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CONCENTRATION METER FOR WIND TUNNEL STUDIES OF GASEOUS DISPERSION

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Abstract—A photo-electric technique is described for instant determination of contaminant concentration in wind tunnel studies of stack gas dispersion. In the method, a roving sensor is used to measure the light scattered by the particles of oil aerosol representing the prototype stack effluent. The miniature probe has a noise level of only 1×10^{-5} of the full linear range of the output signal for a time constant of 5 s. However, the device is also suitable for the measurement of fluctuating flow properties, such as turbulence, where a high frequency response is required.

INTRODUCTION

RELATIVELY simple wind tunnel tests are generally required to determine with confidence the minimum heights of chimneys or stacks which will prevent the occurrence of aerodynamic downwash of their gaseous effluents due to wind action. Under the simplified model law applicable to such tests (LORD and LEUTHEUSSER, 1970), buoyancy may be neglected or approximated by momentum effects; and velocity ratio (i.e. the ratio of gas exit velocity to wind speed) appears as the only significant similitude parameter. Similarly, the otherwise strict requirement for detailed geometric similarity between prototype and model may be relaxed and replaced by similarity in gross configuration of buildings and topographic environment. However, the really outstanding attraction of wind tunnel tests of stack plumes subjected to cross-wind and wake interactions rests in the ease with which, by simple inspection, critical conditions may be detected and corrected. Particularly at incipient downwash relatively small changes in velocity ratio and/or stack height are sufficient to change a bad situation into an acceptable one, and it becomes possible to determine optimum conditions with a minimum of experimental effort.

The same does not hold true when it is desired to complement qualitative observations by quantitative measurements of contaminant concentration: not only is it inherently very time consuming to undertake a possibly large series of point measurements, but also most of the conventional sampling methods are rather slow. To overcome this latter shortcoming the authors propose herein a new technique in which the metering of local contaminant concentration becomes a practically instantaneous process.

The method is based on the use of oil aerosol as effluent from model stacks in wind tunnel studies. This particular tracer fluid is used widely in experimental low-speed aerodynamics (POPE and HARPER, 1966). Oil aerosol is readily generated in either commercially manufactured or custom-built smoke generators and has the triple advantage of being harmless, highly visible and essentially neutrally buoyant.

DESIGN CONSIDERATIONS

In a typical smoke generator, light detergent-free oil is evaporated in a heating element and then forced under controllable pressure through a fine nozzle. Upon ejection, the jet expands and mixes with air thereby forming a dense aerosol composed of particles with a mean diameter of approximately 1 μm (see Fuchs and Sutugin, 1966). The angular distribution of the scattered light computed from the Mie theory for a wavelength of 0.9 μm and a refractive index $m = 1.5$ for oil (see Van de Hulst, 1957), is depicted on Fig. 1.

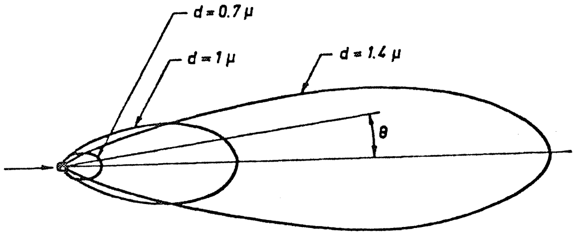

Fig. 1. Forward lobes of scattering patterns of oil aerosol particles. Particle diameters are as indicated; the mean wavelength of the light is 0.9 μm.

The scattering is strongly forward directed, but the scattered light is intense enough for measuring purposes up to scattering angles of 20 or 30°.

The presence of an aerosol can be detected optically either by light transmission or by light scattering measurements (Hodkinson, 1966). At low concentrations of aerosol transmission measurements tend to have outputs which can become comparable to the signals generated by temperature changes and fluctuations of the total light flux. Scattering measurements, on the other hand, produce signals only in the presence of aerosol. This not only minimizes noise and drift levels, but also permits of simpler signal processing. Similarly, scattering measurements facilitate the use of miniature probes since only short optical paths are needed.

Because of these clear advantages a scattering measurement technique using a probe design as depicted in Fig. 2 was considered most suitable for the kind of wind tunnel testing under consideration herein.

