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The effect of the thermal prong–wire interaction on the response of a cold wire in gaseous flows (air, argon and helium)

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This paper deals with the study of the response of a cold wire used as a thermal sensor in a turbulent flow for different types of probes and for several gases (air, argon and helium). It is now well known that in the case of air flows the transfer function of the probe shows a typical step at low frequencies, as pointed out by Perry, Smits & Chong (1979).

In this plateau region the wire temperature may be influenced by the prong temperature through two different paths. The first is conduction between prong and wire, as already discussed by Maye (1970) using the 'cold length' l_c introduced by Betchov (1948). As suggested by Hojstrup, Rasmussen & Larsen (1975) the second is the result of the thermal boundary layer on the prong being very large at low velocities in gases of large thermal diffusivity; this region of influence (by the prong) extends over a length of the wire characterized by the thickness l_b of the thermal boundary layer on the prong.

In this paper a simple analysis of the behaviour of the transfer function of cold wires taking these two effects into account is presented by introducing the parameter $\eta = l_b/l_c$. An experimental investigation of these phenomena has been undertaken using a procedure which allows temperature fluctuations to be produced over a larger range of frequencies than has been usually made up to now.

Good agreement is obtained between experimental results and predictions using this analysis for several types of prong in different gaseous flows (air, argon and helium). An important step in the frequency response is found in the latter case because of the large thermal diffusivity of helium. Furthermore an example of the thermal prong–wire interaction is presented in the case of intermittent temperature measurements.

1. Introduction

Measurements of temperature fluctuations in slightly heated turbulent flows are usually performed with platinum-wire resistance thermometers. In this method the wire is run with a constant current at a very low overheat ratio. The use of wires of small diameter and length allows one to obtain good frequency response and spatial resolution (La Rue, Deaton & Gibson 1975; Hojstrup, Rasmussen & Larsen 1976). However, end-conduction heat loss involves a step change in the frequency response at low frequencies owing to the thermal inertia of the prongs, as pointed out by Hojstrup *et al.* (1976) and Perry, Smits & Chong (1979) in airflows. This leads to a discrepancy between the static and dynamic sensitivities of the sensor. The use of the 'cold length' l_c introduced by Betchov (1948) allows one to predict reasonably well the response of the cold wire at low frequencies. Indeed, for the usual types of probe experimental results in air and argon flows in the velocity range 4 m s^{-1}–30 m s^{-1} show good agreement with predictions based on heat-conduction loss analysis. However, for the same kind of probes for the case of lower velocities (0·5 m s^{-1}–2 m s^{-1}) in air flows, and for the whole range of velocities for helium flows, a large discrepancy between predicted and measured values can be observed owing to the existence of a transient thermal boundary layer on the prongs, as first discussed by Hojstrup *et al.* (1976). In order to analyse this latter effect simply, the transient thermal-boundary-layer thickness l_b around the prongs has been considered. So knowledge of l_b and l_c allows a convenient formulation of the response of a cold wire in a more general way.

2. Influence of end-conduction loss on the frequency response of a cold wire

Recent works (Maye 1970; Hojstrup *et al.* 1976; Perry *et al.* 1979; Paranthoen & Petit 1979) have shown that the transfer function of a cold wire used to measure temperature fluctuations could be strongly modified by conduction between the wire and prongs. At low frequencies in the range from 10^{-2} Hz up to 10 Hz the transfer function $H(n)$ can be written as

$$H(n) = 1 - \frac{2\pi i n(M_0 - M)}{1 + 2\pi i n M_0} 2\frac{l_c}{l}, \tag{1}$$

where M_0 and M are the time constants of the prongs and the wire respectively. l is the length of the wire and l_c is the cold length introduced by Betchov (1948):

$$l_c = \tfrac{1}{2}d\left(\frac{\lambda_w}{\lambda_g}\frac{1}{Nu}\right)^{\frac{1}{2}}, \tag{2}$$

where d is the diameter of the wire, λ_w and λ_g are the thermal conductivities of the wire and of the gas respectively. Nu is the Nusselt number of the wire.

Equation (1) shows that the ratio l/l_c has to be taken into account as a guide to sensor selection rather than l/d generally used by experimentalists, as discussed by Freymuth (1979). All former studies were only concerned with the behaviour of a system of wire and prongs. In the case where an intermediate medium exists (Wollaston) the transfer function can be expressed as follows, after Petit, Paranthoen & Lecordier (1981):

$$H(n) = 1 - \frac{2\pi i n M_0}{1 + 2\pi i n M_0} 2\frac{l_c}{l} F, \tag{3}$$

where L is the whole length of the sensor (wire and Wollaston), M_w the time constant of Wollaston. F, α_w and β_b are given by the following expressions:

$$\alpha_w = \left\{\frac{1}{2a_w M_w}[\{1 + (2\pi n M_w)^2\}^{\frac{1}{2}} + 1]\right\}^{\frac{1}{2}},$$

$$\beta_w = \left\{\frac{1}{2a_w M_w}[\{1 + (2\pi n M_w)^2\}^{\frac{1}{2}} - 1]\right\}^{\frac{1}{2}},$$

$$F = \frac{A + \dfrac{M_w}{M_0} + i\omega M_w}{1 + i\omega M_w},$$

where

$$A = \frac{1}{\cosh[(\alpha_w + i\beta_w)\frac{1}{2}(L-l)]},$$

and a_w is the thermal diffusivity of Wollaston. In order to verify (1) and (3) it is necessary to study the response of the thermal sensor (wire and prongs) to accurately known sinusoidal temperature fluctuations. The internal-heating method cannot be used for that purpose, the prongs never being electrically heated, even at low frequencies, because of their very low electrical resistance. For this reason, Hojstrup *et al.* (1976) induced temperature fluctuations by applying an acoustic field from 2 Hz up to 10^4 Hz. Perry *et al.* (1979) produced square waves by slowly oscillating the wire across two adjacent streams of the same velocity with one stream at an elevated temperature relative to the other in the range (10^{-2} Hz–6 Hz). An alternative method consists of using the procedure described by Schacher & Fairall (1978), and Lecordier, Petit & Paranthoen (1981), where the probe is located in the wake of a periodically heated thin wire.

3. Experimental procedure

The experimental set-up is shown in figure 1. A 3·5 μm diameter platinum–10 % rhodium wire used to create temperature fluctuations is located at the exit of a laminar jet, normal to the flow. The wire is run with a sinusoidal current at frequency f_0 so that temperature fluctuations at frequency $2f_0$ are produced in its wake. The width of the heated wake and the cut off frequency response (f_{3dB}) strongly depend on the gas and on the velocity of the flow, as shown in figure 2 for air and helium flows. The Reynolds number of the wire never exceeded 6 during the experiments, and the aerodynamic perturbation at the distance of measurements was negligible. The bandwidth of sinusoidal temperature signals in an airflow at a distance of 8 mm from the heating wire at 4 m s^{-1} and 24 m s^{-1} is given in figure 3. The fluctuating temperature field at the same distance was found to be uniform in space in the direction parallel to the source wire, as shown in figure 4. So, at this location, the whole system (wire, Wollaston and prongs) is subject to the same fluctuating temperature field. An example of sinusoidal temperature fluctuations obtained at the measurement location is presented in figure 5.

