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Operation and Application of Cooled Film Sensors for Measurements in High Temperature Gases

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Summary

The cooled film sensor is a device permitting measurements in high temperature environments similar to those obtainable at normal temperatures with a hot wire anemometer. The limitations of the technique both in maximum environment conditions and accuracy are discussed. In addition, typical measurements and some special techniques that can be applied are presented. Optimum applications of the cooled film anemometer include environments where transient phenomena are to be measured and where the maximum heat transfer to the sensor (0.15 mm dia. by 1.5 mm long) is less than 10 watts. Up to 20 watts is possible for short term tests.

Introduction

The cooled film sensor is a device for making hot-wire-anemometry-type measurements in a high temperature environment. In the normal hot-wire or hot-film anemometer the temperature of the sensor must be above the environment temperature under conditions where convection dominates the heat transfer. The essential feature of the cooled film is the addition of a heat sink to permit the operation of the sensor below the environment temperature.

Since the introduction of the cooled film sensors (1), additional data has been collected on both operational details and applications. This paper is intended as a review of the work that has been done with cooled probes to date. From this information, a reasonable estimate can be made of the applicability of the cooled film probes to a particular measurement.

The potential of the cooled film sensors for fluid measurements would appear promising. They have many characteristics in common with hot-wire anemometry systems including small sensor size and high frequency response. This permits, ideally, an instantaneous measurement at a point in the fluid stream. In addition, it has the capability of making measurements in temperatures of several thousand degrees where few immersion instruments can survive.

Constant Temperature Anemometry with Wires, Films and Cooled Probes

The electronic control and data reduction technique for cooled film sensors are almost identical to that of the standard constant temperature hot wire or hot film anemometer. Figure 13-1 shows the basic components of a constant temperature anemometer system.

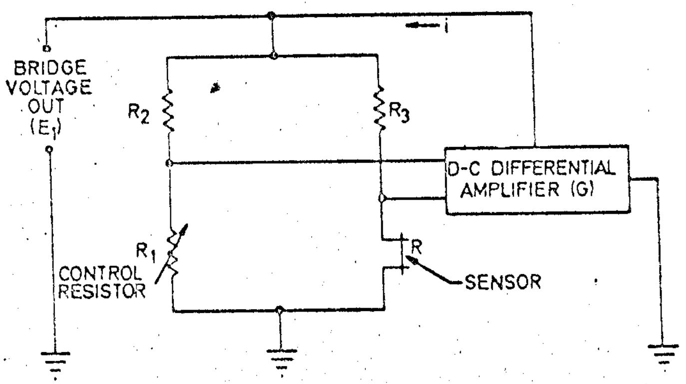


Fig. 13-1 Schematic diagram of constant temperature system

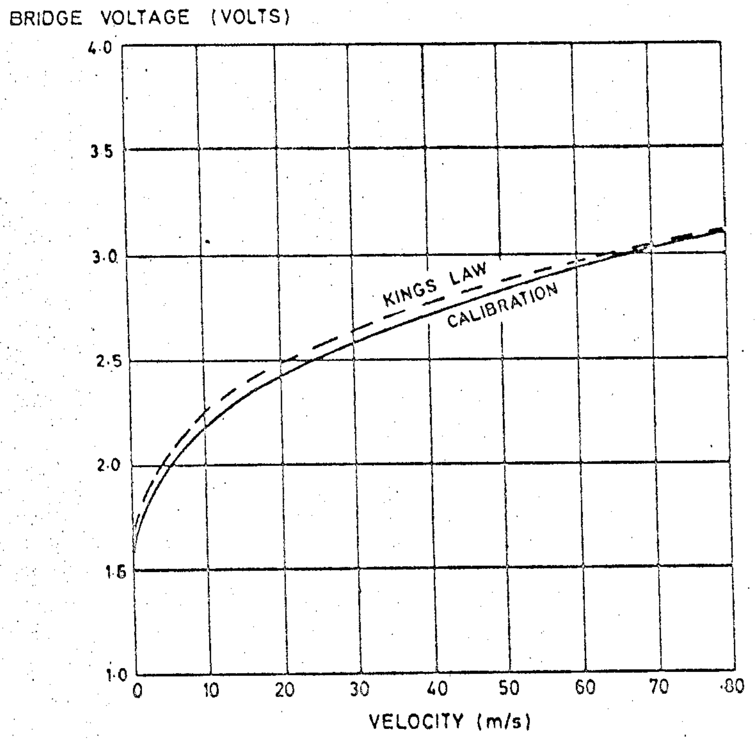


Fig. 13-2 Calibration curve for 0.0038 mm tungsten hot wire and comparison with King's law

The first requirement in the system of Figure 13-1 is that the sensor resistance changes with temperature. For maximum sensitivity, this change of resistance with temperature (temperature coefficient of resistance) should be high. The resistance of the bridge arms are set so that the bridge is in balance with the sensor transferring heat to the environment. The high gain feedback amplifier maintains this condition (a balanced bridge) by adjusting the current through the sensor. For example, as the environment velocity increases, more heat would be transferred between the sensor and its environment. To maintain the sensor temperature, the bridge system increases the current through the sensor. Therefore, the current required by the sensor is a direct measure of the heat transferred between the sensor and its environment. This heat transfer from the sensor (set and maintained at a constant average temperature by the bridge) is therefore the basic measurement.

Heat is transferred from the sensor by convection, radiation, and conduction. Similarly, the rate of heat transfer is affected by any property of the environment that influences heat transfer including temperature, velocity, pressure, composition, etc. In the normal application of anemometry, convection is the dominant mode of heat transfer and velocity is the only environment variable. Hence the term anemometer.

