Improved GSI Out-of-Focus Technique for Application to Dense Sprays and PIV Measurements

Calabria R., Casaburi A., Massoli P.

Istituto Motori - CNR, Via Marconi 8, 80125 Napoli, Italy

An improved scheme for the GSI out of focus technique is proposed. The new approach makes use of double laser pulses with crossed polarizations and of a single CCD for the image acquisition. The use of different polarizations permits a fine recognition of the droplet doublet images from which the velocity of each droplet is determined in addition to its diameter. The new scheme improves the signal to noise ratio and decreases data rejection, thus permitting the extension of the technique to dense sprays. More, the utilisation of beams with different polarisations permits to determine also the velocity direction beside its modulus.

1. Introduction

The characterisation of sprays is fundamental in the analysis of several industrial processes and natural phenomena. In practical industrial systems (e.g., combustion and drying processes) or in simulation test rigs (e.g., in icing tests to simulate droplets freezing in atmosphere) droplets in sprays undergo fast and significant variation of diameter, velocity and composition (and, hence, of refractive index). Many efforts have hence been spent by the scientific community to develop non-intrusive techniques based on the properties of the scattered light to characterise sprays and also to validate integral spray models or submodels. 2D techniques are particularly useful to this aim because they permit to simultaneously perform time and space averaged measurements.

Droplets concentration represents one of the main limitations of imaging techniques for spray analysis that are based on droplet identification. In such techniques a high droplets concentration preventing a good recognition of droplet images decreases the signal to noise ratio and can completely compromise the spray analysis. In GSI out-of-focus technique the droplets characterization is based on the analysis of the scattered field that is imaged inside the defocused picture of droplets in a spray [1,2]. The superimposition of defocused images generates the interference between the electromagnetic fields scattered by different droplets thus causing lower counting rates and also dubious results. This problem is much more critical when velocity of droplet is determined by using a time of flight approach. In such a case, the superimposition of out of focus images prevents the determination of velocity. This is due to the enlargement of the images of droplets when the imaging system is out of focus respect to in focus conditions. To overcome the limitation due to images superimposition, an experimental layout where droplet images were reduced to a string by means an optical compressor was proposed [3]. A commercial system proposes the utilization of two CCDs that view the same area: one is dedicated to the sizing and is placed out of focus, the second CCD is in focus and serves to measure the velocity of droplets [4].

Aim of the paper is to propose a new scheme for the GSI out of focus technique to measure velocity and size of droplets by making use of a single imaging system and a double laser pulse scheme characterised by crossed light polarisations. In the new scheme, each full droplet image is reduced to a "string" by placing a slit in front of the detection system [5,6] (Fig.1). The use laser pulses with horizontal and vertical light polarisation simplifies the analysis of images doublets to infer the motion field. This, in turn, improves the signal to noise ratio and decreases data rejection, thus permitting the extension of the technique to dense sprays. In addition, the use of pulses of different polarisation permitted the unambiguous determination of the direction of velocity as well as to its modulus.

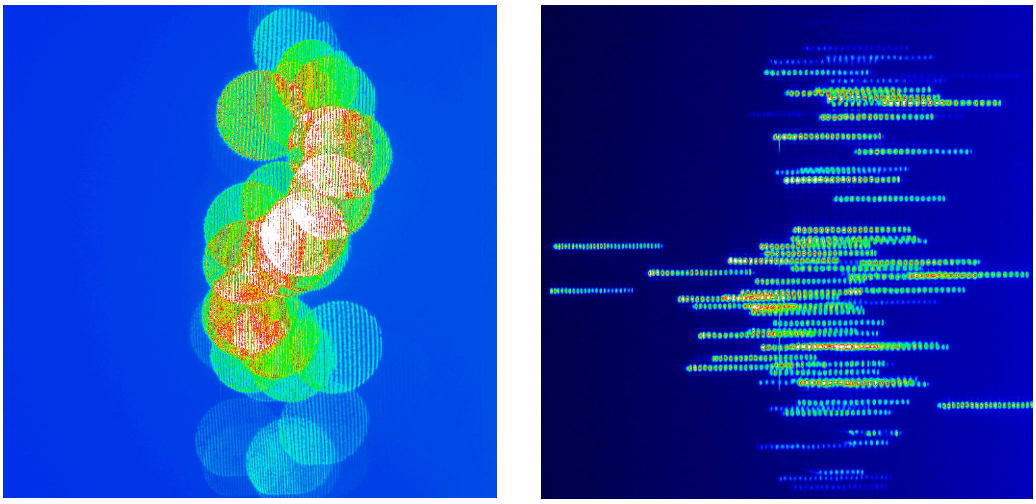

Fig. 1 "Full" and "string" out of focus images of grouped water droplets of 70 µm. Each string in the right picture corresponds to a droplet.

