Effects of Air-Assist on the Dynamics of a Liquid Fuel Jet-in-Crossflow at Elevated Temperatures and Pressures

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Abstract
Modern gas-turbines employ fuel-air mixers that utilize jet-in-cross-flow (JICF) fuel-injection to achieve rapid fuel-air mixing. In recent years, air-assist JICF has been investigated to improve the atomization and fuel-dispersion qualities of JICF. This paper describes an experimental investigation of the effects of air-assist upon the dynamics of JICF at elevated pressures and temperatures. In the investigation, the liquid Jet-A was injected through a wall-recessed orifice, while four slots surrounding the base of the recess supplied air streams that impinged on the jet at 45°. Two arrangements of 10kHz high-speed Mie-scattering imaging were applied to capture the resulting spray plume: (1) simultaneous capture of the plume’s integrated Mie-scattering from the top and side-views using a 2-camera system, and (2) capture of planar Mie-scattering across two different cross-sectional slices of the plume. A novel moments-based post-processing technique was applied to the 2-camera image-sets to obtain instantaneous center-of-gravity (CG) trajectories of the spray plume in 3-dimensional space, as well as the instantaneous dispersion pattern of the plume around the CG. From these, average and time standard-deviations of the CG and dispersions were calculated to investigate the static and dynamic properties of the JICF under different injection conditions. Similar statistics were also obtained from the cross-sectional images. From the instantaneous CG and dispersion values, the instantaneous spray plume can be reconstructed digitally in 3D, which serves as a useful visualization tool for engine designers, and facilitates the comparison of experimental results with CFD.

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Introduction

In the fuel-air mixers of many modern gas-turbines, such as those detailed by Dodds et al. [1] and Foust et al. [2], the main-fuel is injected perpendicularly into a high pressure \( (P) \) and temperature \( (T) \) cross-flow of air. The cross-flow then redirects the fuel jet into the flow direction while atomizing it. In these engines, the cross-flow air can attain temperatures and pressures up to the vicinity of 500°C and 5.05 MPa, respectively, resulting in fine atomization and significant gasification of fuel within the mixer. The mixture then leaves the mixer and enters the combustor. This configuration of fuel-injection is called the jet-in-cross-flow (JICF).

In a conventional JICF, the liquid fuel is typically injected from a plain orifice. However, at high pressures and temperatures (i.e., high Weber numbers), the jet is shear-atomized into very fine droplets that can travel near and/or impinge on the injector’s wall. This was described by Leong et al. [3] and Tan et al. [4]. The slow-moving near-wall fuel has the potential to coke or auto-ignite, both of which shortens the fuel-air mixer’s component lifespan. A recent technique in enhancing the liquid fuel jet’s penetration into the cross-flow and reducing near-wall droplets involved the use of air-streams to assist or blast the liquid fuel jet as it is being injected into the cross-flow [3]. The arrangement of the air-streams can take a variety of forms, from perpendicular fuel-air impingement to co-axial/concentric fuel-air injection.

The study described by this paper is performed on a JICF injector with a plain-orifice fuel nozzle that was recessed into a shallow well (see Fig. 1). The liquid injectant was Jet-A at close to room temperature. Meanwhile, air-assist streams at close to cross-flow temperature were injected from four slots surrounding the base of the well. They impinge upon the fuel jet at 45° angle. The test conditions of the cross-flow air were set at 2.02-2.53 MPa in pressures and 316-427°C in temperatures. Liquid-to-cross-flow momentum-ratios \( (J) \) in this study ranged from 5 to 40. The mass flow-rates of air-assist were controlled by varying the pressure-drops \( (dP) \) across the air-slots from 0 to 6% of cross-flow pressure, which corresponded to air mass-flow rates that were less than 40% of fuel flow-rate at \( J=5 \).

Unlike previous airblast JICF studies by Leong et al. [3] and Li et al. [5], this study used low values of \( dP \) and air-assist-to-fuel mass-flow ratio. This was because it is the intended design of the fuel-air mixer (as illustrated in Fig. 1) to extract air for the air-assist from frontal openings in the mixer, and to channel the air directly to the side-mounted injector orifices without additional pressure-boosting hardware. The low \( dP \) values corresponded to the difference in static and stagnation pressures of the compressor discharge air, and allows the design to operate in the intended manner. Further example of this design can be found in the patent of Myers et al. [6].

