LIMITATIONS OF SPHERE ANEMOMETRY FOR LOW GAS VELOCITY MEASUREMENTS

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ABSTRACT

Sphere anemometry technique is re-visited for low gas velocity measurements during full-scale fire tests. This technique has the advantage of requiring only one channel per sphere for data acquisition, in addition to being cheap and rugged. The results indicate that the technique is useful for small fuel load burns with low radiation levels. For large fuel loads, the usefulness is up to sprinkler activation temperatures.

INTRODUCTION

Sphere anemometry technique is based on the thermal lag of a small (about 10 mm diameter) highly conductive (metal) sphere in a hot gas flow. This technique was first used for low gas velocity measurements during fire experiments at the Factory Mutual Research Cooperation in the late 1970's by G. Heskestad's group. It has been re-examined here to measure low gas velocities during the full scale fire tests at the Center for Environmental Safety and Risk Engineering's Experimental Building-Fire Facility at Victoria University of Technology. One motivation for this research was to help with the prediction of smoke detector and sprinkler behaviour by making available a map of the velocity field in the room.

The advantages of sphere anemometry are, its requiring only one channel per sphere for digital data collection, and its being rugged and cheap. Commonly used bi-directional probes require two channels per probe for data collection. For the low velocities in buoyancy driven turbulence of a fire environment, much better frequency response can be obtained with hot-wire anemometry. However, hot-wire probes are too fragile for high temperature environments with sudd generation, and relatively more expensive electronic equipment is required.

Bi-directional Probes

Heskestad [1] proposed a bi-directional flow tube for fire-induced vent flows, and he used this tube to measure the velocity profile in an open door way to a burn room. With this instrument, it was possible to distinguish inflow or outflow condition of the flow velocities, although it was not possible to determine the exact flow angle.

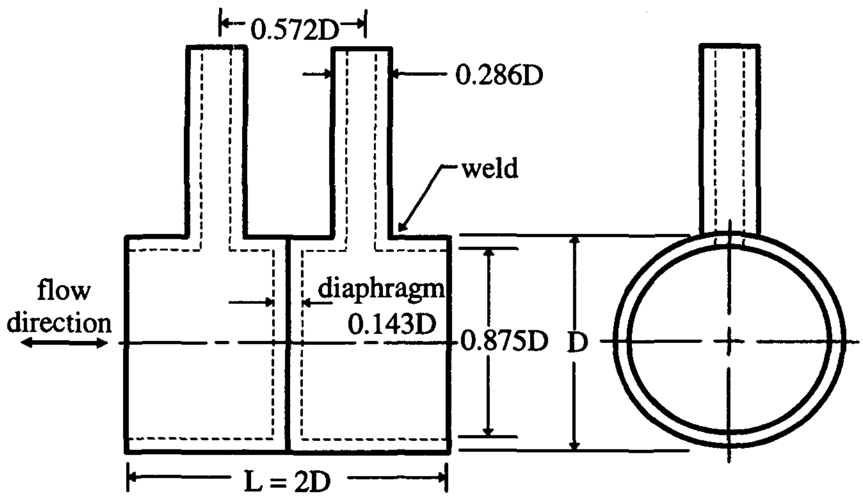


Fig. 1 The basic bi-directional probe design [1], front and side views.

As seen in Figure 1, the bi-directional probe consists of a short piece of stainless steel tubing with a diaphragm in the centre. Two taps are drilled close to, and on either side of the diaphragm [2], [3]. A small ratio of the length to diameter is recommended for compactness. The operation principle of the bi-directional probe is based on the pressure difference, ΔP, which develops between the opposite ports in a fire-induced flow field. The expected pressure differential for a given flow velocity is slightly greater than the pressure difference of a Pitot-static tube. The flow comes in either axial direction of the tube. The upstream tap senses a pressure close to the stagnation pressure and the downstream tap senses slightly less than the static pressure.

Hence, the normalised pressure is sensed as a function of the Reynolds number based on the inner tube diameter, Re_d. A relationship between the pressure difference across the ports of a bi-directional probe, ΔP, and the flow velocity, u, can be obtained as follows, similar to the response of a Pitot-static tube:

$$u = C(\mathrm{Re}_d)\sqrt{\Delta P}\sqrt{\frac{T}{T_c}} ,$$

where $C(Re_d)$ is the calibration constant as a function of the Reynolds number, Re_d; T and T_c are the temperature at the experiment and calibration, respectively.

