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Formation of counter flow jet resulting from impingement of multiple jets radially injected in a crossflow

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ABSTRACT

The process of formation of a counter jet as a result of impinging of jets radially injected into a confined crossflow of cylindrical duct was studied experimentally and numerically. The axial temperature distributions upstream of the jet injection plane were measured at various jets/crossflow mass flow rates, also near the jet injection plane. Obtained data were analyzed, the conditions of formation of the jet toward the main flow were determined. The point estimates of axial and radial mixing fractions in overpenetration mode with counter jet formation have been obtained. Experimental data are in satisfactory agreement with the numerical analysis results.

1. Introduction

Optimization of mixing of transversal multiple jets-in-crossflow (*JIC*) of the cylindrical duct is extensively treated in the literature because of its wide application in various engineering areas, for instance in mixing zone of staged combustor such as Rich-Burn/Quick-Mix/Lean-Burn (*RQL*) combustor. Here in order to meet air quality environmental standards it is required to provide low NO_x emission rate. Optimization of mixing implies that arrays of jets play a key role in forming an uniform equilibrium pattern and composition of exiting flow. A summary of previous multiple *JIC* studies is presented in Refs. [1–4]. Substantial *JIC* research efforts have been undertaken at Pratt and Whitney [5], a numerous variety of NASA-supported numerical and experimental studies have been published earlier that addressed cylindrical and rectangular ducts in the case of either reacting or non-reacting flows [6–18], including an influence of air jets preheating on NO_x emission rate [19,20]. *JIC* studies have been also performed in Germany: in Darmstadt [21,22] with the purpose of optimization of mixing in rectangular duct in *RQL* combustor, in Magdeburg [23,24] where numerical and experimental investigations of mixing of multiple jets discharging into a confined cylindrical crossflow have been conducted in both non-reacting/reacting jet cases. In addition, authors of Ref. [25] studied experimentally an impinging of two opposed round air jets issuing into an air crossflow of rectangular duct with small aspect ratio channel.

JIC mixing problem is of special importance for the mixing of reagents [26,27] and quenching of final products in chemical reactors when the characteristic time of duration of plasmachemical reactions is small, whereas a rate of temperature drop is very high, i.e. in Refs. [28–31] corresponding values are 10–50 ms and 10^6–10^8 K/s.

In most above mentioned studies mixing characteristics have been primarily considered in radial–transverse planes downstream of jet injection plane (*JIP*) as a function of momentum–flux ratio *J* and geometry. Analysis of available literature shows that flow parameters were not measured in the zone upstream of *JIP*, notwithstanding that for some processes, particularly plasma-chemical ones, formation of the counter flow in *JIC* configuration is the most promising technique for the fast quenching of the final product, since it presents the way to control the particles' size distribution and its phase content.

We assume that it is possible to increase the mixing rate and make it controllable by means of impinging of injected jets at axial region of crossflow. In Ref. [32] we started to fill a gap by performing *JIC* experimental investigation and numerical modeling of the turbulent mixing of non-reacting flows under the working conditions of plasma-chemical reactor similar to those in Ref. [31]. Modeling of the overpenetration mode showed that in this case at the center of the duct a counter flow jet formed, and near-wall

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Nomenclature

C	coefficient of proportionality, see Eq. (2)
C_d	orifice discharge coefficient, for example, see Eq. (6), =0.80
D	diameter of cylindrical duct (channel), =32 mm
d	orifice diameter, =5 mm
f_i	nondimensional enthalpy difference ratio, see Eq. (4)
f_T	nondimensional temperature difference ratio, see Eq. (3)
f_{eq}	equilibrium mixture fraction, see Eq. (5)
G	gas flow rate (g/s)
h	radial penetration depth of jet (mm)
h_v	upstream centerline counterflow penetration depth (distance) (mm)
i	gas enthalpy (kJ/kg)
J	jet-to-mainstream momentum–flux ratio, see Eq. (1)
K	constant in Eq. (6)
K'	constant in Eq. (7)
k	turbulent kinetic energy (J/kg)
L	characteristic centerline length of upstream recirculation zone defined as distance between 2nd and 1st stagnation points
n	number of orifices, =8
T	gas temperature (K)
v	mass-averaged velocity of gas flow (m/s)
x	axial coordinate ($x < 0$ – downstream of jet injection plane, $x > 0$ – upstream of jet injection plane)
y	lateral coordinate
z	radial coordinate $x = 0$, $y = 0$, $z = 0$ at point of intersection of duct centerline and jet injection plane
ε	turbulent dissipation rate (m^2/s^3)
ρ	gas density (kg/m^3)

