Measurement of Velocity in Gas Mixtures: Hot-Wire and Hot-Film Anemometry

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This paper extends the use of hot-wire and hot-film anemometry to the measurement of velocities in gas mixtures. It is demonstrated that the velocity data in binary gas mixtures can be satisfactorily predicted by calibration tests in pure systems alone or at any two convenient composition conditions. Furthermore, the actual transport properties of a fluid mixture may be inferred from direct calibrations of hot-wire, or hot-film anemometers in the mixture with known compositions.

The measurement of velocity in gas mixtures is of paramount importance in the study of transport phenomena. The hot-wire anemometer, whose principal advantages are the small size of the sensing element, good response to high frequency fluctuations, and suitability for electronic instrumentation, is probably the most versatile instrument in use today for the measurement of mean and fluctuating velocities.

The many advantages of the hot-wire anemometer are somewhat offset by the uncertainty in the use of heat transfer relations. In this paper we examine the two commonly used heat transfer correlations in anemometric work and extend their use to the interpretation of velocity data in gas mixtures.

In most heat transfer correlations considered, the properties of the fluid are based on the mean film temperature, that is, the arithmetic mean of the wire surface temperature and the ambient fluid temperature. In constant temperature operation this value remains constant and thus the interpretation of data is independent of any inaccuracy in the reported magnitudes of fluid property variations with temperature. Therefore the constant temperature method of operation was used in the present study.

A literature survey (*1*, *3*, *5*, *6*, *8*, *10*, *11*, *13*, *14*) indicates that the heat transfer correlations more commonly employed in the interpretation of the hot-wire anemometric data are those of King (*7*), Van der Hegge Zijnen (*12*), and Collis and Williams (*2*).

King's classical equation is based on the potential flow theory, which has been proven to be unsatisfactory (*3*). Also, King's equation has been reported (*3*) to overestimate the experimental data. The equations of Van der Hegge Zijnen and Collis-Williams appear to be different only in the lower Reynolds number range.

For $0.02 < N_{Re} < 44$, the Collis-Williams equation in terms of the time averaged local velocity takes the form

$$U^{0.45} = \frac{\left(\frac{I^2R}{\Delta T}\right)\left(\frac{1}{\varepsilon\pi l k}\right)\left(\frac{T_m}{T_a}\right)^{-0.17} - 0.24}{0.56\left(\frac{d\rho}{\mu}\right)^{0.45}} \tag{1}$$

A direct comparison of power dissipation against the velocity was made for the various mixtures of air-carbon dioxide, air-water vapor, and air-Freon. Significant concentration effects were established and these results are detailed elsewhere (*1*).

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In constant temperature operation of the wire ΔT, R and (T_m/T_a) are constant. Also for a set of data taken at constant composition ν and k are constant and Equation (1) simplifies to

$$\frac{U_1^{0.45} - U_2^{0.45}}{U_1^{0.45} - U_3^{0.45}} = \frac{I_1^2 - I_2^2}{I_1^2 - I_3^2} \tag{2}$$

Equation (2) provides a test of the Collis-Williams correlation based entirely on experimentally measured quantities, velocity U and current I, and independent of the fluid property values and temperature calibration.

EXPERIMENTAL RESULTS AND DISCUSSION

The equipment shown schematically in Figure 1 was designed to study the power dissipation from hot-wire and hot-film anemometers, as a function of fluid velocity and composition in gaseous mixtures.

Air, carbon dioxide, or a mixture of the two gases was blown, via an orifice meter, into a calming section (approximately 60 pipe diameters long) where velocity profile developed. The fluid with fully developed velocity profile entered the test section housing the anemometer probe, where the symmetry of the profile was checked (*1*). The fluid was then discharged through the discharge section.

The hot wire was set up and calibrated by usual procedures. A detailed account of the experimental apparatus and procedure is available elsewhere (*1*).

