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A FAST-RESPONSE, HEATED-ELEMENT CONCENTRATION DETECTOR FOR WIND-TUNNEL APPLICATIONS

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Summary

The operating characteristics of a small, aspirated concentration sensor based on a hot-film anemometer are described. Constant aspiration velocity past the sensor produces a linear output over a wide range of tracer gas concentration, and a useful bandwidth of 0—500 Hz. A simple experimental technique for dynamic calibration is presented, with frequency response inferred from a model of the effects of molecular diffusion and hot-film response.

Introduction

Laboratory modelling of mixing and dispersion of contaminants often requires information on the fluctuation of species' concentrations. Concentration fluctuation measurements are essential in predicting combustion of LNG spills, hazards of toxic gas releases, and mixing in chemical reactor vessels. The high-frequency fluctuations in small-scale laboratory simulations require concentration sensors with a rise-time of the order of a millisecond, and this paper will describe the operating characteristics of such a detector, suitable for wind-tunnel measurements.

Detectors for scalar fluctuations may be divided into two classes: direct contact, and aspirated. Direct contact sensors include: resistance wires for measuring temperature [1], light-scattering probes for particles [2,3], and electrical conductivity probes [4] for electrolytic solutions such as salt in water.

Aspirated sensors isolate the detector element in a chamber to reduce sensitivity to drift and noise, and to provide a controlled and protected environment. Samples from the flow are sucked along a tube, after which they pass over the detector element. The flame-ionization hydrocarbon detector of Fackrell [5] falls into this category, along with the hot-wire and hot-film detectors which form the subject of this paper. While aspirated detectors have generally better signal-to-noise characteristics than direct contact probes,

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they may suffer from poorer frequency response and from signal distortion caused by the physical distortion of turbulent eddies during sampling,and by molecular diffusion smearing of sharp concentration gradients as the sample is sucked along the sample line. The advantages and deficiencies of various detectors are discussed by Fackrell [6].

The hot-film detector

The probe considered in this paper was developed to provide a fast-response detector small enough for use in a channel with 0.1 m^2 cross-section without causing excessive blockage. An anemometer-driven hot film was selected for the sensing element because it combined robustness with good frequency response, and allowed the use of existing anemometer electronics and signal processing. The hot film senses changes in species concentration through the effect of a fluid's thermal properties on heat transfer, as discussed by Hinze [7a].

While the analytical relationships are complicated and non-linear, it was observed in the present study that a linear proportionality existed between the bridge imbalance E, and the volume concentration $\bar{C}$ of the two tracer gases tested, helium and dichlorodifluoromethane (refrigerant 12). This linear dependence of E on $\bar{C}$ holds for volume concentrations up to ~10%, and for both constant-current and constant-temperature bridges with one, two or four active arms. This linearity is an important advantage of heated-element sensors and allows direct, analog signal processing.

The major deficiency of heated-element sensors is that they have approximately equal sensitivity to fluctuations in fluid density caused by temperature, velocity and pressure fluctuations as they do to changes in the volume concentration of a tracer gas like helium, having a molecular weight and thermal properties that differ greatly from those of the carrier gas. Heated elements in a four-active-arm bridge with two arms sensing a background reference stream have a lower detection limit of ~ 1 p.p.m. helium in air. However, the single-active-arm configuration required to avoid phase lags in a fast-response detector precludes pressure and temperature compensation and produces a noise-limited detection limit of ~100 p.p.m. helium in air.

The sampling velocity of the aspirated probe shown in Fig. 1 is held constant by a choked orifice downstream from the hot-film sensor. This configuration has been used previously by Blackshear and Fingerson [8] and Colin and Olivari [9], and with the choked orifice upstream by Brown and Rebollo [10]. For early prototypes various locations were tried for the choked orifice. Because changes in tracer concentration also alter the sonic velocity at the orifice it was found to be of critical importance to locate the orifice very close to the sensor, so that there would be no significant lag between changes in sampling velocity caused by fluid properties at the orifice, and heat transfer from the sensor. Another essential element in the probe design was the use of a short plug of filter material near the probe inlet. The long fibres of cigarette

