COMPARISON OF VELOCITY MEASUREMENTS BY HIGH TEMPERATURE ANEMOMETER AND LASER-DOPPLER ANEMOMETER WITH RESULTS OF CFD-SIMULATION

by

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In the present work, results of gas velocity measurements with a newly developed vane anemometer (HTA – High Temperature Anemometer) are compared with results of measurements obtained from Laser-Doppler Anemometer (LDA). The measurements were carried out at the combustion test rig of ALSTOM Combustion Services Ltd. in Derby/UK, and demonstrate the usability and accuracy of the HTA under severe conditions. The test rig was provided with a triple register low NO_x *coal burner firing pulverised Colombian blended coal at a constant thermal load of 30 MW. Although the environment was both very hot (up to 1350 °C) and dust laden, the vane anemometer worked with an accuracy comparable to the reference LDA measurement. Since the anemometer represents a relatively simple to use and low cost option compared with LDA, it is seen as a viable alternative for gas velocity measurements in difficult environments. The measurement results are also demonstrated to compare favourably with the results from CFD calculations of the flow in the combustion chamber of the test rig.*

Introduction

Optimisations of combustion processes (*e. g.* operation behaviour of burners regarding flame stability, slagging, heat flow distribution, ...) are often based on CFD calculations and/or on *in-situ* measurements of gas velocities. Besides direct information about velocity fields, such measurements can give information about boundary conditions or special parameters for CFD models. A well established and often used velocity measurement technique is Laser-Doppler Anemometry (LDA) 1, 2 , but the use of LDA equipment is neither simple nor feasible at a reasonable cost. The application of LDA may be further limited by problems of access and the environment which is generally very harsh in industrial boilers (high temperatures and high dust loads). In order to obtain an alternative measurement technique a vane anemometer

(HTA – High Temperature Anemometer) designed to withstand these rough conditions [3] was developed. This vane anemometer is very simple to use and enables in-furnace measurements of velocity to be carried out at an acceptable expense.

In order to validate the high accuracy of the HTA with the best present available standard (LDA), measurements were carried out with both systems (LDA measurements – by ADVANTICA Technologies Ltd. as well as HTA measurements – by Graz University of Technology) at the burner test rig of ALSTOM CSL in Derby/UK. The results of the measurements with HTA and LDA were compared against each other and also jointly against the results of a CFD calculation of the velocity field. Rig operating conditions and the deployed equipment are described together with the results of measurements and of the calculations.

Experimental

Combustion test rig

The combustion test rig (CTR) of ALSTOM CSL in Derby/UK is one of the largest burner test facilities in the world. It is capable of testing full-scale burners for power generation boilers. Figure 1 shows the scheme of the test rig.

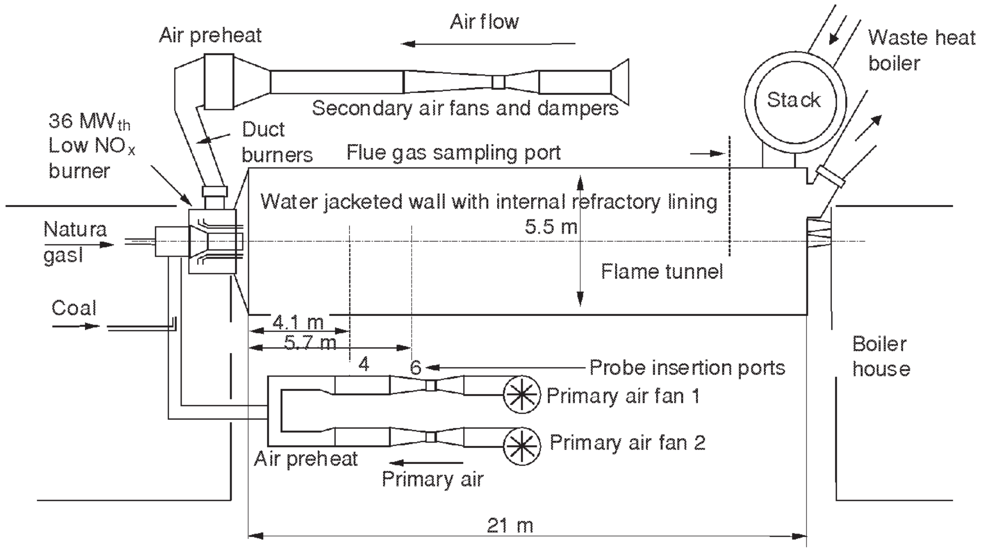

Figure 1. Scheme of ALSTOM's combustion test rig (CTR)

