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# A NOZZLE THERMOCOUPLE FOR MEASUREMENTS IN HIGH-TEMPERATURE GASES

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**Abstract**—A nozzle thermocouple has been devised for measurement of high gas temperatures under conditions of low flow rate.

Calibration curves for such thermocouples are given for monoatomic and diatomic gases. A method to take into account Reynolds number effect is indicated.

## NOMENCLATURE

- $A$, $\pi/4\, d^2$ [cm²];
- $d$, diameter of the throat of the nozzle [cm];
- $M$, mass flow [g/s];
- $N$, exponent of the velocity profile of the gas in any section;
- $p$, absolute static pressure [dyn/cm²];
- $r$, $(T_{wa} - T_s)/(T_t - T_s)$ = recovery factor at the throat of the nozzle without radiation correction;
- $r'$, recovery factor at the throat of the nozzle with radiation correction;
- $T_t$, total gas temperature in the chamber = static gas temperature in the chamber = total gas temperature at the throat [°C or °K];
- $T_s$, static gas temperature at the throat [°C or °K];
- $T_{wa}$, adiabatic wall temperature on the throat [°C or °K];
- $v$, gas velocity [cm/s].

Gas properties

- $c_p$, specific heat at constant pressure [W/s/g degC];
- $k$, thermal conductivity [W/cm degC];
- $\gamma$, specific heat ratio;
- $\mu$, viscosity [g/cm s];
- $\rho$, density [g/cm³].

Dimensionless groups

- $Ma$, $v/v_s$ = Mach number;
- $Pr$, $\mu_s c_{ps}/k_s$ = Prandtl number at the throat;
- $Re$, $\rho_s v_s d/\mu_s$ = Reynolds number at the throat.

Subscripts

- $o$, at normal conditions ($p = 1$ atm and $T = 0$°C);
- $t$, value in the chamber;
- $s$, value at the throat of the nozzle in sonic conditions.

## INTRODUCTION

WHEN the temperature of fluids are measured using thermocouples or resistance thermometers, the temperature actually recorded is that of the probe. This differs from the true temperature of the fluid by an amount dependent on the relation between the rate of heat transfer from the fluid to the probe, and the heat loss from the probe by radiation and conduction: when the heat losses are great and the heat-transfer coefficient small, the temperature of the probe is considerably lower than that of the gas.

Conditions similar to these occurred in the Dragon Project High Temperature Circular Channel Experiment [1], where high gas

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temperature (800–900°C) and low flow rates (0·02 g/s helium and 0·06 g/s air) were recorded.

To measure the gas outlet temperature with sufficient accuracy the authors devised a special probe [2].

## DESCRIPTION OF THE PROBE

The problem of determining the temperature of fluids having poor heat transfer to the measuring probe (low density: gases, low velocity) and high heat losses (high temperatures) has been partly overcome in the past by reducing the probe heat losses to a minimum (by means of shields and guard heaters) and by sucking the fluid at high velocities through a narrow passage, generally the throat of a Venturi, in which the thermocouple wire is inserted. These remedies, however, are not satisfactory for very low fluid flow rates: e.g. in the case of a suction pyrometer,

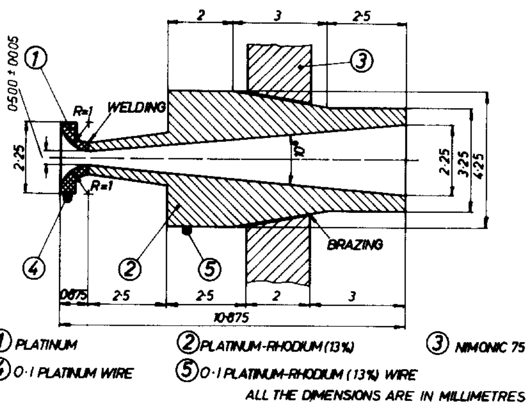


FIG. 1. Nozzle thermocouple.

the passage and thermocouple wire diameter need to be very small to improve heat transfer from the gas to the thermocouple junction and reduce heat losses. In these conditions the wire becomes very weak and easily broken by the vibrations induced by the highly turbulent fluid flow. Furthermore, it is difficult to maintain the wire in the centre of the passage: the wire can easily touch the probe wall, and be influenced by its temperature, which for normal solid probes could be considerably lower than the fluid temperature.

In the special probe developed by the authors the wire is eliminated, the principle innovation being that the thermo-junction is formed in the walls of the hollow probe itself. Figure 1 shows the "nozzle thermocouple"; it consists mainly of a Venturi tube of which the convergent section is made of platinum and the divergent section of platinum–rhodium (13 per cent): the two materials are welded at the throat of the Venturi, giving maximum velocity of the gas past the thermo-junction. The part of the probe in the vicinity of the junction is of relatively light construction (wall thickness 0·1 mm) so reducing the heat losses by conduction through the probe. Without the wire required for a normal suction pyrometer the diameter of the throat can be made very small (0·5 mm) and the overall length of the Venturi is only 11 mm. The inner surface of the nozzle was lapped and the resulting surface roughness was about 1 μ. In the calibration of the probe the minimum thickness of the laminar boundary sublayer was 2 μ, thus the inner surface of the nozzle could be considered hydraulically smooth.

The probe can be manufactured by butt welding, end to end, two cylinders of platinum and platinum–rhodium (13 per cent) respectively, and subsequently machining a thermocouple nozzle to the desired shape (Fig. 1).

The nozzle may then be brazed (melting point of brazing alloy 1250°C) to a suitable Nimonic suction tube, and extension wires spot welded to it.

## CALIBRATION OF THE PROBE

For calibration, the probe was fixed to the end of a $\frac{3}{8}$-in. o.d. Nimonic tube, and protected by a platinum radiation shield. It was then placed in a 1-in. i.d. chamber insulated by 5-in. thick layer of vermiculite. Hot gas, air or helium, was injected into the chamber at various temperatures and simultaneously a vacuum pump connected to the Nimonic tube sucked gas through the nozzle thermocouple. The walls of the chamber were maintained at the gas temperature by means of a guard heater (see Fig. 2).