Limiting the heat transfer to convection, the heat transfer between the sensor and environment where velocity is the only variable, can be expressed approximately by what is commonly referred to as King's law (2):

$$P = I^2R_s = (A + B\sqrt{V}) \quad (T_s - T) \qquad \text{(Eq. 13-1)}$$

where: A, B = constants

V = environment velocity

T_s = sensor temperature

T_∞ = environment temperature

Figure 13-2 shows a calibration curve of a fine hot-wire and the calculated curve using two calibration points (end points) and King's Law. Many heat transfer relations have been derived which are a significant improvement on King's Law. Still, when discussing hot-wire anemometry the simplicity of the relation in equation 13-1 makes it a useful reference.

Figure 13-3 shows two types of sensors commonly used for work in hot wire anemometry. The fine hot wire is the original type of sensor and still is widely used. The hot film (3), (4) is more recent and has advantages in many applications. It consists of a glass substrate with a thin metallic film on the surface. The glass substrate dominates the physical and thermal characteristics of the sensor while the metal film dominates the electrical characteristics.

Figure 13-4 shows the physical characteristics of a typical cooled film sensor and support and a diagram showing its operation. The entire right hand side of equation 13-1 is simply - Q_E (negative since Q_E is shown as heat transfer to the sensor from the environment) in the Figure. Therefore, for an idealized hot film sensor without cooling:

$$P = -Q_E \qquad \text{(Eq. 13-2)}$$

and for an idealized hot film sensor with cooling:

$$P = Q_C - Q_E \qquad \text{(Eq. 13-3)}$$

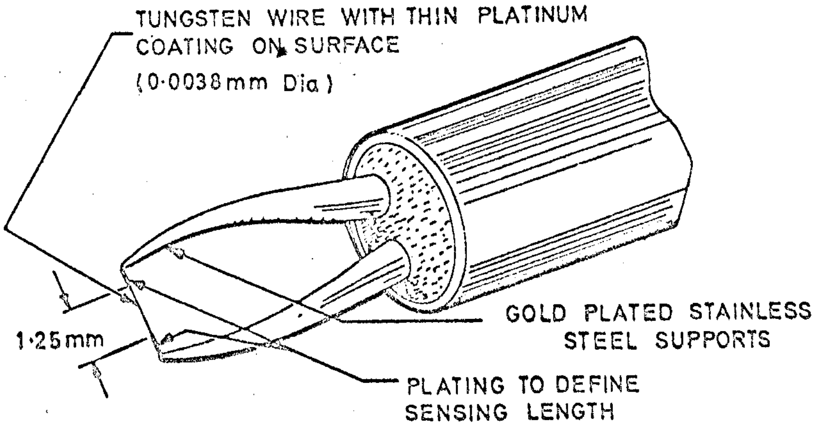
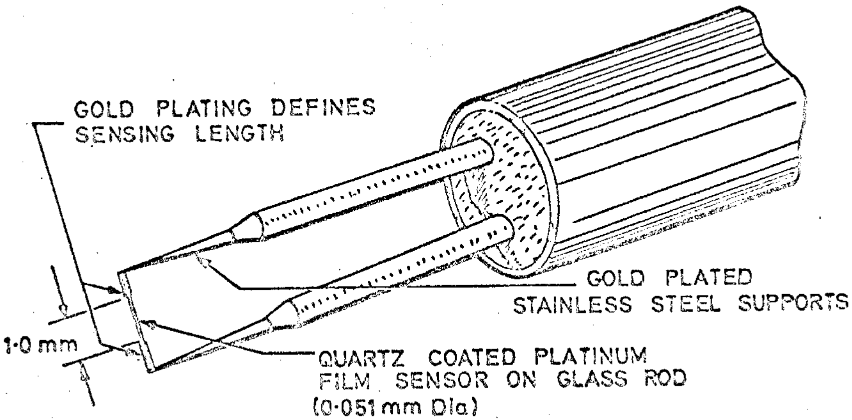
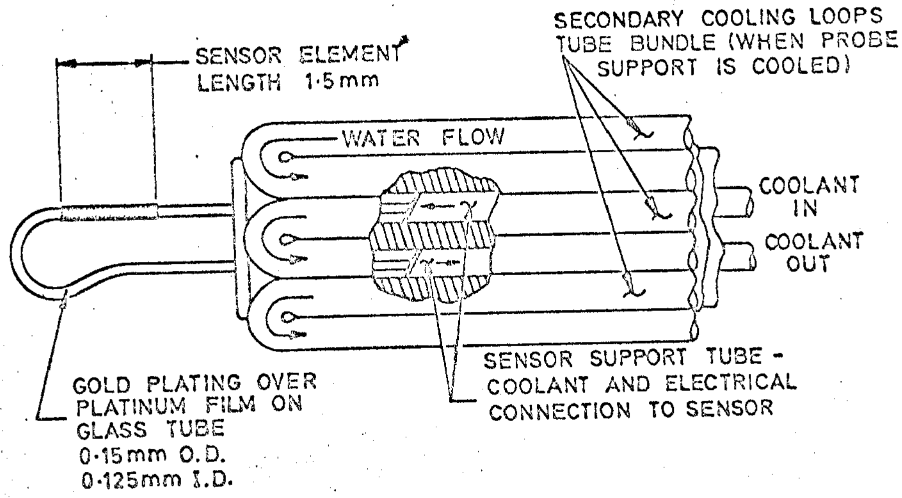
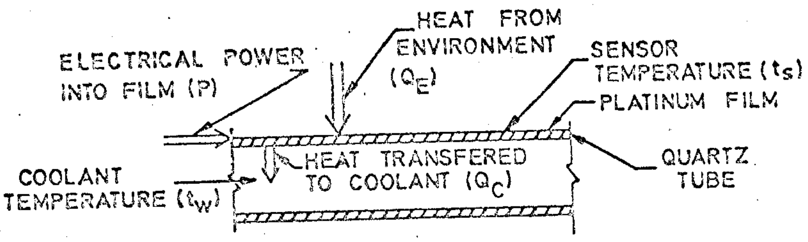


