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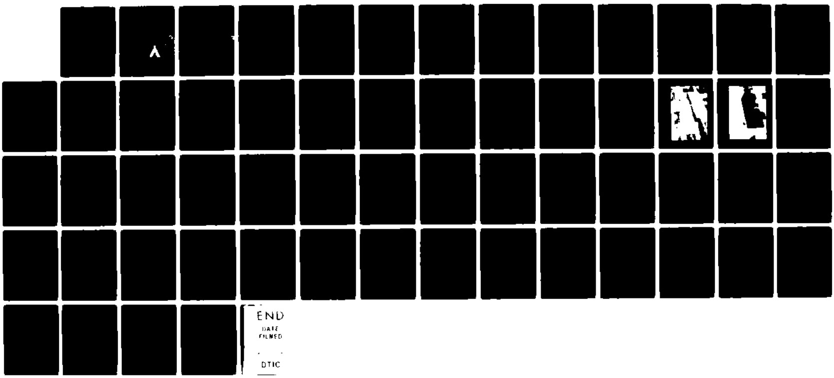

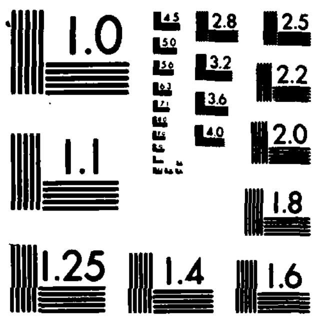

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Noise Thermometry Measurements in Combustion Processes

Artec Final Report 13-176

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Experiments are described in which the temperature of combustion gases is measured by directly sensing the thermal noise emissions from the flowing gases. The temperatures measured by the noise thermometer are compared to reference thermocouple readings. Within the limitations of the reference thermocouple and the accuracy of the noise thermometer calibration standards, the temperature determined by direct noise thermometry appears to represent the true gas temperature and is uncomplicated by con-

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20. Abstract (Continued)

taminating sources of electromagnetic noise.

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1.0 Introduction

This is the final scientific report of a program to study the application of direct Johnson noise thermometry to temperature measurement in combustion processes and products.

If successful this approach can lead to a method of non-obtrusively measuring transient temperatures in optically thick and hostile environments. The method has the additional advantage that it is free from long term calibration drift due to sensor degradation in hot corrosive and radioactive environments.

The research reported herein was begun in July 1981 and completed in September 1982.

1.1 Background

Thermal noise or Johnson noise is the noise produced by thermal agitation of charges in a conductor. The available thermal noise power produced in a resistance is independent of the nature and the value of the resistance but is proportional to the absolute temperature and the frequency bandwidth over which the noise is measured. The measurements are thermodynamically correct even in the presence of particulate matter, flow velocity and high pressure.

Indirect or immersed probe noise thermometry is an established measurement technique and has found many industrial applications (References 1, 2 and 3). For example noise thermometry is used in the nuclear industry to measure liquid metal temperatures to within a kelvin by immersing a sheathed conductor in the molten flow. The main advantage of this technique is its insensitivity to radioactive transmutation of the probe materials. These measurements are made at frequencies of less than 100 kHz and are limited in their time response by the thermal inertia of the probe.

The Soviets report direct temperature measurements of acetylene-oxygen combustion flows made in the 5 to 30 MHz frequency range (Reference 4). They describe a method of making selective measurements of temperature in different but indeterminable locations of a non-uniform plasma by varying the working frequency of their capacitively coupled noise thermometer.

In a previous program (Reference 5), Artec Associates has reported on experiments to measure the temperature of a hot quiescent gas using direct Johnson noise thermometry. Working in the 20 MHz frequency range, temperatures up to 1600 K were measured and correlated to within 1% of a thermocouple standard.

A survey of noise thermometry literature is presented in Appendix 1. This survey includes papers on the theory of thermal noise, research on the measurement of temperature by noise thermometry, and applications of both direct and indirect noise thermometry.

1.2 Research Approach

In the present program, Artec Associates extended its approach to evaluate noise thermometry in an environment of flowing combustion gases where the complications of reaction chemistry, non-uniform flow property distributions and wall effects are present.

Artec's method is to use direct noise thermometry in which the noise emissions from the hot gas itself are used to determine temperature. This is contrasted to indirect noise thermometry in which the noise emissions of a resistive element of a probe immersed in the flow are sensed. The upper limit of the direct approach is believed to be determined by the electromagnetic skin depth of the gas or plasma and is considerably higher than that imposed by material survivability considerations.

