ARTICLE IN PRESS

Fire Safety Journal xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Fire Safety Journal

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

Interaction between water spray and smoke in a fire event in a confined and mechanically ventilated enclosure

Hugues Pretrel

Institut de Radioprotection et de Sûreté Nucléaire (IRSN), PSN-RES, SA2I, Cadarache, St Paul-Lez-Durance 13115 France

ARTICLE INFO

Keywords:
Smoke
Compartment fire
Fluid dynamics
Industrial fire
Droplet flows

ABSTRACT

This work deals with the interaction between water droplet flows and smoke in a fire event in a confined and ventilated enclosure. The objective is to identify the specific effect of water spray in the specific environment of a confined and ventilated enclosure. The study is based on 17 large-scale fire tests performed in one room of 165 m^3 ventilated at a renewal rate of 15.4 h^{-1}. The fire source is a propane gas burner with a heat release rate of between 140 and 290 kW. The water spray system consists of two Deluge nozzles with a nozzle coefficient of 26 l/min/$bar^{0.5}$. The test parameters are the fire heat release rate, the water flow rate, from 50 to 124 l/min, and the activation time. The study focuses on three topics, the interaction of the droplets with the smoke, the droplet evaporation process and the energy transferred to the droplets. The water spray significantly modifies the smoke stratification by mixing and cooling the gas phase. The rate of droplet evaporation has been determined from the water mass balance and is of the same order of magnitude as the rate of water vapor production by the combustion reaction. Heat transfer from the smoke to the droplets has been investigated using the energy balance equation. For a fire scenario in a confined and ventilated enclosure, the energy released by the fire is mainly transferred to the walls and extracted by the ventilation network. In the event of water spray activation, a significant share, up to 65%, is transferred to the droplet flows.

1. Introduction

Research on spray systems for fire safety applications remains significant both for economic reasons and because of the complexity of the interaction between the water droplets and the fire environment. Continuous research is being done to improve the prediction capability of numerical tools (zones or CFD models [1]) and to develop efficient water spray systems for fire suppression, fire control or smoke cooling. Two main areas of interest have been identified: the interaction between the droplets and the flame, with the ultimate goal of fire suppression, and the interaction between the droplets and the smoke layer, for controlling the development of the fire.

This study addresses the second issue in the specific environment of confined and mechanically ventilated enclosures. With this configuration, fires do not develop in the way they would be expected to develop in an open atmosphere environment and, if water sprays are activated, specific phenomena occur. Very few studies of confined and mechanically ventilated compartment fire scenarios have been performed in the scientific community and this contribution proposes to explore them. Three topics have been identified as typical of water spraying in a confined and ventilated enclosure: pressure variation induced by the water spray, smoke cooling efficiency and the process of thermal de-stratification of the smoke layer.

The occurrence of pressure variations is typical of fire events in confined enclosures (Prétrel et al. [2]). When a water spray system is activated, additional pressure variations occur due to the sudden cooling of the gas phase. This phenomenon has recently been highlighted by Prétrel et al. [3], citing low pressure peaks of up to −10,000 Pa.

Another important topic is the phenomenon of smoke cooling and changes in the stratification of the smoke layer. In open atmosphere (or semi-confined) fire scenarios, an important consequence of activating water sprays is the downward displacement of the smoke layer leading to changes in stratification and thus a reduction in visibility. Although water spraying has a positive impact on controlling a fire, it may have negative impact on evacuation. Several analytical approaches have been proposed to assess the downward displacement of the smoke layer as well as the heat transferred from the smoke to the droplet flow (Li et al. [4–7], Li et al. [8], Tang et al. [9] and Chung et al. [10]). The smoke flow and its propagation can also be affected when water spraying is activated. Several studies point out this influence on the doorway flow or the vent flow (Crocker et al. [11], Li et al. [12] and Yao et al. [13]).

The objective of this study is to identify the specific impact of water sprays on the smoke layer in a fire scenario in a confined and ventilated compartment. The study concentrates specifically on the heat and mass transfer between the droplet flow and the smoke layer. The analysis is based on a set of 17 large scale fire experiments for which the test parameters are the fire heat release rate (HRR) and the characteristics of the water spray system. Two water spray system parameters are

http://dx.doi.org/10.1016/j.firesaf.2017.03.025
Received 10 February 2017; Accepted 15 March 2017