In order to extend the bandwidth of the system a compensation network (R–C filter) was introduced between the generator and the source wire. The adjustment of the compensation network was made by means of a 0·7 μm diameter platinum wire ($l/d = 1700$) located at the same place as the probes to be studied and perpendicular to the heating wire in order to prevent the prongs from being heated by the temperature field.

The frequency response of this reference wire is then known to be flat from DC up to about 2 kHz (in air flow at 4 m (s^{-1}), so it is possible to use this to adjust the compensation network in order to increase the bandwidth of the source wire up to around $2f_{3dB}$.

4. Experimental results in airflows in the velocity range 4 m s^{-1}–30 m s^{-1}

Measurements of transfer functions at low frequencies are presented for 0·7 μm and 2·5 μm diameter platinum wires with and without Wollaston placed parallel to the source wire in the symmetry plane and at a distance of 8 mm from it.

They were manufactured by Sigmund Cohn Corp. and Johnson Mathey respectively.

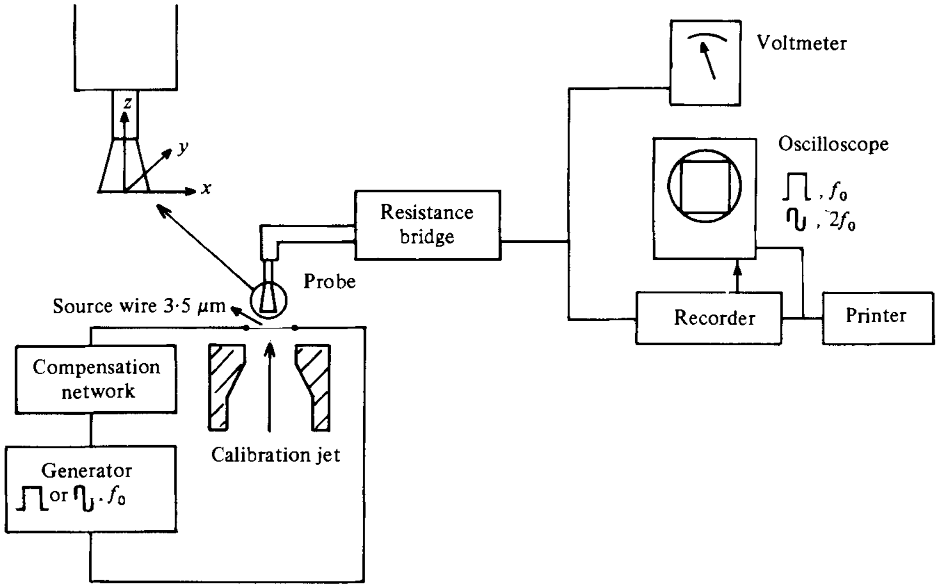

FIGURE 1. Experimental set-up.

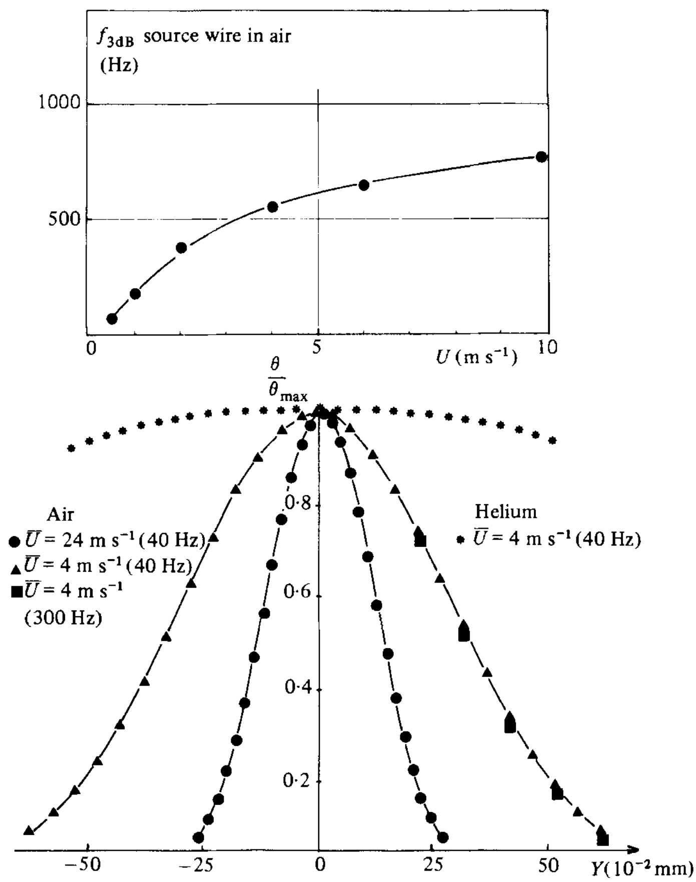

FIGURE 2. Main characteristics of the heated wake (width and frequency response) in air and helium flows.

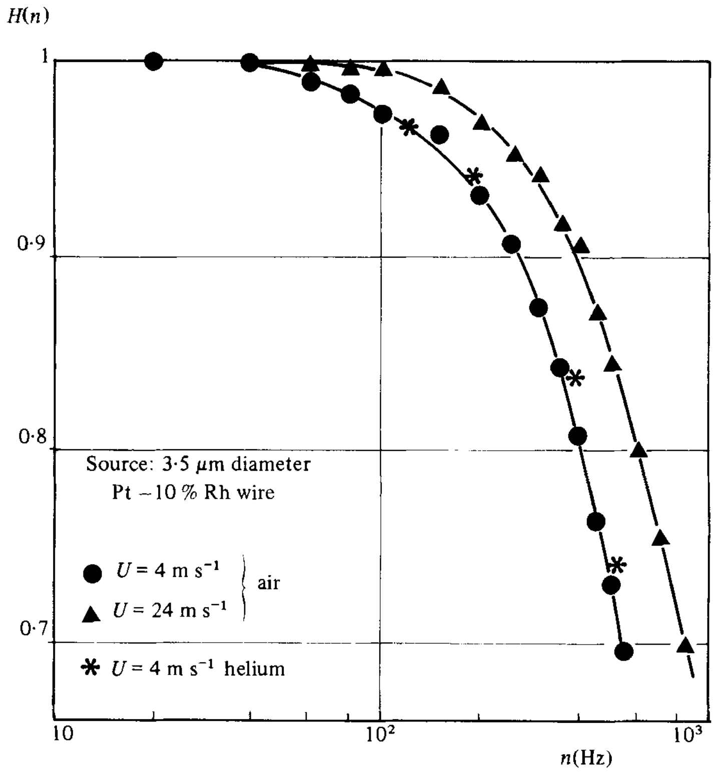

FIGURE 3. Transfer function of the temperature-fluctuation generator at 8 mm from the source wire.