2. The GSI-PIV, out-of-focus technique

It is well known that the scattering pattern of droplets is characterised by large intensity oscillations (scattering lobes), the spacing of which depends on the droplet diameter. Kerker expressed a quantitative relation from which the diameter D of a droplet could be inferred by measuring the oscillation spacing $\Delta\vartheta$ [7]:

$$\Delta\vartheta = 180 / \alpha \qquad (1)$$

However, oscillations in the angular pattern are not so regular and $\Delta\vartheta$ depends on the refractive index, *m*, too. Glantschnig and Chen [8] by using geometrical optics founded a rigorous and complete relation:

$$\Delta\vartheta \cong \frac{2\pi}{\alpha}\left(cos\frac{\vartheta}{2} + \frac{m\,sin\frac{\vartheta}{2}}{\sqrt{1+m^2-2m\,cos\frac{\vartheta}{2}}} \right)^{-1} \qquad (2)$$

that fixed the dependence of $\Delta\vartheta$ on the refractive index and the scattering angle. König et al. proposed an experimental system to determine droplets size by measuring the oscillations spacing o the scattered field [9]. Using a simplified form of relation (2), they demonstrated the applicability of previous theoretical concepts to practical measurements. However, their approach was based on the analysis of the far field of electromagnetic radiation scattered by a single droplet at time in a single spatial location and, therefore, not suitable for 2D spray measurements. Ragucci et al., proposing the out of focus approach, opened the way to the 2D utilisation of the sizing method based on the oscillations angular spacing. In fact, they demonstrated that positioning the imaging system in out of focus, the interior of each defocused droplet picture is the image of the field scattered by the droplet itself (Fig. 1) [1]. Thus, the problem of acquiring on the same 2D picture the far field scattered by different droplets was solved. Using the Lorenz-Mie theory, they found a correlation between drop diameter and number of lobes per degree and sizes of droplets were measured by counting the number of fringes present in each defocused drop image. The Lorenz-Mie theory was used in the reduction of the experimental data in order to overcome limitations due to the use of geometrical optics relations.

Droplets in practical systems undergo fast and remarkable variation of refractive index. This is due to both physical and chemical phenomena (heating, cooling, evaporation, oxidation, liquid phase pyrolysis, etc.). Thus, non homogenous droplets are usually expected in practical system and the Lorenz-Mie theory and geometrical optics should be used with some caution. To overcome such a limitation an extensive theoretical study of the behaviour of the angular scattering pattern of homogeneous and inhomogeneous as well as absorbing and transparent droplets was carried out. Mie theory [7] and Finely Stratified Sphere Scattering Model [10], FSSSM, are used in the analysis of the scattering images. The FSSSM approach allows the computation of the scattering by radially inhomogeneous spheres. The FSSSM approach is particularly relevant in combustion where droplets spend all life in non-stationary regime, that means droplets with a non-homogeneous composition and temperature. In such a condition the use of the Lorenz-Mie theory or geometrical optics is prevented.

At a scattering angle ϑ=60°, the influence of the complex refractive index, *m*, (in case of homogeneous droplets) and of its distribution inside the droplet, *m(r)*, (in case of inhomogeneous droplets) is negligible on the angular spacing of intensity oscillations, $\Delta\vartheta$. More, at ϑ=60°, a very simple relation links $\Delta\vartheta$ to the droplet diameter D [2,11]:

$$\Delta\vartheta\ (\vartheta, m(r), D) = 1.129\ (180° / \alpha) \quad \text{at } \vartheta = 60° \qquad (3)$$

or

$$D = 1.129\ (\lambda / \Delta\vartheta) \quad \text{at } \vartheta = 60° \qquad (4)$$

where $\alpha = \pi D/\lambda$ is the scattering size parameter and λ is the light wavelength. In the relation (4), D and λ are expressed in micron and $\Delta\vartheta$ in radians.

