Local Acquisition of Mean and Turbulent Fluid Acceleration in Highly Turbulent Flow by the Means of Laser-Doppler Velocimetry

B. Lehmann, J. Helbig

Deutsches Zentrum für Luft- und Raumfahrt
Institut für Antriebstechnik
Abt. Turbulenzforschung
Müller-Breslau-Str.8
D-10623 Berlin, Germany
e-mail: bernhard.lehmann@dlr.de

ABSTRACT

The problem of variable velocity in the probe volume of an LDA optics is discussed for introduction. It is shown, that even under the very conservative flow conditions of a low-speed air jet the local turbulent acceleration of fluid leads to velocity variations in the probe volume which make the common assumption of velocity constancy during the measurement very doubtful.

A technique to analyse these velocity differences might be, on the other side, valuable as a source of new and extended information on local turbulent flow properties. The according local acceleration may, by example, give information on particle trajectory and separation processes.

The technique and a crucial experiment are mentioned which are used to estimate experimentally the local acceleration in turbulent flow and to confirm its suitability. The measurement technique is based on multiple frequency analysis of individual Doppler bursts (see Fig.1). The verification experiment is made in a stagnation flow which impinges axially on the end face of a 5 mm diameter rod.

Then in the experiment of actual interest we report the analyses of the local acceleration features in stagnation flows in front of a stagnation plate with and without the presence of combustion. The expectation was that in the case of combustion the level of local accelerations should be increased compared with the cold turbulent flow. This behaviour could not be confirmed by the experiments. It seems more probable that the accelerations are reduced by means of damping effects due to the increase of viscosity in the combustion flow.

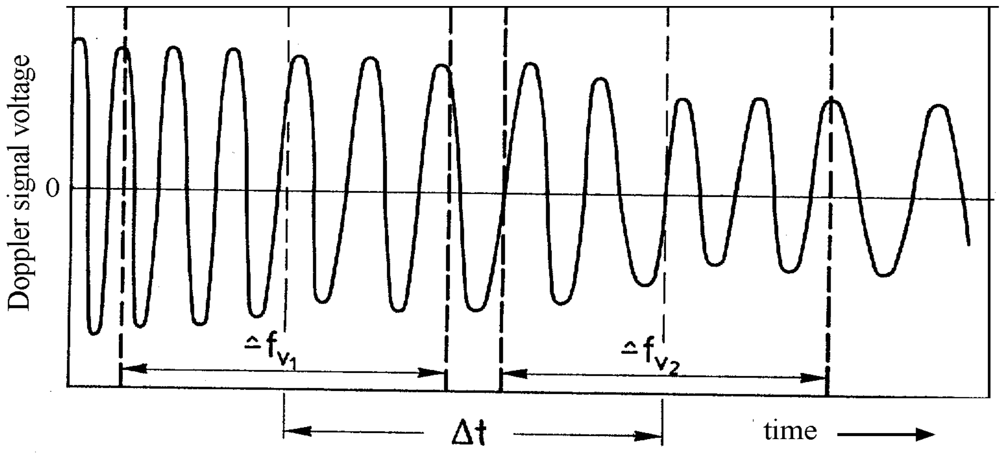

Fig.1: Schematic of multiple frequency analysis of a Doppler burst

1. INTRODUCTION

In the course of using laser-Doppler measurement techniques it is generally assumed, that the velocity to be measured is constant along its trace across the measuring probe volume. This assumption contradicts to the following simple model estimation for possible turbulent fluctuations.

An air jet issuing from a nozzle with D =15 mm diameter and a mean velocity of 10 m/s tends to be unstable with the Strouhal number of St=0.4 according to a frequency of f=267 Hz in this case. The developing instability vortices may attain diameters of the order of the nozzle diameter. A fluid specimen will therefore be swept back and forth relatively to the mean flow by the distance of ± D/2 maximum, if it is entrained into such kind of vortex. In the idealised case of a harmonic fluctuation the maximum acceleration exerted on the particle is $b=D/2\ \omega^2$ where $\omega=2\pi$ f. Thus the data as assumed above give a maximum acceleration of the particle of b_{max}= 21108 m/s^2.