Nomenclature

$\dot{m}$	Mass flow rate (kg/s)
M	Molar mass (g/mol)
D	Length (m)
Cp	Heat capacity (J/kg/K)
g	Gravity (m/s^2)
h	Interface height (m)
HRR	Heat release rate (W)
k_{noz}	Nozzle coefficient (l/min/bar$^{0.5}$)
P	Pressure (Pa)
q_v	Ventilation flow rate (m^3/h)
q_w	Water flow rate (l/min)
$\dot{Q}$	Rate of energy (W)
R	Perfect gas constant (J/mol/K)
S	Section (m^2)
S_T,S_X	Stratification parameter (-)
t	Time (s)
Tr	Renewal rate (h^{-1})
T	Temperature (K)
$\dot{v}$	Volumetric flow rate (m^3/s)
V	Volume (m^3)
X	Volume fraction (mol/mol or %-vol)
Y	Mass fraction (g/g)
z	Vertical coordinate (m)
Greek	Vertical coordinate (m)
ρ	Density (kg/m^3)
ϕ	Total thermal heat flux (W)

subscripts

A	Activation time
SO	Shut off time
ev	Evaporation
C	Combustion
CO_2	Carbon dioxide
f	Fuel
H_2O	Water vapor
$init$	Initial
in	Ventilation inlet
$loss$	Thermal losses
low	Lower layer
$mean$	Average
noz	Nozzle
O_2	Oxygen
out	Ventilation exhaust
P	Production or pressure
up	Upper layer
V	Ventilation
w	Water
i, j	Index

investigated: the water flow rate and the activation starting time. The activation time and the fire HRR were varied in order to obtain different vertical stratification and temperature conditions before the water spray system was activated. The analysis focuses on three topics: the interaction between the droplet flows and the smoke layer, the evaporation process and the energy transferred to the droplet phase.

2. Fire test

2.1. Configuration

The fire scenario, also presented in [3], consists in a fire in a closed and mechanically ventilated compartment. The compartment is a room in IRSN's DIVA facility. It is rectangular (4.88 m×8.67 m=42.3 m^2) with a height of 3.90 m (Fig. 1). The walls, floor and ceiling are made of concrete; the ceiling is covered with calcium silicate panels to protect it from thermal degradation. The ventilation system consists of an inlet vent and exhaust ducts connected to the upper part of the room about 0.80 m from the ceiling. The ventilation ducts are connected to an industrial system equipped with blower and exhaust fans. The fire source is a propane gas fire, which generates a constant and well-controlled heat source. It is a Leader-Group PYROS® gas burner made of a water tank in which a pipe with small orifices bubbles in propane gas to mimic the behavior of a pool fire (Fig. 1). The fire is located in the north-west corner of the room to prevent the fire from being extinguished, so that the interaction of the water sprays with the smoke layer can be studied.

2.2. Water spray system

The water spray system is made of two nozzles located 2.97 m from the ground and about 0.85 m from the ceiling (Fig. 1). The nozzles are connected to a system of pipes equipped with valves, a pressure transducer and a water flow rate device. The water spray is activated and shut off manually using a valve on the water pipe system. The nozzle is a Deluge type, Protectospray® D3, HV nozzle with k coefficient of 26 l/min/bar$^{0.5}$ [15]. The two nozzles produce a total water flow rate in the range [50;124] l/min for operating pressures in the range [92;568] kPa. The nozzle has been characterized using the Phase Doppler Anemometer technique at IRSN's CALIST facility [14], giving the droplet diameter and velocity as well as the spray envelope and the effect of the operating pressure. The nozzle produces a water droplet flow with a maximum 45° angle in relation to the nozzle axis at 124 l/min. The droplet velocity measured 200 mm from the nozzle is in the

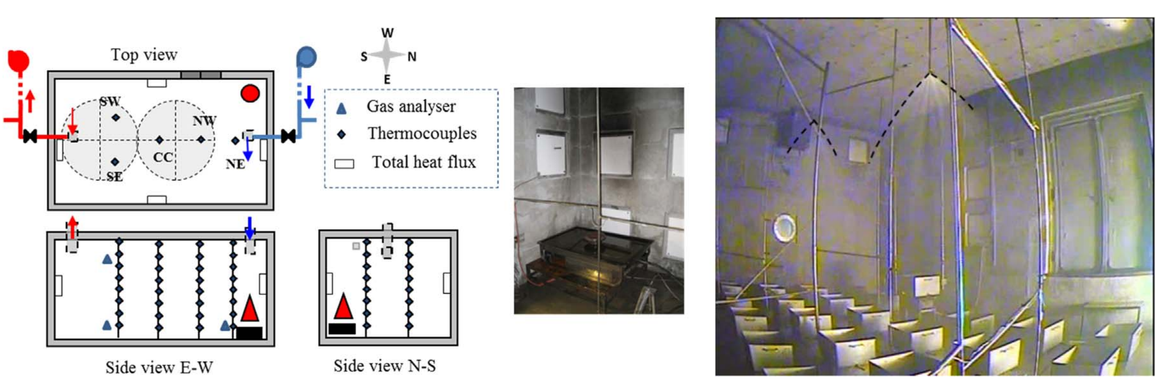

Fig. 1. Sketch of the facility with the locations of the measurement points and picture of the burner apparatus and of the fire room with the water spray system operating.