In *GSI* out of focus technique, the size of a droplet is inferred independently of droplets composition or temperature, by measuring the angular spacing of intensity oscillations of the scattered light in defocused droplet images and by using relations (3) or (4). Thus, GSI technique is particularly suitable to study evaporating droplets in non-stationary regime. Moreover, by measuring the *visibility* of scattering intensity oscillations the absorption of droplets can be determined in addition to their diameter [12]. In this paper we will discuss the improvement of the technique in order to measure droplets velocity in addition to their diameter.

We propose a double laser pulse configuration of GSI technique in order to infer droplets velocity by means a time of flight approach: by measuring the space ran by a droplet in the fixed time the velocity is obtained. Peculiar characteristic of the proposed system is the utilisation of two laser pulses having orthogonal light polarisations. The first one was vertically polarised and used to determine the size of droplets. The second beam, horizontally polarised, was delayed respect to the vertical polarised one and serves to define the position of droplets after the elapsed time. Velocity of droplets is inferred by measuring the shift of the droplets images corresponding to the two laser pulses. Due to the different polarisations, out of focus images generated by the two pulses are easily recognized. Thus, images analysis is really simplified and the velocity is unambiguously determined.

One of the main characteristics permitting to distinguish between out of focus images generated by the scattering of radiation of different polarisation is the oscillation "visibility". At ϑ=60°, the scattering patterns for light horizontally polarised presents oscillations of the intensity less pronounced respect to the pattern for vertical polarisation. The contrast between maxima and minima in an oscillating signal, like the intensity in the angular scattering pattern, can be quantified by using the concept of visibility:

$$\eta = (I_{max}-I_{min})/(I_{max}+I_{min}).$$

According to Fig.2 I_{max} and I_{min} represent the maximum and the minimum values of the scattered intensity, respectively. Visibility assumes values close to 1 for very deep oscillations and tends to zero for a flat signal. For transparent droplets, visibility for vertically polarised light is around 0.9 while is around 0.2 for the horizontal polarisation one. Thus, the analysis of visibility of the pattern inside out of focus images easily allows distinguishing between images corresponding to horizontal and vertical polarised light, respectively. This, in turn, facilitates the identification of doublets of pulses due to each droplet in the spray. More it permits to define the direction of the droplet motion.

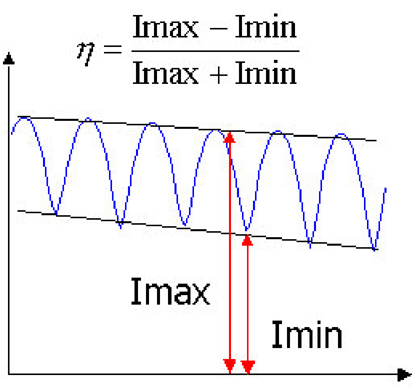

Fig. 2 Visibility of an oscillating signal

2. Experimental set-up and selected results

Figure 3 shows the layout of the experimental set-up. Two Nd-Yag laser pulses @ λ=532 nm of equal intensity and orthogonal polarizations were delayed by means a variable delay generator. In the series of experiments we carried out, the delay was varied between 0.4 ms and 1 ms. The beams were superimposed by using a polarising beam splitter. The energy of the pulses, 8 ns short, was balanced to the same value of about 70 mJ. Both the laser beams were reduced in the measure volume to a sheet 100 µm thin by a cylindrical lens. The first laser pulse, vertically polarised, was used to determine the size of droplets. The second laser pulse, horizontally polarised, was used coupled to the first one to determine the velocity of droplets by a time of flight technique. The different visibility of the oscillations of the scattered field in out of focus images with horizontal and vertical polarisations permitted the unambiguous association between images due to the two beam pulses and corresponding to the same droplet. Figure 4 shows a typical image recorded during the experimental campaign. The doublets of out of focus images of different polarisation and corresponding to different single droplets are easily identifiable in the picture.

A droplet generator was used to produce the spray we investigated. Water was used in the tests. The droplets were dispersed in a primary air flow of 1.75 liter/min and injected in a coaxial secondary air flow that was varied between 2 m^3/h to 8 m^3/h. The spray and coaxial air fluxes were confined in a 40 mm ID cylinder of Plexiglas.

