A Scheme for The Manipulation and Control of A Jet in Crossflow:

The Use of Azimuthal Control Jets

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Abstract

A scheme to manipulate and control the trajectory and entrainment of a jet in crossflow (JICF) is devised and investigated. The scheme is based on the premise that, since the trajectory and entrainment of JICF is closely related to the formation of the large-scale vortical structures in the flow, the effective scheme to manipulate and control JICF should then be focusing on the manipulation of the near-field flow shear layers, the origin of these structures. To implement this, 1) a number of control jets are used to manipulate the near-field flow shear layers, and 2) they are strategically installed at various azimuthal positions near the jet exit, the location near where the near-field flow shear layers are at the onset of developing. The effects of these azimuthal control jets on JICF are then investigated. The investigation is divided into two parts: Part 1) finding the optimal azimuthal position (θ) of the control jets and the mass flowrate ratio of the control jets to the main jet (rm) such that the controlled JICF has lower trajectory, and Part 2) under this optimal control condition, investigating the effects of the control jets on the JICF structure. The experiment is conducted for the JICF with the effective velocity ratio 3.9 and the jet Reynolds number 24,000. The velocity fields are surveyed with a single-sensor hot-film anemometer. The first part of this investigation, which is conducted with a limited range of the two control parameters, shows that the optimal value for θ and rm, which results in the controlled JICF with the lowest trajectory, is ±15 degree and 2 per cent, respectively. In addition, it shows that, when the control jets are deployed on the windward side, the trajectory of the controlled JICF is lower than the uncontrolled one; while deployed on the leeward side, higher. The second part of the investigation shows that the deployment of the control jets at the optimal condition has the effect in suppressing (the development of) the windward jet shear layer while promoting (the development of) the lateral skewed mixing layers, later developing into two dominant counter-rotating streamwise vortical structures (or the counter-rotating vortex pairs) – one on each lateral side. This in turn explains the lower trajectory and the larger lateral spreading of the controlled JICF when compared to those of JICF. Preliminary smoke visualization result also suggests the increase in entrainment in the case of the deployment of two control jets near the leading edge, like in the present optimal case. Finally, the entrainment mechanisms of the vortical structures in JICF and controlled JICF are envisaged, compared, and discussed; consequently, the effects of the two separation distances: spanwise and wall separations, on entrainment and blockage of entrainment are highlighted.

Key words: jet in crossflow, manipulation and control, control jets, trajectory, entrainment
1. Introduction

Jet in crossflow (JICF), or transverse jet, has its applications in many technologies, e.g., energy and combustion, chemical process, gas turbine and aerospace. In these applications, the physical characteristics of JICF that govern the efficient (or inefficient) operation of the equipments are, for example, its trajectory, and entrainment and mixing. Attempts have been made to find a control scheme such that these JICF properties can be manipulated and controlled (in one direction or another, e.g., higher or lower trajectory) in order to achieve efficient operation of these equipments.

For JICF manipulation and control, past works have employed various schemes that can potentially be used to manipulate and control JICF. In this respect, there are a few strands of scheme: vortex generator tab, swirl, and pulsing. Examples are for tab: Liscinsky et al. [1], Zaman and Foss [2], and Bunyajitradulya and Sathapornnan [3]; for swirl: Kavsaogğlu and Schetz [4], Yoshizako et al. [5], Liscinsky et al. [1], Niederhaus et al. [6], and Bunyajitradulya and Sathapornnan [3]; and for pulsing: Hermanson et al. [7], Eroglu and Breidenthal [8], and M’Closkey et al. [9].

For a (fixed) tab, it has an advantage in that it is simple, passive (no external driving energy required), and convenient in some applications. However, it is not yet readily applicable for variable control. Swirl and pulsing have an advantage in that it is readily possible to be applied as variable control, i.e., active. However, swirl has little influence on overall entrainment and mixing, while both swirl and pulsing require significant amount of driving energy.

In the present study, we devise and investigate a new scheme for the manipulation and control of JICF, the use of azimuthal control jets. The present scheme has an advantage in that it can potentially be used as an active control and it consumes relatively small amount of driving energy. The background and details of the scheme are given in the next section.

The objectives of the current study are then 1) to find the appropriate control parameters and to investigate the effect of the control parameters on the jet trajectory, and 2) after choosing the optimal condition from 1), to investigate the effect of the control scheme, i.e., the control jets, on JICF structure and properties.

