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exist for the publication of theoretical and experimental investigations of all aspects of the mechanics and thermodynamics of fluid-flow with special reference to fluid-flow machinery

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Instytut Maszyn Przepływowych PAN
ul. Gen. Józefa Fiszera 14, 80-952 Gdańsk, skr. pocztowa 621, tel. 41-02-13

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SŁAWOMIR BIAŁOSTOCKI

Gdańsk

Critical-Flow Gas Cooling as Working Principle of Immersion Probes for Total Temperature Measurement in Hot Gas Jets*

A gas-cooled probe for contact measurement in hot gas flows is described, in which variable supply pressure of the coolant gas is a principal measured quantity. It is suggested that such probes may be applied for flow temperatures of the order of 2000 - 3000°K.

Symbols used more frequently:

$\dot{m}$ – flow of mass,
$\dot{p}$ – heat flux,
T – static temperature,
T^* – total temperature,
T_h – temperature of a selected point of probe head metal,
T_c – coolant temperature ahead of the exit nozzle,
T_{c0} – coolant temperature at inlet to probe head,
T_{wall} – temperature of wall embracing the hot jet, or environmental temperature,
p – static pressure,
p^* – total pressure,
A – cross-section or surface area,
c_p – specific heat at constant pressure,
K – thermal conductivity,
μ – viscosity,
α – heat transfer coefficient.

Subscripts refer to:

g – external flow of gas about the probe head,
c – coolant properties,
i – internal flow of coolant inside the probe head.

1. Probe design and working principle

A simple concept, seemingly unemployed heretofore among the variety of existing devices for contact measurement of gas stream temperature is the one utilizing a foreign gaseous medium for probe cooling. In spite of it's lower heat extracting capacity, gas-cooling manifests some essential advantages when making use of the laws of critical flow in the internal flow of the cooling agent.

A possibly simplest variation of the suggested probe design may be seen in Figs 1 and 2. A hemispherical, hollow metal body with it's axis aligned with the flow direction of (external) gas stream is cooled by internal flow of a foreign gas supplied from a pres-

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sure cylinder and a pressure regulator. The cooling gas leaves the pressure vessel (plenum) formed by the probe body and the termination of supporting tube through (diversely arranged) sonic-flow orifices or nozzle. The cooling gas is mixed with the external stream