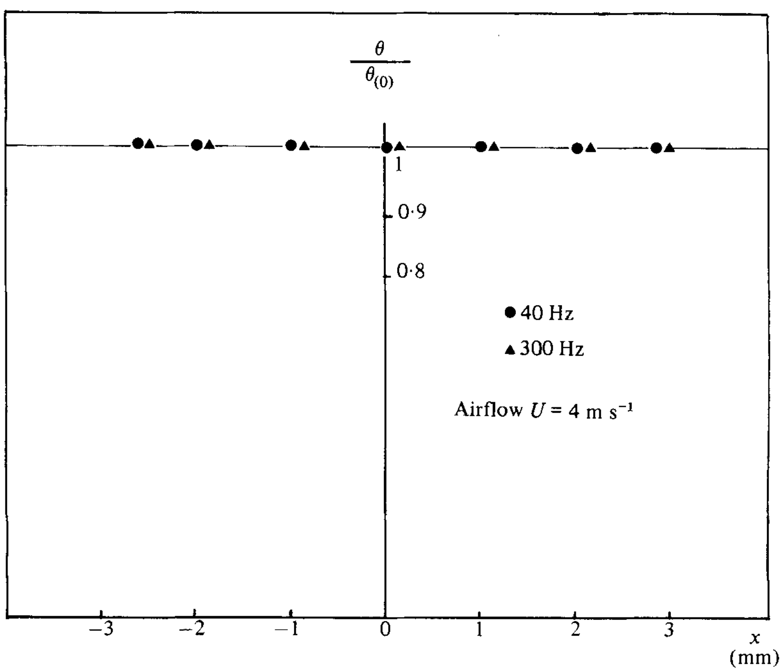

FIGURE 4. Fluctuating temperature field in the direction parallel to the source wire.

In the second case the wholly etched wire is soldered onto either a DISA 31 or a DISA 55 PO 1 probe, while in the first case Wollaston wires are soldered onto a modified DISA 55 PO 1 probe in order to get different values of Wollaston lengths; platinum-wire lengths are always kept equal to a constant value. Modified TSI 9090 probes were also used in order to study the influence of massive prongs on the response

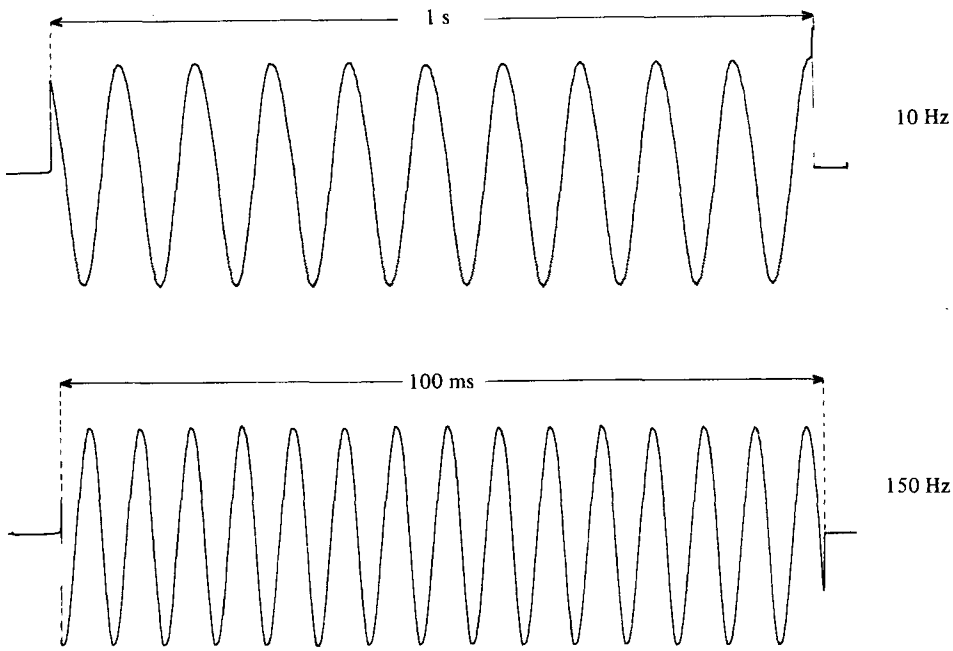

FIGURE 5. Examples of temperature fluctuations produced in the heated wake.

of cold wires. The probe was connected to a temperature bridge manufactured in our laboratory. The overheat ratio never exceeded 2×10^{-2}. At this overheat ratio the velocity sensitivity of the wire was negligible. The amplitude of the transfer function was investigated in the range 10^{-2} Hz–$3\cdot10^{2}$ Hz, the lowest frequency giving the reference level. Experimental results for the case with no Wollaston are shown in figure 6. The transfer function $H(n)$ decreases continuously from 1, corresponding to the static calibration, and reaches a constant value, the plateau level H_p. The experimental value of H_p obtained in this case could be compared with that predicted:

$$H_p = 1-2\frac{l_c}{l}, \qquad (4)$$

where l_c is calculated either from (2) or from

$$l_c = (aM)^{\frac{1}{2}}. \qquad (5)$$

In these expressions, knowledge of the actual values of a and λ_w, the thermal diffusivity and the thermal conductivity of the platinum wire respectively, is needed as pointed out by Lecordier *et al.* (1981). Data agree reasonably well with theoretical curves using (1), (2) and (4). These curves were drawn by calculating the Nusselt number of the wire from the classical relations of Collis & Williams (1959) and Kramers (1946).

However, better agreement is obtained from (1), (2), (4) and (5) where the Nusselt number *Nu* and the time constant *M* are those measured. For instance, in the case of the 2·5 μm diameter platinum wire (l = 0·5 mm) at 4 m s^{-1} the experimental value of H_p can be taken as 0·81 and the calculated values from (2) and (5) give respectively 0·80 and 0·82.

