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Numerical investigation on the reactive gas mixing through interaction between twin square jets side-by-side and a crossflow

F. Roger *, A. Gourara, J.-M. Most, H.Y. Wang

PPRIME Institute, Département Fluides, Thermique, Combustion, CNRS ENSMA Université de Poitiers UPR 3346 ENSMA BP 40109 - 1, rue Clément Ader 86961 FUTUROSCOPE Cedex, France

HIGHLIGHTS

- Twin gas jets in crossflow are modelled by Large Eddy Simulation Technique.
- Gas mixing upstream the reactor is analysed by Large Eddy Simulation Technique.
- Twin gas jets in crossflow are analysed by Particle Image Velocimetry.
- Counter-rotating vortex pair of twin jets in crossflow is well predicted.
- Velocity and Mass-fraction trajectories of twin jets in crossflow are well predicted.

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ABSTRACT

In this work, the mixing of gases by twin square jets mounted side-by-side and exiting into a crossflow is investigated by means of experiment and numerical simulation. The jets are emitted by a blunt injector embedded at the centre of an Eiffel type wind-tunnel, simulating approximately an industrial mixer. In the numerical simulation, the three dimensional, time-dependent Navier–Stokes equations are solved through the use of a Large Eddy Simulation for the turbulent flow. The experimental data serve to validate this numerical model which is then extended to fairly well characterize the interactions between the jets. Both the prediction and experiment indicate that the interaction among the jets is controlled by both the ratio S, determined from the spacing between adjacent jet axes to the hydraulic diameter of the jets, and the blowing ratio, equal to the square root of the momentum flux ratio between jet and crossflow. When the ratio S is large and the blowing ratio is small, each jet behaves as a single jet, even far away from the jet exit. Conversely, as the parameter S decreases, the inner vortices seem weakened with the presence of a strong vertical velocity directed towards the wall of injection, resulting in a modification of the spatial distribution of the axial vorticity, particularly for large blowing ratio. When the inner vortices disappear, the resulting flow seems roughly similar to a single jet issued from a rectangular hole with "high aspect ratio" due to the enhanced blockage forces against the crossflow generated by the jets. As a consequence, the dilution of the injected fluid depends on both the S factor and the blowing ratio.

1. Introduction

In the field of chemical engineering processes, the synthesis of numerous organic compounds like nitric acid, maleic anhydride or hydrogen cyanide requires a strong turbulent mixing between the reactive gases, injected upstream from the catalytic reactor. In industrial mixers, jets mounted side-by-side at the centre of the mixer exiting into a crossflow – like the Oxynator™ [1] – create complex and challenging three dimensional turbulent flow conditions. Three dominant factors such as the blowing ratio, $r = (\rho_{jet} U_{jet}^2 / \rho_{cf} U_{cf}^2)^{0.5}$ equal to the square root of the momentum flux ratio between jet and crossflow, dimensionless spacing between adjacent jet axes, $S = s/D_{jet}$, and dimensionless height of the mixer (not studied here) for manage the resulting flow [2–6]. It is noteworthy that interactions between the adjacent jets in a row cannot be described from a single jet [7]. Therefore, it appears important to analyse the most dominant features produced by twin jets exiting side-by-side into a crossflow (TJICF).

According to Isaac and Schetz [8], the velocity trajectory of TJICF is a few percent below that of a single jet, whereas Toy et al. [9] indicate that the penetration and development of twin jets in width are more important than those from a single jet for a small distance between their axes. By using a k–ε turbulence model,

* Corresponding author. Tel.: +33 549498280; fax: +33 549498291.
E-mail address: roger@ensma.fr (F. Roger).

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Nomenclature

a smallest mesh section
C Smagorinsky constant
D characteristic length (m)
$\vec{g}$ gravity vector (m s^{-2})
L_x, L_y, L_z length, width and height of calculation volume respectively (m)
N_x, N_y, N_z number of knots in the x, y and z directions respectively
p pressure (Pa)
$q_i = a_i/a$ ratio between the i mesh section and the smallest mesh section
$r = \left(\rho_{jet}U_{jet}^2/\rho_{cf}U_{cf}^2\right)^{0.5}$ blowing ratio
$Re_{cf} = U_{cf}D_{jet}/\nu_{cf}$ crossflow reynolds number built on U_{cf} and D_{jet}
$Re_{jet} = U_{jet}D_{jet}/\nu_{jet}$ jet reynolds number built on U_{jet} and D_{jet}
s spacing between adjacent jet axes (m)
$\underline{S} = s/D_{jet}$ dimensionless spacing between adjacent jet axes
$\overline{\overline{S_{ij}}} =$ large scale strain rate tensor (s^{-1})
Sc_t turbulent Schmidt number
t time (s)
$\vec{U} = (u_1, u_2, u_3)$ velocity vector (m s^{-1})
$\vec{x} = (x_1, x_2, x_3) \equiv (x, y, z)$ coordinates (m)
Y_K mass fraction of the species k; $k = 1$ for the crossflow and $k = 2$ for the jet
Δ filter size (m)
$\eta = \sum_{jicf}/\sum_{tjicf}$ ratio of injected fluid dispersions for JICF and TJICF
ν kinematic viscosity (m^2 s^{-1})
ρ density (kg m^{-3})
$\sigma = \left(\frac{\sum q_i(<Y_2'^2>_i+(<Y_2>_i-<Y_2>_m)^2)}{\sum q_i-1}\right)^{0.5}$ dispersion of the injected fluid
$\overline{\overline{\tau}} =$ subgrid stress tensor (N m^{-2})
$\vec{\varphi}^{Y_k} = (\varphi_1^{Y_k}, \varphi_2^{Y_k}, \varphi_3^{Y_k})$ subgrid scalar transport flux of the species k (kg m^{-2} s^{-1})
$<\omega_1> = \left(\frac{\partial<u_3>}{\partial x_2} - \frac{\partial<u_2>}{\partial x_3}\right)$ axial vorticity (s^{-1})