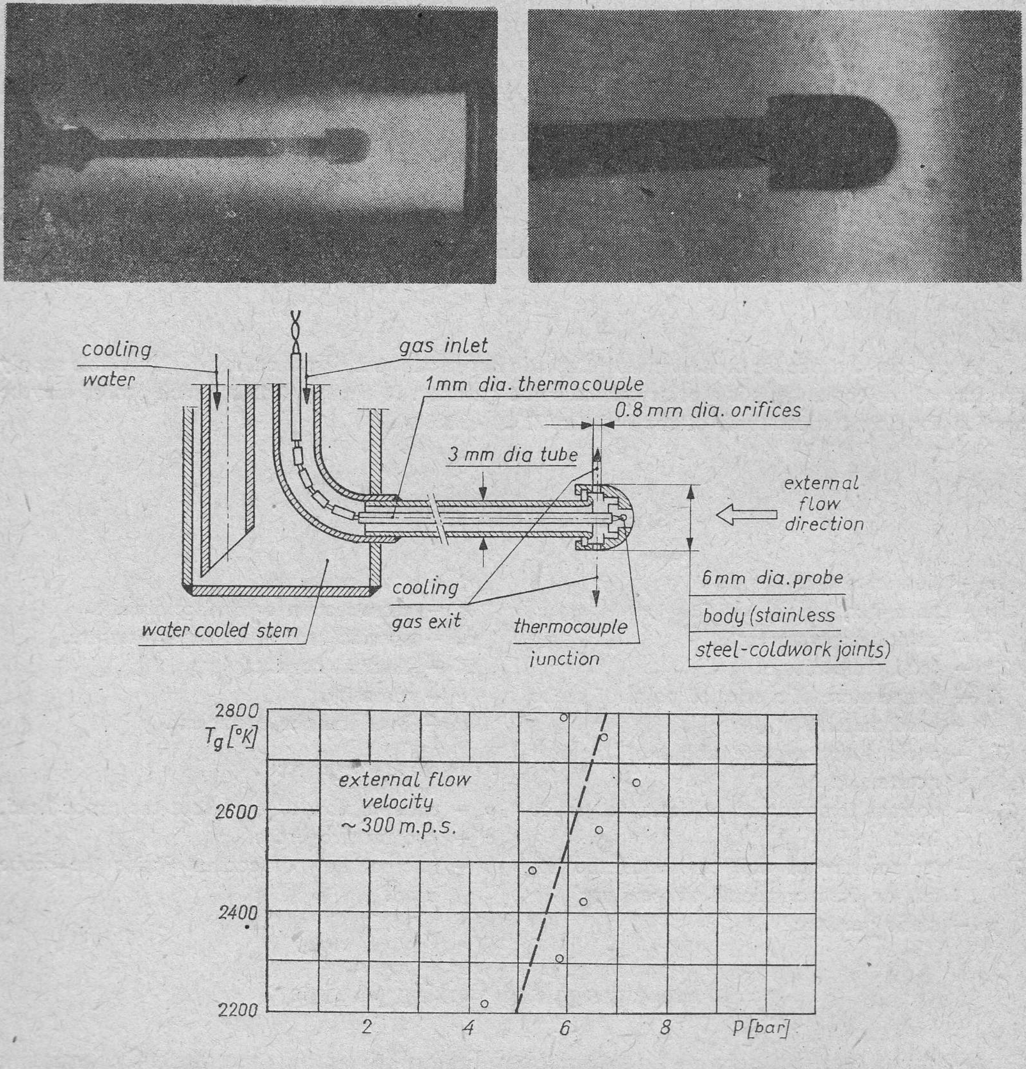

Fig. 1. The design and example of test results of a prototype probe. At top the probe during tests in an open jet of combustion gases: direct photograph (left) and a shadowgraph showing the efflux of cooling gas jets into the hot flow

at exit from the probe body and wasted (if mixing is undesirable, the gas can be led out through an appropriate conduit in the water-cooled stem).

The temperature of the probe head T_h is measured; the thermocouple junction being located close to the point of external flow stagnation. Calibration in a stream of known temperature and velocity leads, in the instances specified below, to a relation between the stream total temperature T_g^*, temperature T_h and cooling gas supply pressure p_c allowing

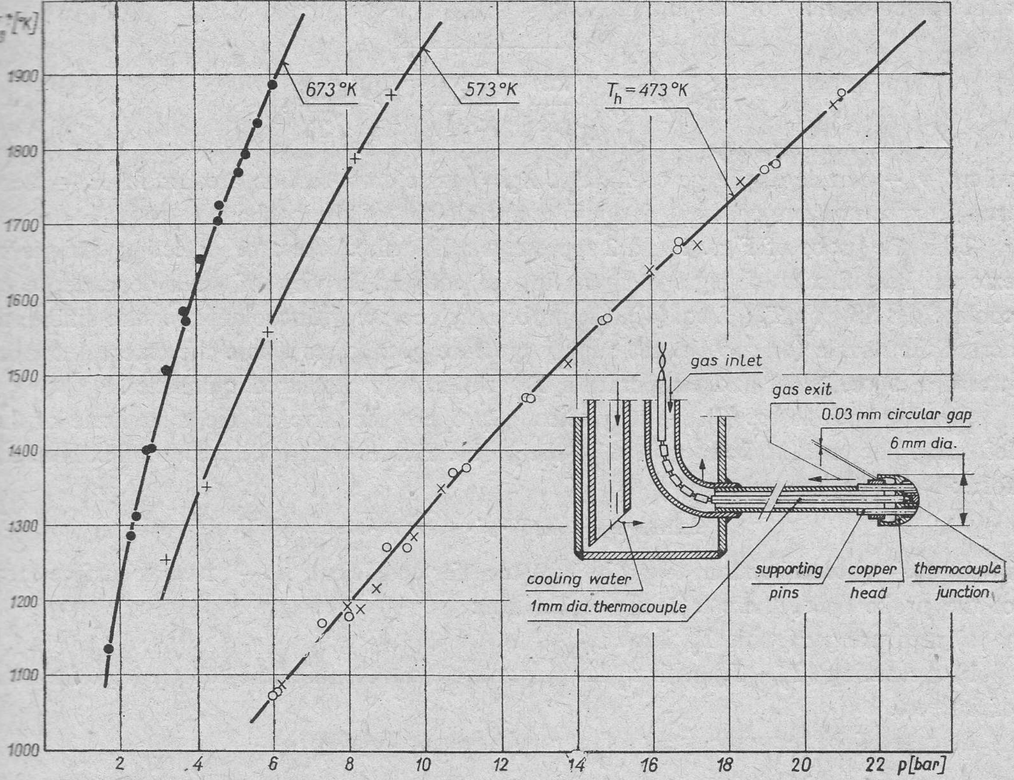

Fig. 2. Layout of a probe (silver soldered, with copper head) and the results of calibration made by comparing with PtRh-Pt thermocouple readings

to use the probe as a total temperature (enthalpy) measuring instrument. It is essential for probe operation to keep T_h=const while the external stream temperature T_g varies, by adjusting the cooling gas flow (the exit nozzle pressure ratio is always kept beyond critical).