Two previous publications by Tan et al. [7], [8] detailed the observations regarding the effects of air-assist upon the penetration and dispersion pattern of the liquid JICF performed using the injector in Fig. 1. It was found that air-assist had very minor effects upon the penetration of the JICF spray’s windward/outer-edge, whereas the response of the inner-edge/wake-region was much stronger. With a moderate amount of air-assist, the inner-edges of the spray can be deflected away from the wall, achieving the effects of reducing near-wall fuel droplets.

The investigation detailed by this paper were intended to further characterize the response of JICF to air-assist, by conducting employing experimental diagnostic tools and post-processing techniques that were geared towards elucidating the dynamic behaviors of the air-assist JICF. The results from this investigation will support engine designers in understanding whether air-assist can provide any beneficial or adverse effects to the dynamics of JICF fuel sprays.

![Figure 1. Left: schematic of the air-assisted JICF injector. Right: illustrated example of the application of air-assist in a typical gas turbine fuel-air injector/mixer.](image-url)
Nomenclature
\[ \begin{align*}
\rho & \quad \text{density} \\
\sigma & \quad \text{standard-deviation} \\
d & \quad \text{fuel orifice diameter} \\
CG & \quad \text{center-of-gravity} \\
dP & \quad \text{air-slots pressure-drop} \\
\text{High-TP} & \quad \text{test-point at 2.53MPa and 427°C} \\
I & \quad \text{image intensity} \\
J & \quad \text{momentum-flux ratio} \\
\text{Low-TP} & \quad \text{test-point at 2.02MPa and 316°C} \\
P & \quad \text{pressure} \\
T & \quad \text{temperature}
\end{align*} \]

Subscript
\[ \begin{align*}
\text{assist} & \quad \text{air-assist} \\
cf & \quad \text{cross-flow} \\
t & \quad \text{time} \\
x & \quad \text{spatial or } x\text{-direction} \\
y & \quad y\text{-direction}
\end{align*} \]

Experimental Setup
High-Temperature and Pressure JICF Facility

The current study was conducted on a high-temperature and pressure facility capable of providing a continuous cross-flow of air in excess of 2.53MPa and 427°C (see Fig. 2). During experiments, the hot, high-pressure air was delivered from a supply line, through an air-restricting orifice, and into a 203 mm diameter flow-settling plenum (also shown in Fig. 3). The air then entered a 63.2 mm × 43.2 mm channel via a bell-shaped in-take. The flow crossed another converging section into a 31.8 mm × 25.4 mm rectangular test-section. The air-assist injector was mounted on one side of this test-section, while the other three sides were quartz windows for optical access. These windows were thin and designed to withstand the hot cross-flow air at a differential pressure of ~15kPa. A thicker outer chamber with thicker quartz windows (Fig. 2) contained high-pressure cooling-air that surrounded the test-section. The three-sided optical access of the test-section allowed a variety of optical diagnostic tools to be applied towards characterizing the JICF spray.

During test, the injected fuel and air were carried by the cross-flow out of the test-section exhaust and expanded into a natural-gas-fired afterburner. The afterburner consumes the fuel before releasing the products through an exhaust duct. A remotely-controlled valve downstream of the test-section controlled the cross-flow velocity during tests.

In this study, the spray-characterizations were carried out at two sets of operating conditions, which will be referred to as Low-TP (2.02MPa, 316°C) and High-TP (2.53MPa, 427°C). The cross-flow velocity was maintained at 75m/s for all cases. These combinations of conditions are located on a typical gas-turbine engine’s operating line.

Figure 2. A schematic of the jet-in-cross-flow spray rig.
Test-Section and Fuel Injector

Shown in Fig. 3, a fuel line delivered liquid Jet-A at near room temperature to the fuel-injector, which was illustrated in Fig. 1. The diameter of the fuel orifice was 0.506\,mm, while the recessed well was 1.861\,mm in diameter and 1.27\,mm deep. The fuel supply was delivered by an external pumping system with a pressure-relief valve and an accumulator to damp out pump vibrations. A turbine flowmeter was installed on the fuel supply line to measure fuel flow-rates, while a remotely-controlled variable valve and multiple solenoids ensured proper flow-rates. When Jet-A was not being injected, high-pressure nitrogen was used to purge and cool the fuel line to prevent coking.

