Experiments on turbulent ethanol spray flames in EEC conditions

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Abstract
An experimental study on the structure of ethanol turbulent spray flames in Excess Enthalpy Combustion (EEC) conditions and cold coflow was conducted Delft Spray in Hot Coflow burner. The setup consists in a spray issuing upwards in either a coflow of ambient air or hot-vitiated combustion products mixture. Different flame structures were observed depending on the coflow Reynolds number, injection pressure and coflow temperature and oxygen volume fraction. For the spray flame in cold air, a double flame structure consisting of two diverging flame fronts connected to the leading edge of the reaction zone and an increase of the lift-off height is observed with increasing injection pressure. In EEC conditions double flame structure is absent, flame exhibits low chemiluminescence and no lift-off height changes are attested with increasing injection pressure. Using Laser Doppler anemometry and Phase Doppler anemometry, we report space and time resolved measurements of the turbulent flow field and droplet spatial spectrum for a number of measurement locations in flames. Droplet radial distributions revealed important difference in the spray structure and the evidence of non-reacting droplet along the spray edges for both cases. The modeling of the flame structures observed represents a challenge for combustion scientists due to the richness of observed physics phenomena.

Introduction

Increasing fuel prices and environmental regulations have prompted great interest in the development of efficient and environment-friendly combustion technologies. EEC, also known as Flameless Oxidation (FLOX), Mild Combustion (MILD) or High Temperature Air Combustion (HiTAC), lends itself to the mixing of fuel, preheated air, and recirculating exhaust gas prior to ignition. In EEC the preheating of combustion air with exhaust gases enables efficient utilization of fuels with the advantage of low nitrogen oxide (NO_x) formation. It has been proved [10, 11] that this combustion process for light oil products produces low amounts of nitric oxide and the combustion characteristics are similar to that of natural gas. However, combustion of other liquid fuel oils revealed significant differences and the effects of the droplet size and dispersion are not yet understood.

The goal of this paper is to report on the results of experiments on ethanol turbulent spray flames in conventional and EEC combustion, thereby, attaining fundamental knowledge on liquid fuel combustion and provide a collection of detailed data covering a range of operational modes that can be used for further development and validation of advanced combustion models.

Experimental Setup

Burner design

The Delft Spray in Hot Coflow (DSHC) flow facility consists of a spray issuing in a rounded one-dimensional upward turbulent flow field with easy optical access for laser diagnostics techniques as shown in Fig.1. This burner is designed to deliver a coflow of either cold air or an oxidiser stream with high temperature carrying little oxygen (<10%) with uniform properties along the radius, yielding a flame burning in circumstances resembling those in EEC conditions with peak temperatures lower than those observed in spray flames in normal air.

Hot-vitiated coflow is generated by the secondary burner as follows: air flows through a tubular flow straightener and two aluminum perforated plates before it enters the burner holder that consists of 234 tubes with a diameter of 5mm packed as shown in Fig.1. Each tube has four 0.5 mm diameter holes located at a 90° angle to the air stream, so that Dutch Natural Gas (DNG) entering the shellside of the tubes emerges from these holes, mixes with the air flowing through the tubes and yields a matrix of premixed flamelets. This design concept was inspired by studies of turbulent temperature field by Merzkirch [5].

The use of a vertical rounded pipe is two-fold: achieve an enthalpy deficit in the coflow of hot combustion products by radiation to the surroundings and shield the hot-vitiated coflow from the surrounding air. Two heat resistant stainless-steel perforated plates are concentrically placed in the vertical rounded pipe providing grid-controlled turbulence scale and intensity and enhancing radiative transfer to the environment. This strategy has

