Fire Safety Journal 93 (2017) 60–73

Contents lists available at ScienceDirect

Fire Safety Journal

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

Experimental study on interaction of water mist spray with high-velocity gas jet

P. Zhu [a,b,1], X.S. Wang [a,*,1], G.C. Li [a], Y.P. Liu [a], X.X. Kong [a], Y.Q. Huang [a], X.D. Zhao [c], J.W. Yuan [c]

[a] State Key Lab. of Fire Science, University of Science and Technology of China, Hefei, 230026, China
[b] Department of Engineering Physics, Tsinghua University, Beijing, 100084, China
[c] State Key Lab. of Safety and Control for Chemicals, Qingdao, 266071, China

ARTICLE INFO

Keywords:
Water mist
High velocity gas jet
2D-PIV
Gas-spray interaction
Flow field structure

ABSTRACT

Water mist spray is considered a potential and effective method for controlling or mitigating the risk of natural gas (NG) leakage. In order to address the lack of understanding of the dynamical behaviours and interacting mechanisms between water mist spray and high-velocity leakage gas jets, a series of small-scale experiments were conducted by means of a 2D particle image velocimetry technique. For safety reasons, nitrogen was tested instead of NG. The results demonstrate that the two-phase flow field could be divided into gas- or spray-dominant flow for different gas-spray momentum ratios. The exponential correlation model based on the effective gas-spray momentum ratio Φ_{Eff} could predict the vertical gas-spray interaction interface position more effectively. The gas-spray momentum ratio and relative gas-spray opening angle values are important factors affecting the gas-spray interaction. An effective gas-spray momentum ratio of $\Phi_{Eff} < 1$ is necessary for practical applications. A counter-rotating vortex pair is formed due to the entrainment effect of the high-velocity gas flow, which may enhance the mitigation efficiency by means of effective gas-droplet mixing. The comparison of Nozzle A with Nozzle B indicates that the water mist spray with larger coverage relative to the gas plume should exhibit superior performance in terms of controlling or mitigation effects.

1. Introduction

The west-east natural gas transmission project in China has resulted in continued focus on natural gas (NG) transmission and storage safety. Transportation and storage systems for NG, such as gas-gathering and transportation stations and urban resident gas pipelines, often consist of a complex network of high-pressure pipelines. Original NG is a combustible mixture of hydrocarbon gases, including methane (CH_4), propane (C_3H_8), carbon dioxide (CO_2) and hydrogen sulphide (H_2S) [1]. Therefore, gas leakage accidents may occur due to pipeline corrosion, which is inevitable given the impurity of NG. Once gas leakage occurs, high-pressure gas is rapidly released to the surroundings, resulting in human intoxication and even causing fire or explosion accidents [2–5], which often have serious consequences for residents and property. Therefore, it is necessary to develop effective and safe emergency handling measures in order to prevent and control the leakage of hazardous gases.

Numerous studies have been performed focusing on gas release characteristics [3,4], as well as fire and explosion behaviours [5,6]. As a relatively clean and effective fire suppressant, water mist has been considered for fire suppression [7–10], fire radiation protection [11,12] and gas explosion mitigation [13–15]. A water curtain or spray curtain has been used in industry applications in order to control and mitigate dense gas, such as LNG vapour clouds, by means of dispersion and absorption; however, only the gas spread in the downwind region has been considered [16,17]. In practical use, the gas released from a small hole in the pipeline usually has a high velocity, corresponding to local sonic speed when the pipe pressure reaches the critical pressure [3,4]. Furthermore, it is more effective to control or mitigate leakage gas within a limited area, and reduce the risk or possibility of fire and explosion. If water mist spray that is generated by means of a mobile or fixed water mist system impinges on a leakage gas jet, the gas jet velocity decays quickly and gas diffusion is prevented, and the absolute concentration of hazardous gas may even be reduced if the sprayed water contains a certain additive. The interaction process between the water spray and gas jet should influence the controlling or mitigation mechanisms, such as

---

* Corresponding author.
E-mail address: wxs@ustc.edu.cn (X.S. Wang).

[1] The authors contributed equally to this work and should be considered co-first authors.

http://dx.doi.org/10.1016/j.firesaf.2017.08.005
Received 7 June 2017; Received in revised form 26 August 2017; Accepted 28 August 2017

0379-7112/© 2017 Elsevier Ltd. All rights reserved.