2. A scheme for the manipulation and control of JICF: The use of azimuthal control jets

Past studies have shown that trajectory, and entrainment and mixing of JICF is closely related to the large-scale vortical structures in the flow, particularly the counterrotating vortex pair (CVP). More specifically, for mixing enhancement Smith and Mungal [10] found that, although the CVP is the main mechanism for entrainment in the far field, it is the formation of the CVP in the near field that results in enhancement of entrainment and mixing of a JICF over a free jet. In addition, the formation of the CVP or the large-scale structure in the flow is closely related to the formation of flow shear layers near the jet exit (Yuan et al. [11], Bunyajitradulya and Sathapornnan [3]). Finally, Yuan and Street [12] (see also Hasselbrink and Mungal [13]) described a close relation between the jet trajectory and its entrainment.
Premise

Therefore, it is our premise that, since the trajectory and entrainment of JICF is closely related to the formation of the large-scale vortical structures in the flow, the effective scheme to manipulate and control JICF should then be focusing on the manipulation of the formation of the near-field flow shear layers, the origin of these structures.

Focus and implementation

The current study then focuses on the manipulation and control of JICF trajectory via the manipulation of the formation of the flow shear layers – at the location near where the flow shear layers and large-scale structures are at the onset of developing. To implement this,

1. a number of control jets are used to manipulate the formation of the near-field flow shear layers, and
2. they are strategically placed at various azimuthal positions near the jet exit, the location near where the near-field flow shear layers are at the onset of developing.

The effects of these azimuthal control jets on JICF trajectory and structure are then investigated.

The main jet and control jets configuration

The main jet and control jets configuration in the present setup is shown in Fig. 1, and their assembly in Fig. 2. The main jet has a diameter $d$ of 22.5 mm. In order to achieve the fully-developed pipe flow profile, there is a straight pipe section of 80$d$ long leading to the main jet exit.

For the control jets configuration, basically it is an array of 24 control jets, aligned radially and separated azimuthally by $15^\circ$, around the circumference of the main jet. $15^\circ$ is the current spatial resolution limit of our manufacturing
process.] Each control jet has a diameter $d_{cj}$ of 1 mm, and there is a straight tube section of $40d_{cj}$ long leading to the control jet exit. The center of the control jets is located near the main jet exit, at the distance 3 mm upstream of the exit. In the current assembly, each control jet can be deployed independently by separated delivery air line, each equipped with valves and a flowmeter.

For ease of reference, we shall designate each control jet by its azimuthal position $\theta$ as shown in Fig. 1.

**Choice of the control parameters ($\theta, r_m$)**

The choice of the control parameters is based on our past result. Namely, Bunyajiradulya and Sathapornnanon [3] experimented on the effect of the azimuthal position of tab disturbance and found that 1) the flow structure can change significantly with the change in the azimuthal position of tab disturbance, and 2) the flow structure is most sensitive to tab disturbance when the tab is placed near the leading edge on the windward side. Thus, we choose the azimuthal position $\theta$ of the control jets as one of the control parameters.

In addition, recognizing that the configuration of the flow of the control jet with respect to the flow of the main jet in the pipe is itself the configuration of a jet in crossflow, in which the penetration of the control jet into the main jet stream depends on the effective velocity ratio $r' = \frac{\rho_{cj} \bar{u}_{cj}^2}{\rho_j \bar{u}_j^2}$, where $\rho$ is density, $\bar{u}$ is area-averaged velocity, and subscripts $cj$ and $j$ refer to the properties of the control jets and main jet, respectively, we then choose the control jet to main jet mass flowrate ratio $r_m = \frac{\dot{m}_{cj}}{\dot{m}_j}$ as the second control parameter. In addition to this, the reason for choosing the convenient parameter $r_m$ is because in a control application $r_m$ is the indicator for the additional mass flowrate that needs to be supplied to the system (for example, we may prefer to have low value of $r_m$). Here, $\dot{m}_{cj}$ is the total mass flow rate of all the control jets deployed (if deploy multiple control jets simultaneously) and $\dot{m}_j$ is the mass flowrate of the main jet. In this paper, we present the value of $r_m$ as per cent, i.e., $r_m = \frac{\dot{m}_{cj}}{\dot{m}_j} \times 100$.

Thus, we choose the two control parameters as the azimuthal position $\theta$ of the control jets and the control jet to main jet mass flowrate ratio $r_m$.