The bi-directional flow probe is relatively insensitive to its yaw orientation with respect to the flow direction. Based on how it is set up in the flow, it can only detect the dominant flow direction with respect to the probe axis. The original probe design is expected to be sensitive down to 0.3 m/s [2] , [4].

Sphere Anemometry

This research tool was used in fire environments first by the Factory Mutual Research Cooperation, FMRC [5]. One reason why FMRC researchers started this work was because a bi-directional probe which had also been developed at FMRC, required two channels, one to record each pressure; whereas for a sphere anemometer, only one was sufficient. Another reason was to reduce the probe disturbance in the flow. A schematic view of a sphere anemometer is given in Figure 2.

FMRC used brass spheres with embedded thermocouples. The principle of operation is the time lag in reaching temperature equilibrium with its surroundings of a relatively massive and highly conductive cool body in a hot gas flow. The gas velocity can be determined by the rate of change of heating of the sphere and the temperature difference between the gas and the sphere.

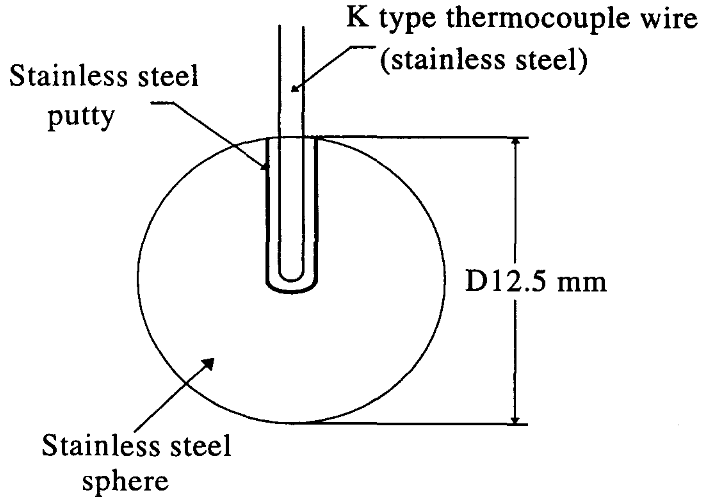


Fig. 2 Sphere anemometer [5].

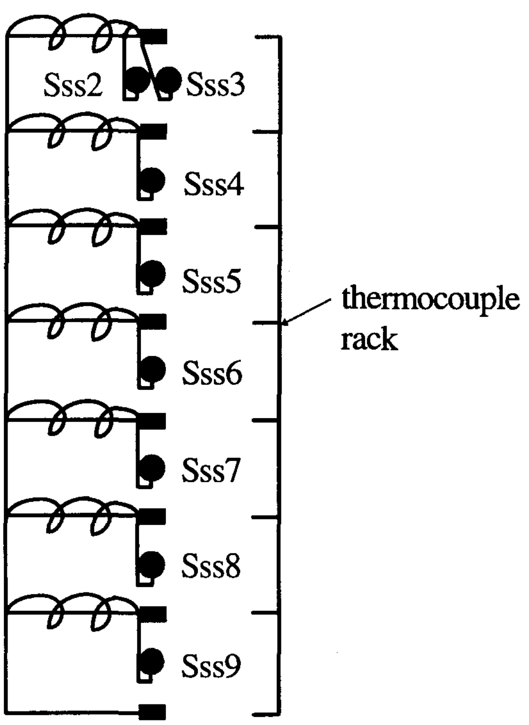
As shown in Appendix A, the following relationship can be obtained for the flow velocity, *u*, in terms of the gas and sphere temperatures, T_g and T_s, respectively:

$$u = \left[\frac{\xi}{(T_g - T_s)} \cdot \frac{dT_s}{dt} \right]^2 ,$$

where ξ is the calibration constant, and dT_s/dt is the time rate of change of the sphere temperature.

Uniqueness of the calibration constant, ξ, its dependence on the sphere Reynolds number, Re_d and accuracy of the method for low velocity measurements are investigated in the present study.

SETUP



— Thermocouple wire
● Sss - Sphere with stainless-steel K type mins
■ Bi-directional probe

Fig. 3 Thermocouple, bi-directional probe and sphere arrangement at the centre of the burn room door.

