

THE TREATMENT OF CALIBRATIONS OF TOTAL AIR TEMPERATURE PROBES FOR USE IN FLIGHT-TEST ANALYSIS WORK

1. NOTATION AND UNITS

		SI	British
A, B	constants supplied by probe manufacturer for the step response of a dual time constant probe, see Appendix B		
C_{p_L}	local pressure coefficient on airframe surface at total temperature probe station, $(p_{s_L} - p_a)/0.7\rho_a M^2$		
E	electrical power rating of temperature probe element	mW	mW
f	denotes functional relationship of type $f[.....]$		
f_{shock}	total pressure loss factor for the airframe-generated shock upstream of total temperature probe at $M > 1$		
H_p	pressure height	m	ft
k	ratio of effective step change of air temperature at probe element to step change of air temperature input to probe ($k < 1$), see Appendix B		
M	Mach number of aircraft		
M_L	local Mach number at edge of airframe boundary layer on aircraft at total temperature probe station in the absence of the probe		
p_a	ambient static pressure*	N/m ²	lbf/ft ²
p_p	fully corrected value of pitot pressure* in pitot system for steady-level-flight conditions	N/m ²	lbf/ft ²
p_{s_L}	static pressure* on airframe surface at total temperature probe station	N/m ²	lbf/ft ²
p_t	total (or isentropic) pressure*, $p_a(1 + 0.2M^2)^{3.5}$	N/m ²	lbf/ft ²
p_{t_L}	total pressure* at total temperature probe station	N/m ²	lbf/ft ²
r	overall recovery factor for total temperature probe for $M \leq 1$, (= $[(T_r/T_a) - 1]/0.2M^2$)		
r'	effective recovery factor for total temperature probe for $M > 1$		
T_a	ambient temperature	K	K
T_{int}	"intermediate" temperature of air at the probe element; for a step increase in T_t , $T_{ss} < T_{int} < T_t$, see Appendix B	K	K

For footnote see end of Notation.

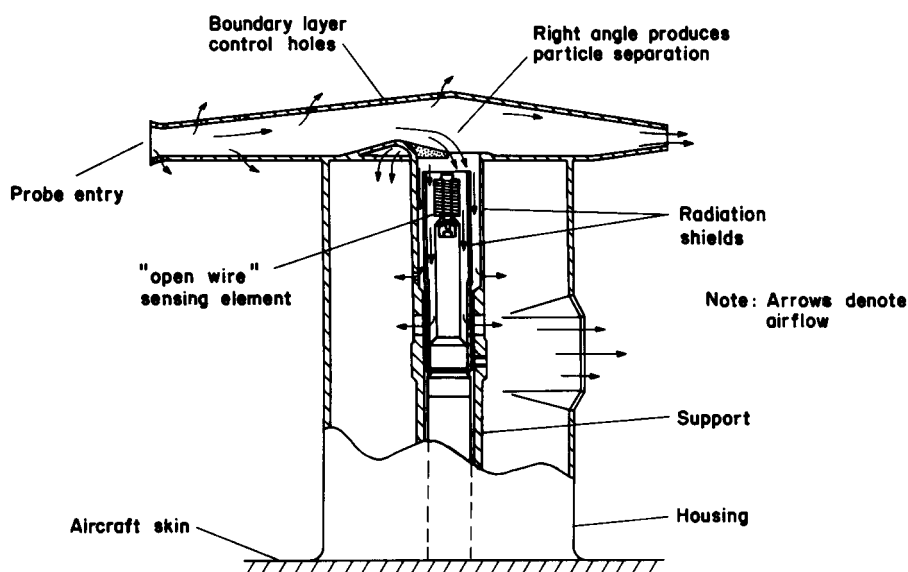
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T_r	temperature registered by an ideal total temperature probe (recovery temperature) or value after correction for probe errors	K	K
T_{r_i}	temperature registered by a total temperature probe and subject to the correction processes given in this Item	K	K
T_{ss}	temperature of probe-element support structure, radiation shield, <i>etc</i>	K	K
T_t	true total temperature, $T_a(1 + 0.2M^2)$	K	K
t	time from start of temperature “ramp” or from time of step change of temperature	s	s
α	angle of attack (angle between projection of true airspeed vector on to aircraft plane of symmetry and angle of attack datum)	deg	deg
β	angle of sideslip (angle between true airspeed vector and its projection on to aircraft plane of symmetry)	deg	deg
γ	ratio of specific heat capacity at constant pressure to that at constant volume (taken as 1.4 for air, but see Section 2)		
$\Delta T_{r_i}, \Delta T_t$	changes in temperatures T_{r_i} and T_t from those at time, $t = 0$	K	K
δT_r	contribution to error in temperature registered by probe	K	K
λ	time constant for an ideal, first-order linear system	s	s
λ_1	time constant for the probe element, measured in isolation	s	s
λ_2	time constant for the probe-element support structure, radiation shield, <i>etc</i>	s	s
λ_T	effective lag time constant for total temperature probe	s	s
η_T	total temperature recovery error, $(T_t - T_r)/T_t$		

Subscripts

lag	denotes lag error
rad	denotes radiation error
sh	denotes self-heating error
$t = 0$	denotes conditions at time $t = 0$
0	denotes conditions at sea level in the International Standard Atmosphere, ISA

* Note that these pressures are absolute.



