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EXPERIMENTAL STUDIES OF CRUDE OIL COMBUSTION IN A TOP-MOUNTED SILO COMBUSTOR

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ABSTRACT

Crude oil is still an attractive fuel for electricity production due to its low extraction costs in relation to other fuels. However, combustion of crude oil in modern gas turbines must meet certain criteria, which mainly include the reduction of harmful gas emissions, the elimination of harmful dust from the exhaust gas, the improvement of turbine efficiency, the limiting of the power degradation process and elimination of hard deposits. Experimental studies are always needed to meet these requirements because of common complexity in CFD crude oil combustion models. This paper presents experimental investigations of the combustion process of crude oil. Using different sorts of crude oil, all experiments are performed in the atmospheric test rig of a top-mounted combustor, which was scaled down from the baseline system. The test rig was optimized for the typical silo gas turbine boundary conditions. The combustion process is described and quantified with the measured temperature and velocity field distributions in the top-mounted combustion chamber for different injector design's parameters. Additionally, measured profiles of the molar fraction of CO_2, are discussed and compared with respect to the injector parameters. Finally, based upon the experimental results gathered, the possibility of fuel flexibility in the top-mounted combustor chamber is discussed.

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NOMENCLATURE

D	Discharge orifice diameter of new nozzle
D_s	Swirl nozzle chamber diameter
d_p	Inlet port diameter
d_{pin}	Pin diameter
d_o	Discharge orifice diameter
f	Local length of the LDA probe
L_s	Swirl nozzle chamber length
N_s	Power of the test rig
N_T	Power of the gas turbine
p	Pressure
R	Combustion chamber radius
x_G	Scaling parameter for geometry
α	Spray cone angle

INTRODUCTION

This paper presents the investigation of crude oil combustion processes in gas turbine combustors. Crude oil combustion is still attractive in the systems built close to crude oil sources. The crude oil combustion process runs in quite a different way compared to the homogenous mixture, like the natural gas and air mixture, especially premix combustion. The crude oil combustion runs in the diffusive flames where the injection, vaporization and atomization process plays the key role. The research presented in this paper has been carried out on the crude oil acquired from the East and Central Europe sources. The crude oil's composition and combustion properties, like vaporization curves, have been compared to those of the oils from other sources, among others obtained from different types of the Arabian crude oil. This problem is also discussed in the literature [1]. As example, the vaporization curves for Arabian crude oil, Russian crude oil and diesel are presented in Figure 1.

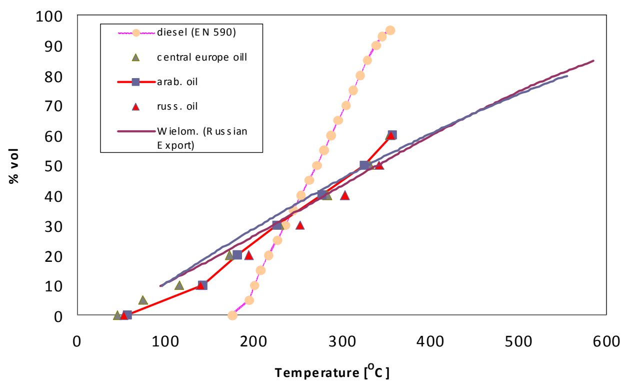

Figure 1. Vaporization curves for different types of crude oil [1].

The graph in Figure 1 shows that the essential difference in the vaporization curves for various liquid fuels applicable in the gas turbines is the difference in their final vaporization temperature. The heat oils or the oils for diesel motors vaporize in the temperature range of 175°C-360°C and reach the vaporization degree exceeding 95%. Only a small mass fraction of these oils remains as a solid phase. The crude oil vaporization starts at 50°C approx. and terminates at 380°C approx. However, about 35% mass fraction of crude oil does not vaporize and remains in the form of solid i.e. asphalts. Only heating of these fractions up to the temperature exceeding 600°C can cause first the pyrolysis of these heavy fractions and then a transition to the carbon black and hydrogen emission. According to the widely reported research results, the carbon black is difficult to burn down and its combustion is accompanied by an excessive particulate emission. Therefore, the crude oil combustion process should be conducted in quite a different way. The fuel must be atomized before it is injected into the flame zone i.e. in the chamber's zone in which the air temperature is relatively low. In this zone, the vaporization of the lighter fractions should begin. The process leads to the possibly fast and deep dispersion of the high-density fractions due to its mechanical dispersion.