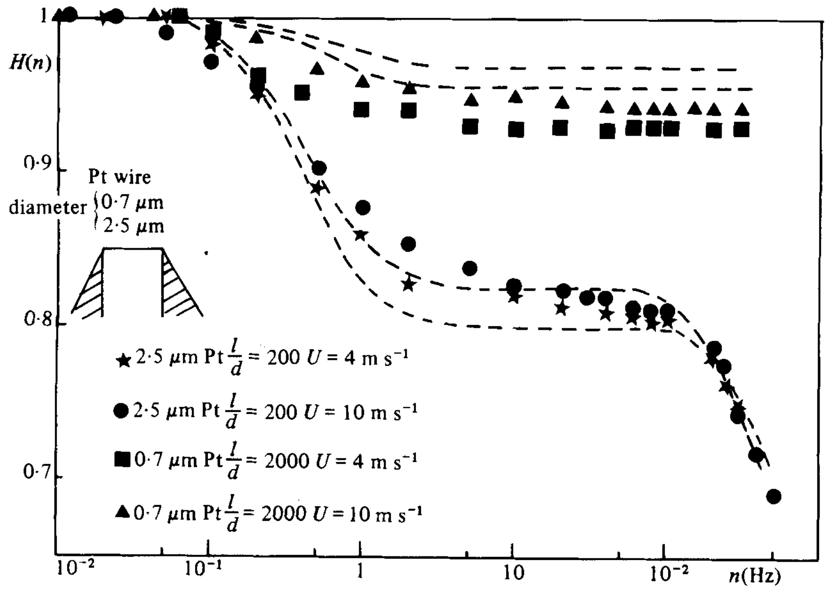

FIGURE 6. Transfer function of cold wires at low frequencies.

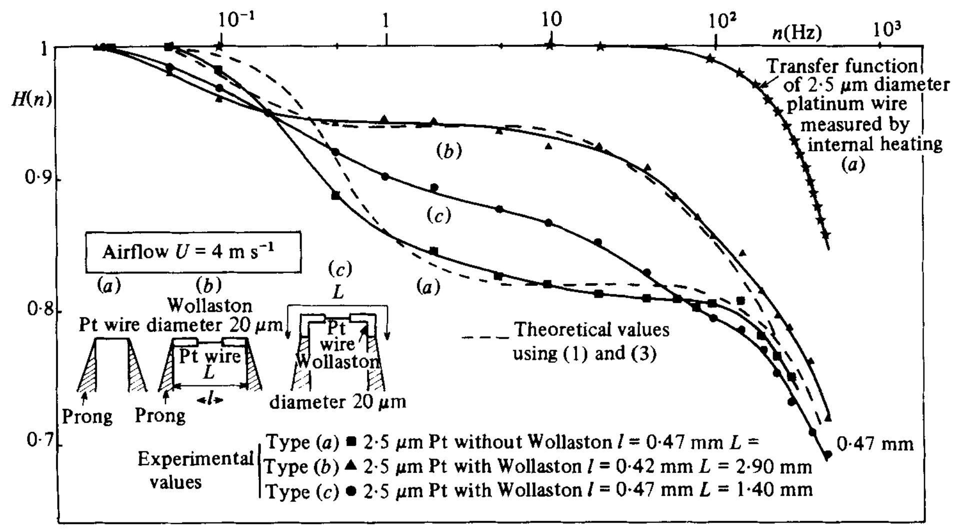

FIGURE 7. Influence of Wollaston length on transfer function.

Results showing the influence of Wollaston length on the transfer function of the wire at low frequencies are given in figure 7. As shown in figure 7 the behaviour of the transfer function strongly depends on the length of the Wollaston portion. It is worth noting that, in the case of the probe geometry used frequently by experimentalists in order to prevent the response of the wire from being affected by the aerodynamic perturbation due to the prongs, the transfer function decreases continuously from 10^{-2} Hz. The transfer function of the probe without Wollaston measured by internal heating as described by Lecordier, Petit & Paranthoen (1980) is also presented in figure 7. Theoretical curves drawn from (3) corresponding to the same values of Wollaston length are also given, and are in good agreement with the experimental results. The phenomenon analysed here could explain the great discrepancy between time constants of cold wires with or without Wollaston, as pointed out by Fielder (1978).

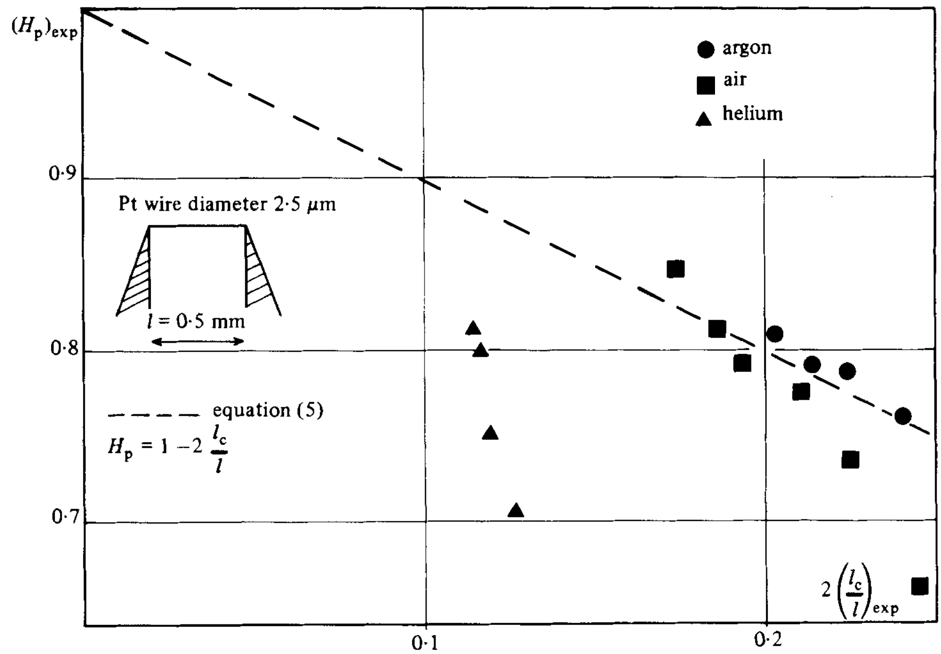

FIGURE 8. Experimental values of H_p in air, argon and helium flows.

5. Experimental results in other gases (helium and argon)

Transfer functions of the same wires (0·7 μm and 2·5 μm) using the same procedure have been measured for helium and argon flows. For the different velocities (2, 4, 6, 10 m s^{-1}) the values H_p of the plateau are plotted in figure 8 as a function of the conduction parameter $2l_c/l$. In the same figure values of H_p for airflow in the velocity range (0·5 m s^{-1}–24 m s^{-1}) have also been included. It can be seen in figure 8 that the experimental values of H_p agree very well with those predicted, taking into account the heat-conduction loss only, in the case of argon flows, for the whole velocity range, and in the upper velocity range (2 m s^{-1}–24 m s^{-1}) in the case of airflows. On the other hand, for helium flows in the whole velocity range, and for the lowest part (0·5 m s^{-1}–2 m s^{-1}) in airflows, a great discrepancy exists between results and predictions. This difference, which depends both on the thermal diffusivity of the gas and on the velocity flow, could be explained by the presence of a thermal-boundary-layer phenomenon due to the prongs. This was already suggested by Hojstrup *et al.* (1976) in airflows at very low velocities (20 cm s^{-1}–100 cm s^{-1}). An analysis taking into account this last effect and heat-conduction loss is presented in §6.