Sketch 1.1 Typical flight-test standard total air temperature probe (non-deiced)

2. INTRODUCTION AND SCOPE

True values of total temperature are of prime importance for most aspects of flight testing associated with the performance and airworthiness certification of an aircraft. For flight-test work these values must be derived from the temperatures registered by a total air temperature probe such as that shown in Sketch 1.1 and so are subject to systematic* errors associated with the probe and its installation on the aircraft. However, while manufacturers' data for total air temperature probes give information concerning the errors in temperature sensing, this information is often restricted to laboratory conditions or the data are not presented in a form suitable for practical application. This Item is concerned with any further treatment of such data that may be required to ensure they apply to flight conditions.

Section 3 describes the information on the principal errors which is supplied by the probe manufacturer. These are the recovery error, η_T , and its related recovery factor, r , the radiation error, $(\delta T_r)_{rad}$, the self-heating error, $(\delta T_r)_{sh}$, and the lag error, $(\delta T_r)_{lag}$. Corrections for errors such as these have to be applied to the temperature, T_{r_i} , registered by a probe so that a true value of total temperature, T_t , may be derived. Section 4 is concerned with the methods of correcting probe errors and calibrations to flight conditions. It also presents the solution for a dual time constant response equation for a probe experiencing a linear rate of change of temperature with time.

Section 5 is concerned with correcting the errors dealt with in Sections 3 and 4 so that true values of total temperature may be obtained. Appendices A and B treat the detailed technical aspects of the derivation of local Mach number, M_L , and the response of a probe to non-steady temperatures.

In this Data Item the value of γ is assumed to be $\gamma = 1.4$. While this is acceptable for total temperatures up to about 400 K, variations in the value of γ are to be expected at higher temperatures. The conditions arise for $M > 4$, approximately, and for such cases the changes needed to the general process of analysis for deriving T_a are given in Data Item Nos 83029 and 88025 (References 7 and 9).

* Random errors are outside the scope of this Item and are considered in References 4 and 5. Errors associated with differences between individual probes of the same model ("interchangeability errors") may be avoided by calibrating each probe, see Reference 6. In addition, the random errors due to flight-test data scatter may be reduced by data smoothing and multiple-sampling techniques. Where such calibrations and techniques are used the residual errors arising from all sources should not exceed ± 0.25 K in T_{r_i} .

The probe illustrated in Sketch 1.1 has a non-sealed (or “open-wire”) sensing element and is non-deiced (see Section 3.3). These features are of advantage in flight-test work as regards accuracy and response but imply that conditions of high humidity and/or icing risk are to be avoided by judicious flight planning.

Additional errors arising from the installation of a probe within an engine air inlet are outside the scope of this Item. Such an installation has the attraction that the probe may be insensitive to flight Mach number and sensitive only to abnormal conditions of engine airflow. On the other hand, the effect of radiation from the engine introduces an additional source of error which must be allowed for. It is also possible that the need for a more rugged probe construction – to reduce the risk of its detachment and ingestion into the engine – will result in relatively longer response times to non-steady temperatures than would otherwise be the case.

3. PROBE ERRORS AND CALIBRATIONS FROM MANUFACTURERS' DATA

Sources such as Reference 4 deal very comprehensively with these errors and calibrations. For the purposes of this Item the main errors experienced when using a total air temperature probe are described in Sections 3.1 to 3.4.

3.1 Recovery Error, η_T , and its Related Recovery Factor, r

The recovery error, η_T , as defined by the probe manufacturer, is

$$\eta_T = (T_t - T_r)/T_t. \quad (3.1)$$

However, for the method of this Item its related recovery factor, r , is used, where,

$$r = 1 - \eta_T \left[1 + \frac{5}{M^2} \right]. \quad (3.2)$$

Note that the definition of Equation (3.2) is consistent with the widely-used relationship

$$T_r = T_a \left[1 + \frac{rM^2}{5} \right]. \quad (3.3)$$

The recovery factor, r , is the proportion of the full adiabatic temperature rise which is registered by the probe and, for a high-efficiency probe mounted outside the airframe boundary layer, is usually between 0.90 and 0.99. These values are for flow directions that are less than about 10 deg relative to the axis of symmetry of the probe forebody. In general, larger angles would be encountered only at low speeds and especially on aircraft capable of vertical flight. The recovery factor tends to be constant for speeds below $M = 0.7$ to 0.8 and increases to values near to unity at high supersonic Mach numbers, *i.e.* $r = f[M]$ in general, see Section 4.1.