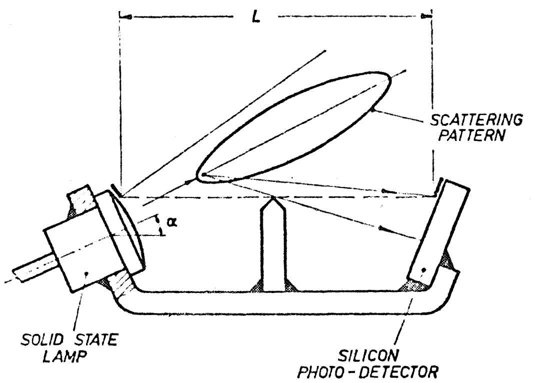

Fig. 2. Photo-electric probe. Solid-state lamp illuminates aerosol particles. A small portion of the scattered light reaches the silicon detector.

DESIGN DETAILS

In the detection device, see FIG. 2, aerosol particles are illuminated by an infra-red GaAs solid-state lamp. Light scattered by the particles impinges on a planar silicon photo-detector. The partition between lamp and sensor prevents direct illumination of the detector by the lamp. Infra-red light is employed because it gives a wider scattering pattern than visible light, and more scattered light can thus reach the detector. Also, the output power of infra-red lamps is higher than that of lamps emitting visible light, and their spectral emission matches the spectral sensitivity of the silicon detector. The mean wavelength of the spectral band is 0.9 μm and, hence, is of the same order of magnitude as the mean diameter of the aerosol particles.

The partition and all other parts of the mechanical structure of the probe are coloured black. This is done to minimize reflections and light scattering on the probe itself which could cause zero-offset of the signal. The system has a minimal number of optical surfaces subjected to aerosol condensation, and can readily be cleaned by simple immersion in a detergent solution.

In order to optimize the mutual position of the system composed of lamp, partition and detector, the total scattered illumination of the detector was computed as a function of, (i) angular distribution of the energy emitted by the lamp, (ii) scattering pattern of the aerosol, (iii) obscuration of the lamp by the partition, (iv) size of the photo-detector, and (v) geometry of the probe. For the particular aerosol used, and for the respective sizes of miniature lamp and detector selected, the analysis suggested on optimum lamp-detector separation L of 10 mm and an angle α (see FIG. 2) of 25°.

The distribution of sensitivity of the probe to aerosol particles as obtained from the same computation is depicted on FIG. 3.

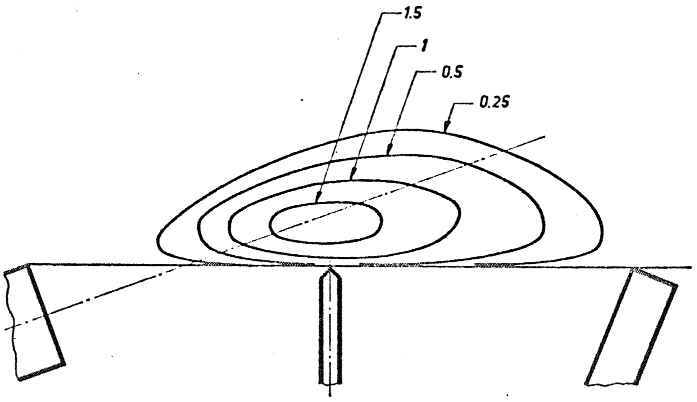

FIG. 3. Sensitivity distribution of the probe. Numbers indicate relative sensitivity prevailing within the various curves. Most of the signal originates from the central part of the probe.

It follows from this presentation that the probe responds most strongly to particles located above the partition. About 90 per cent of the detected scattered light is generated by particles located in a space volume measuring approximately 6 × 2.5 × 2.5 mm.

The solid state lamp of the probe is fed by a 3-kHz square-wave alternating current. The three-stage amplifier of the photo-detector is tuned to this frequency, which eliminates sensitivity to daylight and/or light emitted from laboratory overhead fixtures.

A close-up photograph of the probe is shown in FIG. 4.