The core item of the test rig is a water-cooled combustion chamber of internal dimensions 21.3 m long by 5.5 m square cross section. To accomplish a hot environment the combustion chamber floor, burner end wall and both of the side walls are internally lined with refractory tiles. Part of the roof, 5.5 m from the burner end of the wall, is also covered with ceramic fibre insulation capable of withstanding temperatures of up to 1600 °C. During the measurements with HTA and LDA the test rig was provided with a triple register low NO_x coal burner rated at 36 MW_{th} with a load turn-down capability of 2:1. For the purpose of the tests the burner was operated at a constant thermal load of 30 MW.

The fuel was a pulverised Colombian blended coal of a type widely used in Europe. Table 1 provides an ”average” analysis and other characteristic data of the coal as-fired during the trials. The product was pre-dried to facilitate grinding and conveying requirements, and had an as-fired ash content of 7.0%. The choice of coal was influenced to a degree by the suitability of the product in terms of the requirement for extended and uninterrupted operation of the rig.

Table 1. Fuel data of Colombian blended coal

Proximate analysis wt.-%	as fired	dry
moisture	3.90	–
ash	7.00	7.28
fixed carbon	53.20	55.36
volatile matter	35.90	37.36
Ultimate analysis wt.-%	as fired	dry
carbon	75.60	78.67
hydrogen	4.49	4.67
nitrogen	1.50	1.56
sulphur	0.60	0.62
oxygen	6.91	7.19
Gross calorific value kJ/kg	29 981	31 198
Ash fusion data °C		
initial deformation	1290	
hemisphere point	1400	
flow point	+1400	
Sieve analysis wt.-%	retained	passing
sieve 300 μm	0.10	99.90
sieve 150 μm	1.40	98.50
sieve 75 μm	14.10	84.40

High temperature anemometer

The HTA is a vane anemometer that can measure the velocity of a hot and dust laden gas flow. It was developed by Graz University of Technology, Institut für Apparatebau, Mechanische Verfahrenstechnik und Feuerungstechnik. A scheme of the HTA is shown in Fig. 2.

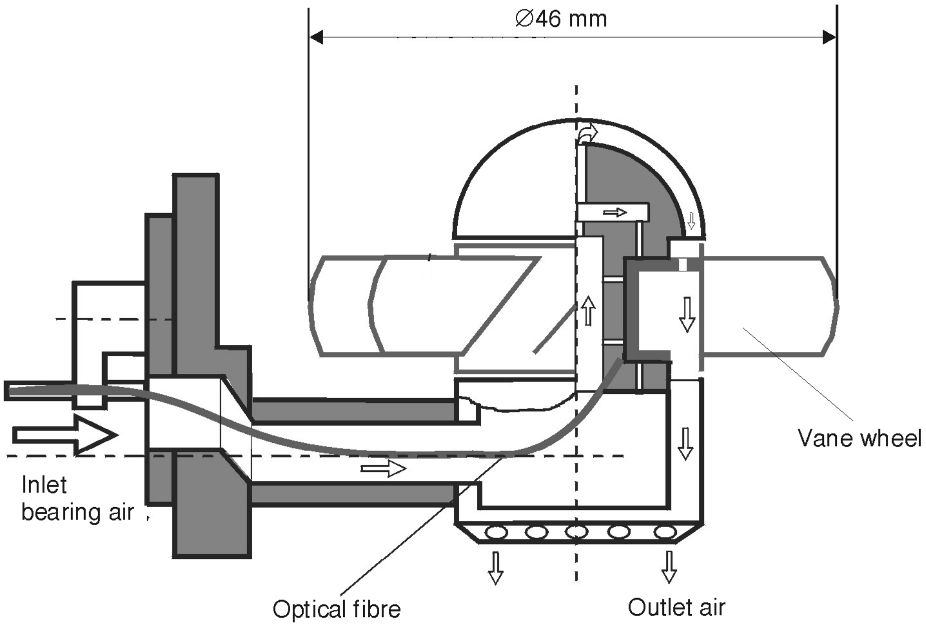

Figure 2. Scheme of the High temperature anemometer (HTA)

