3D-DGV for flow field investigation in pipes

by

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ABSTRACT

DGV is presented as an optical whole filed acquisition technique for the measurement of three dimensional velocity vector fields in pipes. In order to increase the number of measuring points drastically, to measure three dimensional velocity fields and to shorten the measuring time for each velocity field measurement, the 2D-LDA test rig for the investigation of installation effects at PTB has been extended by a Doppler Global Velocimeter in close cooperation with the Institute of Propulsion Technology at the German Aerospace Center (DLR) in Köln, Germany.

Figure 0:  Set-up of the DGV-system for the 3D flow field analysis in pipe configuration and example of a DGV-measurement of the flow field in a pipe with a swirl plate at its inlet.
INTRODUCTION

Many efforts were made in order to reduce the error shifts of flow meters caused by installation effects. To find out effective methods and techniques to minimize these installation effects it is necessary to understand the physics of the chain pipe configuration – disturbed flow profile – change in flow meter behaviour [1, 2, 3, 4]. On one hand installation effects basically depend on the physical principle of the flow meter itself and on its concrete construction. On the other hand the measurement practice shows a wide variety of pipe installation geometries and different duct configurations.

At PTB the influence of the pipe configuration on the flow profile as well as the influence of the disturbed flow profile on the flow meter error has been investigated systematically [1, 2]. The efforts were concentrated on the behaviour of turbine meters because these meters are of great importance for the measurement of large gas volumes in Europe and the metering errors due to installation effects can be as large as several percent. To carry out these experiments an automated two-component LDA test facility for atmospheric airflow was used, which has recently been extended by a 3D-DGV-System. This facility consists of an installation configuration, the optical test unit to measure flow profiles or complete flow fields in the entire cross section of the pipe, the gas meter to be investigated and the flow rate standard consisting of eight critical nozzles put in parallel.

![Figure 1: LDA test facility for the investigation of installation effects](image1)

In a first step the installation configuration, the gas meter to be investigated and the flow rate standard of the facility were used to investigate the flow meter error for different pipe configurations.

![Figure 2: Installation configuration based on a double elbow out of plane mounted in the test facility, corresponding error shift of a turbine gas meter due to the double elbow installation configuration and reduction of the error shift by applying a Zanker flow straightener](image2)
Several types of flow straighteners and conditioners were investigated and evaluated with regard to their efficiency to reduce flow disturbances generated by pipe configurations. Figure 2 for example shows the efficiency of a Zanker straightener to reduce the error shift of a turbine meter caused by a double elbow installation configuration.

Quantitative statements about the effect of different installation configurations on the error shift of turbine gas meters and the efficiency of flow conditioners were possible by extensive systematic investigations of the velocity profiles for a variety of pipe configuration at different distances downstream of the flow [1, 2].

For these investigations the optical unit in the testing rig at PTB allows to analyze the flow field across the entire cross section in a DN 200 pipe at arbitrary inlet conditions. A 2D-LDA measuring unit LDA1 and LDA2 was traversed perpendicular to the pipe axis and could be rotated by a full angle of 360 degrees around the pipe axis (see figure 1). Thus the single point LDA technique delivered detailed knowledge of the flow characteristics inside the pipe configurations of interest by measuring two dimensional velocity profiles point by point.

Figure 3 shows the axial flow profile 3D downstream of a double bend out of plane before and after applying a Zanker flow straightener. Before applying the flow straightener the axial velocity profile is obviously asymmetric and differs significantly from the ‘fully developed’ flow. After applying a Zanker flow straightener the axial flow profile is almost equal to an ideal ‘fully developed’ flow according to the reduction of error shift shown in figure 2.

To make quantitative statements on the relation between flow disturbance and flow meter error as well as the efficiency of flow conditioners in pipe configurations the flow field can be described by flow numbers to quantify the main characteristics of the flow [2] such as the axial momentum number $K_u$ indicating the flatness of the axial velocity profile, the swirl number $K_v$ where the sign related to the rotating direction and the asymmetry number $K_A$ describing the distance of the centroid of the mass flow from the pipe axis. The calculation of these flow numbers will highly depend on the measuring points taken into consideration. For complicated flow field structures the measured flow profiles will highly depend on the chosen LDA traverse. This dependence will also affect the calculation of the flow numbers characterizing the flow field.

In order to increase the number of measuring points drastically, to measure three dimensional velocity fields and to shorten the measuring time for each velocity field measurement the testing rig has been extended by a Doppler Global Velocimeter in close cooperation with the Institute of Propulsion Technology at the German Aerospace Center (DLR) in Köln, Germany.