6. Effect of thermal boundary layers around prongs on transfer function of a wire

6.1. *Analysis*

This analysis deals only with the case of a wholly etched wire. The cold-wire geometry, the boundary-layer conditions and some symbols used in the following calculation are presented in figure 9. For a wire along the x-direction with negligible overheat

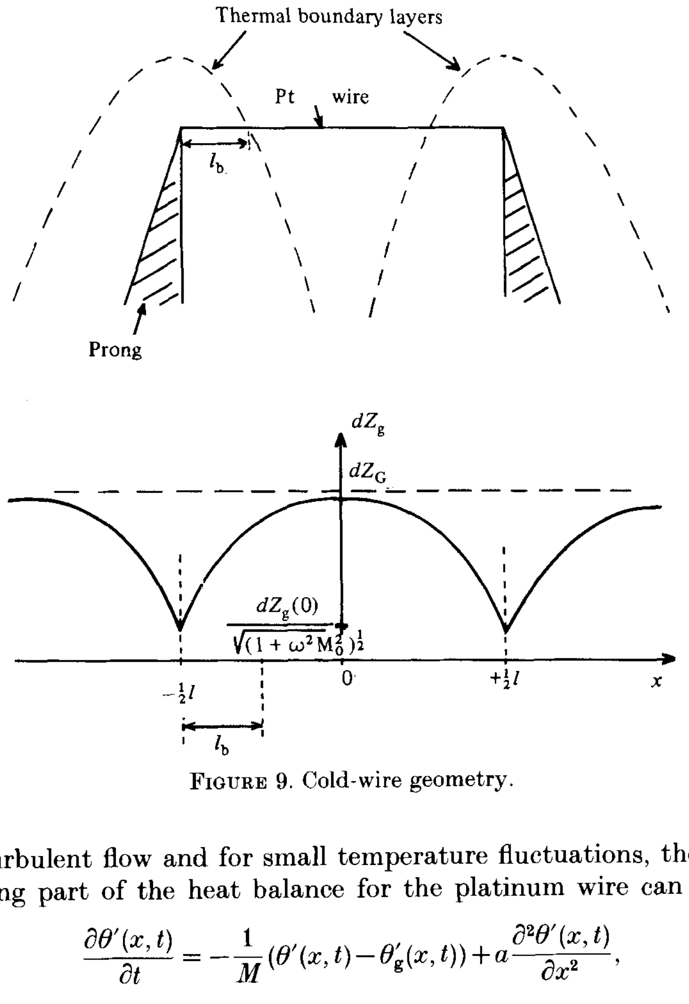

FIGURE 9. Cold-wire geometry.

in a slight turbulent flow and for small temperature fluctuations, the equation for the fluctuating part of the heat balance for the platinum wire can be written as follows:

$$\frac{\partial \theta'(x,t)}{\partial t} = -\frac{1}{M}(\theta'(x,t) - \theta'_g(x,t)) + a\frac{\partial^2 \theta'(x,t)}{\partial x^2}, \tag{6}$$

where $\theta'_g(x,t)$ and $\theta'(x,t)$ are respectively the actual temperature fluctuation applied to the wire by the flow and the local temperature fluctuation of the wire. If $\theta'(x,t)$ and $\theta'_g(x,t)$ are written in terms of Fourier–Stieltjes expansions,

$$\theta'(x,t) = \int_{-\infty}^{+\infty} e^{i\omega t}\, dZ(x,\omega), \quad \theta'_g(x,t) = \int_{-\infty}^{+\infty} e^{i\omega t}\, dZ_g(x,\omega),$$

where ω is the angular frequency, then (6) becomes

$$aM\frac{\partial^2}{\partial x^2} dZ(x,\omega) - (1+i\omega M)\, dZ(x,\omega) = -dZ_g(x,\omega). \tag{7}$$

6.2. *Boundary conditions*

With dZ_G being a temperature fluctuation in the flow that is uniform in space over the dimension of the sensor, the boundary conditions are usually taken as

$$dZ(\pm\tfrac{1}{2}l) = \frac{dZ_G}{1+i\omega M_0}, \tag{8}$$

dZ_G being defined from θ'_G in a similar way to dZ and dZ_g.

Prongs are then assumed to respond to flow-temperature fluctuations as a first-order low-pass filter having a time constant of M_0 as suggested by Hojstrup *et al.* (1976). A similar condition is taken by Perry *et al.* (1979) considering the thermal balance of the prong.

However for the case of small velocity flows and large gas thermal diffusivity and at angular frequencies, such as $\omega M_0 \gg 1$, the thermal-boundary-layer thickness on the prong can be appreciable compared with the length of the wire. In these conditions, in the vicinity of the prongs the instantaneous gas-temperature fluctuation θ'_g is now dependent on the x-coordinate as shown in figure 9 owing to the existence of these thermal boundary layers.

From a physical point of view and for a more tractable treatment, the temperature profile θ'_g has been chosen as follows:

$$dZ_g = dZ_G\left[1-\frac{i\omega M_0}{1+i\omega M_0}\frac{\cosh\dfrac{x}{l_b}}{\cosh\dfrac{l}{2l_b}}\right], \tag{9}$$

where l_b is the thickness of the thermal boundary layer on the prong.

When the region of influence (by the prong) extends over a negligible length of the wire (large value of l/l_b) it can be noticed from (9) that boundary conditions (8) are found again.

Solving (7) leads, after some algebra, to an expression for $dZ(x,\omega)$. $dZ_m(\omega)$, corresponding to the measured temperature, is obtained by averaging $dZ(x,\omega)$ along the platinum wire. The amplitude-transfer function $H(\omega) = dZ_m(\omega)/dZ_G(\omega)$ can be written as

$$H(\omega) = \frac{1}{1+i\omega M}\left\{1+2\frac{l_b}{l}\frac{i\omega M_0}{1+i\omega M_0}\frac{1}{\left(\dfrac{l_c}{l_b}\right)^2\dfrac{1}{1+i\omega M}-1}\tanh\frac{l}{2l_b}\right.$$
$$\left.+\frac{2}{l(\alpha+i\beta)}\left[\frac{i\omega(M-M_0)}{1+i\omega M_0}-\frac{i\omega M_0}{1+i\omega M_0}\frac{1}{\left(\dfrac{l_c}{l_b}\right)^2\dfrac{1}{1+i\omega M}-1}\right]\tanh(\alpha+i\beta)l\right\}, \tag{10}$$

where $\alpha = \left\{\frac{1}{2aM}[(1+\omega^2M^2)^{\frac{1}{2}}+1]\right\}^{\frac{1}{2}}, \quad \beta = \left\{\frac{1}{2aM}[(1+\omega^2M^2)^{\frac{1}{2}}-1]\right\}^{\frac{1}{2}}.$