**The investigation**

In order to achieve the objectives, the investigation is divided into two parts.

Part 1. Finding the effects of the two control parameters $(\theta, r_m)$. Then, choosing the optimal control condition for further investigation in the next part. For the reason that will be described below, the optimal control condition is chosen as the lowest jet trajectory.

Part 2. Under the chosen optimal control condition, investigating the effect of the control jets on the JICF structure and properties.

**3. Experiment**

The experiment is conducted in a 50 × 50 cm$^2$ wind tunnel in the Fluid Mechanics Research Laboratory, Department of Mechanical Engineering, Faculty of Engineering, Chulalongkorn University.
3.1. Diagnostic tool

A single sensor hot-film (Dantec 55R05) anemometer is used as a diagnostic tool. For the measurement of velocity, the sensor axis is aligned in the spanwise (z) direction. Thus, it responds predominantly to the velocity component in the $xy$ plane, $w = \sqrt{w_x^2 + w_y^2}$ where $w_x$ and $w_y$ are the velocity components in the $x$ and $y$ directions, respectively.

3.2. Experiment scheme

Part 1. Survey for the effect of the control parameters $(\theta, r_m)$

Criteria for the optimal control condition

In this survey work, we use the velocity trajectory in the center plane as the response of the control. The velocity trajectory in the center plane is defined here as the locus of the points of maximum $w$ along the traverse in the center plane.

Thus, in Part 1 we survey the traverse $w$ profile at various $x$ locations and find the jet trajectory for each controlled JICF case. Then, we compare the trajectories in order to select the optimal case for Part 2 of the experiment.

Due to the sensitivity of the JICF for the disturbance on the windward side, in this work we first choose the direction of control towards lowering the jet trajectory. Thus, we identify the criterion for the optimal control as the lowest jet trajectory, and identify the optimal value of the control parameters $(\theta_{opt}, r_{m, opt})$ as the one that gives the lowest trajectory. Naturally, we can also identify the control in the opposite direction, i.e., higher trajectory.

Choice of the range of the control parameters

The selection of the range of the azimuthal position $\theta$ of the control jets to be investigated is based on our past work (Bunyajitradulya and Sathapornnanon [3]). Namely, therein we found that the structure of JICF is most sensitive to tab disturbance near the leading edge on the windward side. Thus, the windward locations are focused. Table 1 summarizes the range of $\theta$ that we survey as well as the designation for each case. Note that the survey includes both the cases with only one control jet being deployed and the cases with two control jets being deployed simultaneously.

| Table 1. Control jet(s) azimuthal position, $\theta$ (deg), for Part 1. ($r_m = 2.3\%$) |
|---------------------------------|-----------------|
| One control jet                 | Two control jets |
| JICF                            | I15             | I15             |
| I0                              | ± 15°           | ± 15°           |
| I180                            | ± 30°           | I30             |
| I45                             | ± 45°           | I45             |
| I90                             | ± 90°           | I90             |
| I135                            | ± 135°          | I135            |
| I(0,180)                        | 0°, 180°        | I(0,180)        |

In this experiment, the control jets are deployed with steady flowrate (no pulsing of the control jets is yet performed).

As for the selection of the range of $r_m$ to be surveyed, similar guides are used. Firstly, based on our past work (Bunyajitradulya and Sathapornnanon [3]), we found that only a small amount of tab disturbance at the right azimuthal position can modify the flow structure significantly. [In that work, we used the tab with blockage area of less than 3% of the main jet exit area.] Secondly, as mentioned, as far as a control
application is concerned, we may prefer to have low value of \( r_m \). Thus, the low range of \( r_m \) is focused.

From the result of our preliminary experiment, in this experiment we select the range of \( r_m \) at 0 (no injection, uncontrolled JICF), 0.5, 1, 1.5, 2, and 2.3%. [2.3% is the current limit of the flowmeter in the control jet line.]

**Part 2. Effect of the azimuthal control jets on JICF structure**

This second part is a detailed survey of the velocity at various cross \((yz)\) planes for both cases of JICF and the optimally controlled JICF in order to investigate the effect of the control jets on the JICF structure and properties.

Finally, it is noted that before we conduct the present two-part experiment, we also did a preliminary smoke visualization experiment.

**3.3. Experimental conditions**

The main jet has the following mean properties: fully-developed velocity profile; the exit velocity, measured at \( y = 1.5 \text{ mm} \) along the jet axis, is \( 19.4 \pm 1.0 \text{ m/s} \); the area-averaged velocity is \( 15.7 \pm 0.8 \text{ m/s} \); the temperature is ambient.