A further advantage of direct noise thermometry is that transient temperature measurements can be made. The limit to time resolution is determined by the working frequency of the noise thermometer and by noise power sensor requirements. In practice working frequency is limited to about 50 MHz by measurement difficulties associated with stray capacitances. An accurate power measurement requires about 100 cycles of signal. Thus a practical limit on time resolution is about 1 microsecond.

The Soviet measurements referred to in Section 1.1 were made using a method they describe as a contactless capacitive converter. It is a direct measure of noise temperature similar to Artec's approach but differing in the measurement technique. By measuring the 'Q' of their circuit with and without the combustion source, they obtain the real part of the source impedance. They then measure rms noise voltage with a high impedance microvoltmeter.

Alternately Artec has chosen to measure the impedance magnitude and phase of the combustion source directly and then to measure the noise power using a power sensor.

1.3 Research Objectives

The objectives of this research were to delimit the range of conditions within which Johnson noise thermometry can be applied to combustion processes and other high temperature gasdynamic environments and to identify the physical and chemical phenomena that may affect the practicality or accuracy of such measurements.

Specific goals of this research included:

* measure the highest possible combustion temperatures and the lowest possible combustion product temperatures using direct noise thermometry and correlate these to a reference standard.

* determine whether other sources of electronic noise such as electrode contact noise and noise from ongoing chemical reactions contaminate the thermal noise emissions from the gas thereby complicating or invalidating the temperature determination.

* evaluate the response of direct noise thermometry to temperature and electrical conductivity distributions within the plasma between the sensing electrodes. This includes boundary layer distri-

butions and conductivity variations within zones of chemical reactions.

1.4 Significant Accomplishments

In the experiments, a torch body affixed with a gas burner tip was used to generate a combustion flow down a thick alumina brick channel of square cross-section. Separate and independent temperature measurements were made using a contact electrode Johnson noise thermometer and a sheathed thermocouple for reference. Analysis of all of the data have indicated that this experimental arrangement was marginal primarily because of radiation effects limiting the accuracy of the reference thermocouple. Nevertheless several accomplishments resulted from this work. These are:

* temperature was successfully measured by the Johnson noise thermometer in the 1500 K to 2100 K range in both methane-oxygen and propane oxygen combustion processes. The Johnson noise temperatures fell within 6% of the temperatures independently determined by the reference thermocouple. A major source of the discrepancy is attributed to thermocouple radiation losses to the cooler channel walls.

* within the limits of the correlation no contaminating sources of noise were found to complicate or invalidate the noise thermometry measurements

at working frequencies around 10 to 15 MHz.

* the predicted response of the noise thermometer with electrode separation in a temperature distribution was verified.

* it was demonstrated that noise thermometer temperature measurements are not sensitive to distortion, melting or corrosion of the sensing electrodes.

* major sources of noise thermometry inaccuracy were identified as calibration inaccuracies of the noise measurement electronics and calibration standards.

* the impedance matching transformer was identified as a potentially limiting component in a combustion environment of widely varying electrical conductivity.

2.0 Johnson Noise and Temperature

Thermal or Johnson noise in conductors is a well known physical phenomena and is dealt with extensively in the scientific literature. A representative survey of this literature is given in Appendix 1.

In its most general form it is shown that the fluctuating emf emitted by a linear passive network at temperature T depends only on the real part of the network impedance

$$\overline{v}_S^2 = 4kT\, R_e(Z_S)\,\Delta f \qquad (1)$$

The equivalent circuit of a resistance is a thermal noise source of fluctuating voltage, v_S in series with an ideal noise free impedance, Z_S. For a given amplifier input impedance Z_L (assumed for now to be noise free) the thermal noise power appearing at the amplifier input is

$$P_L = \frac{v_L}{Z_L} = 4kT\Delta f \, \frac{R_e(Z_S)\,R_e(Z_L)}{|Z_S + Z_L|^2} \qquad (2)$$

In flow experiments such as reported herein, temperature and electrical conductivity can vary across the channel. The flow can be electrically characterized by a distribution of ideal noise voltages, noise free resistances and parallel capacitances. The real part of the interelectrode impedance which is used to compute the rms noise voltage is frequency dependent and given by

$$R_e(Z_s) = \int \phi(y)\,dy$$

$$= \int \frac{R(y)}{1+\omega^2 C(y)^2 R(y)^2} dy \tag{3}$$

where $R(y)$ = resistance

$C(y)$ = capacitance

ω = angular frequency $2\pi f$

The noise temperature calculated from $\overline{v}_s^2$ is given by

$$T_s = \frac{\int T(y)\,\phi(y)\,dy}{\int \phi(y)\,dy} \tag{4}$$

The calculated temperature is thus a resistance weighted average.

