Experimental Study of Twin-Fluid Jet-in-Crossflow at Jet-Engine Operating Conditions

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Abstract

Designs for numerous future jet-engine fuel-injector make use of a flow configuration called the “Twin-Fluid Jet-in-Crossflow (TF-JICF)”, where fuel is injected as a jet that is atomized by both co-injected and crossflowing combustor air. TF-JICF injectors theoretically improve combustor performance and durability compared to existing plain-jet JICF injectors. However, experimental studies of TF-JICF are very sparse. Furthermore, the “standard model” of TF-JICF that was adopted by earlier studies is increasingly showing discrepancy with emerging data. We conducted an investigation to resolve this discrepancy by experimentally characterizing the TF-JICF produced by a single injector across extremely wide ranges of conditions (i.e., crossflow Weber number = 175-1050, crossflow pressure \( P_{cf} = 1.8-9.5 \text{ atm} \), momentum-flux ratio \( J = 5-40 \) and air-nozzle \( dP = 0-150\% \) of \( P_{cf} \)). These covered the conditions used to develop the standard model, recently studied conditions where discrepancies were found, and high-density conditions that are found only in jet-engine combustors. Consequently, the investigation found a spectrum of new TF-JICF spray characteristics, as well as an unusual non-monotonic relation between spray penetration and air-nozzle \( dP \). Based on these observations, we propose that TF-JICF is comprised of four regimes with different sets of dominant spray-formation mechanisms. Certain regimes are beneficial towards jet-engine fuel-injectors while others are counter-productive. Critically, the proposed four-regime understanding of TF-JICF is also consistent with all experimental data to date. In this new understanding, the TF-JICF standard model was found to be applicable only to the highest \( dP \) regime, contrary to their early applications across all operating conditions.

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Introduction
Jet-Engine Fuel-Injector and the Jet-in-Crossflow Spray

This paper describes the study of a nascent jet-engine fuel-injector configuration called the “twin-fluid jet-in-crossflow” (TF-JICF). Modern jet-engines have annular combustors that are continuously supplied with fresh reactants via a multitude of “fuel-air mixers”. While the designs of fuel-air mixers vary, many of them have a central pressure-swirl atomizer from which the pilot-fuel is injected during low-power engine operation [1-2]. These fuel-air mixers also have a separate outer annulus that contains a swirling airflow, shown as “CF” in Fig. 1. For high-power operation, the main-fuel is injected as multiple radial jets into this outer annulus [1][3-5]. Subsequently, the crossflow (CF) of swirling air redirects the fuel into the flow direction and atomizes the fuel into fine droplets that rapidly evaporate and mix with the air to form a combustible mixture. This “jet-in-crossflow” (JICF) injection technique is commonly used because it provides consistent atomization quality and rapid fuel-air mixing over wide ranges of fuel flow rates, while requiring very low fuel-nozzle pressure-drops (i.e., low pumping requirement).

JICF sprays have been extensively studied to date [6-11]. Figure 2 summarizes the key spray-formation processes in a JICF. Liquid injectant is typically introduced as a low-velocity jet, which is progressively flattened into an ellipse and bent downstream by the combination of pressure and viscous forces exerted by the crossflow [12-15]. During bending, the jet develops large-scale Rayleigh-Taylor (RT) instabilities, which deform the entire jet in a sinuous shape [7][12][16-17]. The windward-facing wave crests grow into thick nodes, while the leeward-facing troughs are stretched until they pinch off due to capillary forces. The pinch-off sheds large clusters of liquid into the crossflow, which continue to disintegrate into increasingly smaller clusters and droplets, forming the dense spray-core [7][18-21]. The structures of the RT-waves strongly depend on the intensity of the crossflow, which is commonly expressed as the crossflow aerodynamic Weber number \( W_{e,cf} \), as defined below:

\[
W_{e,cf} = \frac{\rho_{cf}U_{cf}^2 d_f}{\sigma_f}
\]

where the subscript \( cf \) denotes the crossflow, and \( f \) denotes the fuel/liquid. The variables \( \rho, U \) and \( d_f \) are density, velocity and fuel orifice diameter, respectively. The work of Ng et al. [22] and Mazallon et al. [12] show that RT-waves amplitude is proportional to \( W_{e,cf} \) (i.e., crossflow intensity).

Figure 2 shows that in addition to RT-waves, smaller (~10% of \( d_f \)) Kelvin-Helmholtz (KH) shear-waves develop on the liquid surface when...
We\textsubscript{cf} is high [11][23-26]. KH-waves propagate parallel to the crossflow and grow as they wrap around the jet’s periphery, eventually resulting in the extrusion of micro ligaments on the jet’s lateral sides. These ligaments stretch until they are pinched off, releasing small droplets that are readily entrained into the crossflow (e.g., labeled “sheared droplets in wake” in Fig. 2) [12][14-15][27].

The distinct processes of atomization driven by RT-wave and KH-wave cause the JICF spray-plume to develop two zones with different droplet sizes and concentrations: (i) the densely-populated spray-core with large droplets formed by RT-waves and (ii) the dilute wake-region with small droplets due to KH-waves. The intensities of RT- and KH-wave atomization are both positively related to We\textsubscript{cf}. Thus, JICF sprays are commonly classified into regimes based on We\textsubscript{cf} [12][14]. For example, Sallam et al. [15] observed column breakup regime at We\textsubscript{cf} = 3, the bag breakup regime at We\textsubscript{cf} = 8, and multimode breakup at We\textsubscript{cf} = 30 (where KH-waves first start forming). They noted that as We\textsubscript{cf} increases, sizes of disturbances decrease until eventually the jet appears to disintegrate directly into tiny droplets. This direct disintegration was referred to as the “shear-breakup” regime, which typically begins at We\textsubscript{cf} = 200 [28]. Shear-breakup is most relevant to jet-engines fuel-air mixers, which operate at We\textsubscript{cf} ≈ 1500-3000. Notably, although JICF regimes are usually correlated with We\textsubscript{cf}, higher liquid-to-crossflow momentum-flux ratio \( J \equiv \frac{\rho_l U_l^2}{\rho_{cf} U_{\text{cf}}^2} \) was also found to produce smaller ligaments and droplets [12][29-32]. It is worth emphasizing that although all We\textsubscript{cf} > 200 JICF are considered to be in the shear-breakup regime, the spray’s behavior and droplet sizes continue to vary significantly with We\textsubscript{cf} within this regime (with diminishing effect at very high We\textsubscript{cf}). For example, Figure 5 in [33] shows droplet sizes varying inversely with We\textsubscript{cf}, but asymptoting to a constant at We\textsubscript{cf} = 800.