In the treatment of the data, radiation heat transfer was neglected. Estimating the radiant heat transfer from the wire on the basis of a small body (wire) in an enclosure (approximately long tube) and comparing it to the convective heat transfer, we found that in the case of the hot wire, the maximum contribution by radiant transfer amounted to less than 1%. In the case of the hot film it was less than 2%. Also, the magnitude of rarefied gas effects was estimated by calculating the Knudsen number, and in the present study it was found to be negligible.

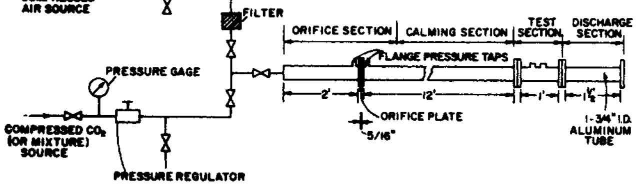

Fig. 1. Flow system.

The Reynolds number, based on the diameter and the fluid properties evaluated at the mean film temperature, varied from 0.044 to 0.32 for the hot wire and from 0.56 to 4.6 for the hot film. The contribution of the free convection to the total heat transfer was neglected. At the conditions of the experiment the ratio of the Grashof number to the square of the Reynolds number varied from 1×10^{-2} to 1×10^{-5}.

Attempts were made to establish the difference between the Van der Hegge Zijnen's and the Collis-Williams relation regarding the exponent of the velocity (or Reynolds number) in relation to the power dissipation (*1*). However, with the precision of our data, we could not differentiate between the two equations since the exponent in question differs only by 0.05.

Attempts to predict the velocity behavior of mixtures of different gases by a calibration in one of the components have been reported in literature (*4*). Our attempts to do so also resulted in overestimation of the relative change in composition as found by Corrsin (*4*). The main discrepancy was in the intercept of the predicted lines, where the equations indicate a linear behavior of I^2 with conductivity k. Slopes of the lines for different concentrations in the air-carbon dioxide system were predicted to be essentially constant and found to be so within experimental error.

However, further attempts to correlate the anemometric data revealed that if calibration data of both the pure components are employed, together with the linear interpolation of their physical and transport properties,* a better estimation of the velocity data in gas mixtures is obtained as demonstrated in Figures 2 and 4. In Figure 2 the best fits to I^2 versus $U^{0.45}$ plots of air and carbon dioxide data obtained using a hot-film were assumed as standard and the dashed lines for 20 and 50% carbon dioxide-air were predicted.† The actual procedure is illustrated in Figure 3. The intercepts of the best fit lines to air and carbon dioxide data were plotted against respective conductivities, and joined by a straight line; this linearity is based on the Collis-Williams equation (2). Then using the calculated conductivities for 20% carbon dioxide–80% air and 50% carbon dioxide–50% air mixture, we read off their intercepts. Similar procedure was followed for predicting the slopes. Then the respective intercepts and slopes were used in plotting the predicted line. The experimental data points

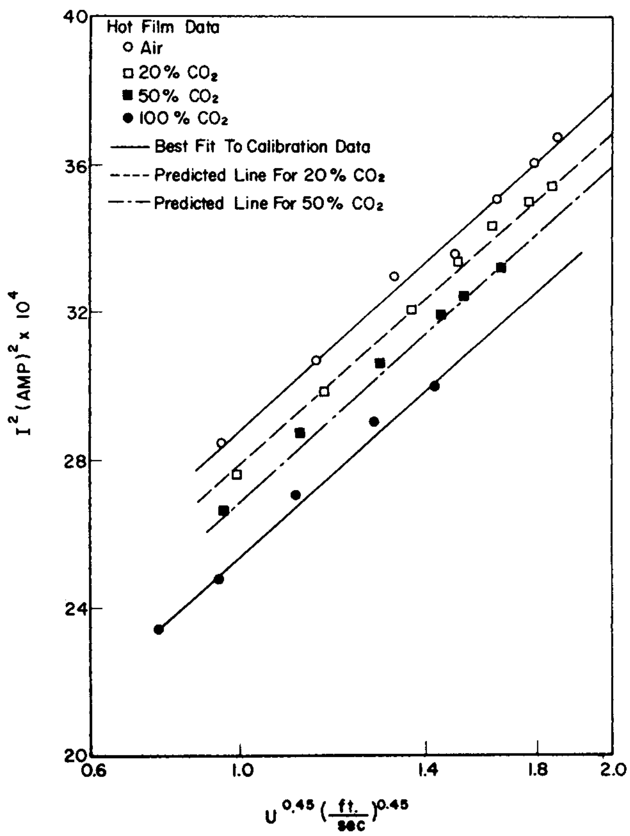

Fig. 2. Prediction of velocity data in a mixture from calibration data in pure systems.

