DEVELOPMENT OF AN ENHANCED PDA-SYSTEM FOR SIMULTANEOUS MEASUREMENT OF BOTH PHASES IN TWO-PHASE FLOWS

by

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ABSTRACT

The requirements on gas turbine and automotive combustion systems permanently increase due to more stringent emission standards. Thereby, fuel mixture generation provides a high potential concerning a reduction of toxic emissions. Hence, for development of future applications it is indispensable to have powerful measurement tools that provide a detailed insight into two-phase flows to optimize fuel mixture generation. In fluid mechanical applications laser optical measurement systems like PIV, LDV or PDA are established as state-of-the-art systems. However, only LDV and PDA provide the necessary temporal resolution required in the analysis of highly transient phenomena, like turbulent dispersion of liquid droplets or the interaction of droplets with large vortices in the case of combustion oscillations. The major drawback is their limitation to the detection of only one phase, either gaseous or liquid.

For an optimization of two-phase flows it is necessary to gain information about the interaction between both phases. So the standard measurement techniques have to be adapted to fulfil these requirements. Rottenkolber et al. (2000) showed that a one-dimensional analysis of the gas phase of a two-phase flow in presence of the disperse phase is possible via a fluorescent LDV system (FLDV), using the fluorescent light to determine the velocity. In this paper, an enhanced two-dimensional PDA-system is presented, based on the experience of the FLDV-system. It provides a simultaneous, two-dimensional analysis of gas and droplet velocities in a two-phase flow. It will also be possible to obtain information about the diameter distribution of the disperse phase. A spectral phase discrimination is applied, using fluorescent tracer particles. Evaluation will be made by means of an appropriate post-processing,. Hence, the PDA-system, using fluorescent tracer particles to mark the gas flow, allows a more detailed insight into the two-phase flow regarding the interaction between the two phases.

1. INTRODUCTION

The application of dry low NOx combustion systems to heavy duty gas turbines, based on a lean premixed combustion of natural gas has yielded remarkable advances concerning a reduction of toxic emissions. Due to more stringent emission standards, an adaptation of the LPP-combustion concept to liquid fuels has to take place in the near future. Thereby combustion oscillations, auto ignition and flashback represent a challenge and have to be prevented. For a better understanding of unsteady processes during LPP-combustion, which can lead to instable operating conditions, it is indispensable to study the two-phase flow in detail inside the premixing and the reaction zone. Thereby measurement techniques that provide high spatial and temporal resolution are of particular importance. Furthermore the interaction between gas- and liquid phase, e.g. in case of a periodic vortex breakdown, is of specific importance. Thus, simultaneous information about the velocity distribution of both phases is of particular interest. Also, detailed information about the diameter distribution is crucial for future optimization of mixture formation.

In the last decades different measurement techniques have been developed, that fulfil some of the depicted requirements. The Doppler-effect-based techniques like LDV and PDA are able to study technical flows with a very high temporal resolution (up to 100kHz). However, both work with a very small probe volume (single spot), thus mapping a larger area can only be achieved by repeating the measurement at different positions in the flow field. Velocities of single particles can be determined with both techniques, but the fields of application of LDV usually are single phase flows whereas PDA is used for investigating the disperse phase of a two-phase flow. PDA also provides additional information about the diameter of individual droplets inside a spray. Particle Image Velocimetry (PIV) offers a much larger probe volume (2D field), but temporal resolution is actually limited by the refresh-rate of digital cameras. Moreover, particle diameters cannot be determined directly by PIV. An improvement in terms of temporal resolution has been achieved by using high-speed cameras, so that a limited number of images can be taken within a short period of time. An improved instrument for simultaneous analysis of a two-phase flow is enabled by the use of fluorescent tracer particles in PIV-techniques is described by Richter et al. 2001.

Two-phase flows in gas turbine applications usually show periodic and non-periodic, transient phenomena, thus only measurement systems with a high temporal resolution can be used (Hehle et al. 2002). Hence, only systems, based on the Doppler-effect can be applied to investigate the flow field. In standard configuration Phase Doppler Anemometry (PDA) offers a two-dimensional velocity analysis and additional diameter information about each particle. Therefore the objective of this work is to simultaneously detect velocity and diameter of both phases in a two-phase flow with high temporal resolution by means of using an existing standard PDA-system, extended with an additional photo multiplier tube (PMT) as well as an appropriate post-processing scheme for phase discrimination. Thus, systematic predictions about the interaction between both phases and fuel mixture preparation will be enabled, providing necessary information for future optimisations of gas turbine or IC engine combustion. Due to a high temporal resolution, unsteady phenomena like vortex breakdown or combustion oscillations can be observed and evaluated in detail.