The vane-wheel of the HTA is manufactured from heat and corrosion resistant materials, and has an outer diameter of 46 mm. The vane-wheel is suspended by a frictionless aerostatic bearing and is internally cooled by the air of the bearing. This bearing air further prevents the penetration of particles into the bearing zone. The frequency of rotation of the vane-wheel is detected by a fibre optic system with a frequency of detection of 1 second. The direction of rotation is also detected by this optic sensor system. The dependency of the frequency of rotation of the vane-wheel on the velocity of the gas is determined by calibration of the HTA in a wind tunnel at ambient temperature. For HTA measurements in a combustion chamber, the only requirement is access through a port with a nominal diameter of 50 mm. The HTA is mounted on a water-cooled probe, which allows measurements in the combustion chamber at insertion depths of up to 5 m.

The measuring range of the HTA is 1 to 40 m/s with an absolute error of 1% of this span. The accuracy of the instrument in the velocity range below 10 m/s can be increased by using a vane-wheel with a lower slope of the vanes. Measurements with the HTA are possible in environments at dust-loads of up to 80 kg/m^3 typical of Circulating Fluidised Bed reactors (CFB) 4 . The HTA-system is easy to handle and transport, very rugged and can be employed in harsh environments. Only cooling water for the probe, dry and oil-free pressurised air and a supply of electrical power is needed to operate the HTA.

Laser-Doppler anemometer

The LDA measurements were made using a commercially available system from DANTEC. The light source for the system was a coherent 5 W argon ion laser, operated in broadband mode. The laser light was passed to a DANTEC colour separator which performed three functions: Firstly, it separated out the two main colours from the incoming laser light, generating two beams at 514.5 nm and two beams at 488 nm. Secondly, a Bragg cell added a frequency shift to one 514.5 nm and one 488 nm beam in order to eliminate the directional ambiguity inherent in a stationary fringe pattern. Thirdly, a series of manipulators and couplers directed the laser light into four fibre optic cables, two for the 514.5 nm and two for the 488 nm. The fibre optic cables (25 m in length) transmitted the laser light to a measurement head of 30 mm diameter. This head incorporated a 2X beam expander and focusing lens of 120 mm focal length, which focused the four beams to an intersection at the measurement location. The two pairs of beams were configured at 90 degrees to generate two measurement volumes within the beam intersections, allowing the simultaneous measurement of two components of velocity (the U and V components). For the measurements in question, V was along the furnace away from the burner, and U was orthogonal and vertical to V measurement. The same transmission lens also collected the scattered light from the particles passing through the measurement volume and transmitted it to a collection fibre in the LDA head. This fibre passed the light back to two photo-multipliers – one for the 514.5 nm (green line) and one for the 488 nm (blue line).

For the measurements inside the combustion furnace of the ALSTOM test rig, the LDA head was mounted inside a 5 m water-cooled, nitrogen-purged probe. At the end of the probe, there was a quartz window assembly that was purged with nitrogen in order both to cool the window as well as to prevent the deposition of particles onto the window. In this way it was possible to maintain good optical access through the window. The signals from the photo-multipliers were analysed for Doppler frequency using two channels of DANTEC enhanced Burst System Analysers (BSAs). The BSAs were controlled by a PC, which also collected, processed and archived the velocity data.

Measurements

The CTR was operated at a constant thermal load of 30 MW throughout the whole test period. Measurements with HTA and LDA took place alternating between port 4 and port 6 of the chamber (see Fig. 1). The gas velocity was measured at different insertion depths in horizontal traverses with both systems.

For the HTA, the velocity of the flue gas was measured in the horizontal direction parallel to the furnace axis. At each measuring point (insertion depth), signals were taken in triplicate, each over a period of 30 seconds. The HTA measurements were obtained for two sets of vane-wheels with respective vane angles of 45° and of 60°.