The calibration was carried out at atmospheric pressure by comparing the reading of the nozzle thermocouple with that of a platinum–platinum–rhodium (13 per cent) couple placed near it in a platinum sheath.

The following assumptions were made:

(1) The static pressure in the chamber is obtained by extrapolating the values obtained with pressure tappings located along the tube heating the gas.
(2) The reading of the conventional thermocouple gives the total gas temperature in the chamber, and therefore, due to the low velocity, equals the static temperature.
(3) The heat exchange to and from the Venturi is neglected, therefore the total gas temperature remains constant in the nozzle, the expansion in the nozzle is adiabatic and the reading of the nozzle thermocouple is equal to the adiabatic wall temperature on the throat of the nozzle.

The first assumption is self-explaining and does not produce any significant uncertainty or approximation in the results. The static pressure was measured in eight sections along the tube so that the extrapolation to the end of the tube was quite accurate. The pressure recovery due to the expansion in the chamber was calculated. This rather cumbersome procedure was due to the accidental circumstance that no pressure tapping was available in the mixing chamber. A considerable simplification would be, when using this nozzle thermocouple, the presence of a pressure tapping directly measuring the static pressure of the chamber where the nozzle is placed.

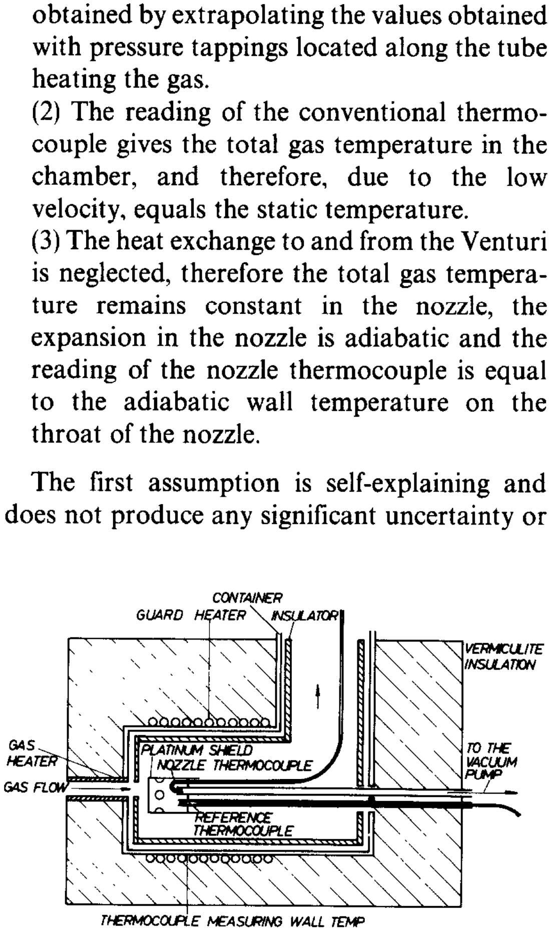

FIG. 2. Assembly of nozzle thermocouple.

The justification and the limiting effects of assumptions (2) and (3) will be discussed in the next paragraphs. With the assumptions (1), (2), (3) it is possible to calculate recovery factors and Prandtl numbers for the throat of the nozzle (see Appendix). The results for helium and air are shown respectively in Tables 1 and 2.*

It can be seen that the mass flow necessary to make the nozzle sonic is very small; however, it should be noted that the mass flow is proportional to pressure [see equation (7)], so that at pressures higher than atmospheric the flow is proportionally higher.

Figures 3 and 4 show the calibration curves for the nozzle thermocouple, i.e. the gas total temperature which corresponds to a certain reading of the nozzle thermocouple ($T_{wa}$) with sonic conditions at the throat.

In first approximation $T_t/T_s$ and $r$ depend, for $Ma = 1$, only on $\gamma$. Indeed, from equation (4) of the Appendix, $T_t/T_s = (\gamma + 1)/2$ and from equation (2) $r = Pr^{0 \cdot 3708}$, while the kinetic theory of gases [3] suggests the approximate relationship: $Pr = 4\gamma/(9\gamma - 5)$. It is therefore logical to assume that the calibration of Fig. 3 is valid for any monoatomic gas and that of Fig. 4 for any diatomic gas.

## DISCUSSION OF RESULTS

Figures 5 and 6 show the recovery factor at the throat of the nozzle vs. the static temperature: the points plotted were obtained from the present experiments, the solid lines represent theoretical values. These were obtained by Tucker and Maslen [4] assuming that velocity

* In Tables 1 and 2 all the results of the experiments are given in numbers, to give the possibility to a possible user of this probe to make the calibration curves more precisely than just making use of the diagrams from this article.