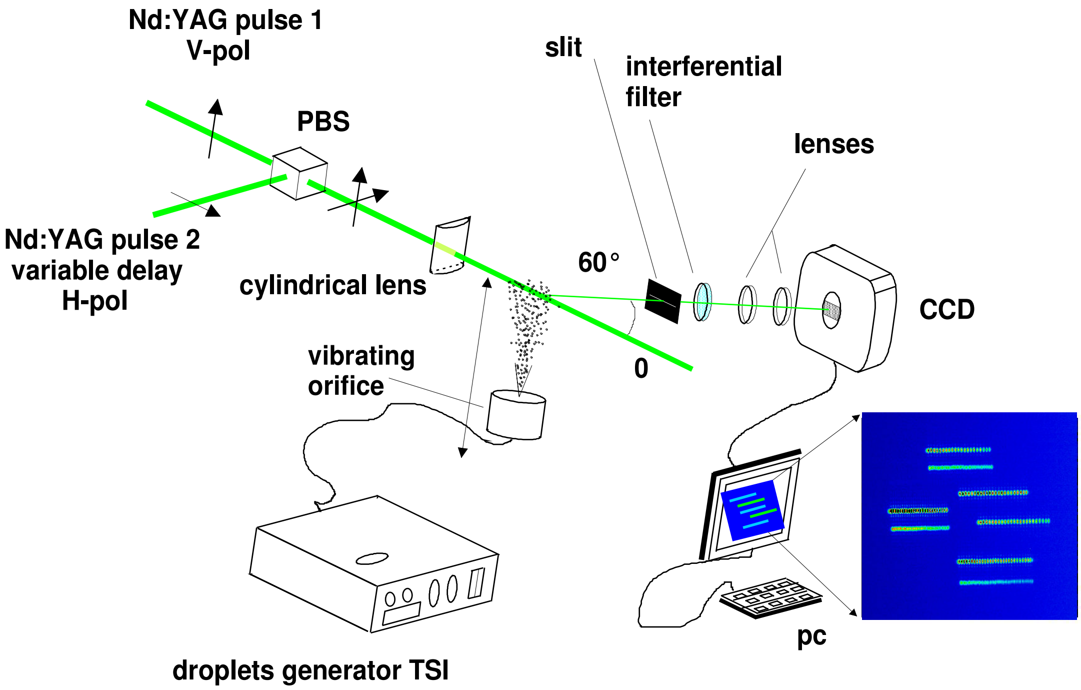

Fig. 3 Experimental set-up.

The imaging system captured images of droplets passing through the double light sheet pulses in the probe volume. The CCD (1024x1024 pixels square array) was placed, in all experiments, at an out-of-focus distance of 22.5 mm. The detection optics is placed at a scattering angle of 60°. In order to avoid superimposition of images and, hence, to increase the counting rate, a slit of 250 µm was placed in front of the collecting optics. Using this configuration the circular image of each droplet is reduced to a strip (Fig.s 1 and 4).

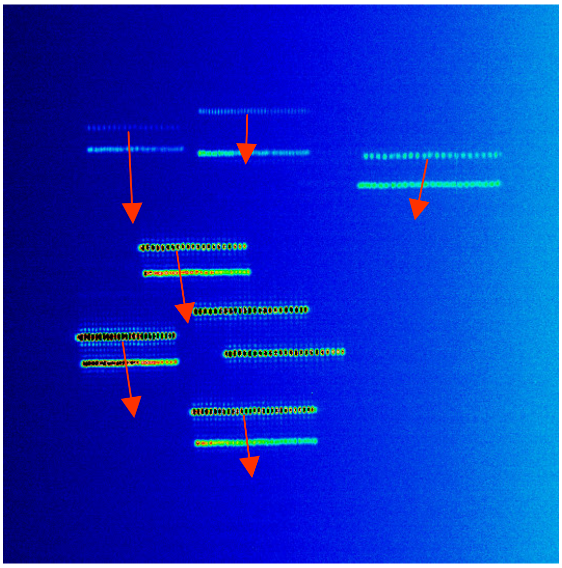

Fig. 4 GSI-PIV out of focus image doublets of water droplets of 70 µm. Each doublet of strings corresponds to a single droplet. Also the velocities are represented in the picture.