The penetration and dispersion of the jet and spray-plume into the crossflow is another very important aspect of JICF that pertains to the placement of fuel within the fuel-air mixer. Researchers describe JICF spray penetration by use of statistically averaged trajectories, which can be correlated to the following expression by Wu et al. [14]:

\[
\frac{x}{d_j} = \frac{z}{d_j} \left( \frac{\pi}{C_0} \right) \left( \frac{\rho_l U_l^2}{\rho_{cf} U_{\text{cf}}^2} \right) \equiv C_0 \times J^{0.5} \times \left( \frac{z}{d_j} \right)^{0.5} \tag{2}
\]

where the liquid penetration \( x \) as it travels along the crossflow direction \( z \) is expressed in terms of injector diameter \( d_j \) and \( J \). The \( \left( \frac{z}{d_j} \right)^{0.5} \) term can be considered a shape-function for the self-similar trajectories. Equation (2) is often generalized to better fit experimental data by relaxing the form of the shape-function, as well as the exponents’ values [34-38]. Notably, Equation (2) only holds for a constant crossflow We\textsubscript{cf}, because higher We\textsubscript{cf} leads to lower penetration due to decreasing droplet sizes [39-40]. Finally, we should remark that Wu et al. [14]’s expression was developed based on an idealized liquid segment that only interacts aerodynamically with a uniform crossflow. In the research of JICF for wall-film cooling applications [41-42], JICF of very low \( J \) are known to develop spray-cores that are attached to the lower-wall due to spray-wall interactions. These interactions change the flow-field in a way that is not captured by Equation (2). At typical jet-engine operating conditions and \( J \) values, the spray plumes can potentially become wall-attached. Thus, we need to exercise care in identifying and analyzing wall-attached versus -detached plumes.

The characteristics of JICF described above pose some critical disadvantages to jet-engine fuel-air mixers. For example, the spray penetration varies strongly with fuel flow-rate, resulting in flow-rate-dependent fuel distribution and flame patternation. At the same time, as shown in Fig. 2, the rapid entrainment of shear-disintegrated droplets into the spray’s wake-region places large amounts of tiny droplets near the mixer’s lower wall. These droplets can impinge on the wall and lead to carbon deposits. They can also vaporize to form a combustible mixture, resulting in device-damaging near-wall burning or flashback, especially in the low-velocity wake-region and boundary-layer [1][43]. These disadvantages are becoming increasingly severe as engine operating pressures and temperatures continue to increase with each new generation, thus shortening fuel autoignition delay time.

These disadvantages spurred the recent interest in a new class of fuel-injection technique called the Twin-Fluid (TF) JICF, where the liquid fuel is co-injected with airstreams that surround it concentrically. One such device is illustrated in Fig. 3 based on the patent of Hsieh et al. [2]. Designers expect the co-injected air to assist the fuel in its penetration into the center of the main-fuel annulus away from the walls. Notably, there is no dedicated compressor to power the co-injected air in this design. Pressure-drop \( (dP) \) for air-injection is provided by the difference between the ramming
air’s stagnation pressure ($P_0$) and the lower crossflow static pressure ($P_{cf}$) downstream. This limits $dP$ to <10% of $P_{cf}$. The air-nozzle’s area is also generally small to limit the diversion of air from crossflow to co-injection, such that the co-injected air-to-fuel’s mass-flow ratio ($ALR$) is generally less than unity in this design.

**Twin-Fluid JICF Background**

The TF-JICF configuration has only been recently investigated for its potential application in jet-engine combustors, including by Samuelsen in 1995 [44], Leong et al. in 2000-2001 [39][45-46], Hsieh et al. in 2008 [2], Lee et al. in 2010 [47], Fu et al. in 2014 [43] and Sinha and Ravikrishna 2013-2015 [48-49]. TF-JICF was also investigated by Li et al. in 2006-2010 [50-52] for non-engine usages such as spray-coating friction-surfactant from a moving train onto railway tracks. Table 1 summarizes the test configurations and conditions of these studies. We briefly summarize the very limited knowledgebase of TF-JICF below to set the foundation for our discussion.

The pioneering series of work by Leong et al. [39][45-46] was conducted on a 90°-impinging internal-mixing nozzle to support combustor designs by Samuelsen [44]. Their air-nozzle $dP$ was limited to low levels to allow for a similar operation principle as Fig. 3. They found that as $P_{cf}$ (thus, $W_{cf}$) increased the jet disintegrated more rapidly, placing large amounts of droplets near the wall, until the spray-plume became attached to the test-channel wall at 5atm. The introduction of co-injected air caused even more rapid atomization, to the point where the injected fuel was instantaneously atomized within the injector cavity. They called this instantaneous breakup process (which differs from RT- or KH-waves processes) “prompt-atomization”, after Lefebvre’s reports [53-54] on a similar phenomenon found in twin-fluid (i.e., “airblast”) jets in quiescent environment. Despite the enhanced atomization, the prompt-atomized sprays had enhanced penetrations that detached them from the wall, due to the momentum the droplets gained from the fast injected air.