On its way across a probe volume with a diameter of Δs=0.1 mm the particle changes its velocity v under the influence of the calculated acceleration by $\Delta v=b_{max}\cdot\ \Delta s/v$. If the instantaneous velocity of the particle is v=5m/s, the velocity variation is Δv=0.42 m/s. Thus, in spite of the assumed very conservative conditions a velocity uncertainty of nearly 10% of the actual velocity exists which is generally not recognised in the course of LDA measurement.

The maximum turbulent acceleration is linearly proportional with the fluctuation amplitudes and with the square of frequencies. Though arising turbulent fluctuation frequencies are commonly connected with a decrease of fluctuation amplitudes an increased turbulent activity will produce considerably increased turbulent acceleration. Therefore maximum turbulent acceleration of the order of 10^5 m/s^2 to 10^6 m/s^2 must be expected in mean turbulent shear flow. The question, what actually LDA measures in such flows and whether the interpretation of results must be revised, shall not be discussed here.

Lehmann & Helbig (1999) we have demonstrated by the means of a key experiment the ability to locally acquire the acceleration features in stagnation flow. Starting with this verification experiment we are going to report here an experiment, which we assumed to be connected with very intense local acceleration processes. This is the question of the local acceleration behaviour in a flow with combustion. We will finally see, that our assumption could not be confirmed from the reported results and the possible reasons will be discussed.

2. THE TECHNIQUE OF ESTIMATING LOCAL ACCELERATION

The fundamentals of the discussed technique have been already reported by Lehmann et al. (1990) under another point of view. With the aim to verify the technique for simple uni-directional acceleration estimates Lehmann and Helbig (1999) have used a suitably configured stagnation flow in front of the end face of a cylindrical rod with a diameter of 5 mm. The result shall be shortly repeated here.

Fig. 1 shows the digitised part of a Doppler burst of a conventional Doppler measurement. We split this part into two halves and analyse the Doppler frequencies of both by the means of highly resolving FFT techniques. From the well-known digitisation quantities we are able to estimate the mean velocity difference along the mean time epoch of the digitised burst which results in a mean acceleration. This is the most simple stage of possible refinements of the estimation, but it suffices for the present measuring aims.

Fig. 2 is the result of two different kinds of acceleration estimates in the stagnation flow in front of the above-mentioned rod. The closed points are the results of the described burst-split technique. The open points are deduced from the measured velocity variations along the stagnation line together with the mean time differences as calculated from arithmetic mean velocities along the geometric point distances. We find a fairly good agreement between the results of both techniques which proves us the suitability of the local estimation.

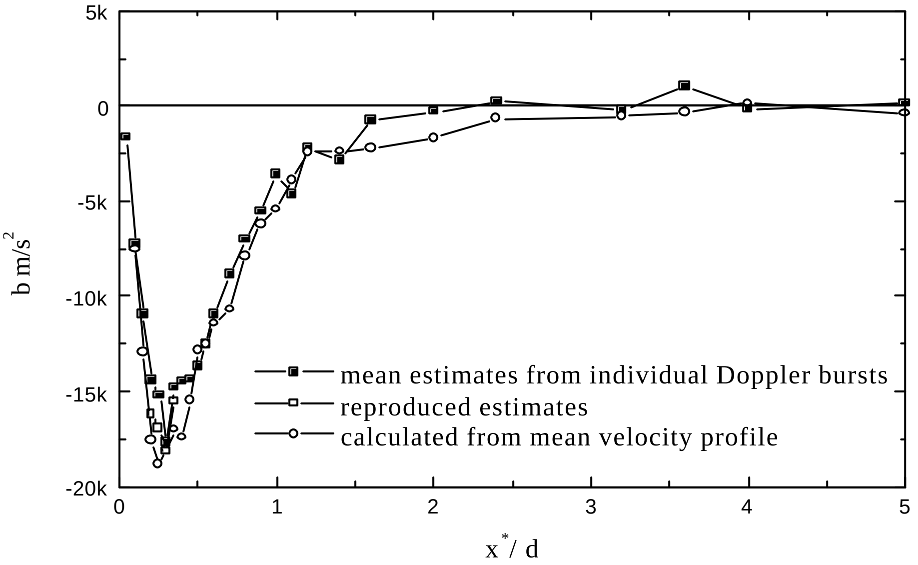

Fig. 2: Mean axial retardation in stagnation flow in front of the end face of a d=5 mm rod, two experimental techniques compared. Undisturbed flow: u_0=12.2 m/s, turbulence degree Tu < 1 %,, x*: distance from stagnation point

The approximate local estimate, however, contains not only the statistically mean acceleration which is the mean of its steady and unsteady portions. With a sufficiently high signal rate we also obtain the time history of accelerations as well as the correlations between velocities and accelerations. These features will be discussed together with the upcoming measurement results.

