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THE USE OF BUBBLES IN A WIND TUNNEL FOR FLOW-VISUALISATION AND THE POSSIBLE REPRESENTATION OF RAINDROPS

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Summary

The appearance of bubbles used for flow visualisation around bluff bodies in a wind tunnel is illustrated. It is demonstrated that the large diameter and low density properties of bubbles could enable them to be used to represent raindrops in a wind tunnel.

Introduction

The production, in recent years, of soap bubble generators able to produce a controlled flow of bubbles of variable diameter has been useful for flow-visualisation and for the measurement of velocities, the latter by stroboscopic methods. Randall has demonstrated the use of bubbles, for monitoring air motions inside livestock buildings [1]. The representation of raindrop trajectories around model buildings in a wind tunnel has hitherto been particularly difficult requiring as it does a particle several times larger than a raindrop but only two to three times the density of air [2]. Such a simulation would enable regions of high rain impaction rates on buildings to be identified and would be useful for testing remedial measures intended to control the rain impaction. For the general problem of rain penetration, however, the amount of water reaching a building surface is only one component in a series of factors that cause water to bridge the shell of the building[3]. The meteorological conditions at the site of the building, the design and assembly of the building all have a part to play. Only the wind and raindrop trajectories are amenable to "whole-building" modelling in a wind tunnel. In the longer term it might be possible to classify the type of wind, turbulence and rain environment that exists at different parts of a building which in turn could determine some of the parameters necessary for the testing of full size building components.

The bubble generator

The bubble generator used in the following tests is retailed by Armfield Engineering Limited, Model F 11. A sketch of the head is shown in Fig. 1. It consists of three concentric tubes, the central tube carrying for example an air or helium supply, the middle tube a special soap solution and the outer tube air. Needle valves control the rates of flow in the tubes and the manufacturers claim that the diameters of the bubbles can be varied from 1.5 to 6 mm and that their lifetimes are at least 30 seconds.

Flow visualisation

Figures 2 and 3 show the familiar pattern of flow, marked out by bubbles, round a model representing a tall slab building (see for example Penwarden and Wise [4]). The vortex flow in front of the tall block is evident and for Fig. 3, where the block is raised on pillars, the strong flow underneath is shown exhausting into the turbulent wake behind the block. These photographs were taken in the Environmental Wind Tunnel at the Building Research Station, Garston.

A cine or video-tape record of these flows produce streak lines from which velocities can be measured. Difficulties arise, of course, where the bubbles have a component of motion towards or away from the camera but by looking at a sufficient number of shots and arranging a narrow plane of illumination the maximum velocities can be determined.

Some unavoidable distortion in the flow pattern must occur when the bubbles enter a region of highly sheared flow because centripetal and lift forces prevent the bubbles penetrating deeply into the region [5]. On the illustrations shown, however, this does not seem to be a problem except perhaps in the closed vortex.

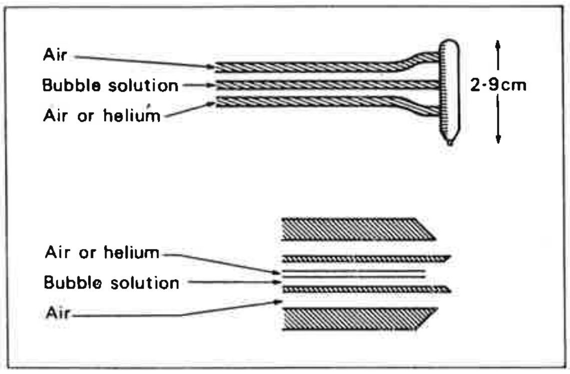

Fig. 1. Sketch of the bubble generator head.

