DEVELOPMENT OF A LDV PROBE FOR VELOCITY MEASUREMENTS IN A 600MW PULVERIZED COAL POWER PLANT

by

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ABSTRACT

A complete understanding of the phenomena involved in combustion processes is necessary in order to select the more appropriate physical models for designing and optimizing advanced industrial combustion systems. These models are integrated into numerical calculations for the prediction of the combustion efficiency enhancement and the pollutant emission reduction, particularly for NOx and SOx. To validate such a tridimensional (3D) numerical code, an experimental program was conducted in order to characterize the aerothermochemistry of the flow in a 600MWe pulverized coal (PC) power plant. A Laser Doppler Velocimetry (LDV) probe was specially designed and adapted to measurements of the three velocity components in a large scale industrial situation. Preliminary tests were performed at the laboratory to evaluate and optimize the validity of the optical diagnostic technique. Then, the aerodynamic field of the flow was determined in the full scale PC burner flame. The data processing shows the validity and the applicability of the optical LDV technique to provide information on the coal combustion behavior. The available data can be used to validate three dimensional numerical results.

1. OBJECTIVES

The development of numerical tools becomes more and more necessary to the engineer both to design new generations of industrial burners, furnaces, boilers or power plants, and to optimize their operating conditions (mean global equivalence ratio, burner configuration, fuel origin and type). The numerical codes should integrate physical models taking into account all phenomena involved in large scale multiphase turbulent reactive flows: fluid mechanics, turbulent combustion, two-phase combustion efficiency, flame stabilization processes, energy transfer to the heat exchangers, chemical mechanisms for coal combustion and pollutant formation such as carbon monoxide CO, nitrogen and sulfur oxides (NOx, SOx.) The results using global models based on energy and mass balances between the fluxes going in and out of the combustion system are generally insufficient. So, the numerical approach should incorporate the coal characteristics in order to optimize the boiler, the burner design and the working parameters.

The present work contributes to this objective by an experimental validation of calculations applied to advanced pulverized coal (PC) power plants. Measurements of velocity, turbulence, temperature, coal granulometry, heat radiation in a full scale combustion chamber, were conducted to select and adapt available models for the reactive system modeling (coal type, granulometry and composition, volatilization characteristics) and to validate the obtained numerical predictions. These experimental results show the location of the reaction zone and the shear stress regions at the burner exit (boundary condition and flame stabilization processes). Then, active or passive controls can be proposed to avoid large residence times of the combustion products favorable to the production of thermal nitrogen oxides. An enhancement of distribution of the heat release can also optimize the heat exchanges. To understand a reactive flow, the velocity field is one of the most important characteristics.

For some years, a new laser diagnostic technique has been available*: the Particle Image Velocimetry (PIV).* This method, based on image processing of the light scattered by particles moving in a laser sheet, is presently adapted at the laboratory for the characterization of large scale combusting flame. Though this diagnostic provides an interesting alternative to classical LDV, some implantation limitations remain to solve: the size of the explored region is limited to several hundred of square centimeters, the flame radiation perturbs the image increasing the signal noise, the relative positions of the laser sheet and camera are difficult to adapt in a furnace with limited access without a fiber optic system. Due to the restrictions of the PIV method to such an environment, a more classical technique was chosen: *the Laser Doppler Velocimetry (LDV)*.

The objective of the present study will be to scientifically design, develop, optimize, and use a new specific probe for velocity and turbulence measurements in the burner zone of a full scale pulverized coal power plant. The Laser Doppler Velocimetry (LDV) technique is adapted to measurements in large scale flame by introducing the LDV optical head into the combustion chamber. This intrusive optical LDV method, applied for many years in industrial sites, is here optimized to a very large scale system with specific PC flame considerations and for flow characterization in horizontal plane.

The LDV experimental results are completed by a thermochemical study of the flow: temperature field (suction pyrometer), coal particle samplings (granulometry distribution by laser granulometer), stable chemical specie concentrations (sonic nozzle sampling and on line gas analysis). From the obtained numerical results, both the combustion chamber geometry, burner characteristics and settings, and the operating parameters can be optimized for each given flame regime (fuel type and properties, thermal output power).

2. GENERALITIES ON THE VELOCIMETRY TECHNIQUE

Since the arrival of the LDV diagnostic in the seventies, numerous authors sought to measure flow velocities in industrial flames (Baker, 1974). The first truly usable results were obtained in a natural gas flame by Barlow (1982) and in the case of a pulverized coal flame by Thiele (1986), Probstle (1989), Abbot (1989), Most (1989, 1991, 1991) and Weber (1994). During this period, other sets of measurements were conducted in semi-industrial furnaces, burners and boilers.

For large scale environments, the application of the LDV technique entails specific limitations. Beam steering due to refractive index gradients causes problems with alignment and coincidence of the beams in the measurement control volume. Beam fluctuations induced by temperature gradients (refractive index gradients) lead to a decrease of the data rate depending on the position in furnace inducing a long measurement time. With a beam length of 1 meter between the furnace wall and the measurement volume, the beams are crossing each other probably less than one percent of the time (Abbott, 1989). Moreover, a relative medium opacity results from a heavy solid particle concentration in the two phase flows. The most common solution to these limitations is to decrease the distance of the traveling beams in the hot flow before crossing. The optic fibers have provided a new degree of flexibility not available with conventional LDV systems. They allow, in an industrial site, easy translation of the LDV probe from the laser source to the measurement volume.