Shown in both Figs. 2 and 3, an air-line with heater and thermal-insulation jackets extracted hot, high-pressure air from upstream of the air-restricting orifice of the rig, and delivered the air at close to $T_{cf}$ to a cylindrical plenum within the injector. The air settled momentarily in the plenum before being injected through four slots around the bottom of the injector well. The angled injection slots were 0.394\,mm wide, and encircled nearly the entire spray-well circumference, such that the total slot area was 1.66\,mm$^2$. The slots’ bores were angled at approximately 45° with respect to the fuel bore. A differential pressure transducer (“$dP$” in Fig. 3) was used to measure the pressure-drop between the air-assist line and the test-channel (via a static port located next to the injector well, as shown in Fig. 4). A thermocouple also measure the temperatures of the assist air close to the injector, to make sure they are very close to $T_{cf}$. $dP$ represented the pressure-drop across the air-slots, and it was remotely controlled by a variable valve. The relationship between $dP$, $\rho_{assit}$ and $m_{assit}$ has been obtained through benchtop calibrations prior to the JICF experiments, such that the flow-rates of the assisting air were always known.

In the coordinate system of the test-section, which will be used throughout this paper, $z$ denotes the longitudinal/cross-flow direction, $x$ denotes the fuel jet penetration direction, and $y$ denotes the lateral direction. The coordinate system’s origin is located at the injection orifice, flush to the wall. Distances will be given in terms of multiples of the fuel orifice diameter (e.g., $z/d$).
Spray Optical-Diagnostic Systems

Two spray-imaging arrangements based on 10kHz high-speed Mie-scattering were used to capture images of the air-assist JICF for analysis. In the first arrangement (left of Fig. 5), a 2-camera setup was used to simultaneously capture images of the spray from the top-view (looking onto the injector plate) and the side-view (injector plate parallel to the line of sight). In this setup, diffused pulsed laser light was directed into the test-channel using an optical fiber. The laser light scattered off any fuel droplets in its path of propagation to produce integrated Mie-scattering signals. Typical instantaneous images from the 2-camera setup are shown in Fig. 6. These images had an effective exposure time of ~8ns, and a resolution of 3.6/pixel/ld. >5600 images were recorded per test point. Note that due to the direction from which the laser light was introduced, the spray plume from the top-view was brighter on the spray’s right, whereas the dense-spray region of the side-view showed up as dark shadows. These will affect the accuracy of results in the dense-spray region and the interpretation of the spray’s true lateral positions. However, the general trends and conclusions that will be drawn in this paper will be independent of these inaccuracies.

The second arrangement (right of Fig. 5) was used to capture spray images within a cross-sectional slice of the spray. In this arrangement, the pulse laser light was formed into a laser-sheet, which intersected the spray from the side, with the plane of the sheet being perpendicular to the injector plate. A single high-speed camera was positioned from the top side of the spray and oriented at 45⁰ with respect to the laser-sheet to capture the illuminated cross-section. Cross-sections at the longitudinal positions of z/d=14 and 41 were imaged. Typical instantaneous images from this setup are shown in Fig. 7. The images from this arrangement had to be corrected for perspective distortion due to the 45⁰ orientation. Note that due to the strong Mie-scattered lights, some out-of-plane droplets were also illuminated. This may affect the accuracy of results derived from this imaging arrangement.

Figure 5. Left: Schematic of the 2-camera setup. Right: Schematic of the cross-section imaging setup.

Figure 6. Typical instantaneous image of side- and top-view from the 2-camera setup.
Post-Processing Technique

A novel moments-based post-processing technique was applied to quantify the spray’s instantaneous position and dispersion patterns. The technique improves upon common intensity-threshold/gradient-based edge-tracking methods by being entirely independent of user inputs and adjustments. In this technique, the spray’s position and dispersion in every single high-speed image-frame are described by: (1) the line of center-of-gravity (CG) vs. z/d that represent the balance-point of the spray plume across each vertical pixel-column, and (2) the spatial standard-deviation ($\sigma_x$) vs. z/d, which describes the spatial distribution of the spray plume around the CG in each vertical pixel-column. The instantaneous CG of the spray was determined through the calculation of the 1st normalized moment of a spray image’s intensities across each pixel-column, defined mathematically as:

$$CG_x (\frac{z}{d}) = \frac{\sum(\frac{z}{d}) (\frac{z}{d}) I(\frac{z}{d})}{\sum(\frac{z}{d})}$$  \[1\]

where the subscript x denotes CG in the penetration direction (i.e., from side-view image). $CG_y$ can be similarly calculated by summing across $\frac{z}{d}$. The time-averaged trajectory of the spray’s center-of-gravity (aveCGₓ and aveCGᵧ) can then be determined through the arithmetic average of $CG_x$ and $CG_y$ across all images of a test-point.

