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EXPERIMENTAL METHOD TO MEASURE 3D AIR VELOCITY

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ABSTRACT

A method is being developed for visualization of air flow with application to the indoor problems of heating, ventilating and air conditioning. Photographic images of the soap bubbles seeded in space reveal features of the flow which can be quantified by the digitizing operations. Determination of the velocity vector field from the experimentally recorded images is possible.

air flow visualization; digital image pocessing; soap bubble tracer

1. EXPERIMENTAL PROCEDURE

1.1 Method (Fig. 1)

The investigated space is seeded with the soap bubbles of diameter 3 - 4 mm. They are being transported with the air streams resulting from jets or convective sources. To make the phenomena not only visible but also adapted for recording , the space is darkened and illuminated by the well defined light sheet. By this mean only the bubbles which are actually crossing the light plane become contrastly visible on the dark background. the photographic camera is placed perpendiculary to the light sheet. The long exposed film is integrating the time position dependence resulting in the trajectory images. Applying the three color lighting and the time marking the features of the velocity vector are coded into the bubble track images. Automated digitizing and image treatment are used to extract the quantified flow field from the experimental photographs. Method is orientated to be used not necessarily in laboratory chambers but also in the real spaces. The necessary condition is darkening of the room.

1.2 Soap bubbles

The soap bubbles used for seeding the flow are produced by the standard generator from Sage Action Inc.,(USA). The batch of the bubbles passes through the selector for eliminating those which are too heavy. The homogeneous population of bubbles performing the settling velocity in the still air of about 5 cm/s (diameter 3 - 4 mm) is transferred to the experimental space. The average life time of a bubble amounts to several minutes .