Rottenkolber et al. (2000) presented a fluorescent LDV-system (FLDV) that provides one-dimensional velocity information of the gas phase in presence of the disperse phase by adding fluorescent tracer particles to the gas flow and by analyzing the modulated fluorescence signal. This approach is based on a spectral discrimination into Mie-scattered and fluorescent light of the acquired burst signals, presented by Lemoine et al. (1999). Velocity evaluation for the disperse phase is done by analysing the Doppler-frequency in a standard configuration. For fluorescent light the explanation for the generation of a modulated Doppler signal is different but the authors demonstrated that the temporal behaviour of excitation and emission of DCM as fluorescent laser dye is sufficient to follow changes of light-intensity caused by passing particles through the measurement volume, so that the particles velocity can be obtained. Two- or three-dimensional velocity information cannot be obtained in this configuration because the spectral emission of fluorescence is independent of the exciting laser wavelength. Therefore two or three-dimensional measurements with phase discrimination using the laser wavelength (as it is done in a standard-PDA-system) cannot be done. Other procedures for phase discrimination as they were presented in the literature by Hardalupas and Taylor (1988) (size discrimination), Qui et al. (1990) (phase information), Levy (1986) (light intensity) or Muste et al. (1996) (diffraction in the near on-axis region) cannot be used for tracer particles having similar sizes like droplets in the disperse phase (fine spray or evaporating droplets). A different approach, using differences in the algebraic sign in the phase-size relation, which occurs in case of significantly different refractive properties between seeding particles and disperse phase, was proposed by Domnick et al. (1996). The aim of the present work is to improve the phase discrimination used by Rottenkolber et al. and to adapt it to a PDA-system. The main purpose is to extend the fluorescence velocity components to more-dimensional measurements and to improve validation of fluorescence signals in order to enable simultaneous measurements in two-phase flows. The setup of the experiments is based on the experimental setup

presented by Rottenkolber et al. (2000). First, requirements to fluorescent tracer particles, influencing variables on signal quality and development of an appropriate post-processing will be discussed. Finally, the obtained experimental results from validation tests will be presented and a discussion on future optimisation strategies and applications will draw the conclusion.