3. THE EXPERIMENTAL MODEL FLOW

3.1 Motivation

The experiment which we are going to report is based on our experiences with combusting flows. If, by example, you have a nozzle-initiated combustion field with a lifted flame configuration, you may observe in front of the reaction zone that the frequency spectrum of the unstable cold flow has a power-spectral peak with a well-defined spectral width. This holds at least for the results of spectral analysis made by means of laser-Doppler measurements which may deliver short-time frequency spectra with a high local resolution. In the region of combustion such peak cannot be observed and instead the frequency spectrum shows a large number of needle peaks distributed over a wide range of the frequency scale.

We tend to interpret these frequency peaks in the reaction zone as the instantaneous and temporally very restricted frequency spectra of small locally swinging areas in the flow. The volumes of such areas are initiated to swing due to an intense reaction of locally embedded fuel which forms on account of uncomplete mixing of fuel and air. The observed different frequencies are assumed to compare with the different eigen frequencies of the swinging volumes and they depend on the individual amount of locally reacting fuel resp. the locally produced thermal power.

Considering these possible circumstances we expect, that tracer particles, if they are embedded in those swinging regions, would offer an amplified acceleration behaviour under combustion compared with the accelerations in the cold turbulent flow. So we used a stagnation flow without and with the presence of combustion as the experimental configuration to verify these supposition.

3.2 Experimental devices

A couple of two small pipes were partly inserted in a pipe with 5 mm inner diameter to supply an air flow (d_i=2.5 mm) and a methane (CH_4) fuel flow (d_i=1.5 mm). Both partial flows could premix along their path length of more than 25 pipe diameters along the remaining length of the main pipe. The vertically issuing premixed flow was directed against a stagnation plate with the diameter D=60 mm. In Fig. 3 the main pipe can be seen the exit of which is positioned at 45 mm in front of the stagnation plate.

Fig.4 shows a photograph view upwards against the stagnation plate where the position of the ring-shaped combustion region was kept stable. In the obviously reaction-free zone nearby the centre of the plate the convection velocities of the flow field are too high to keep the flame. In the axis of the figure the diffuse image of the main pipe can be seen, the other rods are to fix the plate.