Note that the measurement of the initial velocity of the main jet is made when the crossflow and the control jets are turned off. The crossflow velocity is \( 4.05 \pm 0.21 \text{ m/s} \); the temperature is ambient.

The crossflow boundary layer, measured at seven spanwise positions \( z = 0d, \pm 0.5d, \pm 1d, \) and \( \pm 1.5d \), at \( x = -4.1d \), is laminar with thickness variation from 7.1 to 8.1 mm. The ambient temperature is \( 31.5 \pm 1.5 \degree \text{C} \). For the control jets, no other measurement is made except for the volume flowrate. As the result in Part 1 will show, the chosen optimal condition that is used in Part 2 is the following: each control jet has an average velocity of 80 m/s, the temperature is ambient.

These result in the JICF with the effective velocity ratio of 3.9, and the jet and crossflow Reynolds numbers of 24,000 and 6,000, respectively. The effective velocity ratio \( r \) is defined as the square root of the momentum flux ratio, \( r = \sqrt{\frac{\rho_j \bar{u}_j^2}{\rho_{cf} u_{cf}^2}} \), where subscript \( cf \) refers to the properties of the crossflow. In this experiment, since the jet and crossflow temperatures are the same at ambient, we have \( r = \frac{\bar{u}_j}{u_{cf}} = r' \), the velocity ratio. The jet and crossflow Reynolds number are defined as \( \frac{\bar{u}_j d}{\nu_j} \) and \( \frac{u_{cf} d}{\nu_{cf}} \), respectively. As the result in Part 1 will show, these result in the optimal condition for each of the control jet in Part 2 as follows: the control jet to main jet effective velocity ratio \( r' \) is 5.1.

**4. Results**

**4.1. Initial velocity profiles of the main jet**

Figure 3 shows the initial mean velocity profiles of the main jet along the traverses in the \( x \) and \( z \) directions at \( y = 1.5 \text{ mm} \). (The coordinate axes are shown in Fig. 1.) The fully-developed profile is also plot for comparison. The result shows that the main jet exits with reasonable axis-symmetry and fully-developed. As remarked earlier, the configuration of the control jet in the stream of the main jet is by itself a jet in crossflow. Therefore, in order to give some indication of the penetration scale of the control jet into the profile of the main jet, the scale of \( l(r'd_{cz}) \) is also given in the figure.
4.2. The effect of the control parameters and the optimal control parameters

In this part, we survey for the effect of the control parameters \((\theta, r_m)\) on the jet trajectory, and identify the value of the optimal parameters \((\theta_{opt}, r_{m, opt})\) such that the trajectory is the lowest. In order to achieve this, we proceed in two steps.

1. First, we survey for \(\theta_{opt}\) by varying the azimuthal position \(\theta\) of the control jets according to Table 1 while fixing the mass flowrate ratio \(r_m\) at 2.3%. For each case, we then traverse the velocity profile in the center \((xy)\) plane at various \(x/r_d\) positions \((x/r_d = 0.5, 1, 1.5, 2, 3, 4)\) and find the velocity trajectory.

We then identify the \(\theta_{opt}\) as the \(\theta\) that gives the lowest jet trajectory.

2. Second, once \(\theta_{opt}\) is identified, we then survey for \(r_{m, opt}\) by varying \(r_m\) at 0.5, 1, 1.5, 2, and 2.3% while fixing the control jet azimuthal position at \(\theta_{opt}\). In order to find \(r_{m, opt}\), for each case we traverse the velocity profile at \(x/r_d = 1.5\) and locate the point on the velocity trajectory (the point at which \(w\) is maximum). Then, we identify the \(r_{m, opt}\) with the \(r_m\) that gives the lowest trajectory (at \(x/r_d = 1.5\)).

For \(\theta_{opt}\), Fig. 4 shows examples of traverse profile at \(x/r_d = 1\) for the surveyed cases. The result shows that, among all others, the case I15, the cases in which we deploy two steady control jets simultaneously at \(\theta = \pm 15^\circ\), has faster decay as well as more uniformity, significantly faster and more uniform than the JICF. When the velocity trajectories are compared in Fig. 5, it also has the lowest trajectory, significantly lower than that of the JICF. Therefore, here we identify \(\theta_{opt}\) to be \(15^\circ\), and we choose case I15 for more detailed investigation in Part 2.