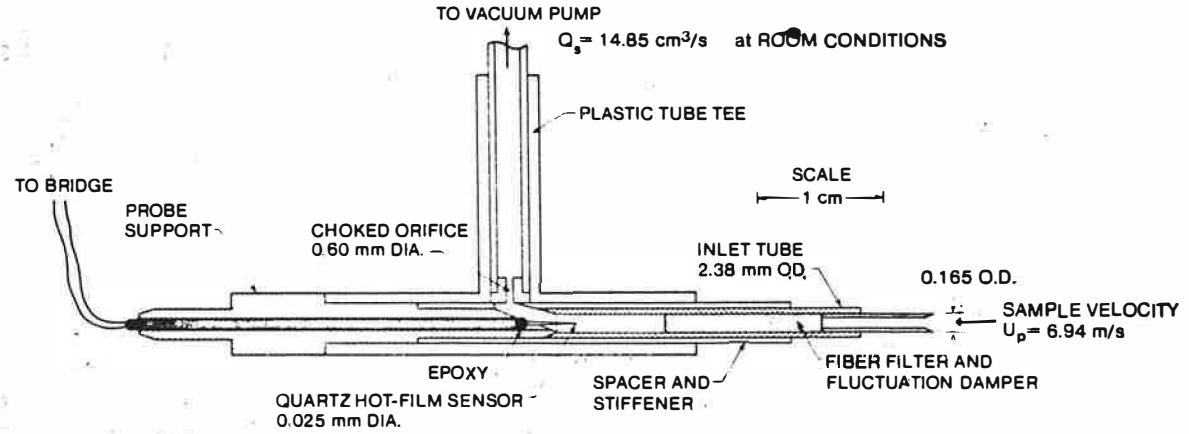

Fig. 1. The fast-response concentration detector.

filters provided the best noise attenuation without excessive concentration smearing. This filter damps out turbulent stagnation pressure fluctuations by its large flow resistance, which in the present study caused a pressure drop of $\sim 5 \times 10^4$ N m^{-2} (0.5 atm) which was probably close to frictional choking. With the filter in place the output noise level from the anemometer was ~100—200 p.p.m. helium in air when the r.m.s. turbulent approach flow velocities were U_T = 7 m s^{-1} and u' = 1.0 m s^{-1}.

The output signal level for a fixed change in tracer gas concentration depends on the suction velocity U_s past the sensor. This velocity is set by the size chosen for the choked orifice and must be high enough to maintain heat transfer dominated by forced rather than by free convection in order to produce signal linearity and rapid transient response. On the other hand, a low suction velocity U_s is desirable to reduce the relative size of velocity fluctuations caused by internal flow separations, and to maintain good spatial resolution. The final design minimized internal noise by using an angled sensor mount, shown in Fig. 1, to turn the flow between the hot film and the choked orifice. The suction velocity U_s was maintained at ~ 14 m s^{-1}, although any velocity in the range 5—15 m s^{-1} is probably acceptable. Because variations in suction velocity change the slope of the linear calibration curve, a fixed velocity is maintained and the probe must sample anisokinetically from varying tunnel velocities. The resulting streamline convergence or divergence at the mouth of the probe is shown later to have no adverse effect on the measured concentration fluctuations.

Response to steady concentration

Output linearity was measured by exposing the sensor to a range of steady concentrations ranging from 1 p.p.th. to 10 p.p.th. (parts per thousand by volume). Two tracer gases were tested: helium, as having the largest difference in thermal properties from air; and refrigerant 12 (R12), a heavy, fluorinated hydrocarbon with a molecular weight of 122. The tracer—air mixtures were

produced by using rotameters to meter air and tracer gas streams into a mixing chamber. The gas mixture was passed through copper coils immersed in room-temperature water to avoid temperature fluctuations, and then blown over the probe by placing the probe tip in the 1-cm diameter tube-exit. The rotameters were calibrated to provide concentrations accurate to ±4%.