*Table 1. Calibration results with helium*

| No. | $T_t$ (°C) | $T_{wa}$ (°C) | $T_s$ (°C) | $r$ | $r'$ | $M_s$ (g/s) | $Re_s \times 10^4$ |
|---|---|---|---|---|---|---|---|
| 1 | 22·1 | 11·7 | −51·7 | 0·859 | 0·859 | 0·0313 | 0·492 |
| 2 | 21·1 | 11·1 | −52·5 | 0·864 | 0·864 | 0·0314 | 0·492 |
| 3 | 20·6 | 10·8 | −52·8 | 0·866 | 0·866 | 0·0314 | 0·492 |
| 4 | 19·8 | 10·4 | −53·4 | 0·871 | 0·871 | 0·0315 | 0·492 |
| 5 | 19·3 | 10·0 | −53·8 | 0·874 | 0·874 | 0·0315 | 0·492 |
| 6 | 18·8 | 10·8 | −54·2 | 0·891 | 0·891 | 0·0315 | 0·492 |
| 7 | 18·5 | 10·3 | −54·4 | 0·888 | 0·888 | 0·0315 | 0·492 |
| 8 | 19·0 | 9·0 | −54·0 | 0·863 | 0·863 | 0·0315 | 0·492 |
| 9 | 19·5 | 9·8 | −53·7 | 0·868 | 0·868 | 0·0315 | 0·496 |
| 10 | 18·8 | 9·7 | −54·2 | 0·875 | 0·875 | 0·0442 | 0·699 |
| 11 | 18·6 | 9·5 | −54·3 | 0·875 | 0·875 | 0·0442 | 0·699 |
| 12 | 18·1 | 9·7 | −54·7 | 0·885 | 0·885 | 0·0569 | 0·899 |
| 13 | 20·0 | 9·5 | −53·3 | 0·856 | 0·856 | 0·0252 | 0·396 |
| 14 | 20·4 | 9·3 | −53·0 | 0·849 | 0·849 | 0·0539 | 0·847 |
| 15 | 20·0 | 9·0 | −53·3 | 0·850 | 0·850 | 0·0381 | 0·599 |
| 16 | 20·7 | 9·9 | −52·8 | 0·853 | 0·853 | 0·0422 | 0·663 |
| 17 | 19·9 | 9·3 | −53·4 | 0·856 | 0·856 | 0·0317 | 0·498 |
| 18 | 94·5 | 82·3 | 2·6 | 0·868 | 0·867 | 0·0168 | 0·228 |
| 19 | 77·4 | 67·2 | −10·2 | 0·883 | 0·883 | 0·0172 | 0·244 |
| 20 | 81·4 | 71·2 | −7·3 | 0·886 | 0·885 | 0·0171 | 0·239 |
| 21 | 82·6 | 75·0 | −6·3 | 0·914 | 0·913 | 0·0168 | 0·230 |
| 22 | 142·1 | 128·7 | 38·3 | 0·871 | 0·870 | 0·0154 | 0·191 |
| 23 | 130·5 | 116·6 | 29·6 | 0·863 | 0·862 | 0·0160 | 0·201 |
| 24 | 118·4 | 110·1 | 20·5 | 0·915 | 0·914 | 0·0158 | 0·199 |
| 25 | 126·8 | 115·6 | 26·8 | 0·888 | 0·887 | 0·0157 | 0·198 |
| 26 | 133·0 | 119·6 | 31·4 | 0·868 | 0·867 | 0·0158 | 0·198 |
| 27 | 128·5 | 116·7 | 28·1 | 0·883 | 0·883 | 0·0158 | 0·201 |
| 28 | 146·3 | 132·0 | 41·5 | 0·863 | 0·863 | 0·0157 | 0·195 |
| 29 | 136·5 | 123·4 | 34·1 | 0·872 | 0·871 | 0·0164 | 0·207 |
| 30 | 141·3 | 128·9 | 37·7 | 0·881 | 0·881 | 0·0172 | 0·215 |
| 31 | 148·6 | 136·4 | 43·2 | 0·885 | 0·884 | 0·0168 | 0·207 |
| 32 | 155·4 | 145·3 | 48·3 | 0·906 | 0·905 | 0·0195 | 0·237 |
| 33 | 395·6 | 389·9 | 228·4 | 0·966 | 0·962 | 0·0124 | 0·108 |
| 34 | 433·5 | 423·4 | 256·8 | 0·943 | 0·939 | 0·0121 | 0·101 |
| 35 | 447·2 | 432·4 | 267·1 | 0·918 | 0·911 | 0·0120 | 0·100 |
| 36 | 453·4 | 434·7 | 271·8 | 0·897 | 0·894 | 0·0121 | 0·100 |
| 37 | 445·0 | 422·5 | 265·5 | 0·875 | 0·871 | 0·0119 | 0·099 |
| 38 | 438·2 | 416·1 | 260·3 | 0·876 | 0·872 | 0·0121 | 0·101 |
| 39 | 469·7 | 456·5 | 284·0 | 0·929 | 0·928 | 0·0161 | 0·132 |
| 40 | 468·9 | 451·7 | 283·4 | 0·907 | 0·904 | 0·0168 | 0·138 |
| 41 | 445·1 | 429·6 | 265·5 | 0·914 | 0·911 | 0·0174 | 0·145 |
| 42 | 434·0 | 416·5 | 257·2 | 0·901 | 0·897 | 0·0120 | 0·102 |
| 43 | 628·5 | 622·4 | 403·1 | 0·973 | 0·970 | 0·0107 | 0·076 |
| 44 | 613·0 | 595·5 | 391·5 | 0·921 | 0·916 | 0·0105 | 0·076 |
| 45 | 641·6 | 618·2 | 412·9 | 0·898 | 0·892 | 0·0107 | 0·075 |
| 46 | 610·8 | 595·5 | 389·8 | 0·931 | 0·926 | 0·0106 | 0·085 |
| 47 | 551·8 | 548·3 | 345·6 | 0·983 | 0·976 | 0·0110 | 0·083 |
| 48 | 578·6 | 571·5 | 365·7 | 0·967 | 0·961 | 0·0108 | 0·080 |
| 49 | 632·1 | 608·1 | 405·8 | 0·894 | 0·886 | 0·0109 | 0·077 |
| 50 | 637·0 | 615·5 | 409·5 | 0·906 | 0·899 | 0·0119 | 0·084 |
| 51 | 627·1 | 608·7 | 402·0 | 0·918 | 0·914 | 0·0157 | 0·112 |
| 52 | 852·4 | 856·0 | 571·0 | 1·013 | 1·004 | 0·0097 | 0·059 |
| 53 | 917·1 | 903·6 | 619·5 | 0·955 | 0·945 | 0·0098 | 0·058 |
| 54 | 909·4 | 904·9 | 613·8 | 0·985 | 0·977 | 0·0094 | 0·055 |