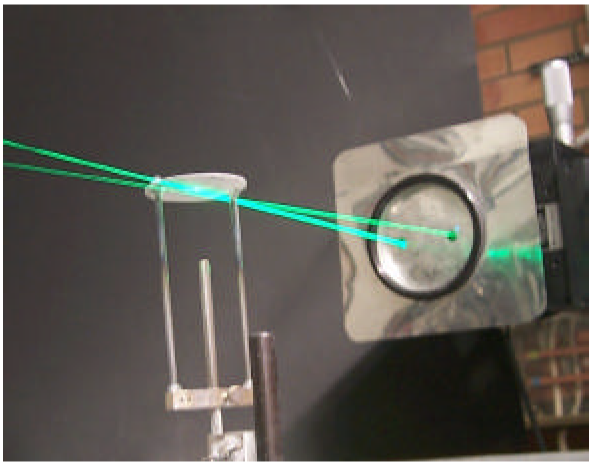

Fig. 3: Stagnation plate with main flow pipe and the measuring laser beams

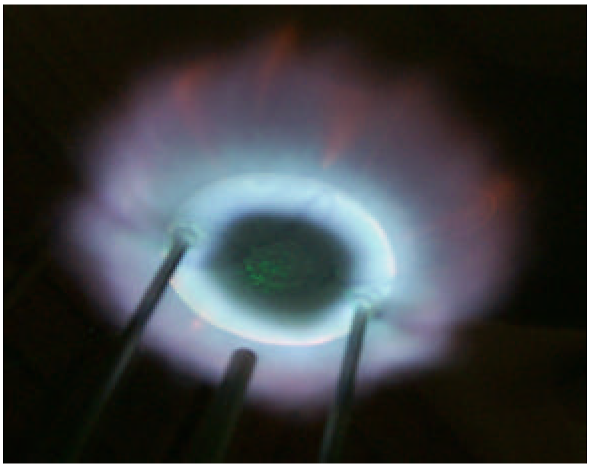

Fig. 4: View on the stagnation plate with the flame

For the Doppler measurements a simple one-component optics was used which applied a frequency shift of 40 MHz. The measuring light wave length was 514.5 nm and the scattered light was received approximately in forward direction. Tracer particles were ball-shaped SiO_2 particles with diameters of 0.8 μm which varied by about ±10 %. These particles were introduced through a hose with a diameter of 20 mm into the surrounding of the stagnation flow with velocities low enough to prevent a direct interaction with the flow of interest. This technique was applied in order to avoid the cross-sections of the small pipes to be reduced or blocked due to the settlement of the particles if they would be directly driven with the flows through these pipes.

The experimental device was driven under constant conditions for all reported measurements. In the case of measuring the flow without combustion, the methane-gas flow was replaced by an additional air flow the volume flow of which was adapted to that of the fuel gas.

Doppler-signal analysis was carried out by means of a self-developed software FFT analyser which worked on the basis of the Motorola 68000 processor (Atari). This device was developed and used already before the commercial FFT systems of today were available. The system offers a high flexibility to vary by example the digitised time-series of a Doppler-modulated burst up to 4096 points. An additional frequency interpolation gives us frequency resolutions of up to 10^{-4} to 10^{-5}. This resolution we need for the intended estimation of accelerations.

With this system we experienced that the accuracy of the individual frequency results depends strongly on the burst modulation amplitudes within the available space of input amplification. Therefore we introduced software routines which expanded all modulation amplitudes to the maximum possible value of the input amplifier. Thus the preparation of the burst for analysis consisted of expanding its amplitudes to maximum, splitting the burst into two parts consisting of 256 digitised points each, multiplying a Hanning window over the partial bursts, analysing them by means of FFT and finally interpolating the obtained FFT results in the frequency spectrum in order to refine the spectral position of the most intensified frequency peak.

The calculations were supported by four additional signal processors in order to accelerate the evaluation. Our resolution and accuracy tests showed, that, with the available equipment, we may analyse the acceleration from harmonic generator signals with an absolute accuracy of 100 to 200 m/s^2. The more or less noisy signals of turbulent flows reduce the accuracy to the order of 1000 to 2000 m/s^2. This was already reported by Lehmann et al. (1987).

3.3 Experimental results

The experimental results reported here consider the profiles of only the radial velocity component at $x^* = 1$ mm in front of the stagnation plate. The y traverse was directed parallel with the plate and through its axis of symmetry. The small distance of one millimeter away of the plate was chosen, because a measurement at $x^*= 5$ mm gave no results in the expected sense. So we approached to $x^* = 1$ mm though already at $x^* = 5$ mm we were sure to cross definitely the reaction zone.

Fig. 5 is the plot of the measured mean radial velocity and of the rms profiles of radial velocity fluctuations with and without the presence of combustion. It is obvious in this case that the mean velocity profile is influenced by the combustion but that the fluctuation rms values are scarcely changed.