Regions in the gas between the sensing electrodes that are at different temperature and electrical conductivity will dominate the thermal noise spectrum at frequencies that maximize their contribution to the real part of the circuit impedance. Regions of non-uniform temperature can therefore be detected by varying the working frequency of the noise thermometer. However the spatial location and/ or distribution of these regions cannot be easily specified.

2.1 Experiment Overview

The elements of the experiment are shown schematically in Figure 1. The combustion source is a torch body and gas burner tip. A thick wall alumina brick channel of square cross-section (26mm by 26mm) directs the combustion flow past the temperature measurement stations.

An alumina sheathed tungsten-rhenium thermocouple is mounted such that its element can measure centerline temperature or traverse the channel for temperature distribution. Thermocouple temperature readings are made using a digital voltmeter and are corrected for ambient temperature. Survivability of the thermocouple sheath in the combustion flow limited the maximum temperatures that data could be taken to just over 2100 K.

A pair of 50mm by 25mm Inconel electrodes that sense the thermal noise emissions are mounted 25mm downstream of the thermocouple station. The electrode separation is adjustable and the electrodes can be retracted to be flush with the channel walls.

The electrodes are attached directly to an impedance transformer that approximately matches the several thousand ohm combustion gas impedance to the 50 ohm noise

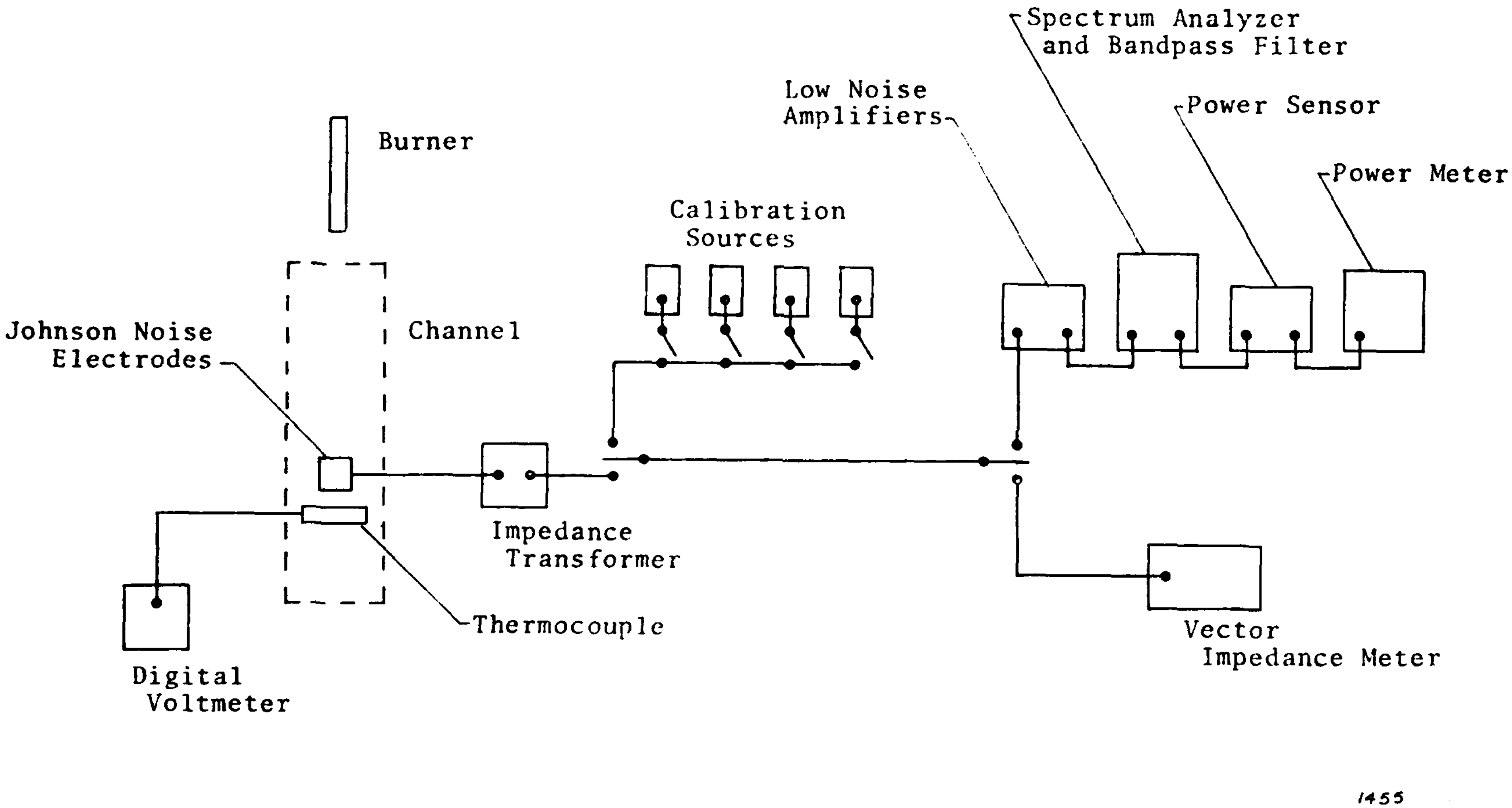


Figure 1. Elements of the Johnson Noise Combustion Experiments

measurement apparatus. The purpose of the transformer is to maintain reasonably efficient power transfer. Small residual impedance mismatches are fully accounted for in the data handling procedures.

The output of the transformer is connected directly to the noise measurement electronics which measure both the transformed interelectrode impedance and the transformed noise power. The measurement system can also be switched to view a number of calibrated impedances at known temperatures.

The combustion gas temperature is determined by an analysis of the measured combustion gas impedance, noise power and calibration data. The only assumption made in the analysis is that the impedance transformer and noise measurement apparatus behave linearly. This assumption has been experimentally verified.

The entire experimental apparatus was housed in an electromagnetically quiet room (a Faraday cage of copper screen) to minimize outside sources of contaminating noise in the megahertz frequency range.

The experimental apparatus is shown in Figures 2 and 3 and the channel layout is depicted schematically in Figure 4. The relevant specifications and dimensions of the