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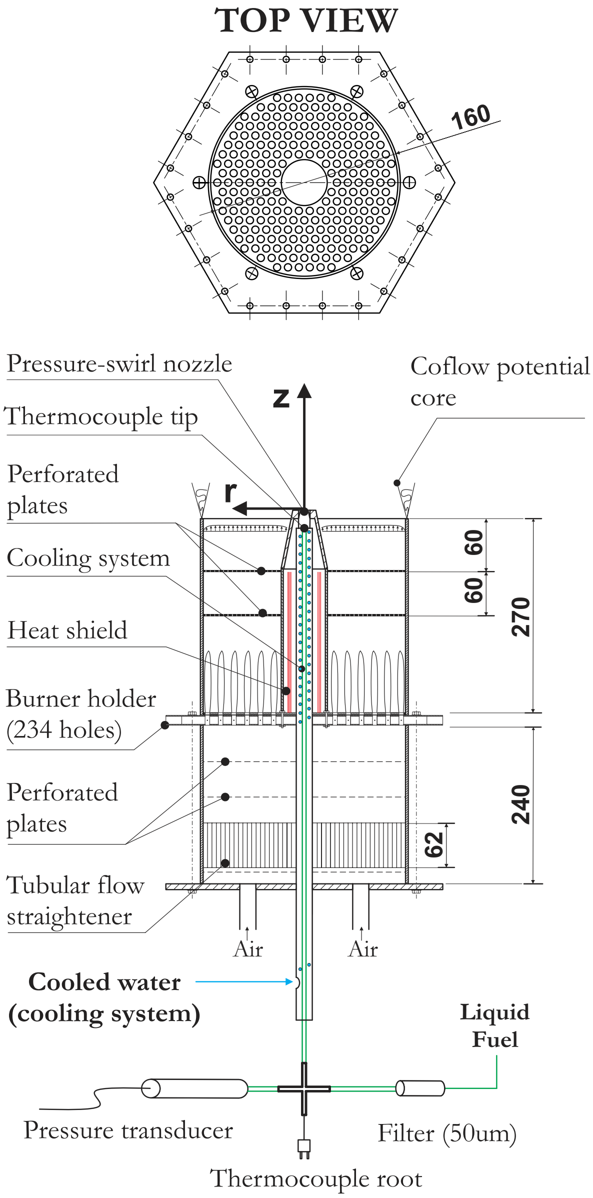

Figure 1: Schematic of the Delft Spray in Hot Coflow with relevant dimensions in millimeters

significant advantages over the use of N_2, which far outweigh the drawback of acoustic resonant oscillations. These were avoid by lifting the vertical rounded pipe by 3mm from the burner-holder. Thus, temperature and oxygen control with reasonably turbulent uniform flow field of burned gas is achieved over a wide range by varying the DNG to air ratio.

The experiments are restrict to a commercial pressure-swirl solid cone Delavan atomizer (WDA 0.5 GPH) with an 0.21mm exit hole and 60° spray angle coupled to 2mm inner diameter stainless steel pipe whereby liquid fuel is fed. The pipe is wrapped in helical copper water-cooling system and additional heat resistant stainless steel foils to prevent pre-vaporization. Liquid temperature and pressure are measured on-line by means of a thermocouple (Thermocoax Type K) and a pressure transducer (Omegadyne MMA). Both analog outputs are connected to a TSI EIC external data collection system for combined velocities, droplet size, pressure and temperature measurements. Flow rates were controlled by a mass flow controllers chosen to provide the maximum accuracy and resolution within the desired flow range.

Diagnostic Techniques

Laser Doppler Anemometry

Laser Doppler Anemometry (LDA) measurements were performed with a two-component, dual beam TSI-system operating in back-scattering mode. The green line (514.5 nm) and blue line (488 nm) of a 10W Continuum Argon-ion laser were used to measure the axial and radial velocity components directly (z and r, respectively). Two of the incident beams were frequency pre-shifted over 40 MHz by a Bragg cell to enable the detection of flow reversals. The length and diameter of the measurement volume were 1.24 mm and 0.086 mm, respectively. The photomultiplier output signals were fed to a FSA-3000 processor.

Phase Doppler Anemometry

The transmitting optics used for the Phase Doppler Anemometry (PDA) are identical to those of the LDA system. The optical receiving system was configured for first order refracted light with the receiving optics positioned at Brewsters for the ethanol refractive index and the signal processing was performed by a FSA-4000 processor and the associated software FlowSizer. All the parameters of the PDA system, i.e. optical, geometrical and electronic parameters of the PDA system as well as the Argon-ion laser, were kept constant in the experiments. The reason was that velocity of particles measured directly by the PDA depend in a rather complicated manner on the parameters of the instrument, when a polydisperse ensemble of drops is being measured.