The magnitude of fluctuation of the CG in time was characterized through the time standard-deviation ($\sigma_t$) of the CG, defined as:

$$\sigma_t, t \left( \frac{x}{d} \right) = \left\{ \frac{1}{n_{frame} \sum_{frames}} \left[ CG_x \left( \frac{z}{d} \right) - CG_{Mean,x} \left( \frac{z}{d} \right) \right]^2 \right\}^{0.5}$$  \[2\]

where the second subscript x denotes that this is standard-deviation in the penetration-direction.

The spatial width of the instantaneous spray plume can be characterized by finding the instantaneous spatial standard-deviation ($\sigma_s$) of the plume, defined as the square-root of the 2nd moment:

$$\sigma_s, x \left( \frac{x}{d} \right) = \left\{ \left( \frac{1}{\sum_{i} (\frac{x}{d})} \sum \left( \frac{x}{d} - CG_x \left( \frac{z}{d} \right) \right)^2 I \left( \frac{x}{d} \right) \right)^{0.5} \right\}$$  \[3\]

The description of instantaneous spray width using Eq. 3 assumes the spray cross-section can be represented by an equivalent Gaussian distribution- which is not necessarily most accurate for instantaneous cross-sections, but is generally true for averaged spray cross-sections. The CG, $\sigma_t$ and $\sigma_s$ have units of $d_{inj}$, and can be calculated for the side-view/top-view (as lines) and cross-section images (as points). Figure 8 demonstrates the technique by plotting the mean CG, along with $\sigma_t$ and $\sigma_s$ upon an averaged side-view image.

An approximate spray plume can be reconstructed digitally in 3-dimensional space based on the side- and top-view images’ CG, $\sigma_t$ and $\sigma_s$. An ellipse can be drawn at each z/d position with the major/minor axes equivalent to 4$\sigma_{s,x}$ and 4$\sigma_{s,y}$, while the center of the ellipse is centered about ($CG_x, CG_y$). If major/minor axes based on 4$\sigma_s$ are used, the ellipse is expected to contain 95% of the spray droplets/image intensities. The stack of ellipses across longitudinal distance z forms a 3D spray plume, an example of which is shown in Fig. 9. Work is in progress to include skewness into the statistics and reconstructions to better represent the dispersion of spray materials, which are typically not symmetric about the CG.

Figure 7. Typical instantaneous images of cross-sections at z/d=15 and z/d=40.

Figure 8. Plot of the average CG with multiples of $\sigma_t$ and $\sigma_s$, superimposed on the averaged Mie image.
**Test Results**

**Average Spray Penetrations and Plume Widths**

Figure 10 shows the average \( CG_x \) curves (i.e., spray CG trajectories in the penetration-direction) for eight representative test-points. The eight curves show that \( CG_x \) grows with \( z/d \) in an approximately log-natural or square-root fashion, similar to the growth of spray outer-borders as observed by many authors [8-10]. On average, the \( J \rightarrow 20 \) \( CG_x \)’s penetrated twice as far as the \( J \rightarrow 5 \) \( CG_x \)’s, and the addition of air-assist enhanced the penetrations by up to 10%. For a given \( dp \) value, the enhancements were generally lower when \( J \) is higher, because the momentum-flux contribution of the air-assist becomes lower relative to the fuel momentum-flux. This effect has been described in more details in the works of Leong et al. [3], Li et al. [5] and Tan et al. [8]. It can also be observed that the \( CG_x \) in Fig. 10 curves are not entirely monotonic with \( z/d \), particularly for the case of Low-\( TP \), \( J \rightarrow 5 \), \( dp=0\% \), where \( CG_x \) reached a peak at \( z/d \sim 30 \), and curved back towards the wall. This may be connected with the process of liquid fuel vaporization, where the outer regions of the spray plume were more directly exposed to hot cross-flow air, causing them to vaporize before the near-wall region, which caused the \( CG_x \) of the liquid plume to descend.