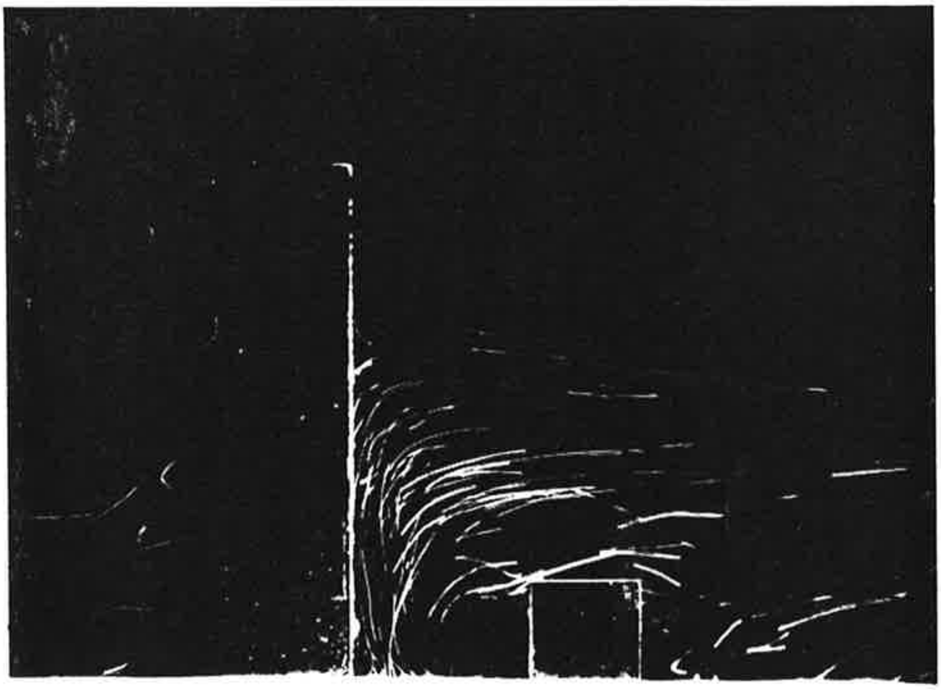

Fig. 2. Flow visualisation, using bubbles, in a wind tunnel.

Modelling-equations for representing raindrops in a wind tunnel

Figure 4 shows the forces acting on a spherical raindrop in a curved and sheared flow. The forces acting are: Gravity, $G \propto (\rho_d - \rho_A)\, d^3\, g$, Inertia, $I \propto (\rho_d - \rho_A)\, d^3\, v^2/l$, Drag, $D \propto \rho_A\, V_r^2\, d^2\, C_D$, Lift, $L \propto V_r\, d^2 \sqrt{(V/d)}$, where V = air velocity, v = drop velocity, $V_r = V - v$ = drop velocity relative to air, ρ_A = air density, ρ_d = drop density, d = drop diameter, l = geometric length, and C_D = drag coefficient.

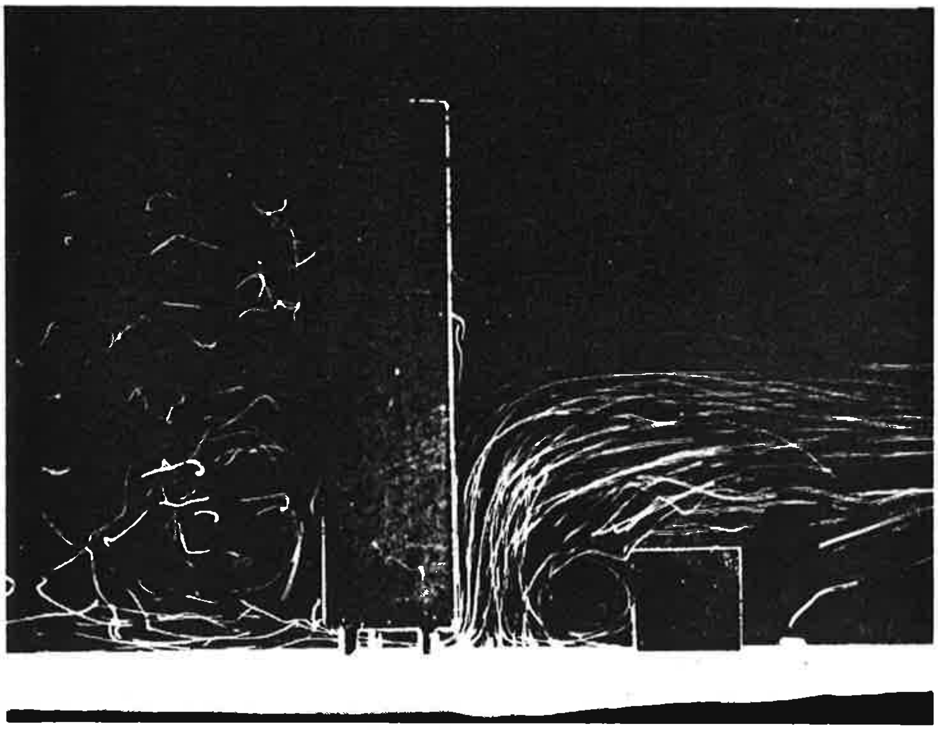

Fig. 3. Flow visualisation round a model representing a tall slab building raised on pillars.

