ARTICLE IN PRESS

INTERNATIONAL JOURNAL OF HYDROGEN ENERGY XXX (2018) 1–20

Available online at www.sciencedirect.com

ScienceDirect

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

Experimental and numerical investigation of turbulent jets issuing through a realistic pipeline geometry: Asymmetry effects for air, helium, and hydrogen

Majid Soleimani nia, Brian Maxwell, Peter Oshkai, Nedjib Djilali*

Institute for Integrated Energy Systems, University of Victoria, PO Box 1700 STN CSC, Victoria, V8W 2Y2, Canada

ARTICLE INFO

Article history:
Received 8 December 2017
Received in revised form
20 March 2018
Accepted 26 March 2018
Available online xxx

Keywords:
Turbulent jets
Particle image velocimetry
Planar laser induced fluorescence
Large eddy simulation
Hydrogen infrastructure
Turbulent mixing

ABSTRACT

Experiments and numerical simulations were conducted to investigate the dispersion of turbulent jets issuing from realistic pipe geometries. The effect of jet densities and Reynolds numbers on vertical buoyant jets were investigated, as they emerged from the side wall of a circular pipe, through a round orifice. Particle image velocimetry (PIV) and planar laser-induced fluorescence (PLIF) techniques were employed simultaneously to provide time-averaged flow velocity and concentrations fields. Large eddy simulation (LES) was applied to provide further detail with regards to the three-dimensionality of air, helium, and hydrogen jets. These jets were always asymmetric and found to deflect about the vertical axis. The deflection was influenced by buoyancy, where heavier gases deflected more than lighter gases. Significant turbulent mixing was also observed in the near field. The jets from realistic pipe geometries experienced faster velocity decay and asymmetric jet spreading compared to round jets. These findings indicate that conventional round jet assumptions are, to some extent, inadequate to predict gas concentration, entrainment rates and, consequently, the extent of the flammability envelope of realistic gas leaks.

Introduction

Worldwide efforts continue to improve renewable energy technologies, as alternatives for traditional power supply in the energy grid and transportation applications. Hydrogen, as one renewable energy vector, can burn or react with almost no pollution. Commonly, it is used in electrochemical fuel cells to power vehicle and electrical devices. It can also be burned directly in engines. However, modern safety standards for hydrogen infrastructure must be assured before widespread public use can become possible. As a result, there has been much focus on advancing research to understand dispersion and ignition behaviour of hydrogen leaks in order to assess associated safety hazards. To date, a number of experiments have shown that hydrogen jets are easily ignitable [1], and have a wide range of ignition limits (between 4% and 75% by volume) [2]. It is therefore of paramount interest to understand the dispersive nature of hydrogen, which is a highly compressible gas, in order to adequately develop codes and standards. The current study addressed, through experimental measurements and numerical simulation, the effect of

* *Corresponding author.*
E-mail address: majids@uvic.ca (M. Soleimani nia).
https://doi.org/10.1016/j.ijhydene.2018.03.197

jet exit conditions on the dispersion of fuel leaks from a realistic pipeline geometry. The piping arrangement considered here was novel, as we examined the dispersion of vertical jets which emerged through a circular hole located in the side wall of a round pipe, perpendicular to the mean flow within the pipe. The aim was to provide insight into the flow structures associated with hydrogen outflow from a realistic fuel leak scenario.

Traditionally, scientific research has been limited to compressible fuel leaks through flat surfaces, aligned in the direction of the mean flow origin. To date, much is known about the axisymmetric and self-similar nature of such jet configurations, emerging through round holes, for a wide range of Reynolds numbers and gas densities. A recent review on round turbulent jets [3] presented experimental and numerical advances for a period of 86 years, starting with the work of Tollmien (1926) [4]. Of these, significant advances in round jet theory have been made possible from statistical analysis of many physical experiments [5–17]. Where round jet behaviour described through self-similarity of statistical analysis, along with those measurements in hydrogen round jets [18,19], owing the axisymmetic and self-similar nature of round jets. Advances in computational resources have also allowed numerical simulation, through large eddy simulation (LES), to prove useful for determining entire flow fields of such round jets [20–24]. In most experiments, data has been collected for air, helium, and CO_2 jets, due to the reactive nature of hydrogen. However, numerical simulation have also proved useful for determining ignition limits associated with hydrogen [23]; quantifying the effect of initial conditions on the turbulent mixing properties of hydrogen round jets [25]; and highlighting the need to consider the impact of transient flow structures and associated incursions of high flammability concentrations [26]. In general, one can categorize a round jet nozzle type through a flat surface as a sharp-edged orifice plate (OP), smooth contraction (SC), or a long pipe (LP). Among these three different nozzles, the most detailed research was performed on SC nozzles [12,27]. It has been shown that SC jets have a nearly laminar flow profile at the jet exit with a uniform ‘top-hat’ velocity profile. LP nozzles [9,10,28], on the other hand, produce a nearly Gaussian velocity profile due to fully developed turbulent conditions at the pipe exit. These jets also have thicker initial shear layers compared to the SC jets. Sharp-edged OP jets have received more recent attention, in the last decade, where detailed measurements [29,30] have revealed that this configuration has the highest mixing rates downstream from the release nozzle.