Velocity data obtained during five full-scale burns with sphere anemometers have been compared with bi-directional probe results. During four of the burns, 3 kg (a half slab) to 16 kg (three slabs) of polyurethane was used as the fuel in a standard room of 5.3m × 3.6m floor area, providing 0.2 to 1.1 kg/m^2 wood equivalent. These burns lasted 500 to 600 seconds. For the fifth experiment, 544 kg of real furniture was the fuel in the same room, corresponding to 28.5 kg/m^2 wood equivalent. For this case, the fire lasted 2600 seconds, and it was allowed to continue to flashover.

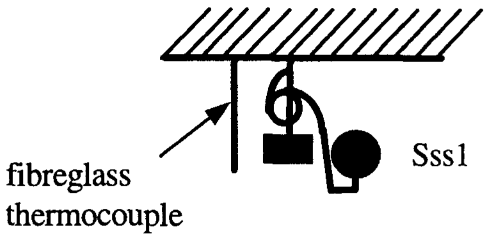


Fig. 4 Thermocouplope, bi-directional probe and sphere arrangement under the corridor ceiling.

Eight spheres were placed along the centre-line of the burn room door way, next to bi-directional probes as shown in Figure 3. The lowest bi-directional probe was 250 mm above the floor level in this figure, and the distance between any two bi-directional probes was 250 mm. An additional sphere was located under the corridor ceiling next to a bi-directional probe, as shown in Figure 4. The interface between the hot and cold layers was about 1200 to 1500 mm from the floor level during the full-scale burns reported here. Hence, Sphere Sss3 in Figure 3, which was fully within the hot layer has been chosen for discussion.

DISCUSSION OF RESULTS

In Figure 5, gas and sphere temperatures are plotted during Burn 1. The fuel load was a single slab of polyurethane during this burn. The gas and sphere temperatures were similar from the ignition point to 40 seconds. 40 seconds after ignition, temperature differences occurred. At about 500 seconds, the gas and sphere temperatures became the same. After the 500th second, the sphere cooled down faster than the gas.

In Figure 6, the calibration factor, ξ, is plotted for Burn 1. The value of ξ is about 100 $(ms)^{1/2}$ for this burn. The value given by Heskestad [5] is 214.9 $(ms)^{1/2}$, or 387 $(fts)^{1/2}$. To calculate ξ, experimentally measured velocity values as obtained with a bi-directional probe were used in equation (A.5) after a nine-point averaging. Gas and sphere temperatures were averaged similarly. The time derivative of sphere temperature had to be averaged twice to eliminate high frequency oscillations caused by numerical differentiation.

The ξ value hence calculated was used in determining the gas velocity as measured by Sphere Sss3. In Figure 7, the gas velocity measured by and with Sphere Sss3 the bi-directional probe at the same level as Sphere Sss3 are plotted. The values measured by sphere Sss3 are lower than those of the bi-directional probe. In this analysis, when the gas and sphere temperatures became equal, or when the derivatives of sphere temperature approached zero, the gas velocity was interpolated.

In Figure 8, the gas velocities measured by the bi-directional probe are compared with the values calculated from Sphere Sss3 with ξ =100 and with ξ = 121 during Burn 2. Except for 280 ± 40 seconds after ignition, the second ξ value was calculated similar to the ξ calculation for Burn 1. The fuel load was a half slab of polyurethane during Burn 2. The three sets of results are within experimental error of each other. The difference between the sphere and gas temperatures was small during the time period of about 240 to 320 second after the ignition. As a result, the sphere velocities had to be interpolated. Consequently, this is the period of maximum deviation between the bi-directional probe and sphere velocities.

A similar comparison is given in Figure 9 for Burn 3. The fuel load was three slabs of polyurethane. ξ = 100 is used in obtaining the results in Figure 9 with nine and nineteen-point averaging of experimental velocity and temperature data. The ξ value calculated with the data of Burn 3 was 76. Due to increased radiation, the sphere measurements started to deviate substantially from those of bi-directional probe measurements. Nineteen-point averaging was necessary with the increased fuel load.

During Burn 5, the fuel was real furniture in the burn room. The gas and sphere temperatures were quite similar, as shown in Figure 10. The resulting velocities are plotted in Figure 11. The ξ value calculated with the data of Burn 5 was 128. The difference between the velocities measured with the bi-directional probe and Sphere Sss3 was substantial for most of the duration of Burn 5. Especially from 700 to 1200 second after the ignition, this difference was caused by almost equal sphere and gas temperatures.