Fig. 13-3a Tungsten hot wire sensor and support needles - 0.00015" dia. (0.0038 mm)



b Cylindrical hot film sensor and support needles - 0.002" dia. (0.051 mm)





$$Q_C = U_C(t_s - t_w) = \text{Constant}$$

U_C = Heat Transfer Coefficient, J/S-°K

$$Q_C = P + Q_E$$

Q_E = Heat Transfer From Environment to Sensor

Since $P > 0$

$Q_C > Q_E$ For Proper Operations

Fig. 13-4 Cooled probe and fundamental heat transfer relation where: P = electrical power input to the sensor

Q_C = heat transferred from the sensor surface to the cooling fluid

Q_E = heat transferred from the environment to the sensor surface

Equation 13-3 gives the basic information on maximum environment conditions. Since P must be greater than zero, for proper operation:

$$Q_C > Q_E \qquad \text{(Eq. 13-4)}$$

The maximum heat transfer from the environment to the sensor is then equal to the cooling rate. On present sensors the practical upper limit for short term tests is 20 watts with 10 watts being realistic for continuous use in most types of environments. These figures are for the heat transfer rate in watts from the environment to the sensor surface area (0.15 mm dia. by 1.5 mm long). Frequency responses of up to 50 KHz can be attained (-3db point) using cooled film sensors.

An important requirement of the cooled film sensor is that the term Q_c remains constant, independent of external environment conditions. The circuit operates to maintain the average sensor surface temperature constant. If the entering cooling fluid temperature and flow rate is also constant, then ideally the term Q_c will remain constant. A number of factors affect this idealized situation but in actual operation of the cooled probe this assumption must usually be made. Some potential errors in the assumption are discussed later.

In a constant temperature, constant composition environment a calibration curve similar to that shown in Figure 13-2 could be plotted for a cooled probe. The operation and data reduction technique under these conditions are then essentially identical to those for a hot wire of similar diameter operated at constant temperature. The term Q_c can be handled like the free convection term is for a hot-wire.

Perhaps the most important difficulty with the cooled probes is that a high temperature environment seldom, if ever, satisfies the constant temperature condition. In addition composition changes are common due to different constituents, chemical reactions, or even ionization. In this sense measurements with cooled probes resemble more closely measurements in supersonic flows with hot wires. An important difference is that in supersonic flows the hot-wire can usually be operated very close to the environment temperature. This permits quite effective separation of velocity and temperature when two probes are used operating at different surface temperatures. In high temperature gases this separation is much more difficult since the sensor cannot be operated close to the environment temperature. Other complexities in cooled probe systems are: the need to water cool the probe, increasing both cost and size; the need for water tight connections with no condensation that can cause electrical shorting; difficulties in inserting the probe in many high temperature environments; and higher power required from control circuitry. These are practical problems that are largely eliminated by proper design and operation of the system.

At high heat fluxes, the cooling fluid in the sensor will be turbulent to maintain the desired cooling rate. This lowers the signal-to-noise ratio of the system when compared with a normal hot wire, since the low frequency signals get transmitted through the tube to the sensitive film. Finally, the cooling also limits over heat ratios because for a given coolant temperature, the heat flux from the surface to the coolant is determined by the sensor operating temperature. Arbitrary selection of a sensor temperature can result in (a) this cooling rate being excessively high, so the cooling water boils or the sensor burns out or (b) the cooling rate,

Q_c, being less than maximum heat transfer from the environment to the sensor, Q_E. Under these conditions the circuit shuts off and no data is obtained until the inequality in equation 13-4 is again satisfied. The result is that it is the maximum expected heat flux, Q_E, that determines sensor operating temperature rather than a selected overheat ratio as in hot-wire anemometer operation.

Heat Transfer Correlation for Cooled Probes

For a cooled-film sensor placed normal to a high temperature fluid stream of low Mach number, the forced convective heat transfer to the film is a function of stream temperature, stream velocity and the fluid transport properties. For a stream composed of a binary mixture, the transport properties of the mixture are functions of the mixture ratio. Thus, a cooled-film anemometer may be calibrated to measure temperature, velocity and percentage composition of a binary mixture flow. Direct calibration is straightforward for measurements in flows where only one of the independent parameters is a variable, as discussed earlier for the common measurement of velocity in low-speed aerodynamics. For measurements in fluid streams where more than one of the independent parameters is a variable, such as in hypersonic wakes, mixing regions of jets of dissimilar fluids and/or of dissimilar temperatures, and diffusion flames, a direct calibration over the entire range of variables is often tedious and time consuming. For such cases interpretation of measured heat flux data by means of a more general, nevertheless accurate, correlation of the appropriate dimensionless groups involved is more appropriate.

In considering the nature of the cooled-film operation and its application for measurements in diffusion flames and hypersonic wakes, one may stipulate that the required heat transfer correlation must be valid for the following cases:

(a) when the transfer of heat is from the environment to the sensor (i.e. $T_\infty > T_s$).

(b) when the temperature difference between the sensor and the environment is large (i.e. $T_\infty/T_s > 2$).

(c) when the environment is composed of flows of different gases and gas mixtures.

(d) when the Reynolds number (based on sensor diameter) of the flow is low, (i.e. $Re < 100$).

It may be noted that conditions of very low Reynolds numbers, where free and forced convection may interact, also conditions of high Knudsen numbers where free molecular effects may be important, have been left out of the stipulated conditions.

Forced convective heat transfer involving cylinders has been extensively investigated. However none of the investigations, individually or all of them collectively, cover the entire range of conditions mentioned above (5). It must be emphasized that such correlations as that obtained by careful experimentation by Collis and Williams (6) for hot-wire work are not applicable to precise cooled-film work (when $T_s < T_\infty$). This is because of the different nature of dynamical dissimilarity with temperature loading between cases of heating and cooling (5). On the other hand, data obtained for the heating of cooled cylinders such as those by Churchill and Brier (7) are for Reynolds numbers above 300. A detailed discussion of the existing correlations has been presented in (5).