Water cooled probes are designed to thermally protect the miniature LDV heads. To maximize the reduction both of the outer probe diameter, and of the LDV head distance from the measuring volume (MV), the first systems used the smallest LDV heads. The short distance between the MV and the probe tip distance (8 to 16cm) was always suspected to perturb the measurements. Our group (Most et al. (1989, 1991, 1991)) has developed a system including a 30mm diameter (ϕ) optical LDV head in a 3m long, 70mm diameter water cooled jacket to perform measurements both in a 3MW pulverized coal flame, a 1MW natural gas pool fire, and in an industrial cement precalciner (Most, 1991). The LDV probe front end was thermally protected by two silica windows separated by a film of water allowing the optical measurements. This first version of water cooled probe had a focal length of 16 cm leading to a measurement volume position of 12cm away from the probe tip. The nitrogen sweeping on the frontal window avoids coal particle deposition. Ereaut and Gover (1991) used a ϕ 25mm probe enclosed in a 70mm outside diameter, 5.2 m long water-cooled jacket to perform measurements in a coal-fired power station. The probe front end was air cooled with a flow introduced at relative pressures of 0.21 to 1.4 bar, depending on the cooling needs. This air flow was also used to prevent window contamination. The last pioneers for LDV measurements in large scale combusting flows were Dugué et al. (1994) who designed another probe type. Although the intrusive LDV technique is currently effective, some problems should be again solved. The probe perturbation should be evaluated for each application, the spontaneous flame emission should not introduce noise susceptible to damage the Doppler signal, the particles acting as scattering centers should follow the fluctuations of the reactive flow. The results should be directly used to select physical models and validate the numerical calculations.

The objective of the present paper will be, at first, to describe the new developed probe and the specific problems related to the probe cooling, the optical access cleaning, the effects of the volumetric probe intrusiveness and the validity of a particle size discrimination method based on signal amplitude (visibility method). The second part of the work will be dedicated to the feasibility and the accuracy of the method by in-situ measurements on the large scale industrial conditions.

3. THE PULVERIZED COAL 600MW POWER PLANT

The velocity measurements were conducted in the “Electricité de France” power station Q600 of Cordemais (West of France). The combustion chamber size is 16x16m and 100m height, the electrical output power is 600MWe (1850MW thermal power). Three sets each consisting of three pulverized coal (P.C.) burners are located on each chamber corner (Figure 1). Each burner is composed of a primary air loaded with pulverized coal particles (about 12 t/hr at maximum load). Secondary air is introduced into the furnace above and under each PC jet. The angle of the two-phase PC jet with the furnace wall is equal to 39°. The air excess is about 1.2.

The velocity measurements were executed close to the PC central burner exit. Three holes (16cm diameter) were performed in the furnace wall, at the 33m level of the combustion chamber, to allow probe introduction (2.25, 3.72, 6.37m from the burner exit corner). The LDV probe reached the PC air jet up to 5.m away from the furnace wall.

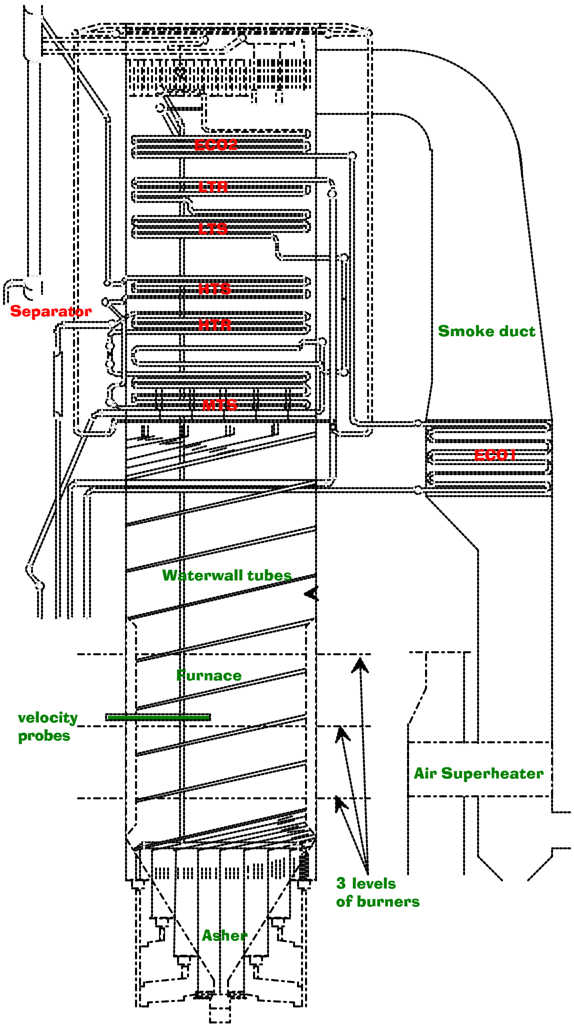

Figure 1: Scheme of the combustion system

4. THE LDV TECHNIQUE AND WATER-COOLED PROBE DESIGN

4.1. <u>The size and velocity information for coal particles</u>

The information on the coal particles size is a necessity for the understanding of two phase combustion systems and for modeling coal volatilization, particle burning and heat release. In some conditions, using a specific process of the Doppler signal, the particle diameter can be deduced from the measurement of the phase shifting between two Doppler signals collected from two different observation angles (Phase Doppler Granulometry technique). This well known method is based on the Mie scattering of particles. It requires a light scattering detection out-off optical axis. This last restriction limits the use of the method to a system included in a compact probe. Nevertheless, recently, an optical probe was designed and adapted to the study of complex industrial systems (Blondel et al, 1998; Bultynck, 1998). Designed for measurements in diesel or spark ignition engines, this optical arrangement has a short focal length f. Unfortunately this optical system assembly cannot be resized for a much larger focal length and has not been retained. This last restriction can probably be avoided by developing another specific optical configuration by positioning, for example, the LDV emitting optic and photodetectors on the same probe (see Figure 2). This last adaptation necessitates the design of a small receiving optical system not commercially available. Unfortunately, the phase Doppler Granulometry method is still only adapted for diameter measurements of spherical scattering centers which is not at all the case for coal particles. Many research workers are trying to extend the phase Doppler method to non-spherical particles Top Hat Method (based on visibility), Dual Mode Phase Doppler Granulometry (Tropea, 1996)), or cylindrical particles (Mignon et al., 1996). These adaptations cannot be directly used in the present industrial situation.