The probe body heat balance equation:

$$\dot{q}_{\left[\substack{\text{convection from}\\ \text{external stream}}\right]} = \dot{q}_{\left[\substack{\text{internal}\\ \text{cooling}}\right]} + \dot{q}_{[\text{radiation}]} + \dot{q}_{[\text{conduction}]} \tag{1}$$

where $\dot{q}_{[\dots\dots]}$ — component heat fluxes may then, for a number of experimental conditions encountered in practice, be much simplified. The radiation term may, as first approximation, be regarded as independent of T_g^* in view of T_h=const. Together with the conduction term, this term may be considered as a calibration correction weakly dependent on the measured gas temperature. Rewriting (1) into:

$$\dot{q}_{[\text{ext. stream convection}]} \approx \dot{q}_{[\text{int. cooling}]} \tag{2}$$

one may state that for T_h=const, any change in the external heat flux $\Delta\dot{q}$ must be compensated by a change in coolant flow $\Delta\dot{m}_c$ i.e. a change in the coolant supply pressure Δp_c since

$$\dot{q}_{[\text{int. cooling}]} \approx \dot{m}_c \cdot c_{pc}(T_c - T_{c0}) \tag{3}$$

and, for sonic flow of coolant

$$\dot{m} \sim \varphi \cdot A_{cr} \sqrt{\frac{\kappa M}{R} \cdot \left(\frac{2}{\kappa+1}\right)^{\frac{\kappa+1}{\kappa-1}}} \cdot \frac{p_c - p_g}{\sqrt{T_c}}, \tag{4}$$

where φ — nozzle discharge coefficient, A_{cr}=nozzle cross-section area, κ, M, R — isentropic exponent, gas constant and molecular weight of the coolant.

Thus the probe of Figs. 1 and 2 represents a heat flux indicator detecting changes in external heat flux as changes in mass flow of coolant. In view of weak dependence of coolant gas flow on T_c (cf. eq. (4)), the probe may operate with coolant pressure difference across the nozzle (or coolant gas supply pressure p_c in cases where the external stream pressure is constant) and temperature T_h as the only measured quantities.

Coming back to eq. (2) one may select a property decisive of the magnitude of the left-hand side term, to be measured by the probe. Expressing the convection flux in usual form:

$$\dot{q}_{[\text{stream convection}]} = \alpha_g \cdot A (T_g^* - T_h), \tag{5}$$

where α_g — external stream to probe heat transfer coefficient, A — external surface area of the probe head, there is a choice between:

a) measuring α_g with T_g^* known,

b) measuring $(T_g^* - T_h)$ with α_g known and constant within the temperature interval of interest.

In case of b) we may speak of a rough proportionality

$$T_g^* \sim p_c \tag{6}$$

with T_h fixed.

The purpose of the above brief analysis was not to suggest the probe of the type considered as an "autonomic" instrument with characteristics (6) capable of being determined "a priori". The probe of Figs 1 and 2 requires calibration for rather obvious reasons, and the analysis has been made merely to indicate that simple dependencies of the sort of (6) may be expected.

The condition T_h=const serves also to eliminate nozzle dilation errors. The probe itself may be classified as one of the rate-of-heat-transfer measuring devices [1], while critical flow relations are employed similarly as in the suction pyrometers [2]. The reversion of flow direction, as compared to the suction pyrometers or other devices based on external flow aspiration, offers some important advantages: there is no nozzle contamination; the material constants of the pure cooling gas are non-changing and known accurately.

The probes of Figs 1 and 2 have been tested in the free exhaust jet of a laboratory combustion chamber [3] in order to check:

— if the gas-cooling secures probe working temperatures beyond those of the contact temperature measuring devices available commercially,

— if the T_g^* vs. p_c calibration curve manifests the expected properties.