In the present investigation the flow conditions were simulated in a plasma-jet

(jet orifice diameter 12 cm.) The jet conditions were maintained such that at the points of heat transfer measurement (i.e. at the potential core of the jet, where the distribution of velocity, temperature and concentration are uniform) ionization was negligible and recombination was complete. By means of a cooled-film the maximum relative intensity of heat flux fluctuations was found to be less than 3%. If it is considered that the heat flux fluctuations are due only to velocity fluctuations, the error in heat transfer measurement will be less than 2% due to turbulence.

Constant temperature, quartz coated, cooled-films were used as the heat transfer surface. The film is obtained by a deposition of platinum of thickness 1000 - 2000 Å on a loop made on Vycor tube, 0.0152 cm O.D. and 0.0102 cm I.D. The sensitive section of the film is isolated by a heavy gold plating (0.013 - 0.025 mm thick) on the rest of the loop. The length of the sensing film is 0.103 cm and the thickness of its quartz coating is around 5000 Å. Along with the heat transfer measured by the cooled film, velocity and temperature were obtained by means of a carbon tipped pitot probe of orifice diameter 0.103 cm and a Pt - Pt 10% Rh thermocouple of bead diameter .127 cm respectively. Further details of experimental set-up and procedure may be found in (5). The variables and the variable ranges considered in the investigation are as follows:

a. Temperature loading. The range of jet temperature considered was 800°K to 1600°K, and the film temperature was varied in three steps between 350°K to 525°K. From this a temperature loading (T_∞/T_s) range of 1.5 to 4.5 was obtained.

b. Reynolds number. The range of Re based on cylinder diameter was 4 to 80.

c. Flow composition. The plasma-jet was composed of He, N_2 and mixtures of He - N_2, N_2 - CO_2. Two mixture ratios were considered for each mixture.

The true jet temperature was obtained from the thermocouple temperature by applying correction for radiation and conduction errors. Transport property values of the gas species and specie mixtures for data analysis were calculated from the expressions collected in (8).

In the course of data analysis the following points were noted:

a. Consideration of the film temperature ($T_f = \frac{T_\infty + T_s}{2}$) for the evaluation of fluid properties in the dimensionless parameters Nusselt number and Reynolds number, was not sufficient to eliminate the temperature loading effect. The residual effect caused a decrease in Nusselt number with increased temperature loading at a particular Re for the present case of heating of cylinders.

b. Replacement of the usual temperature ratio in the temperature loading factor by a kinematic viscosity ratio enabled a unique correlation to be derived for flows composed of gas species whose transport property value variations with temperature are different. This conclusion is supported by arguments presented in (9) for hot wires.

c. The expected slight influence of the small variation of Prandtl number (because of the consideration of different flow species and specie mixtures and also because of variation of temperature), could not be discerned.

d. The Re_f dependency of Nu_f was found to be different from that according to King's Law.

e. A discontinuity in the heat transfer curve was noted between $Re_f = 40$ and $Re_f = 55$. Unfortunately, no data were collected between these values of Re_f and no specific investigation was carried out to determine a change in the flow features, (viz. onset of eddy shedding) in this range. For the present, data collected in the Re_f range below $Re_f = 40$ was considered for correlation purpose.

In view of the above discussion, the following form of correlation was considered:

$$Nu_f\,(\nu_\infty/\nu_f)^n = C + D\,Re_f^{\,m}$$

The constants n, m, C and D evaluated by the least square method were found to be as follows:

Re_f	n	m	C	D
4 - 40	.15	.45	.2068	.4966

Figure 13.5 shows the effectiveness of this relation in correlating the entire body of data below $Re_f = 40$. The rms deviation considering this range of data was .0924.

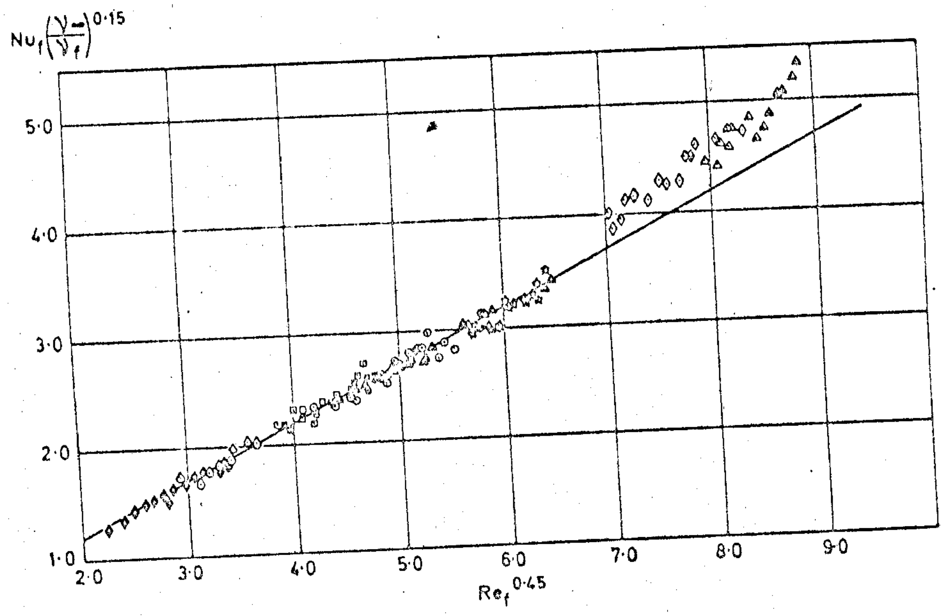
Finally 13-6 compares values of Nu_f calculated from some of the correlations obtained for heat transfer from heated cylinders with values calculated from the present correlation. The evaluation is for an identical condition of heat transfer to a cooled cylinder with $T_s = 400°K$, $T_\infty = 1200°K$ and the flow composed of N_2. Even considering the wide discrepancies in values calculated from correlations obtained for heated cylinders only, the error involved in using them to analyse heat transfer to cooled cylinders is quite apparent.