![Figure 3. Left: cutaway of a TF-JICF fuel-air mixer, from Hsieh et al. [2]. Right: zoomed-in schematic of the TF-JICF injection technique.](image)

<table>
<thead>
<tr>
<th>Injectors</th>
<th>Leong et al. [39][45-46]</th>
<th>Li et al. [51-52]</th>
<th>Lee et al. [47]</th>
<th>Sinha et al. [49]</th>
<th>Tan et al. [55-56]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{cf}$ (atm)</td>
<td>1.5</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>19.25</td>
</tr>
<tr>
<td>$T_{cf}$ (°C)</td>
<td>≈ 25</td>
<td>≈ 25</td>
<td>≈ -56</td>
<td>≈ 25</td>
<td>316-427</td>
</tr>
<tr>
<td>$U_{cf}$ (m/s)</td>
<td>31.87</td>
<td>5.6-13.9</td>
<td>42-136</td>
<td>46-103</td>
<td>75</td>
</tr>
<tr>
<td>$W_{cf}$</td>
<td>≈ 14-240</td>
<td>0.7-8.0</td>
<td>15-150</td>
<td>15-158</td>
<td>1600-1900</td>
</tr>
<tr>
<td>$J$</td>
<td>≈ 0.3-4.4</td>
<td>≈ 0.5-12</td>
<td>≈ 0.5-12</td>
<td>≈ 5-420</td>
<td>5-126</td>
</tr>
<tr>
<td>$dP$ (%) of $P_{cf}$</td>
<td>≈ 0.6</td>
<td>≈ 9.2-64</td>
<td>-</td>
<td>≈ 25-870</td>
<td>0.5-6</td>
</tr>
<tr>
<td>$ALR$</td>
<td>≈ 0.115</td>
<td>≈ 1.2-2.4</td>
<td>0.59.4</td>
<td>0.1-0.5</td>
<td>0.0-4</td>
</tr>
</tbody>
</table>

Table 1. List of test parameters in the TF-JICF literature. Values with “≈” are best estimates based on available data.
Leong et al. [39][45] proposed an extension to the J-based Equation (2) to account for the effect of air on the penetration of TF-JICF. Their proposition was inspired by the works of Edelman et al. [57], Salzman & Schwartz [58] and Han & Chung [59] in particles-laden gaseous-JICF. In these earlier works, the particles were well-mixed with gas and the uniform mixture was injected into a crossflow. The penetration of the resulting particle-gas plume was correlated to the average momentum of the mixture. Similarly, as shown in Figure 4, Leong et al. [39][45] proposed that since the liquid jet is prompt-atomized near the injector, the resulting fine droplets exchange momentum rapidly with the air. Thus, a well-mixed fuel-air plume emerges from the injector having some high average momentum, which can be used to correlate the plume’s penetration, as follows:

\[ \frac{x}{d_f} = c_0 \times J_{eff}^{c_1} \times \left( \frac{z}{d_f} \right)^{c_2} \]  
\[ J_{eff} = \frac{\rho_{mix}U_{mix}^2}{\rho_fU_{cf}^2} \]  
\[ = \frac{A_{air} \rho_{air}u_{air}^2 + A_{cf} \rho_f u_{cf}^2}{A_{total} \rho_f u_{cf}^2} \]  

where the subscripts mix, air and f denote overall mixture, co-injected air and fuel property, respectively. \( J_{eff} \) is an effective momentum-flux ratio. \( A_{air} \) is the air-nozzle’s area, \( A_f \) is the fuel orifice area, while \( A_{total} \) was defined as the sum of both. This correlation fitted their experimental data across the entire tested range, including at \( dP=0\% \). The empirical constants \( c_i \) varied according to the type of trajectory that was being correlated (e.g., spray outer-edge, centerline or inner-edge).

Subsequently, Li et al. [50-52] studied TF-JICF using a co-axial external-mixing injector where the air was injected at velocities approximately two orders of magnitude higher than the liquid injection velocities. They reported a good fit of their data with Equations (3) and (4), though in their cases \( J_{eff} \) was always dominated by the air’s momentum-flux. The more recent investigation by Sinha et al. [49] studied TF-JICF using an internal-impingement nozzle, with air-nozzle’s \( dP \) up to 900% of crossflow pressure (i.e., far exceeding the levels available from the ram-pressurization design shown in Fig. 3). Despite the intended application for jet-engine, their \( W_{cf} \) were 13.8-158, below the shear-regime typical of jet-engine. Sinha et al. [49]’s work is interesting as they reported an unusual spray-bifurcation phenomenon at lower \( dP \) levels (discussed further in the next sub-section). They reported that the measured spray penetrations fitted the \( J_{eff} \)-correlation in Equations (3) and (4). Interestingly, the combination of these studies suggests that the \( J_{eff} \)-correlation is applicable to TF-JICF injectors of very different configurations (i.e., co-axial to 90° impinging). Finally, the works of Leong et al. [47] made mention of the \( J_{eff} \)-correlation but did not explicitly use it to fit their data. Fu et al. [43] did not explicitly report spray results from their study of TF-JICF combustor.

**Summary of Recent Findings**

The \( J_{eff} \)-correlation in Equations (3) and (4) is currently adopted in literature as the standard model for TF-JICF, which suggests that TF-JICF spray-formation and droplets penetration are primarily governed by the prompt-atomization and rapid fuel-air momentum-exchange mechanisms. In our early investigations of TF-JICF for jet-engine application [55-56], we characterized spray penetrations at \( dP \) and \( ALR \) that were significantly lower than most existing studies (see Table 1). We found that the co-injected air “lifted” the spray’s wake away from the test-channel wall as the design intended (i.e., reducing near-wall fuel concentrations), but enhancements to the spray’s centerline and outer-edge penetrations were insubstantial. The \( J_{eff} \)-correlation consistently over-predicted the penetration-enhancing effect of air. Consequently, in [55-56] we proposed a modified \( J_{eff} \)-correlation where an adjustment constant \( c_3 \) was added to scale down the air’s effective momentum flux, as shown below:

\[ J_{eff,2} = \frac{c_3A_{air} \rho_{air}u_{air}^2 + A_{cf} \rho_f u_{cf}^2}{A_{total} \rho_f u_{cf}^2} \]  

The normalizing area \( A_{total} \) was also replaced by \( A_f \) such that \( J_{eff,2} \) becomes identical to the Classical-JICF’s J when \( U_{air}=0 \). The addition of \( c_3 \) assumed...
that different injector configuration may influence the effectiveness of fuel-air momentum-exchange (i.e., an intuitive but so far undocumented influence). The new parameter $J_{df2}$ improved the correlation fit, with $c_f$=0 for the spray’s outer-edges and closer to unity for inner-edges. However, we also observed that $c_f$ varied significantly with crossflow conditions, suggesting the presence of additional physics that was not well-captured by $J_{df2}$ (and the standard $J_{df}$). This last point remained unresolved in [55-56].