Results and discussion

Burner stability diagram

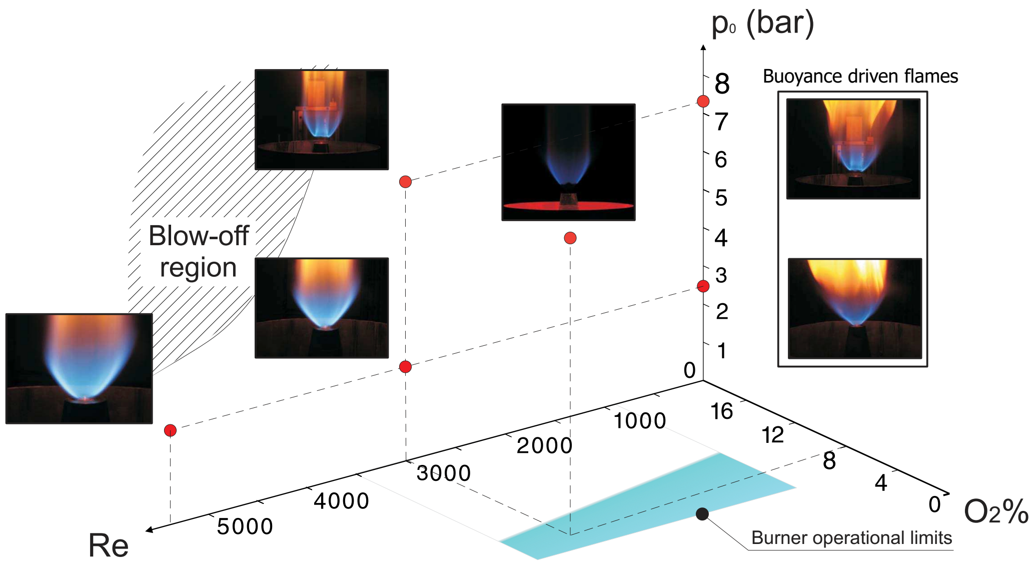

Figure 2: Combustion modes available: Ethanol turbulent spray flames in cold and hot-vitiated coflow

The stability characteristics of the burner for pure ethanol (C_2H_5OH) are summarized in figure 2. The results are presented for two coflow conditions: ambient air blown through the circular pipe, hereafter referred as cold coflow ($Re - p_0$ plane); and hot-vitiated coflow where combined DNG and ambient air yield a hot combustion products coflow with a specific temperature and O_2 volume fraction. The Reynolds number (Re) is defined by the outer pipe diameter and the kinematic viscosity based on the hot products at 1500K for the hot-vitiated conditions.

For the injection pressure range shown in figure 2, the flame without air coflow range exhibits an intermittent behavior. Under this operating conditions the spray flame grows in size, then appears to collapse (although not to complete extinction), inflates again, and continues this motion in a regular periodic fashion. Such pulsating type of behavior of the flame shape has been observed before, it is not clear exactly what is the mechanism responsible nonetheless [6].

Two distinct flame morphologies can be attested depending on the injection pressure used in the presence of a coflow. Pressures below 2.5bar yield a conical-like flame shape and a lift-off much smaller than expected from auto-ignition times. Furthermore, as the coflow Reynolds number is increased flame brightness decreases and no apparent changes occur in the flame-front. For higher pressures a double reaction zone consisting of two diverging flame fronts on each side of the spray centerline that join together at the flame base are witnessed. The flame base is characterized by low frequency flickering with an amplitude of the order of 2mm. As the Reynolds number grow high, the amplitude of the wiggles decreases and flame flickering is intensified.

Last, under hot-vitiated conditions a low-luminescent highly transparent flame with no sharp flame-front is observed. The flame forms a clearly lifted flame at some distance from the nozzle with a faint-blue in the bottom portion and high luminosity at the edges. Then, a orange flame appears on the top. Compared with a lifted-flame in cold conditions, it is more stable like a laminar flame. As the temperature goes down, the flame-front flickering appears and an increase of the flame luminosity is attested. Blow-off was absent for the burner operation limits.

Cases descriptions

Two different settings of the burner, with increasing complexity, were used to attain insight of spray phenomena in different conditions: Reacting Spray in Cold Coflow (RSCC) and Reacting Spray in Hot-Vitiated Coflow (RSHVC) resembling EEC conditions . Table 1 lists the input conditions of the different flames that were considered in this study. Snapshots of the reacting sprays taken for test cases are presented along with the respective boundary conditions in figure 3 and 4.