2. EXPERIMENTAL METHOD AND SETUP

2.1 Experimental setup

The experimental setup for the first tests was similar to the one presented by Rottenkolber et al. and is schematically shown in Fig. 1. A standard PDA-system (Dantec, 58N80 Multi PDA-processor) is set up in first order refraction (F=30°) at an atmospheric spray test rig. A Laskin-nozzle nebulizer is used to produce fluorescent tracer particles (DCM, 4-Dicyanomethylen-2-Methyl-6-p-Dimethylaminostyryl-4HPyran). Different spray nozzles can be mounted on a computer-controlled 3D-traverse. A second Laskin-nozzle nebulizer can also be hooked up for additional non-fluorescent seeding of the gas flow, which allows having a two-phase flow with fluorescent and non-fluorescent tracers of the same size distribution. This kind of two-phase flow is used for validation experiments.
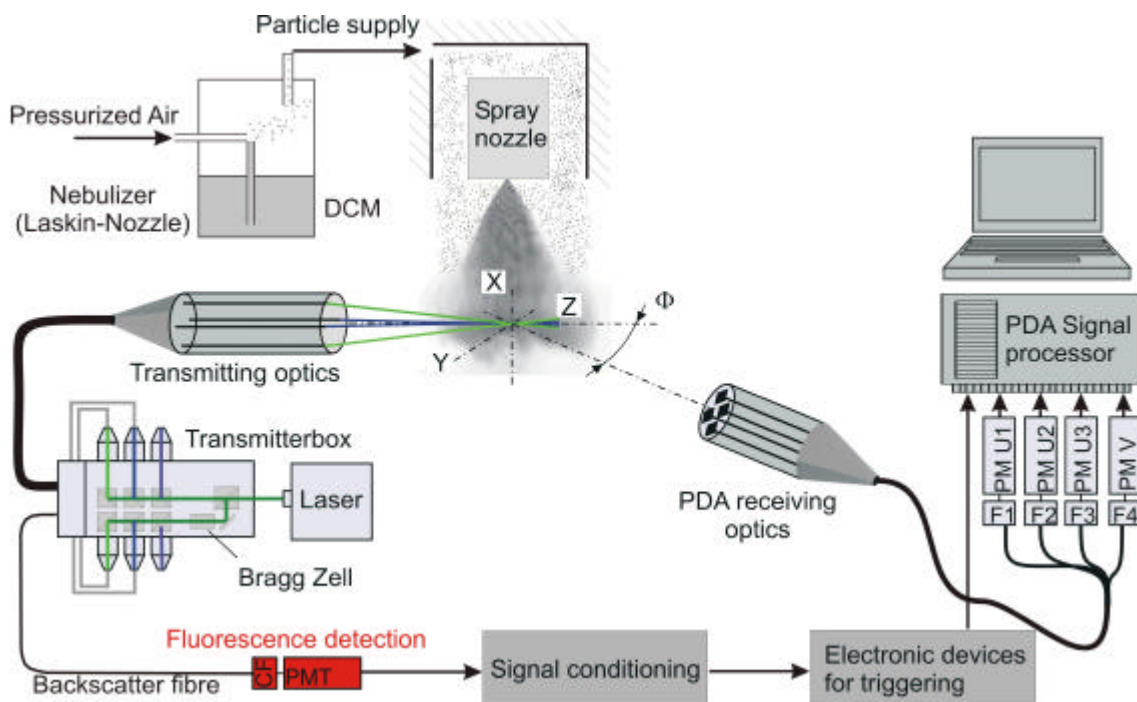

Figure 1 Experimental setup for fluorescent PDA (FPDA)

Fluorescence light was detected through a long pass glass colour filter (OG590) with an additional Photomultiplier (PMT) which was mounted either to the backscatter fibre of a standard 2D transmitting probe or to the PDA receiving optics. Appropriate signal conditioning by means of low pass filtering generates the envelope-signal of the fluorescence burst. The evaluation of the signal of fluorescent particles (tracers) enables phase discrimination also for a two-dimensional velocity analysis based on Mie-scattering. More details about constraints for fluorescent tracer particles, influencing variables for signal quality and appropriate post-processing for phase discrimination will be presented subsequently.

2.2 Fluorescence and tracer particles

As it is well known, it is necessary to seed the flow with tracer particles in order to study a gas flow field with laser optical measurement systems like PIV or LDV. For a good representation of the flow field, tracer particles have to fulfil a certain amount of requirements. Those were discussed in literature by Hjemfelt and Mockros (1965), Hinze (1975), and Melling (1997). All authors analysed the motion of particles in a velocity field and it is generally accepted that only very small particles are able to correctly represent the gas flow as they follow without a remarkable phase shift. However, light emission by small particles, either Mie-scattered or fluorescent, is influenced by size. In the case of Mie-scattering, light intensity depends on the particles' diameter and the position of the receiving optics. The characteristics of fluorescence emission differs from Mie-scattered light. Fluorescence describes a material property, to absorb light of a discrete frequency band and to emit the absorbed energy spontaneously in a specific frequency band. If these frequency bands do not overlap, a spectral discrimination of fluorescent light and coincident Mie-scattered light is possible. Due to the spherical emission characteristics of fluorescence, it can be assumed that the observation angle has no influence. The fluorescent light intensity is much lower than the Mie-scattered light. Therefore, detection of fluorescence is more critical and implies very sensitive photomultipliers. Influences on FPDA-measurements will be discussed in the following.

2.3 Parameters influencing signal quality and characteristics

For a systematic extension of an existing PDA-system to enable simultaneous measurements in two-phase flows, signal quality and characteristics have to fulfil different specifications. If the fluorescent light, as presented here, is only used for the discrimination between fluorescent or non-fluorescent particles, other possibilities and constraints arise than in the fluorescent LDV, where the modulated fluorescence signal is used to determine the particles' velocity. For the fluorescent PDA (FPDA) the modulation in the fluorescence signal will not be analyzed. The important part is the pedestal of the fluorescence burst. Therefore, the objective to optimize the signal quality is to generate maximal signal levels, independent of the modulation depth reached.