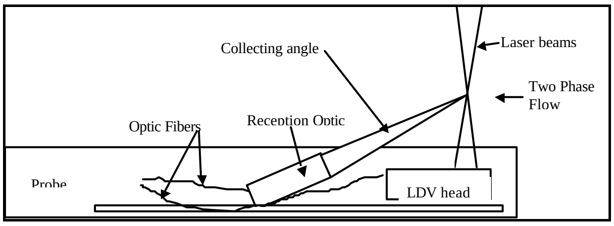

Figure 2: Scheme of the Intrusive Phase Doppler Granulometer

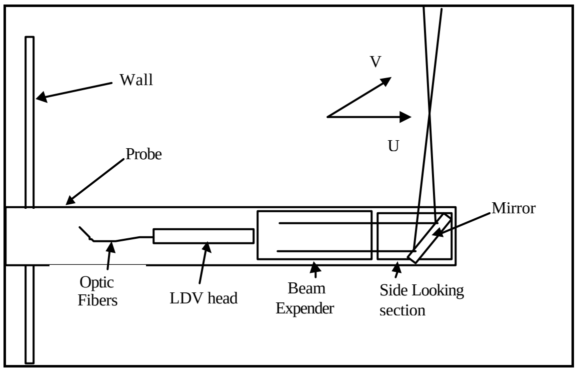

Figure 3. LDV System with Beam Expender and Side Looking Section

Due to the experimental difficulties to obtain the size, the shape and the velocity information simultaneously for non spherical coal particles, the basic Laser Doppler Anemometry diagnostic technique will be used after small adaptations for the aerodynamic characterization of the Cordemais Q600 PC power plant.

The described intrusive LDV technique requires the introduction of a LDV head inside the reactive zone close to the measuring volume (MV) location. That necessitates the design of a water-cooled probe (thermal and mechanical studies) equipped with clean optical access (shield between flame and optic elements, no particles contamination of the window).

4.2. The LDV System

In this study, a complete mapping of the aerodynamic field, close to the pulverized coal burner exit, was required for the combusting flow characterization. The large size of the furnace and the complexity of the studied flow necessitable the knowledge of the three velocity component properties (3D mean and fluctuating velocity values (turbulent energy), turbulent length scales, and spectral analysis if possible). Previous probes (Most (1989, 1991) were not directly adapted for such a 3D velocity determination using a 2D LDV system. In fact, this former system led to the measurement of the velocity components in a plane perpendicular to the optical axis of the LDV head. The third velocity component remained unattainable. This optical configuration has been developed.

The solution consists of developing a LDV probe for measuring the velocity components in a plane parallel to the probe axis, and obtaining the third component by velocity recombination after a probe rotation. A side looking element is used to focus the laser beams laterally after reflection on a mirror (Figure 3). This configuration requires a LDV focal length f larger than in the previous configurations (f was equal to 0.16m) in order to avoid a reduction of the light amplitude scattered by particles. The main part of the optical head is composed of a DANTEC LDV probe (0.014m diameter - ref: DANTEC 60X17). The initial distance (0.008m) between each pair of beams is expended to 0.032 m by means of a beam expender (expender ratio: 4). The focal length f is increased from 0.16m to 0.30m keeping constant both the beam angle (6.2°) to conserve the angle between the laser beams (theoretical MV size: diameter: 30µm, length: 0.00037m, ellipsoidal MV volume:$1.8.10^{-13}$ m^3) and the scattered light collecting angle. Then, the light intensity at the MV is strongly intensified allowing again the detection of smaller particles. The distance between the MV and the probe body is equal to 0.20m.

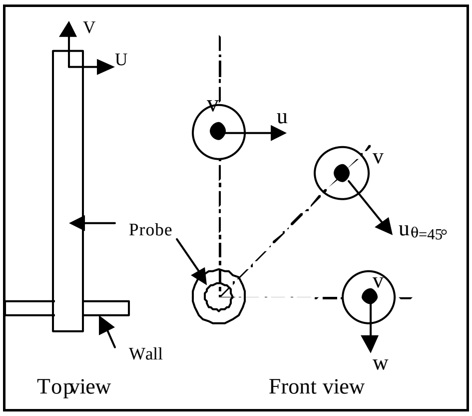

Figure 4: Measured velocity components as probe angle. v is the velocity component parallel to the probe axis

By a probe rotation of 90°, the measured velocity component perpendicular to the probe axis changes from v to w velocity components, but, obviously, during this operation, the location of the MV is modified (Figure 4). For a probe rotation of 45° or 90°, the displacement of the MV is respectively about 0.15m to 0.29cm, which is small in comparison with the furnace scale. Assuming that the flow length scale is greater than the MV displacement, the three velocity components can be easily calculated from the knowledge of two velocity components measured at these two different positions. It is important to verify that the measurements are not performed in the probe wake.

The LDV head orientation is precisely adjusted inside the probe so that the fringe grid is perpendicular to the wall (coordinate axis parallel to wall directions).

The scattered light by particles is collected in backscattering mode with another optic fiber and detected by photomultipliers. The Doppler signal is processed by two DANTEC Spectrum Analyzers (BSA) operating on the two colors; a minicomputer has in charge the data save and the statistical analysis.

4.3. <u>The Water-Cooled Probe</u>

The water-cooled probe (Figure 5) was designed by CERCHAR, to operate in an environment at a mean temperature around 1500°C. It should maintain the optical system at a maximum temperature of 50°C. A water temperature over 70°C can induce local water vaporization capable of emptying the probe and leading to the destruction of the LDV head. A thermal calculation was made to determine the water mass flow rate and operating pressure. A water maximum temperature increase of 10°C through the probe was obtained for an admission pressure of 7 bars.