Recent publications by Lee et al. [47] and Sinha et al. [49] highlighted the new TF-JICF phenomenon of spray-bifurcation. Lee et al. [47] found that in the absence of air-injection, their liquid jet disintegrated gradually in the crossflow into large droplets due to sub-shear regime $We_{eff}$. At the low $ALR$ of 0-0.59 only a portion of the liquid jet (presumably the jet’s outer-layer) was atomized by the co-injected air into mist-like droplets, while the remaining liquid formed large droplets, resulting in a bi-modal droplets size distribution. The smaller droplets were more readily entrained into the crossflow due to their higher drag-to-inertia ratio, causing the spray to bifurcate. As $ALR$ increased, the population of large droplets decreased while the population of mist-like droplets increased. The penetrations of both large and small droplets increased with $ALR$, though the fit with the $J_{df}$ correlation was not reported. Similarly, Sinha et al. [49] found that under certain low $ALR$ conditions, only a portion of the liquid jet was rapidly atomized by the co-injected air into small droplets. The remaining jet underwent more gradual disintegration in the crossflow to form larger droplets. The spray-plume thus bifurcated into two distinct streams. Notably, their data show the onset of bifurcation was sensitive to absolute air flow-rate and not scalable by $ALR$ alone. Their spray trajectories were reported to fit the $J_{df}$-correlation, although it was not clear whether this refer to the trajectories of the large or small droplets in the event of bifurcation.

**Objective**

The recent findings by Lee et al. [47], Sinha et al. [49] and Tan et al. [55-56] reveal critical issues/gaps in the existing understanding of TF-JICF. Firstly, the new spray-bifurcation [47][49] and low penetration-enhancement [55-56] phenomena are either not captured by or at odds with the standard $J_{df}$ understanding. Secondly, the $J_{df}$ model was previously proposed to fit across all TF-JICF operating conditions including $dP$=0, while the new phenomena all occurred at lower $dP$ or $ALR$ conditions. This suggests low $dP$ or $ALR$ spray-formation processes may actually violate $J_{df}$’s assumptions. Thirdly, no existing study has covered a large enough $dP$ range at sufficiently small intervals to produce the full spectrum of reported TF-JICF characteristics (i.e., low penetration-enhancement, bifurcation and $J_{df}$). Thus, it remains unclear whether certain low $dP$ characteristics are universal to all TF-JICF or injector-dependent.

This paper reports an investigation we conducted to address these gaps. Our investigation has three objectives:

1. To operate our injector [55-56] far above its original $dP$<10% design points while varying $dP$ at fine intervals in an attempt to reproduce [47][49]’s bifurcation phenomenon, as well as the $J_{df}$ dependence. This objective was aimed as ascertaining whether these characteristics are injector-specific or potentially universal to TF-JICF.
2. To operate our injector at ranges of $J$ and $We_{eff}$ that cover jet-engine operating conditions, as well as the literature’s near-atmospheric conditions. This objective explores the dependence of TF-JICF on $We_{eff}$ to determine whether the TF-JICF knowledge developed from near-atmospheric tests is applicable to high-pressure conditions.
3. To employ the observed trends in recommendations for injector designs.

**Experimental Approach**

**Design of Experiment**

Table 2 shows the three dimensional test-matrix (varying $J$, $dP$ and $We_{eff}$) that was developed to meet the investigation’s objectives. In this matrix, $U_f$ was fixed at ~70m/s, a typical value for jet-engine fuel-air mixers. The crossflow temperature was fixed at a level that was high enough to prevent water condensation on the test chamber windows, but low enough to limit fuel vaporization to an amount that would not impact the interpretation of the atomization processes.

$We_{eff}$ was varied by changing $P_f$ and, thus, $\rho_f$. The lowest $We_{eff}$ is just below the shear-breakup regime (i.e., comparable to literature) while the highest $We_{eff}$ is expected to produce droplets with sizes that are effectively identical to full jet-engine conditions [33]. The middle value of $We_{eff}$=350 is well within the JICF shear-breakup regime, and is expected to produce droplets sizes halfway between $We_{eff}$=175 and 1050. Table 2 also shows $J$ ranging from 5 to 40. $J$=20 represents the typical fuel flow-rate at near take-off conditions. $J$=5-10 are encountered at near-idle power, and are phenomenologically interesting because they produce low-penetrating sprays that are typically attached to the test-channel wall (which adversely affects engine durability and is the prime reason for applying penetration-enhancing air-injection). The
$J=25-40$ range represents fuel flow-rates in excess of typical full engine power setting.

Figure 5 compares the ranges of $dP$ and $ALR$ covered in this investigation and the studies of Leong et al. [39][45-46], Sinha et al. [48-49] and Li et al. [50-52]. Our $dP$ starts at “Classical” JICF ($dP=0$) and exceeds the full ranges of [39][45-46] and [50-52], while missing the topmost $dP$ in [48-49]. Despite the large $dP$ range, we could not match the $ALR$ ranges in [39][45-46] and [50-52], because their injectors had larger air-to-fuel nozzle area ratio, which were then operated at low fuel flow-rates. Critically, Fig. 5 shows that the current test-matrix enveloped very wide ranges of TF-JICF operating conditions while employing a very large number of test-points to best capture any subtle transitions in TF-JICF behaviors at different conditions.