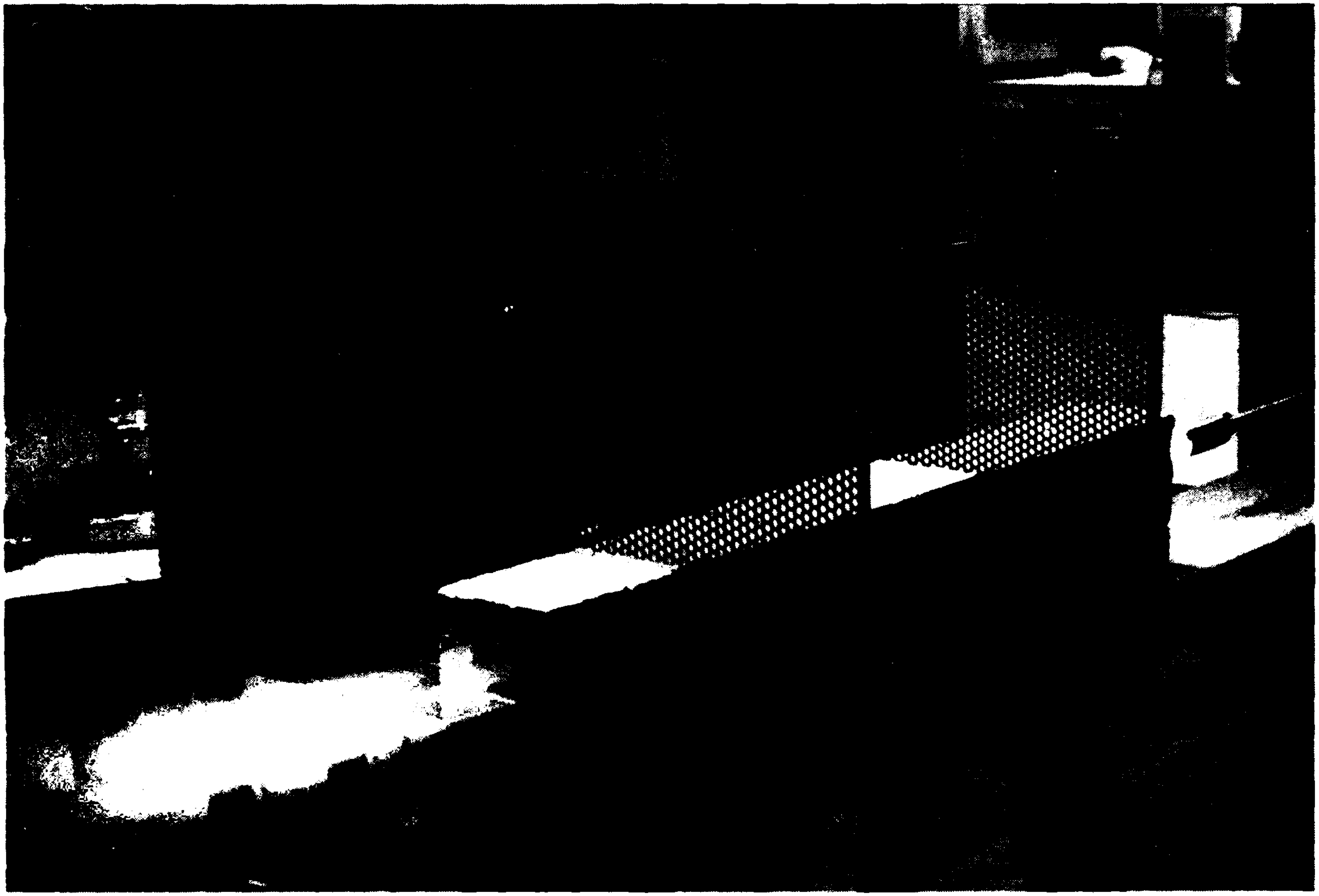


Figure 2. Combustion Channel and Burner

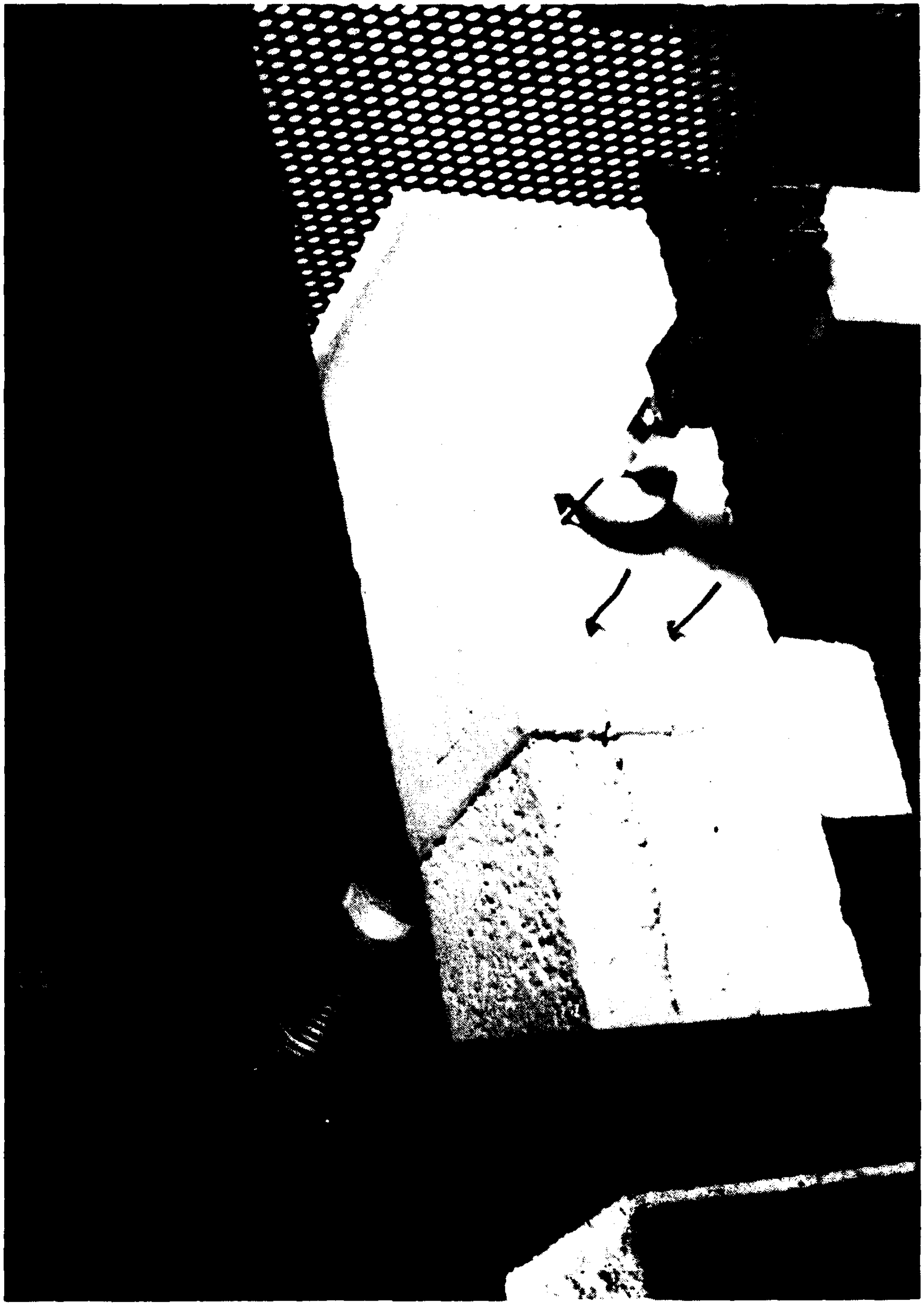


Figure 3. Detail of Thermocouple, Johnson Noise Electrodes and Impedance Transformer