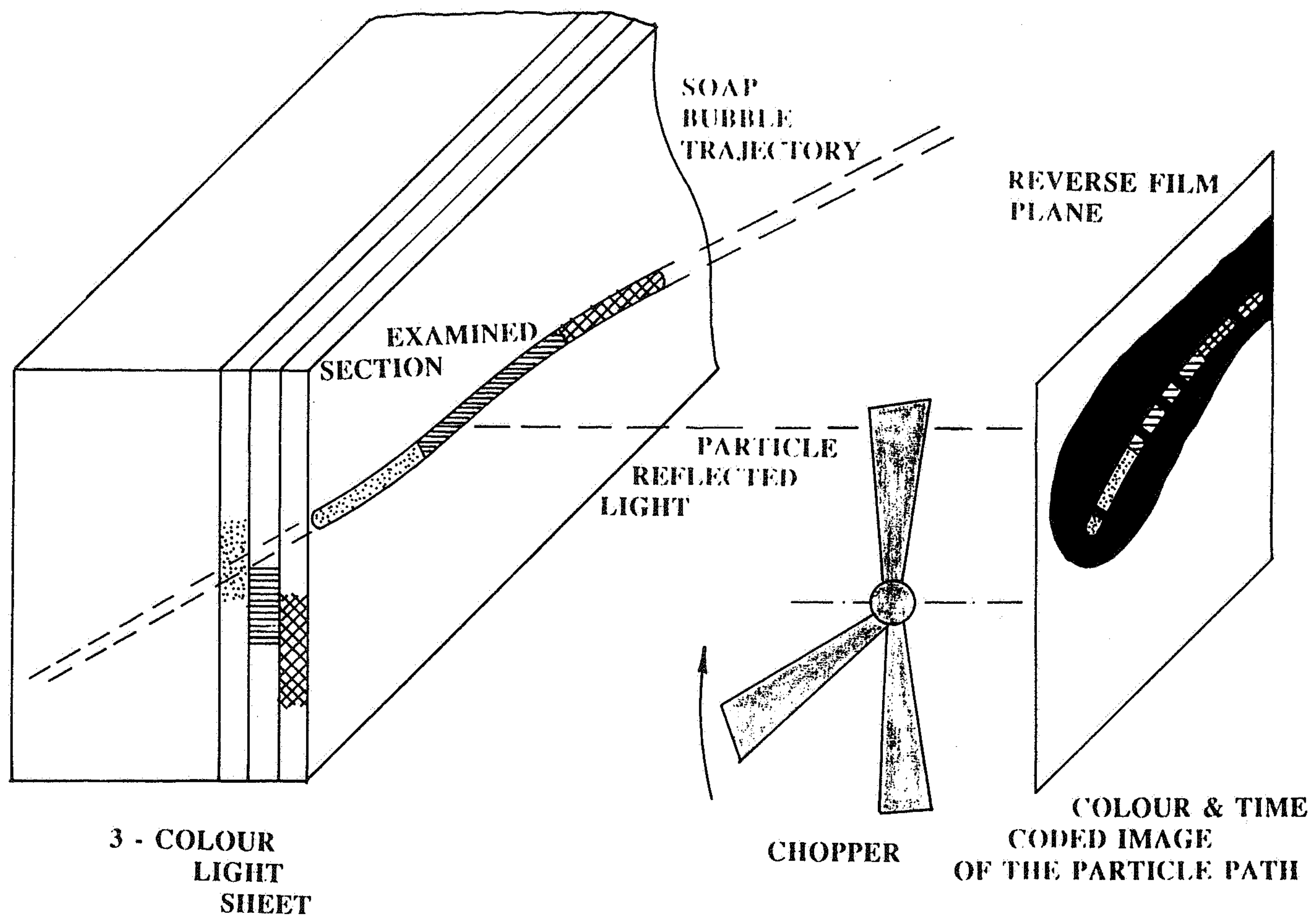

Fig. 1 The scheme of the experiment

The helium filling option foreseen by the manufacturer is not used. Helium is strongly influencing the selection process : even the thick - wall bubbles (i.e. too heavy) arrive to survive in the gravitational selector and get into the experimental space. There, the rapidly diffusing helium (small molecular weight) is decreasing the buoancy and bubbles fall down rapidly.
The neighbourhood of the air outlets and other areas of higher speed (e.g. convective sources) are the places suitable for introducing the tracer.
The comparison had been made between the indications of the omnidirectional DANTEC Flow Velocity Analyzer Type 54N50 and the photographic recording of the bubbles. The experiment was run in the chamber of stabilized horizontal flow (Fig. 2).

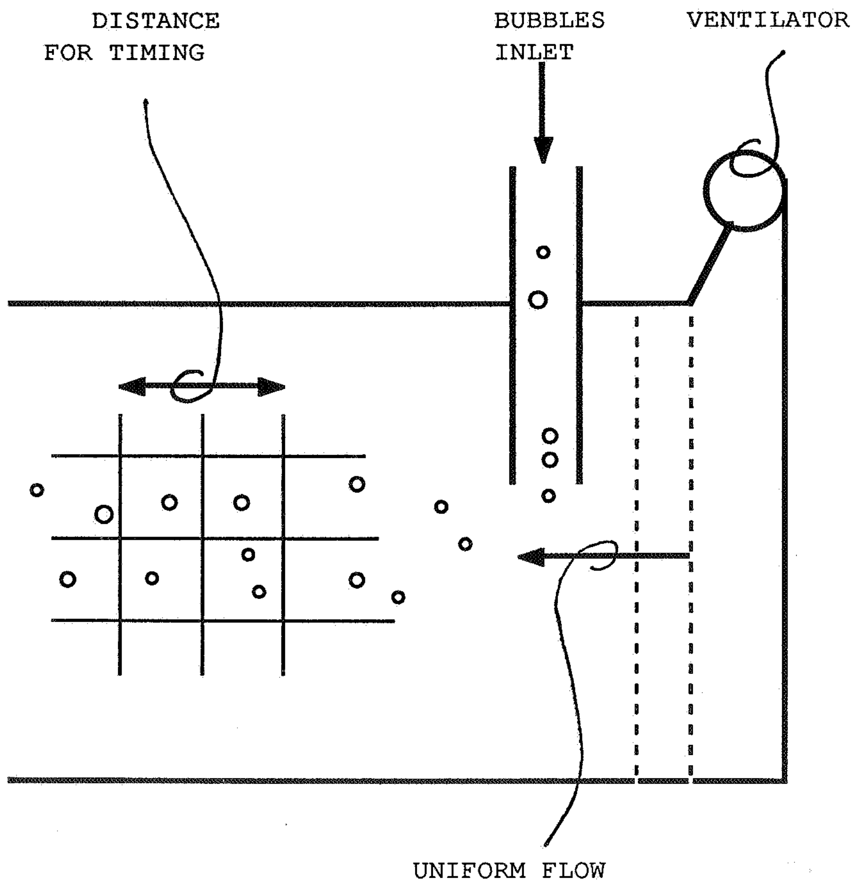

Fig. 2 Flow Visualization vs. Anemometer

The simultaneous measurements arrived to be impossible to realize : the presence of the anemometer strongly perturbated the movement of the bubbles passing at the proximity of the protection cage or holder and those which were close to the sensor were too rare and presenting danger to be deposited on the sensor itself. In this situation velocity was measured before and after series of photographs.