The demand for good tracking behaviour in a gas flow implies particles with sizes between less than 1µm up to max. 5µm. This implies a span in signal intensity of up to 1000 as the fluorescence emission is proportional to $d^3_{particle}$. Compared for the same range of diameters to the Mie-scattered light ($I \sim d^2_{particle}$), the range of fluorescent light intensity is 10 times larger. Considering the weaker signal of fluorescent light, it may be possible, that the PDA-system is still able to detect "Mie"-particles, while the fluorescence is too weak to be detected by the photomultiplier. A possible solution would be to mark the disperse phase with a fluorescent dye and to use non-fluorescent tracers for the air flow. In the current development, DCM will be used as fluorescent dye. Rottenkolber et al. (2000) investigated several dyes and found that DCM has an optimum of properties concerning fluorescence intensity and application as tracer particles. However a significant problem is the solubility of DCM in typical fuels. Furthermore, the FPDA-system is to be developed for two-phase flows which do not allow phase discrimination by particle size, as typical sprays for gas turbine or IC engine combustion imply droplets of similar sizes as the tracer particles. Thus, it would also be possible to have particles in the disperse phase that are too small to be detected.

It is indispensable to have coincident signals on both channels (Mie and fluorescence) for the implementation of a fluorescence detection capability to the PDA-system. Thus, ideally only one probe is used to detect both signals. The applied Dantec probe (57X50) offers four optical fibres to collect light, emerging from the measurement volume. Depending on the front lens of the transmitter, the size of the measurement volume and associated with this, the local laser intensity, the signal intensity varies. Higher intensities lead to stronger fluorescence signals and short focal distances for the receiving probe lead to higher signal levels, caused by the spherical emission characteristics of fluorescence particles. The available PDA-system, equipped with standard PMT's is unable to detect fluorescent light through the receiving probe, as the standard PMT's are optimized for wavelengths around 500nm. Therefore the backscatter probe or an additional PMT, optimized for fluorescence light, have to be used for fluorescence detection. In the case of using two probes, it is crucial that both probes are perfectly optically aligned to get coincident signals of good quality on both channels.

Due to a non-ideal transmission behaviour, the long pass glass colour filter does not block the Mie-scattered light totally. For large droplets, the Mie-scattered light is more intense than the fluorescent light of small tracers by several decades. Therefore, the photomultiplier for fluorescence light detects signals from disperse particles, too. To reduce this

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influence, the probe for fluorescence detection could be placed in a direction, where Mie-scattering is weak. Another possibility would be the use of a prism, combined with slit apertures to enable a better spectral discrimination of the detected light.

2.4 Experimental method

As previously described, the FPDA uses Mie-scattered light (488nm and 514nm) and fluorescence light (550 – 700nm, maximum at ~630nm) which is discriminated by means of glass colour filters. Appropriate signal conditioning and post-processing is required to investigate two-phase flows. Two approaches were pursued in order to perform a simultaneous analysis of both phases. By means of an electronic trigger device a TTL signal was generated and sent to the PDA system every time a fluorescent signal was detected. With this online technique high data rates were achieved but advanced processing schemes could not be implemented. A more versatile approach, applied also, used an offline, software based technique. The electrical signal of fluorescence was collected with an A/D interface card simultaneous to the PDA-measurement and an appropriate post-processing scheme for phase discrimination was performed afterwards. Different experimental and optical setups were applied for testing and validating the new evaluation routines. Acquiring the fluorescence signals through the transmitting probe in backscatter mode as well as via the receiving probe combined with a new, more sensitive photo multiplier tube (PMT) was tested.