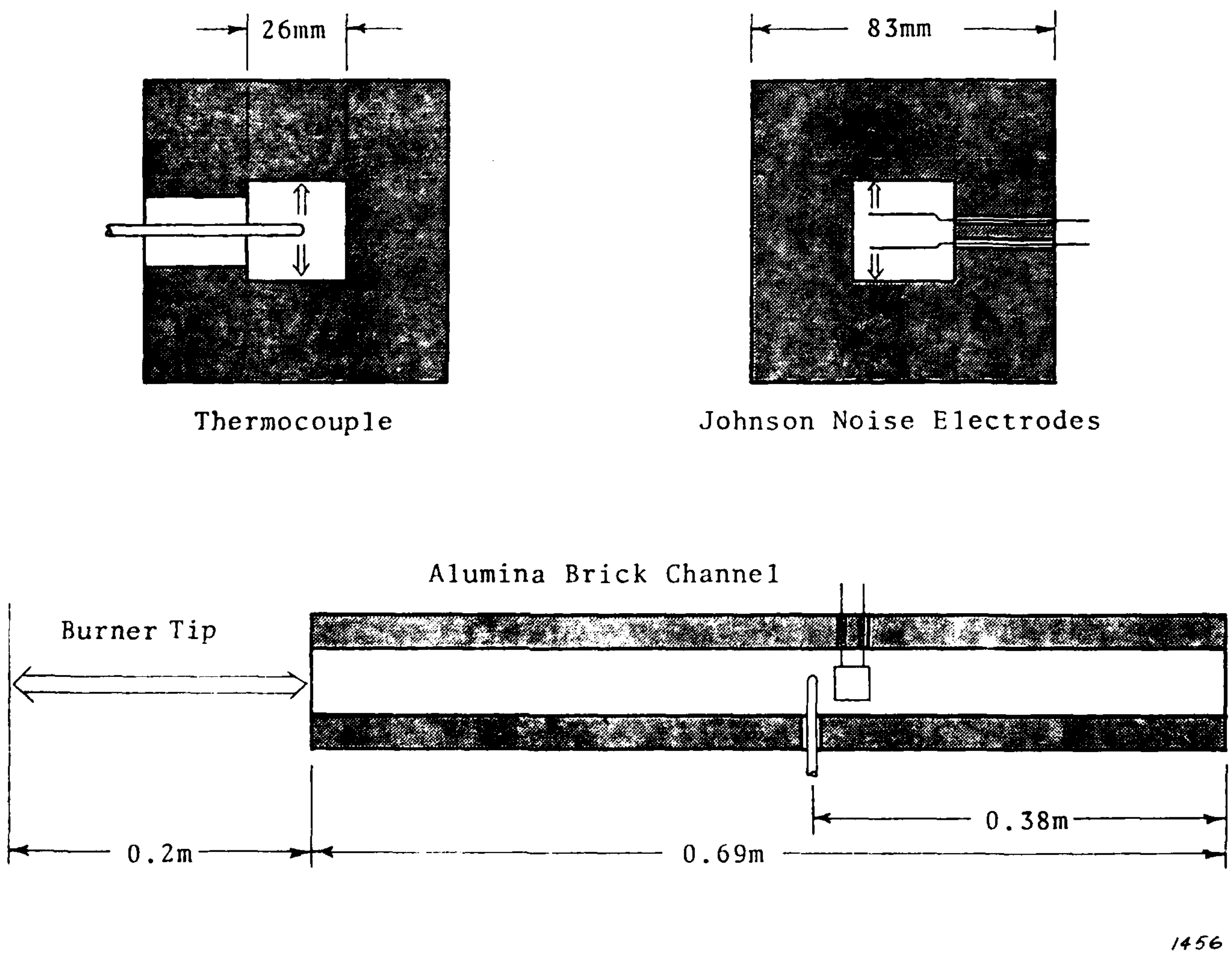


Figure 4. Schematic of the Combustion Channel

burner, channel, reference thermocouple and Johnson noise electrodes are given in Tables 1 and 2.