Subscripts
cf crossflow
cl centreline
jet jet
max maximum
m space average
sg subgrid scales

Operators
$\bar{}$ filter
$\sim$ Favre filter
<> time averaging operator

Acronyms
CVP counter-rotating vortex pair
ID injection device
(T) JICF (twin) jet(s) in crossflow

Chang and Choi [10] suggest that the jet trajectory penetrates deeply into the crossflow as S increases for a high value of the blowing ratio. On the other hand, the turbulence rate and the crossflow Reynolds number have little influence [2] and, diameter of the injector and density ratio between jets and crossflow do not affect jet penetration [4]. For Savory and Toy [11], the inner vortices rapidly diminish such that the outer vortices then form a pair similar to that of a simple jet case. Moreover, Vranos et al. [12] attribute the displacement towards the wall of the vortices in an opposite rotation to the interaction between the neighbouring vortices from adjacent jets. By comparing the vorticity transport between jet in crossflow (JICF) and TJICF, Kolář et al. [13] explained that the most dominant properties are strongly dependent on the parameter S.

A large panorama of the mean scalar distributions for different geometries and flow conditions in mixers is proposed [2–6,14,15]. Each jet diffuses near its injector without interferences, but the interactions downstream modify strongly the shape of the distributions compared with a JICF. According to Doerr et al. [3], the mixing region is enhanced by enlarging the spacing and reaches a maximum at $r = 4.5 – 5.5$, depending on the height of the mixer. Beyond this critical value, the mixing rate does not decrease in contrast to a situation with narrow spacing between jet axes. Besides, the Reynolds number at the injection [2] and the shape of the injector [14] have a little influence for intermediate r values.

The aim of this work is to further understand, by means of experiment and numerical simulation, the behaviour of twin jets mounted side-by-side, exiting into a crossflow in the similar conditions to those used frequently in industrial mixers. As the controlled parameters do not simply influence the response variables, a study of the flow behaviour and, more precisely, of the Counter-rotating Vortex Pairs (CVPs) is done below. Trajectories of the jet, velocity $<u_3>$ and mass fraction of the injected fluid distributions in cross sections are analysed.

2. Experimental set-up and diagnostic techniques

The experimental set-up, described in [16], includes an Eiffel wind-tunnel, equipped with a rectangular (0.4×0.7 m^2) test section, and an Injection Device (ID) for producing two pairs of vertical, square jets, through which air is supplied in the opposite directions from the middle of the channel. The ID, shown in Fig. 1, is made up of a parallelepiped ($8 \times 40 \times 5$ cm^3) fitted upstream with a semi-elliptical leading edge with a 5 cm half big axis and a 5 cm small axis to eliminate fluid filament detachment

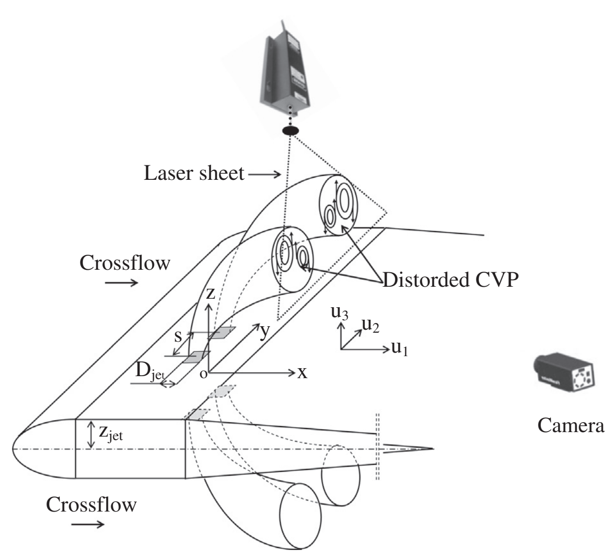

Fig. 1. Schematic representation of the square jets exiting into crossflow.