Table 1. Comparison of the anemometer indications vs. photographic recordings.

			Mean
Measured velocity BEFORE			
RMS = 0.8 Tu = 0.04 U 5% = 18 U95% = 21.5			19.6 cm/s
Photo # 1	Track # 1	U1 = 22.0 cm/s	
	2	U2 = 22.0	
	3	U3 = 22.0	
	4	U4 = 22.4	
	5	U5 = 23.2	
	6	U6 = 19.7	
Photo # 2	Track # 1	U1 = 23.6	
	2	U2 = 18.9	
	3	U3 = 23.0	
	4	U4 = 23.0	
Photo # 3	Track # 1	U1 = 23.0	
	2	U2 = 22.5	
	3	U3 = 22.0	
	4	U4 = 22.8	
	5	U5 = 23.4	
Photo # 4	Track # 1	U1 = 23.0	
	2	U2 = 24.8	
	3	U3 = 24.0	22.5 cm/s
Measured velocity AFTER			
RMS = 0.6 Tu = 0.02 U5% = 19.2 U95% = 21.1			20.1 cm/s
Measured velocity BEFORE			
RMS = 1.0 Tu = 0.07 U5% = 11.3 U95% = 14.9			13.1 cm/s
Photo # 1	Track # 1	U1 = 15.0 cm/s	
	2	U2 = 15.0	
	3	U3 = 15.0	
	4	U4 = 16.4	
Photo # 2	Track # 1	U1 = 15.0	
	2	U2 = 16.0	
	3	U3 = 15.5	
Photo # 3	Track # 1	U1 = 16.1	
	2	U2 = 16.5	
	3	U3 = 12.1	
	4	U4 = 17.0	
Photo # 4	Track # 1	U1 = 16.0	

	2	U2 = 14.0	
	3	U3 = 15.0	
Photo # 5	Track # 1	U1 = 15.0	
	2	U2 = 14.8	
	3	U3 = 14.3	
	4	U4 = 13.8	15.1 cm/s
Measured velocity AFTER			
RMS = 1.0 Tu = 0.07	U 5% = 10.9	U95% = 14.5	12.8 cm/s

The anemometer presents a systematic negative off-set. The quantifying of this effect calls for new calibration and examination of the velocity field (uniformity) in the chamber.
The recorded trajectories from the flow in the above experiment as well from the flow the real rooms have smooth character indicating a damping effect (like a low pass filter). Contrary to the hot wire recording the turbulence spectrum is not detectable.

1.2 Lighting

The light sheet is consisting of the 3 distinctly separated colours. By that mean the trajectories which are not parallel to the light sheet (ditto observation plane) are resulting in tracks of coloured sequence. Color change is marking the movement of the tracer perpendicular to the observation plane.
The point light source (halogen metal vapour arc lamp) of the equivalent temperature 5600 deg C is used. The thickness of the light sheet is to be related to the density of tracer distribution in space : if it were too narrow the probability to illuminate the sufficient number of the tracer particles in one shot would be very low. The thickness of 4 cm revealed to be optimal for the middle plane (the red colour) which serves as a depth indicator for the third dimension.

1.3 The Photographic Technique

Standard reflex camera 24 x 36 mm is used. The images are taken on the colour reversal film 1600 ASA. The high equivalent temperature of the light source allows to use the daylight emulsion without any filter corrections.
The shutter is opened for relatively long time (typically 1-2 s) but the effective exposure in that laps of time is shortly interrupted by the rotating chopper ahead of camera lenses. The moment of opening / closing the shutter is synchronized with the position of the distinct arm of the chopper just passing by before the lenses. Due to that the recording of the not complete chopper turns is reduced (i.e. images contain less tracks which must be rejected while treatment as being not integrally exposed).
The non - symetry of the chopper is marking the time evolution on the photographed image otherwise speaking allows detection if the tracer was moving e.g from left to right or vice versa.

1.4 The Third Dimension

In the observation plane (xy) the real distances are scaled to the image using the physical marks in the experiment or by superposing the experimental images with the reference grid from the test shot.
The depth (3rd dimension: along ' z ', perpendicular to xy) is controlled by the thickness of the middle light plane (red colour) On the experimental images the movement of the tracer along ' z ' is resulting in colour changes , e.g. from blue - to - red and red - to - green.
The colour selectivity of the illumination is essential to recognize the 3D flow. Nevertheless the precision of measure the velocity component perpendicular to the observation plane (V z) is lower than for the x - y plane (V x , V y).