Concerning maximum data rates up to 100 kHz for spray investigations, it is obvious, that online processing is only possible by means of fast hardware-processing. However, the highest achievable data rate is still restricted by the fact that signal processing must not take longer than the time difference between two signal bursts. Fig. 2 shows the setup for online-processing. Due to the specific features of the PDA-processor, the problem of the online approach was to attribute fluorescent and Mie-signals correctly. The additional PMT together with a signal conditioner generates a TTL-signal if fluorescence is detected. At the PDA-processor it was used as an encoder signal (set to the rising edge) and the encoder time was reset, every time a TTL-signal arrived. With this procedure, the presence of fluorescent particles in the probe volume can be detected by checking the encoder time of the collected PDA data. The PDA processor opens a "detector gate" when the intensity of the generated envelope signal of a burst signal passes a discrete level. The burst is accepted (gate closed), if an additional, higher level is reached and if the signal drops afterwards under level 1. In this case, the actual arrival time is assigned to the detected particle. This means that both signals have a time delay of almost one burst length (transit time). For application to real flow fields, signal detection encounters problems, if higher data rates have to be detected, because attributing fluorescence and Mie-signals fails for more particles. It also has to be considered, that signal conditioning (low pass filtering) can lead to a measurable phase shift for the fluorescence signal which means that time difference between both signals decreases and a direct comparison between time difference and transit time is impossible.
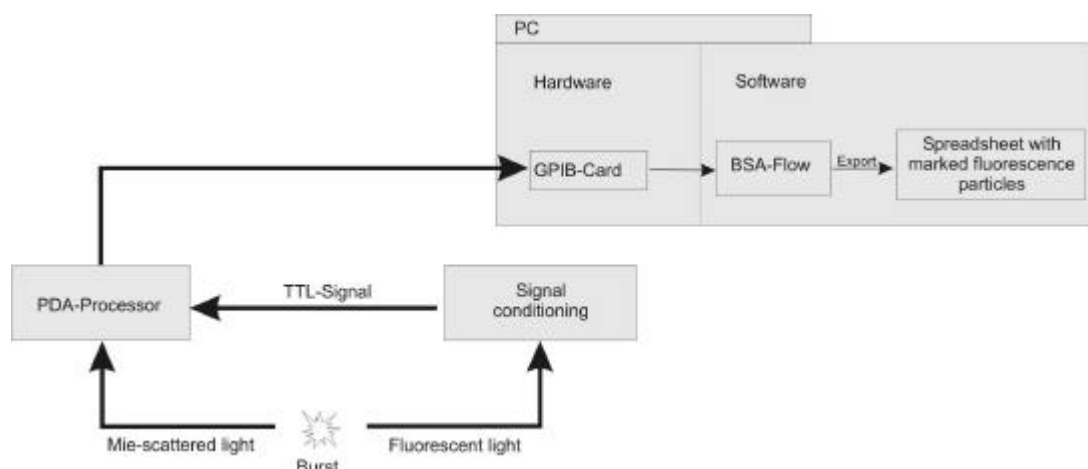

Figure 2: Schematic view on the realized setup for the online-processing

Another critical feature for optical setups, using the transmitting probe to detect the pedestal portion of the fluorescent burst, is the fact that its measurement volume is larger than the one of the receiving probe. At higher droplet densities

more than one droplet signal may be collected at the same time, because fluorescence emission occurs from each particle that is hit by laser light. This phenomenon is visible by generally higher data rates on the backscatter channel and might cause false triggering on the PDA processor especially if higher data rates have to be detected.

