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An experimental study on the near flow field of a round jet affected by upstream multi-lateral side-jet

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ABSTRACT

The application of lateral jets into a confined flow in industry is a common method for mixing of reagents. However, there is limited understanding of the fundamentals surrounding the flow structures, flow evolution and their respective effects on a downstream outflow of a round jet nozzle when there are multiple jets inside the nozzle. To address this, an experimental study of the near-field outflow of a turbulent round water jet affected by multiple side-jet injected laterally into the round flow upstream of the nozzle exit has been conducted. Planar Laser Induced Fluorescence and Particles Image Velocimetry were used to investigate the fluid mixing and velocity in the near-field, respectively. The influence of jet to cross-flow momentum ratio on flow characteristics; including mixing and turbulence intensity, were assessed by varying the primary jet and side injection flow rates. Results indicated that side injection has major effects on the resulting near-field region flow. Flow cases with side-jets show an increase in shear layer roll-ups and spread. Velocity decay rates and turbulence intensity within the jet core increase with increasing jet to cross-flow momentum ratio. However, these effects extend only to the near-field region, as no significant perturbations beyond two primary jet diameters downstream are observed. This indicates that the side injection has significant effect on the flow and mixing in the near-field region, but minor influences further downstream.

1. Introduction

Jets in cross-flow (JICF) have been used in various industrial applications, such as gas-turbine combustion chambers, stage combustors operating on the Rich Burn/Quick Quench/Lean Burn (RQL) mode, and reagents mixing. An everyday example of JICF can be seen in the dispersion of fumes from chimneys. The mixing and evolution of flow from a jet with a cross-flow has been subjected to many studies which are well documented in the literature [1–4]. However, in many industrial applications, JICF is often used in a confined environment. Fundamentally, JICF and jets in confined cross-flow (JICCF) are similar, however, the jets trajectories [5] and vortices [6] may be affected by the shape of the confinement and any opposing jets that may exist. Many studies undertaken to study JICF trajectories [7], flow-fields [1], and vortices are done in an unconfined environment, which negate the effects of parameters such as opposing jets and boundary layers [2]. However, there are limited available studies on JICCF, in particular on cases involving small aspect ratio JICCF (ratio of primary diameter to jet, $(D_P/D_{inj}) \leq 10$). In addition, whilst the vortical evolution for JICF flow cases are well studied and documented, little data can be found on jet evolution, development and vortical spreading in confined round jet flows.

One aspect of JICCF that has been recently investigated is flow regime scaling. Multiple jets injected into a confined round flow can be scaled with respect to the momentum ratio (MR) of jet to cross-flow [8], as expressed in the equation

$$\frac{G_{inj}}{G_P} = \frac{(\rho V^2 A)_{inj}}{(\rho V^2 A)_P} \tag{1}$$

where subscripts *inj* and *P* denote the injection flow and primary flow, respectively; ρ denotes the fluid density [$\mathrm{kg\,m^{-3}}$]; and A denotes the hydraulic area [$\mathrm{m^2}$]. Using Eq. (1), flows can be categorized into three regimes: streaming flow regime; impinging flow regime; and backflow regime [9].

JICF have also been investigated as a mean to control turbulent jets [10,11]. By placing side-jets near the nozzle exit (both laterally and at an angle), it has been demonstrated that the properties of the exiting turbulent jet can be manipulated, in particular, the potential core length and flow exit profile. They have also suggested that the increase in flow turbulence results in an increase in ambient fluid entrainment into the jet. However, the influence

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of JICCF placed a short distance upstream of the nozzle exit on the outflow is less well understood. Part of the current work is to assess if placing the JICCF a short distance upstream of a nozzle exit will result in an increase in entrainment of fluid at the nozzle exit due to the hypothesized increase of turbulence in the flow. If such an increase in entrainment is possible, then there may be potential in using such method for turbulent jet flames stabilization, which is an additional aspect of the current study.

The efficacy of JICF in mixing is attributed to the induced vortices in the flow, which include Counter-rotating Vortex Pairs (CVPs), horse-shoe vortices, and other shear induced vortices [4]. New and Tay [10] has previously demonstrated the flow structures that can be generated by injecting single and opposing jets into a round flow. This study is conducted on an orifice flow with two side jets. However, the flow properties from both an orifice and smooth-contraction differs from that of a long-pipe [12], which is required for the current study. Furthermore, the effect of four side-jets is expected to differ from the two side-jets [13].

The application of the current study will ultimately be for the purpose of fuel-air mixing in turbulent jet flames. Current reactants mixing methods can be sub-categorized into passive and active mixing methods. While passive reactants mixing has been utilized extensively in the industry, it has limitations in adapting to different fuel blends and operating conditions. Active reactants mixing allows more flexibility with control, but are typically more expensive and complex. It is proposed that a JICCF method be used as an active mixing method, which can be more cost effective and simpler than other active methods available.