The right plot in Fig. 5 compares the current investigation against literature on a $We_{air}$ versus $We_{cf}$ map. The plot highlights an important distinction between TF-JICF and TF-jets in quiescent environment. Whereas in the latter the ambient gas has no active role in atomizing the liquid, in the former the crossflow is classically the driving force behind atomization. Thus, whereas the co-injected air can easily enhance atomization in a quiescent environment, it has to compete with the crossflow in TF-JICF. Thus, if we assume that the air’s atomization potential (which is not fully understood) is positively related to its Weber number ($We_{air}=\rho_{air}U_{air}^2d_f/\sigma_f$), the air is not expected to enhance atomization if $We_{air}$ is not significantly higher than the “omni-present” crossflow’s $We_{cf}$. Based on this principle, a line of $We_{air}=We_{cf}$ has been drawn across Fig. 5’s right plot. Below this line, the atomization process is likely driven by the crossflow, while far above this line they are likely driven by the co-injected air. The literature’s test-points are generally above this line, while our test-points straddle this line to increase the likelihood of observing transitions in the dominant atomizing force.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Values</th>
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<td>$P_{cf}$</td>
<td>~1.8, 3.8, 9.5 atm</td>
</tr>
<tr>
<td>$T_{cf}$</td>
<td>~150°C</td>
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<tr>
<td>$U_{cf}$</td>
<td>~70 m/s</td>
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<tr>
<td>$We_{cf}$</td>
<td>175, 350, 1050</td>
</tr>
<tr>
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<td>10, 20 for $We_{cf} = 175$</td>
</tr>
<tr>
<td></td>
<td>5, 20, 40 for $We_{cf} = 350$</td>
</tr>
<tr>
<td></td>
<td>5, 20, 25 for $We_{cf} = 1050$</td>
</tr>
<tr>
<td>$%dP$</td>
<td>0, 3, 5, 13, 25, 50, 75, 100, 150</td>
</tr>
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</table>

Table 2. Test-matrix.

![Figure 5](image-url) Comparison of our test-matrix against Leong et al. [45], Li et al. [51-52] and Sinha et al. [49] in terms of $\%dP$-vs-$ALR$ and $We_{air}$-vs-$We_{cf}$. Dotted box: test-range for Tan et al. [55-56] where non-$J_{cf}$ behavior was encountered. Solid line: line of $We_{air} = We_{cf}$. 
JICF Test-Facility

This subsection briefly describes our JICF test-facility, while further details can be found in [55-56]. Figure 6 shows that hot, pressurized crossflow air entered the test-facility at the top-left and flowed through two layers of flow-straightening meshes before settling in a 150mm diameter air plenum. The flow was then accelerated through two converging sections into a small, thin-walled rectangular test-section having the cross-sectional dimensions of 62.2×43.2mm where the JICF spray was produced. A thick-walled outer chamber surrounded the test-section with cold (<100°C) air at nearly the same pressure as the crossflow, serving as the pressure-containing wall of the vessel. Both the cooling air and hot fuel-air mixture exited the facility from the bottom where they were mixed and combusted in an afterburner before being released into the lab’s exhaust-stack.

Figure 6. Top: schematic of the JICF test-facility. Bottom: zoomed-in view of the optically-accessible test-section with the mounted injector.

Figure 6 also shows a photo of the rectangular inner test-section. The test-section had three sides of quartz windows for optical access, while the injector was mounted on the fourth side. The outer chamber (not shown) employed thicker round quartz windows to allow optical access while maintaining pressure containment. A pitot-static pressure/temperature probe was installed upstream of the test-section to monitor the crossflow’s temperature, stagnation and dynamic pressures during tests, from which the flow’s velocity and density were determined. An additional static port ($P_f$ port in Fig. 6) measured crossflow static pressure closer to the spray-plume, and was used to calculate the %$dP$ pressure-drop from the air-nozzles to the crossflow. PIV measurements determined the boundary-layer thickness in this test-section to be ~2.5mm (or 5$d$), while the freestream region’s turbulence intensities were ~2.5%. Notably, the coordinate system shown in this photo will be used throughout this paper.

Injector and Fluid-Supply Systems

Figure 7 shows schematics of our twin-fluid JICF injector, which was the same unit studied in [55-56]. The injector’s back-side contained four connection ports: air-supply, fuel bypass/out-flow (plugged and unused), fuel-supply and instrumentation (used to measure fuel temperature close to the fuel-orifice). A slender horizontal plenum was located within the top part of the injector, connecting to the fuel bypass and supply ports at each end. The mid-point of the plenum branched off into a straight injection bore that led to a circular fuel-orifice having the diameter of $d_f=0.506mm$. The fuel-orifice was recessed into a “spraywell” cavity that had a diameter of 1.861mm and depth of 1.27mm. Fuel was supplied to this injector from nitrogen-pressurized holding tanks, with the flow-rate regulated by a turbine flow-meter and motorized needle-valve.

Figure 7 also shows that the fuel-orifice was surrounded by four slot-type air-nozzles, which spanned nearly the entire circumference of the spraywell’s side wall, separated only by thin support struts that were, on average, each as wide as 6% of the spraywell’s circumference. The average height of the air-nozzles was 0.394mm and their total area was 1.66mm². The air-nozzles were oriented at 45° with respect to the fuel nozzle. The point of fuel-air impingement was ~0.14mm below the spraywell’s lip; i.e., effectively flushed with the injector’s top surface and test-channel wall. Since a suitable source of high-pressure air was not available to drive $dP$ up to 150% of $P_f$, the system was supplied by high-pressure nitrogen gas cylinders. Nitrogen gas is a close approximation of air, having only 3.35% lower density. The small density difference is not expected to cause significant differences to the TF-JICF behaviors, especially in this non-reacting flow study. (For the convenience of discussion, we will continue to refer to the co-injected nitrogen as “air”).
Figure 7. Top- and side-views of the injector. Shaded region on top-view shows the surface that is mounted flushed against the test-section wall. Inset: zoomed-in view of the injector’s internal flow-path and nozzles arrangement.

Optical Diagnostic System

Figure 8 shows a schematic of the shadowgraph-imaging setup used to characterize the TF-JICF sprays in our experiments. The setup employed a FOculus FO531SB monochrome camera fitted with a Micro-Nikkor 55mm f/2.8 AI-s prime lens to image the spray from the side-view (i.e., imaging the $xz$-plane). This camera’s native resolution is 1600×1200px and it was installed to capture the spray in the domain of $z/d_f \approx 0-38$, providing a resolution of $13.52\mu m/px \pm 0.87\%$. The laser employed in this setup was a Photonics Industries DS20-355 Nd:YAG laser that emitted 532nm light at 30Hz (synchronized with the camera). The laser light was focused by a lens onto one end of a fiber-optic cable, which was then threaded through the test-facility’s outer chamber wall (see Fig. 8). The other end of the cable illuminated the laser onto a light-diffusing plate positioned parallel to the inner test-section’s window. A filter-cell containing Exciton’s pyrromethene 567 fluorophor dye dissolved in high-purity vacuum oil was placed between the test-section and the diffusing plate. This dye was excited by the 532nm laser light and fluoresced in the yellow spectrum (549-592nm). The fluorescence formed a speckle-free back-light for the shadowgraph-imaging.