To test the validity of the proposed approach, measurements of droplets diameter and velocity, were performed at 280 mm below the droplets generator head. Figure 5 shows the velocity distributions for different secondary air flow rates. Increasing the secondary air rate, mainly the axial velocity, and in minor extent the radial one, increased. This indicates that in the fluid dynamic configuration analysed the secondary air plays a prominent role. Figure 6 reports the diameter-velocity correlations for both axial and radial velocity. No marked differences were observed as function of diameter for the radial velocity whereas a slight dependence with the droplets size was observed for the axial one. This is due to the peculiar features of the spray and to the fluid dynamic arrangement. In fact, it should be remarked that the spray was composed of droplets with almost the same initial velocity and directed coaxially to the secondary air. Finally, in Fig. 7 are shown the correlations between axial and radial droplet velocity components for the different secondary air flow rates.

3. Conclusions

The set of experiments discussed in the paper shows that the GSI-PIV out of focus configuration is able to measure diameter and velocity of droplets in case of sprays moderately concentrated. The choice of a scattering angle of $\vartheta=60°$ permitted to measure the droplet size with no regard to their refractive index. The velocity of droplets is determined by using a time of flight approach based on double laser pulses. The utilisation of laser pulses with orthogonal polarisations simplified noticeably the recognition of doublets of out of focus images corresponding to each droplet. This permits to increase the counting rate and the application to denser sprays. In addition, GSI-PIV out of focus technique allows determining the velocity direction as well as to its modulus. Finally, it should be remarked that the facility in the identification of an image doublet, generated by the same particle passing trough the two differently polarised laser pulses, is gained by exploiting the out of focus configuration of the imaging system. In fact, only in out of focus conditions, images of droplets represent the scattered field, thus, permitting the distinction of effects due to different polarisations.

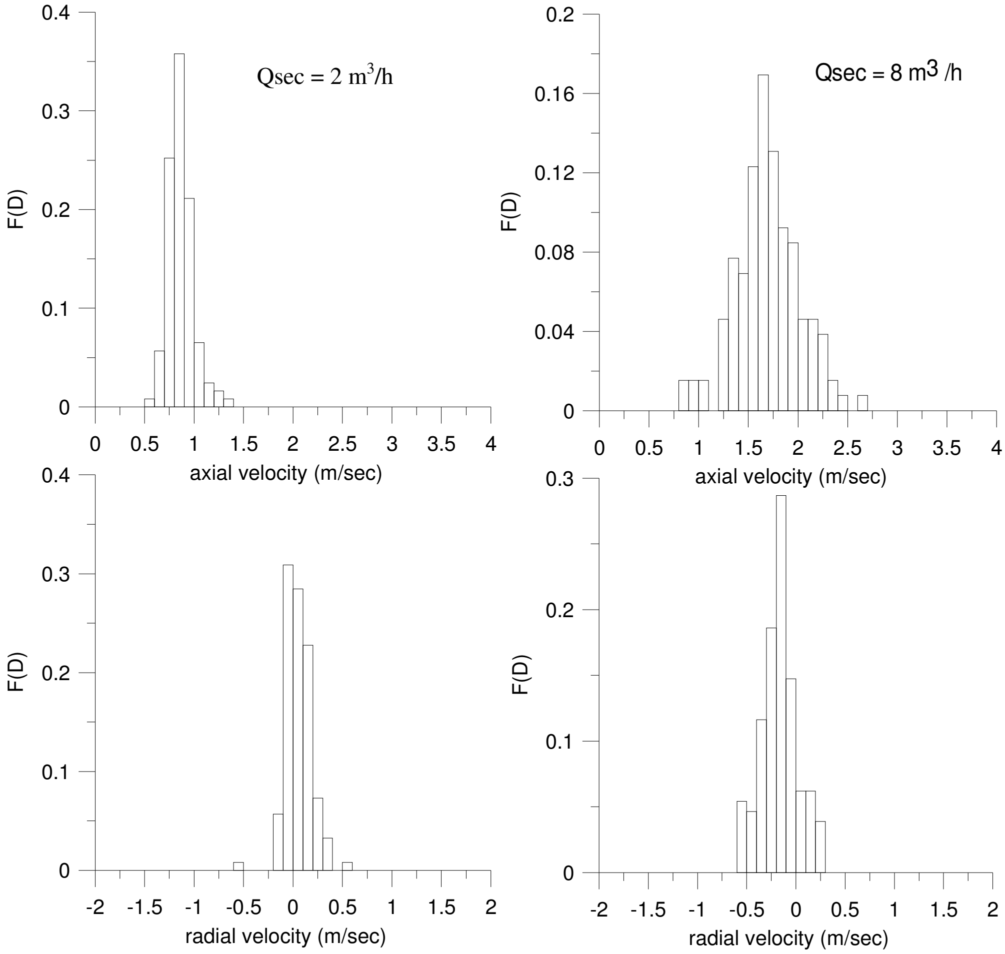

Fig. 5 Axial and radial velocity components at the same spatial location and for two different secondary flow rates.