The main goal of the research presented in the paper was to gain knowledge on the crude oil combustion process. This paper presents the discussion of the way of measurement as well as the analysis of results of velocity distribution, temperature and molar fraction in a scale top-mounted Alstom silo combustor.

DESCRIPTION OF THE TEST RIG

Experiments on the real gas turbine are extremely expensive and often infeasible. Therefore, a special test rig has been designed in the Poznan University of Technology. The rig has been developed according to the rules of scaling of the operation pressure and geometrical dimensions of the combustion chamber. The following parameters have been scaled:

- Combustion chamber dimensions
- Pressure
- Power
- Injection nozzle
- Combustion parameters

The first scaling criterion was the admissible heating capacity of the test rig. The test rig has been designed to operate under the atmospheric pressure. The scaling has been performed according to the criterion (1).

$$N_S = \frac{1}{x_G^2}\frac{1}{p}N_T \qquad (1)$$

Using the equation (1), the test rig power can be calculated. Additional scaling criterion was the scaling of combustion process. An examination of scaling from the specific point of view of combustion has been described in literature [2, 3, 4]. Scaling methodologies are required to make use of the test results for the design of a new hardware or a new technology. Measurements should connect test results to the new design or new methodology. According to [5], the best scaling method for liquid fuel combustion is to use identical geometry of injector elements in the small size combustor as found in the full size combustor. Thus, the energy characteristics divided into atomization, vaporization, mixing and reaction can be made identical depending on the combustion chamber geometry. If the pressure is also scaled, the Crocco scaling rule can be applied [3]. Crocco assumed that conversion time of chemical species is inversely proportional to the chamber pressure. However, the Crocco method cannot be applied to scale the chemical reaction from the gas turbine's operation pressure to the atmospheric pressure. Referring to the performed experiments as well as to the literature [1, 6, 7], the droplets size formed in the atomization process under atmospheric pressure is smaller than the size of droplets formed under higher pressure. In Figure 2, the comparison of the droplets size of the crude oil after atomization under pressure of 1bar and 7.3 bars, constant injection pressure and constant temperature is presented. The measurements have been carried out in laboratory, on the special test rig. For the pressure of 1 bar and 7.3 bars, the diameter of the majority of droplets was 90 micrometers and 180 micrometers, respectively. It is very difficult to obtain an exact combustion similarity between the two combustion flows. All components of the combustion process, i.e. velocity, temperature, heat release, flame position appearing for different geometries (scaled) shall be similar.

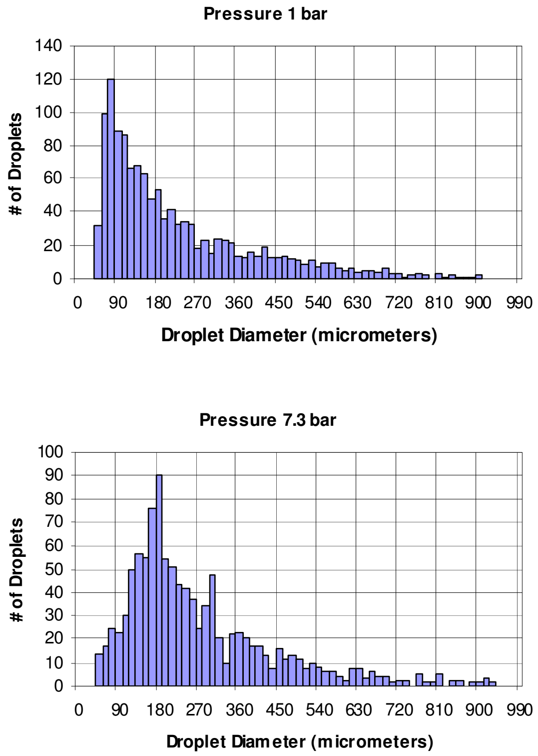

FIGURE 2. Droplets Size for two pressure values: 1bar and 7.3 bars.