The offline approach for simultaneous measurement of both phases in two-phase flows allows more powerful and detailed interpretation of the acquired data, but the main disadvantage besides the fact that an online check of the results is not possible is the large post processing time necessary. On the other hand, iterative data analysis between PDA-data and fluorescence information can be used to improve measurement validation. Fig. 3 shows a schematic view on the developed post-processing scheme.
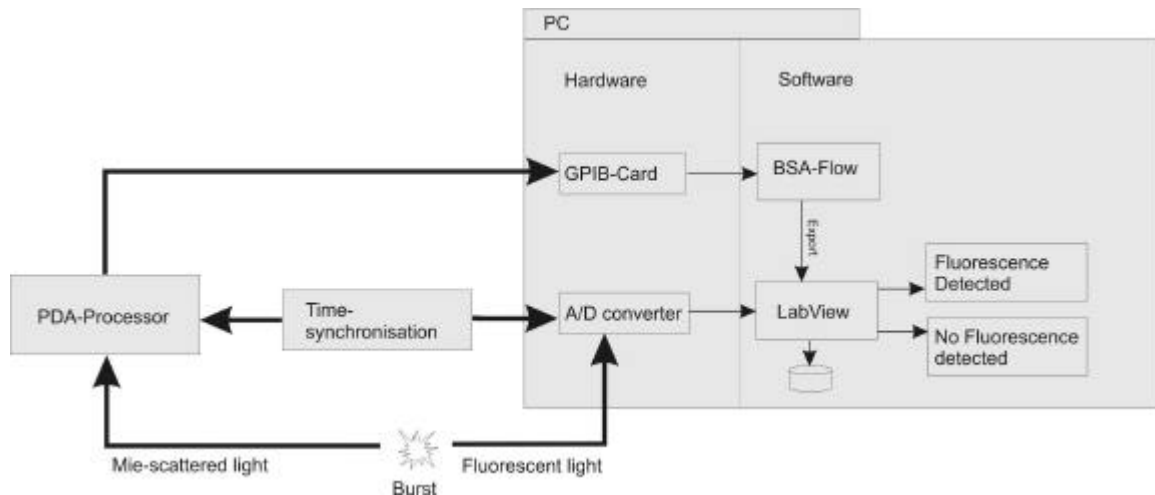

Figure 3: Schematic view on the realized setup for the post-processing

The Mie-bursts were acquired with a standard PDA-system equipped with a Dantec 58N80 MultiPDA processor. The signal of the additional PMT for fluorescence detection is sent to a National Instruments analog-to-digital converter (ADC) (16bit, 500kHz) which records the electrical signal with 250 kHz and saves it as byte stream on the hard disk. Considering the Nyquist-criterion, the maximum data rate that can be acquired with the presented setup is less than 125 kHz. The software routine written in LabView imports the acquired PDA-and A/D-data. To guarantee an exact time synchronisation a 1 Hz reference TTL-signal from a function generator is connected to the PDA encoder input as well as to channel 2 of the ADC board. For accurate pedestal measurements, a compensation of the dark current and the DC-level varying with the PMT's high voltage is necessary. Signal recording and processing to determine different thresholds for the post-processing is done by the ADC board and a LabView routine prior to the measurements.
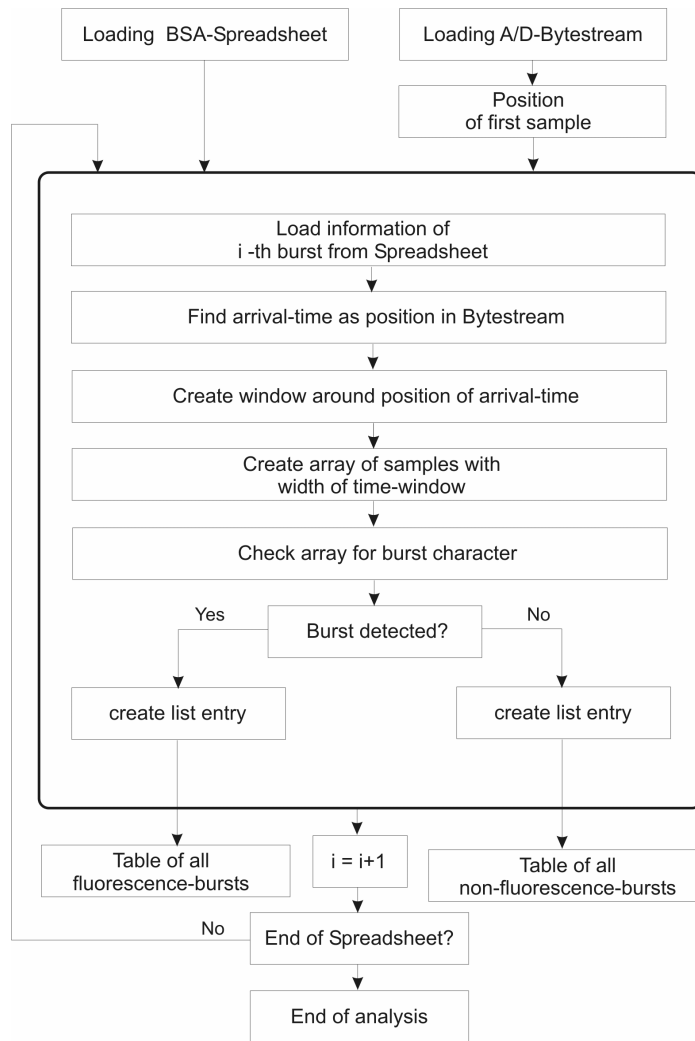
Figure 4: Schematic data flow for the post-processing routine

