CONTENTS

	Page
ABSTRACT	1
NOMENCLATURE	1
INTRODUCTION	2
SUMMARY	2
Conclusions	4
Recommendations	4
APPLICATION AREAS	4
RAREFIED GAS EFFECTS	5
Calculation of Knudsen Number	5
Application to Fluid Temperature Sensor	6
MATERIAL EXPLORATIONS	13
Carbon/Carbon Composites	13
Oxidation of Unprotected Carbon/Carbon and Barrier Considerations	13
Coefficient of Thermal Expansion Considerations	14
Application of Carbon/Carbon to the Temperature Sensor	15
Ceramic Matrix Composites	17
Toughness Considerations	17
Creep Resistance	18
Fatigue	19
Oxidation	19
Strength	19
Material Candidates	20
Long Term Material	20
Materials For Short Term Use	21
Refractory Metals	23
PRESSURE TRANSDUCERS	24
Piezoelectric Transducers	24
Potential Suppliers and Products	24
Solid State Transducers	25

Page

ANALYTICAL TIME RESPONSE STUDIES 25
Time Response 25
Dissociation Effects 29

FABRICATION CAPABILITIES 34
Lockheed Missiles and Space Co. Inc. 34
Rosemount Inc., Aerospace Division 34
Schlumberger Industries, Aerospace Division 35
TSI Incorporated 35
Volna Engineering 35

CONCLUSIONS 36
Pressure Transducers 36
Materials 36
Rarefied Gas Effects 36
Fabrication Capability 37

APPENDIX A - Fluid Temperature Sensor: A Brief History A-1

APPENDIX B - References B-1

APPENDIX C - Sources of Carbon/Carbon Composites C-1

APPENDIX D - Pressure Transducer Manufacturers D-1

APPENDIX E - Bibliography E-1

ILLUSTRATIONS

Figure		Page
1	Knudsen Number vs Altitude and Mach Number	12
2	3-D Carbon/Carbon Orthogonal Weave	16
3	4-D Carbon/Carbon Hexagonal Weave	16
4	5-D Carbon/Carbon Weave	16
5	Ceramic Composite Stress/Deflection	18
6	Temperature Sensor Flow Calibration Curve	27
7	Fluid Temperature Sensor Time Response Variation With Temperature	28
8	Fluid Temperature Sensor Time Response Variation With Pressure	30
9	Fluid Temperature Sensor Time Response Variation With Heat Transfer Coefficient	31
10	Fluid Temperature Sensor Time Response Monatomic and Diatomic Gases	32
11	Calculated Speed of Sound Functions	33

TABLES

1-A	Knudsen Number: Mach Numbers 1.0 and 2.0	8
1-B	Knudsen Number: Mach Numbers 3.0 and 4.0	9
1-C	Knudsen Number: Mach Numbers 5.0 and 10.0	10
1-D	Knudsen Number: Mach Numbers 15.0 and 20.0	11
2	Comparison of Selected Ceramic Reinforcements and Composites	22

ABSTRACT

Under a NASA Dryden-sponsored contract in the mid 1960s, temperatures of up to 2200 °C (4000 °F) were successfully measured using a fluid oscillator. The current program, although limited in scope, explores the problem areas which must be solved if this technique is to be extended to 10,000 °R. The potential for measuring extremely high temperatures, using fluid oscillator techniques, stems from the fact that the measuring element is the fluid itself. The containing structure of the oscillator need not be brought to equilibrium temperature with the fluid for temperature measurement, provided that a suitable calibration can be arranged. This program concentrated on review of high-temperature material developments since the original program was completed. Other areas of limited study included related pressure instrumentation requirements, dissociation, rarefied gas effects, and analysis of sensor time response.

NOMENCLATURE

°C	degrees Centigrade
C^*	constant in thermal response calculation (defined in text)
C_p	specific heat of a gas at constant pressure
C_v	specific heat of a gas at constant volume
°F	degrees Fahrenheit
K	Knudsen number
K^*	constant in thermal response calculation (defined in text)
M	Mach number
°R	degrees Rankine
Re	Reynolds number
T	temperature
a	speed of sound
d	a characteristic dimension
e	base of natural logarithms
p	pressure
t	time
γ	ratio of specific heats, C_p/C_v
λ	mean free molecular path
ρ	gas density
τ	time constant
μ	gas viscosity

Subscripts

0	free-stream conditions
2	conditions behind normal shock
in	characteristic of gas entering temperature sensor
m	characteristic of gas inside temperature sensor
t	total (pressure, temperature)

INTRODUCTION

This program is, in a sense, a continuation of NASA effort begun more than 25 years ago. At that time, interests within NASA saw need for a temperature sensor to measure very high total temperatures in compressible gases. NASA Dryden sponsored a program with Honeywell Inc. which produced instrumentation, based on fluidic techniques, capable of measuring to a level of 2200 °C (4000 °F). For a more complete introduction to the current program a short history of the earlier NASA program is included as Appendix A.