Subscripts

j	jet
m	mainstream (crossflow)

areas of intensive turbulent mixing occurred upstream of *JIP*. It was established experimentally and confirmed by modeling that a length of recirculation zone upstream of *JIP* depended linearly on square root of *J*. Here again in the constant cylindrical 8-orifice geometry the only parameter to be varied in wide range is momentum–flux ratio *J*. With this in mind, this paper is focused on:

1. determining *JIC* conditions under which counter flow occurs;
2. obtaining the point estimates of premixing upstream of *JIP* in overpenetration mode in the case of counter flow jet formation.

2. Experimental

2.1. Setup

The plasma-chemical setup [31] was used to perform the model experiments of the *JIC* system in the mode of counter flow jet formation in the near-axis section of the channel. The bottom part of the setup attached to the plasma torch is shown schematically in Fig. 1. Geometry of the test section can be found in the previous paper [32], whereas its bottom part is shown in Fig. 1.

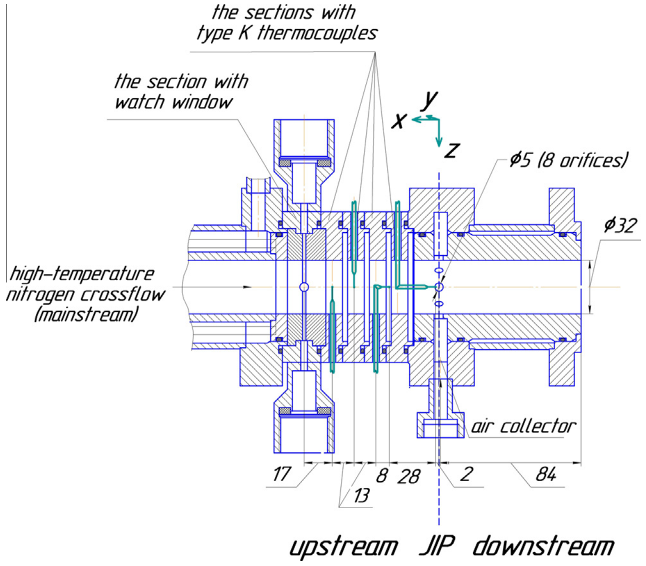

Fig. 1. Schematic of 1st configuration of type K thermocouples positioning at the bottom of the reactor. All sizes in mm.

The main flow (nitrogen) passed into the channel from the water-cooled direct-current linear-scheme plasma torch with inter-electrode inserts (IEI-plasma torch), with the rated power of 17 kW [33]. The room-temperature air was utilized as an injected gas. The air was injected into the channel from an annular circular collector through 8 holes, each of 5 mm in diameter, perpendicularly to the main flow.

In order to perform the experimental modeling of the counter flow jet formation as radially injected jets impinge, the sections were installed upstream of the section of injection of jets: some of them had thermocouples, and one has the watch window (see Fig. 1). To measure the temperature on the reactor axis, two configurations of thermocouples positioning were set. In the first one, four thermocouples (type K) were installed upstream of *JIP*; the distances between the thermocouples and the plane of the radial jet injection were 2, 30, 51, and 64 mm respectively (Fig. 1).

In the second configuration the distances from *JIP* to the thermocouples are 13, 38, and 51 mm, respectively. The diameter of thermocouple junction is 0.5 mm, the diameter of its corundum case is 3 mm. Each successive thermocouple was rotated about the previous one by 90° to reduce the disturbance introduced by the thermocouple into the flow. The readings were registered by the multi-channel temperature meter MIT-12TP.

Electric power of the plasma torch, the flow rate of the crossflow (plasma-forming nitrogen) and radially injected air jets, as well as water flow rate for cooling of channel walls were chosen in such a way to provide the maximal temperature of the main flow at arbitrary measurement point being below the upper range value of the type K thermocouples (1600 K).

2.2. Operating conditions

The main parameters characterizing 5 tests are presented in Table 1 below. For the constant geometry (8 round orifices) of a cylindrical duct, the main variable is the jet-to-mainstream momentum–flux ratio:

$$J = \frac{\rho_j v_j^2}{\rho_m v_m^2} \qquad (1)$$

As will be shown later, flow field in the channel is influenced by *J*, which is presented in Table 1. Here ρ is the density, v is the