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► **To cite this version:**

Romain Schuster, Dominique Heitz, Philippe Georgeault, Etienne Mémin. On-site airflow measurement of a laboratory fume hood using customized large-scale image-based velocimetry. Roomvent & Ventilation 2018, Jun 2018, Espoo, Finland. pp.1-6. <hal-01957995>

HAL Id: hal-01957995

<https://hal.science/hal-01957995v1>

Submitted on 17 Dec 2018

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ON-SITE AIRFLOW MEASUREMENT OF A LABORATORY FUME HOOD USING CUSTOMIZED LARGE-SCALE IMAGE-BASED VELOCIMETRY

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SUMMARY

This study demonstrates the feasibility of conducting on-site large-scale image-based measurements for indoor airflows characterization. We chose to study the suction flow generated by a laboratory fume hood in operating conditions. As a matter of fact laboratory fume hoods are frequently subject to routine checks during which air speed measurements by hot-wire anemometry are performed. However classical point-to-point hot-wire anemometry may not be sufficient to detect and localize potential leakages. To improve these controls we developed and tested a new method based on particle image velocimetry principles, which is non-intrusive and authorizes a good spatio-temporal analysis. To face large-scale and on-site issues we had to make some adaptations. For this reason, we used tracers like bubbles or smoke which have good scattering properties. We also developed our own low-cost light system. To compute velocities from image sequences we developed an optical flow algorithm based on a large-scale flow model instead of using traditional correlation. The tested method gave good results with a good agreement with sparse HWA measurements but with a wider spatial distribution. In addition the method provided turbulence intensity estimation and a good monitoring of dynamic flow features, which is important for leakages detection.

Keywords: fume hood, large-scale PIV, optical flow

1 INTRODUCTION

Laboratory fume hoods are protection devices generally used in places where harmful substances are handled. They are aimed at limiting the exposure of humans to contaminants by capturing and removing hazardous fumes or dust generated inside the enclosure thanks to a suction flow. To insure their good performance through time, fume hoods are subject to periodical controls. These controls usually consist of a three-part evaluation process composed by a face flow rate evaluation, a smoke visualization and a tracer gas test. This protocol does not give any information on the presence or the location of potential leakages. To detect potential pollutants leakages it is necessary to understand the aerodynamics features of the fume hood. It can be done by flow visualization as shown by some studies (Tseng et al., 2006 and Chen et al., 2016). However in these studies flow visualization is only qualitative. In fact it is possible to extract quantitative flow motion estimation from flow visualization (Heitz et al., 2010). This is what we propose in this paper.

In this study we propose to perform image-based air velocities measurements on a laboratory fume hood in operating conditions. Traditionally particle image velocimetry (PIV) is carried out to estimate fluid motion. This method is widely used to study turbulent flows in fluid mechanics community. PIV principles and advancements have been carefully explained and detailed in the book Particle Image Velocimetry (Adrian and Westerweel, 2011). Image-based velocimetry techniques like PIV are non-intrusive and provide instantaneous velocity fields. PIV was originally designed for laboratories and well-controlled flows, and its transposition to an on-site measurement tool is not immediate. Some

ventilation or air conditioning systems inside cars, planes or rooms were investigated by PIV (Cao et al., 2014) but experiments were mostly carried out in research laboratories on specifically designed models and rarely in real conditions. Thus performing PIV in real conditions needs some adaptations.

As fields of investigation are getting bigger, classical particles like oil droplets cannot be used as tracer, they are too small. Two options are then possible: using bigger particles like Helium Filled Soap Bubbles (HFSB) or using smoke. The advantage of HFSB is that they are big enough (diameter around 300 μm) to strongly scatter the light and being visible from far. Secondly thanks to the helium, bubbles have the neutral buoyancy needed to follow the flow with high fidelity (Scarano et al., 2015). The interest of employing a smoke generator is its simplicity and availability. Smoke is composed of a high density of oil droplet haze scattering the light and providing smooth images, difficult to analyse with correlation techniques but from which fluid motion can be estimated via optical flow approaches (Heitz et al., 2010).