When the operation pressure is scaled to the atmospheric pressure, the similarity parameters (Reynolds number, Schmidt number, Prandtl number, Mach number and Freude number) can be used. But these are not explicit criteria. In the case of scaling in atmospheric pressure it is difficult to obtain compliance with the similarity parameters. However, the goal of the scaling as well as the goal of measurements should be taken into account. The main goal of the investigations described in this paper was to understand the mechanisms of the crude oil combustion, and our interest was especially focused on how the tangential and vertical velocities affect the process of the deposit's formation. Therefore, the swirl number and the spray cone angle became the crucial parameters. To meet such conditions, the swirler installed on the test rig has been designed in a way to obtain the swirl number identical to the original swirler in the gas turbine. However, the injector scaling proved to be a very complex task. To obtain an adequate spray cone angle, a new design of the injector with a special pin has been developed [8, 9]. The injector design is shown in Figure 3. Detailed tests of the injector with pin for water and crude oil have been presented in literature [9]. The designed combustion chamber has been additionally equipped with a series of measuring windows. The combustion chamber scheme is shown in Figure 4. The air delivered to the combustion chamber was heated up to the temperature equal to that behind the compressor of the real gas turbine.

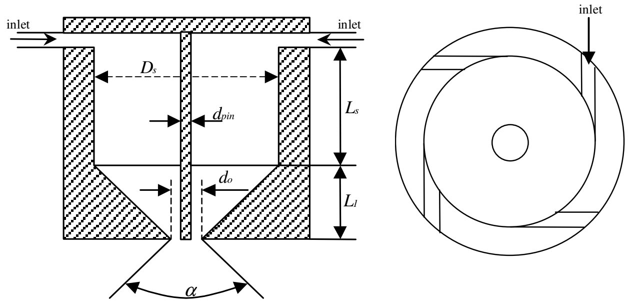

FIGURE 3. Geometry of the nozzle with the special pin [9].

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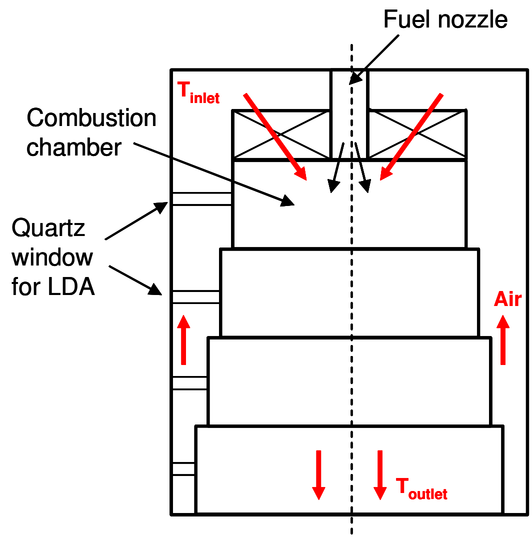

FIGURE 4. Test rig for crude oil combustion.

The goal of experiments was to identify the crucial operating parameters of the combustor responsible for the crude oil combustion quality. Therefore, the following measurements have been performed:

- Axial and tangential flow velocity in the combustion chamber, measured with the double-beam laser anemometer (LDA)
- Temperature distribution within the combustion chamber, measured with the suction pyrometer
- CO_2 molar fraction distributions across the combustion chamber.

To maintain the proper distribution of the air flux entering the combustion chamber through the burner, lateral inlets and slots, the adjusting rings have been installed in the combustion chamber. For experiments with crude oil, the control system has been additionally equipped with a separate system for detection of the burned crude oil flame, based on the UV radiation measurement using the UV probe. Lack of the feedback signal from the UV probe resulted in the shut-off of the fuel inlet valve and transition into the emergency status. Moreover, the shut-off of the fuel inlet resulted in the activation of the cooling system and rinsing the fuel nozzle with water to prevent the scorch of the crude oil in the fuel nozzle.

VELOCITY MEASUREMENTS METHODOLOGY

To understand the flow processes in the combustion chamber, i.e. velocities and direction of the flowing gases, the measuring technique has been used based on application of the two-dimensional Laser Doppler Anemometry (Figure 5). With that method, two velocity components, vertical and tangential, can be measured. To measure the third component of velocity, an additional laser source located at a right angle in relation to two other beams became necessary. In this paper only the results for two velocity components are reported.