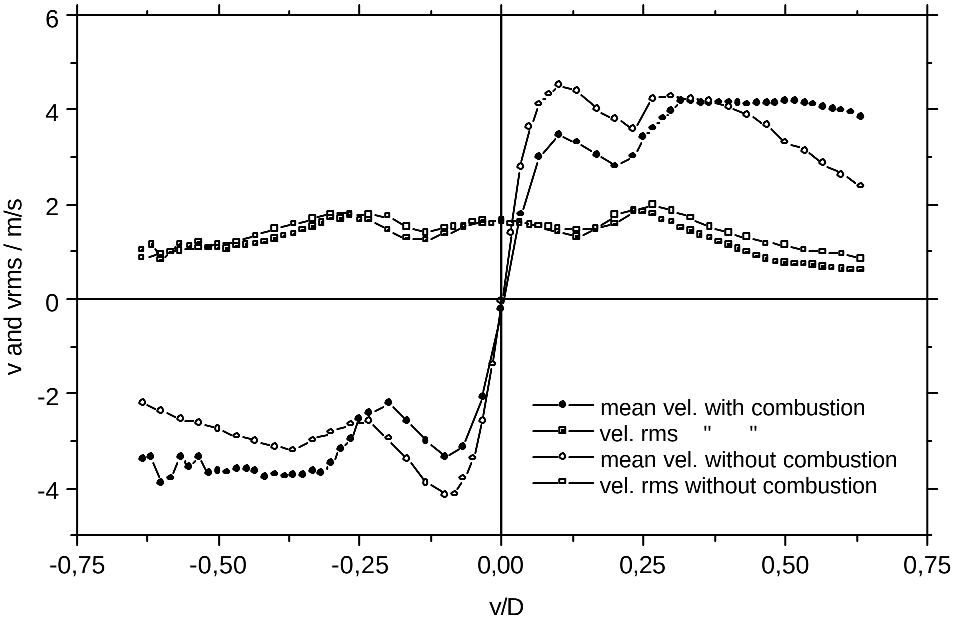

Fig. 5: Mean and rms radial velocities at x* = 1 mm in front of the stagnation plate

Fig. 6 shows for the case of combustion the pdf of the velocities, the acceleration pdf and a correlation plot of the velocities and the related accelerations taken at the position x*=1mm and y=-15 mm (y/D = -0.25 with the plate diameter D). In spite of a strongly skewed velocity pdf the acceleration pdf is symmetrical and the distribution of accelerations spreads along a range of at least ± $3x10^5$ m/s^2.