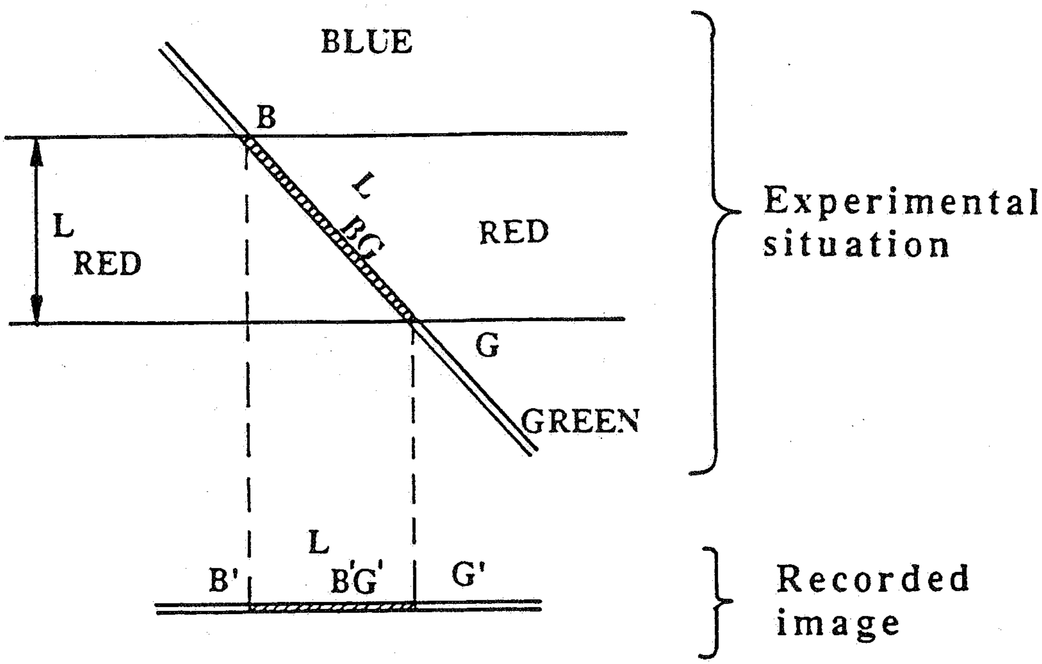

Fig. 3 The reconstruction of the 3rd dimension

The reconstruction of the real depth situation is possible according to Fig. 3:

$$L_{BG} = \sqrt{L^2_{B'G'} + L^2_{RED}}$$

EVALUATION OF THE TRAJECTORIES

When photographing, the camera shutter is opened relatively long so that the chopper completes several rotations during the exposition time. This results in "cutting" the tracer trajectories into segments each consisting three lines, a long one, a shorter and the shortest one. Knowing the sense of rotation of the chopper the direction of the tracer displacement can be determined.

In the observation plane (xy) the real distances are scaled to the image using the physical marks in the experiment. The depth information (the z coordinate) is defined by the colour of the picture, knowing the thickness of the light plane. The intervals on the trajectory image are time marked according to the chopper geometry and the speed of rotation. Taking the sequence of segments in the scanned picture the magnitudes of the velocity vector can be calculated. The opening and closing time has been defined so, that at constant velocity along a straight line the distances between the first and second points equal to the distances between the second and sixth points. This allows a futher control in the trajectory evaluation process.
At the present arrangement the camera and the chopper are not synchronized so that the first and the last recorded track length contains no reliable information.

The colour in the trajectory image is related to depth. The purity of the colours is essential. Each of the colours is associated with a gray scale value determined by light filtering when scanning the photograph.

Colour control is performed on the each level of the procedure. First, the light source temperature is known . Then, the filters used to produce the colour in the light sheets are adapted to the colour reverse film sensitivity. Finally, digitizing is performed adapting filter settings for the best colour distinction after electronic conversion.

DIGITAL IMAGE PROCESSING

The slides are digitized three times (once for each colour) with a CCD-sensor). For every colour, information is stored in the computer,that means per slide one obtains three different matrices in the computer.

Figures 2 and 3 show an electronic image, a 50 x 50 array cut out from a picture for detailed investigation.

Using such arrays the different tracks can be visualized in a number of steps steps. A segment of the original matrix may look like Figure 2.