With respect to the LDA measurements, flue gas velocities were obtained in both the horizontal and vertical directions, together with their respective fluctuations. The LDA measurements were carried out in duplicate at the same locations used for the HTA measurements. From the LDA signals, average values were calculated applying an averaging time of 45 seconds. Figure 3 shows a typical result, expressed as the probability density function, of the LDA measurement for a specific location inside the chamber. The broad velocity distribution is characteristic for the highly in-stationary flame of a coal burner.

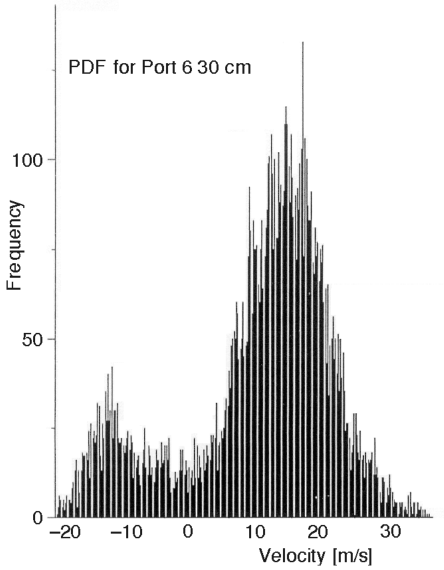

Figure 3. Velocity distribution in horizontal direction measured by LDA in port 6 in an insertion depth of 30 cm

The objectives of the measurements with HTA and LDA were (I) comparison of HTA and LDA measurements under same conditions, (II) validation of the HTA calibration (obtained from tests in a wind tunnel at ambient temperature) at high temperature, (III) verification of the maximum allowable temperature for HTA measurements, (IV) investigation of maximum allowable load of the aerostatic bearing of the vane-wheel, and (V) investigation of the influence of a particle layer on the vane-wheel on the accuracy of the HTA. Finally, the results of the measurements by HTA and LDA were used in order to validate CFD calculations performed by ALSTOM CSL.

CFD calculation of the velocity field in the combustion chamber

The calculation of the velocity field inside the combustion chamber of the ALSTOM CTR was achieved by combining two different sub-models developed using the commercial software package FLUENT (version 5.0.2). The modelling of the burner and CTR as a single entity was found to be impractical due to the large number of cells required to achieve the desired level of accuracy. The approach adopted therefore was to merge two sub-models, a detailed burner model and a furnace model with a simplified representation of the burner geometry. From the burner model, the boundary conditions (velocity components, turbulence quantities and pulverised fuel particle tracks, ...) prevalent at the burner exit were established for input to the furnace model.

The results of the CFD analysis were initially required to establish suitable probe locations for the HTA and LDA tests, as well as to back up the practical measurements and confirm that the experimental work was proceeding correctly. Once the experimental measurements had been completed the model was refined in order to more closely represent the fuel characteristics and the actual operating conditions for the tests.

Burner model

A 90°-sector model incorporating the important aspects of burner geometry was used to allow good resolution of the flow in the burner and to obtain reliable boundary conditions for the furnace model. Overall the burner model contained more than 200 000 grid cells. Time averaged conservation equations for continuity and momentum were solved, together with the standard semi-empirical k-ε turbulence model. Since the flow variables of interest would be predominately unaffected by the combustion process at the position of their extraction it was decided to use a non-combusting model.

The particle boundary conditions were set at the inlet to the primary air register on the model, on the assumption that the particles were evenly distributed at this point. In order to obtain an adequate representation of the particle size range, ten size fractions were introduced. The particle tracking algorithm within FLUENT provided the velocity and direction of the particles leaving the burner. These values obtained at the exit from the burner were then used as inlet boundary conditions to the CTR furnace model.

Furnace model

In order to provide a reasonably good representation of the furnace geometry (as described) for the initial runs, a mesh of about 100 000 grid cells was applied to the CFD model. Following the experimental test work, the furnace was re-meshed using GAMBIT to provide a 270 000 grid cell representation with a relatively high cell concentration in the near-burner region.

Combustion modelling was based on the properties of the coal, as given in Table 1, and appropriate constants for devolatilisation and char reactivity. A finite rate combustion model was used to describe the combustion process in terms of particle heat-up, volatile release and char combustion. The radiation model selected accounted for the exchange mechanism between the furnace gas and the particles.