Tests in Severe Environments

The maximum environment capabilities of the cooled film probe have been expressed in terms of heat transfer rates from the environment to the sensor. To convert this to temperature and velocity requires an accurate heat transfer relation or tests where the conditions are well known. Although the following data does not completely satisfy either criteria, it does give some indication of the capability of the cooled film sensors.

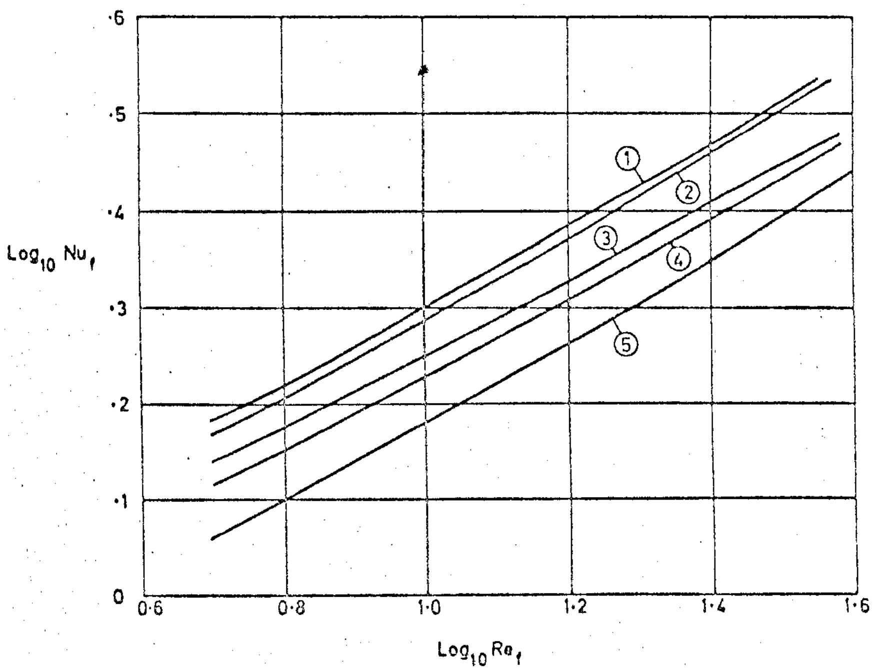
Figure 13-7 shows a traverse across the tip of an acetylene torch for two distances from the tip. The inside diameter of the tip is 3.8 mm and maximum heat flux to the sensor is 16 watts. Referring to Figure 13-7, the traverse was made from left to right. The sensor did shift in resistance during each traverse, as shown by the failure of the points on the right to approach closer to the abscissa. A single traverse took approximately five minutes. The 16 watts represents a heat transfer rate to the 0.15 mm dia. sensor of 2.66 KW/cm^2.

Reference (10) is another application where the cooled film sensors were exposed to a severe environment. The cooled sensors were used in a combustor that burned ethanol and liquid oxygen at an average chamber pressure of 178 psia. Pressure oscillations of ±15 per cent were sustained at 1190 cps with a siren mounted directly downstream of the exhaust nozzle. Under test conditions the average environment temperature was calculated to be 1900°K and the maximum velocity (measured from streak photographs) about 110 m/second. Velocity



Flow	T K	T_S K	Symbol
Nitrogen	852 -1660	361 -496	△
Helium	803 - 1360	387 - 532	◊
He 40% by vol. N_2 60% by vol.	900 -1269	361 - 496	⊙
He 77.5% by vol. N_2 22.5% by vol.	900 - 1270	387 - 532	⊡
He 42% by vol. CO_2 58% by vol.	701 -1088	342 -465	◈
He 93.5% by vol. CO_2 6.5% by vol.	702 - 1090	342 - 465	◊
N_2 50% by vol. CO_2 50% by vol.	703 - 1278	367 - 512	◊
N_2 30% by vol. CO_2 70% by vol.	703 - 1277	367 - 512	▲

Fig. 13-5 $Nu_m(\nu_{oo}/\nu_m)^{.15}$ vs $Re_m{}^{.45}$ showing all heat transfer data for various species and specie Mixtures and for various temperature loadings uniquely correlated by the relation $Nu_m(\nu_{oo}/\nu_m)^{.15} = .2068 + .4966\ Re_m{}^{.45}$ in the Re_m range of 5 to 40.



(1) Kramer (18)	$Nu_f = 0.42\ Pr_f^{0.20} + 0.57 Pr_f^{0.33} Re_f^{0.50}$
(2) Van der Hegge Zijnen (19)	$Nu_f = 0.35 + 0.5 Re_f^{0.5} + .001 Re_f$
(3) Collis and Williams	$Nu_f = (0.24 + 0.56\ Re_f^{0.45}) \left(\frac{T_f}{T}\right)^{.17}$
(4) Hilpert (20)	$Nu_f = .821\ (Re_f (T_s/T)^{.25})^{.385}$
(5) Present result	$Nu_f = (0.2068 + .496\ Re_f^{0.45}) \left(\frac{\mu_f}{\mu_s}\right)^{-.15}$

$T_s = 400$ K, $T = 1200$ K, flow = Nitrogen

Fig. 13-6 Comparison of present correlation for forced convective heat transfer to cooled cylinders in heated cross-flow with previous correlations for heat transfer from heated cylinders in ambient or near-ambient cross-flow.