The original matrix can be modified e.g. by the "Roberts-operator" as follows:

$$b(i,j) = [(a(i,j)-a(i+1,j+1))^2 + (a(i+1,j)-a(i,j+1))^2]^{0.5}$$

where a (i,j) is the value at the pixel position i,j before and b(i,j) the value at the same position after transformation. The effect of

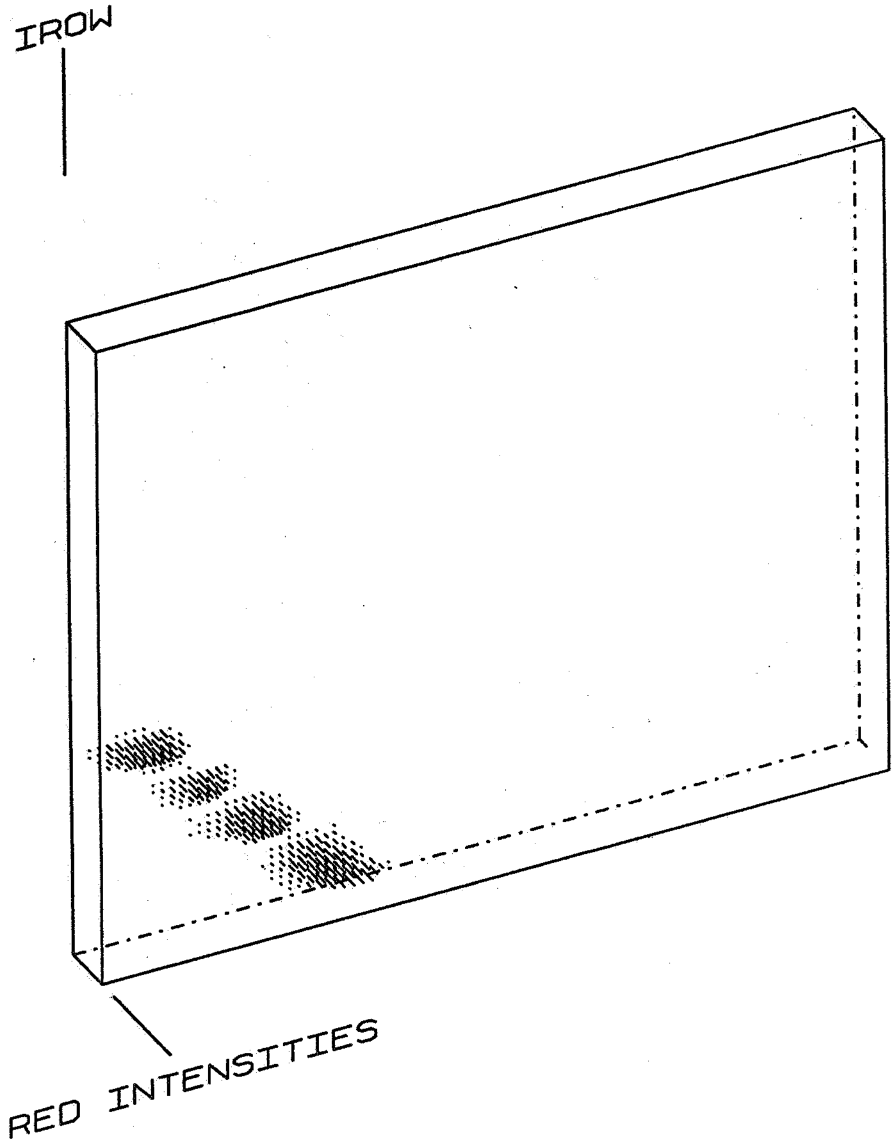

Figure 2. A red intensiy array as scanned

this transformation (in connection with the array shown in Figure 2) is illustrated in Figure 3.