The following study is aimed at demonstrating the feasibility of an on-site PIV-like measurement of a fume hood airflow in operating conditions. We will compare the two kinds of tracers mentioned above: HFSB and smoke, in order to determine what tracer is the best suited for large-scale on-site flow characterization. The rest of this paper is organized as follows. In Section 2, the image-based method is described in detail. Then results and performances of the method are presented and commented in Section 3. Finally, conclusion is discussed in Section 4.

2 METHODS

The method consists of bringing to light the invisible airflow generated by a laboratory fume hood. To make it possible, the flow is seeded with a tracer (particles or smoke). In the same time a light sheet is emitted by an illumination system in order to enlighten the tracers in the zone of interest. The light scattered by the tracer is recorded by a camera at a given frame rate. By computing tracer's displacements between successive frames thanks to a motion estimation method it is possible to obtain an estimation of the velocity field in the illuminated slice. Naturally as we only illuminate a plane and use only one camera we can only retrieve two components of the velocity in two directions (2D2C). However 2D2C PIV is relevant for strongly bidimensional flows, as it is the case for fume hood.

2.1 Experimental setup

Usually, to perform a PIV measurement a Nd:YAG pulsed laser at 532 nm combined with a cylindrical lens is employed in order to generate a light sheet. The light delivered by the laser is powerful enough for large-scale applications but the whole light system is not easy to move everywhere and is very expensive. Therefore we have chosen to develop our own illumination system more transportable, easy handling and less expensive. Our device consists of an array of LEDs coupled with a linear Fresnel lens that produces a collimated light sheet. LEDs were chosen to emit at 432 nm because of their better efficiency at this wavelength. The LEDs array generates a 1 m high and about 10 mm thick light sheet. The illumination system can be run both in trigger mode and in continuous mode. The advantage of trigger mode is the possibility of scaling up the light power for a short duration. In our configuration the LEDs array was placed vertically facing the fume hood front opening.

The HFSB generator that we used produces small bubbles down to 300 μm diameter size with a high seeding density (up to 2 million bubbles per second).

Image recordings were acquired with a CCD camera equipped with a 35 mm focal lens and storing 1024 x 1024 pixels images at 60, 125 and 250 fps. The camera was positioned perpendicular to the illuminated plane at a distance of 1,5 m from it.

The laboratory fume hood used for this study was located at the Irstea center of Rennes. We were constrained by the geometry of the room. Experiments were conducted at sash window heights of 500 mm. For this study the fume hood was unoccupied. We think that performing our method with a manikin should be relevant to see the influence of human body on the flow, but this will be carried out in further studies.

2.2 Motion estimation from image sequences method

As mentioned above, we seeded the region of interest with a tracer in order to make the fluid flow visible. With a well-chosen tracer that can closely follow the fluid motion, we can assume that the tracer motion equals the fluid motion. In this section we expose our strategy to estimate the fluid motion from observations of tracer displacements during an image sequence. This issue is frequently addressed, in PIV community, by a correlation based processing between two images. Here, to compute the motion from two successive snapshots we used an optical flow method. Optical flow is a method that comes from the computer vision community (Horn and Schunck, 1981). Precisely what is called optical flow is the apparent motion between two successive images. Optical flow is based on an observation model that links the spatio-temporal tracer luminance variations to the apparent fluid motion field. One of the benefits of using optical flow is that it provides a dense motion field (1 vector/pixel), much better than correlation resolution limited to 0.13 vector/pixel in the best case. Moreover, compared to correlation approaches optical flow provides a framework to use physical-based models (Heitz et al., 2010), which improves the estimation. Several observation models have been investigated to cope with complex fluid motion. In our case we developed a largescale observation model that takes into account the effects of unresolved scales and errors, on the scale of the measured velocity. In this model introduced by Mémin (2014), non-observed scales are expressed thanks to stochastic formalism. Based on the passive scalar transport equation where subpixel scales are assumed random, this model is well suited for large-scale observations encountered in real world. This new stochastic multiscale data term has already shown good performances for the motion estimations of turbulent flows (Cai et al., 2017). Concerning the optimization strategy we chose a local resolution scheme exposed by Lucas and Kanade (1981), which is well-suited for parallelization (because each pixel is processed independently), this is interesting for real-time in situ applications.