The total length of the stainless steel probe is 6.5m for respectively outer and inner diameters of 114mm and 64mm, in order to accept a 60mm diameter side looking section and beam expender. The total weight of the probe including the cooling water is 133kg. The maximum operating bending is 8 mm for an overhang at 4m, so that, the shear stress and the tensor at the fulcrum are respected to satisfy the reversibility of the elasticity conditions.

To lock the heat radiant and convective flux through the optical window, two parallel silica panes, separated by a 0.5mm film of desilicated and carbonate free water, are used. A numerical simulation was made to evaluate the heat exchanges and to size the window. The absorption of the system both for the emitting laser beams and for particle scattered light were found inferior to 3% of the incident light intensity.

To get a non-noisy Doppler signal, the optical path through the probe silica window, should remain perfectly clean without any ash or coal particles contamination, deterioration, or mineral deposition between the two window panes. A flow of nitrogen inside the probe avoids water condensation upon the optical elements. Besides, a gas curtain on the window was numerically studied to obtain an optimized window protection both from heat transfer and particle aggression (the silica window is damaged by particle with temperature over 300°C).

4.4. <u>Numerical modeling of the probe window protection</u>

The aerodynamics of the sweeping fluid are predicted and optimized in the vicinity of the window. The physical modeling assumes a steady state non-reactive laminar flow. The radiant and viscous heat exchanges and the buoyancy effects are not taken into account. The molecular diffusion properties are modeled by Newton, Fourier and Fick laws respectively for momentum, energy and species conservative equations. The system of equations is solved by a finite volume method. The algorithm is SIMPLE using a first order linearization scheme (FLUENT commercial code). The grid is body-fitted with 50 nodes on each curvilinear direction corresponding to 2401 finite volumes. Several probe geometry, operating conditions and sweeping gases influence were modeled. An hemispheric boundary condition (giving static pressure) is defined 32.5 10^{-3}m away from the window center. The window temperature is assumed constant at 300K and the environment temperature at 1500K.

Argon	μ (Pa.s)	k ($W.m^{-1}.K^{-1}$)	c_p ($J.kg^{-1}.K^{-1}$)
300 K	2.125 10^{-5}	1.58 10^{-2}	5.20 10^{2}
1000 K	6.107 10^{-5}	4.77 10^{-2}	5.20 10^{2}
1500 K	7.396 10^{-5}	5.77 10^{-2}	5.20 10^{2}

Air	μ (Pa.s)	k ($W.m^{-1}.K^{-1}$)	c_p ($J.kg^{-1}.K^{-1}$)
300 K	1.789 10^{-5}	2.42 10^{-2}	1.01 10^{3}
1000 K	4.440 10^{-5}	7.46 10^{-2}	1.13 10^{3}
1500 K	5.950 10^{-5}	1.07 10^{-2}	1.22 10^{3}

Table 1: Air and Argon physical properties

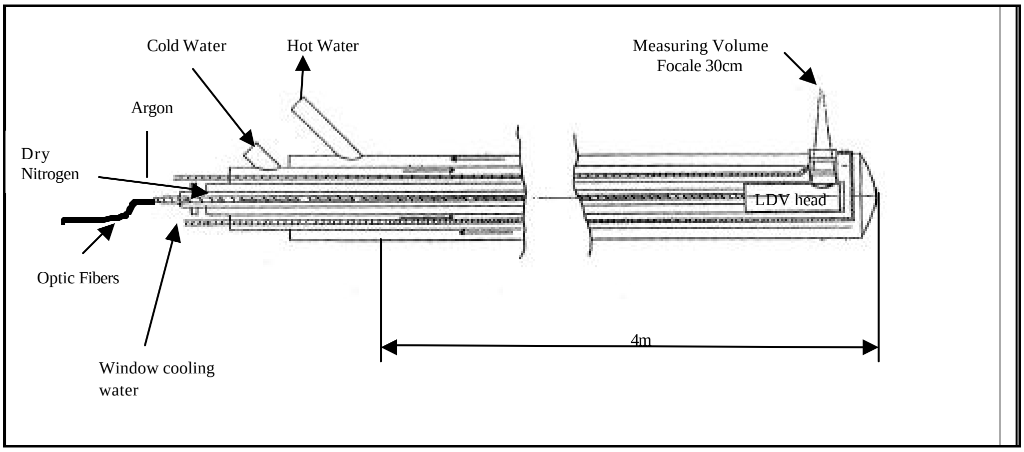

Figure 5. Scheme of the water cooled LDV probe

To optimize the gas sweeping, various gases were considered. Air and Argon properties are compared in table 1, where μ is the dynamic viscosity, k the thermal conductivity, and Cp the heat capacity. From these physical properties, Argon seems to be the more suitable as a purge flow. For a maximum given gas mass flow rate of $3m^3$/hr, the influence of the gas type, injection slot orientation, and shape of the window system tip was predicted.

The first configuration studied is close to those of Most or Dugué. The purge flow is axi-symmetrical (Figure 6 left) with Argon injection through a circular slot of 0.5mm height all around the window. The Argon injection velocity is 11m/s corresponding to $3m^3$/hr. The numerical results quantify the effect of the Argon gas injection on sweeping efficiency. A central axi-symmetrical jet is formed, centered on the system axis (Figure 7). For a gas injection parallel to the pane (θ=0°), a recirculation zone is susceptible to be formed along the pane trapping particles. At the window center, the gas is at rest. Only the inertia of the jet protects to silica. For a 45° injection initial angle (θ=45°) (Figure 8), the Argon flow seems to sweep the pane more efficiently. The coal particles are deflected by the mean jet velocity but, in some conditions, the momentum may be not sufficient to avoid contamination of coal particles moving at 40m/s. Moreover, an increase of the sweeping gas velocity, could perturb the flow to be measured at the Measuring Volume 0.20m ahead the probe tip.