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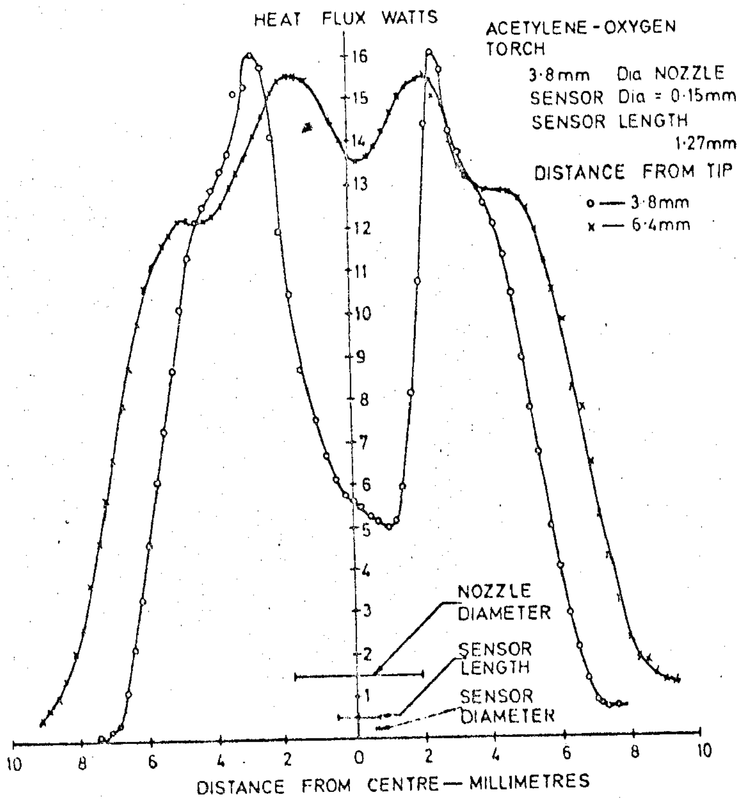

Fig. 13-7 Heat flux traverse of acetylene torch.

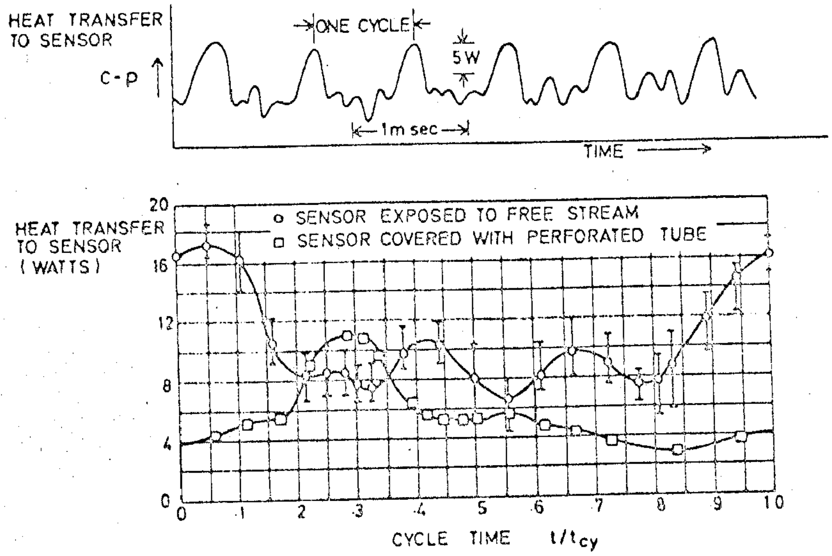

Fig. 13-8 Typical heat-flux sensor output and average heat flux for one cycle of oscillation. (reprinted from (10)

(possibly temperature and/or composition included) fluctuations gave heat flux variations to the sensor of about 6 to 17 watts (10). In this case the standard sensor diameter (0.15 mm) was used but it was shorter than standard length (1.0 mm).

The value of Q_c set for the experiments of (10) was 20 watts, which went down to 18.8 watts after the one second run even for 'successful' runs. Initially, sensor breakage was a serious problem which was corrected by shielding the sensor during engine start-up. Even then, as reported in (10), sensor stability and longevity caused a serious problem for the experiments. The velocities calculated from cooled sensor data did not agree with the streak photographs. As pointed out in the reference, no detailed calibration was deemed practical so the heat transfer relation used could be suspect, in addition to other sources of error. The maximum Reynolds number of 580 is well beyond the calibration data of Figure 13-5.

Figure 13-8 shows a typical set of data from the cooled sensor when exposed to the test chamber of (10). The lower curve is for the sensor when shielded on the inlet side. This data was taken to identify the reverse flow point, since a cylindrical sensor cannot differentiate flow direction.

The environment of (10) would seem to be at the upper heat flux limit for useful data from cooled sensors. Since many environments exceed these conditions (e.g. hydrogen oxygen combustors, plasmas, etc.) there is a need to extend the range of cooled sensors to higher temperatures. Some efforts have been made in this direction (11) which led to the present sensor design using Vycor rather than the original Pyrex (1). Although further improvement is always possible, the difficulty of cooling a small tube adequately for survival seems to preclude a significant improvement. Going to larger tubes is not generally desirable since characteristics such as frequency response and spatial resolution would be compromised.

Accuracies With Cooled Probes

Experimental data on the accuracy of the cooled probes is limited. Reference (11) discusses several potential sources of error and gives calculated estimates of the effects while (12) gives details on the error in the two-sensor technique. The consistency of the calibration data in this paper indicates the kind of reproducibility that can be expected for mean measurements.

The primary source of error is in the assumption that the heat transfer from the sensor surface to the cooling fluid, Q_c, is constant during external environment changes. One source of error is the exposed part of the sensor tube between the protective cooling jacket and the 'sensitive' portion of the sensor. In a high temperature environment the water temperature will rise in this passage, while during the tare reading of Q_c there would be no temperature rise. Another cause of error is the re-distribution of sensor surface temperature between the tare reading and the reading in the environment. Some measurements of sensor surface temperature distribution are given in (12). For the calculated conditions in (11), the error estimate for all the above factors was 5.2 per cent on the heat flux reading.