![Figure 3: Axial flow profile 3D downstream of a double bend out of plane (see figure 2) and axial flow profile 3D downstream of a double bend out of plane after applying a Zanker flow straightener in order get a nearly 'fully developed' flow profile describing an undisturbed flow.](image)
Doppler Global Velocimetry is a relatively new technique for the investigation of flow fields, invented by Hiroshi Komine in 1990 [5]. In the last years this technique has become a promising flow field diagnostic tool for research and development tasks in aerospace and car industry [6, 7, 8, 9]. At the PTB the Doppler Global Velocimetry based test facility is used to investigate flow fields in pipe configurations in order to get more information about installation effects affecting the measurement of gas flow rates. In this facility three components of velocity can be acquired over a two-dimensional field in only a few minutes.

**DOPPLER GLOBAL VELOCIMETRY: PRINCIPLE**

In difference to other Doppler techniques the Doppler Global velocimetry (DGV) uses an absorption cell to evaluate the Doppler shift of the laser light scattered from particles embedded in the flow. However DGV uses an optical frequency discrimination technique to evaluate the velocity of the tracer particles. By tuning the frequency of a powerful laser to the edge of an absorption line filter (Argon laser frequency $\nu_0$, Iodine cell transmission $T(\nu_0) = 50\%$) changes in the scattered light frequency ($\nu_0 \pm \nu_D$) can be transferred into transmission changes $T(\nu)$ of the $J_2$-absorption cell (see figure 5).

As the scattered light frequency changes due to the Doppler effect $\nu_D$, the light intensity detected behind the absorption cell can be evaluated to measure the velocity of the scattering particles. Therefore, the idea of DGV is to transfer the Doppler shift of scattered light into a light intensity, which can be measured easily by a diode or pixel arrangement of a CCD camera. The letter one allows to measure the velocity at many points in the flow field (light sheet) simultaneously.
The component of velocity which can be measured is given by the geometry of the setup and depends on the angle between the incident direction of the laser light sheet and the observation direction:

\[ v_D = V_0 \frac{(\hat{d} - \hat{i})}{c} \hat{v} \]

**DGV IN PIPE CONFIGURATIONS**

By employing a powerful frequency stabilized laser and an absorption cell to evaluate the Doppler shift of the scattered light it is possible to measure complete velocity fields when the flow region of interest is illuminated by a laser light sheet. By the use of three different incident light sheet directions three components of velocity can be acquired along the cross section of the pipe (see figure 8). For this the light of a Lexel laser with an output power of 1 W at the wavelength of 514.5 nm is stabilized by a micro controller based frequency stabilization unit controlling the temperature of the etalon and the resonator length by a piezo element driven laser mirror. The emission frequency of the laser is stabilized at \( \nu_0 \) corresponding to a transmission \( T(\nu_0) = 50 \% \) on the absorption wing of the iodine absorption line. The laser beam is then sequentially coupled into three laser light sheet heads (see figure 8) by the use of an optical switch and a fiber launching system (see figure 6).

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**Figure 6:** Setup of the laser frequency stabilization and fibre-coupling unit with optical switch.

**Figure 7:** Principle of the light sheet generation by a rotating glass square plate.
Each fiber coupled light sheet head generates a light sheet by a rotating glass square plate (see figure 7). The optical access for the generated light sheets to illuminate the cross section inside the pipe is realized by a special window construction over a 3 mm slit in the pipe. The scattered light from the sequentially generated light sheets 1, 2 and 3 is imaged onto the cameras CCD1 and CCD2 via a mirror mounted 5D downstream from the light sheet plane in the pipe section to avoid flow field disturbances upstream in the measurement plane.

Figure 8: Setup of the DGV-system for the flow field analysis in pipe configuration.

To measure the velocity field, it is necessary to take two images of the same flow region, one viewed through the absorption cell (signal camera CCD 2), and one viewed directly (reference camera CCD 1), so that the intensity variations across the imaged area can be normalized. The CCD cameras had an active image array of 384 x 286 pixel each. Imaging the illuminated cross section of the pipe onto the cameras about 85,000 pixels could be used for the representation of the flow filed inside the pipe. Division of the images from the signal and the reference camera on a pixel-by-pixel basis produces a 2D map of the absorption cell transmission over the viewed area. This information delivers via the cell calibration the information about the local Doppler shifts and thus the local velocity components according to the geometry of the optical setup. Evaluating the successively taken images for each light sheet one gets three dimensional velocity fields.