The coflow turbulent flow field was measured until the radial position were the presence of droplets was attested. Such was evident in the LDA measurements by the presence of measurements with frequency shifts higher than expected. Although PDA allows to discern droplet size, not enough small droplets exist in this region to describe the gas turbulent field. Oxygen measurements were performed with a Testo 335 flue gas analyser, with a specified inaccuracy of $\pm 0.20\%$.

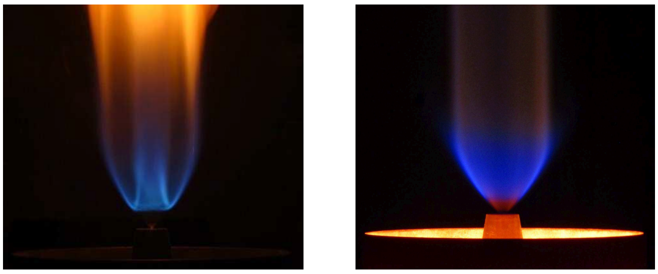

Figure 3: Images of the RSCC (left) and RSHVC (right) test cases.

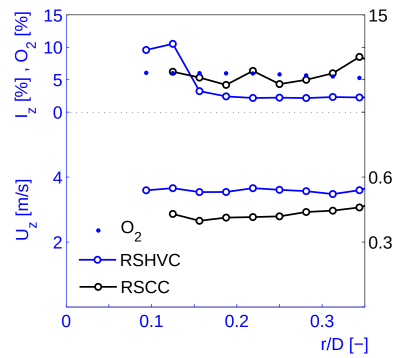

Figure 4: Boundary conditions for both test cases at z=1mm

	Coflow				Spray		
Flame Reference	$\dot{m}_{air}$ (g/min)	$\dot{m}_{DNG}$ (g/min)	$\bar{U}_z$ (m/s)	O_2 (%)	$\dot{m}_{liq}$ (g/min)	p_0 (bar)	$\bar{T}$(C)
RSCC	500	-	0.33	20.9	26.7	9.6	23.1
RSHVC	1117	59.2	3.41	6.8	23.3	10.3	34.2

Table 1: Characteristics of the spray and coflow stream for the studied flames. Y_{O_2} is a volume fraction weighted average between r=10 mm and r=70 mm, at z = 1mm. The amount of natural gas to generate the coflow and the total amount of air are given in columns two and three.

Results and Discussion

Single-point measurements at different axial stations are displayed in figure 5 for the two test cases. z/D=0.05 represents an axial station below the lift-off height for both cases. Vertical dashed lines represent the boundaries of the flame front seen in the photographs.

For RSCC case, figure 5, droplets are spread over the flow field resembling a typical structure from a solid cone pressure-swirl nozzle. Between the region bounded by the two flame-fronts an increase of the ensemble droplet velocity due to the expansion of the hot combustion products whereas in the outer region of the spray