Figure 5 also shows that, when the control jets are deployed on the windward side (I0, I15, I30, I45), the trajectory is lower than that of the JICF. On the other hand, when they are deployed on the leeward side (I135, I180), it is higher.

Next, we survey for \(r_{m, opt}\) by varying \(r_m\) at 0.5, 1, 1.5, 2, and 2.3% for case I15. Figure 6 shows the penetration of the jet trajectory at
The result shows that as \( r_{\text{m}} \) increases, the jet trajectory penetration monotonically decreases. From this trend and our smoke visualization result, it is expected that as \( r_{\text{m}} \) is increased further than 2.3%, the jet trajectory can be made even lower. For control application, where we may want to use low \( r_{\text{m}} \), we then identify \( r_{\text{m, opt}} \) for the current experiment as 2%.

With these, we therefore identify the optimal values of the control parameters for the present experiment as \( \theta = \pm 15^\circ \) and \( r_{\text{m}} = 2\% \) and choose this case for more detailed investigation. From hereon, we shall simply refer to this case of two control jets at \( \theta = \pm 15^\circ \) and \( r_{\text{m}} = 2\% \) as I15.

4.3. Effect of the azimuthal control jets on JICF structure

Next, we investigate the effect of the control jets on the JICF structure by comparing the properties of JICF and I15 in various cross planes.

Figure 7 shows the normalized \( w (w/u_{\text{cf}}) \) in the planes \( x/rd = 0.25 \) and 1. The result shows that the control jets have the effects in reducing the penetration of the jet and in spreading the jet out laterally (spanwise). In addition, when the control jets are deployed, instead of having mushroom structure like in JICF, especially at the location of the windward jet shear layer, we have two dominant counter-rotating streamwise vortical structures (or the counter-rotating vortex pairs) – one on each lateral side. Note that the two streamwise vortical structures have larger spanwise separation than that of the CVP in the uncontrolled JICF. The presence of these two streamwise vortical structures is corroborated by our smoke visualization result.

It is then concluded that the control jets have the effect in suppressing – though may not be altogether getting rid off - (the development of) the windward jet shear layer while promoting (the development of) the lateral skewed mixing layers, later developing into two dominant streamwise vortical structures – one on each lateral side. This in turn explains the reduction in penetration and the larger lateral spreading of the controlled JICF.

When the corresponding turbulent intensities are examined in Fig. 8, we find that the deployment of the control jets promotes and augments turbulence, especially in the region between the two vortical structures. At \( x/rd = 0.25 \) and 1, the maximum turbulent intensity in I15 is increased by approximately 30% and 15%, respectively, over that of the JICF.
Fig. 7. Comparison of normalized $w (w/u_c)$ in planes $x/rd = 0.25$ and 1.

Fig. 8. Comparison of per cent turbulent intensity ($\frac{w_{rms}}{w} \times 100$) in planes $x/rd = 0.25$ and 1.
5. Discussions

The optimal value \((\theta_{\text{opt}}, r_{m,\text{opt}})\)

The optimal value of the control parameters \((\theta_{\text{opt}}, r_{m,\text{opt}})\) for the lowest jet trajectory in the present experiment deserves some discussion. With respect to \(\theta_{\text{opt}}\), due to the spatial resolution limit of the current assembly \((15^\circ)\), we cannot experiment in the range \(0 < |\theta| < 15^\circ\). However, it is quite probable that the JICF trajectory can be made even lower when \(\theta\) is in this range. This is also suggested by the trajectory in Fig. 5. Similarly, with respect to \(r_{m,\text{opt}}\), as the trend in Fig. 6 suggests, it is expected that the JICF trajectory can be made even lower when \(r_m\) is increased further beyond the current flowmeter limit of 2.3%. Our preliminary smoke visualization, which is conducted before the installation of the flowmeter in the line of the control jet, did suggest that this is in fact the case. In conclusion, these evidences suggest that more controlling effect (i.e., the jet trajectory can be made even lower) can be achieved if we decrease \(|\theta|\) and/or increase \(r_m\) beyond the current limits.

Trajectory, structure, spanwise and wall separations, and entrainment and blockage of entrainment

We make some comment regarding the effect of the control scheme on entrainment and mixing of JICF.