The location of a probe on an airframe is usually such that the probe experiences a local Mach number, M_L , which differs from the freestream value, M , and as a result corrections, considered in Section 4.2, have to be applied. These corrections have most significance for transonic Mach numbers. When the local flow is supersonic, *i.e.* $M_L > 1.0$, a further correction has to be made to take proper account of the flow at the probe entry being downstream of a normal shock. This correction is included in the material given in Section 4.2 but an explanation of its origin (and a comparison with other methods) is given in Section 4.1.

The use of flight tests to obtain values of recovery factor is described in Reference 6 and is commented on in Section 6 here.

3.2 Radiation Error, $(\delta T_r)_{rad}$

For total air temperature probes that are fitted with effective internal radiation shields, this error only becomes significant for flight at $H_p > 40\,000$ ft and $M > 2$. For example, for a shielded probe at $M = 2.5$, $(\delta T_r)_{rad}$ is typically about -0.05 per cent of T_r at $60\,000$ ft and about -0.1 per cent of T_r at $80\,000$ ft. Probes not so equipped experience significant errors at lower heights and speeds. Values of the error $(\delta T_r)_{rad}$ are frequently presented in terms of total pressure and Mach number although one of a number of alternative forms of this functional relationship may be used, for example,

$$(\delta T_r)_{rad} = f[p_a, p_p/p_a].$$

3.3 Self-Heating Error, $(\delta T_r)_{sh}$

This error is a characteristic of the resistance thermometer used for total air temperature measurements and in which the electrical current in the measuring circuit flows through the temperature-sensing element and produces heat. The equilibrium temperature for the sensing element is thus increased and the error in temperature is a function of the air mass flow passing through the probe. It follows that the error is always positive, increases as height increases or as speed decreases and is proportional to the electrical power rating, E , of the measuring circuit. As for $(\delta T_r)_{rad}$, a number of alternative forms of the functional relationship for the calibration data may be set up. One such is

$$(\delta T_r)_{sh} = f[E, p_a, p_p/p_a].$$

Above some high subsonic Mach number, the value of which depends on the design of the probe, the air mass flow through the probe is constant so that changes in Mach number (or p_p/p_a) do not further affect the error.

Self-heating error may be negligible for power ratings below 5 mW, typical of galvanometer instrumentation and of servo-instruments. However, the error will be important for ratiometer instrumentation where the power rating may exceed 40 mW. Typical values for this error would be around 0.01 K/mW for sea-level conditions and about 0.04 K/mW for $60\,000$ ft.

While non-deiced probes are advantageous for flight tests (see Sketch 1.1), many production aircraft use probes with integral deicing. The heat used to keep the probe ice free introduces a further source of error and this must be corrected using data supplied by the manufacturer or measured in a wind tunnel.

3.4 Probe Response to Non-Steady Conditions

When T_t varies with time the temperature, T_{r_i} , registered by the probe lags behind the input. For flight-test conditions of value for analysis the variation with time may be taken as linear or as a series of segments with $(dT_{r_i}/dt) = \text{constant}$. However, in general, the response of a probe to non-steady conditions is presented by probe manufacturers in terms of the response to a step change in input total temperature.

3.4.1 Representation of probe response as a first-order linear system

For some probes the response may be assumed with negligible error to be that of an ideal first-order linear system so that at all times the instantaneous relationship between “input” and “output” temperature is completely defined by a **time constant**, λ , where

$$\lambda = \frac{T_t - T_{r_i}}{dT_{r_i}/dt}. \quad (3.4)$$

This subject is dealt with in many sources such as References 1 and 4. The usual response equations for a probe which closely approximates a first-order linear system, for particular variations in input total temperature, are as follows.

For a step change, ΔT_t , in input total temperature the temperature lag error is given by a response equation having a single term, *i.e.*

$$\frac{(\delta T_r)_{lag}}{\Delta T_t} = -e^{-t/\lambda_1} \quad (3.5)$$

where λ_1 is, in effect, the time constant of the probe element alone. See Sketch 4.1 for a graphical presentation.