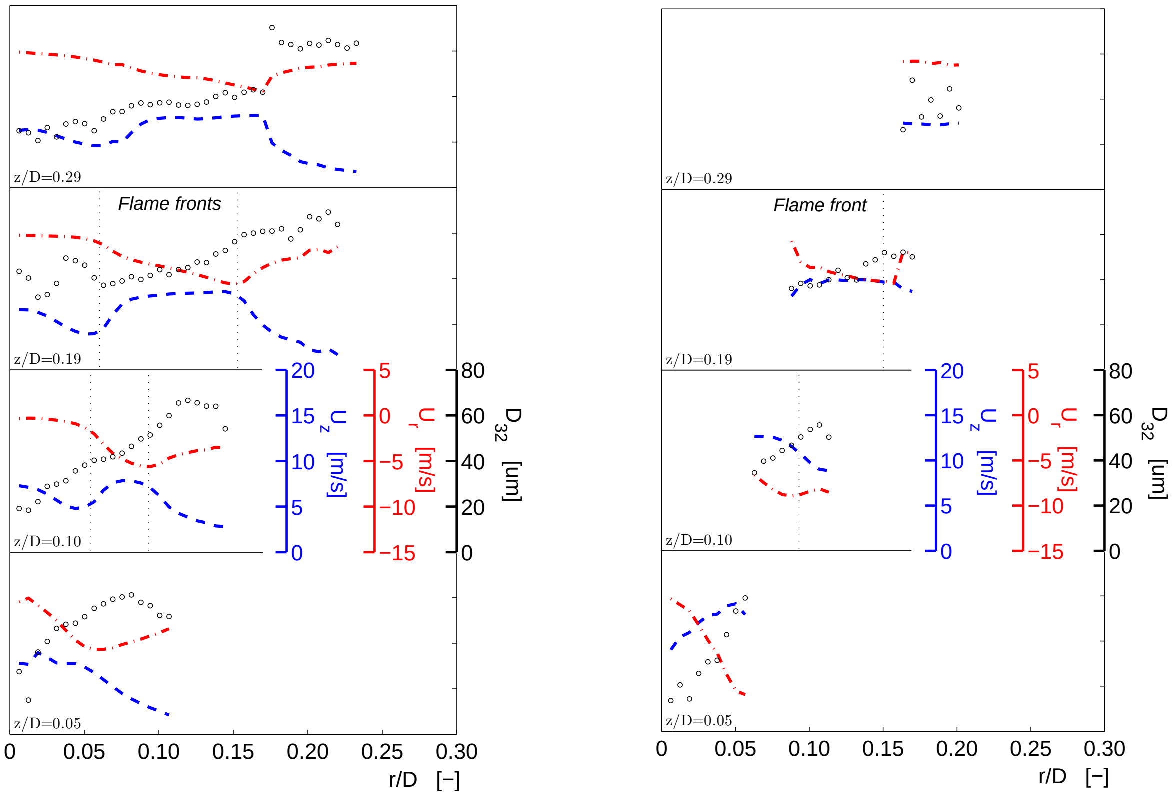

Figure 5: Velocity and droplet spectrum at different axial stations for the RSCC (left) and RSHVC (right) cases.

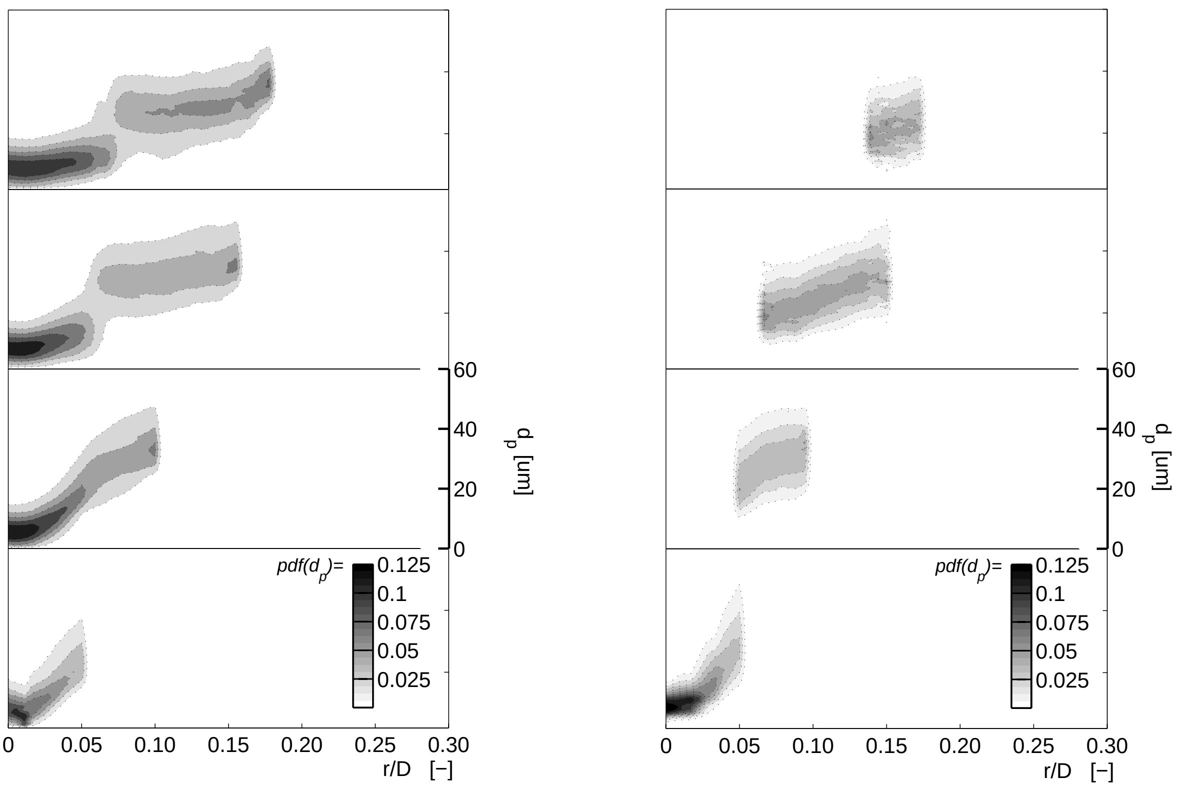

Figure 6: Contour plot of the droplet density number PDF $p(d_p)$ for the RSCC (left) and RSHVC (right) cases.