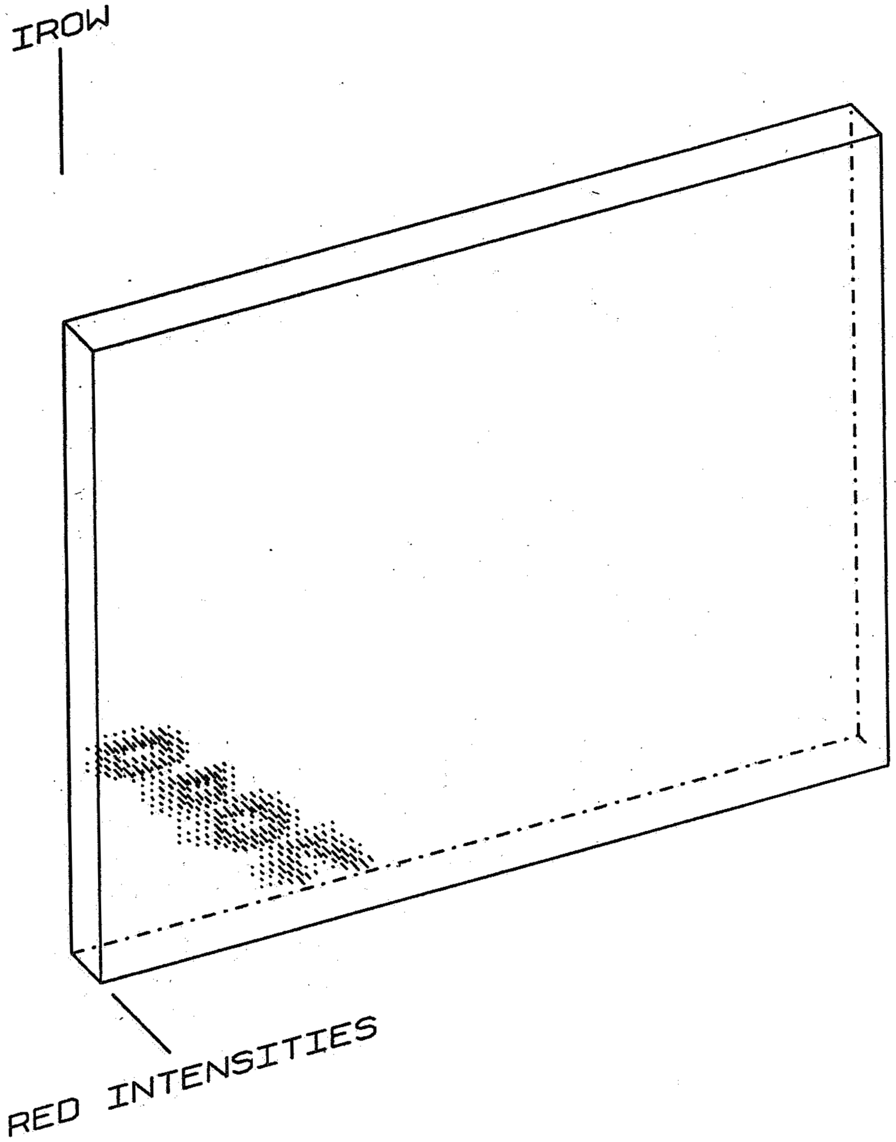

Figure 3. A modified array

This example shows a way to make image edges became "visible" for further recognition operations. Length and orientation determination of the tracks in x,y,z-space is a tedious but straightforward procedure:

Interpretating the sub-sections of the tracks as being tangential to the streamlines, the instantaneous direction of the velocity vector can be computed. This corresponds to an Eulerian type of description.

Longer sequences of the tracer positions (i.e. longer sections of the trajectories) cannot be associated with any one point of observation. Magnitude of the velocity still must be calculated from the time marked sections of the trajectory. When evaluating the magnitude of the velocity, a Lagrangian type of description is used.

It is the resolution (in space and time) and also the interpolation technique which determine which one of the descriptions is taking over.

A series of operations has to be done to achieve good results. This series, at present time, cannot always be predefined, therefore this instrument is at present time rather a research and development tool, than for field application as a routine task.

The velocity vector field is different from what is calculated using only the information stored in the trajectories. To quantify the difference between the air flow field and the vector field constructed from the tracer trajectories (caused by inertia, buoyancy, drag, gravity, centrifugal force, lift, diffusion, etc.) is a further step, still to be done. However, these are second order effects and do not essentially influence neither the above presented results, nor the statement about the applicability of the method.

CONCLUSIONS

Quantitative identification and visualization of the low-speed air streams in ventilated/heated spaces using solid tracers is today feasible. The air flow pattern can be studied using reconstructed velocity vector.

The progress in many associated areas (such as particle tracking in water, colour CCD-cameras, digital image processing software, colour photography, vectorized high speed computing,etc.) keeps fostering development of the presented method. Therefore it is highly probable that this method will soon become a convenient engineering tool, suitable also for field applications.

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Discussion
Paper 13

E. Olsson (Chalmers University, Sweden)

What are the size of bubbles?

G. Gottschalk (ETH-Zentrum, Switzerland)
3 - 4 mm