The Thermo-Systems 1276-10A hot-film sensor was driven at an overheat ratio of 1.5 by a DISA 55D05 battery-powered constant-temperature anemometer, chosen because of its low noise in the 50—100-Hz band. A battery-operated voltage offset allowed the zero tracer signal to be set at any convenient level. The effect of zero drift on the single-arm CTA bridge was corrected by switching the tracer off every 10 s and subtracting the resulting zero reading from adjacent tracer-on values. The zero drift of the sensor is large, and makes it unsuitable for measuring concentration transients that persist for longer than a few seconds. For measurements of continuous mixing processes, such as a point-source plume, the sensor should be AC-coupled and used only to monitor fluctuations with frequencies higher than ~0.1 Hz. Mean concentrations must be determined with a four-active-arm, gas chromatograph thermal conductivity cell.

Typical calibration curves for helium and R-12 are shown in Fig. 2. The

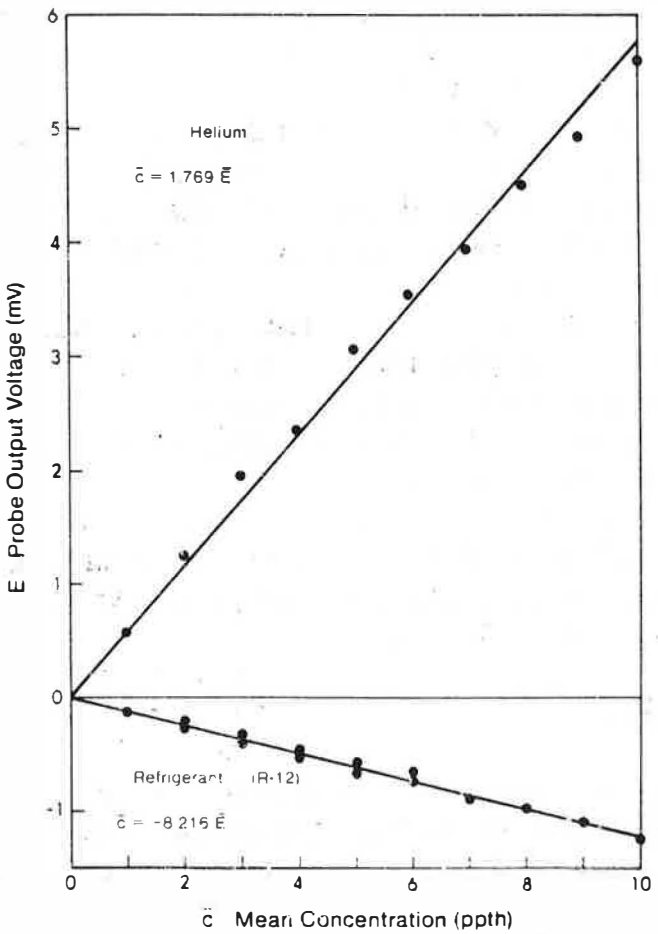

Fig. 2. Calibration curves for steady concentrations.

probe support shown in Fig. 1 could be removed from the plastic tube tee for sensor replacement without disturbing the inlet filter or the choked orifice. The probe support was sealed in place with silicone rubber caulking-compound. Six different hot-film sensors were calibrated and produced linear curves similar to that shown in Fig. 2, with slopes which varied by ±20% from the typical calibration shown. Helium, which produces a signal five times larger than R-12 and gives a positive slope of E versus $\overline{C}$, appears to be the most suitable tracer gas.

In order to produce a neutrally buoyant tracer gas, calibrations were carried out for a mixture of 79% helium, 21% R-12 (by volume). This mixture, having the same density as air, produced only an insignificant signal, rather than the large output expected from the high helium concentration. These measurements show that the effects of binary gas mixtures cannot be predicted from a linear superposition of the individual components. They also emphasize that buoyancy effects of the tracer can only be removed by operating the wind tunnel at high speed to maintain high values for the densiometric Froude number.

Dynamic response

A unit step function at the probe inlet is the most useful test signal to determine system response. However, diffusion smears the boundary between volumes with high concentration gradients. The key to producing a sharp step was to expose the probe to high *temporal* (rather than *spatial*) concentration gradients. This was accomplished by swinging the probe rapidly on a pendulum across the outlet of a 10 p.p.th. helium—air jet. As the moving probe passes the sharp jet boundary the steep concentration gradient required is provided.