Nomenclature

c_p	Specific heat at constant pressure ($Jkg^{-1}\ K^{-1}$)
c_v	Specific heat at constant volume ($Jkg^{-1}\ K^{-1}$)
CPR	Critical pressure ratio
k	Heat capacity ratio
$\boldsymbol{K}$	Flow discharging coefficient ($Lmin^{-1}MPa^{-0.5}$)
$\dot{M}_g$	Gas jet momentum ($kgms^{-2}$)
$\dot{M}_w$	Water spray momentum ($kgms^{-2}$)
$\dot{M}_{w,Eff}$	Effective spray momentum ($kgms^{-2}$)
P_a	Absolute ambient pressure (Pa)
P_{in}	Absolute pressure in pipeline (Pa)
$P_{in,cr}$	Critical absolute pressure in pipeline (Pa)
P_w	Water spray operation pressure (MPa)
$\dot{Q}_{Mg,calc}$	Calculated gas mass flow rate ($kgmin^{-1}$)
$\dot{Q}_{Mg,exp}$	Measured gas mass flow rate ($kgmin^{-1}$)
$\dot{Q}_{Mw}$	Total mass flow rate of water spray ($kgmin^{-1}$)
$\dot{Q}_w$	Water flow rate ($Lmin^{-1}$)
$\dot{Q}_{Vg}$	Gas volume flow rate ($Lmin^{-1}$)
$\dot{Q}_{Vw}$	Total water flow rate ($Lmin^{-1}$)
$\boldsymbol{R}$	Radius of spray cross-section at $z = 0$ mm
$\boldsymbol{R_b}$	Radius of effective spray cross-section (mm) at $z = z_b$
R_g	Gas constant
$\boldsymbol{R_p}$	Radius of extended area of effective spray cross-section at $z = 0$ mm
$\boldsymbol{R_S}$	Radius of S_{ECS} (mm)
S_{ECS}	Equivalent cross-section between gas jet and spray
T_{in}	Stagnation temperature in pipeline (K)
u_{g0}	Calculated gas jet velocity at nozzle exit (ms^{-1})
u_{w0}	Droplet velocity at water mist nozzle exit (ms^{-1})
$u_z(r)$	Vertical average droplet velocity profile in radial at $z = 0$ mm
$V_{flux}(r)$	Mist volume flux profile in radial at $z = 0$ mm
z_0	Constant coefficient in formula
z_b	Lift-up distance of gas plume (mm)
z_{bc}	Critical lift-up distance of gas plume (mm)
z_b^*	Normalised lift-up distance of gas plume
Z_S	Vertical position of S_{ECS} (mm)

Greek symbols

Φ	Gas-spray momentum ratio
θ_g	Gas jet opening angle (°)
θ_w	Spray cone angle (°)
ρ	Fluid density (kgm^{-3})

Subscripts

a	Ambient condition
b	Gas-spray interaction boundary
Bc	Critical gas-spray interaction boundary
Eff	Effective
g	Gas
s	Equivalent cross-section S_{ECS}
w	Water mist spray

gas-mist mixing and toxic component absorption. Moreover, the gas-spray impinging process must differ from that of previous studies [18–21], where only hot gases or fire plumes with relatively low velocity were considered. Therefore, it is necessary to investigate the dynamic process of the gas-spray interaction in order to deepen our knowledge and obtain valuable data for practical applications of leakage gas control/mitigation by means of water mist.

Therefore, in this study, the dynamic behaviours of the interactions between the water mist spray and high-velocity gas jet are investigated preliminarily, through a series of small-scale experiments. A planar particle image velocimetry (2D PIV) method, which has been extensively applied in gas or liquid flow field measurements [22,23], was utilised in order to obtain the time-averaged velocity, vorticity and turbulent kinetic energy of the gas-spray interaction flow field. For safety reasons, nitrogen (N_2) was used instead of NG. Water mist characteristics such as droplet size distribution and velocity were measured by a Particle-Master Shadow system, as described in the literature [24,25]. The results can guide the selection of a water mist system for the emergency handling of gas leakage accidents and provide valuable data for model development.

2. Experimental setup and measurement methodology

2.1. Experimental arrangement

A schematic diagram of the experimental setup is provided in Fig. 1. The system consists of three major components: (1) water mist system; (2) gas jet generation system; and (3) PIV measurement system.

A water mist system mainly includes a water tank, water pump and water mist nozzle. A nozzle with a single orifice was used in the tests, due to the measurement space limitations. The water flow rate was measured by an LA Fuda-type flowmeter with range of 10–500 LH^{-1} and precision of ±0.5%, while the operation pressure was measured by a pressure gauge. High pure N_2 (99.99%) was supplied by means of a high-pressure cylinder and the leakage flow rate was controlled by two SevenStar CS230A mass flow controllers (MFC, accuracy ±1.0% F.S.) with full scales of 100 and 300 SLM. As shown in Fig. 1b, one hollow cylinder cavity (with a length of 400 mm and inner diameter of 40 mm) with a gas release nozzle was used to simulate the gas release from a small pipeline hole. The vertical distance between the gas nozzle and spray nozzle was fixed at 500 mm. A digital pressure gauge (MIK-Y180, accuracy ±0.4% F.S.) was fixed to the cylinder near the leakage exit in order to monitor the pressure. A wastewater collection tray was installed on the support framework below the cylinder. The PIV measurement system is introduced in detail in the following section.

Fig. 2 illustrates the nozzle structure and its spray pattern. Two solid-cone spray nozzles with orifice diameters of 0.5 and 0.9 mm, denoted by Nozzle A and Nozzle B, respectively, were used, and their water flow rate and spray angle as measured under different operation pressures are listed in Table 1. Another key factor in terms of the nozzle is the flow discharging coefficient K ($Lmin^{-1}MPa^{-0.5}$), which is calculated by the following equation:

$$K = \dot{Q}_w \Big/ \sqrt{10P_w}, \tag{1}$$

where $\dot{Q}_w$ is the water flow rate ($Lmin^{-1}$) and P_w is the water operation pressure (MPa) measured at the spray head. The K of Nozzle A and Nozzle B are 0.12 and 0.29 $Lmin^{-1}MPa^{-0.5}$, respectively. It can be observed that the water flow rate and spray angle values of Nozzle B are approximately twice those of Nozzle A.

2.2. PIV measurement system

Flow velocity is determined by the displacement of imaged particles within a thin laser light sheet and time intervals, by means of the PIV system. As illustrated in Fig. 1a, the centre plane (along the nozzle's central axis) of the gas-spray interaction flow field was focused on and tested. A double-pulsed Nd:YAG laser with a 200 mJ/pulse, 532 nm wavelength and 15 Hz repetition rate was used to illuminate the test

Download English Version:

https://daneshyari.com/en/article/4920820

Download Persian Version:

https://daneshyari.com/article/4920820

Daneshyari.com