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Upstream penetration behavior of the developed counter flow jet resulting from multiple jet impingement in the crossflow of cylindrical duct

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Experimental and numerical investigations of ultimate upstream penetration of developed counter flow jet formed as result of impingement of multiple round jets radially injected into a high-temperature confined crossflow have been performed. These investigations aimed to reveal an influence of strength of the developed counter flow jet on mixing intensity of jets in crossflow of cylindrical duct. Based on analysis of experimental data, the analytical dependence between dimensionless parameter of upstream penetration depth of counter flow jet and the square root of jets-to-mainstream momentum-flux ratio J has been established. The dependence proved to consist of linear region as well as nonlinear and asymptotic ones. For a given geometry an ultimate upstream penetration depth of the counter flow jet has been estimated to be approximately 2.1–2.3 diameter of the cylindrical duct. The corresponding value obtained on the base of numerical simulation turned out to be 1.8–2.0 diameter of the cylindrical duct. The dimensionless parameter h/D of radial jet penetration depth proved to be an appropriate to describe adequately an empirical character of upstream penetration of the counter flow jet within the linear region. Based on results of numerical simulation, axial velocity, temperature and pressure profiles as well as centerline turbulent kinetic energy contours have been obtained. It has been has also shown that an increase of the momentum-flux ratio promotes mixing in upstream recirculation flow zone and improves overall mixing performance as well.

1. Introduction

Mixing of transverse round multiple jets-in-crossflow (*JIC*) of the cylindrical duct is of special importance in various technological applications; mixing in the Rich-Burn/Qiuck-Mix/Lean-Burn (*RQL*) staged combustor is among most important. Optimization of mixing implies an almost uniform profile of the preset temperature and components composition at the mixing zone exit, and interaction between radially injected quenching jets and crossflow plays the key role here. Comprehensive reviews of the works devoted to *JIC*, both about a single jet in the crossflow and a multi-jet injection are presented in [1–4]. A number of investigations of *JIC*, both experimental and numerical, have been performed within recent decades; they dealt with the effect of the geometry of the *RQL* combustor mixer and jet parameters on their interaction in reacting and non-reacting flows of the cylindrical duct [5–21]. In this work cycle, Holdeman proposed the parameter C as an indicator of the mixing uniformity which is proportional to the square root of the momentum-flux ratio J related to the number of jets n. Extensive calculation and experimental works were also addressed to the same challenge in [22–24].

The complexity of multi-parameter *JIC* problem governed the further theoretical investigations; the target was to find a universal dimensionless parameter describing the physical character of the dependence of the trajectory of the transverse jets issuing into the crossflow [25]. Ktalkherman [26–28] proposed the h/D parameter of the radial jet penetration as a value to describe reagent mixing in fast-mixing chemical reactors and final product quenching; this parameter was also used in [29].

Numerical analyses of *JIC* conducted by Clayton and Jones [30] and Ivanova et al. [31] demonstrated a superiority of Large Eddy Simulation (*LES*) model over Reynolds Averaged Navier-Stokes (*RANS*) approach under conditions of multiple jet injection and single jet injection, respectively. Nevertheless, Urson et al. [32] applied *RANS*-based standard κ-ε model of turbulence to study multiple jet injection into crossflow of cylindrical duct and compared numerical results with experimental data of [5]. Recently,

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Davoudzadeh and Forliti [33] used low Reynolds number κ-ε model to perform numerical study of flow and mixing properties of single transverse jet in a confined system. The results show that the numerical simulations predict the experimental data with a good degree of accuracy. The reported results of the experimental and numerical simulation of the processes in the mixing region in *RQL* combustor geometry with water tests [34–37] are of special interest. Numerous works dealing with the *JIC* processes of quenching in mixers and fast mixing of components in chemical reactors prove that this problem is topical [38–45].

Understanding of the *JIC* processes occurring during the formation of the counter flow directed toward a crossflow of the cylindrical duct is very important from the viewpoint of design and optimization of the units of fast-mixing of reagents, or the zones of rapid quenching in chemical reactors. In this case, the conditions of counter flow mixing and fast jet dilution of crossflow could be fulfilled. The studies by Kartaev et al. [46,47] have been devoted to the analysis of the gas dynamics of the interacting impinging jets and crossflow and their mixing under the conditions of counter jet formation and development. By now, however, a relation between the axial penetration depth of the *developed* counter jet and large values of momentum-flux ratio *J* is still unclear. At the same time a lot of experimental data has been accumulated, a number of numerical calculations have been performed concerning counterflowing jet-in-mainstream (*CJIM*)) interaction in the cylindrical or non-cylindrical duct [48–56]. Here, the jet emanates from a tube on the channel axis towards mainstream flow. Morgan et al. [49] found the nonlinear relation between counter flow jet penetration depth and jet-to-mainstream velocity ratios (equal to *J* for equi-density flows); the ultimate counter jet penetration depth was evaluated in [56]. Li et al. [57] controlled the crystal phase formation and size fraction of synthesized titania particles by means of the centerline counter flow jet issuing from the tube in the plasma-chemical reactor. Settumba and Garrick [58] applied cold argon counter jet to control the rate of aluminum vapor condensation in the heated flow of argon plasma. Recently, the counter flow model was used for the axial separation of the counter jets (axial jet separator) in the accelerator mass spectrometry [59].