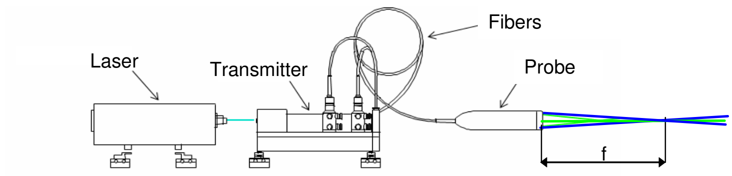

FIGURE 5. Laser Doppler Anemometry (LDA).

The transmitter used in experiments splits a laser beam into two beams of different length: green 514,5 nm and blue 488 nm. Each color beam is responsible for one velocity component. The laser beam from the probe with local length of 800 mm was scattered on the seeding or fuel particles. In the measurements, the TiO_2 particles were used as seeding. The scattered light goes back to the laser probe and then a light impulse is analyzed in the processor. For a complete analysis of the obtained velocity component values (database for further computations), the BSA Flow program has been used. Velocity of the flowing fuel was measured through the five quartz windows placed in the combustor on five levels (Figure 8). Data on the velocity distribution was acquired by moving the laser probe on the PC-controlled traverse system.

TEMPERATURE MEASUREMENTS METHODOLOGY

Temperature measurement in the flame and the exhaust gases is one of the most difficult diagnostic measurements made during the combustion process. It can be performed using plenty of measuring techniques like the Coherent Anti-Stokes Raman Spectroscopy (CARS) or using the suction pyrometer. The CARS method consists of measuring the temperature by a laser beam. A detailed description of this method was presented in [10]. The second method relies on the direct measurement of temperature of the post-flame gases with the suction pyrometer probe equipped with an S-type thermocouple of measuring range 500°-1600°C and the temperature measurement accuracy ± 1%. The probe's scheme is shown in Figure 6.

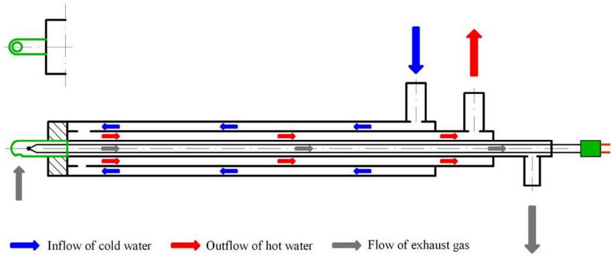

FIGURE 6. Suction pyrometer – schematic design.

Despite of the thermocouple mentioned above, basic elements of the probe are: the double water shell which cools the probe during measurements and the ceramic protection at the tip of the probe which protects the thermocouple's measuring junction against the influence of the radiation emitted by both the flame and the post-flame gases. Moreover, there is a measuring hole in the ceramic part through which the combustion gases are sucked down into the probe. In the measuring process, the measuring hole is placed in the chosen point of the combustion chamber and then the post-flame gases are sucked out from the area adjacent to the measuring hole. The gases are sucked into the probe using the exhaust gases' pump and are washing the thermocouple's measuring junction. The velocity of flow through the ceramic pipe exceeds 100 m/s and the measuring duration time at the point under consideration is of 200-300 seconds. The measured temperature value is registered on line (every second) in the data recorder. The temperature value for an actual position of the probe is presented as an average for the analyzed time of measurement. To provide the measurements' repeatability under different boundary conditions (i.e. different fuel types or various angles of the fuel injection cone), a precise positioning of the measuring probe in the combustion chamber became necessary. Therefore, the implementation of a traverse system controlled by the microprocessor has been needed. The accuracy of the measuring probe's positioning in the combustion chamber with the implemented traverse system is of 1mm. Due to the system's control software, the on- line observation of the measuring point position became possible and the errors in the probe's positioning became neutralized.

MOLAR FRACTION MEASUREMENTS METHODOLOGY

Measurements of the molar fractions of chemical compounds formed during the combustion process have been carried out using the same suction pyrometer-type as for the temperature measurements. The combustion gases have been transported by the probe (Figure 7), filtering system and then by the coolers compressors to the continuously operating Beckman's analyzers. The instantaneous value of the measured magnitude could be read out during the measurements while the total measurement is registered by the back-up systems.