*Table 1—continued*

| No. | $T_t$ (°C) | $T_{wa}$ (°C) | $T_s$ (°C) | $r$ | $r'$ | $M_s$ (g/s) | $Re_s \times 10^4$ |
|---|---|---|---|---|---|---|---|
| 55 | 889·2 | 889·1 | 598·7 | 0·999 | 0·990 | 0·0094 | 0·056 |
| 56 | 871·1 | 868·5 | 585·0 | 0·991 | 0·979 | 0·0095 | 0·057 |
| 57 | 855·0 | 855·9 | 573·0 | 1·003 | 0·996 | 0·0095 | 0·053 |
| 58 | 905·8 | 888·1 | 611·1 | 0·940 | 0·932 | 0·0096 | 0·057 |
| 59 | 893·2 | 870·8 | 601·6 | 0·923 | 0·912 | 0·0100 | 0·059 |
| 60 | 870·8 | 848·1 | 584·8 | 0·921 | 0·909 | 0·0115 | 0·070 |

*Table 2. Calibration results with air*

| No. | $T_t$ (°C) | $T_{wa}$ (°C) | $T_s$ (°C) | $r$ | $r'$ | $M_s$ (g/s) | $Re_s \times 10^4$ |
|---|---|---|---|---|---|---|---|
| 1 | 18·7 | 13·1 | −27·8 | 0·880 | 0·880 | 0·1752 | 2·837 |
| 2 | 18·6 | 13·2 | −27·9 | 0·884 | 0·884 | 0·1752 | 2·830 |
| 3 | 18·3 | 13·1 | −28·1 | 0·887 | 0·887 | 0·1753 | 2·850 |
| 4 | 18·2 | 12·9 | −28·2 | 0·885 | 0·885 | 0·1753 | 2·850 |
| 5 | 18·2 | 12·9 | −28·2 | 0·886 | 0·886 | 0·1753 | 2·851 |
| 6 | 17·4 | 12·7 | −28·9 | 0·899 | 0·899 | 0·1116 | 1·795 |
| 7 | 17·5 | 12·9 | −28·8 | 0·900 | 0·900 | 0·1122 | 1·807 |
| 8 | 18·2 | 13·6 | −28·2 | 0·900 | 0·900 | 0·1141 | 1·832 |
| 9 | 17·9 | 13·5 | −28·5 | 0·905 | 0·905 | 0·1114 | 1·789 |
| 10 | 18·2 | 14·7 | −28·2 | 0·924 | 0·924 | 0·0539 | 0·866 |
| 11 | 18·2 | 14·8 | −28·2 | 0·926 | 0·926 | 0·0539 | 0·866 |
| 12 | 17·0 | 13·3 | −29·2 | 0·921 | 0·921 | 0·0539 | 0·866 |
| 13 | 22·5 | 17·6 | −24·6 | 0·896 | 0·896 | 0·0861 | 1·367 |
| 14 | 22·7 | 17·7 | −24·4 | 0·894 | 0·894 | 0·0865 | 1·373 |
| 15 | 20·2 | 15·8 | −26·6 | 0·907 | 0·907 | 0·0869 | 1·388 |
| 16 | 19·2 | 15·1 | −27·2 | 0·912 | 0·912 | 0·0869 | 1·385 |
| 17 | 22·7 | 17·4 | −24·5 | 0·889 | 0·889 | 0·0869 | 1·370 |
| 18 | 20·9 | 15·8 | −26·0 | 0·891 | 0·891 | 0·0635 | 1·020 |
| 19 | 20·0 | 15·5 | −26·7 | 0·904 | 0·904 | 0·0797 | 1·274 |
| 20 | 19·7 | 15·3 | −26·9 | 0·905 | 0·905 | 0·0926 | 1·481 |
| 21 | 19·7 | 15·1 | −27·0 | 0·902 | 0·902 | 0·1115 | 1·783 |
| 22 | 19·7 | 14·8 | −27·0 | 0·895 | 0·895 | 0·1406 | 2·249 |
| 23 | 19·2 | 14·4 | −27·4 | 0·897 | 0·897 | 9·1437 | 2·301 |
| 24 | 20·7 | 16·3 | −26·1 | 0·905 | 0·905 | 0·1424 | 2·272 |
| 25 | 47·8 | 43·2 | −5·0 | 0·913 | 0·912 | 0·0469 | 0·694 |
| 26 | 100·9 | 95·3 | 39·3 | 0·909 | 0·908 | 0·0526 | 0·700 |
| 27 | 91·5 | 87·4 | 32·2 | 0·931 | 0·930 | 0·0895 | 1·217 |
| 28 | 95·8 | 89·5 | 35·5 | 0·896 | 0·895 | 0·0422 | 0·564 |
| 29 | 93·4 | 87·7 | 33·5 | 0·905 | 0·904 | 0·0424 | 0·574 |
| 30 | 85·1 | 78·9 | 27·0 | 0·893 | 0·892 | 0·0429 | 0·598 |
| 31 | 88·4 | 82·7 | 29·5 | 0·903 | 0·902 | 0·0426 | 0·581 |
| 32 | 84·1 | 78·8 | 26·1 | 0·909 | 0·908 | 0·0428 | 0·589 |
| 33 | 74·9 | 70·8 | 18·2 | 0·928 | 0·927 | 0·0434 | 0·608 |
| 34 | 77·2 | 71·7 | 20·0 | 0·904 | 0·903 | 0·0418 | 0·584 |
| 35 | 84·1 | 77·3 | 26·1 | 0·883 | 0·881 | 0·0418 | 0·575 |
| 36 | 138·0 | 132·7 | 70·0 | 0·923 | 0·921 | 0·0401 | 0·499 |
| 37 | 136·8 | 131·4 | 69·0 | 0·921 | 0·920 | 0·0399 | 0·497 |
| 38 | 124·7 | 118·5 | 59·0 | 0·906 | 0·904 | 0·0403 | 0·518 |
| 39 | 144·8 | 138·2 | 78·2 | 0·902 | 0·900 | 0·0403 | 0·390 |
| 40 | 132·3 | 125·7 | 64·7 | 0·902 | 0·901 | 0·0396 | 0·497 |