The current program focused on the problems to be solved if this technology is to be taken to temperatures of approximately 5500 °C (10,000 °F). The most difficult area is that of material followed closely by the pressure transducer technology required to get pressure pulse signal out of the fluidic other concerns, regarding dissociation and continuum flows in rarefied environments, were explored by a limited analysis.

SUMMARY

The fluid temperature sensor is unique in that, for gaseous fluids, the fluid itself is the measuring element. As a result it is not necessary for any solid material to be brought to ultra high temperatures to accomplish a measurement. The oscillation frequency of a fluid oscillator is very nearly a linear function of the square root of the absolute temperature of the gas flowing through it. In the mid-1960s, NASA sponsored a development program which successfully measured air temperatures of 2200 °C (4000 °F) using this technology. The current program explored major questions relative to applying this technique to measure temperatures of 5538 °C (10,000 °F). Measurement of temperatures of this magnitude may be possible because the temperature gradient between the flowing fluid and survivable material temperatures is accomplished across the boundary layer of the gas.

The major objectives of this program as defined in the statement of work were:

* Define NASA areas of application for measuring ultra- high temperatures as a guide for developing a design specification
* Review progress in the development of materials for use at high temperatures
* Review developments in the field of high temperature, high frequency pressure transducers
* Explore effect of dissociation and rarefied gas effects on performance of the fluid temperature sensor

* Define potential sources for fabricating experimental temperature sensor.

NASA requirements for an ultra-high temperature sensor were explored during discussions with research personnel at Ames and at Dryden. The nature of research at both facilities demands that materials and technology chosen for an advanced capability temperature sensor must be capable of operation in an oxidizing environment. There was common interest in the rapid time response that is characteristic of the fluid temperature sensor. While measuring capability to 2500 °C (4500 °F) is adequate for materials research, re-entry instrumentation needs a 10,000 °R capability. Mach 10 in a standard atmosphere produces total temperatures in the 8,000–10,000 °R range. Considering other potential applications in the propulsion field, all NASA users work in an oxidizing atmosphere.

Materials for fabricating a 10,000 °R sensor are a difficult problem. Carbon/carbon is an attractive but disappointing option. While carbon increases in strength to temperatures of approximately 2200 °C (4000 °F), it begins to vaporize at about 425 °C (800 °F). Some refer to it as "frozen smoke." The structural properties of carbon/carbon have spurred a great deal of work on protective coatings but no really successful coating has been developed for the oxidizing, thermal cycling environment required for temperature sensor applications.

Ceramic matrix composites present even more complex problems. The conventional considerations of strength, fatigue, bending modulus and creep resistance remain important. In addition, thermochemical compatibility between the ceramic matrix material and the reinforcing fibers comes into play. Because of the rigors of an oxidizing environment, most non-oxide materials require oxide protection systems as with carbon, especially after microcracking begins in the matrix material. As a practical matter, because of oxidation problems, potentially useful ceramics for temperature sensor fabrication are mainly limited to oxide/oxide (oxide reinforcing fibers in an oxide matrix) composites.

Pressure transducers with high frequency capability have made limited progress since the earlier NASA programs. Threshold levels and resolution have been improved. However, high temperature capability, as required for temperature sensor applications, has receded somewhat. This has occurred because, by placing emphasis on ease of use, some manufacturers are incorporating amplifier circuitry into the transducer body. This limits the operating temperature to the capability imposed by the semiconductor materials rather than the limit of the basic piezoelectric element (quartz for example). Although basic transducers are still available, the high temperature "special use" versions used previously, are no longer available.

Dissociation effects will become important somewhere in the temperature region of 2800 °C (5000 °F) and above. A limited analytical study of the dissociative effect was made by comparing the speed of sound in a gas, with γ = constant and with γ computed from tabular values in reference 1, up to 6400 °R. At this temperature, with this data source, no dissociative effects were evident. More work, with experimentally determined real gas parameters at higher temperatures, is required to adequately define the dissociative effects.

The Cuyuna Corporation has only limited capability to fabricate and test experimental temperature sensors. Discussions with several instrumentation manufacturers have determined that one major manufacturer of airborne total temperature sensors is interested in cooperating with Cuyuna in developing an advanced version of the basic sensor design. Another large aerospace company has offered a cooperative effort on material development.