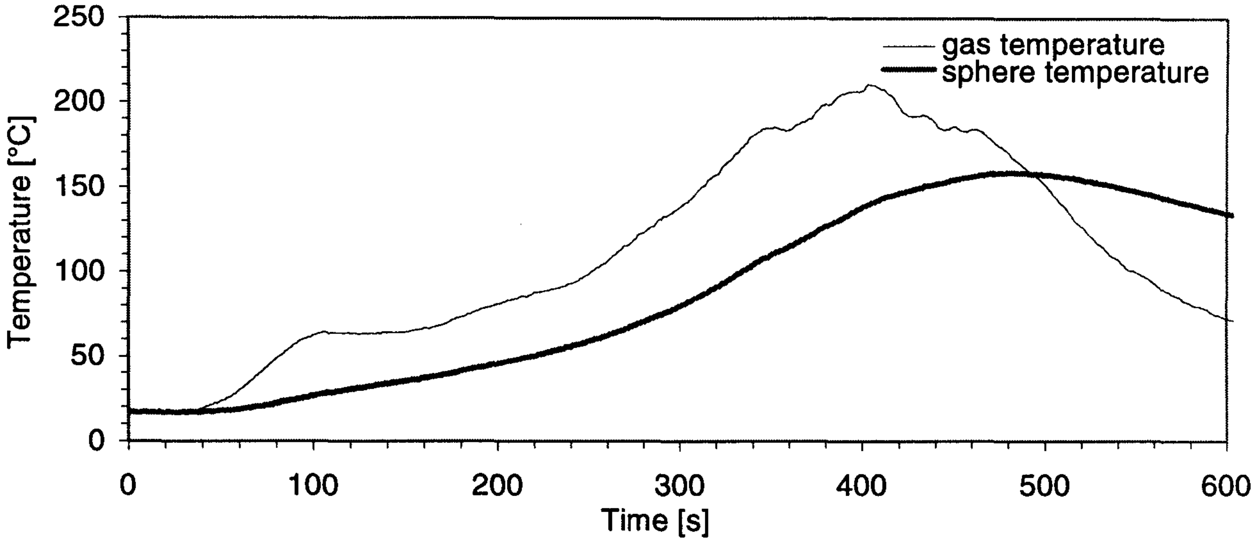


Fig. 5 Gas and sphere temperatures for Burn 1.

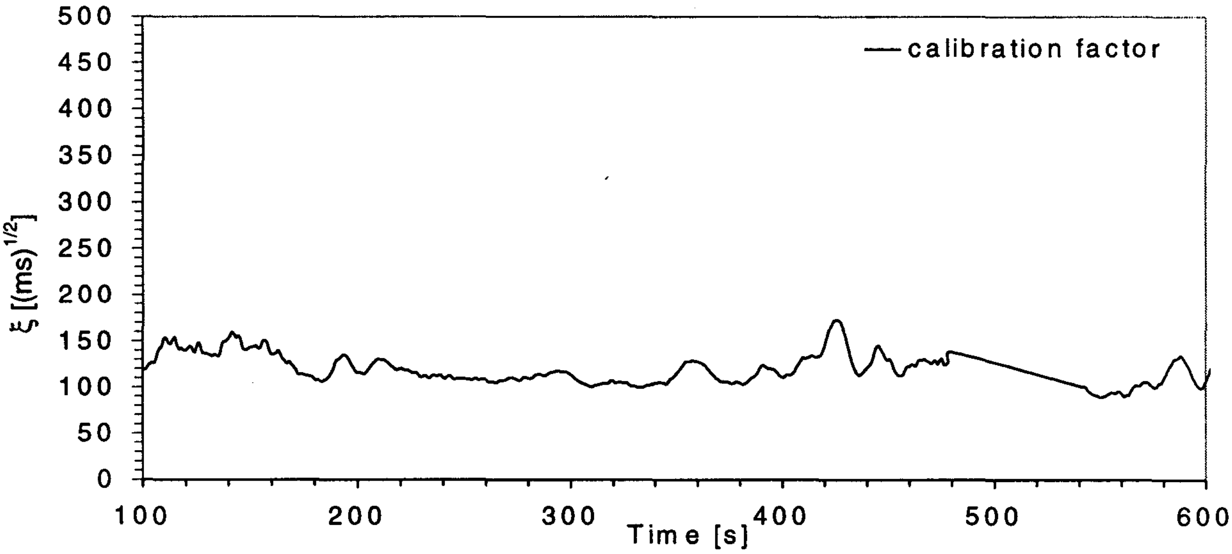


Fig. 6 Calibration factor, ξ, for Burn 1.