*Table 2—continued*

| No. | $T_t$ (°C) | $T_{wa}$ (°C) | $T_s$ (°C) | $r$ | $r'$ | $M_s$ (g/s) | $Re_s \times 10^4$ |
|---|---|---|---|---|---|---|---|
| 41 | 101·3 | 96·4 | 39·8 | 0·921 | 0·920 | 0·0416 | 0·557 |
| 42 | 88·7 | 84·5 | 29·9 | 0·929 | 0·927 | 0·0419 | 0·569 |
| 43 | 130·7 | 127·3 | 63·5 | 0·949 | 0·948 | 0·0395 | 0·498 |
| 44 | 144·5 | 138·9 | 75·5 | 0·919 | 0·917 | 0·0417 | 0·404 |
| 45 | 139·5 | 135·0 | 70·8 | 0·934 | 0·933 | 0·0423 | 0·524 |
| 46 | 145·0 | 140·5 | 75·5 | 0·935 | 0·932 | 0·0475 | 0·584 |
| 47 | 413·9 | 406·3 | 304·7 | 0·930 | 0·926 | 0·0307 | 0·265 |
| 48 | 398·2 | 391·8 | 291·5 | 0·940 | 0·935 | 0·0306 | 0·268 |
| 49 | 381·3 | 377·6 | 277·0 | 0·965 | 0·959 | 0·0308 | 0·274 |
| 50 | 344·5 | 337·6 | 246·0 | 0·930 | 0·919 | 0·0319 | 0·296 |
| 51 | 362·2 | 359·4 | 261·0 | 0·972 | 0·964 | 0·0315 | 0·285 |
| 52 | 436·2 | 428·2 | 324·0 | 0·929 | 0·924 | 0·0324 | 0·274 |
| 53 | 411·2 | 401·9 | 302·3 | 0·915 | 0·913 | 0·0404 | 0·351 |
| 54 | 430·6 | 419·5 | 319·0 | 0·901 | 0·895 | 0·0363 | 0·368 |
| 55 | 453·4 | 447·8 | 339·3 | 0·951 | 0·946 | 0·0339 | 0·282 |
| 56 | 429·5 | 422·4 | 317·7 | 0·937 | 0·931 | 0·0520 | 0·442 |
| 57 | 437·5 | 432·3 | 325·0 | 0·954 | 0·947 | 0·0323 | 0·273 |
| 58 | 382·8 | 371·7 | 278·8 | 0·893 | 0·891 | 0·0336 | 0·299 |
| 59 | 599·5 | 590·6 | 466·7 | 0·933 | 0·928 | 0·0610 | 0·450 |
| 60 | 606·4 | 597·1 | 472·0 | 0·931 | 0·917 | 0·0364 | 0·268 |
| 61 | 619·3 | 610·4 | 483·5 | 0·935 | 0·924 | 0·0363 | 0·264 |
| 62 | 621·0 | 612·8 | 485·1 | 0·940 | 0·929 | 0·0356 | 0·258 |
| 63 | 635·5 | 627·2 | 497·5 | 0·940 | 0·931 | 0·0598 | 0·345 |
| 64 | 646·8 | 637·7 | 507·5 | 0·935 | 0·922 | 0·0350 | 0·250 |
| 65 | 615·6 | 610·6 | 480·5 | 0·963 | 0·953 | 0·0284 | 0·207 |
| 66 | 599·9 | 595·2 | 467·3 | 0·965 | 0·954 | 0·0273 | 0·201 |
| 67 | 577·8 | 575·0 | 448·0 | 0·978 | 0·966 | 0·0275 | 0·206 |
| 68 | 586·4 | 582·8 | 455·3 | 0·973 | 0·959 | 0·0275 | 0·205 |
| 69 | 562·5 | 562·5 | 434·0 | 1·000 | 0·984 | 0·0275 | 0·208 |
| 70 | 558·1 | 558·9 | 430·3 | 1·006 | 0·986 | 0·0273 | 0·207 |
| 71 | 543·8 | 545·9 | 417·0 | 1·017 | 0·995 | 0·0273 | 0·210 |
| 72 | 623·6 | 615·2 | 487·0 | 0·939 | 0·926 | 0·0296 | 0·215 |
| 73 | 535·6 | 536·0 | 411·1 | 1·003 | 0·993 | 0·0285 | 0·221 |
| 74 | 874·7 | 868·1 | 709·5 | 0·960 | 0·946 | 0·0350 | 0·217 |
| 75 | 859·4 | 852·5 | 695·0 | 0·958 | 0·939 | 0·0520 | 0·326 |
| 76 | 870·1 | 865·6 | 705·0 | 0·973 | 0·956 | 0·0301 | 0·187 |
| 77 | 783·9 | 800·1 | 628·2 | 1·104 | 1·079 | 0·0250 | 0·163 |
| 78 | 697·8 | 714·1 | 552·1 | 1·112 | 1·067 | 0·0260 | 0·179 |
| 79 | 815·5 | 827·7 | 665·5 | 1·081 | 1·059 | 0·0247 | 0·158 |
| 80 | 849·7 | 858·4 | 685·3 | 1·053 | 1·038 | 0·0243 | 0·153 |
| 81 | 851·5 | 855·5 | 688·5 | 1·025 | 1·015 | 0·0245 | 0·154 |
| 82 | 881·3 | 882·3 | 715·0 | 1·006 | 0·997 | 0·0251 | 0·155 |
| 83 | 881·9 | 881·8 | 715·9 | 0·999 | 0·994 | 0·0329 | 0·203 |
| 84 | 893·9 | 889·4 | 726·1 | 0·973 | 0·955 | 0·0474 | 0·290 |

profile is represented by a power law, and a similarity exists between the squared velocity and the static temperature difference profiles. The following equation approximated the computations to within 1 per cent:

$$r = Pr^{\frac{N+1+0\cdot528\,Ma^2}{3N+1+Ma^2}} \qquad (1)$$

For turbulent flow $N = 7$, for $Ma = 1$ equation (1) thus becomes:

$$r = Pr^{0\cdot3708}. \qquad (2)$$

For helium two lines are shown in Fig. 5: one according to values of $Pr$ obtained by Keyes [5], values usually accepted until recently and derived