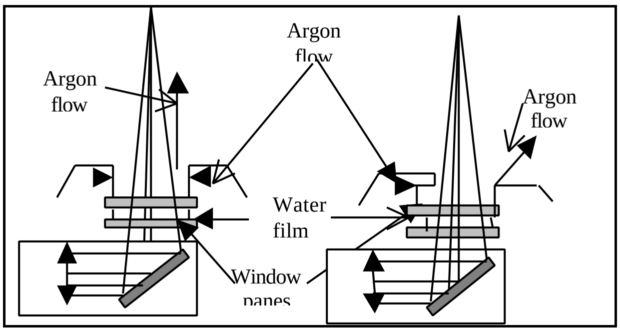

Figure 6. Left side: axi-symmetrical Argon injection
Right side: One side Injection

In order to increase the wall shear stress, a second Argon blowing configuration was tested. Argon is injected with a θ angle of 45° only along one third of the circumference of the window (Figure 6 right) to form a gas curtain on the pane (two dimensional configuration). The Argon mass flow rate is always kept constant at $3m^3$/hr which corresponds to a higher injection velocity of 30m/s through the 0.5mm height slot. The numerical simulation (Figure 9) shows the good efficiency of the gas curtain. Despite a lower momemtum of purge jet, the gas induces an efficient sweeping flow entraining the particles out of the window vicinity, and avoids their deposition.

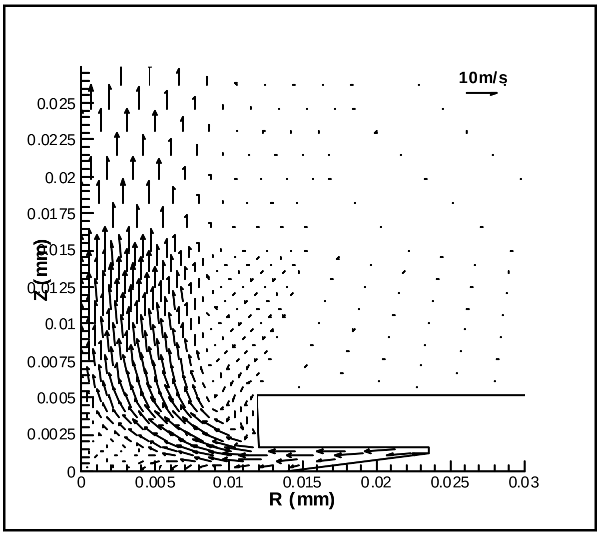

Figure 7. Velocity vectors for Axisymmetrical Argon injection at θ=0°- velocity: 11m/s

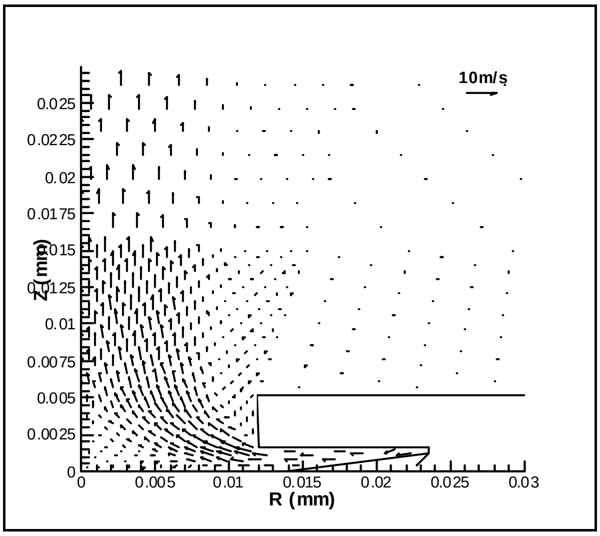

Figure 8. Velocity vectors for Axisymmetrical Argon injection at θ=45°- velocity: 11m/s

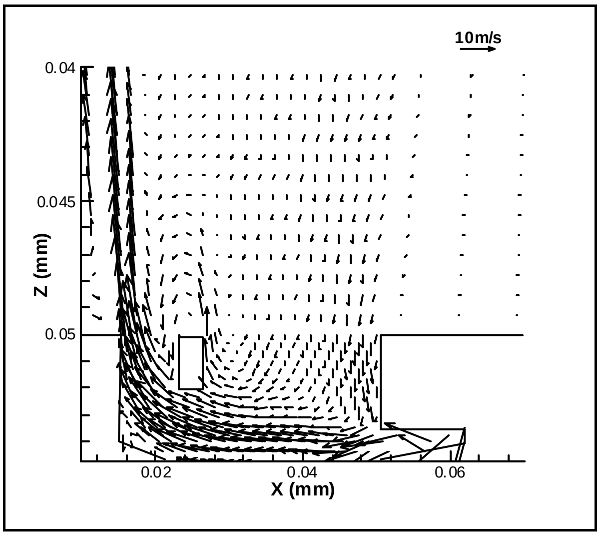

Figure 9. Velocity vectors for on-side Argon injection at θ=45° velocity: 30m/s

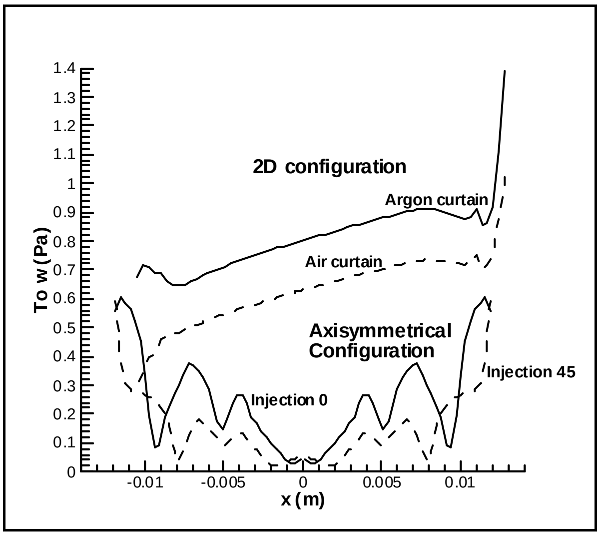

Figure 10. Wall shear stress along the window for same gas mass flow rates (Argon or air)