The objective of this work:

(1) carry out numerical and experimental investigations of behavior of the *developed* counter flow jet formed by impinging round cooling jets transversely injected into high-temperature crossflow for given geometry of the cylindrical duct;
(2) conduct the analysis of the mixing intensity in the recirculation flow zone upstream of the jet injection plane (*JIP*) as function of *J* or derived parameters under conditions of developed counter flow jet.

2. Analogy of *CJIM* and *JIC*

Fig. 1 presents two configurations of the counter flow jet in the crossflow confined by cylindrical duct walls: (1) as a result of jet emanating from the tube on the channel axis – the counterflowing jet-in-mainstream *CJIM* (Fig. 1a) [56]; (2) as a result of impingement of the jets transversely injected into the channel – the multiple jets-in-crossflow *JIC* (Fig. 1b) [35,36]. The same figure shows the flow velocity profiles u_x on the channel axis normalized by the mass-average velocity U_m of the mainstream. The positive direction of the *x* axis coincides with the velocity vector U_m direction, thus the flow velocity u_x on the channel axis is negative in the recirculation flow zone, *RFZ* [30], which is shaped as a toroidal eddy.

It is evident that the areas of recirculation mixing form in both cases, though they are of different shapes. In the first case, the exit tube section means the jet injection plane with the axial velocity V_j; in the second case, it is the plane formed by intersection of orifice axes, the jets are injected with the radial velocity V_j (jet injection plane (*JIP*)). The directions are presented in Fig. 1. In both cases, the penetration depth l_p of the counter jets is deemed to be the axial distance between the flow stagnation point and *JIP*. In the *JIC* case, two points of flow stagnation form on the channel axis (see Fig. 1b), the 1st stagnation point is located downstream of the *JIP* at low jets' flow rate, whereas at higher flow rates, the stagnation point is almost coincident with the *JIP*. In the case of mixing of non-isothermic flows the axial depth h_v of cold counter jet penetration into the high-temperature crossflow can be evaluated on the base of the temperature decrease by a certain preset

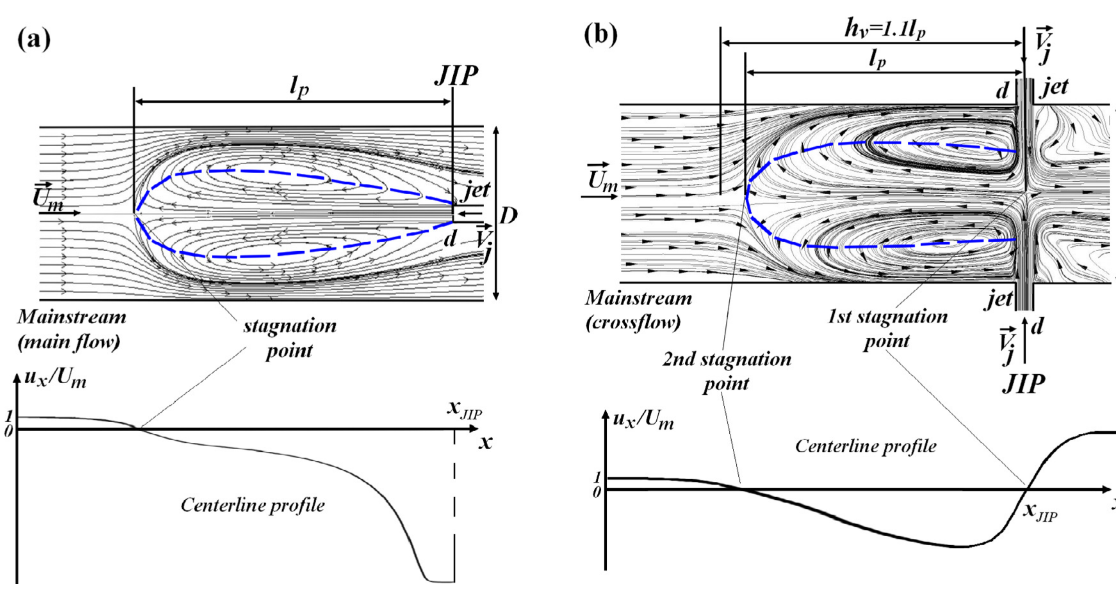

Fig. 1. Configurations of the counter flow jet in mainstream confined by cylindrical duct walls and respective profiles of centerline dimensionless velocity: (a) – tube counterflowing jet-in-mainflow (*CJIM*); (b) – multiple jets-in-crossflow (*JIC*). Zero axial velocity surfaces (stagnation surfaces) are drawn by dotted lines based on streamline curvature.