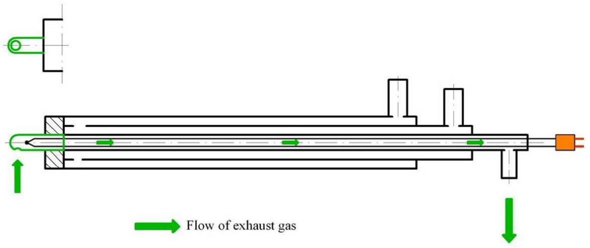

FIGURE 7. Exhaust gases intake probe.

For CO_2 measurement the Beckman 870 analyzer has been used. To obtain the correct results of measurements of the molar fraction of compounds formed in the combustion process, the indications of the analyzers used in tests had to be calibrated.

RESULTS DISCUSSION

The goal of experimental measurements was to find how the spray cone angle is related to the velocity (vertical and tangential), temperature and molar fraction within the combustion chamber. The fuel was the crude oil from the Eastern Europe sources with density 840 kg/m^3. To obtain the regular layout of the measuring points in the considered space, an automatic traversing system was built.

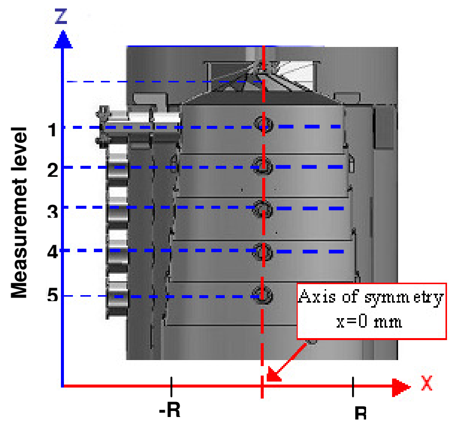

FIGURE 8. Measurement points for velocity, temperature and molar fraction measurements.

In Figure 8, the layout of measuring points for measurement of velocity, temperature and CO_2 content is shown. In velocity measurements, the highly swirled flows are a troublesome subject of experiments due to the strong drag forces resulting from significant differences in density of the seeding particles and to the fuel used in experiments. Regarding the differences in density as well as the inertial drag forces, the size of seeding particles should be as small as possible. However, regarding the LDA operating conditions, a minimum size of the seeding particles on which the scattering of the laser light occurs is required. According to the theory of the scattered light on spherical surfaces presented by Mie, the seeding particle's size should be at least five times the length of the scattered light. For the laser applied in our measurements, the minimum assumed seeding particle's size was 2.5 mm when two coherent light beams of wave length 488 nm (blue) and 514,5 nm (green) have been emitted (Figure 5). Due to the required resistance to high temperatures as the seeding particles can be used MgO, TiO_2 or Al_2O_3. All these materials are of high density of 4 g/cm^3 and the diameter of 2.5 mm. Due to application of the TiO_2 particles, the scattering light in the experiments on the flow can be obtained with combustion up to the temperatures of 2800 K. In the zone where the fuel is injected into the combustion chamber, the molecules existing in the crude oil can be used as the seeding particles. A bit different conditions are at the end of the combustion chamber where the crude oil, evaporated and burned, turns into gas. Better results of measurements have been obtained after having added the seeding particles.

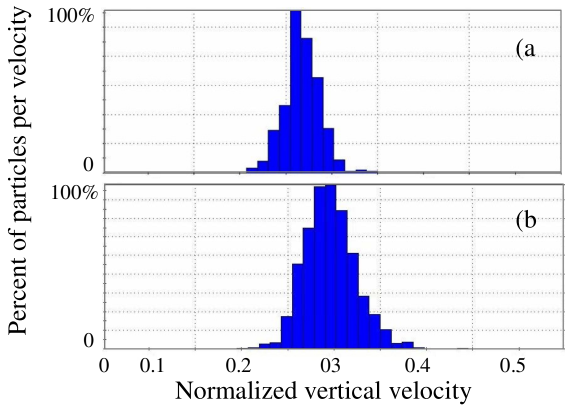

FIGURE 9. Gaussian velocity distribution for one measuring point for measurements: a) without seeding, b) with seeding

The quality of the obtained results can be defined by the width of the Gaussian distribution. In Figure 9, the Gaussian velocity distribution is presented for one measurement point with and without seeding particles. More samples have been gathered during measurements with seeding particles (Figure 9b). The Gaussian graph for measurements with seeding particles (Figure 9b) is more wide comparing to the graph in Figure 9a. Also, the range of the measured velocity has been larger than that during measurements without seeding particles. In Figure 10, the comparison of the vertical velocity measured at the level 5 (see Figure 8) with and without seeding particles is shown. There are appreciable differences in measured velocities. It is very interesting, because the method of measurement with seeding particles and without them can be applied to the qualitative assessment of the amount of deposit in the flame.