The top of the probe stem was fixed in a nylon block through which a hinge pin was passed, with the pin axis perpendicular to the plane of Fig. 1. The probe tip then swung along an arc of 0.5 m radius. The helium—air jet issued vertically from a 1 × 2-cm rectangular orifice located at the bottom of the pendulum swing. The pendulum swing amplitude was adjusted so that the probe passed across the jet exit at ~ 7 m s^{-1}, and so sampled the jet boundary isokinetically. The anemometer voltage was stored on an oscilloscope which was triggered as the probe reached the jet by a fine wire making contact with the moving metal probe stem.

A typical oscilloscope trace is presented in Fig. 3, showing a rapid rise followed by an overshoot, with the steady state reached after ~2 × 10^{-3} s. During this time the probe tip moves ~ 1.5 cm through the jet. The jet boundary through which the probe passes is not sharp, but has been broadened by molecular diffusion. The width of this diffusion zone may be estimated as $\delta \simeq \sqrt{8Dt_1}$, where t_1 is the time for probe travel from the jet exit to a point 1.5 cm above the exit where the probe tip intersects the jet boundary. Using D = 0.6 cm^2 s^{-1} for the diffusivity of dilute helium in air, and a travel time

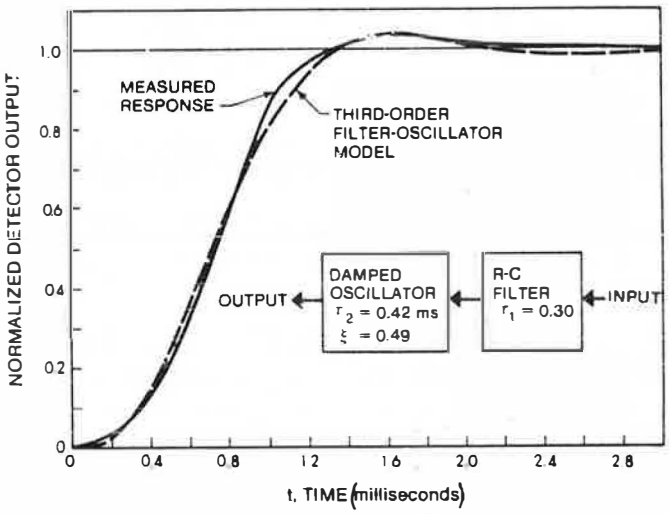

Fig. 3. Response to a step input of concentration.

$t_1 = 5 \times 10^{-4}$ s for a jet velocity of 3 m s^{-1}, the zone of concentration gradient has a thickness $\delta \simeq 0.15$ cm. At a swing velocity of 7 m s^{-1} the probe tip will traverse this region in $\sim 2 \times 10^{-4}$ s. In the analysis which follows, this gradient zone will be ignored and a step input assumed. By lumping this rise-time with the probe response, the theory will underestimate the upper frequency limit of the fast-response sensor, and hence provides a conservative prediction for bandwidth.

The sensor response can be modelled by two elements in series as shown in Fig. 3. The first element is the filter plug whose long filaments aligned with the flow may be thought of as a bundle of parallel tubes. As the step change in concentration passes through the filter, longitudinal diffusion causes the concentration profile to take on an error function distribution according to Taylor's solution for laminar diffusion in tubes [11]. Excluding the gradual leading leading edge of the concentration gradient, this error function distribution may be well approximated by an exponential term with time constant τ_1, characteristic of a simple resistance—capacitance filter.