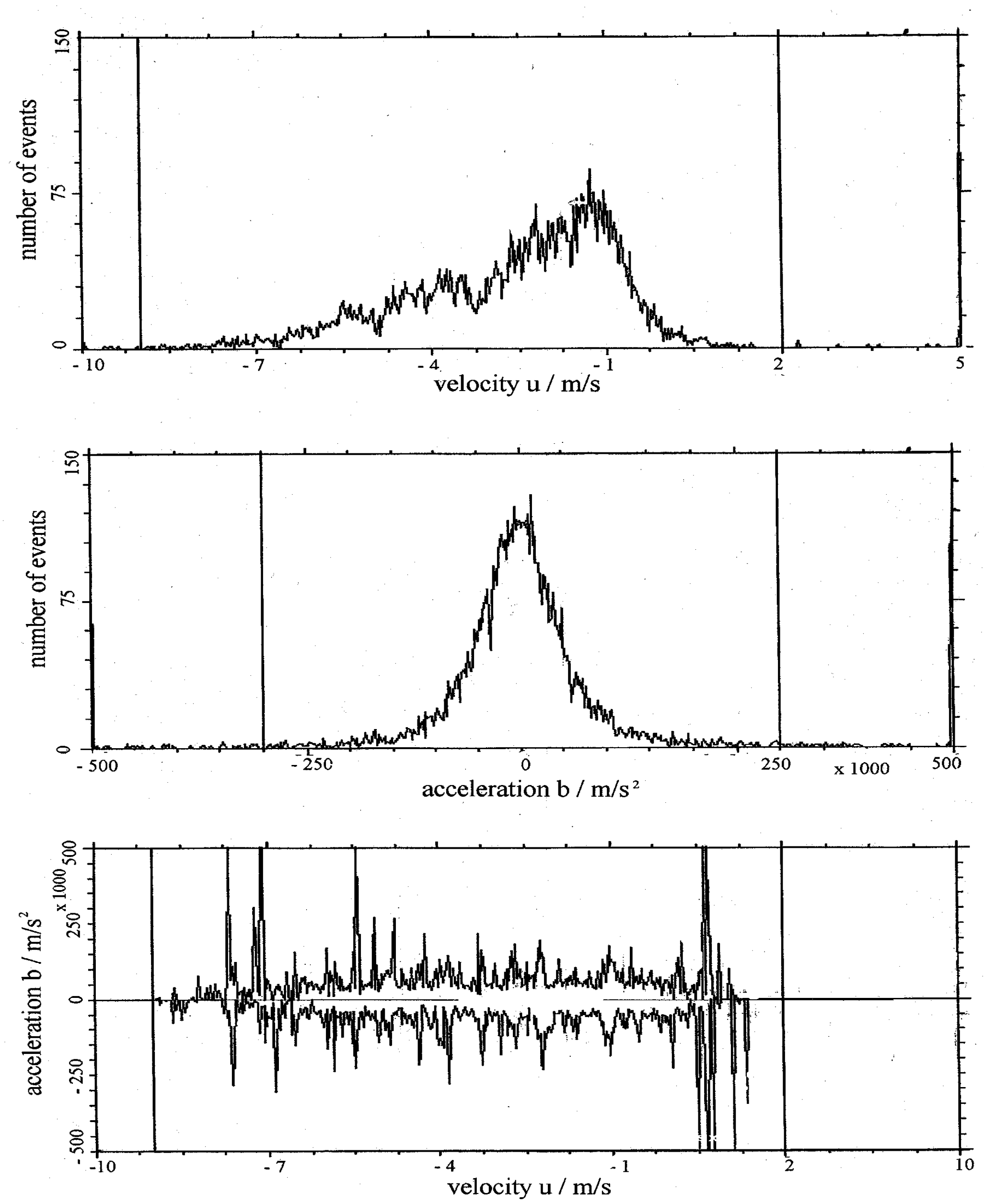

Fig. 6: Flow with combustion: radial velocity pdf , acceleration pdf and the mean statistical correlation of the velocities with the proper accelerations

The third plot in Fig. 6 correlates the measured velocities with the estimated accelerations after having split them due to their sign. The total number of measured events is about 7000 which gives a rather definite statistical relationship between the correlated values but does not prevent the occurrence of a number of acceleration spikes. We interpret those spikes as errors of the individual acceleration estimates which arise with preference in the regions where the acceleration tends to attain zero values so that our estimates become highly uncertain. On the other side the correlation shows a clear dependency between the correlated values and expresses in this way the fundamentally correct work of the estimation technique

Splitting the total mean acceleration results into positive and negative values seems valuable for the interpretation of the results because in the real flow a correlation must exist between both sign-related velocities and accelerations. The difference between mean positive and mean negative acceleration expresses the existence of gradient properties of the turbulent fluctuations and it is generally lower by the amount of a decade than the sign-related means.

Fig. 7 shows for the flow with combustion the distribution of the different mean acceleration values and the acceleration rms values across the stagnation plate. The total mean acceleration profile is not very different from zero except nearby the stagnation point of the flow (y/D=0) were the profile shows a clear change of its sign but does not exceed the acceleration of $\pm 10^4$ m/s^2.

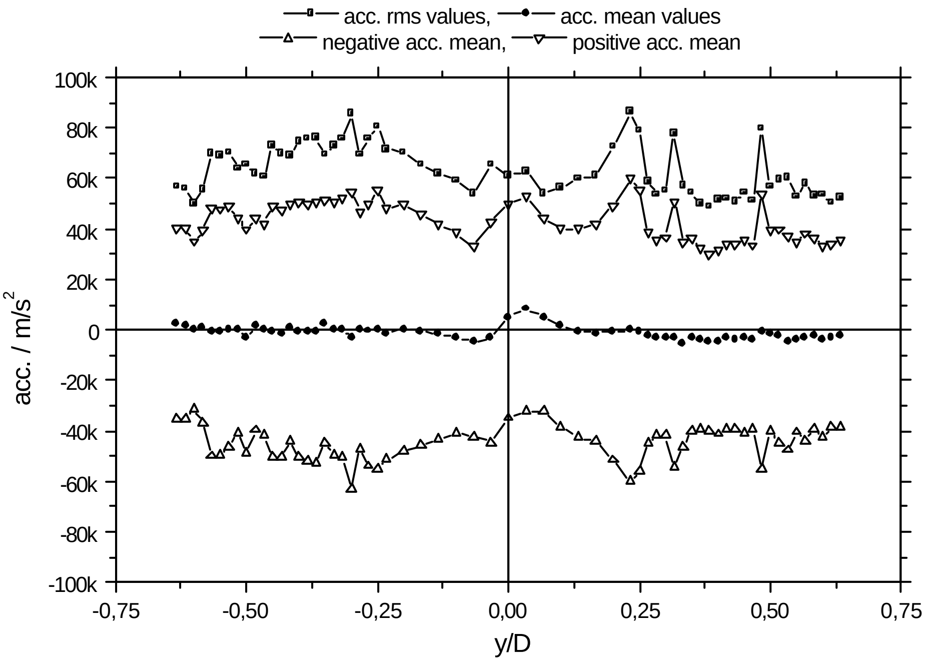

Fig. 7: Flow with combustion: mean turbulent acceleration, rms values and mean positive and mean negative acceleration portions