These qualitative results are corroborated by the wall shear stress representation along the window pane (Figure 10). For the three calculated probe tips, the influence of the angle of injection of the gas is not very clear due to the high degree of containment. For an axi-symmetrical injection, the shear stress falls to zero at the window center while for the two dimensional configuration, the shear stress decreases continuously along the pane, but is always greater than those of the first configuration. The last result confirms the better efficiency of Argon for the sweeping. In conclusion, an asymmetrical Argon injection enhances the sweeping effect without any perturbation of the flow at the measuring volume. The coal particles are not decelerated at the window proximity, but deflected off the pane. This technique will be preferred in highly coal loaded zones.

During tests, to control the efficiency of the probe-cooling, thermocouples measure the water intake and outlet temperatures, the probe tip and temperatures of the optic. Rotameters are used to determine the water, nitrogen and Argon mass flow rates. To move the heavy water-cooled probe into and out the furnace, a specific probe wagon was designed and built. The maximum MV position uncertainty from the furnace wall is evaluated at 5 mm.

4.5. The ash and coal particle behavior

Laser Doppler Velocimetry technique measures the velocity of the flow particles, and not the fluid velocity itself. For highly turbulent flows, particles cannot be considered as following the flow. Their response may not be instantaneous so that a bias, linked to particle lag problem and a low frequency cut-off of the turbulent spectrum, may appear. Therefore the particle movement should be studied to evaluate the slipping between the fluid and particle velocities.

To evaluate the orders of magnitude of the forces acting on a particle, a good approximation is to consider that the product of the particle mass by its acceleration is equal to the Stokes term (viscous drag). This simplification supposes that the influence of the pressure gradient, the inertia effects, the Basset force (history of the particle accelerations), and the external forces effects, are all negligible. The equation of a particle is:

$$\frac{d\vec{V}_p}{dt} = k\left(\vec{V}_f - \vec{V}_p\right) \quad \text{with} \qquad k = \frac{18\mu}{\rho_p D_p^2} = \frac{1}{\tau_p}$$

$\vec{V}_f$ and $\vec{V}_p$ are respectively the fluid and particle velocity, D_p the particle diameter, ρ_p the particle density, k the Stokes coefficient and τ_p the particle time constant. If we assume a sinusoidal evolution of the reactive flow velocity $U_{gas} \equiv \overline{U}\, e^{i\varpi t}$, the particle velocity will be $U_{part} \equiv \frac{\overline{U}}{1 + i\varpi\tau_p} e^{i\varpi t}$ (Sanquer, 1998). The limitation of the slipping velocity between particle and gas is less than 1%, if we have: $(\varpi\tau_p)^2 < 0.01$. Table 2 gives the relationships between the particle diameter and the cut-off frequency $f_c=\varpi/2\pi$.

These results show that only particles with a diameter inferior to 5µm can follow flow fluctuation frequency up to 4.5kHz, this threshold is considered as sufficient in the present configuration. Bigger particles are susceptible to provide instantaneous velocities non representative of the flow motion and their Doppler signal should be eliminated from the statistic analysis.

D_p (µm)	1	2	5	10	20	50
k (s^{-1})	$9.\ 10^5$	225000	36000	9000	2250	360
τ (s)	$1.11\ 10^{-6}$	$4.4\ 10^{-6}$	$2.77\ 10^{-4}$	$1.11\ 10^{-4}$	$4.4\ 10^{-4}$	$2.77\ 10^{-3}$
f_c	9kHz	4.5kHz	1.8kHz	900Hz	450Hz	180Hz

Table 2: Particle behavior

The measured particle diameter distributions for 5 locations inside the studied region are reported in Figure 11. The maximum particle mass is observed for particle diameter around 25µm while a simple data process (Figure 12) shows a rapid fall down of the particles number for diameters over 1.5µm. In conclusion, if the optical LDV system is able to detect micrometer ash or coal particles, the detected scattering light from diameter particles over 5µm will be statistically negligible and will not alter the velocities statistical analysis.

From the above observations, two conclusions can be deduced:

- particles with diameter less than 5µm can follow the flow fluctuations with a maximum frequency of 1.8kHz, that is supposed reasonable compared with the large scales of the flow;
- 99.5% of the particles have a diameter less that 1µm, 89% of the other ones have a diameter range included between 1 to 5µm.

These results clearly show that, if one micrometer diameter scattering centers can be detected and processed by the LDV system, a maximum of 11% of the acquired Doppler signals are scattered by coal or ash particles with diameter greater than 5µm. This last percentage decreases exponentially with the particle size. To reach these criteria, tests are conducted to determine the setting of the LDV system (light intensity at the MV, gain of the photomultipliers, LDV processors setting) leading to detection of 1µm particle. As it is impossible to get, on the one hand, a dispersing coal powder, and on the other hand, spherical coal particles, the LDV detection threshold has been determined using water calibrated droplets. To compare respectively the scattered light intensities from water droplets and coal particles (supposed spherical), a Mie scattering calculation is made. Figure 13 shows an equivalent scattered light intensity by both water and coal for diameter up to 1.7μm. For larger particles, water becomes a better scattering center. Then, to adjust the operating setting, the detection threshold is determined with one micrometer calibrated water droplets (in the real measurement conditions: silica windows and water film).