Figure 11 shows the average widths of the spray plumes in the penetration-direction and lateral-direction, for the same cases as Fig. 10. In this paper, the “width” is defined as 6 times the average spatial standard-deviation, such that 99.7% of the Mie-scattering-intensities fall within the bounds of the defined width. From Fig 11, it can be seen that increasing \( J \) from 5 to 20 increased the penetration-widths by less than 100%, compared to \( CG_x \) which doubled. The application of \( dp \sim 5\% \) air-assist increased the penetration-widths of \( J \rightarrow 5 \) sprays significantly between \( z/d \sim 0 \) and 10, and less significantly for \( z/d \sim 10 \). Air-assist had less effects on increasing the penetration-widths of \( J \rightarrow 20 \) sprays. The penetration-widths of the Low-\( TP \) sprays appear to reach their maximums at \( z/d \sim 30 \sim 40 \) (likely due to vaporization of the plume’s outer regions), whereas the High-\( TP \) plumes appear to grow continuously up to \( z/d \sim 40 \).

Figure 11 also shows that for non-air-assist JICF, the \( J \rightarrow 5 \) plumes were narrower than \( J \rightarrow 20 \) plumes in the lateral direction, but not by a lot. The application of \( dp \sim 5\% \) air-assist increased the sprays’ lateral-widths for all \( J \) by significant amounts, in such a way that the \( J \rightarrow 5 \) and \( J \rightarrow 20 \) plumes now have nearly identical lateral widths. In general, the Low-\( TP \) spray plumes appear to be wider in the lateral direction than the High-\( TP \) plumes. By comparison of penetration- and lateral-widths, it is observed that at \( J \rightarrow 5 \) the plumes were generally wider than they were tall, whereas at \( J \rightarrow 20 \) the penetration-widths outgrew lateral-widths such that the plumes were now taller than wide.

To improve the confidence regarding the accuracy of the moments-based post-processing method and the repeatability of the experiment, separate tests were conducted where the spray plumes were illuminated by laser-sheets and imaged in the cross-sectional planes (instead of top/side-views). Figure 12 contains a comparison of the results derived from the 2-camera and cross-sectional images at the \( z/d \sim 41 \) position. The central markers are the average CG positions (artificially centered in the y direction to neglect asymmetry caused by the one-sided laser-illumination). The ellipses represent the spray’s widths. In general, the CG locations and widths derived from the two imaging methods are slightly different. However, their qualitative behaviors as a function of \( J \) and \( dp \) were the same.
Figure 10. Average spray penetrations at different conditions, from the side-view of 2-camera Mie images.

Figure 11. 3-sigma spray widths at different $J$, $dP$ and operating conditions. Results from 2cam Mie images.

Figure 12. Comparison of CG and plume-widths measured via 2cam and cross-sectional Mie-scattering.
CG Fluctuation Magnitude

One of many advantages of the moments-based method is its ability to calculate CG and spray widths without user adjustments for every instantaneous frame of the raw high-speed footage, such that information regarding the spray dynamics can be extracted. Figure 13 shows the fluctuation amplitudes of the spray’s CG over time for a few representative cases. The curves are 6 times $\sigma_t$, such that for 99.7% of the time, the CG is expected to be located within a boundary as wide as of the curves’ values.

According to Fig. 13, the spray’s $\sigma_t$ in the penetration-direction increased rapidly in the region of $z/d=0$ to 10, then grew slowly between $z/d=10$ to 35. In the Low-TP cases, the $\sigma_{lx}$ rapidly increased again beginning at $z/d=40$. For High-TP cases, the “kink” in $\sigma_{lx}$ curves began at $z/d=30$, but the subsequent increases were less rapid. These sudden increases in $\sigma_{lx}$ were most likely connected to the onset of rapid spray vaporization as the injected fuel reached certain temperatures. The locations of the sudden increases coincided with the locations where spray penetrations were observed to fall or asymptote in Fig. 10. It is also evident in Fig. 13 that higher $J$ resulted in higher $\sigma_{lx}$, especially for the High-TP cases. Whereas, air-assist did not have a consistent or pronounced effect on $\sigma_{lx}$.