From (10) it can be seen that for angular frequencies, such that $\omega M_0 \gg 1$ and $\omega M \ll 1$, a plateau exists, as is the case when heat-conduction loss effects only are taken into account. Under these circumstances $\alpha \approx 1/l_c$ and $\beta = 0$. In practical cases, the ratios $l/2l_b$ and $l/2l_c$ are greater than 3, so that

$$\tanh\frac{l}{2l_c} \approx \tanh\frac{l}{2l_b} \approx 1.$$

The level H_p of the plateau can be written as

$$H_p = 1+\frac{2l_b}{l}\frac{1}{\left(\frac{l_c}{l_b}\right)^2-1}-2\frac{l_c}{l}\left[1+\frac{1}{\left(\frac{l_c}{l_b}\right)^2-1}\right]. \tag{11}$$

This formulation suggests the introduction of the parameter $\eta = l_b/l_c$. Finally, (11) leads to a very simple expression

$$H_p = 1-2\frac{l_c}{l}\frac{\eta^3-1}{\eta^2-1} = 1-2\frac{l_c}{l}f(\eta), \tag{12}$$

with the following special cases:

$$l_c = 0 \;\; (\eta = \infty), \quad H_p = 1-2\frac{l_b}{l}, \quad l_b = 0 \;\; (\eta = 0), \quad H_p = 1-2\frac{l_c}{l}.$$

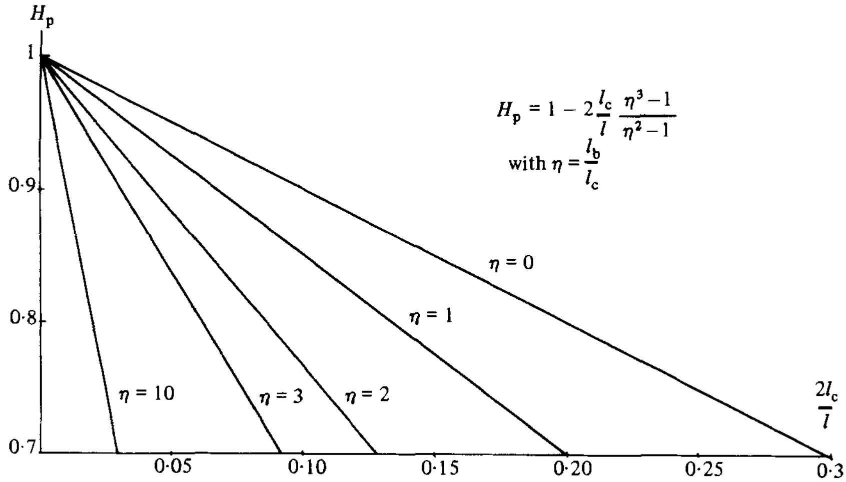

FIGURE 10. Theoretical values of H_p, taking into account the thermal interaction between wire and prongs.

It is worth noting that the expression (4) is found again as a particular case ($\eta = 0$) of our analysis.

Predicted values of H_p versus $2l_c/l$ for several values of η are shown in figure 10. It can be noticed that in some cases an appreciable discrepancy between values of H_p given by (12) and those given by (4) exists, for instance 50 % on $1-H_p$ for $\eta = 1$.

Whereas l_c can be estimated from (2) or (5), it is obviously impossible to give an analytical formulation of l_b, the thickness of the thermal boundary layer on prongs for all kinds of probes. However, a rough estimate of the order of magnitude of l_b can be made by:

$$l_b \sim \left\{\frac{aD}{U}\right\}^{\frac{1}{2}},$$

where D is the dimension of the prong tips.

A quantitative estimate of l_b actually shows that for the case of helium flows at low velocities the region of influence (by the prong) extends over a non-negligible length of the wire.

For a more-tractable treatment l_b can be expressed as

$$l_b = k\left\{\frac{a}{U}\right\}^{\frac{1}{2}}, \tag{13}$$

a and U being known accurately. The factor k, dimensionally the root of a length, is then a characteristic of each probe.

Therefore k has to be determined experimentally from (12) and (13) in a particular case, and then used to calculate from (13) the l_b values for all other cases.

The agreement between experimental values H_p and the predicted ones from (12), l_b being so determined, is obviously necessary to justify this method.

7. Comparison between analysis and experimental results

Experimental values of H_p obtained in helium, air and argon flows at different velocities, plotted in figure 8, are considered again using the analysis described just above. As indicated in the method proposed here the first step consists of determining the value of l_b in a particular case; the result for helium flow at 2 m s^{-1} has been chosen for better accuracy. From this experiment the value $k = 0{\cdot}068$ cm$^{\frac{1}{2}}$ has been calculated. Values of $2l_b/l$ in all other cases were then deduced using (13).

Gas	U (m s^{-1})	$2\left(\frac{l_c}{l}\right)_{meas}$ *	$\frac{2l_b}{l}$	$\eta = \frac{l_b}{l_c}$	$f(\eta) = \frac{\eta^3-1}{\eta^2-1}$	$(H_p)_{meas}$	$(H_p)_{pred}$
He	2	0·131	0·250	1·908	2·252	0·705	†
	4	0·125	0·177	1·414	1·830	0·750	0·771
	6	0·120	0·144	1·203	1·655	0·784	0·801
	10	0·115	0·112	0·972	1·469	0·816	0·831
Air	0·5	0·245	0·174	0·712	1·296	0·664	0·682
	1	0·225	0·123	0·547	1·193	0·722	0·731
	2	0·210	0·087	0·416	1·122	0·758	0·764
	4	0·193	0·062	0·320	1·078	0·788	0·792
	6	0·185	0·050	0·272	1·058	0·806	0·804
	10	0·178	0·039	0·220	1·040	0·817	0·815

* Deduced from (2).
† Point used for adjustment of l_b.

TABLE 1.

Results concerning helium and air flows are gathered in table 1 and figure 11. For the case of argon flows in the studied velocity range, the influence of the parameter $2l_b/l$ is negligible. Very good agreement is obtained between experimental values of $1-H_p$ and predicted ones using the method described above.

It is interesting to note that taking into account only the effect of heat-conduction loss due to the prongs (characterized by the parameter $2l_c/l$) is not sufficient to predict the response of a wire at low frequencies. In fact, for gases with large thermal diffusivities, regardless of the flow velocity, and in other cases at very low velocity, the effect of a prong thermal boundary layer is generally predominant. It is worthy of note that in the preceding calculation only the influence of the transient thermal boundary layer has been considered, while the steady dynamical boundary layer has been ignored for the purpose of simplicity. However, in the case of large values of $2l_b/l$ this last point obviously has to be considered.