Burner

Harris 43-2 torch body with oxy-natural gas or oxy-propane multi-flame heating tip. Operated with neutral flame.

Burner Tip	Flow Rate $m^3/s (x10^3)$		Gas
	O_2	Gas	
Harris 2290-2H	1.73	.43	propane or methane
Harris 2290-3H	5.03	1.26	propane or methane

Channel

Inside Dimensions: 26mm by 26mm

Outside Dimensions: 83mm by 83mm

Material: Purotab Coarse

As cast density: 2630 kg/m^3

Thermal conductivity: 1.4 watts/m-K

Maximum working temperature: 2150 K

Combustion Burner and Flow Channel Data

Table 1

Thermocouple

Standard NANOPAK high temperature thermocouple probe ungrounded thermal junction with closed end alumina sheath

Element: Tungsten 5% Rhenium/Tungsten 26% Rhenium

Sheath: Alumina 3mm dia x 76mm long

Upper Working Temperature: 2170 K

Lead Wire: NANMAC Alloy 405 - Alloy 426 ISA type W5X

Readout: Fluke 8050A digital voltmeter
NANMAC thermocouple tables
corrected for room temperature

Noise Thermometer

Electrodes:	50mm by 25mm by 1.59mm
Leads:	1.59mm dia
Material:	Inconel 600
Separation:	0 to 26mm

Thermocouple and Noise Thermometer Data

Table 2

2.2 Measurement Technique

2.2.1 Thermocouple Reference Temperature

In the experiments to correlate noise temperature with a known reference, an alumina sheathed tungsten-rhenium thermocouple was positioned 25mm upstream of the Johnson noise electrodes with the thermocouple element positioned on the channel centerline. The position of the burner tip varied between .5m and .3m upstream of the thermocouple element during the experiments. The thermocouple positioning is illustrated schematically in Figure 4. The important thermocouple specifications and dimensions are given in Table 2.

When a thermocouple reference temperature was read, the flow and thermocouple were allowed to come to equilibrium. Equilibrium conditions were considered established when both the thermocouple reading and the flow impedance readings fluctuated randomly about a mean for a period of at least 30 seconds.

An order of magnitude estimate was made of thermocouple error. The thermocouple was modeled as a spherical element at the center of a spherical shell of sheath material but separated from the sheath by an air gap. The heat balance included conduction losses down the thermocouple leads, radiation losses from the sheath to the channel walls, radiation gain by the sheath from the burner tip and convective heat transfer from the gas flow to the sheath. Wall temperature was determined by a heat balance between convective heat transfer from the gas flow and conduction losses through the wall.

The analysis indicated that the apparent thermocouple reading is about 7% lower than the core flow temperature at the highest conditions encountered in the experiments and about 4% lower at the lowest conditions. Most of this error is from radiation losses from the thermocouple sheath to the cooler channel walls.

The channel walls were cast from Purotab Coarse alumina mortar (Reference 6) having a cast density of 2630 kg/m^3. The thermal conductivity of this alumina brick is 1.4 watt/m-K which is 16 times less than that of theoretical density alumina. The combination of the thick channel walls and the relatively low thermal conductivity of the brick allowed the inside channel wall temperature to remain high and minimized thermocouple radiation losses to the walls.

The thermocouple was used to measure a temperature distribution across the channel. Uncorrected distributions representative of the experiments are shown in

Figure 5. The measured temperature near the wall is in substantial agreement with the computed temperature based on the heat balance analysis of the flow and the channel walls.

2.2.2 Impedance Matching Transformer

For efficient power transfer from the high impedance gas to the 50 ohm input of the noise measurement system, a transmission line impedance matching transformer was built to convert source impedances in the 2000 to 10,000 ohm range. The optimum working frequency of this design is centered at 10.7 MHz. The transformer was housed in a metallic grounding cage to isolate it from stray capacitance.