The second element is the combined hot-film anemometer response, which may be represented by a damped, single-degree-of-freedom oscillator with time constant τ_1 and critical damping ratio ζ. The two series elements produce a third-order system whose response to step and harmonic inputs is available from control theory. The system transfer function is $[(1 + \tau_1 S)(\tau^2_2 S^2 + 2\zeta\tau_2 S + 1)]^{-1}$ and D'Azzo and Houpis [12] give the inverse transform for the output response to a unit step function input as

$$E_{out}/E_{in} = 1 - \frac{(\tau_1/\tau_2)^2 \exp(-t/\tau_1)}{1 - 2\zeta(\tau_1/\tau_2) + (\tau_1/\tau_2)^2} + \frac{\exp(-\zeta t/\tau_2)\sin[\sqrt{(1-\zeta^2)}\, t/\tau_2 - \Phi]}{\{(1-\zeta^2)[1 - 2\zeta(\tau_1/\tau_2) + (\tau_1/\tau_2)^2]\}^{1/2}} \quad (1)$$

where

$$\Phi = \tan^{-1}[-\sqrt{(1-\zeta^2)}/\zeta] + \tan^{-1}\left[\frac{\sqrt{(1-\zeta^2)}\,\tau_1/\tau_2}{1 - \zeta\tau_1/\tau_2}\right]$$

The optimum values $\tau_1 = 4.2 \times 10^{-4}$ s, $\tau_2 = 3.0 \times 10^{-4}$ s and $\zeta = 0.49$ were determined by a best fit of eqn. (1) to the data in Fig. 3. The predicted response curve compares well with the measurements.

The response of the system to a steady, unit sine wave of frequency f is simply the modulus of the transfer function with $S \equiv i(2\pi f)$. This response function is the gain G of the system:

$$G = \{[1-(1+2\zeta\tau_1/\tau_2)F^2]^2 + [F\{2\zeta + (1-F^2)\tau_1/\tau_2\}]^2\}^{-1/2} \qquad (2)$$

where $F = f/f_n$ and f_n is the resonant frequency, $1/2\pi\tau_2$. For $\tau_2 = 3.0 \times 10^{-4}$ s, the resonant frequency is $f_n = 530$ Hz. From eqn. (2) the fast-response sensor has a gain $G = 0.9$ at $f = 300$ Hz and is 3 dB ($G = 0.5$) lower at ~600 Hz. Whether or not this response is adequate depends on the specific situation.

Measurements were made in a typical situation in a 0.3 × 0.3-m wind-tunnel test section. Figure 4 shows the frequency spectrum of fluctuating concentration measured downstream from a point source of pure helium tracer emitted at a height of 3 cm above the wall of a rough-surface boundary layer.