In measurements with hot-wire and hot-film probes, an assumption is made that the steady-state calibration can be used directly to interpret unsteady-state data. This seems valid for the very fine hot wires used near atmospheric temperature and pressure conditions. For the larger cooled films at high Reynolds numbers,

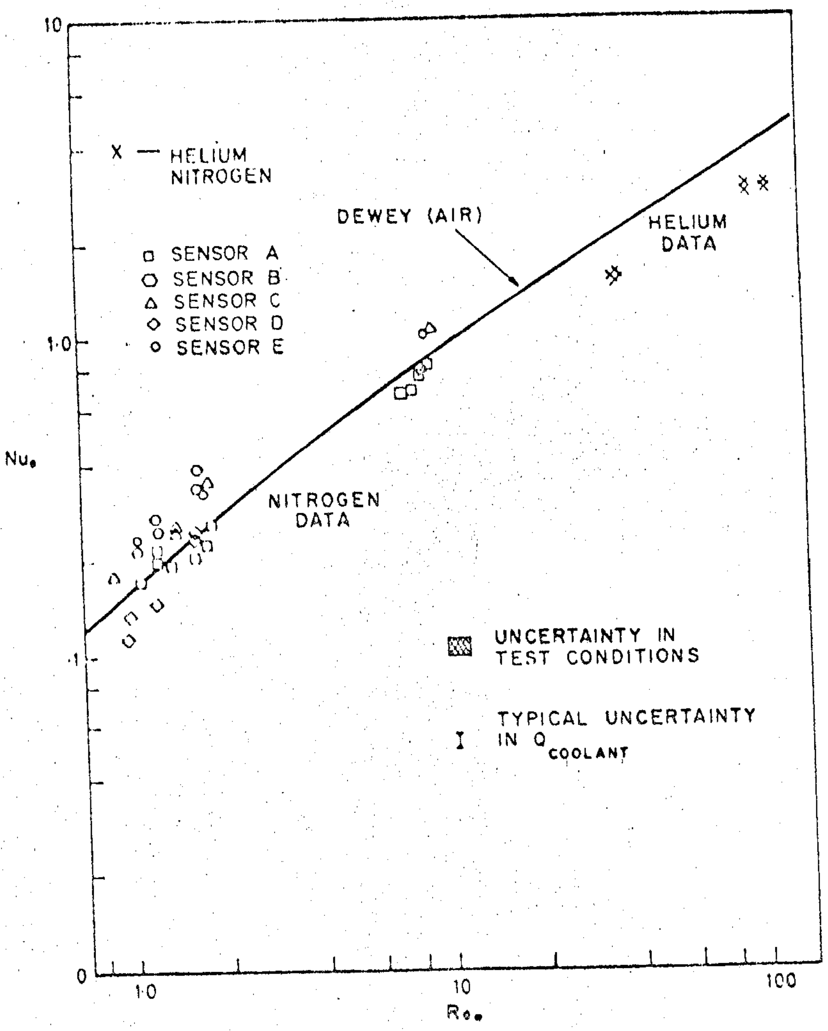

Fig. 13-9 Nusselt-Reynolds number calibration data. (reprinted from (14)

flow separation effects around the sensor could invalidate the assumption. In addition, the complex nature of the cooled film can cause transient errors due to changes in surface temperature distribution both longitudinally and radially under varying flow conditions.

Applications of Cooled Film Sensors

Much of the data given above has been concerned with the problems associated with cooled film sensors. It is important to recognise these problems before undertaking measurements. At the same time, the unique capabilities of the cooled sensors make them not only a valuable tool, but sometimes the only tool that can give the required data in a given situation.

The measurements in a rocket chamber have been discussed as an example of the upper limit of conditions where the cooled films are applicable. Other applications that data are available on are:

a. Measurements of a hypersonic boundary layer

b. Measurements in the wake of a hypersonic projectile

Other applications are certainly feasible and in fact have been made, but no published data is available.

Hypersonic boundary layer measurements were made by McCroskey, *et al* (13), (14). Nominal test conditions in the nitrogen tunnel were: $T_{01} = 2000°K$, $P_{01} = 135 - 340$ atm, $M_\infty = 23 - 26$, and Re/cm = 2,950 - 5,900. Tests in Helium were run at $T_{01} = 297°K$, $P_{01} = 15.3$ atm, M_∞ 16.5, and Re/cm = 47,200 (15) with hot wires. Although there is some scatter, most of it is between sensors and the slope for all sensors agrees with Dewey's results.

In this work a pitot probe, a cooled film probe, and the recovery temperature of a hot wire were used to calculate the variables of interest such as velocity, density, and pressure near the leading edge of a sharp flat plate. In the measurements with cooled probes, one of the problems that came up was inadequate resolution. Even though the total temperature of the environment was high, the total heat flux to the probe was 0.1 to 0.5 watts. Therefore, to increase sensitivity and lower dependence on entering coolant temperature, nitrogen was used for cooling rather than water. This increased resolution by permitting a much higher temperature difference between sensor surface and coolant, while keeping the total power dissipation to the coolant low.

An extensive investigation of turbulence characteristics of hypersonic wakes by means of cooled-film anemometers is being carried out at the Canadian Armament Research and Development Establishment at Val Cartier, Quebec (12), (16), (17). Owing to the high temperature encountered in the near wake region of hypersonic projectiles, the application of the cooled-film technique appears appropriate. Further, cooled-films have proved to be sufficiently robust to survive the hypersonic range environment at least for a sufficient length of time to record a signal of several thousand body diameters in duration (15).

The above experiments are performed in the CARDE Hypersonic Range No. 5 which consists of a light gas gun with a 102 mm barrel capable of launching projectiles into a depressurized tank of 122 m length at velocities in excess of 415 m/s (17). Two constant-temperature cooled-film sensors with different sensor surface temperatures, positioned several thousandths' of a centimeter apart are located near the flight axis of the projectile, (16). The cooled film anemometer bridge voltage is recorded by means of oscilloscopes viewed by Wollensak Fastax cameras.

The two cooled film sensors are operated at two different surface temperatures to attempt the separation of environment temperature and velocity. It is important that the temperature difference between sensors be large to optimize the accuracy using this technique (11), (12). At the same time, it is best to have both anemometer circuits operating at about the same power level for nearly equivalent frequency response and sensitivity. One way to satisfy these criteria is to use water as the coolant for the sensor with low surface temperature and an oil (such as Fluorolube FS or Silicon Oil 704) for the sensor with high surface temperature (12). The method of reduction of recorded voltage data in terms of velocity and temperature distribution in the wake, to determine their power spectral density functions has been shown in (12).