In terms of combustion systems, JICCF has been used extensively for hot fume quenching in combustion chambers. For example, JICCF has been adopted for use within the RQL burner systems as a solution for quick quenching of hot combustion product [14]. Cooler air is injected into hot combustion product via lateral jets to rapidly reduce the temperature of fumes. The development of RQL burners [15,14,16] have indirectly contributed to JICCF studies, in particular on the matter of enhanced mixing between lateral jets and confined cross-flows. There are no parameters which defines "enhanced mixing" and that the definition varies on a case-by-case basis [15]. Despite the exhaustive studies related to RQL, not much data can be synthesized to illustrate the mixing effect that JICCF has on reactants mixing for turbulent jet flames.

The current study investigates the influence of mixing from multiple side-jet injection into a symmetrical configuration upstream of the round nozzle exit on the near-field of the jet outflow. This study can also be viewed as the build-up on the results of a previous study [10] by assessing a four side-jets flow case, placed upstream of a long-pipe (LP) nozzle. The specific focus of this study is to better understand how side-jets and primary flow rates, therefore momentum ratio, influence the flow fields in the near-field outflow of the perturbed round LP flow.

2. Methodology

Particle Image Velocimetry (PIV) and Planar Laser Induced Fluorescence (PLIF) techniques were used simultaneously during the experiments. The experiments were conducted in a closed loop water tunnel with working section measuring 500 mm × 500 mm × 1800 mm. The tunnel walls are made from acrylic to enable optical access for laser-based and visual measurement techniques.

The experimental nozzle is constructed from a one meter long clear acrylic central pipe with nominal diameter (D_P) of 56 mm and with four clear acrylic, radially orientated side-jets, placed equi-distant at one primary diameter ($1D_P$) upstream of the nozzle exit. The side-jets each measure 150 mm long with nominal diameter of 6 mm. The one meter long pipe is equivalent to approximately 16 central diameters in length and is connected to the flow source via a smooth diverging nozzle. The flow is conditioned far upstream with a honeycomb section to provide a developed and predictable pipe flow. Despite the relatively short development length, the velocity and concentration profiles at the nozzle exit show an almost uniform profile and a top hat profile (as seen in Fig. 11), respectively.

Fig. 1 shows the schematic diagram to the four side-jets configuration used for the current study. As indicated by the section A-A in the figure, the nozzle was rotated 45 deg to its longitudinal axis simply to fit within the water tunnel.

Fluid for the primary and side-jets flow were sourced from two separate 400 L capacity reservoirs, both seeded with Dantec Dynamics PSP-50 Polyamide Seeding Particles for PIV data collection. One reservoir was dyed with aqueous Rhodamine 6G fluorescent dye for PLIF collection. The dye was chosen as its peak absorption is at approximately 530 nm [17], which is closed to the emitted wavelength of the available frequency-doubled Nd: YAG lasers, whilst the emission of the dye is in the visible range of approximately 560 nm. The dye mixture was produced by premixing 0.1grams of Rhodamine 6G solids into 400 L of clean water.

Light was sourced from a Quantel Brilliant B Nd:YAG laser, frequency doubled to 532 nm and pulsed at 10 Hz. The laser light sheet was formed using an optics train (combination of plano convex spherical lens of *focal length* 100 mm; a bi-concave spherical lens of *focal length* −50 mm; and a cylindrical plano concave lens of *focal length* −25 mm) to form a laser sheet of approximately 2 mm thick. A silvered mirror (reflectance ⩾ 97.5%) was placed downstream of the sheet forming optic to reflect the laser sheet to illuminate the region of interest. The nozzle and the light sheet were aligned such that the sheet was incident on the nozzle centreline, illuminating the region of interest (ROI).

Two Princeton Instruments CCD Megaplus II ES4020 camera units were used for image collection. Each of the CCDs feature 2048 pixels × 2048 pixels arrays and were triggered by a Berkeley Nucleonics Corporation (BNC) 565 Delay Generator at a duty cycle of 2.5 Hz. The overall physical imaging region is approximated to be 200 mm × 200 mm, which translates to a spatial resolution of approximately 10.2 pixels/mm. Both CCDs were fitted with Tamron lens sets of 50 mm with $f1/4D$. The CCD for PLIF collection was fitted with an Orange Glass (OG) filter to exclude elastic scattering from PIV particles at 532 nm wavelength. EPIX XCAP 3.8 software and suitable frame grabbers were used for image acquisition and for camera shutter control.

To collect cross-plane data, the sheet forming optic was rotated by 90 deg and the silvered mirror was moved to align the formed laser sheet with the ROI. An additional mirror was placed far downstream of the nozzle exit in the water tunnel, so not to disrupt the bulk of the jet outflow, and angled at 45 deg to allow imaging (access) into the pipe. Only PLIF data was collected for this region.

A Fischer and Porter rotameter tube FP-1-27-G-10 with float 1-GNSVGT-68 was used to monitor the primary flow and a FP-3/4-21-G-10 with float 3/4-GUSVT-510 was used for the side-jets' flow. The side-jets' rotameter was connected to a distribution manifold downstream that, ideally, distributes the flow equally to the side-jets via four flexible tubes of equal length. The flow conditions for the current study are as detailed in Table 1.

Primary flow and side-jets' injection flow are manipulated to achieve the differences in the flow momentum ratio (MR). The total bulk flow is not conserved for most cases, however is conserved for flow case MR = 0.03; MR = 0.08; and MR = 0.15.