Figure 8. Layout of shadowgraph imaging system, as viewed along the crossflow ($z$) direction.

Results and Discussions

Analysis of Spray Structures

Figure 9 shows instantaneous images of our baseline “Classical-JICF” sprays at $dP=0\%$. These images have the same grayscale-mapping so their intensities are directly comparable. The horizontal row of $We_{cf}=350$ Classical-JICF demonstrates the direct relationship between spray penetration and $J$. Interestingly, between $J=20-40$ the sprays have a distinct spray-core and a wake-region, whereas the two regions are indistinguishable at $J=5$ and large droplets are present along the wall (i.e., the spray-core is wall-attached at $J=5$, which increases near-wall burning/coking risks). The vertical column of $J=20$ images shows that increasing $We_{cf}$ increases the wake-region’s droplets concentration and reduces the spray’s droplets sizes (evident from the $We_{cf}=1050$ case’s more mist-like appearance), both of which worsens near-wall burning/coking risks. Notably, a comparison of the $We_{cf}=175$ and 1050
cases illustrates the difference between near-atmospheric and real engine spray behaviors.

Next, Fig. 10 elucidates the effect of air-injection on a wall-attached spray by showing instantaneous and average images of the TF-JICF at \( J=5 \) and \( We_{cf}=350 \) across the full range of tested \( dP \). The first two sets of images cover the very low \( dP \) range investigated in our earlier papers [55-56]. The spray’s outer-edge penetration is slightly enhanced, while the near-wall region became almost devoid of droplets when \( dP \) was increased from 0 to 5%. Consequently, the spray’s dispersion is reduced, as evident from the more elliptic contours in the \( dP=5\% \) averaged image. The rightmost images in Figure 10 belong to the high end of the tested \( dP \) range. Small droplets can be observed exiting from the very edges of the spraywell, indicating near-instantaneous atomization and dispersion within the spraywell cavity (i.e., Leong et al. [39][45-46]’s “prompt-atomization” mechanism at work). At the same time, large counter-clockwise vortical structures manifested on the windward edge of the spray plume, a phenomenon not observed in Classical-JICF. The vortical structures suggest two things: i) very small droplets capable of tracking vortical flows were present on the windward edge, ii) since such small droplets cannot penetrate to the windward edge on their own inertia, their presence there suggests significantly momentum exchange between fuel and air was occurring (i.e., the droplets were carried upwards by an underlying current of fast air). These features suggest our \( dP=75\% \) TF-JICF is phenomenologically similar to Leong et al. [45]’s uniform fuel-air plume (see Fig. 4) where fuel-air momenta exchange rapidly and \( J_{eff} \) correlation is applicable.

The strong contrast in TF-JICF spray structures between \( dP=5 \) and 75% is reported for the first time here. They strongly indicate different spray-formation mechanisms were dominant in these different \( dP \) ranges. In particular, we hypothesize that co-injection of air at \( dP \) on the order of 5% served to “sheath” the jet against atomization by crossflow (i.e., the air wraps protectively around the fuel jet while disrupting it minimally). This is evident from the \( dP=5\% \) jet’s intactness, the absence of surface-sheared droplets near the wall, and the jet’s low RT-wave amplitudes when compared to \( dP=0\% \). In contrast, the large amounts of small droplets near the wall and the spraywell’s periphery at \( dP=25-75\% \) demonstrates the co-injected air’s disruptive potential at higher \( dP \). This description supports our earlier hypothesis (Fig. 5) that the co-injected air may transition from protecting to disrupting the jet when its \( We_{air} \) (i.e., \( dP \)) rises with respect to \( We_{cf} \). Most importantly, results shown in Fig. 10 allow us to potentially connect our earlier low \( dP \), low ALR data [55-56]
(which cannot be correlated by $J_{ef}$) to Leong et al. [39][45-46] and Li et al. [50-52]'s high $dP$, high ALR data (which can be correlated by $J_{ef}$). However, the mid-ALR spray-bifurcation behavior from Lee et al. [47] and Sinha et al. [49] was not replicated on the $J=5$ TF-JICF.

Figure 10. Instantaneous and colorized average images depicting the effects of $dP$ on TF-JICF structures at $J=5$ and $We_{ef}=350$. Dotted-lines: edges of the spraywell (3.68$d_0$ apart). Dashed line: presence of window stain behind which faint droplets are not very visible.

Figure 11 shows the sensitivity of a $J=40$ TF-JICF to $dP$. In agreement with our earlier reports [55-56], high $J$ TF-JICF are not significantly affected by low $dP$ air-injection. Compared to $J=5$, the $J=40$ jet did not develop very large RT-waves at $dP=0\%$ (i.e., it was resistant to crossflow-driven atomization), and the resulting spray was well-separated from the wall. Consequently, the injection of air was not observed to have a significant “sheathing” effect. At the maximum $dP$ levels, droplets can be found on the spraywell’s periphery and windward-edge vortical structures developed once again, indicative of the $J_{ef}$ mechanism at work. Interestingly, the jet can often be observed to bifurcate at $dP=25\%$ on the instantaneous images. The bifurcated branch of droplets was somewhat unsteady and, when averaged, it is detectable as a minor inflection on the otherwise elliptical color-contour. The bifurcated branch and inflection point penetrated higher as $dP$ increased, until they eventually merged into the spray-core, which has now become mist-like and highly disrupted by air. At $dP=150\%$ a second type of bifurcation (which was mostly only detectible from the average image) developed closer to the wall. This second type of bifurcation was also visible on the $J=5$ $dP=75\%$ image in Fig. 10, though it was less pronounced.