The time constant of probe and ancillary electronics is about 2 ms. If a strip chart recorder is used, the time constant increases approximately to 60 ms and the recorded noise level is about 1×10^{-4} of the full linear range of the output signal. For measurement of steady state aerosol distributions the time constant can be further increased to, say, 5 s by additional bandwidth filters. In this way the random noise may be depressed to a level of better than 1×10^{-5} of the full linear range.

CALIBRATION PROCEDURE

Measurement of contaminant concentration in wind tunnel experiments is best effected in terms of relative units related to, say, the maximum smoke concentration prevailing near the effluent source, viz. the model stack. However, to this end the probe response must be linear with concentration over the whole of the anticipated working range.

For the purpose of checking the linearity of the detection device, the probe was placed in a plexiglass container of 0.2-m^3 volume, equipped with both an interior mixing fan and a staff gauge for metering visibility. Visibility, a convenient visual parameter inversely proportional to concentration is used for estimating the upper limit of the linear range. The container was first filled with dense aerosol and then discharged at a constant rate by means of a vacuum pump. During the emptying process clean air was permitted to flow into the container from the atmosphere. It replaced the aerosol whose concentration thus decreased exponentially in accordance with the relation:

$$C = C_0 \exp(-\text{const} \times t) \tag{1}$$

where C_0 = initial concentration, and t = elapsed time.

During the verification experiment the concentration decrease was recorded as a continuous function of time. The record was eventually re-drawn in a semi-logarithmic presentation. The resulting graph, see FIG. 5, shows no significant departure from linearity up to an aerosol concentration corresponding to a visibility of 5 cm. Above this concentration multiple scattering occurs, leading to a non-linear output signal and, finally, to saturation.

APPLICATION

FIGURE 6 portrays a typical wind-tunnel test of smoke dispersion from a boiler-house stack. The model scale is 1:240 and the velocity ratio of the test is 2.0. In the experiments the probe was placed in several selected measuring positions on and behind the model building downwind of the stack. To determine the signal corresponding to the reference (100 per cent) concentration, the probe was positioned near the stack exit. In this position a visibility measurement must be done, to make sure that the signal is within the linear range of the probe. If this is not the case the smoke must be diluted by mixing with air in a glass tube open on both ends, positioned in such a way that all the smoke passes through it. Mixing ratio is established by velocity measurement of both the air in the tube and the smoke at the stack exit.

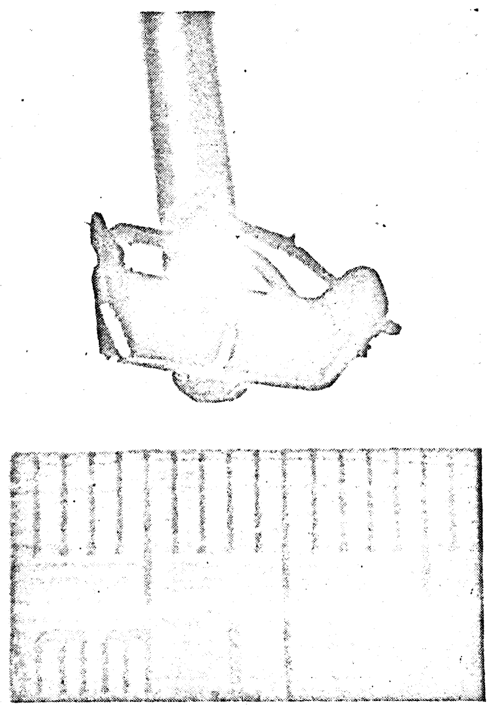

FIG. 4. Photograph of the probe.