The probe of Fig. 1 has been tested for external stream temperature 2200 - 2800°K, measured with the use of sodium line reversal method. Carbon dioxide in amounts not exceeding 3 kg per hour was applied as the cooling agent. The probe sustained the above-given external gas stream temperatures without damage (with T_h up to 1200°K). However, the probe characteristic obtained was not satisfactory, which resulted from excessive conduction error and a rather poor accuracy of the reference instrument used for hot flow temperature measurement. The probe was redesigned (see Fig. 2) to minimize the conduction error, and calibrated in a temperature range lowered to enable the use of a bare platinum thermocouple as a reference instrument. Fig. 2 gives the results. The shape of the $T_g^*(p_c)$ curves indicates the possibility of obtaining an unique calibration relation which appears to be fairly linear for the conditions given. The slope of the $T_g^*(p_c)$ curve (a reciprocal of which represents probe sensitivity) may be easily adjusted by selecting a convenient value of T_h. One of the curves shows the probe sensitivity of the order of 2 bars per a hundred degrees centigrade, which seems to be quite satisfactory. The observable repeatedness of the results may be regarded as an evidence of prospectous accuracy. Corrections in the nozzle cross-section area allow to adjust the coolant pressure to the range being at disposal. In conclusion, in spite of the need of calibration "in situ", the gas cooled probes of the type shown in Fig. 2 may be useful in surveillance of hot gas jets, due to their simplicity and ease of miniaturization.

2. Possible modifications of probe design

The analysis of the probe heat transfer given in the foregoing paragraph is oversimplified. It should, at least, be complemented by the following comments:

— The neglect of radiation term in the probe heat balance (1) will be justified if neither the measured stream absorption nor the wall temperature vary markedly within the interval of variation of the stream conditions (as may often be the case with water cooled walls or with an open gas jet radiating to cold environment). In other cases the share of radiation in the calibration correction may be calculable.