Figure 12 shows H_p values obtained in the case of a transformed TSI probe with massive prongs in airflows over a large range of velocities (0·5 m s^{-1}–24 m s^{-1}). In this case agreement with predicted values calculated from (12) is not so good. This could be explained by the fact that the preceding calculation does not take the presence

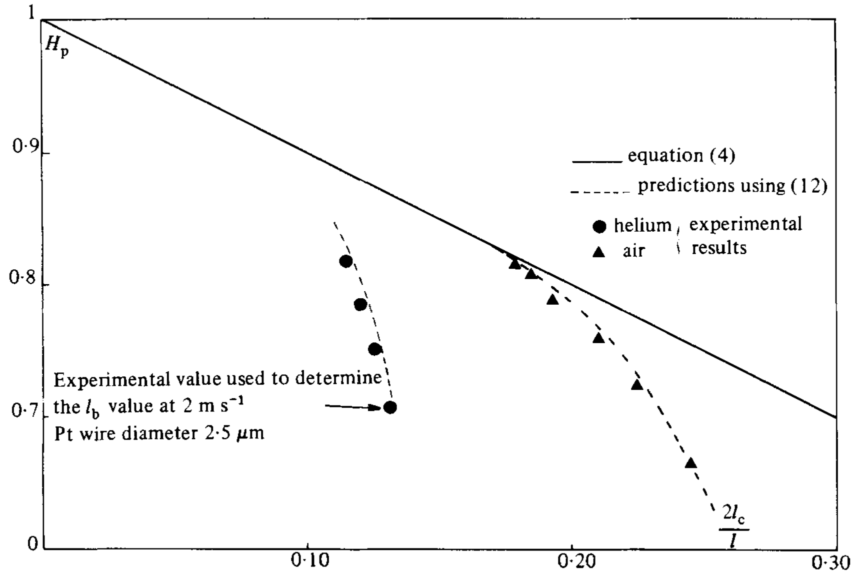

FIGURE 11. Experimental and predicted values of H_p in air and helium flows.

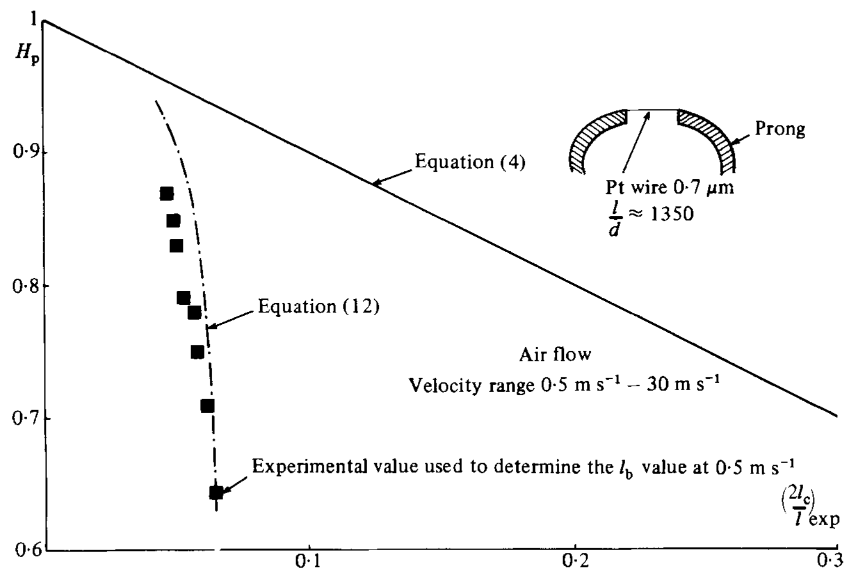

FIGURE 12. Experimental and predicted values of H_p in air flows in the case of massive prongs.

of permanent velocity boundary layers into account. The thickness of permanent layers is not negligible (towards the length of the wire) for this type of probe. The cold wire has to be run with a very low current in order to minimize the velocity contamination, as pointed out by Fulachier (1978). Results presented here provide evidence that in particular cases (low velocity, large gas thermal diffusivities, massive prongs) temperature-fluctuation measurements can be strongly affected both by velocity and concentration fluctuations u' and c' in the flow through the existence of thermal boundary layers on the prongs. This contamination obviously depends on the correlations $\overline{u'\theta'}$ and $\overline{c'\theta'}$.

Up to now studies concerning the interaction effects between wire and prongs have pointed out that the sensitivity of the cold wire can be noticeably reduced.

In §8 the influence of this effect on temperature measurements in the particular case of intermittent signals is analysed.

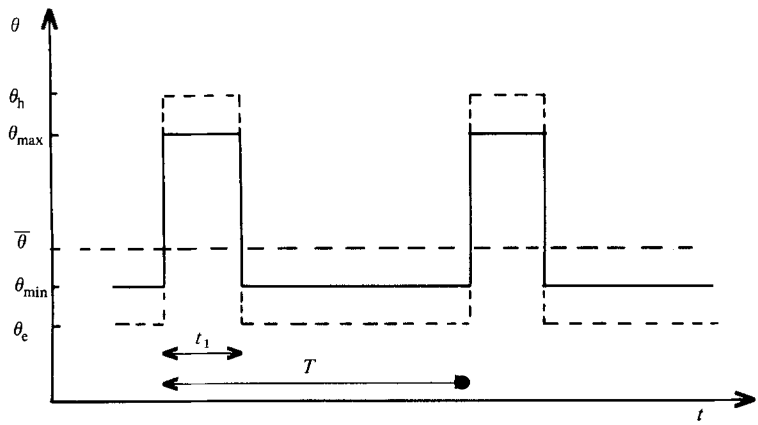

FIGURE 13. Sketch of intermittent temperature fluctuations.

8. Intermittent temperature measurements

In the simple case of a bimodal and periodic temperature distribution in a constant flow, as indicated in figure 13, the thermal signal can be over a period T characterized by the non-heated-flow temperature θ_e, the heated-flow temperature θ_h (during t_1); so γ_θ, the thermal intermittency coefficient, can be defined as the ratio t_1/T.

After some algebra γ_θ can be expressed as:

$$\gamma_\theta = \frac{\bar{\theta}-\theta_e}{\theta_h-\theta_e}, \tag{14}$$

where $\bar{\theta}$ is the mean temperature of the flow. Let us consider a wholly etched platinum wire of length l characterized by the two-parameters l_c and l_b previously defined.