The thermal boundary conditions imposed on the CTR furnace allowed both for the water cooling of the walls, and for the pattern of refractory lining. Inner wall temperatures were calculated by an iterative process, given suitable constants for surface emissivity and heat transfer coefficients. Refinement of the constants enabled the heat absorption within the furnace to reflect the experimental measurement of the gas exit temperature.

The model output included the distribution of oxygen and temperature in the furnace in addition to the particle velocities, which are reported for the region of interest.

Results

Figures 4 and 5 show results of velocity measurements with LDA and HTA in port 6 as well as the results of the CFD-calculation. The velocities measured by HTA presented in Fig. 4 were obtained using a HTA vane-wheel with vanes of 60° slope. The velocities presented in Fig. 5 were obtained from HTA measurements using a vane-wheel with vanes of 45° slope. As can be seen from the Figs. (4 and 5) the highest gas velocities are present in the vicinity of the furnace wall. Then with increasing

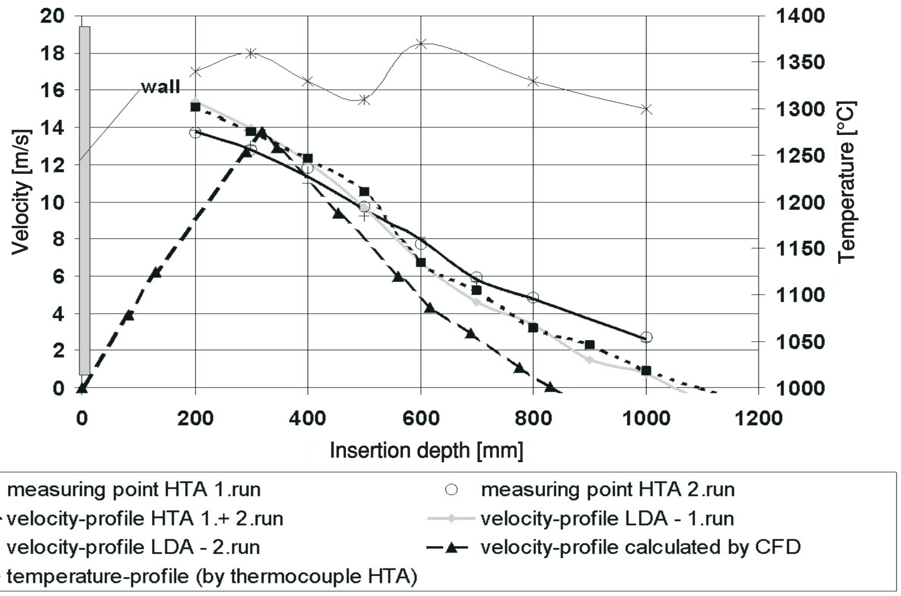

Figure 4. Results of velocity measurements by HTA (slope of the vanes = 60°) and LDA in port 6 and CFD-calculation

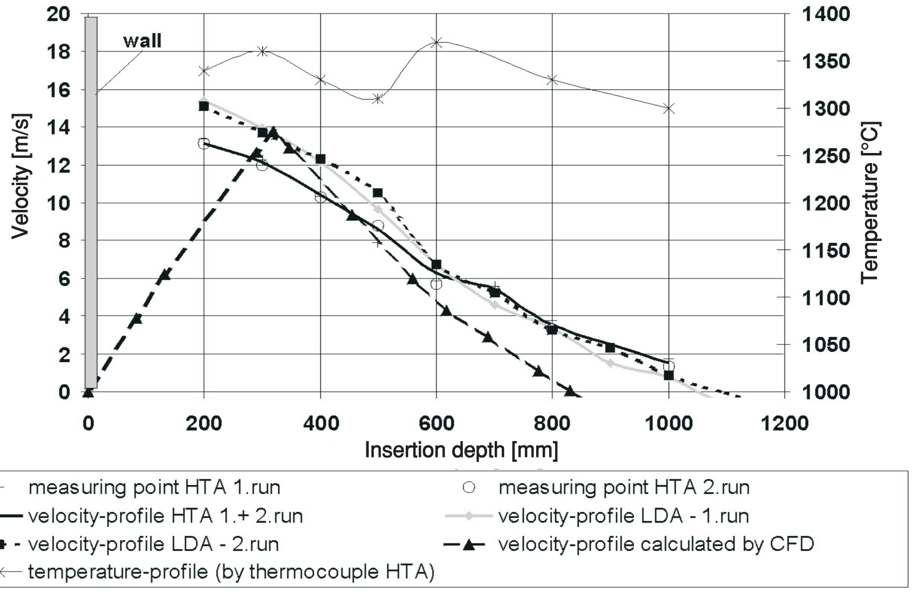

Figure 5. Results of velocity merasurements by HTA (slope of the vanes = 45°) and LDA in port 6 and CFD-calculation