In contrast, the second part of Fig. 13 shows that the sprays’ lateral CG fluctuations ($\sigma_{ly}$) were nearly zero at the point of injection, and grew almost linearly with $z/d$. Higher $J$ consistently resulted in lower $\sigma_{ly}$, likely because the higher masses of injected fuel damped the lateral motions of the plume. Higher $dP$, on the other hand, resulted in increased $\sigma_{ly}$, especially for the $J=20$ cases. The different growth rates between $\sigma_{lx}$ and $\sigma_{ly}$, and the different ways they responded to $J$ and $dP$ may suggest that these motions originated from different mechanisms.

Figure 14 compares the average CG and 6$\sigma_t$ ellipses as calculated from the 2-camera and cross-sectional Mie images, at the $z/d=41$ location. In general, there are substantial quantitative mismatches between the results. However, they all elucidate the same trends of spray response towards $J$ and $dP$. From Fig. 14, it is observed that although the $\sigma_{ly}$ were smaller than $\sigma_{lx}$ near the injector, they eventually outgrew $\sigma_{lx}$, such that at $z/d=41$, the spray’s lateral fluctuations were substantially more than fluctuations in the penetration-direction. This has important implications towards the spacing of adjacent injector orifices in a typical multi-orifice JICF engine fuel-air mixer, where collision between adjacent plumes should be avoided. Fig. 14 confirms the earlier observation that $\sigma_{ly}$ drop with increasing $J$, whereas $\sigma_{lx}$ increased slightly. The application of air-assist resulted in a large increase of $\sigma_{ly}$ for the $J=20$ cases.

Figure 13. CG fluctuation at High-TP conditions, for different $J$ and $dP$. Results from 2cam Mie images.
**CG Fluctuation Frequency**

Figure 15 shows the time-traces of the lateral and penetration CG positions for two cases to illustrate potential frequency information that can be derived from the data. Both the lateral and penetration CG time-traces contain very high frequency fluctuations that are likely to be above the Nyquist frequency of the 10kHz imaging system. The amplitudes of these fluctuations similar were for \( dP=0 \) and 5%, while amplitudes were slightly larger for the lateral fluctuations.

In addition to the very high frequency fluctuations, the lateral CG time-traces clearly show the presence of very large and low-frequency fluctuations that have periods lasting from 0.05 to 0.1s. They appear to behave in a repetitive but non-periodic manner. Figure 16 shows two instantaneous top-view images of the spray plumes when they were at the extremes of the low-frequency motion. It is evident from the uniform deflection of the entire plume that the wavelengths of the motion far exceeded the residence time of the injected fuel in the test-channel. These wavelengths also far exceeded the sizes of the commonly identified vortices within a JICF plume, as illustrated in Fig. 16. Therefore, investigations are still underway to determine the source of this long-period lateral motion.
Concluding Remarks

- The static and dynamic behaviors of an air-assist JICF spray at different operating conditions, $J$ and $dP$ were characterized using two arrangements of high-speed Mie-scattering imaging techniques, and a novel moments-based post-processing technique.
- It was found that air-assist enhances the penetration of the spray’s CG into the crossflow. The amount of enhancement is larger at lower $J$. In many cases, the CG’s distance from the lower-wall grew with $z$ from $z/d=0$ to $~40$, after which the spray’s CG appeared to drop towards the wall again. This is likely due to vaporization of the outer region of the spray plume.
- Higher $J$ resulted in larger plume-widths in the penetration-direction. Higher $dP$ had very minor effects on these widths. On the other hand, lateral spray-widths were less sensitive to $J$. Higher $J$ and $dP$ increased the lateral...
widths by similar degrees. Lower $J$ sprays were wider than they were tall, while higher $J$ sprays were taller than they were wide.

- The $\sigma_{\text{t,x}}$ and $\sigma_{\text{t,y}}$ of the sprays’ CG evolved differently with $z/d$. Higher $J$ resulted in larger $\sigma_{\text{t,x}}$ and smaller $\sigma_{\text{t,y}}$. Higher $dP$ increased $\sigma_{\text{t,y}}$ while having negligible effects on $\sigma_{\text{t,x}}$.

- The CG’s in the penetration direction were observed fluctuate at very high frequencies and moderate amplitudes. Whereas the CG’s in the lateral direction contain very high frequencies fluctuations, as well as large-amplitude and very long-period fluctuations that were repetitive but not periodic.

**References:**