In addition to round jets, several investigations [31–34] have examined jet releases through different shaped orifices of varying aspect ratios, also through flat plates. Results from these investigations have shown that asymmetric behaviours emerge, such as the *axis-switching* phenomenon. Such behaviour, and other related mechanisms, lead to increased mixing, turbulence intensity, and entrainment rates compared to round jets. In other investigations, buoyancy effects on vertical jets [16] have been investigated, while others [35,36] have extended the survey of all available experimental data for both turbulent buoyant/pure jets and plumes to provide a quantitative study into the buoyancy effects. According to theory [37], jets and plumes both have different states of partial or local self-similarity. However, the global evolution of jets and plumes have a tendency to evolve towards complete self-similarity through a universal route, in the far-field, even with presence of buoyancy. It has also been concluded that large-scale structures of turbulence drives the evolution of the self-similarity profile, and buoyancy has an effect in exciting these coherent structures [36].

The influence of initial conditions on turbulent mixing and combustion performance in reactive jets, has also been of active interest in the scientific community [38–40]. In last two decades, due to rapid growth in the use of hydrogen powered fuel cell vehicle, several experimental and numerical studies [41–44] have also addressed different accidental hydrogen dispersion scenarios in enclosed and open spaces, while others [23,45–48] investigated laboratory small-scale unintended hydrogen round jet release in ambient air. It is noteworthy that all aforementioned studies, as well as related previous investigations on jets or plumes, have been limited to leaks through flat surfaces, where the direction of the jet mean flow was aligned with the flow origin. All of this work has been of prime importance to determine the dispersive nature of gases, for fuel-safety purposes, for gas leaks of various hole geometries and inflow conditions. In reality, however, accidental fuel leaks would not be limited to flows through flat surfaces. From a practical point of view, flow patterns and dispersion of gas originating from holes in the side walls of circular pipes should also receive attention. To date, and to the our knowledge, no such investigation has been formally published.

In the current investigation, jets issuing from such realistic geometry were considered experimentally and numerically. Turbulent vertical jets, flowing through a 2 mm diameter round hole in the side of a 6.36 mm diameter round tube, were studied. The investigation thus considered flow through a curved surface from a source whose original velocity components were nearly perpendicular to the direction of the ensuing jets. From now on, we refer to this jet configuration as a 3D jet. This orientation permitted practical flow velocity and concentration field measurements for a realistic scenario, which were compared to axisymmetric leaks through flat surfaces accordingly. Particle imaging velocimetry (PIV) and acetone-seeded planar laser-induced fluorescence (PLIF) were used to measure high-resolution instantaneous velocity and concentration fields, respectively, through experiment. To compliment the experiments, large eddy simulation (LES) was also employed to model the gas dispersion. An efficient Godunov solver was used, and coupled with adaptive mesh refinement (AMR) to provide high-resolution solutions only in areas of interest. The fluids considered experimentally and numerically were air and helium. Hydrogen was also considered for the numerical investigation. Thus, different fluid densities, ratio of specific heats, and buoyancy were considered accordingly. The outer-scale flow Reynolds numbers, based on the orifice diameter, and Mach numbers of the jets ranged from 18,000 to 56,000 and 0.4 to 1.5, respectively. The purpose was to identify and characterize departures from standard axisymmetric jet conditions, and to highlight the asymmetric nature of the 3D jets, which ensued from a practical geometry arrangement. To further compare the 3D