The schematic data flow of the post-processing routine is shown in fig. 4. First of all, both datasets are being loaded and the information of each burst is read line-by-line. Based on the arrival time, the corresponding position in the byte stream has to be found. Using the transit time combined with user defined criteria, a time window around the position in the byte stream is defined. Voltage data inside the window is read, integrated and written to an array for a burst character test. Two criteria are used to avoid erroneous fluorescence detection from noisy signals. The signal threshold and an integral threshold have to be determined in test-experiments before the measurements. Both criteria have to be exceeded to characterise a valid burst. If the burst is accepted, the corresponding particle-data is written to a file, where all fluorescent particles (gas phase) are saved. If no burst is detected, the particle is saved as non-fluorescent particle (disperse phase). Special care has to be taken to reach a high level of correct validation for fluorescence detection, because all measurements that are not marked as fluorescence are handled as disperse phase and would influence the results of the disperse phase. Thus, detailed experiments for testing the validation procedure in the post-processing routines were conducted and are described in the following sections.

3. RESULTS AND DISCUSSION

Several validation tests were conducted to check the correct mode of operation of the post-processing. Also first measurements with a two-phase flow, seeded with fluorescent and non-fluorescent tracer particles were performed. Initially, burst analysis and creation of time-window was tested by means of using the PDA receiving probe and analysing two detector-channels with the post-processing routine. For this setup only green laser light (514nm, 1D-setup) and fluorescent tracer particles were used. Instead of analyzing the fluorescence light, the coincident Mie-scattered light was sent to both PMT's. Influencing variables like coincidence and phase shift respectively, caused by low-pass filtering, could be evaluated with this setup. 99.4% of all acquired bursts were validated by the developed post-processing routine. 81% of the non-validated data (0.6%) did not reach the threshold level and 19% did not fulfil the integral threshold criterion. Violation of the integral threshold criterion could be attributed to an inaccurate creation of the time window, caused by false values in arrival time and transit time respectively. To make sure that the identified bursts were detected correctly and were not caused by noise or the like, it was tested to detect parts of the A/D-data with no burst signals. Therefore, using the same spreadsheet with manually changed values of arrival time, which were increased by +400µs, evaluation was done again.
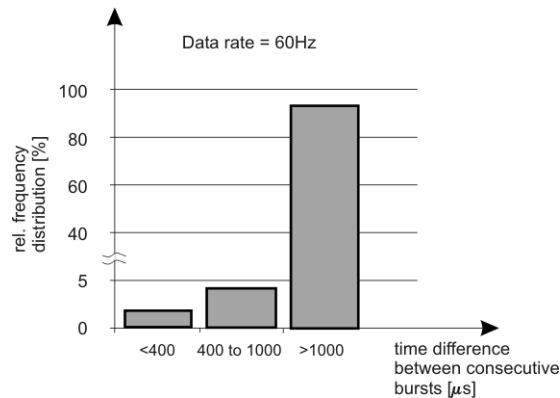

Figure 5: Relative frequency distribution of time difference between consecutive bursts

Considering the frequency distribution of time difference between consecutive bursts (see Fig. 5), it can be shown, that approximately 2% of all events should be shifted to the time window of the consecutive burst, if a data rate of 60Hz (as it was in this experiment) is applied. In this case, 2% would be detected as burst. The test showed that 98% of all events in the modified spreadsheet were not detected as bursts. Hereby it was shown, that the developed post-processing enables a reliable detection of the pedestal signal parts of bursts. The test was also conducted with higher data rates and showed similar results.

After making sure that the post-processing works properly, external effects on the correct validation were investigated. As discussed, the transmitting probe had to be used for fluorescence detection. Therefore, the same validation tests, as previously described, were conducted with this setup, too, using Mie-scattered light instead of fluorescence. 94% of all bursts were detected through the transmitting probe, combined with the post-processing. The remaining 6% didn't reach the integral threshold criterion and were discarded. This phenomenon might be caused by the use of two separate probes for detection. If they do not have a completely congruent measurement volume, a particle can be seen on one channel, while there is no or only a weak signal on the other channel. Furthermore, some signals showed a temporal shift up to 50% of a burst length. This may lead to problems in evaluating the integral threshold. However, the results showed that the developed post-processing proves to be a powerful tool for burst detection and evaluation.