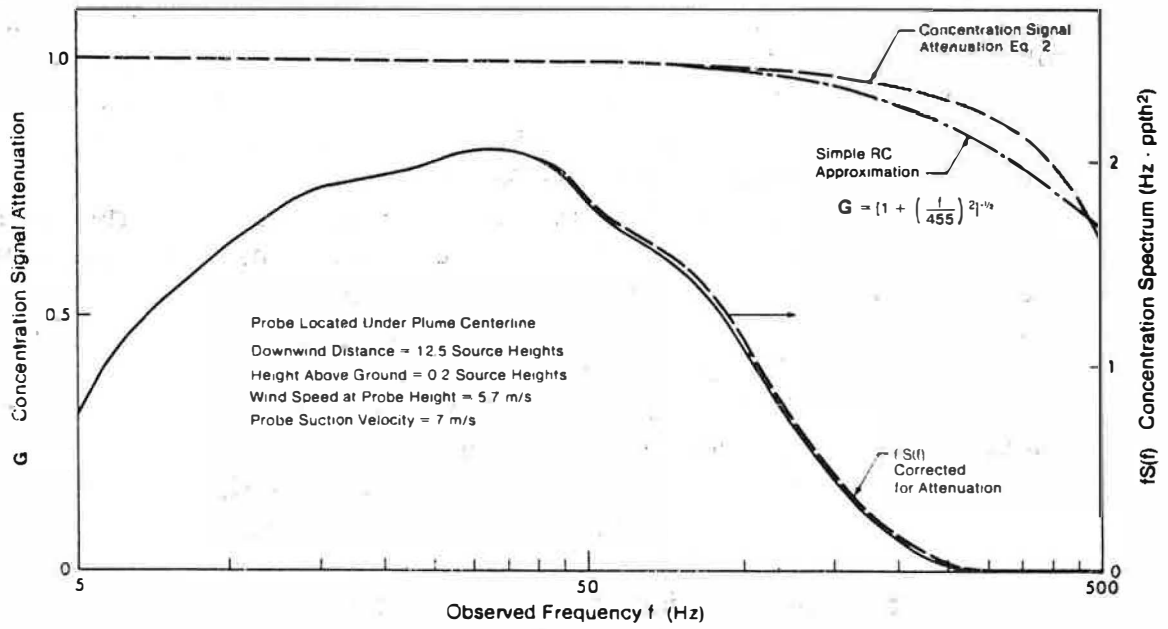

Fig. 4. Probe-induced attenuation of concentration spectrum.

The boundary-layer thickness was 12 cm and the log-law surface roughness length $z_0 = 4.5 \times 10^{-4}$ cm, corresponding to a velocity power-law $U \propto z^a$ with $a = 0.167$. The signal gain for the third-order filter oscillator-response model is shown along with the gain of a single-element resistance—capacitance filter with a time constant of 3.5×10^{-4} s, which was a best (but poor) fit to the measured response curve in Fig. 3. For this typical situation the sensor response characteristics are adequate to prevent any significant error in the variance $\overline{C'^2}$ of the measured concentration due to high frequency cutoff.

We will show in the following section that the fluctuation frequency is not altered by the probe. With this in mind, it is of interest to determine whether the fast-response sensor is capable of measuring concentration fluctuations which are in the process of being strongly dissipated by molecular diffusion. For helium tracer gas, with a diffusivity D about four times larger than the kinetic viscosity ν, the Kolmogoroff concentration microscale is $\eta_C = (D^3/\epsilon)^{0.25}$, where ϵ is the dissipation rate of turbulence kinetic energy. For our test case we find $\eta_C = 0.04$ cm. The maximum in the dissipation spectrum occurs at a frequency $f \simeq 0.2 U_T/2\pi\eta_C$ (see Hinze [7b]), which corresponds to $f = 450$ Hz for $U_T = 5.7$ m s^{-1}. This is near the upper frequency limit of the sensor, and some of the dissipation spectrum will thus be attenuated by roll-off in the frequency response. However, for some applications with lower tunnel velocities, or larger concentration microscales, the fast-response sensor would be suitable for direct dissipation measurements.

Effects of anisokinetic sampling

Because the probe aspiration velocity is fixed by the choked orifice, the probe will usually sample at a velocity U_p different from the approach flow speed U_T, as shown schematically in Fig. 5. The velocity U_s over the sensor will be different from the sampling velocity U_p, due to a decrease in density ρ as the pressure drops through the filter plug as well as to changes in cross-sectional area A inside the probe. The effect of the flow distortion at the probe entrance and the subsequent acceleration inside the probe may be estimated by assuming quasi-steady flow in the stream tube ingested by the sensor, so that