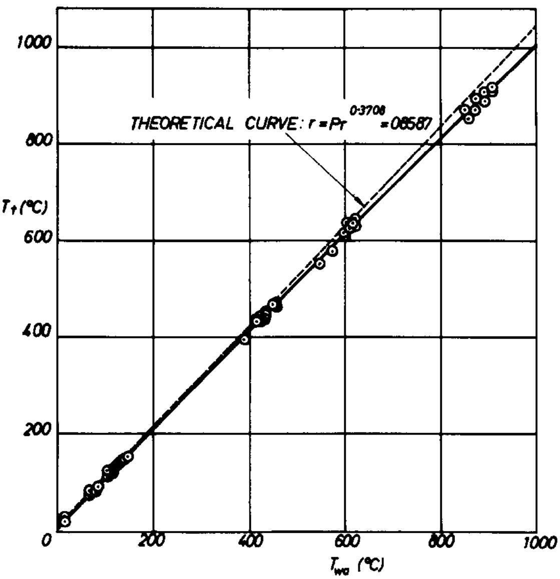


FIG. 3. Nozzle thermocouple calibration curve—helium.

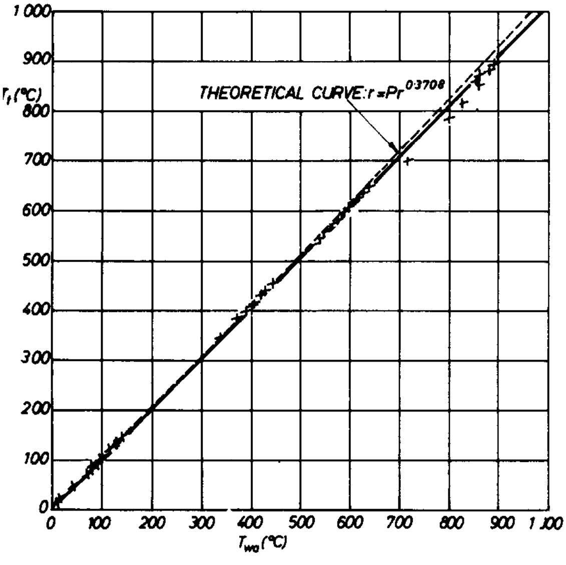


FIG. 4. Nozzle thermocouple calibration curve—air.

from measurements of specific heat, dynamic viscosity and thermal conductivity, the other to the more recent study of Stroom, Ibele and Irvine [6], where the Prandtl numbers were obtained by measuring recovery factors in a nozzle with flow of helium in laminar regime. The values given by this last report are practically temperature independent, which is in agreement with the kinetic theory for monoatomic gases.*

The difference in the value of *Pr* derives by uncertainties in measuring *k*, while $c_p$ and $\mu$ are well established. Keyes [5] and Hilsenrath and Touloukian [7] give values of *k* which are in agreement with the values of *Pr* of [4], but more recent work performed by Mann and Blais [8], Tzederber and Popov [9], and Zaitseva [10], and also some work done by the authors on heat transfer with helium, suggest higher values of *k* at high temperatures, and therefore confirm that the Prandtl number for helium is independent of temperature.

Although the Reynolds numbers are quite small (see Tables 1 and 2) the values of *r* are surficiently high to suggest that the flow in the nozzle is turbulent, this is probably due to the very complicated geometry which disturbs the flow pattern at its entrance. However, the points lie above the theoretical lines in the whole range of temperatures. The possible causes of this are:

(1) The nozzle throat is not perfectly adiabatic and receives some heat by radiation from the environment (related to assumption (3) of the preceding paragraph).
(2) The nozzle was not properly choked during the experiment ($Ma \neq 1$ at the throat).
(3) Formula (1) is not valid.
(4) The values of *Pr* assumed are not correct.
(5) The reading of the conventional thermocouple is wrong or it does not give the value of the gas total temperature (related to assumption (2) of the preceding paragraph).
(6) The nozzle throat receives some heat by conduction through the walls of the nozzle itself (related to assumption (3) of the preceding paragraph).

* The kinetic theory of gases [3] suggests the relationship: $Pr = 4\gamma/(9\gamma - 5)$, where for a monoatomic gas $\gamma$ is constant and equal to $\frac{5}{3}$, therefore $Pr = \frac{2}{3} = 0{\cdot}667$, while Stroom, Ibele and Irvine find $Pr = 0{\cdot}664$.

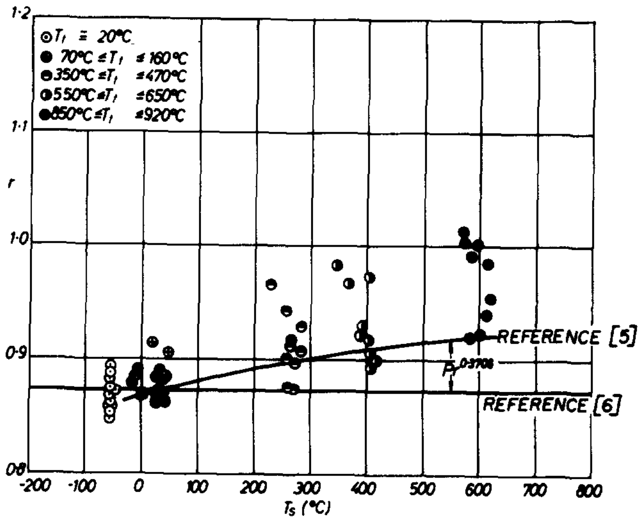


FIG. 5. Recovery factor vs. static temperature in the throat, without radiation correction—helium.