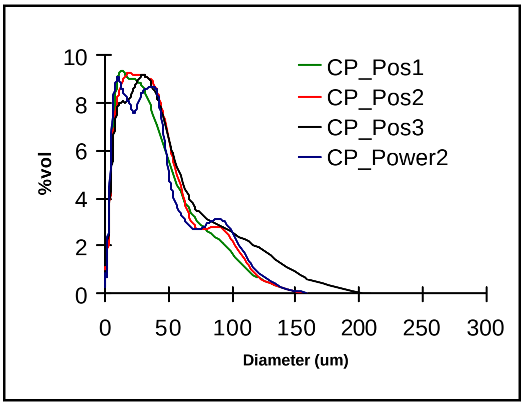

Figure 11. Particle distribution in volume for different PC jet locations.

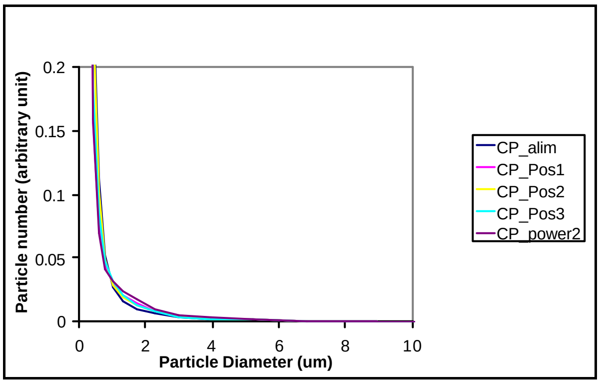

Figure 12. Particle distribution in number for different PC jet locations.

As the complex index m of coal particles (function of the coal temperature and origin) is unknown, previous calculations (Figure 13) were made for complex indexes values included in the following range:

$$m = 1.5\,(\pm 0.2) + i \quad 0.6\,(\pm 0.2)$$

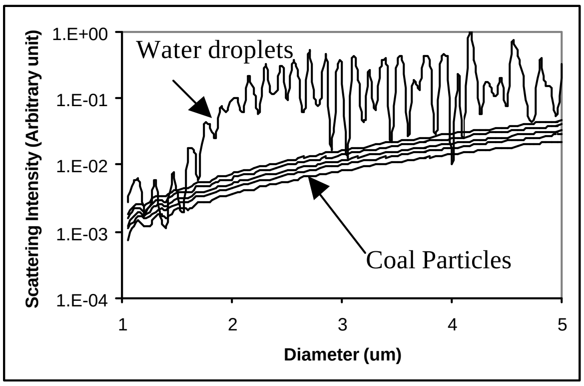

Figure 13: Mie scattering intensity for water droplets and spherical coal particles.

5. VELOCITY DATA OBTAINED IN THE Q600 CORDEMAIS Electricité de France POWER PLANT

5.1. Data Processing

From the LDV velocity data obtained during the measurement campaign in Cordemais Q600 power plant, histograms, velocity time evolutions, mean and fluctuating velocities of particles were determined from a minimum of 3096 instantaneous validated Doppler bursts (instantaneous velocities). Sets of measurements were performed with two different orientations of the LDV optical axis (component measurements in the horizontal plane (0°) and with a 45° rotation). Other sets of measurements were accomplished for 90° rotation and 135° but not processed because they are perturbed by the probe wake while the mean flow was slightly decreased. Measurements for probe orientation at 180° allow the determination of u and v components, 40cm under the 0° orientation. From a change of the coordinate axis system, the three velocity components were easily deduced from 2D measurements at two probe orientation angles. This operating procedure supposed that the MV shifting (around 0.15m) can be neglected in comparison with the furnace scale. For numerical code validation, this assumption is not necessary. In fact, the modeler analytically calculates the theoretical velocity components at the MV by interpolation and projection of his results on the adapted coordinate system. Considering the very high cost of making numerous orifices in the furnace wall, the technique provides optimal information. For high data rates, the turbulent length scales can be evaluated from a spectral analysis of the Doppler signal not presented in the present study.

5.2. Probe behavior

The probe design was found well adapted to such measurements. The temperature increase between intake and outlet cooling water flow was always less than 20° certifying a good heat exchange between the probe skin and the cooling water. The delay for the first LDV measurement from the probe introduction time into the furnace was very short (around 20s). The first tests have shown that the main problem was the efficiency of the Argon sweeping along the optical window. From theoretical calculations, the two Argon jets with 45° injection angle seemed to be the most efficient. Nevertheless, for some MV locations in the highly loaded zone, the window contamination was rapid (several minutes), and many window cleanings were necessary, which increased the measurement time.

5.3. Velocity Histogram

One of the best means of validating LDV measurements is the velocity histogram analysis: the observation of a pseudo-normal velocity distribution generally indicates the validity of the turbulence spectrum. Many of the obtained histograms show one peak (Figure 14) centered on the mean velocity U_m. For the same data set, a typical velocity evolution is shown in Figure 15. The high Doppler data rate is sufficient to follow the turbulent eddy frequency. A lower frequency velocity oscillation (≈150Hz at this location) is superposed on the turbulent fluctuations. To get a representative statistical velocity and turbulence profile ($Um \approx 35m/s\,;\,\overline{u'^2} \approx 37m^2/s^2$), the sampling time should be much larger than this characteristic time (≈7.10^{-3}s). Otherwise, the velocity histogram should present two peaks characteristic of a sampling during a shorter time. At this MV location, the larger turbulent length scale is found around 0.25m. These results, time and length turbulent scales, are both very important, to validate reactive flow calculations using a Large Eddy Simulation model, and to determine the minimum acquisition time to get a representative statistic velocity. Moreover, it can be observed that the MV-probe tip distance is probably sufficient to limit any probe perturbation at the MV.

The particle density in the flow has been sufficiently high to resolve the turbulent motion, and small enough, to eliminate the unfavorable cases where two particles are simultaneously present in the MV. A typical data rate of 12kHz (particle number through the MV per second) is observed for mean velocity around 20m/s that corresponds to a volumetric fraction f_v around 4.5 10^{-7} (if all particles are supposed micrometrical and spherical). It can be deduced that, firstly the particle concentration is not too high (a highly loaded flow is considered for a f_v value over 10^{-3}), secondly less than one particle is present at a time in the MV (a mean value of 0.15 micrometrical particles).