Conclusions

From the data presented, some tentative conclusions can be drawn for cooled film sensors presently available:

The maximum heat-fluxes from the environment to the sensor are:

a. About 10 watts for good sensor stability and longevity

b. Up to 20 watts maximum with decreasing stability at increasing heat fluxes.

The use of a coolant other than water is often desirable for a given measurement situation.

Accuracies of better than + five per cent on heat flux are probably not possible unless the calibration covers a range that includes the test conditions exactly.

The heat transfer correlation presented indicates that the cooled sensors can be calibrated in high temperature environments. Of particular interest is the successful use of a transport property (kinematic viscosity) to correlate different compositions.

The cooled film sensor greatly extends the temperature range of the hot-wire or hot-film anemometer. It retains many of the important features such as small size, high frequency response, and high resolution which make the hot-wire anemometer a valuable tool in fluid mechanics research. Also, like the hot wire, it has definite limitations in both accuracy and environment conditions which must be recognized before measurements are attempted.

References

1. Fingerson, L.M., 'A Heat Flux Probe for Measurements in High Temperature Gases,' Ph.D. Thesis, Univ. of Minnesota, 1961.

2. King, L.V., 'On the Convection of Heat from Small Cylinders in a Stream of Fluid: Determination of the Convective Constants of Small Platinum Wires with Applications to Hot-Wire Anemometry,' Proc. Roy. Soc. (London), Vol., 214A, No. 14, 1914, p. 373.

3. Ling, S.L., and Hubbard, P.G., 'The Hot-Film Anemometer A New Device for Fluid Mechanics Research,' Jour. Aero. Sci., Vol. 23, 1956, p.890.

4. Lowell, Herman H., 'Response of Two-Material Laminated Cylinders to Simple Harmonic Environment Temperature Change,' Jour. Appl. Phys. Vol. 24, No. 12, 1953, p.1473.

5. Ahmed, A.M., 'Forced Convective Heat Transfer to Cooled Cylinders at Low Reynolds Numbers and With Large Temperature Difference,' McGill MERL. T.N. 67-5.

6. Collis, D.C., Williams, M.J., 'Two Dimensional Convection from Heated Wires at Low Reynolds Numbers,' J. of Fluid Mech. Vol. 6, 1959, p.357.

7. Churchill, S.W., Brier, J.C., 'Convective Heat Transfer from a Gas Stream at High Temperature to a Circular Cylinder Normal to the Flow,' Chem. Eng. Progr. Symposium Series, No. 17, 51, 57, 1955.

8. Brokaw, R.S., 'Alignment Charts for Transport Properties Viscosity, Thermal Conductivity and Diffusion Coefficients for Nonpolar Gases and Gas Mixtures at Low Density,' NASA TR-R81.

9. Davies, P.O.A.L., and Fisher, M.J., 'Heat Transfer from Electrically Heated Cylinders,' Proc. of the Royal Society, A, Vol. 280, 1964, pp.486-527.

10. Povinelli, Frederick P., and Ingebo, Robert D., 'Evaluation of a Thin-Film, Heat-Flux Probe for Measuring Gas Velocities in an Unstable Rocket Combustor,' NASA Tech. Mem. TM X-1333, Feb., 1967.

11. Fingerson, L.M., 'Research on the Development and Evaluation of a Two-Sensor Enthalpy Probe,' Aerospace Res. Lab. Rep. ARL 64-161, Oct., 1964.

12. Ellington, D., and Trottier, G., 'Some Observations on the Application of Cooled-Film Anemometry to the Study of the Turbulent Characteristics of Hypersonic Wakes,' Canadian Armament Research and Development Establishment Report CARDE T.N. 1773/67, Sept. 1967.

13. McCroskey, W.J., Bogdonoff, S.M., and McDougall, J.G., 'An Experimental Model for the Leading Edge of a Sharp Flat Plate in Rarefied Hypersonic Flow,' AIAA Paper 66-31, 1966.

14. McCroskey, W.J., 'A new Probe for Hot-Wire Anemometry at High Temperature,' Princeton Gas Dynamics Lab. Int. Mem. 7, Aug. 1965.

15. Dewey, C.F., 'Hot Wire Measurements in Low Reynolds Number Hypersonic Flows,' J. ARS, Vol. 31, No. 12, Dec. 1961, p. 1709.

16. Trottier, G., Ahmed, A.M., Ellington, D., 'Cooled-Film Anemometer Measurements in the Hypersonic Wake,' CARDE TN 1720/66, May, 1966.

17. Staff of Aerophysics Wing - Compiled by D. Heckman, 'Re-Entry Physics Research Program on Turbulent Wakes,' CARDE TN 1741/67, Jan. 1967.

18. Kramer, H., Physics, Vol. 12, no. 2-3, 61, 1946.

19. Van der Hegge Zijnen, B.G., Appl. Sci. Research A, Vol. 6, 129, 1956.

20. Hilpert, R., Forsch, Gebiete Ingenieurw., 4, 215, 1933.

Nomenclature

A, B, C, D = constants
d = sensor diameter
I = current in sensor
M = Mach number
m, n = constants
P = electrical power input to sensor
Q_c = heat transferred from sensor surface to cooling fluid
Q_E = heat transferred from environment to sensor surface
Re = Reynolds number (Vd/ν)
R_s = sensor operating resistance
t = temperature
T = absolute temperature
V = environment velocity
ν = kinematic viscosity

Subscripts:

s = sensor surface
f = arithmetic mean (when referring to fluid properties, signifies they are evaluated at the arithmetic mean temperature (e.g.

$$T_f = \frac{T_\infty + T_s}{2}$$

∞ = free stream