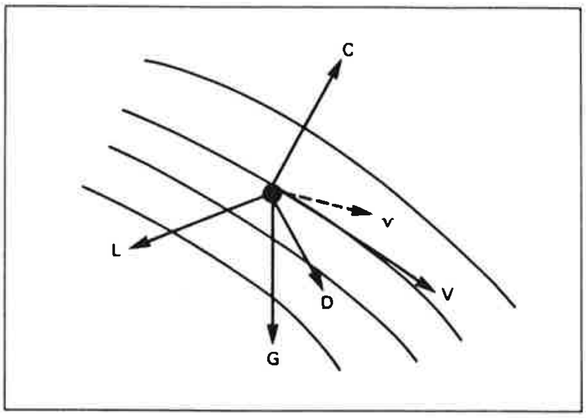

Fig. 4. Forces acting on a raindrop.

The expression for the lift is a scaled version of that given by Morsi and Alexander [6].

For the accurate modelling of drops in a wind tunnel the ratios of the forces must be the same as on the full scale. Using a subscript m to denote the model, the following conditions are derivable.

From the ratio of the inertia to gravity forces and the relation for equal trajectories, i.e. $V_r/V = V_{rm}/V_m$, there results

$$(V/V_m)^2 = l/l_m \qquad (1)$$

This means, for example, that if the model buildings were 1/100 th of the full scale and $V = 10$ m/s then V_m would have to be 1 m/s.

Since the drag coefficient varies with Reynolds' number this must be the same in both cases, thus $V_r d = V_{rm} d_m$. Combining this with the ratio of the inertia to drag forces gives

$$(\rho_{dm} - \rho_A)/(\rho_d - \rho_A) = (d/d_m)^3 \qquad (2)$$

and

$$\sqrt{l/l_m} = d_m/d \qquad (3)$$

Relations (1), (2) and (3) are the same as those given by Flower and Lawson [2]. In addition the ratio of the inertia to lift forces, not considered by Flower and Lawson, also produces equation (3). Though these lift forces are not important at full scale it is not immediately obvious that bubbles at model scale would not be subject to lift forces, hence destroying the scaling. Merzkirch [5] shows that large particles in a vortex can form stable rings with a balance between centripetal and lift forces. However, the fact that equation (3) is satisfied for the lift forces clears this possible problem. Figure 5 sets out equations (2) and (3) graphically. By way of example if $l/l_m = 100$ then, referring to Fig. 5, the model drop would have to be 10 times the diameter of a full scale drop but only about twice the density of air. The suitability of bubbles to meet these scaling relationships will now be discussed.

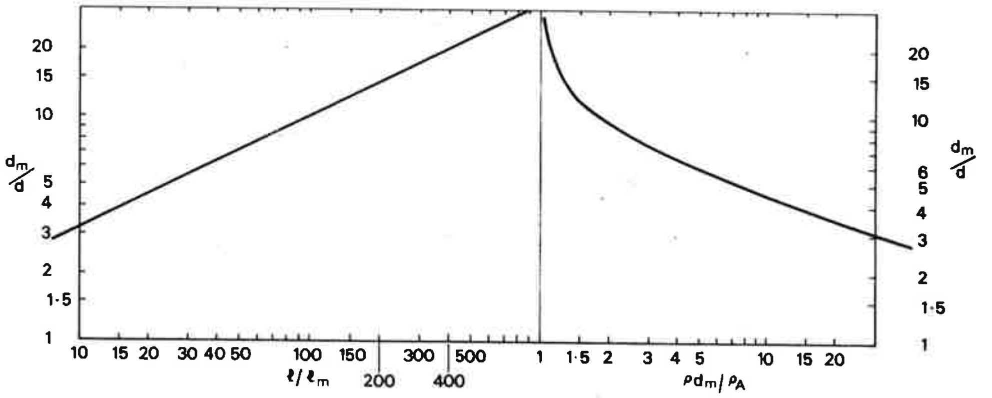

Fig. 5. Model scaling for simulating raindrops in a wind tunnel.