3 RESULTS AND DISCUSSION

3.1 Mean flow analysis

Figure 1 shows two mean velocity fields obtained from HFSB seeding and smoke seeding. As we can see, the two presented fields are not exactly the same although they are supposed to represent the same flow. In the central region of the sash opening the two mean fields are quite similar, but at the bottom and at the top the two vector fields differ. It comes from the fact that the smoke was not well distributed everywhere during the image acquisition process. As a matter of fact the smoke generator was driven manually and it was not easy to constantly cover the entire zone of interest. Moreover images need to have a lot of luminance gradients, so the smoke generation should be pulsed in order to create smoke structures and not a diffuse haze. For this reasons some regions like bottom or top of the fume hood were not always well seeded leading to underestimated vectors. In opposition the HFSB generation was run automatically so it was easier to insure a dense homogeneous and continuous seeding in the whole field of observation.

Figure 2 shows vertical profiles of the mean velocity magnitude taken between the fume hood workbench (height = 0 mm) and the glass inferior edge (height = 500 mm). The goal is to compare our method to a typical measurement that is commonly done during periodical controls namely spot hot-wire anemometry. As we can see, the HFSB seeding gave results close enough to the HWA (except at extremities where the airspeed was too weak to be measured by the hot-wire anemometer) but with a

clearly better spatial resolution. As expected, the smoke gave the global trend but slightly underestimated the velocity for the reasons mentioned above.

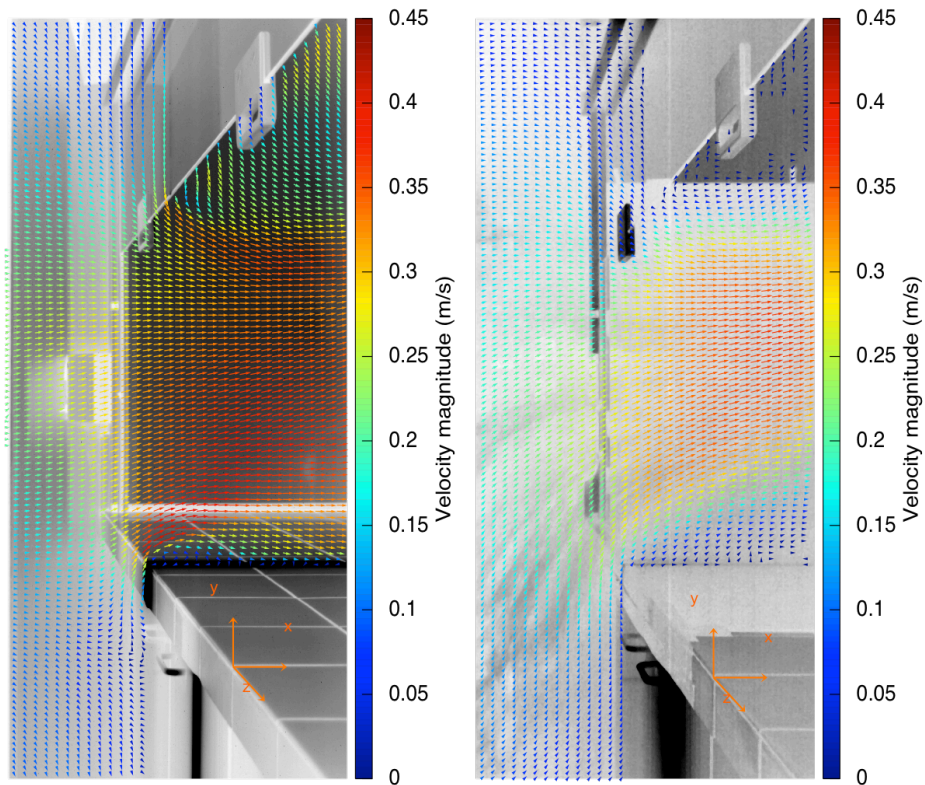


Figure 1. Mean velocity fields obtained for an opening height of 500 mm with a continuous light. Results for two kinds of seeding are shown: HFSB (left) and smoke (right).