$$\rho_T U_T A_T = \rho_s U_s A_s$$

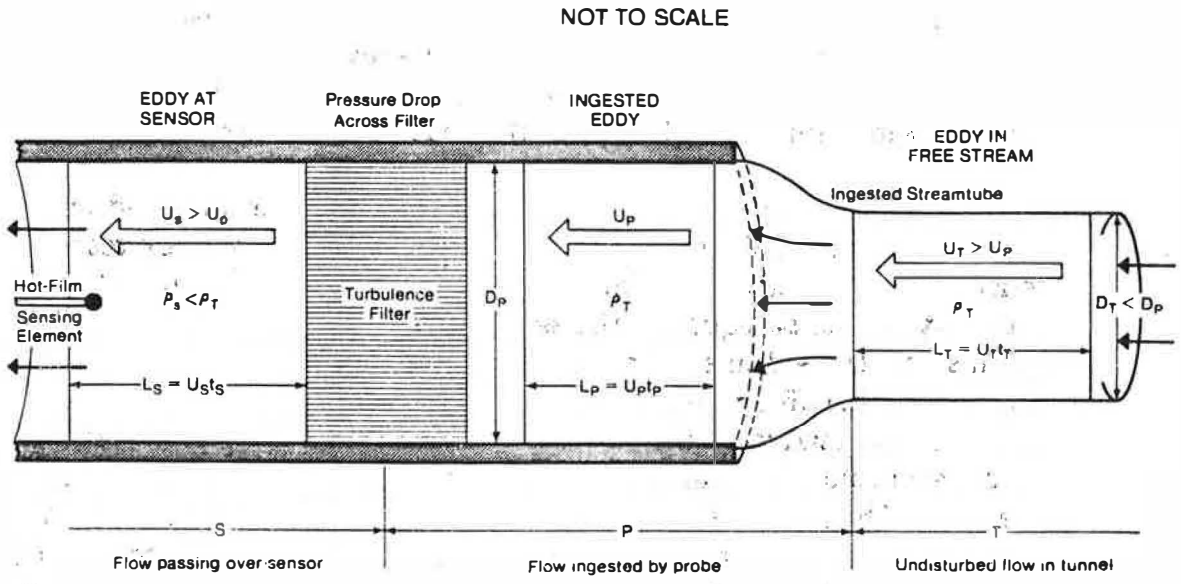

Fig. 5. Anisokinetic sampling by aspirated probe.

The mass within an individual eddy is conserved, neglecting molecular diffusion out of the moving control volume, so that

$$\rho_T L_T A_T = \rho_s L_s A_s$$

Combining these two equations yields

$$L_s/U_s = L_T/U_T$$

which simply states that the length of an eddy distorts as it accelerates so that the transit time $t_s = t_T$ past any point on a stream tube is kept constant. This leads to the important conclusion that fluctuation frequencies will not be changed by anisokinetic sampling.

To test the validity of this simple model, frequency spectra of concentration fluctuations were measured for the point source in the boundary layer described in the preceding section. The wind speed U_T at probe height was varied from the isokinetic value of 7 m s^{-1} to 14 m s^{-1}. Spectral peaks were all observed to occur at a normalized frequency $2\pi f/U_T$ of 11.4 $m^{-1} \pm 0.1$, confirming that the sensor frequency exactly follows the tunnel concentration frequency.

By mass conservation considerations it is easy to show that the mean concentration $\overline{C}$ and the fluctuation variance $\overline{C'^2}$ must be normalized so that $\overline{C}U_T/Q$ and $\overline{C'^2}U_T^2/Q^2$ remain constant for a point source emitting tracer at a volume flow rate Q. These relations were confirmed for anisokinetic sampling by simultaneously varying Q and U_T by a factor of three, while maintaining U_T/Q constant. Within the experimental uncertainty of ±5%, the values of $\overline{C}$ and $\overline{C'^2}$ remained constant.

Conclusions

The aspirated, fast-response concentration sensor based on a hot-film anemometer was found to have a signal output linear with the volume concentration of the tracer gas. Its wide frequency bandwidth, typically 0—500 Hz, combined with ease of fabrication, economy, and small size, make it a useful tool for wind-tunnel modelling of fluctuating concentrations in turbulent mixing.

It should be kept in mind that the stream diameter ingested by the probe will control the probe's resolution as much as the frequency response of the sensor. For a specific application the spatial resolution can be estimated from Fig. 5 by taking t_T equal to the sensor rise-time shown in Fig. 3. Taking t_T = 1.0 ms and U_T = 7 m s^{-1}, the spatial resolution of this configuration was a streamtube 0.165 cm in diameter by 0.7 cm long.

Its major disadvantage, shared with other heated-element detectors, is a high noise level caused by sensitivity to turbulent pressure and temperature fluctuations. While noise from these sources was greatly reduced by the use of a fiber filter plug between the probe entrance and the hot-film sensor, slow, temperature-induced drift makes the single-active-arm sensor bridge suitable

only for measurements of concentrations fluctuating at a frequency of 0.1 Hz or higher.

Perhaps the most important conclusion is that anisokinetic sampling does not cause any measurable distortion of either the amplitude or the frequency of concentration fluctuations. This is particularly important because in a highly turbulent flow the sensor will almost never sample isokinetically, even when the time-mean velocity U_T and the sample velocity U_p are the same.

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