Experimental results from the bubble generator

The effect of the flow rate settings of the bubble generator on the diameters (d_m) and the corresponding densities (ρ_{dm}) of the bubbles had to be found. In all the tests the bubbles were filled with air. Diameters were measured for some of the bubbles by collection on paper and for others by photographing them falling in still air. The arrangement for the photographic technique is shown schematically on Fig. 6. A double reflection, one from the rear inside face and one from the front surface of the bubble, shows up on the photographs as can be seen on Fig. 7. Where the light source, bubble and camera lie in the same plane the two reflections line up horizontally. The projected distance between the two reflections was found using a travelling microscope. This distance was then corrected for the parallax error introduced by the fact that the bubbles were closer to the camera than the scale markings. Letting the corrected distance be s' the diameter of a bubble is then given by

$$d_m = s'/\sin(\theta/2)$$

where θ is the angle between the light source and the camera (see Fig. 6). Not all the diameters were measured in this way and on average the diameters measured by collection on paper were 0.35 mm greater than those measured photographically.

For determining the densities of the bubbles it was necessary to find their terminal velocities. This was done for some of the bubbles by using stroboscopic illumination of 100 Hz giving bubble tracks as shown on Fig. 7. Making due allowance for parallax errors, the densities of the bubbles were then found by combining the diameter and terminal velocity data with the relation between the drag and gravity forces acting on the bubbles. The relation is

$$\tfrac{1}{8}\,\rho_A\, d_m^2\, \pi\, V_T^2\, C_D = \tfrac{1}{6}\,(\rho_{dm} - \rho_A)\, d_m^3\, \pi\, g$$

where V_T is the terminal velocity. C_D is a function of Reynolds' number and the Schillar—Nauman [7] expression was used for this:

$$C_D = \frac{24}{Re}\,(1 + 0.15\,Re^{\,0.687})$$

where $Re = V_T d_m/\nu$ and ν is the kinematic viscosity of air ($=1.466 \times 10^{-5}$ m²/s). In general the Reynolds' numbers of the bubbles were less than 500.

The terminal velocities of the bubbles, whose diameters were estimated by collection on paper, were found by timing their fall in still air with a stopwatch. Though this stopwatch—paper method was not so accurate as the photographic technique a larger variation of bubble size was covered. Both sets of results are presented on Fig. 8 where the shaded area represents the results from the stopwatch—paper method and the dots from the photographic method. The vertical lines on Fig. 8 are drawn from equations (2) and (3) and where the lines intersect the shaded area an accurate modelling of raindrops in the wind tunnel is possible.

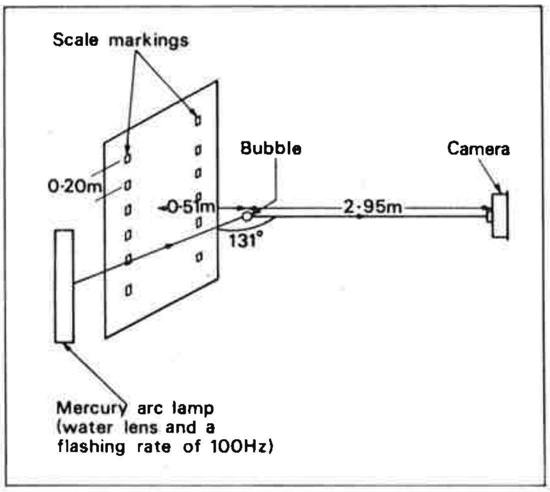

Fig. 6. Schematic arrangement for photographing freely falling bubbles.