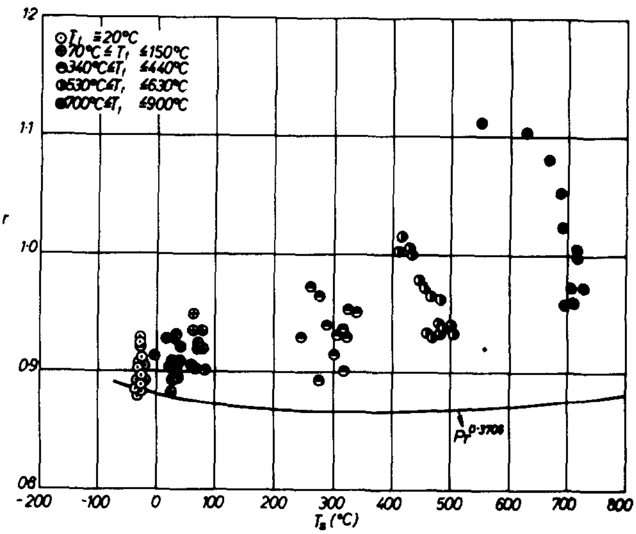

FIG. 6. Recovery factor vs. static temperature in the throat, without radiation correction—air.

(7) The recovery factor depends not only on the Prandtl number, but also on the Reynolds number.

Tables 1 and 2 show the values of the recovery factor $r'$ corrected for radiation: the influence of radiation is negligible as one would expect due to the fact that at room temperature the radiation error must be extremely low.

Every care was taken during the experiment to ensure that the nozzle was properly choked: temperature measurements were taken only when the velocity at the throat was sonic. This was indicated by reductions on back pressure having no influence on upstream pressure.

Formula (1) is well established and it is generally accepted that in turbulent regime $r =$

$Pr^{1/3}$, while in laminar regime $r = Pr^{1/2}$; both these formulae would produce values of $r$ smaller than those obtained in the present experiment.

Values of $Pr$ are not known very precisely, but uncertainties are not such as to explain the differences between theoretical and experimental values of $r$.

With the help of the thermocouples placed on the wall of the chamber containing the two thermocouples (reference- and nozzle-thermocouple) the conduction and radiation errors of the reference thermocouple were calculated. They were in every case smaller than 0·1 degC. The calculated difference between total and static temperature was also negligible.

It is not possible to calculate the error in $r$ due to conduction of heat through the walls of the nozzle since the temperature gradient in the walls in the vicinity of the section corresponding to the throat is not known. However, it is obvious that for a given nozzle, i.e. for given geometry and nozzle material, this error depends mainly on the Reynolds number in the throat and on the environment temperature, because the first parameter establishes the rate of heat transfer to the nozzle and the second the rate of

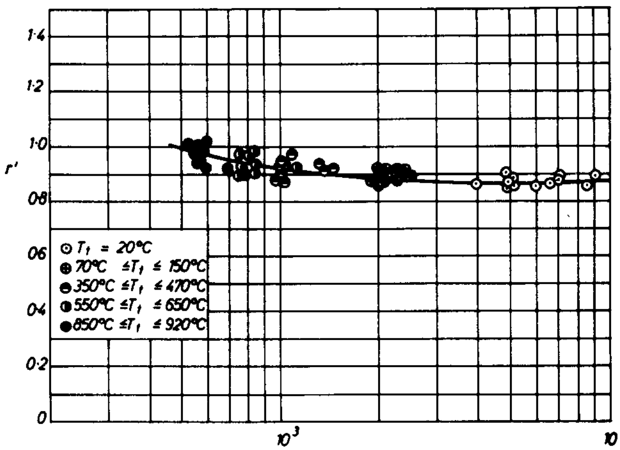


FIG. 7. Reynolds-number effect on recovery factor—helium.

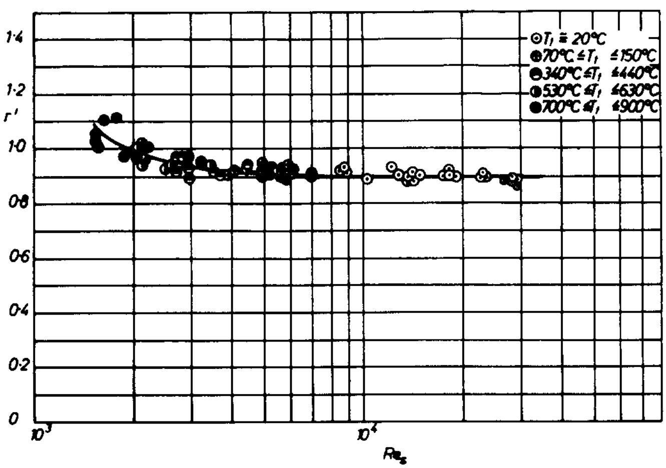


FIG. 8. Reynolds-number effect on recovery factor—air.

heat transfer from the nozzle. Figures 7 and 8 show recovery factors vs. Reynolds numbers at the throat for various temperatures: the temperature parameter seems to have no appreciable effect on $r$, which suggests that the conduction error is negligible.

The only parameter, besides the well known effect of the Prandtl number which seems to affect $r$, is therefore $Re_s$. This is in accordance, for the same range of $Re_s$ numbers, with a previous experiment of Deissler, Weiland and Lowdermilk [11].

## CONCLUSIONS AND RECOMMENDATIONS

The nozzle-thermocouple has the advantage of a very good heat-transfer rate between probe and fluid. It is therefore particularly suitable to obtain good measurement of temperature of a gas at high temperature and low flow rate.

With a platinum–platinum–rhodium (13 per cent) nozzle of the dimensions indicated in Fig. 1, the error is less than 0·5 degC in the range between 20°C and 1000°C. However, to obtain this accuracy for temperatures above 500°C, a platinum shield is recommended and possibly a guard heater.

Where great precision is not required, but simplicity is the main factor, Figs. 3 and 4 give the calibration curve ($T_{wa}$ is the reading of the probe, $T_t$ the gas temperature).