For temperature signal frequencies $1/T$ such that $M_0 \gg T$, the temperature prong can be considered to be equal to the mean temperature of the flow. In these conditions thermal interaction between wire and prongs leads to an attenuation of the temperature signal, as shown in figure 13. Then the wire cannot have either the heated-flow temperature θ_h, nor the non-heated temperature θ_e. However, the temperature distribution is also bimodal, but with temperature levels θ_{max} and θ_{min}, these being related to the actual temperatures of the flow by the following relations:

$$\theta_{max}-\bar{\theta} = (\theta_h-\bar{\theta})\left[1-2\frac{l_c}{l}f(\eta)\right], \tag{15}$$

$$\theta_{min}-\bar{\theta} = (\theta_e-\bar{\theta})\left[1-2\frac{l_c}{l}f(\eta)\right], \tag{16}$$

where $f(\eta)$ has already defined in (12). Using (14)–(16) it appears that θ_{min} can be noticeably different from the non-heated flow temperature θ_e:

$$\theta_{min}-\theta_e = \gamma_\theta 2\frac{l_c}{l}f(\eta)[\theta_h-\theta_e]. \tag{17}$$

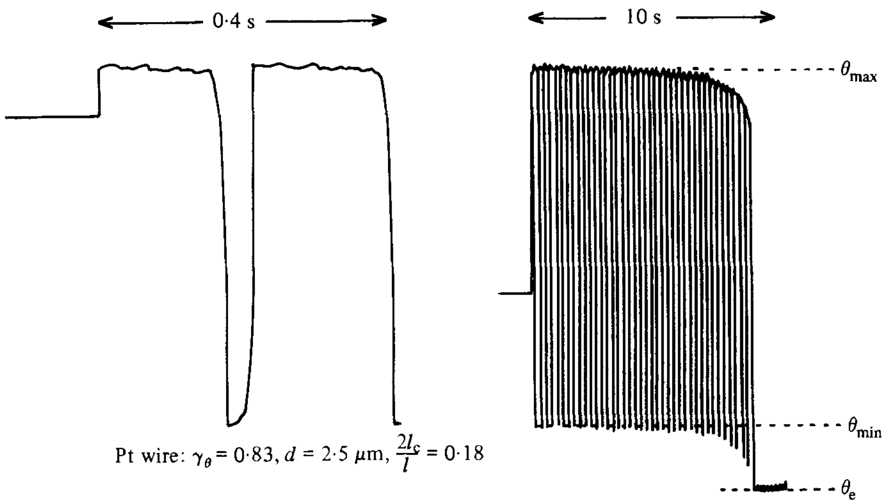

FIGURE 14. Example of intermittent temperature fluctuations measured in the heated wake ($\gamma_\theta = 0{\cdot}83$).

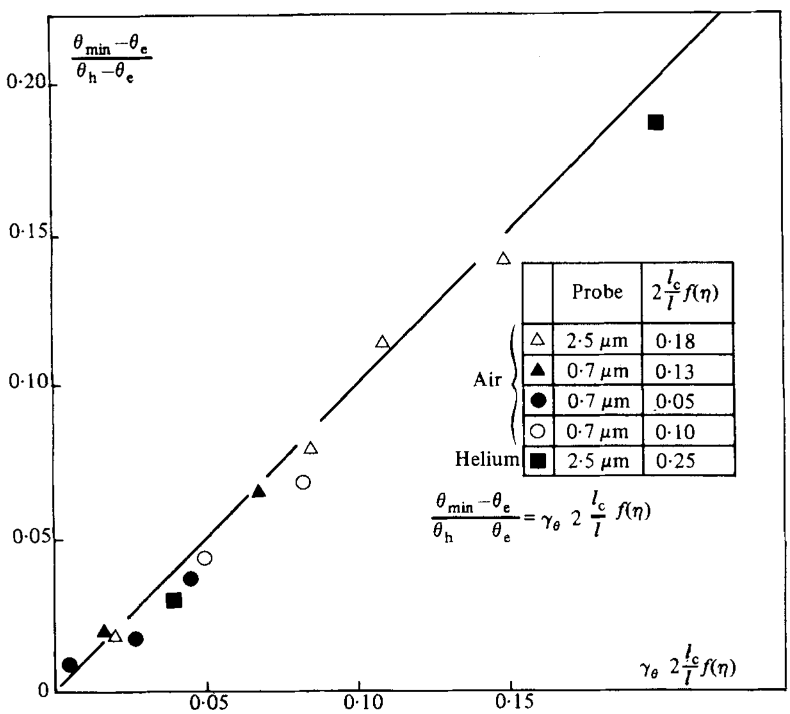

FIGURE 15. Experimental and predicted values of $\theta_{min} - \theta_e$ in air and helium flows.

Equation (17) shows that the difference $\theta_{min}-\theta_e$ for a given wire depends on the prong geometry, the thermal properties of the gas, the flow velocity and the thermal intermittency coefficient.

An experimental investigation of (17) has been undertaken using the previously described procedure, which allows temperature fluctuations to be produced. By this means temperature signals similar to those considered in figure 13 have been produced. The response of 0·7 μm and 2·5 μm diameter platinum wires has been studied successively in air and helium flows at 4 m s^{-1}. An example of such a response of a 2·5 μm diameter wire in the case of an airflow ($\gamma_\theta = 0{\cdot}83$) is presented in figure 14. The observed transient part corresponds to the time needed for the prongs to reach the mean temperature of the flow. The difference $\theta_{min}-\theta_e$ is given in figure 15 for several values of γ_θ, $2\,l_c/l$ and $f(\eta)$ in air and helium flows. Experimental results show good agreement with predicted values using (17).

So, interaction effects between prongs and the wire could explain, at least partly, the difference of temperature between the non-turbulent zones and the free stream pointed out by Fulachier, Arzoumanian & Dumas (1978), and Davies, Keffer & Baines (1975) for the case of intermittent temperature measurements. On the other hand Antonia, Prabhu & Stephenson (1975), using a longer cold wire (Pt/10 % Rh, 1 μm, $l/d = 1000$) did not report this fact in the intermittent zone of a turbulent heated jet.

9. Concluding remarks

For the case of a cold wire, interaction effects between prongs and wire are generally complicated. In this paper a simpler formulation of these phenomena is proposed, including both the effect of pure end conduction loss, characterized by the parameter l_c/l, and the effect of thermal boundary layers due to the prongs. This latter effect is conveniently characterized by the ratio l_b/l, where the thermal-boundary-layer thickness l_b on the prongs strongly depends on the thermal diffusivity of the gas and the velocity of the flow. This effect is particularly important in helium flows because of the large thermal diffusivity of helium.

A way to make these effects relatively negligible is to increase the length of the wire, this being limited by the spatial resolution, as mentioned by Millon (1977). However when a short wire is needed it is then important to reduce this thermal perturbation. For that purpose a wire with Wollaston sheaths could be chosen, as indicated by Comte-Bellot, Strohl & Alcaraz (1971) in order to minimize the aerodynamic perturbation. However the behaviour of transfer function of such cold wires over a large range of frequencies is more complicated than for wholly etched wires, as pointed out by Petit *et al.* (1981). Improvement could also be obtained by using a probe with sharpened prong tips.

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