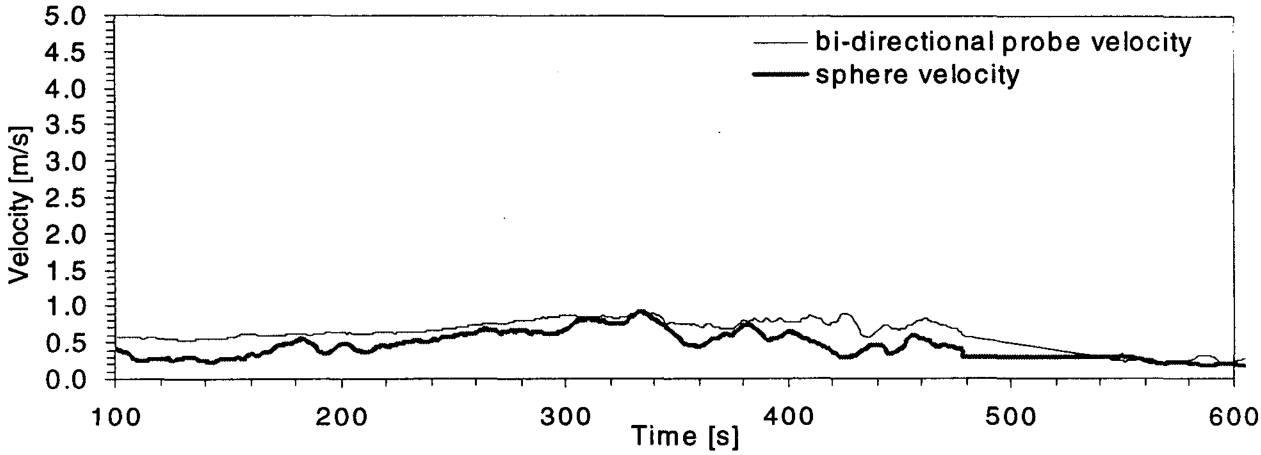


Fig. 7 Bi-directional and sphere velocities for Burn 1.

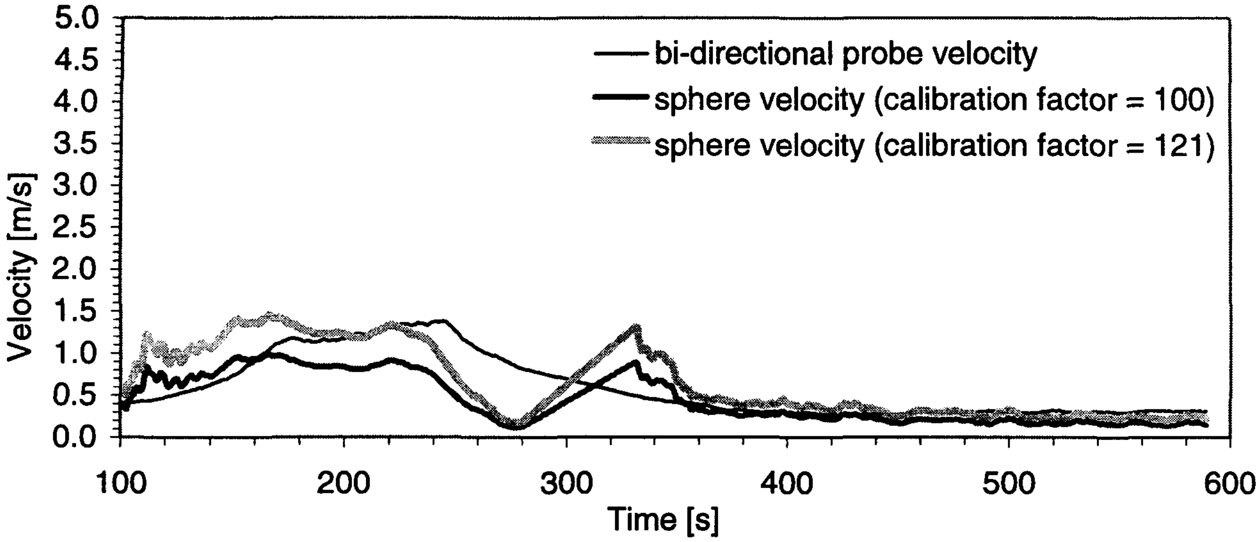


Fig. 8 Bi-directional and sphere velocities for Burn 2.