Conclusions

Since transducer technology has not advanced relative to high temperature capability, effective cooling will be required to get information out of the sensor via pressure sensing techniques.

Material developments have not advanced high temperature materials to a level which will permit the fabrication of an fluid temperature sensor whose oscillation cavity operates at 5,500 °C (10,000 °F) without cooling. It may be possible to build a simple, uncooled oscillator cavity for long term operation up to 1650 °C (3000 °F). For 5–10 hour life in a cycling environment some materials may allow use of an uncooled cavity to temperatures of approximately 1900–2200 °C (3500–4000 °F).

For measurements to 10,000 °F, designs based on refractory metals, having reasonable oxidation resistance, should be explored. High thermal conductivity combined with efficient cooling of the oscillator cavity may offer the best hope for an ultra-high temperature sensor based on fluid techniques.

Recommendations

Reproduce a sensor design developed under the earlier program but using high temperature materials developed by NASA Ames material developers. Objective: reestablish the technology base and evaluate fabrication techniques needed for advanced materials.

Design a sensor cavity from a refractory metal and incorporating extensive cooling passages. Evaluate, by analysis, the feasibility of rejecting enough heat to sustain cavity surfaces to temperatures below serious oxidation levels. Conduct experimental verification. Objective: determine the potential for heat transfer techniques to support a 10,000 °F sensor for long term use.

Explore potential materials and fabrication methods with the aerospace firm which has offered to participate in a cooperative effort. Objective: obtain better, first hand knowledge of material capability and to determine suitability of various high temperature materials for diffusion bonding.

Begin a search for an oscillation detection technique which overcomes the limitations of pressure port length and temperature capability imposed by pressure transducers.

APPLICATION AREAS

Discussions with personnel at NASA Dryden Flight Research Facility and NASA Ames Research Center isolated the following application areas:

Supersonic Flight Test and Research

Atmospheric Reentry Measurements

Propulsion System Measurements

Wind Tunnel Applications (Free Stream and Boundary Layer)

Arc Tunnel Measurements Materials Research

Each of these areas has its own operational environment and related requirements. In general, the flight research application seeks the highest possible temperature capability while other measurement capabilities are more restricted and better defined physical constraints. Research

applications can also tolerate more “care and feeding” such as auxiliary cooling and pretest calibration.

Flight applications carry the usual, well defined, needs for resistance to shock, vibration etc. with pressure and temperature ranges determined by the flight envelope of the vehicle. For manned vehicles, the temperature sensor can usually be constructed using the same materials or techniques as the vehicle itself. Since the sensor is small and has no moving parts, it can be relatively massive in external configuration giving it ruggedness, strength and thermal mass without adding significant weight to a flight system. Reentry systems could possibly be designed to survive on energy sinking techniques relying only on the thermal mass of the instrument. Measurements for longer flight applications might consider periodic measurements with an extending and retracting probe with cooling applied during the retracted phase.

Wind tunnel interests expressed a need for high temperature boundary layer profile measurements which brings consideration of miniaturization and vertical cascades of individual sensors. This leads to rarefied gas considerations, i.e., the mean free path of the gas molecules relative to the size of the instrument.

The operating environment is largely oxidizing, whether in the flight atmosphere, the wind tunnel or in the propulsion setting. This severely restricts the choice of materials and requires that otherwise promising material candidates, carbon/carbon composites for example, be protected with oxidation resistant coatings.

RAREFIED GAS EFFECTS

The expressed need for reentry instrumentation and for miniaturized sensors for boundary layer measurements led to the following limited exploration of real gas effects.

Reentry conditions and flight at very high altitudes is often conducted at high Mach number which results in extremely high gas temperatures. Typically, at Mach numbers of approximately 6 and above, so called “real gas effects” come into play. At the related elevated temperatures, molecular vibration, dissociation and ionization effects become important. A rigorous discussion of these issues is beyond the scope of this program; however, a limited analysis, dealing with mostly with low density effects, was conducted for the purpose of shaping the general problem areas. As a result, conclusions from this analysis should recall the limitations and be used with care.

Calculation of Knudsen Number

The aerodynamic and heat transfer effects encountered in a flow field change when the gas no longer acts as a continuous medium and the molecular character of the gas becomes important. In general, this occurs when the mean free path, γ, of the molecules is of the same order of magnitude as some characteristic dimension in the system. This condition is sometimes described in terms of the Knudsen number, K, defined as:

$$K = \frac{\lambda}{d}$$

Knudsen number can be expressed in terms of the more familiar aerodynamic parameters, Mach number and Reynolds number.

$$M = \frac{V}{a} \quad \text{and} \quad Re = \frac{Vd\rho}{\mu}$$

where:

V = gas velocity

ρ = gas density

μ = gas viscosity.