The presence of two bifurcation types was not encountered by Lee et al. [47] and Sinha et al. [49]. We hypothesize that these bifurcations were caused by distinctly different mechanisms made possible through a 45° fuel-air impingement nozzle such as ours. Specifically, our nozzle likely produces an initial fuel-air impingement zone just within the spraywell’s outlet, after which the air is turned upwards and wraps around the fuel jet like a co-axial twin-fluid jet (i.e., shearing instead of impinging). The first bifurcation type at $dP=25-75\%$ likely occurs when sufficiently large fuel-air relative velocities led to gradual atomization in the shearing zone. The sheared droplets are subsequently stripped away by the crossflow while the intact jet continues to travel upwards, resulting in the bifurcation. Higher $dP$ imparts more penetration momentum on the sheared droplets while also destabilizing the jet more, causing both of them to eventually merge. On the other hand, the $dP=150\%$ bifurcation likely occurs when fuel-air impingement becomes sufficiently intense to cause partial prompt-atomization of the jet in the impingement zone. The prompt-atomized droplets are stripped by the crossflow while larger bulks of liquid near the jet’s center continue to penetrate further, leading to the second bifurcation. This theory is at least consistent with Lee et al. [47]'s observation of only a single bifurcation type on their non-impinging co-axial nozzle. The theory also highlights a key difference between TF-JICF and TF-jet in quiescent environment. Whereas in the latter all fluids tend to travel in the same direction, in TF-JICF fluids will become bifurcated if they have significantly different size and inertia. Critically, through results shown in Figs. 10 and 11, we have successfully demonstrated that all of the TF-JICF characteristics reported in the literature can be replicated (to first order) on a single injector, thus suggesting these characteristics belong to different operating regimes of TF-JICF instead of being injector-specific.
Our results also show that the intensity of co-injected air-driven atomization is proportional to $W_{e/cf}$ and inversely proportional to $J$. For example, Fig. 10 shows intense prompt-atomization and windward-edge vortical structures at $dP=75\%$ when $J=5$, while the same features only manifest at $dP=150\%$ when $J=40$. On the other hand, Fig. 12 shows that at $J=20$ and $dP=50\%$, the jet remained fairly intact (though highly corrugated by fuel-air shearing) at $W_{e/cf}=175$, whereas it became significantly prompt-atomized with dense populations of droplets emerging out of the spraywell’s periphery at $W_{e/cf}=1050$. These dependences are likely related to the fact that when $dP$ is constant, $ALR$ increases with decreasing $J$ and increasing $W_{e/cf}$ (i.e., the air density varies proportionally with crossflow density).

![Figure 11. Instantaneous and colorized average images depicting the effects of $dP$ on TF-JICF structures at $J=40$ and $W_{e/cf}=350$.](image)

![Figure 12. Instantaneous images depicting the influence of $W_{e/cf}$ on spray structures at $J=20$ and $dP=50\%$.](image)

**TF-JICF Regimes and Penetration Trends**

In this subsection we discuss the response of TF-JICF penetration to $dP$ to further examine the potential connections between the piecewise results in literature. Images such as those shown in Figs. 10 and 11 were used to derive the sprays’ average outer-edge and centerline trajectories. Tan et al. [60] provides a detailed account of the post-processing techniques. In brief, the outer-edge was determined by binarizing instantaneous spray images using the Otsu algorithm, and then tracing along the windward edges of the spray-containing regions. These instantaneous outer-edge were then averaged to yield the average outer-edge, which represents the average path of the highest inertia droplets. The centerline was determined by averaging the instantaneous spray images and tracing along the locus of darkest pixels. This trajectory is interpretable as the average path of the spray-core’s centroid. After the trajectories were obtained, they were curve-fitted to a log-based shape profile function, as follows:

$$\left( \frac{x}{dy} \right) = P_1 \times f \left( \frac{z}{dy} \right) = P_1 \times \ln \left[ \frac{z}{dy} - \frac{z}{d_{f,origin}} + 1 \right]$$  \hspace{1cm} (6)

$z/d_{f}$ is zero at the fuel orifice’s center and $z/d_{f,origin}$ is the measured trajectory’s actual origin,
which may be in front of \( z/d_f = 0 \) at high \( dP \) due to the forward ejection of droplets by air. \( P_I \) expresses the “magnitude of penetration”, scaling the shape function \( f(z/d_f) \) to the raw trajectory \( (x/d_f) \). It is used here to conveniently express a 2D trajectory as a single number to simplify plotting.

Figure 13 shows the dependence of \( P_I \) on \( dP \) and \( We_{cf} \) when \( J=20 \). Contrary to the literature’s results and the \( J_{eff}=correlation’s prediction, the

![Figure 13](Image)

**Figure 13.** Spray outer-edge and centerline penetrations as a function of \( dP \) and \( We_{cf} \) for \( J=20 \). Dotted lines: approximate regime boundaries. Error bars show the standard deviation of curve-fit. The lowest \( dP \) test-points where air was completely shut off show slightly negative \( dP \) due to the crossflow’s “suction” effect on the spraywell.

Based on Figs. 10, 11 and 13, we hypothesize that different sets of spray-formation mechanisms were dominant in different \( dP \) ranges, leading to different types of spray structures and \( P_I-dP \) relationships. Hence, we interpret the sudden reversals in the \( P_I-dP \) relationship in Fig. 13 as transition points between dominant spray-formation mechanisms. Using this interpretation, the results in Fig. 13 has been divided into different TF-JICF spray-formation regimes. The first range of \( dP=0-13\% \) is named the “Air-Assist (AA) JICF” regime, where the injected air sheaths the fuel jet and mildly “assists” its penetration into the crossflow. The next regime is named “Airblast (AB) JICF”, where the air is sufficiently strong to disrupt the fuel jet, resulting in decreasing spray penetration decreases with increasing \( dP \). The last regime is referred to as “Airblast Spray-in-Crossflow (AB-SICF)” because its \( P_I \) trend and spray structures are both similar to the high \( ALR \) results of the literature (which some authors called the “AB-SICF”, alluding to the prompt-atomization of the fuel into a spray before it even encounters the crossflow). Fig. 13 shows that the transitions between regimes occurred at lower \( dP \) where \( We_{cf} \) is higher. This is consistent with earlier observations that the fuel jet is more easily disrupted by air at higher \( We_{cf} \).