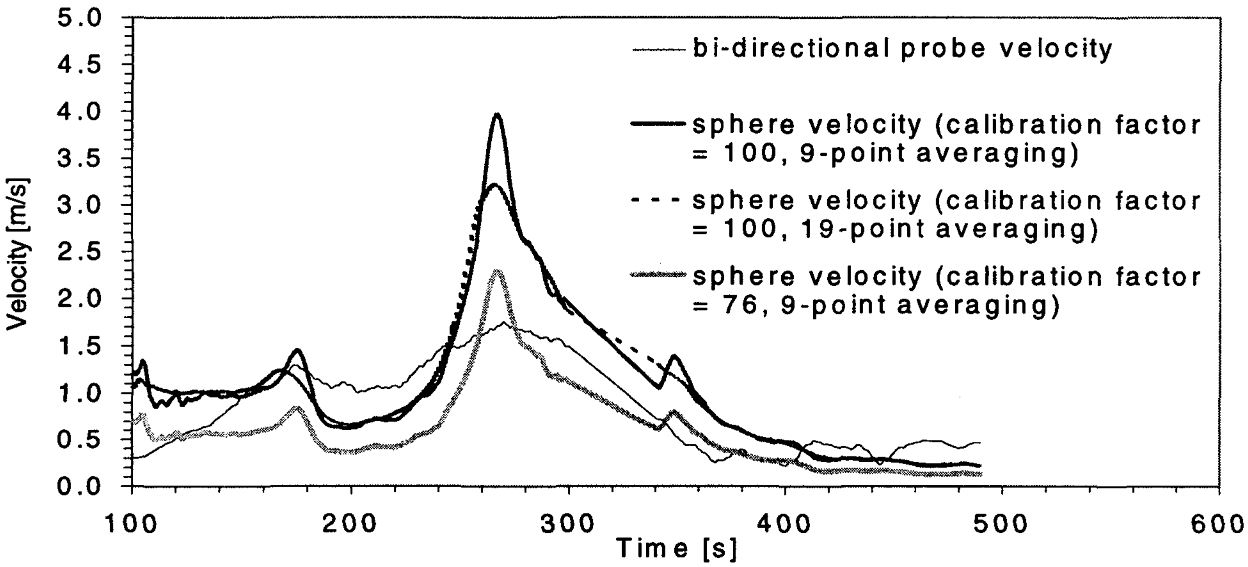


Fig. 9 Bi-directional and sphere velocities for Burn 3.

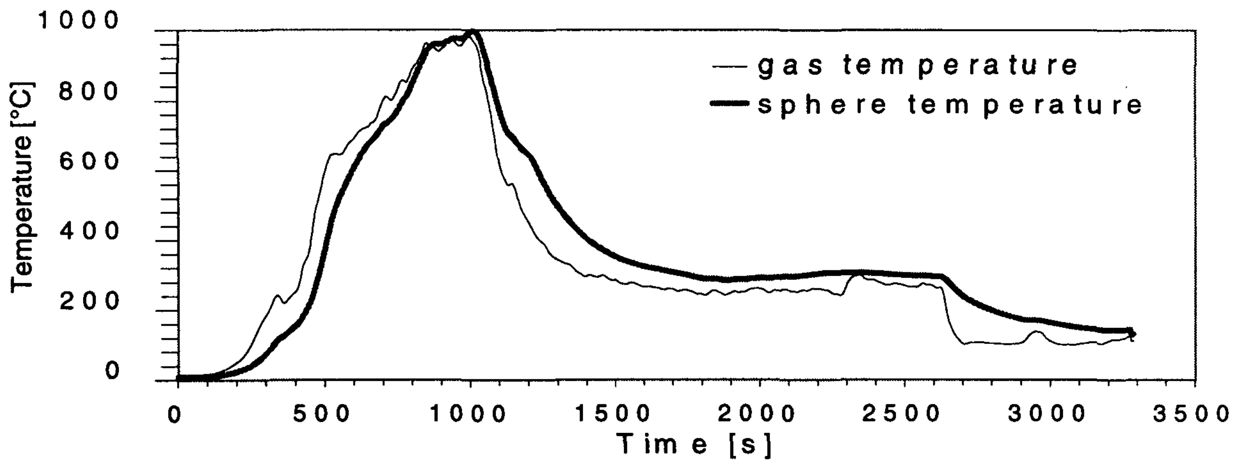


Fig. 10 Gas and sphere temperatures for Burn 5.