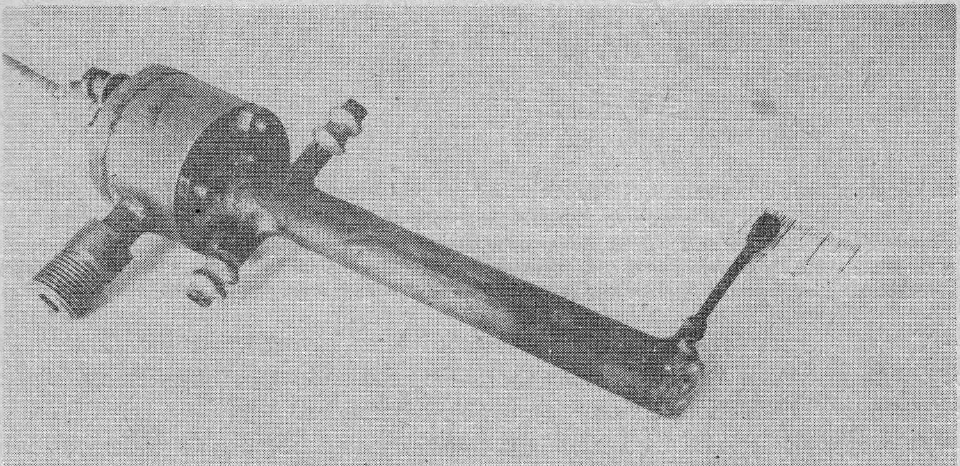

Fig. 3. Picture of the probe of Fig. 1

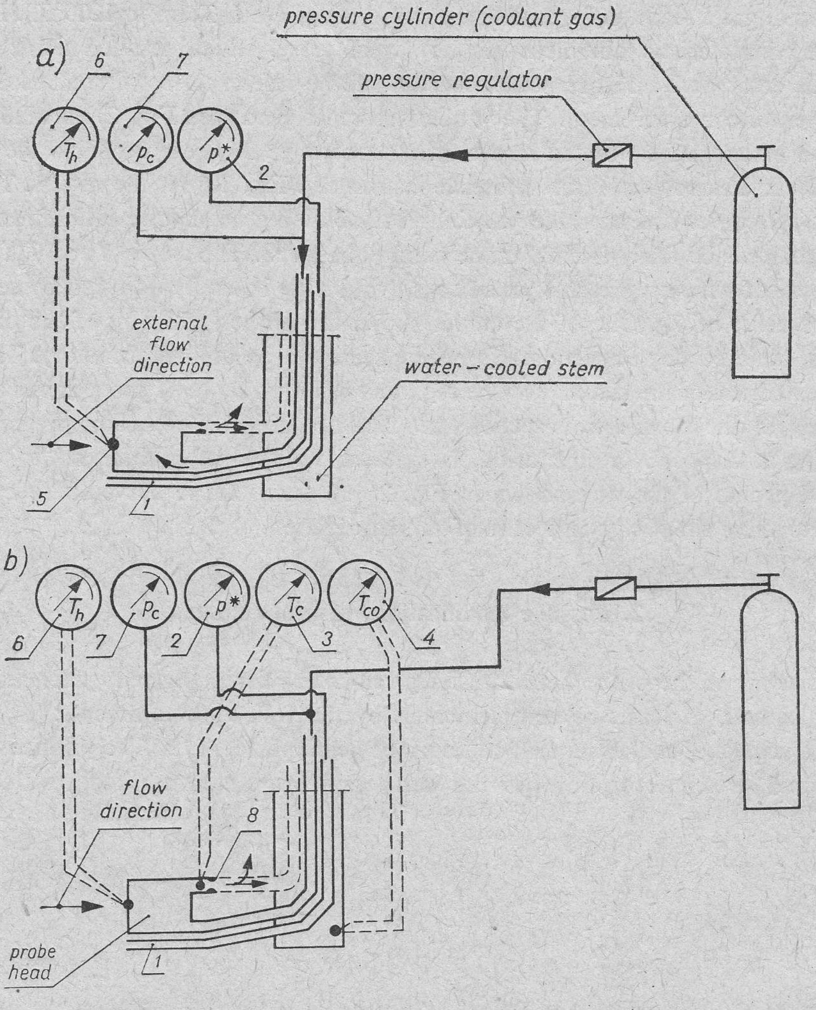

Fig. 4a. Diagrammatic arrangement of a probe with total pressure measurement. b. Probe modification allowing to analyze the probe heat balance

1 – total pressure measuring conduit, *2* – total pressure meter (external flow), *3* – measurement of coolant gas temperature ahead of the nozzle – T_c, *4* – measurement of coolant gas temperature at inlet to probe head – T_{co}, *5* – point of probe head temperature measurement, *6* – probe head temperature meter, *7* – coolant gas pressure meter, *8* – nozzle

— The smallness of conduction term, assumed when having written eq. (2), requires probe design where the contact between the probe head and supporting element is minimized; excessive conduction leads to intolerable corrections.

— A proper analysis of the probe heat transfer would be possible under condition that further information on the flux of heat extracted by internal cooling are collected. The internal cooling flux may be expressed as

$$\dot{q}_{[\text{int. cooling}]}=\alpha_i \cdot A_i \cdot \Delta T_i, \tag{7}$$

where α_i — internal heat transfer coefficient, A_i — internal heat transfer area, ΔT_i — coolant gas to internal wall temperature gradient.

Both α_i and ΔT_i seem to be hardly pre-determinable due to obvious difficulties connected with the specification of internal flow pattern, the probe head body temperature distribution etc. If the probe head interior behaves as a plenum, the value of α_i will be governed by wall to coolant conduction. A choice of optically non-transparent gas as the coolant may make this process radiation-controlled. In conclusion, we are dealing here with a non-conventional problem of complex heat transfer with a broad range of gas density variation, in which no quantitative assessment can be made on the basis of (7). The examination of probe behaviour may be started by measuring the quantities T_c and T_{co} appearing in (3). A corresponding probe modification is shown schematically in Fig. 3. It requires additional sensors to read the coolant temperature at inlet T_c and outlet T_{co} of the probe head. Probable difficulties connected with the measurement of T_c can be avoided if, instead of T_c, an independent measurement of $\dot{m}_c$ in the supply line is taken (by pressure cylinder weighing or a critical flow-meter) since T_c may be eliminated when employing (3) and (4) simultaneously.

– The heat transfer coefficient α_i appearing in (5) involves a rather complex dependence on temperature T_g via the material properties of hot gas (c_p, k, μ), but in the first place it depends on the external stream velocity (Reynolds number). Therefore a very useful modification of the probe will consist in furnishing it with an orifice and conduit designed for measuring the stream total pressure p_g^*, as sketched schematically in Figs. 4a and b.