Further tests were performed with fluorescent tracer particles, using a long pass glass coloured filter to detect the fluorescent light through the transmitting probe. 80% of all acquired particles were reliably detected as fluorescence. Taking into consideration, that 94% of all particles had been detected with the same setup, using Mie-scattered light, the enhanced PDA-system is able to detect 85% of all possible data. The lack of 15% non-validated data is caused by low intensity of fluorescence signals. Additional tests were conducted to resolve this phenomenon. Averaged pedestal

fluorescence signal levels as well as maximum and minimum signal levels for each class of particle size, determined by the PDA-software, were evaluated. Measurement data showed, that averaged signal levels as well as the maximum levels increase with particle size. However, minimum levels are nearly constant for each particle size. This means that in each size class some particles exist producing a low fluorescence signal and therefore may not be detected as they pass the measurement volume on an outer area, where the laser intensity is lower, caused by the Gaussian intensity distribution. A challenge for all experiments that use the transmitting probe to receive the pedestal portion of fluorescent light is that its measurement volume is larger than the one of the receiving probe and therefore more particles produce a signal, because fluorescence emission is forced in each particle that is hit by laser light. This phenomenon causes higher data rates on the backscatter channel which can lead to false triggering on the PDA processor if higher data rates have to be detected.

Validation measurements in a real two-phase flow were also conducted. An automotive injection nozzle for SI-engines was mounted to the test rig. Fluorescent tracer particles were added to the gas flow. Measurement data showed that Mie-scattered light, caused by large disperse particles, was detected on the fluorescence channel. This phenomenon is based on the transmission characteristics of the glass coloured filter (OG590). According to the manufacturer's specification, transmission is below 0.001% up to a wavelength of 540nm. Regarding that the intensity of Mie-scattered light is multiple orders of magnitude higher than the fluorescent light, emitted by the same particle, it is obvious that some of the Mie-scattered light still passes the filter and produces signals on the PMT. Therefore, for future applications to two-phase flows it will be necessary to change the type of spectral filtering. For future experiments, a prism in combination with slit apertures will be applied to enable better spectral filtering. However, validation experiments showed that a two-dimensional analysis of velocities and simultaneous diameter information of both phases in two-phase flows can be reached by using an additional PMT for fluorescence detection.

4. CONCLUSIONS

With regard to the future development of combustion systems, powerful measurement tools are indispensable to improve e.g. mixture formation or to analyse combustion oscillations. Therefore, multi-dimensional velocity information and diameter distributions with a high temporal resolution are necessary. Thus, an enhanced PDA-system, using fluorescent tracer particles (FPDA), has been developed to enable simultaneous detection and evaluation of both phases in two-phase flows.

Based on the FLDV-system, presented by Rottenkolber et al. (2000), fluorescence is used for phase discrimination. For an extension to more-dimensional measurements, velocities cannot be evaluated by using the modulated fluorescence signal. Therefore fluorescence signals are only used to identify fluorescent seeding particles. Velocity and diameter evaluation is conducted by a standard PDA-system. Different approaches for the detection of fluorescent particles were made and discussed. Optical phase discrimination was performed by means of spectral discrimination of fluorescent and Mie-scattered light. Appropriate post-processing was developed and tested for phase discrimination. Acquiring fluorescence data by means of the transmitting optics produces reliable validation rates of up to 85% for fluorescence detection. The fluorescent PDA (FPDA) therefore represents a powerful tool for analysing two-phase flows for future applications. Simultaneous information about velocities and diameter distributions in both phases will allow to obtain important data for development or for a numerical simulation of two-phase flows.

For future applications of the fluorescent PDA-system (FPDA) the efficiency of the spectral discrimination will be improved by using a prism instead of a long pass coloured filter. The use of the original PDA receiving probe for fluorescence detection enables simultaneous measurements with higher data rates, because of absolutely identical measurement volumes.

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