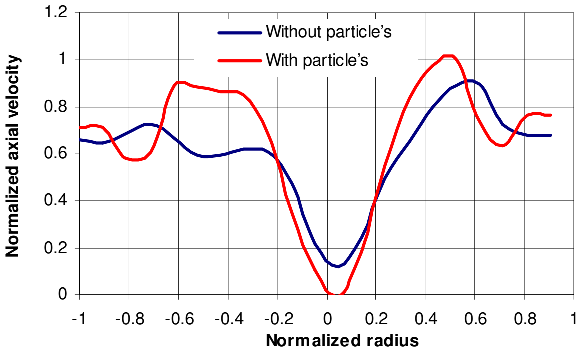

FIGURE 10. Vertical velocity measured with and without seeding particles.

The amount of deposits in the flame affects the deposit's formation on the turbine's blades. Thus, it can be supposed that the higher the difference in the measurements with and without particles, the lower is the amount of contaminations in the flame and probably, the lower the deposit on the turbine's blades. It is a significant observation regarding optimization of the power degradation and minimization of the deposit. In future research, such a method can be used in the parametrical assessment of the quantity and quality of the deposit being developed on the turbine's blades.

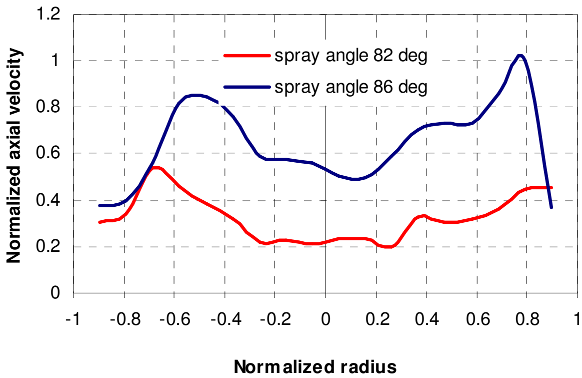

FIGURE 11. Vertical velocity measurements for two different spray cone angles: 82deg and 86deg (window at level 3, ref. Figure 8).

All subsequent measurements reported in this paper have been done using LDA system with seeding particles inside the combustion chamber. The velocity measurements have been carried out in two directions, i.e. vertical and tangential, for different nozzles providing different spray cone angles 82 deg and 86 deg. The vertical velocity's measuring presented in Figure 11 show how the vertical velocity depends on the spray cone angle. Vertical velocity is higher for the spray angle of 86 deg in the entire cross-section of the flame whereas the tangential velocity (Figure 12) remains on the same level. It means the tangential velocity does not depend on the spray cone angle.

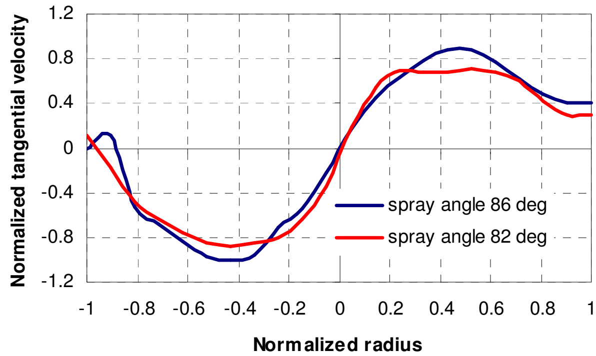

FIGURE 12. Tangential velocity measurements for two different spray cone angles: 82 deg and 86 deg (window at level 5, ref. Figure 8).

Having analyzed the temperature distribution (Figure 13) measured at level 1 (ref. Figure 8), it can be noted that the maximum flame temperature for the nozzle with the spray cone angle of 52 deg is lower by about 12% than the flame temperature measured for the nozzle with the spray cone angle 86 deg. The small spray angle means the different atomization and vaporization processes. The temperature distribution shown in Figure 13 has been measured very close to the injection nozzle; the fuel drops are larger and the vaporization time is also longer. In turn, the temperature close to the injection nozzle is lower.