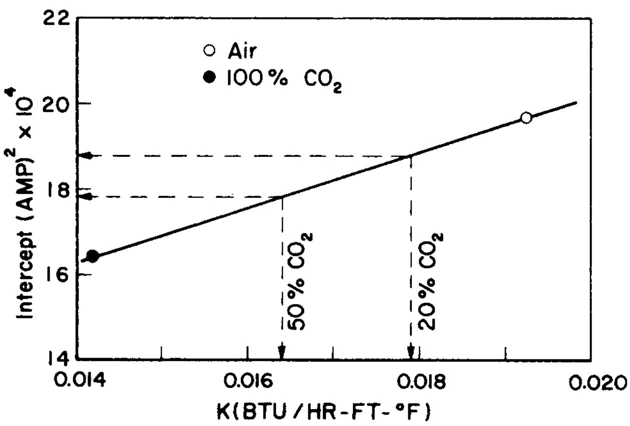

Fig. 3. Intercept versus thermal conductivity for air-carbon dioxide mixture (hot-film data).

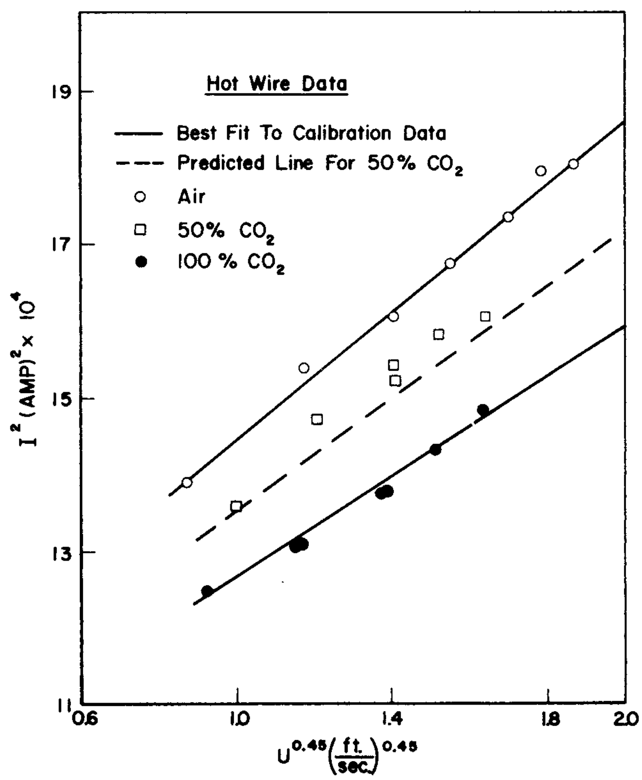

Fig. 4. Prediction of velocity data in a mixture from calibration data in pure systems (hot-wire data).

*The viscosity of the gaseous mixture was computed using Wilke's correlation (*15*) and conductivity was estimated from Brokaw's correlation as reported by Reid and Sherwood (*9*). The density and specific heat for the mixture were taken as mole averages.

†The relative percentages of gases reported throughout this paper are based on volume percent.