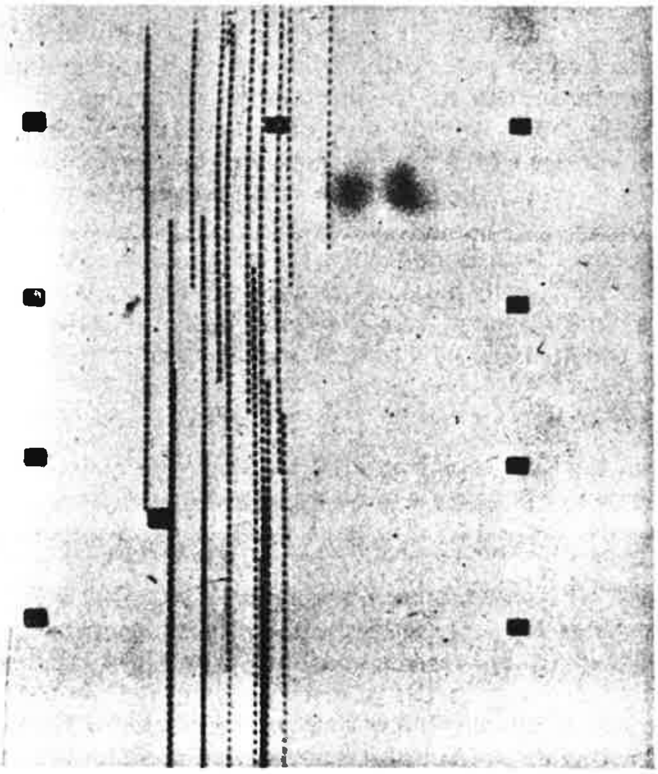

Fig. 7. Stroboscopic illumination of bubbles falling in still air, for the measurement of their diameters and densities. Vertical distance between rectangular markings is 20 cm but, due to parallax, this is 17.1 cm in the plane of the bubbles. The illumination frequency is 100 Hz.

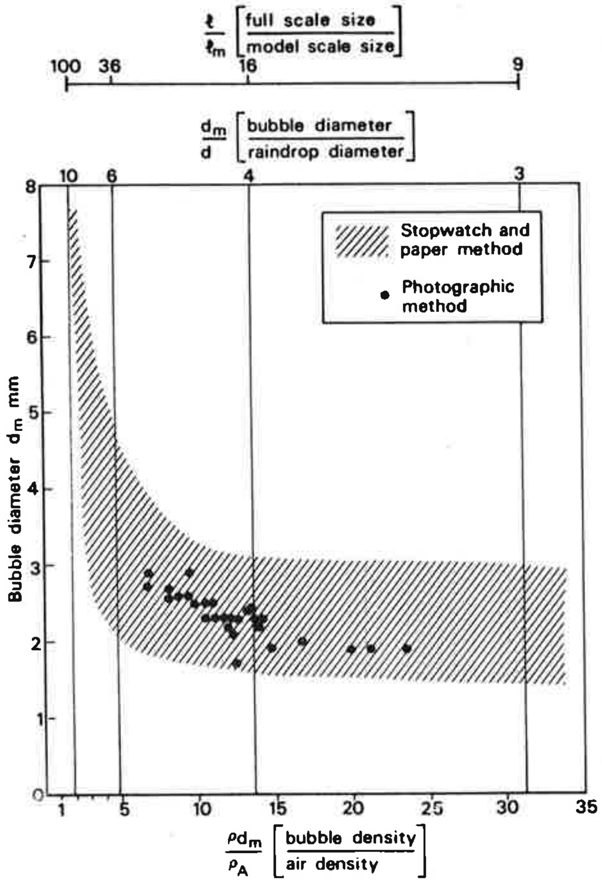

Fig. 8. Bubble diameters and corresponding densities produced by a commercially available bubble generator. The vertical lines (see text) give the requirements for the accurate modelling of raindrop trajectories in a wind tunnel.

Discussion

It is clear that the largest raindrops that can be modelled with these bubbles have a diameter of about 1 mm. According to Best [8] such a diameter covers the drops that carry the greatest volume of water in a period of light continuous rain i.e. excluding thunderstorms and very heavy rain. This limitation is being overcome by building a bubble generator designed at the National Institute of Agricultural Engineers [1] which can produce bubbles with up to several centimetres diameter.

From Fig. 8 it is evident that where the diameter of the bubble drops below about 3 mm a large variation in density is possible and to cope with this in the wind tunnel it will be necessary to develop a method of monitoring the bubbles before their release into the airstream.

Finally, on the "catchment" of bubbles on buildings, a possible technique is to study the trajectories on video-tape (briefly mentioned by Flower and Lawson [2]). This would be quite a tedious method and an alternative might be to cover the surface of the building by absorbent sections which could then be weighed. The bubble solution used would allow this since it has a very low rate of evaporation. The testing of the efficacy of rain shielding attachments to buildings should be quite straightforward though allowance will have to be made for the increased size of the raindrops at model scale. The validity of all these techniques, however, must await experimentation.

Acknowledgment

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