The mean positive and the mean negative accelerations are of the order of $\pm(4\div5)\mathrm{x}10^4$ m/s^2. They show some systematic variations across the plate. Despite of some strong local changes one might recognise a tendency of both profiles to form flat maxima in the region y/D=-0.25 to y/D=-0.5 and to form flat minima on the other side at y/D=0.25 to y/D=0.5. So one might interpret a tendency of more extended acceleration fluctuations in the region of negative y than in the region of positive y. This fact is also expressed by the rms profile of acceleration fluctuations which shows smaller values for the positive than for negative y traverses.

It must be assumed that this asymmetric acceleration behaviour is due to a not exactly symmetrical stagnation flow in reference to the stagnation plate. A related small asymmetry of the flow field can be recognised already from the mean velocity profiles in Fig. 5. The local outbreaks of acceleration might be caused by circumferential inhomogeneities, which tend to develop in radially expanding stagnation flows under isothermal and under combustion conditions as well.

The same measurement as for the combustion flow were made for the flow without combustion. The fuel volume flow was replaced in this case with an adapted air volume flow. So the comparison can be made between the estimated accelerations in isothermal and in the combustion flows. This is done in Fig. 8 for the estimated mean positive and mean negative accelerations.

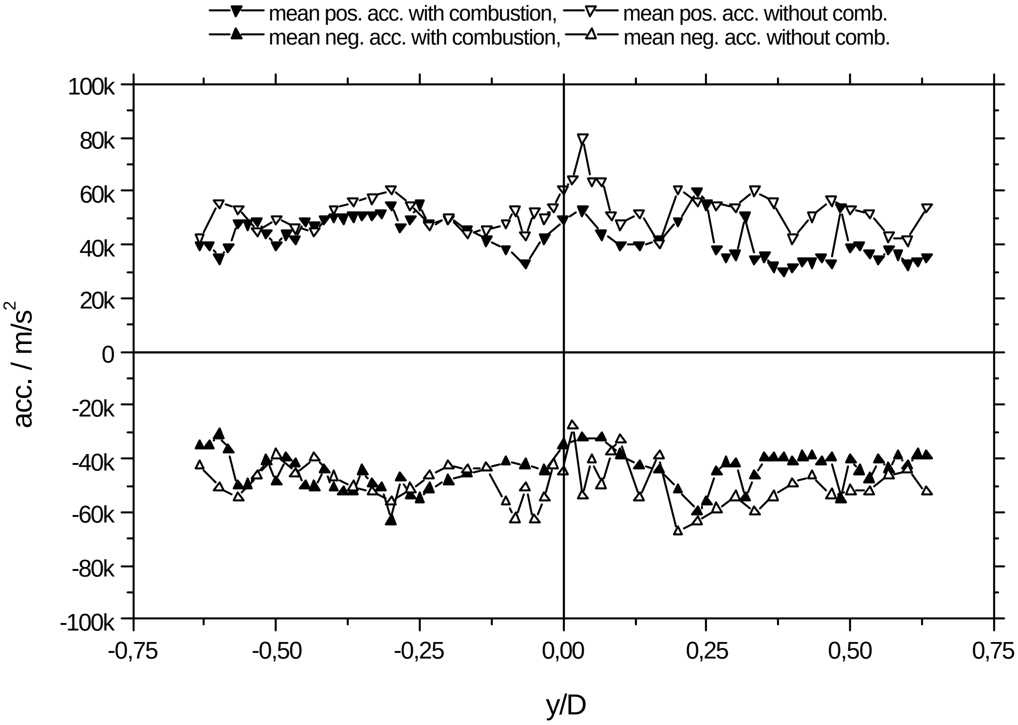

Fig. 8: Mean positive and mean negative acceleration portions compared for combusting and isothermal stagnation flow

We can see from Fig. 8 that only relative small differences exist between the profiles of cold and hot flow. The differences of the sign-related acceleration mean values are smaller for the negative y traverses than for the positive ones. An increased spread of the results and also some systematic deviation might be recognised for the positive y-values. There, if at all, the accelerations of combusting flow seem to be lower than for the cold flow. This holds also for the acceleration rms values and may be explained due to the flow viscosity which increases with temperature.