the presence of droplets is witnessed with no combustion taking place. In hot vitiated conditions the inner core region is completely devoided of droplets due to the high temperature of the co flow. Non reacting droplets are also present along the spray cone edge. The process of momentum transfer between the two-phases is from the droplets to the gas and it is intensified due to the high momentum ratio of both phases. Thus, droplets velocity of the droplets are strongly attenuated.

Figure 6 presents the spatial PDF droplet distribution in the spray for both cases at the same axial stations. A clear segregation of small droplets in the spray inner core for the RSCC case is present for all axial stations. The droplet evaporation of the small droplets in the reaction zone leads to an increase of the probability of bigger droplets. Droplet distribution in the RSHVC tens to lower diameter values due to the higher evaporation rates.

Figure 7 presents the axial and radial velocity jointPDFs for two radial stations at the station z/D=10. For RSCC case, both droplet velocity components are uncorrelated in the center, however, as shown by the shifts in the PDFs plots, droplets move from center to the flame periphery in a specific direction depending on the radial position and may, eventually, escape the flame envelope depending on their size and temperature experienced. The same effect is even more noticeable for the RSHVC case due to the low number density of smaller droplets. As a result of this, there is a clear indication that most droplets do not follow the average gas motion.

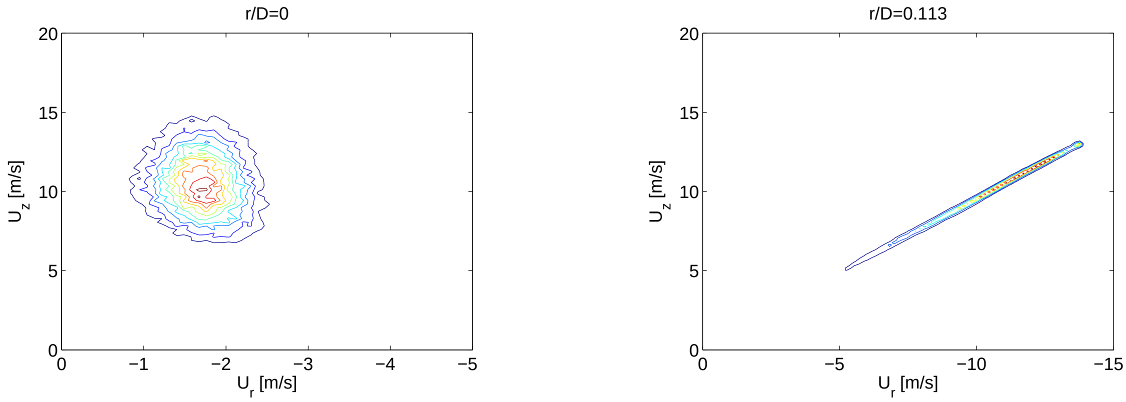

Figure 7: Velocity JointPDF at two different radial positions, z/D=0.10

Summary and Conclusions

An experimental setup was developed whereby several ethanol turbulent spray flames can be produced. An experimental study was conducted by laser doppler anemometry and phase doppler anemometry in two ethanol spray flames in cold and hot-vitiated coflow. It was observed that a significant fraction of the spray is not burned in the main flame zones but enters the surrounding region. In the EEC conditions the inner part of the cone is devoid of droplets and a double reaction zone as seen in the cold coflow case, is absent in the EEC case. The reason why the flame front propagates through the inner core is not yet understood. A direct comparison with other EEC setups is still difficult because data on the thermochemical properties of the coflow with the used operational conditions are still be measured to determine the adiabatic flame temperature of the spray jet. Thus, Coherent Anti-Stokes Raman Scattering (CARS) will be applied to complement the boundary conditions description in the near future.

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