Summarizing the above remarks we may state that the necessity of probe calibration may be reduced or eliminated on cost of greater complexity of the construction. The properties of the probe variants mentioned above may be listed as follows:

Probe modification	Measured quantities	Necessity of calibration	Quantities determined from accompanying measurements and material properties
1	2	3	4
after Fig. 2	p_c T_h	in a stream of known velocity and temperature T_g	static pressure p_g wall or environment temperature T_{wall} viscosity μ_g thermal conductivity k_g specific heat c_{pg} probe head recovery coefficient r coolant specific heat c_{pc}
after Fig. 4	p_c T_h p_g	in a stream of known T_g	
after Fig. 5	p_c T_h p_g^* T_c(or $\dot{m}_c$) T_{co}	–	

A variety of layouts of the probes employing the considered "variable density cooling" principle may be invented, including modes of operation other than the suggested one where T_h=const, different methods of measuring the quantities listed in column 2, etc. Also different approaches are possible to the problem of intensification of the internal heat transfer, aimed at coolant flow reduction. At the very end of these possibilities is a probe with coolant supplied in liquid phase to the head and vaporized completely ahead of the nozzle, which would lead to extreme growth of the capability of heat extraction.

3. Conclusions

A principal reason for drawing attention to the probes of the suggested type is simplicity of the working principle, allowing to determine some thermal properties of a hot gas jet from a manometer reading. Employed either as a heat flux change indicator or as a temperature indicator, the probe seems to be suited especially for examining non-uniform temperature fields in hot flows of sufficiently large transversal dimensions. Further miniaturization seems feasible; from the presented probe variants the one comprising total pressure measurement (Fig. 4a) may be recommended in the first place.

The results given are provisional, and further investigations are indispensable in order to make the probe behaviour fully predictable, to check the working temperature and velocity ranges etc.

Since these investigations do not fit to the program of his mother research organization, it is believed by the author that the suggested method may find application in other laboratories.

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Krytyczny przepływ gazu chłodzącego jako zasada działania sond do stykowego pomiaru temperatury całkowitej gorących strug gazowych

Streszczenie

W opracowaniu omówiono zasadę działania sond do stykowego pomiaru wysokich temperatur strumienia gazu, polegającą na pomiarze zmiennego natężenia przepływu czynnika gazowego chłodzącego sondę. Gaz chłodzący czułkę sondy doprowadzony jest do wnętrza czułki pod regulowanym ciśnieniem i wypływa przez wbudowaną w nią dyszę o nadkrytycznym spadku ciśnienia. Wykorzystanie zależności dla przepływu krytycznego umożliwia, przy odpowiednim wzorcowaniu, budowę przyrządów pomiarowych, w których podstawową wielkością mierzoną bezpośrednio jest ciśnienie gazu chłodzącego. Granice zmian natężenia przepływu gazu wyznaczane są przez przekrój przelotowy dyszy i rozporządzalne ciśnienie zasilania. Czułka sondy jest miniaturowym naczyniem ciśnieniowym, a jednocześnie wymiennikiem ciepła gaz — gaz; sondę zaliczyć należy do grupy przyrządów mierzących szybkość wymiany ciepła. Zaletą proponowanej metody pomiaru [4] jest prostota pomiaru i możliwość miniaturyzacji sond wprowadzanych do strumienia będącego obiektem pomiaru. Wyniki prób sond wskazują na możliwość ich stosowania dla temperatur całkowitych 2000 - 3000°K.

Metoda wydaje się szczególnie przydatna do pomiaru lokalnych wartości temperatury (entalpii) całkowitej w polu o znanym kierunku prędkości.

Критическое течение охлаждающего газа как основа действия зондов для контактного замера температуры торможения горячих газовых струй

Резюме

В работе обсуждается принцип действия зондов для контактного замера высоких температур потока газа, основанный на замере переменного расхода газовой среды, охлаждающей зонд. Газ, охлаждающий датчик зонда, подается внутрь зонда под регулируемым давлением и вытекает через встроенное в датчик сопло для сверхкритического перепада давления. Использование зависимости для критического истечения позволяет, при соответствующей юстировке, строить измерительные приборы, в которых основной непосредственно замеряемой величиной является давление охлаждающего газа.

Пределы изменений расхода газа определяются полем поперечного сечения сопла и располагаемым давлением питания. Датчик зонда является миниатюрным напорным сосудом и одновременно теплообменником „газ — газ”. Зонд следует зачислить в группу приборов, замеряющих скорость теплообмена. Достоинством предлагаемого измерительного метода [4] являются простота замера и возможность миниатюризации зондов, вводимых в поток являющийся объектом замера. Результаты испытаний зондов указывают на возможность и применения для замера температур торможения порядка 2000 - 3000°K.

Метод кажется быть особенно пригодным для замера местных значений температуры (энтальпии) торможения в поле с известным направлением скорости течения.