**DGV MEASUREMENTS: EXPERIMENTAL RESULTS**

DGV measurements have been performed for several pipe configurations and have been compared with the 2D-LDA flow profile measurements. The comparison of the measuring results of the LDA and the DGV system obtained for the same pipe configurations will show the potential of Doppler Global Velocimetry for the characterization of flow fields in pipe configurations. The following figures exemplarily show some of the experimental results.
The measurement results shown in figure 9 were obtained behind a straight pipe of the length of 28D in order to get nearly a fully developed turbulent flow profile as reference profile for an undisturbed flow. The results presented in figure 11 show the flow field behind a double elbow pipe configuration (see figure 10) where the swirl is mainly eliminated by a honeycomb flow conditioner. The axial flow field remains highly deformed at 4D downstream of the elbow even with the flow conditioner.

Figure 9: DGV-measurement and LDA-profile measurement of a “fully developed” flow profile as reference for an undisturbed flow. (Re = 1 \cdot 10^5)

Figure 10: Double elbow pipe configuration with a honeycomb flow conditioner.

Figure 11: DGV-measurement and LDA-profile measurement of the flow field behind the pipe configuration see figure 10 (Re = 2 \cdot 10^5)
DGV measurements especially allow to investigate the propagation of flow profile deformations in pipe configurations in relatively short measuring times (see figure 12 and figure 13).

**Figure 12:** Axial velocity profiles at different measurement positions 1D, 3D and 4D downstream of an OIML high level disturbance with a Laws flow straightener.
The same OIML high level disturbance without using a flow straightener leads to the axial flow fields shown in figure 13, which additionally show a slight rotation of the axial flow velocity maximum.

**Figure 13:** Axial flow profile 1D, 3D and 4D downstream of an OIML high level disturbance without using a flow straightener.
Figure 14 shows a DGV measurement result of a flow field influenced by a swirl plate at the inlet of a straight pipe. In difference to the experimental results shown in figure 9 obtained for an undisturbed flow or in figure 11 and 12 for already straightened flows with no or negligible in-plane velocity components, figure 14 clearly shows a swirl besides the deformation of the axial flow field.

Thus DGV is a powerful tool for the investigation of installation effects and the reduction of error shifts in flow rate measurement facilities. Additionally DGV delivers a higher information density in a shorter measurement time compared to the LDA-technique.

**DGV FLOW RATE MONITORING**

Besides the systematical investigation of three dimensional flow fields in pipe configurations to get more information about installation effects, the DGV technique may also be used for the direct measurement of volume flow rates independently on flow field deformations.

In a first step the volume flow rate was directly determined by calculating the product of the cross section $A$ of the pipe with the mean value of all axial velocity values corresponding to the evaluated pixels in the CCD camera images. The resulting volume flow rates for different pipe configurations were directly compared with the flow rates obtained by the critical Laval nozzle stage in the test facility representing the flow rate standard for the measurements. The quotients of the flow rates measured by DGV $q_{DGV}$ and Laval nozzle $q_{Lav}$ were determined for different pipe configurations including different types of flow straighteners. The mean value of the relative measuring deviations over ten different flow rate measurements given by the quotients $q_{DGV} / q_{Lav}$ is less than 5 %. Single flow rate measurement have even higher deviations for the relatively low flow velocities in the pipe below 25 m/s. By increasing the absolute accuracy of DGV in the near future, it may be an interesting aspect to use this technique also for flow rate monitoring independent of installation effects.
CONCLUSIONS

Doppler Global Velocimetry has been shown as an interesting whole filed technique for the measurement of flow fields in pipe configurations in order to investigate flow meter errors by analyzing upstream flow profiles depending on installation effects.

The resolution for the DGV velocity measurement is in the range of 1 m/s so that velocity field deformations can be analyzed even for relatively small flow velocities up to 25 m/s.

The deviations of first flow rate measurements in pipes based on DGV are relatively high at the moment (some per cent over the performed measurements). To measure flow rates on-line independently of flow profile deformations in pipe configurations the absolute accuracy of the DGV-setup has to be increased.

The main advantage of the applied DGV-system is its capability of measuring 3D velocity vector fields with a high measuring point density of about 100,000 pixels per image plane in only a few minutes. Thus systematic flow field investigations can be performed in drastically reduced measuring times compared to the application of LDA-techniques.

REFERENCES