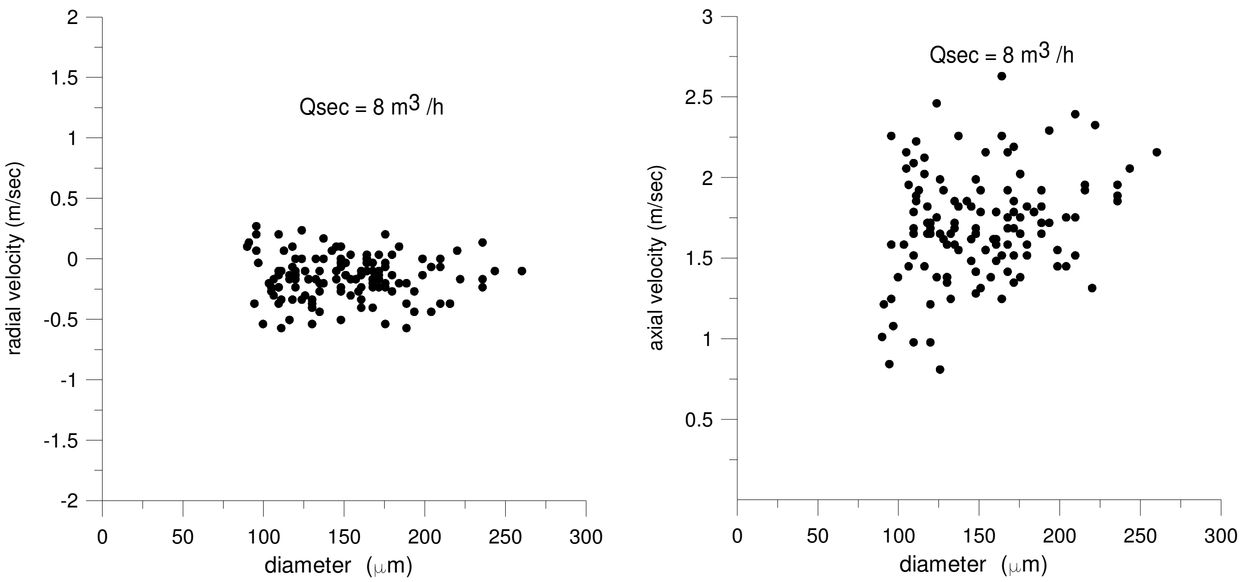

Fig. 6 Axial and radial velocity components versus droplets diameter.

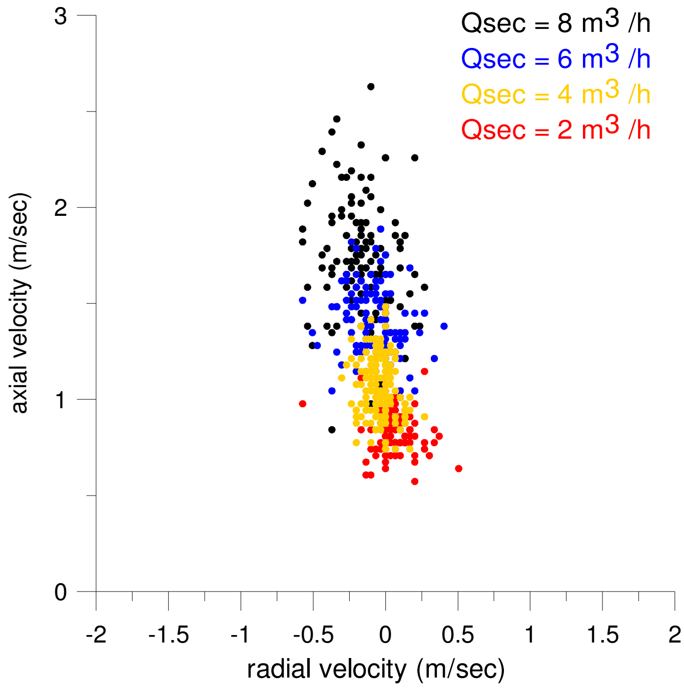

Fig. 7 Correlation between axial and radial velocity components

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