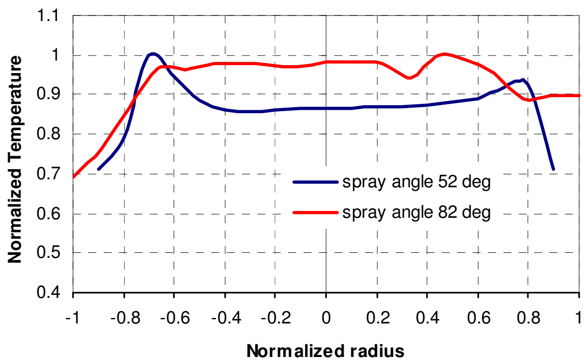

FIGURE 13. Temperature distribution across combustion chamber (level 1, ref. Figure 8) for two different spray angles: 52 deg and 86 deg

Half way into the combustion chamber, the maximum value of the flame temperature for two injection nozzles is on a similar level. However, as shown in Figure 14, the cross-section temperature distribution is different.

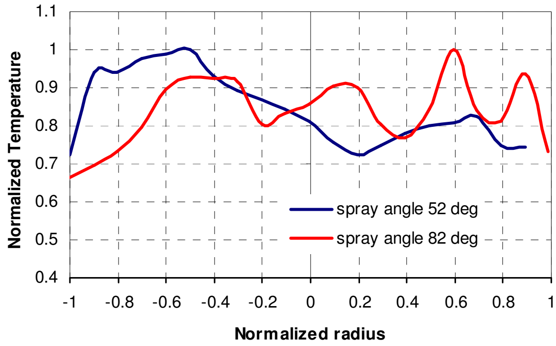

FIGURE 14. Temperature distribution across combustion chamber (level 3, ref. Fig. 8) for two different spray angles: 52 deg and 86 deg.

Differences in the temperature distribution result from the various spray cone angles. The CO_2 distribution is similar (Figure 15). For the spray cone angle of 52 deg measured at the level 2 (ref. Figure 8), the CO_2 distribution is at nearly the same level across the combustion chamber. However, for the spray cone angle of 82 deg, the CO_2 level drops nearby the combustor's walls. The maximum value of CO_2 for the angle of 82 deg is much higher than that for the angle of 52 deg. Therefore, the conclusion can be drawn that the CO_2 level depends on the spray cone angle. The smaller the spray cone angle, the lower the CO_2 level. However, to confirm such a relationship, additional parametric investigations for different geometries and different combustion parameters are necessary.

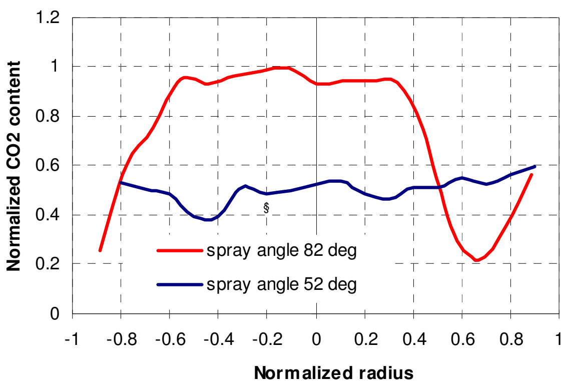

FIGURE 15. CO_2 distribution across the combustion chamber (level 2, ref. Figure 8) for two different spray angles: 52 deg and 82 deg.

CONCLUSION

In this paper, the results of investigations of the crude oil combustion have been presented. The experiments have been carried out on the test rig built on the basis of the Alstom top mounted silo combustor. The combustion chamber has been equipped with the measuring windows for measurements of velocity profiles, temperature and molar fraction. The way of scaling the geometry and the combustion reaction have been described. Distribution of two components of the velocity vector: along the combustor's axis (vertical component) and on the combustor's perimeter (tangential component) are reported. Moreover, the temperature distribution and the CO_2 distribution within the combustion chamber have been investigated. The most significant conclusion drawn from the reported experiments is that the velocity measurements (LDA) can be used to the qualitative assessment of the amount of deposit in the flame. Further investigations on the crude oil combustion shall be focused to analyze the reaction of the deposit's formation on the blades depending on the various combustion parameters.

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