Sprays’ penetrations \((P_I)\) varied non-monotonically with \( dP \). Instead, \( P_I \) of the outer-edges and centerlines increased in the range of \( dP=0-13\% \). They then became inversely related to \( dP \) in the range of \( dP=25-100\% \). Subsequently at \( dP\geq100\% \), \( P_I \) increased with \( dP \) once again. Although the outer-edges’ and centerlines’ \( P_I \) responded to \( dP \) with different magnitudes, their general trends are in qualitative agreement.

Figure 14 shows \( P_I \) as a function of \( dP \) and \( J \) for \( We_{cf}=350 \). The non-monotonic relationship between \( P_I \) and \( dP \) can be seen here as well. Interestingly, the transition \( dP \) values between the AA-JICF and AB-JICF regimes were insensitive to \( J \), while the transition \( dP \) between AB-JICF and AB-SICF were significantly lower at lower \( J \). This is at least partially consistent with earlier observation that the lower \( J \) fuel jets are more easily disrupted by air. Additionally, Fig. 14 shows that TF-JICF with initially higher penetrations (i.e., a higher \( J \)) seem to experience generally declining penetrations as \( dP \) increased, whereas the lower \( J \) sprays experience significant penetration enhancement over the range of \( dP=0 \) to 150\%. This may explain why Leong et al. [39][45-46] and Li et al. [51-52] only observed increased penetration with increasing \( dP \), since their experiments’ \( J \) values were very low compared to ours.

Figures 13 and 14 strongly suggest that TF-JICF are comprised of four regimes (including the \( dP=0\% \) Classical regime) whose penetrations depend differently on \( dP \). As proposed earlier, only the trends and spray structures found in the AB-SICF regime appear similar to Leong et al. [39][45-46], Li et al. [47] and Sinha et al. [49]’s high \( ALR \) results where \( J_{eff} \) is applicable. To test this
proposition further, we subjected the spray trajectories to the $J_{\text{eff}}$-correlation. The left of Fig. 15 shows the raw outer-edges of $J=5$, $We_{cf}=350$ TF-JICF, grouped by shades of gray according to their regime. The right of Fig. 15 shows these outer-edges after normalization by $J_{\text{eff}}^{0.5}$. Trajectories that are correlated to $J_{\text{eff}}$ should become closely collapsed after this normalization, per Equations (3) and (4). Figure 15 shows the AB-SICF regime’s outer-edges being closely collapsed, while the lower regimes’ outer-edges are spread further apart (i.e., poorly correlated). This supports our proposition that $J_{\text{eff}}$ only describes the AB-SICF regime. Our proposition continues to hold for all tested cases of $J=5$-$40$ and $We_{cf}=175$-$1050$. These results will not be repeated here for brevity.

**Conclusion**

Our investigation was motivated by recent experimental results that contradicted the existing understanding of TF-JICF rooted in the $J_{\text{eff}}$-correlation [39][45-46][51-52]. For example, we reported that low ALR TF-JICF had significantly lower than predicted penetrations [55-56], while Lee et al. [47] and Sinha et al. [49] reported that mid-ALR TF-JICF spray-plumes tend to bifurcate. However, the complete spectrum of behaviors has not been observed on a single injector so far, posing the possibility that some of these behaviors may be injector-specific. We addressed this unknown by characterizing TF-JICF from a single injector across wide ranges of $dP$, $J$ and $We_{cf}$. Our results produced TF-JICF behaviors that can be classified into four distinct regimes: (i) a Classical-JICF regime at $dP=0\%$, followed by (ii) the AA-JICF regime where the fuel jet is sheathed by the co-injected air against crossflow-driven atomization, resulting in slightly enhanced penetration and reduced dispersion, (iii) the subsequent AB-JICF regime where the stronger air disrupts the jet, causing reduced penetration as well as bifurcation, and (iv) the AB-SICF regime where spray penetration is enhanced by air in accordance with $J_{\text{eff}}$. Critically, all TF-JICF behaviors reported in separate literature sources so far have been successfully replicated on our injector, lending us to hypothesize that these behaviors are not injector-specific, but pieces of a universal set of
TF-JICF characteristics which manifest at different operating conditions.

With regards to jet-engine fuel-injector design, the results suggest operation in the AA-JICF regime will lead to reduced fuel concentration near the wall especially at low fuel flow-rates, which satisfies the original intent of mitigating near-wall burning/coking risks. The low \(dP\) requirement of this regime also makes it suitable for designs where a dedicated high-pressure source of air is not available. The AB-JICF regime is largely counter-productive for the purpose of jet-engine fuel-injector, since the rate of fuel atomization is not significantly enhanced, while spray penetration is reduced as \(dP\) increases, putting more fuel close to the wall. The AB-SICF regime is potentially beneficial to jet-engine, because the fuel-jet is promptly atomized and the spray penetration can be very high. However, the extreme levels of \(dP\) (or ALR) required for this regime may make unsuitable for practical designs.

A future publication will examine the spray images in more details, to compare spray dispersions and jet disturbances quantitatively at different conditions, in order to develop detailed understandings of TF-JICF spray-formation processes in each regime.

**Nomenclature**

- \(A_{\text{air}}\): air-nozzle area
- \(A_f\): fuel orifice area
- \(A_{\text{total}}\): total injector area
- \(\rho_{\text{air}}\): air density
- \(\rho_{\text{cf}}\): crossflow density
- \(\rho_f\): fuel density
- \(\rho_{\text{mix}}\): mixture density
- \(\sigma_f\): fuel surface tension
- \(\text{ALR}\): air-to-fuel mass flow-ratio
- \(C_p\): jet drag coefficient
- \(C_i\): empirical constants \(i\)
- \(d_f\): fuel orifice diameter
- \(dP\): air-nozzle pressure-drop
- \(J\): momentum-flux ratio
- \(J_{\text{eff}}\): effective momentum-flux ratio
- \(P_0\): stagnation pressure
- \(P_{\text{cf}}\): crossflow pressure
- \(U_{\text{cf}}\): crossflow velocity
- \(U_f\): fuel velocity
- \(W_{\text{eair}}\): air Weber number
- \(W_{\text{eef}}\): crossflow Weber number
- \(x\): distance in jet direction
- \(z\): distance in crossflow direction

**References:**

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