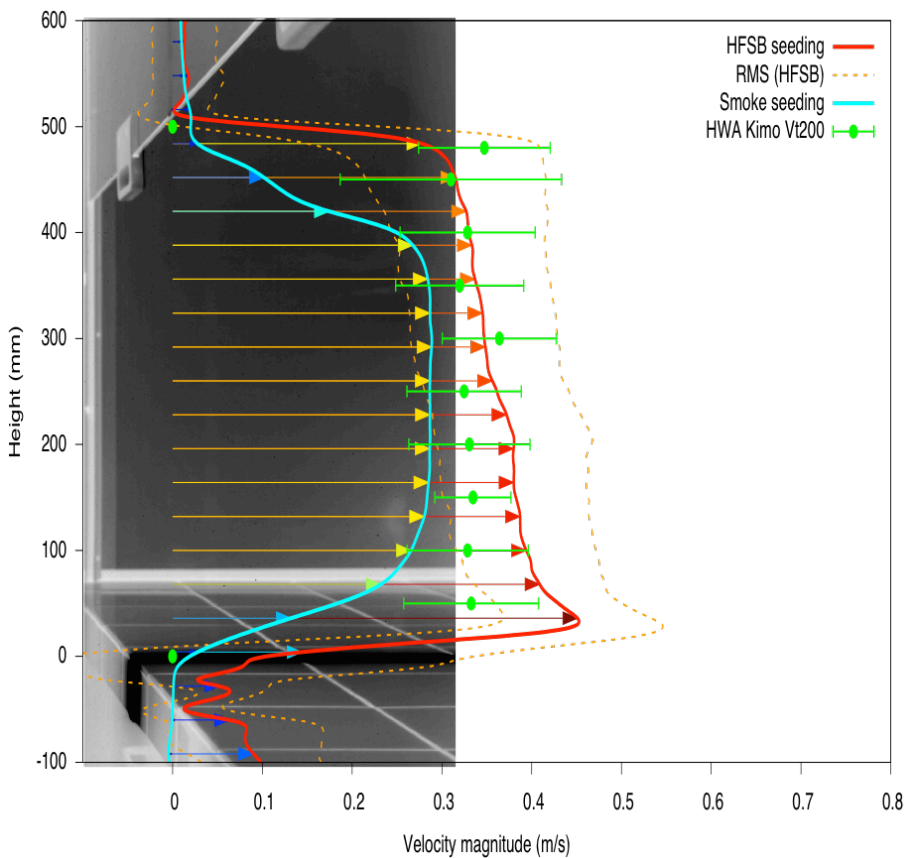


Figure 2. Vertical profiles of the U_x mean velocity component taken at the glass door position on the x -axis. Results from HFSB seeding (red line and orange dashed-line) and Smoke seeding (blue line) are compared to sparse hot-wire anemometry measurements (green errorbars).

3.2 Turbulent flow features analysis

Figure 3a is a map of the flow turbulence intensity defined as $\langle u'^2 \rangle / U_{out}^2$ where $\langle u'^2 \rangle$ stands for the quadratic time average of instantaneous fluctuations defined as $u'(t) = u(t) - U_{mean}$. We can clearly distinguish areas where the turbulence is stronger. The obvious one is located just behind the edge of the bench where the flow is highly turbulent due to the corner wake and bench boundary layer. Another area, but with lower intensity, corresponds to the wake of the bottom edge of the sash. Finally a third big area at the top inside the fume hood behind the glass seems to present a high level of turbulence. As we will see next, turbulence activity is a sign of flow unsteadiness, which can give rise to eddies and in the worst case cause leakages. The main interest of an image-based method compared to HWA is the possibility of visualizing the space and time flow evolution and thus following dynamic flow features, which is difficult with HWA. Figure 3b and 3c shows instantaneous streamlines and vorticity fields taken from the HFSB sequence. As we can see we can retrieve flow features that were already observed through visualization by Tseng et al. (2006) and by Chen et al. (2016), like recirculation area behind the bench corner or vortex shedding in the bottom edge of sash wake. The intensity and persistence in time of such flow structures give an indication about the location of potential leakages.