Nevertheless, the expected increase of the total amount of accelerations due to combustion cannot be found in this case. So our expectation might be wrong or the inspected model flow and/or the applied experimental techniques could be erroneous which will be discussed in the next chapter.

4. CONCLUSIONS

The following conclusions postulate that the seeding particles used for the LDA measurements were sufficiently mixed with the inspected flow regions so that no concentration bias would occur between the different mixing portions of the flow. This is not totally sure because the particles were introduced with a separate flow from the surrounding. In the flow region, however, where the measurements were done, the particles must have travelled across extended turbulent regions thus that the postulation above is assumed to hold.

The original idea of these experiments was to inspect a possible verification of locally concentrated thermal activity in the course of the combustion process via possible local fluid acceleration. Thus the model of thermally ignited short-time swinging of local fluid regions seems to be not realistic or does not effect the acceleration properties in the expected manner.

In the stagnation flow under research the combustion process tends to reduce the turbulent accelerations more than to excite them. A reason for this behaviour may be found in the viscosity features of the gas flow, which increases with the temperatures and thus exerts an increasing damping effect on the velocity fluctuations of the combusting flow compared with the cold one.

Splitting the relatively insensitive total mean acceleration values into positive and negative mean values offers a more detailed insight into the features of the different kind of flows. Experience shows that the total mean velocity is very difficult to be influenced by means of an interaction from outwards. The individual turbulent accelerations are such high that, in the mean, they are difficult to be influenced by means of external mechanical excitation.

The acceleration pdfs from local turbulent flows tend to be approximately Gaussian-like symmetrical also if the belonging velocity pdfs are heavily skewed or even if they are bimodal. Relatively weakly skewed acceleration pdfs have been observed with preference in the regions of thin shear layers with large mean velocity gradients.

The measurement technique enables us to separate and to analyse a mean local acceleration and the locally unsteady acceleration fluctuations. Referring to the equations of fluid motion we seem to estimate the substantial acceleration which we can split into the convectional and the local portions. Both are correlated with a local pressure gradient in the flow and with the local pressure fluctuations. In this sense, a measure is available which gives at least indirect information on relative local pressure fluctuations in turbulent flow.

5. OUTLOOK

The reported measurement technique is still in a very original state of development. Considerable improvements can be done with the conventional PC techniques of today. Faster and deeper digitisers and a more sophisticated trigger technique together with highly accelerated computation enables the application of refined software estimation modules for the acceleration with improved resolution and accuracy.

Another aim of our work is directed on multiple-component acceleration measurements. The obtained information can be used to estimate the radii of curvatures of the particle trajectories in the probe volume. If the particles correctly follow the flow, we suppose that these radii are statistically connected with the local turbulent scales' statistics in the flow. In that case the measurement technique would offer an increasing accuracy of analysis if the turbulent scales decrease.

In this sense the question is to be discussed whether the reported kind of information could be valuable for future flow research, experimental and numerical.

6. REFERENCES

Lehmann, B., Helbig, J., Simon, B: A Software Processor using FFT for Signal Burst Analysis in LDA. Internat. Specialists Meeting on "The Use of Computers in Laser Velocimetry", 1987, Saint Louis, France.

Lehmann, B., Helbig, J., Hassa, C.: LDA Method to measure the Acceleration of Particles and the Curvature radii of Particle Trajectories. Fifth International Symposium on Application of Laser Techniques to Fluid Mechanics and Workshop on the Use of Computers in Flow Measurement, July 1990, Lisbon, Portugal.

Lehmann, B., Helbig, J.: Laser-Doppler-Messung lokaler Beschleunigungen in turbulenter Strömung,7. GALA-Fachtagung " Lasermethoden in der Strömungsmeßtechnik", 27. bis 29. Sept. 1999, Deutsch-Französisches Forschungsinstitut Saint Louis (ISL), Saint Louis, France.