Combining these relationships with kinetic theory gives:

$$\mu = \frac{1}{2} \rho \lambda a \sqrt{8/\pi\gamma}$$

and

$$K = \frac{1.25 \sqrt{\gamma} M}{Re}$$

where γ is the ratio of the specific heats of the gas.

Dividing the flow regimes in terms of Knudsen number, free molecular flow can be defined as a Knudsen number exceeding 10 and slip flow as Knudsen numbers of the order of a "few percent."(2)

Application to Fluid Temperature Sensor

Consideration was given to flight conditions within the atmosphere and for Mach numbers from 1.0 to 20.0. The Knudsen number was computed for the fluid temperature sensor using a Reynolds number based on the size of the total head port of the sensor. A spread sheet was set up to compute the various intermediate parameters as well as the Knudsen. The standard atmosphere of reference 3 was used in these computations. Because of the wide range of temperatures involved, all the commonly used "constants" were calculated as a function of temperature. These "constants" include C_p, C_v, and γ.

Data for air at elevated temperatures from reference 1 were fitted to polynomials to give the following expressions for the specific heats of air.

$$C_p = \frac{0.24275 - 1.01314'\text{E} - 04 * T + 1.35025'\text{E} - 07 * T^2}{1 - 3.335989'\text{E} - 04 * T + 4.4793'\text{E} - 07 * T^2 - 3.105338'\text{E} - 12 * T^3}$$

$$C_v = \frac{0.1742 - 7.36565'\text{E}{-}05 * T + 1.04694'\text{E} - 07 * T^2}{1 - 3.0737'\text{E} - 04 * T + 4.457474'\text{E} - 07 * T^2 - 3.62076{-}12 * T^3}$$

$$\gamma = \frac{C_p}{C_v}$$

The total pressure as a function of Mach number is given by:

$$p_{to} = p_o \frac{1}{\left[1 + \frac{\gamma - 1}{2} M^2\right]^{\left[\frac{-\gamma}{\gamma - 1}\right]}}$$

and the total temperature by:

$$T_{to} = T_o\left[1 + \frac{\gamma - 1}{2}M^2\right]$$

If it is assumed that the temperature sensor inlet will operate behind a normal shock, the following relationships apply:

$$\frac{p_{t2}}{p_{to}} = \left[\frac{(\gamma+1)M^2}{(\gamma-1)M^2+2}\right]^{\left[\frac{\gamma}{\gamma-1}\right]}\left[\frac{\gamma+1}{2\gamma M^2-(\gamma-1)}\right]^{\left[\frac{1}{\gamma-1}\right]}$$

$$\frac{T_{t2}}{T_{to}} = \left[\frac{2\gamma M^2-(\gamma-1)}{\gamma+1}\right]\left[\frac{(\gamma-1)M^2+2}{(\gamma+1)M^2}\right]$$

$$\frac{\rho_2}{\rho_o} = \frac{(\gamma+1)M^2}{(\gamma-1)M^2+2}$$

$$M_2 = \left[\frac{(\gamma-1)M^2+2}{2\ M^2-(\gamma-1)}\right]^{\frac{1}{2}}$$

The viscosity of air was computed as a function of temperature from the following relationship:

$$\mu * 10^{10} = 0.317\ T°'R^{1.5}\left[\frac{734.7}{(T°'R + 216)}\right]$$

Atmospheric values for pressure, temperature and density were computed from the equations of reference 3. Then, using the above expressions, Knudsen numbers were calculated for various Mach numbers and altitudes. These data and intermediate values of interest are presented in tabular form in Tables 1-A, 1-B, 1-C, and 1-D for a sensor inlet opening of 0.020".

The data from these tables are plotted in figure 1, showing Knudsen number as a function of altitude and Mach number. The figure shows that the larger values of Knudsen number occur at the lower values of Mach number and the data pack very closely for Mach numbers greater than $M = 4$ or 5. This results from the assumption that the sensor will always operate behind a normal shock. Inspecting the intermediate data in the tables indicates only minor changes in M_2 beyond $M = 5$. Further, V_2 and ρ_2 conspire to hold the Reynolds number, based on sensor port dimension (0.020"), remarkably constant.

Based on the foregoing criterion for free molecular flow we see that nowhere in the altitude range to 200,000 feet and Mach number to 20 does the Knudsen number approach 10. However, the Knudsen number criterion of “a few percent” is approached for nearly all Mach numbers at altitudes in excess of 120,000–140,000 feet.

Table 1