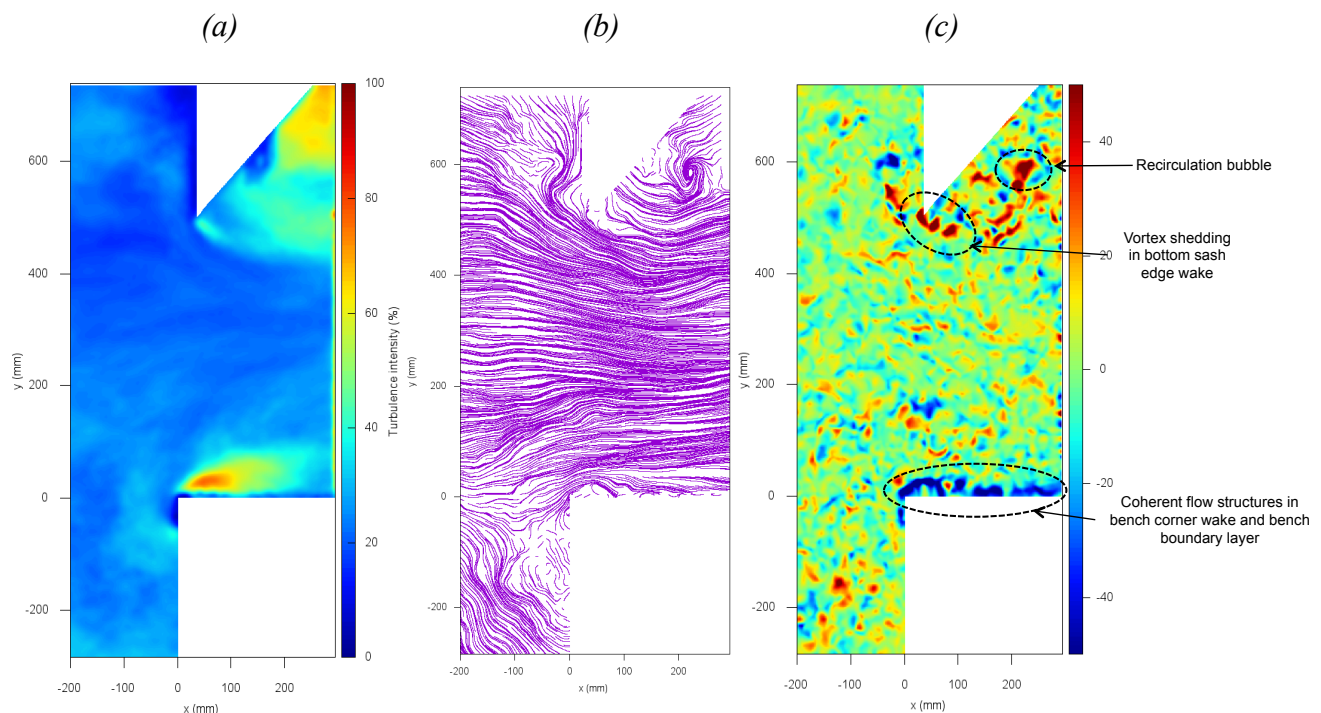


Figure 3. From the left to the right: (a), mean turbulence intensity; (b), instantaneous streamlines; (c), instantaneous vorticity fields obtained with HFSB seeding. U_{out}/H normalizes vorticity where H stands for the opening height (here 500 mm) and U_{out} stands for the global mean suction velocity (here 0.254 m/s).

5 CONCLUSIONS

In this study we have demonstrated the possibility of performing on-site large-scale PIV measurements on an operating fume hood. We tested two seeding systems: HFSB and smoke. Results were better with bubbles than with smoke. However the smoke generator can be improved and when

the smoke distribution is well structured the vector fields can be quite good (Heitz et al., 2010). Thanks to our method we could first retrieve the mean velocity field over an extended area. There are clear advantages over HWA: we got a large distribution of two-components velocities on a whole plane when for HWA we only got one-component sparse spot measurements. We also could quantify the turbulence intensity and some aerodynamic features of the flow like recirculation bubbles or coherent flow structures, which is very important for leakages detection.

To complete this study, the next step could be to perform our method on several planes (vertical and horizontal) in order to have a 3D map of the flow features. We also would like to test the method with a manikin standing in front the opening to see the effect of the presence of a human body on the flow.

In conclusion, this study let us believe that the exposed method could be widely applied for periodical control of laboratory fume hoods or other ventilation system inside buildings. To our minds it delivers a much more complete flow characterization than actual periodical controls based on hot-wire anemometry.

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