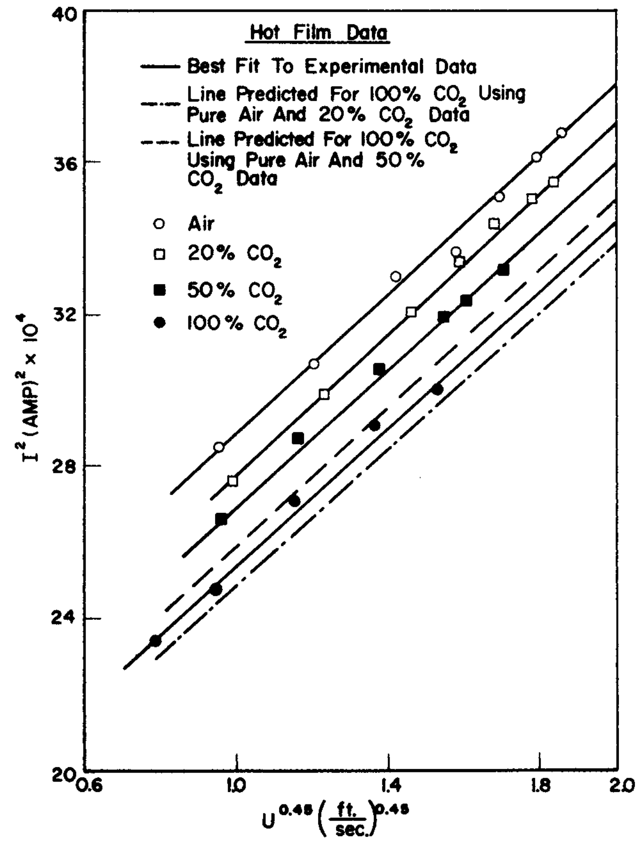

Fig. 5. Prediction of velocity data for pure carbon dioxide from calibration data in pure air and a mixture.

placed on the graphs show that a very good agreement is obtained between the predicted and the actual velocity data. Similar procedure was used to predict the 50% carbon dioxide-50% air line in the hot wire case depicted in Figure 4.

Figure 5 shows the use of the above procedure to extrapolate the data. Using air and one other mixture as standard, a theoretical line for carbon dioxide was predicted. Two combinations were used: air and 20% carbon dioxide-80% air mixture, and air and 50% carbon dioxide-50% air mixture. The figure shows that the predicted lines fall on either side of the actual best fit line to pure carbon dioxide data. The intercept predicted by either combination was within 5% of the actual value.

Thus graphs 2, 4, and 5 show that both interpolation and extrapolation of velocity data in gas mixtures are possible if calibration is performed at two composition conditions. Furthermore, a reasonable agreement between the actual velocity data and the predicted values based on the estimated transport properties of the mixture suggests that the actual transport properties of gas mixtures could be inferred from direct calibrations of hot-wire or hot-film anemometers in mixtures with known compositions.

Recognizing that the main application of hot-wire anemometry lies in the measurement of fluctuating quantities, we also derived sensitivity relationships based on the Collis and Williams' correlation; they are presented elsewhere (*1*).

CONCLUSIONS

Results of the present study show that the hot-wire and hot-film anemometry can be used for velocity measurements in binary systems. Calibration performed in any two suitable mixtures (including pure components) can be used to interpret the anemometric data in the whole composition range by using an interpolation or extrapolation of the transport properties. These findings should be of value in the measurement of the time-averaged velocity in transport processes involving mass transfer and kinetic studies.

The hot-wire or hot-film anemometric technique could be used for inferring the actual transport properties of fluid mixtures from direct calibrations of hot wires or film sensor in the mixture with known compositions. This finding needs to be corroborated with further experimental tests.

The above procedure, although not tested in the present study, should be applicable to ternary and other multicomponent mixtures.

ACKNOWLEDGMENT

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NOTATION

d = diameter of the sensor
I = current
k = conductivity of the fluid
l = length of the sensor
N_{Gr} = Grashof number = $\dfrac{d^3\rho^2 g}{\mu^2}\,\beta'(\Delta T)$
N_{Pr} = Prandtl number = $\dfrac{c_p \mu}{k}$
N_{Re} = Reynolds number = $\dfrac{du}{\nu}$
R = resistance of the hot wire at operating temperature
T_a = ambient temperature
T_m = mean film temperature
U = velocity

Greek Letters

ε = conversion factor
ν = kinematic viscosity
μ = dynamic viscosity
ρ = density
π = constant
ΔT = temperature difference

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