insertion depth, a decrease in the velocity was determined. Further, a region with reverse flow was found in the centre of the combustion chamber. Here gases are sucked back in the direction to the burner in the centre of the combustion chamber. Figures 4 and 5 also show the temperatures measured in port 6 with a thermocouple mounted on the HTA. The maximum measured temperature in port 6 was about 1350 °C.

A comparison of the velocities obtained from the HTA presented in Figs. 4 and 5 with the results obtained from LDA shows that with the HTA in the lower velocity range (up to 10 m/s) better results are achieved if vanes of 45° slope are used. In the upper velocity range (velocities > 10 m/s), better results are obtained if vanes of 60° slope are used. But generally it can be seen, that there is a good agreement between results obtained from LDA and HTA with regard to the shape of the velocity profile as well as the absolute velocity values. Although the absolute velocity values calculated by CFD are marginally lower than the measured velocities, the shape of the velocity profile shows also good agreement.

In port 4 the maximum temperature was above 1400 °C. At this temperature both measurement techniques (HTA and LDA) failed. The cause of failure of the HTA was a decomposition of the glue that was used to fix the tip of the optical fibre inside the HTA. Therefore the optic signal used for detection of the frequency of rotation of the vane-wheel was lost. This problem was subsequently eliminated using a new optical fibre system with a glue-less mount.

The results of the tests further show that the calibration of the HTA, which was done in a wind tunnel at ambient temperature, is also valid at high temperatures. It can be concluded, that the aerostatic bearing of the HTA vane-wheel is nearly free of friction, and that the bearing can withstand the load forced by the in-stationary flow in the flame of the coal fired burner.

Ash particles sticking on the outer radius of the uncooled vanes (as can be seen in Fig. 6) do not influence the accuracy of the HTA. Finally it must be noted that no problems with the mechanical parts of the HTA (*e. g.* the uncooled vanes) occurred.

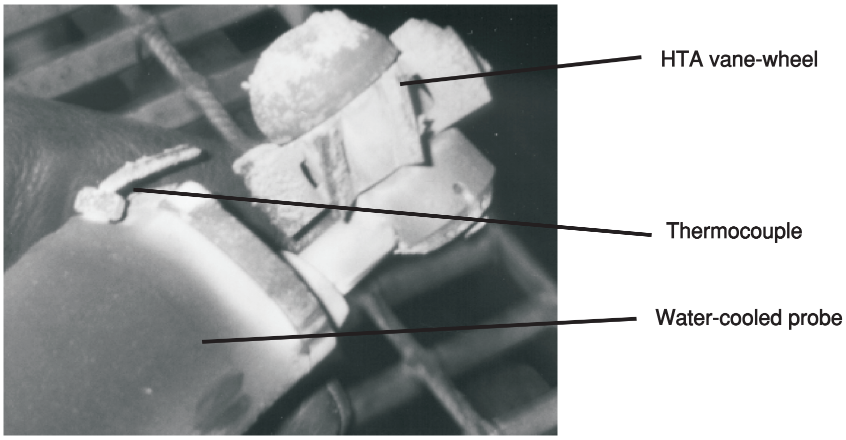

Figure 6. Ash deposition on the HTA after use for more than 1 hour in port 6 of the CTR Derby

Conclusions

The tests with LDA and HTA at the CTR in Derby show close agreement between the average velocities of the hot and dust laden gas flow measured by the respective systems. The tests established that the HTA is an accurate, cost effective and simple to use instrument for measurement of gas velocities under conditions represented by the combustion chamber of coal fired plants. Furthermore, the tests demonstrate the ability to measure the local velocity and velocity distribution by HTA in existing combustion chambers with economy of time and expense.

Acknowledgements

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