If it is necessary to take into account the Reynolds number effect, then $Re_s$ has to be calculated (see the Appendix). Figures 7 and 8 give $r$ for mono and diatomic gases respectively and $T_t$ can be calculated from the equation:

$$T_t\,(^\circ\mathrm{K}) = T_{wa}\,(^\circ\mathrm{K})\,\frac{\gamma + 1}{r(\gamma - 1) + 2},$$

which derives from equation (4) and the definition of $r$ (see Nomenclature). The precision of nozzle dimensions does not affect the accuracy of the measurement very much. In particular the most important dimension, the diameter of the throat, affects the value of $r$ while it is proportional to $Re_s$ [see equation (8)]. For the higher values of $Re_s$ the dependence of $r$ on $Re_s$ is practically nil. For the lower values of $Re_s$ ($Re_s \leqslant 10^3$) a variation of 1 per cent in the throat dimensions produces an error of 0·2 per cent in $T_t$.

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## APPENDIX

$T_t$, $T_{wa}$ and $p_t$ are directly measured; $T_s$ is obtained by the relation:

$$T_s = \frac{T_t}{1 + (\gamma - 1/2)\,Ma^2} \tag{3}$$

at the throat $Ma = 1$,

$$\text{therefore } T_s = \frac{2T_t}{\gamma + 1}. \tag{4}$$

If the expansion in the nozzle is considered adiabatic the static pressure at the throat is given by:

$$p_s = p_t\left(\frac{T_s}{T_t}\right)^{\frac{\gamma}{\gamma-1}}$$

and for the equation (4):

$$p_s = p_t\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma}{\gamma-1}}. \qquad (5)$$

The velocity at the throat is:

$$v_s = \sqrt{\left(\gamma\frac{p_s}{\rho_s}\right)} \qquad (6)$$

and therefore the mass flow across the nozzle is:

$$M_s = A\rho_s v_s = A\rho_s\sqrt{\left(\gamma\frac{p_s}{\rho_s}\right)} = A\sqrt{(\gamma\,\rho_s p_s)}$$

$$= A\sqrt{\left(\gamma\frac{\rho_o}{p_o}\frac{T_o}{T_s}p_s^2\right)} = Ap_s\sqrt{\left(\frac{\gamma\,\rho_o T_o(\gamma+1)}{p_o 2T_t}\right)},$$

therefore

$$M_s = \frac{p_t}{\sqrt{(T_t)}}A\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma}{\gamma-1}} \times\sqrt{\left(\frac{\gamma(\gamma+1)\,\rho_o T_o}{2p_o}\right)}. \qquad (7)$$

The Reynolds number at the throat is given by:

$$Re_s = \frac{\rho_s v_s d}{\mu_s} = \frac{dM_s}{A\mu_s},$$

therefore

$$Re_s = \frac{p_t}{\sqrt{(T_t)}}\frac{d}{\mu_s}\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma}{\gamma-1}} \times\sqrt{\left(\frac{\gamma(\gamma+1)\,\rho_o T_o}{2p_o}\right)}. \qquad (8)$$

The numerical values are given by:

$$d = 0{\cdot}05 \text{ cm},$$

$$A = \frac{\pi}{4}d^2 = \frac{\pi}{4}\,.\,0{\cdot}05^2 = 0{\cdot}19635\,.\,10^{-2}\text{ cm}^2,$$

$$p_o = 1{\cdot}01325\,.\,10^6 \text{ dyn/cm}^2,$$

and $T_o = 273{\cdot}1°\text{K}$;

for helium:

$$\gamma = \tfrac{5}{3},$$

and $\rho_o = 0{\cdot}17847\,.\,10^{-3}$ g/cm$^3$;

and for air:

$\gamma = 1{\cdot}379$ (in the range $0 \leqslant T_s \leqslant 600°\text{C}$)

and $\rho_o = 1{\cdot}2929\,.\,10^{-3}$ g/cm$^3$.

Equations (4), (7), and (8) become for helium:

$$T_s = 0{\cdot}75\,T_t\,(°\text{K}), \qquad (4)'$$

$$M_s = 0{\cdot}7823\,.\,10^{-3}\frac{p_t\,(\text{in of } H_2O)}{\sqrt{(T_t)}\,(°\text{K})}\text{ g/s}, \qquad (7)'$$

and $$Re_s = 0{\cdot}01992\frac{p_t\,(\text{in of } H_2O)}{\mu_s(\text{g/cm s})\sqrt{(T_t)}\,(°\text{K})}, \qquad (8)'$$

and for air:

$$T_s = 0{\cdot}8407\,T_t\,(°\text{K}), \qquad (4)''$$

$$M_s = 1{\cdot}971\,.\,10^{-3}\frac{p_t\,(\text{in of } H_2O)}{\sqrt{(T_t)}\,(°\text{K})}\text{ g/s}, \qquad (7)''$$

and $$Re_s = 0{\cdot}05019\frac{p_t\,(\text{in of } H_2O)}{\mu_s(\text{g/cm s})\sqrt{(T_t)}\,(°\text{K})}. \qquad (8)''$$

**Résumé**—On a imaginé une tuyère thermocouple pour la mesure des températures élevées de gaz sous des conditions de faible débit.

Les courbes d'étalonnage pour de tels thermocouples sont données pour des gaz monoatomiques et diatomiques. On indique une méthode pour tenir compte de l'effet du nombre de Reynolds.

**Zusammenfassung**—Ein Düsenthermoelement wurde entwickelt, um hohe Gastemperaturen bei geringen Durchsatzmengen zu messen.

Eichkurven dieser Thermoelemente sind für einatomige und zweiatomige Gase angegeben. Eine Methode zur Berücksichtigung des Einflusses der Reynoldszahl wird angedeutet.

**Аннотация**—Для измерения высоких температур газов в условиях низкой скорости течения разработана термопара в виде сопла.

Калибровочные кривые для таких термопар приводятся для одноатомных и двуатомных газов. Указан метод учета эффекта критерия Рейнольдса.