combustion process, by modifying the flow rate of oxygen entering the enclosure or that of combustion products released towards adjacent rooms. The prediction of these flows using engineering zone codes or more advanced CFD tools remains a major issue for safety assessments.

The present contribution focuses on the flow through a horizontal opening and its effect on smoke propagation in adjacent enclosures (Fig. 1a). This type of flow shows similarities with doorway flow, which has been deeply investigated in literature [2–4]. However, it presents more complex behaviour, mainly due to the orientation of the flow section, which is perpendicular to the gravity direction (whereas for a doorway, the gravity direction is in the plane of the flow section). This flow demonstrates several regimes: uni-directional upward, bi-directional upward and downward, and uni-directional downward. In particular, the bi-directional flow may present a complex flow pattern due to the undetermined location of the upward or downward flow section. The differences in temperature and pressure on both sides of the opening are the governing parameters. For natural convection with no pressure difference between the rooms, at a steady state the flow is bi-directional with equal mass flow rates in both directions. When a pressure difference is applied to the vent, due to the action of mechanical ventilation for instance, a mixed convection flow occurs at the vent. If the pressure difference is below a critical level, named the "flooding" or "purge" pressure, the flow remains bi-directional. Above this critical pressure level, the counter-flow opposing buoyancy is stopped and only a uni-directional flow is observed.

Experimental studies have established an initial basis for under-

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Nomenclature

C	Coefficient (-)
C_D	Vent flow coefficient (-)
D	Equivalent diameter (m)
$\dot{m}$, MLR	Mass flow rate (kg/s)
HRR	Heat release rate (W)
P	Pressure (Pa)
Q or qv	Volumetric flow rate (m^3/s)
S	Section (m^2)
t	Time (s)
Tr	Renewal rate (h^{-1})
T	Temperature (°C)
U	Velocity (m/s)
V	Volume (m^3)

Greek

ρ	Density (kg/m^3)
ΔH	Enthalpy (J/kg)

Subscripts

v	Ventilation
vent	Vent or horizontal opening
adm	Ventilation inlet or admission
ex	Ventilation outlet or exhaust
net	Net
up	Upward or upper layer
low	Lower layer
L4	Upper room L4
L3	Lower room L3
ref	Reference
C3H8	Propane
Bal	Computed from Mass balance
o	Before ignition
+	Upward direction
-	Downward direction
cri	Critical
ex	Exchange (in Cooper's formulation)

standing such a "vent flow" (Brown [5], Epstein [6], Heskestad [7] and Tan & Jaluria [8]). Based on small-scale experimental approaches, they have proposed the formulation of a pure buoyancy bi-directional flow based on the Froude number as well as the purge conditions when mechanical ventilation is applied. From these approaches and the corresponding database, Cooper [9,10] proposed two correlations, given a prediction of the flow rate from pure natural convection to mixed convection, with the final aim of introducing them in zone codes. However, very few experimental studies have focused on this type of smoke flow. Cooper's models, which are used in most fire zone codes, have been validated based on only a very limited number of experiments and their performance is still under discussion in the scientific community [11]. In addition, very little work has been carried out on the validation of computational fire models based on large-scale fire tests [11–13], especially for confined and mechanically ventilated enclosures. Recent work on under-ventilated fire scenarios has highlighted the key influence of the vent flow on the combustion regime [14]. For these types of situations, there is a need for additional experimental and theoretical investigations, to help us improve our understanding of these flows in physical terms, to assess existing correlations, and to propose new developments.

The present contribution deals with a specific configuration presented in Fig. 1. This consisted of two rooms, which were mechanically ventilated and connected to each other by a horizontal opening (the vent) with a fire located in the lower room. With such a configuration, different flow regimes were possible depending on the fire power and the ventilation set-up. Based on 17 large-scale fire tests, we investigated the behaviour of the flow according to several fire scenario parameters: the fire heat release rate, the fire position, the ventilation configuration and the ventilation flow rate. This range of parameters enabled us to focus on the flow behaviours, from a pure natural convection regime to a forced convection regime. This study expands on previous works proposed by Prétrel for only four tests and with only the ventilation flow rate as a test parameter [15,16]. The new set of data obtained, which includes the fire HRR, the location of the fire source and the ventilation configuration as parameters, offers new insights for understanding the flow and developing models.

2. Fire test

2.1. Test facility

The facility consisted of two superposed rooms separated by a horizontal opening, the vent (see Fig. 3). The room dimensions were as follows: 4 m in height ×5 m×6 m =120 m^3 for the lower room, named "L3", and 4 m in height ×5 m×8.5 m =170 m^3 for the upper room, named "L4". The rooms were mechanically ventilated by an industrial network, with admission and exhaust branches located in the upper part of each room. The ventilation inlets and outlets within the rooms were positioned so that they did not influence the flow at the horizontal opening (the directions are indicated by red and blue arrows in Fig. 2 and Fig. 3b). The horizontal opening was a rectangular section, measuring 1030 mm ×1030 mm = 1.061 m^2, located in the centre of the fire room (off-centre in the upper room, as indicated in Fig. 2). The depth of the opening was 385 mm. The test parameters were the location of the fire source, the fire heat release rate (HRR), the ventilation flow rate and the ventilation configuration. The fire source was a propane gas burner located either below the vent (centre position) or in the north-west corner of the lower room (off-centre position). Three ventilation configurations were set up, with one or both branches shut off, as presented in Fig. 2:

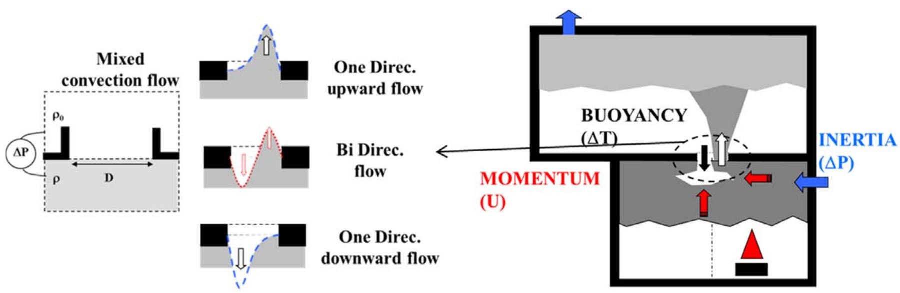

Fig. 1. Illustration of the flow at the opening in confined and ventilated compartments.