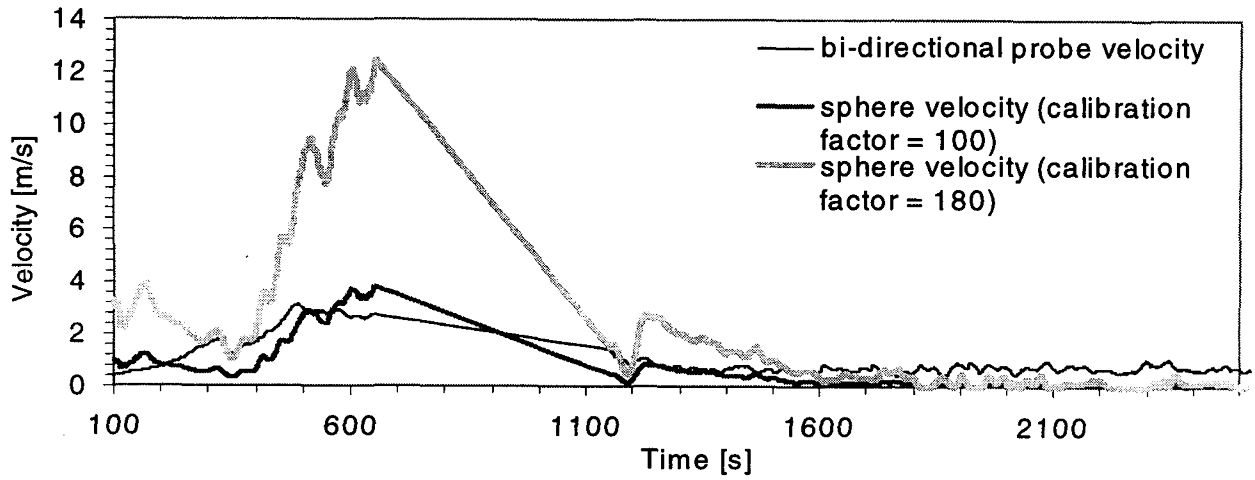


Fig. 11 Bi-directional and sphere velocities for Burn 5.

CONCLUSIONS

The experimental results indicate that sphere anemometry can be used for the small polyurethane burns with relatively slow burning rates. When the fuel load is high and radiation effects dominate, as in the fifth real furniture burn, the method is not feasible, as expected. For such cases, the method can still be useful only until sprinkler activation temperatures of less than 200 °C are reached.

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APPENDIX A

Calibration of a Sphere Anemometer

The heat balance for the forced convective heating of a highly conductive sphere can be expressed as follows:

$$\frac{dT_s}{dt} = \tau^{-1}(T_g - T_s), \tag{A.1}$$

where T_g = *the gas temperature,*
T_s = *the sphere temperature,*
t = *time,*
τ = *the time constant of the sphere.*

τ is defined as,

$$\tau = \frac{mc}{hA}, \tag{A.2}$$

where m = *sphere mass,*
c = *specific heat of sphere material,*
h = *convective heat-transfer coefficient,*
A = *surface area of sphere.*

Since $h \propto u^{1/2}$ and $\tau \propto u^{-1/2}$;

$$\tau\, u^{1/2} = \text{constant},$$

$$= \xi, \tag{A.3}$$

where ξ = *calibration factor.*

From Equation A.1,

$$\frac{dT_s}{dt} = \frac{1}{\tau}(T_g - T_s),$$

$$(T_g - T_s)dt = dT_s\tau,$$

$$\therefore \tau = T_g - T_s \cdot \frac{1}{(dT_s/dt)}. \tag{A.4}$$

Substituting Equation A.4 into Equation A.3,

$$\tau\sqrt{u} = \xi,$$

$$\sqrt{u} = \frac{\xi}{\tau},$$

$$\sqrt{u} = \frac{\xi}{(T_g - T_s)} \cdot \frac{1}{\left[1/(dT_s/dt)\right]},$$

$$\therefore u = \left[\frac{\xi}{(T_g - T_s)} \cdot \frac{dT_s}{dt}\right]^2. \tag{A.5}$$