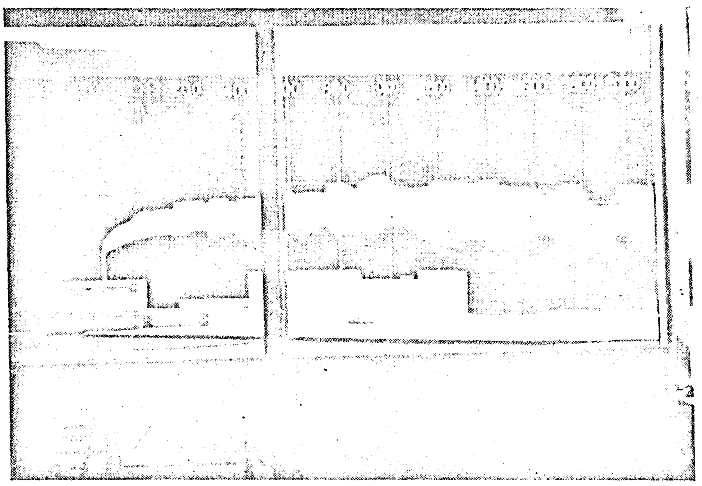

FIG. 6. Typical wind-tunnel test of smoke dispersion.

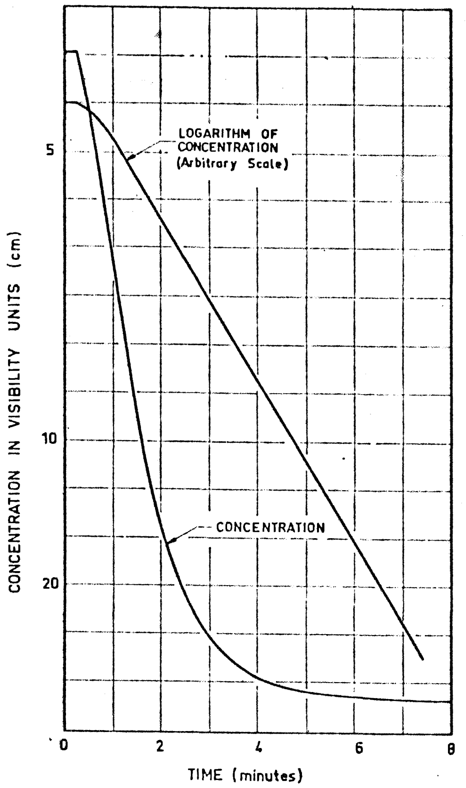

FIG. 5. Linearity verification of the probe. Concentration vs time, as re-drawn from a strip chart record, for an exponential decrease in concentration. Semi-logarithmic presentation identifies the region of linearity of the probe response.

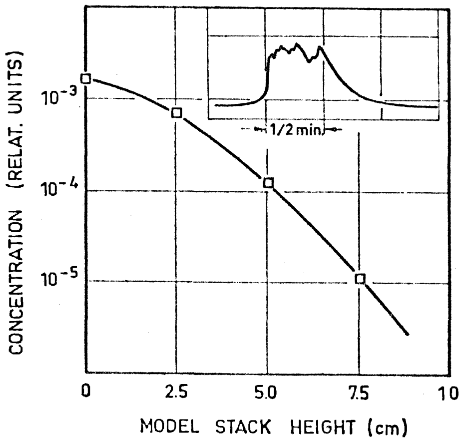

FIG. 7. Typical plot of decrease in local contaminant concentration with increase in stack height. Diagram in top right-hand corner shows example of a concentration vs time record for fixed probe position and stack height, obtained with a long time constant.

Figure 7 shows a representative result depicting the decrease in local contaminant concentration with increase in stack height. The graph in the top right-hand corner is a re-drawn strip chart record of concentration vs. time for fixed probe position and stack height, and a time constant of the detector of 5 s.

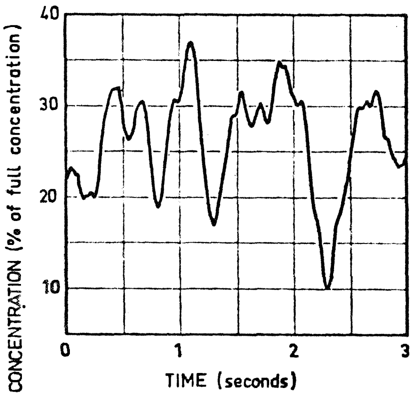

Fig. 8. Typical probe output signal for a short time constant. Measured in a plume 1 m downwind of model stack.

Figure 8 portrays a re-drawn strip chart record of variation of concentration with time which was obtained with a time constant of 100 ms. The probe was positioned 1 m downwind of the stack in the middle of the plume.

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