For a “ramp” change in input total temperature, with $dT_t/dt = \text{constant}$, the lag error, after the decay of the initial transient (*i.e.* after, say, $5\lambda_1$), is for practical purposes given by

$$(\delta T_r)_{lag} = -\lambda_1(dT_t/dt) = -\lambda_1(dT_{r_i}/dt), \quad (3.6)$$

i.e. the output lags the input by a constant time interval so that $(dT_{r_i}/dt) = (dT_t/dt)$. Thus, for this type of system the “effective lag time constant”, λ_T , required in the method of Reference 7 is given by $\lambda_T = \lambda_1$.

Values of λ_1 are dependent on probe design, the type of element housing and mounting and vary with M as shown in Reference 4. For an element that is not encased in any protective material, λ_1 will be of the order of 0.025 seconds whereas an encased, or sealed, element has values of λ_1 which can be two orders of magnitude greater.

3.4.2 Representation of probe response by dual time constants

Some probes are characterised by two time constants, λ_1 and λ_2 , and their response to a step change in input total temperature is governed by an equation having two terms, see Appendix B, Equations (B2.1) and (B2.2). For such probes it is shown in Appendix B that for a ramp change in input total temperature an “effective time constant”, λ_T , may be defined such that the lag error is given by

$$(\delta T_r)_{lag} = -\lambda_T(dT_{r_i}/dt). \quad (3.7)$$

However, depending on the particular case considered, the value of λ_T in Equation (3.7) may not be unique and independent of the variation of input total temperature. This problem is considered in Section 4.3.3 and Appendix B where it is shown that

$$\lambda_T = f[A, t, \lambda_1, \lambda_2].$$

4. CORRECTION OF TEMPERATURE PROBE ERRORS AND CALIBRATIONS TO FLIGHT CONDITIONS

4.1 Effect of Supersonic Flow on Recovery Factor for an Isolated Probe

For an isolated probe in supersonic flow, *i.e.* $M > 1.0$, a normal shock is positioned at or close to the probe entry. The probe is then operating in subsonic flow but at a total temperature appropriate to the freestream (since there is no loss of total temperature through a shock). As an example of the subsonic velocity behind a normal shock, a value of $M = 1.5$ results in a Mach number of 0.7, approximately, at the probe entry.

For such conditions it is convenient to use an effective recovery factor, r' , which allows for the greater effective efficiency of temperature recovery brought about by the action of the shock. Reference 1 shows that for $M > 1.0$ the effective recovery factor, r' , is related to the value of the recovery factor r at $M = 1.0$ by the relationship,

$$\frac{1 - r'}{1 - r} = \frac{\left[1 + \frac{2\gamma}{(\gamma + 1)}(M^2 - 1)\right] \left[1 + \frac{(\gamma - 1)}{2}M^2\right]^2}{\frac{(\gamma + 1)}{2}M^4 \left[\gamma M^2 - \frac{(\gamma - 1)}{2}\right]} \quad (4.1)$$

Using the value $\gamma = 1.4$, this may also be expressed in the form,

$$r' = 1 - (1 - r) \frac{(5 + M^2)^2}{36M^4} \quad (4.2)$$

where, again, r is the value of the recovery factor at $M = 1.0$. (For $M = 1.0$, Equations (4.1) and (4.2) simplify to give $r' = r$ and this identity holds for all subsonic values of M .)

Note that in applying the relationship of Equations (4.1) and (4.2) to a probe installed on an aircraft, it is necessary to consider the local Mach number at the probe and not the freestream value, see Section 4.2.

Some manufacturers' data suggest $\eta_T = \text{constant}$ for supersonic Mach numbers. However, such an interpretation is incorrect because at very high Mach numbers nearly all the temperature rise occurs at the shock and takes place at 100 per cent efficiency. For example, for a typical high-efficiency probe $\eta_T = 0.004$ at $M = 1.0$ so that, from Equation (3.2), $r = 0.9760$ at the same value of M . If η_T were taken as constant, then Equation (3.2) would give values of r as shown in the first line of the following table. If, on the other hand, Equation (4.2) is used (with $r = 0.9760$ at $M = 1.0$) to calculate r' , the values shown on the second line of the table are obtained. To emphasise this point, the final line of the table shows the decrease in the values of η_T with M deduced by solving Equation (3.2) for η_T with r replaced by the values of r' from the table.

M	=	1.0	1.4	1.8	2.2	2.6
For $\eta_T = 0.004$, Equation (3.2) gives, $r =$		0.976 0	0.985 8	0.989 8	0.991 9	0.993 0
For $r = 0.9760$, Equation (4.2) gives, $r' =$		0.976 0	0.991 6	0.995 7	0.997 2	0.998 0
For values of r' , above, Equation (3.2) gives, $\eta_T =$		0.004 0	0.002 4	0.001 7	0.001 4	0.001 1