The above result confirms the assumptions that the LDV system can detect micrometer particles, and, that the majority of particles are under 5μm micrometer in diameter. An additional information, given by the LDV processor, corroborates the previous observations. The DANTEC Burst Spectrum Analyzers give the opportunity to electronically eliminate large particles by two ways: limiting the photomultiplier current to a threshold level, and applying the visibility criteria (a Doppler signal is validated as soon as the pedestal – envelop ratio is over a given value). The invariability of the velocity data for different LDV processor setting confirms the previous conclusions.
Since the flow seeding by ash or coal particles is not a priori homogeneous, a statistical bias can appear. Meyers (1984) has proposed a criteria based on the calculation of the correlation coefficient C between the measured velocity and the data rate:

$$C = \frac{\langle (u_i - U_m)(\Delta t_i - \Delta t_m) \rangle}{\sigma_u \sigma_{\Delta t}}$$

where u_i and U_m are the instantaneous and mean velocities, Δt, the instantaneous data rate, and σ the corresponding root mean squares of the fluctuation. At all locations in the studied region, the C coefficients were found to be randomly distributed with small values, less than ±0.1, except close to the coal jet boundary where C reaches 0.3. For such C values, Meyers (1984) concluded that, in general, classical velocity bias was not present and that the dependence of the data rate upon velocity was small. Although this dependence was small, the "BSA dead time" facility was used (the LDV processor took into account only the first validated Doppler signal on a given time interval) to resolve the low frequency flow fluctuation and to uncorrelate velocity and particle arrival time. The used mean dead time value was around 0.1ms.

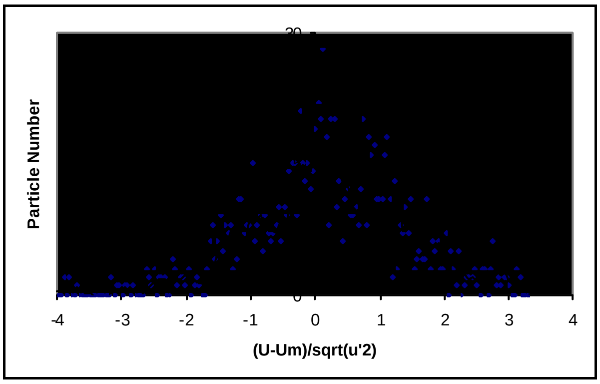

Figure 14: Velocity histogram

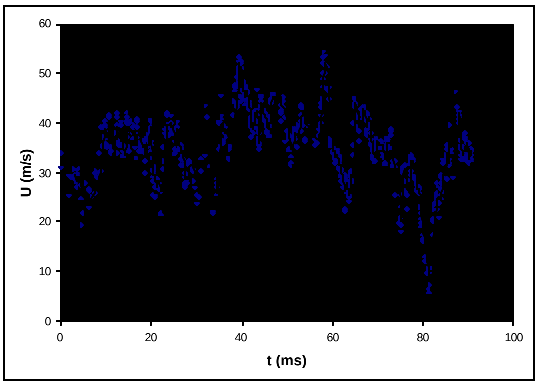

Figure 15: Typical Velocity Evolution

5.4. Representative Velocity Results

As an example of the obtained results, table 3 reports a small part of the 3D velocity components due to the data privacy. The conclusion on these observations will not be developed, but it can be clearly observed that the PC jet expansion in the mean flow goes down. These first results are in good agreement with numerical predictions.

Y(m)	Um	Vm	Wm	u’2	v’2
0.4	14.5	-3.01	-25.2	5.46	5.98
0.8	14.9	-6.9	-24.7	5.63	8.8
1.2	23.3	-7.52	-18.7	7.48	9.41
1.6	30.3	2.9	-7.31	8.95	7.6

Table 3 Example of Velocity results

6. CONCLUSION

A new water cooled LDV probe was designed for velocity measurements in a large scale thermal 1850MW coal-fired power station. Due to the extremely high cost of the measurement campaign (preliminary studies, specific operating conditions of the power plant during the tests in charge of the research group (specific thermal power outputs, burner configuration, intrusive techniques implantation), only short experimental times were available and required the optimization of both the acquisition time and the data processing (maximum of 3D velocity data using three holes in the furnace wall). The water cooled probe design was perfectly adapted to the measurement (good mechanical and thermal behavior in an hostile environment, good handling ability of the probe carrying system). The main problem for the experiments was the window contamination by coal or ash particles.

The three component velocity data were obtained in the vicinity ($25m^2$) of a PC burner exit. The large scale of the system allows the use of the 3D velocity component composition technique from probe rotation. This method is validated despite the shifting of the measurement volume location (0.15m) which is small in comparison with the turbulent scale (around 0.25m).

Much information was obtained on the flow velocity field (location and expansion of the PC jet, relative positions of maximum heat release region and shear stress, description of the recirculating zone along the wall). The complete results (velocity, temperature, stable chemical species fields, particle granulometry, heat exchanges) provides all the data necessary to understand the two-phase turbulent reactive flow behavior in order to validate a numerical modeling in full size.

7. PERSPECTIVES

The technical difficulties inherent in large scale industrial environment and the high cost of the LDV measurements delay the complete two-phase reactive flow characterization. The next measurement campaign is scheduled for the beginning of next year and unfortunately results cannot be presented in this paper.
The efficiency of the LDV intrusive method using water-cooled probe was again successfully adapted to measurement in full scale PC flame. The validity of the velocity results was clearly demonstrated. The fast developments of the PIV

method, based on image processing of Mie scattering of moving particles in a laser sheet, should be adapted soon to such a flow characterization. This presents a challenge for velocity measurements in large industrial flames during the next few years.

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