Even though no direct measurement of entrainment and mixing is yet made, our preliminary smoke visualization result suggests that the deployment of two control jets near the leading edge on the windward side – with small amount of injection like in I15 - does enhance entrainment. Specifically, more smoke dispersion is observed when the control jets are deployed. This can well be explained in terms of the two streamwise vortical structures and the corresponding increase in turbulence in the region between the two structures (see Figs. 7 and 8). More quantitative result is needed to confirm this, however. Nonetheless, we offer some elaboration and anticipation, describe and compare entrainment mechanisms of JICF and the controlled JICF, and as a consequence highlight the effects of two separation distances that can affect entrainment below.

With respect to entrainment, a related point must be made. Specifically, Denev et al. [14] has studied a swirling jet in crossflow and found that while increased swirl stimulates entrainment and mixing, it also causes the jet to be more and more approaching the bottom wall and thus the jet entrainment is gradually attenuated due to the larger blocking of the secondary flow by the wall. As a final result of these two competing effects, they found that the overall mixing efficiency of SJICF is merely unchanged with the addition of swirl.

In a similar manner, while the application of the control jets to JICF with \(r = 3.9\) in the present study results in two dominant streamwise vortical structures and these two vortical structures, which are well-separated laterally (compared to those in JICF), can be the main mechanism that is responsible for the increases in smoke dispersion and entrainment, the increase in the wall proximity of the two vortical structures (compared to those in JICF) may have counter effect to entrainment.

With these, we envisage and compare the mechanisms for entrainment in JICF and the
controlled JICF as described in Fig. 9. In JICF, there can be some contributions to entrainment from both windward jet shear layer and the CVP. However, because the spanwise proximity of the vortex pairs creates mutual blocking of the streamwise vortical entrainment to each one of the pairs, the entrainment of the pairs may not be as effective. On the other hand, in the case of the controlled JICF, the development of the windward jet shear layer is suppressed while the development of the two streamwise vortical structures – with larger spanwise separation - is promoted. As a result, while the windward jet shear layer entrainment may have been reduced, larger spanwise separation of the vortex pairs (and possibly the suppression of the windward jet shear layer itself) results in less blocking of

entainment of the incoming crossflow stream by each one of the pairs; hence, the streamwise vortical entrainment of the vortex pairs is promoted.

With the effects of the two separation distances on entrainment blockage in mind (Fig. 9), it is expected that for the use of control jets on the windward side in enhancing entrainment to be effective, 1) the spanwise separation of the two streamwise vortical structures, and 2) the wall separation (distance from the wall) of each vortical structure must be tuned so that entrainment is most effective.

In this regard, for example, 1) the use of the control jets like I15 is expected to be more effective for JICF with larger \( r \), in which the trajectory of the JICF is relatively high (wall separation is large), than JICF with lower \( r \), and 2) for JICF with a given \( r \), the optimal value \( (\theta_{\text{opt}}, r_m, \text{opt}) \) - and especially \( r_m, \text{opt} \) - can be tuned such that we have optimal values of spanwise and wall separations so that the two streamwise vortical structures can work the entrainment more effectively. This naturally has to take the resulting vortex strength into account as these control parameters are varied.

6. Conclusions

The present investigation of a scheme to manipulate and control the trajectory of a jet in crossflow using radially aligned, azimuthal control jets shows the followings.

The first part of the investigation shows that, under the condition of the present investigation, the optimal value of the control parameters, which results in the controlled JICF with the lowest trajectory, is \( \theta = \pm 15^\circ \) and \( r_m = 2\% \). In addition, it also shows that, when the control jets are
deployed on the windward side, the trajectory of the controlled JICF is lower than the uncontrolled one; while deployed on the leeward side, higher. More controlling effect in the direction of lowering the jet trajectory is expected if \(|\varphi|\) is decreased or \(r_{\text{in}}\) is increased further beyond the current experiment limit.

The second part of the experiment shows that the deployment of the control jets at the optimal condition has the effect in suppressing (the development of) the windward jet shear layer while promoting (the development of) the lateral skewed mixing layers, later developing into two dominant counter-rotating streamwise vortical structures – one on each lateral side. This in turn explains the lower trajectory and the larger lateral spreading of the controlled JICF.

Finally, the entrainment mechanisms of the vortical structures in JICF and controlled JICF are envisaged, compared, and discussed. As a consequence, the effects of the two separation distances: spanwise separation and wall separation, on entrainment and blockage of entrainment are highlighted. Broad guide for tuning the control parameters for effective entrainment is then suggested.

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8. References