The transformer is a passive linear network and can be represented by a set of linear equations. Known resistive sources are affixed to the high impedance transformer input and the output impedances measured. The vector coefficients of the linear equations are determined by a least squares fit to the data. The true source temperature T_A is related to the apparent temperature T_B at the transformer output by a relation of the form

$$T_A = f_1(Z_B)T_B \tag{5}$$

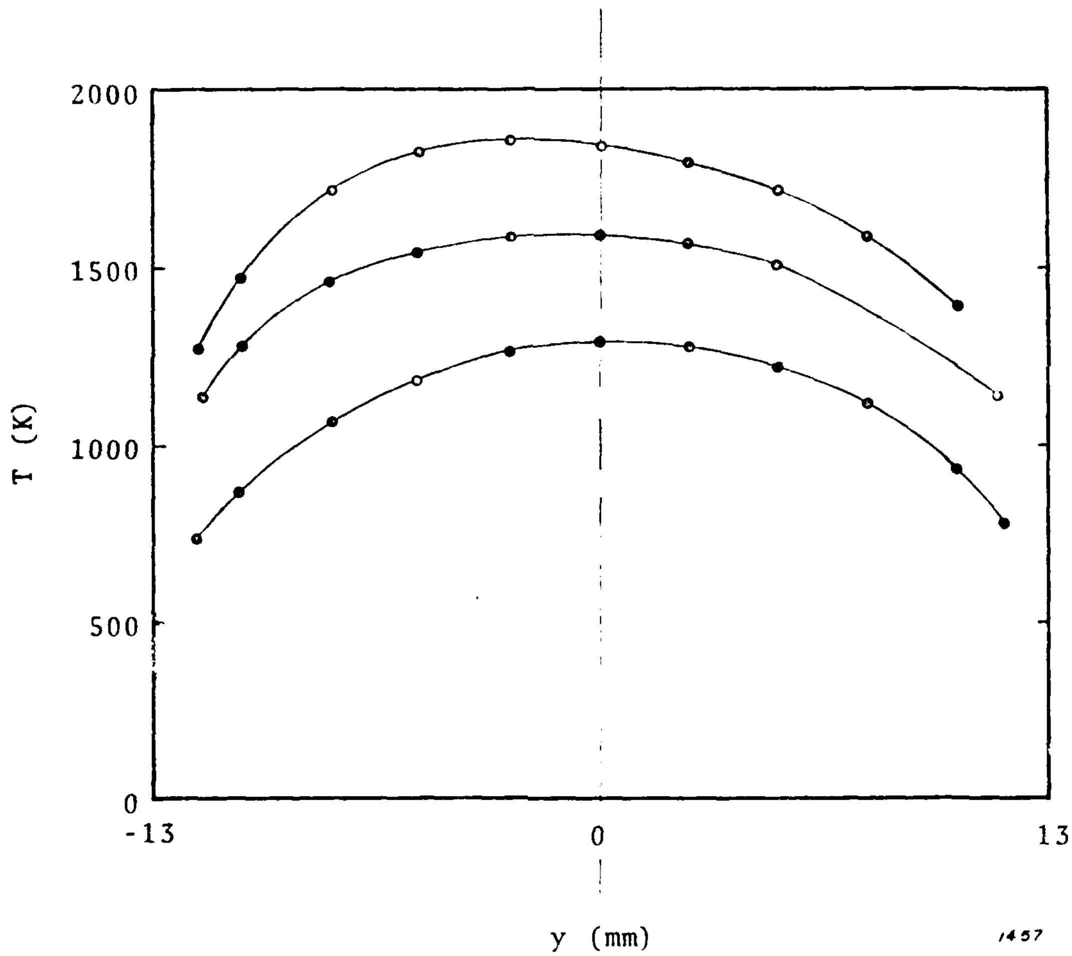


Figure 5. Uncorrected Thermocouple Temperature Distributions Across The Combustion Channel

where f_1 is a vector function of the measured transformer output impedance Z_B. The function f_1 represents the power loss of the transformer and is of the order of 5 to 15% for the present experiments. Relation (5) is derived in Appendix 2.

The transformer used in the present experiments worked well when limited to its design frequency of 10.7 MHz. In future work, broad band video impedance matching transformers could be designed to permit efficient operation over a range of working frequencies.

2.2.3 Impedance and Noise Power Measurement System

A vector impedance meter was used to measure the magnitude and phase of the apparent source impedance at the transformer output. This instrument was also used to determine the impedances of the standard sources used for calibration and the input/output impedances of the low noise amplifiers. All measurements were made at the working frequency of 10.7 MHz. The accuracy of these measurements was limited by the ability to read the meter movement and by the stray capacitance limit of the vector impedance meter probe tip.

The noise power appearing at the transformer output is amplified by two 50 ohm low noise amplifiers with a total gain of 88 dB. The signal is passed through a bandwidth filter of either .3, 1 or 3 MHz which in these experiments was provided by a spectrum analyzer mainframe. The filtered signal was then input into a noise power sensor which was monitored by a noise power meter with meter movement.

The noise measuring system is an active linear network (verified by experiments) and can be represented as a set of linear equations. The apparent temperature of the source at the output of the transformer and input of the amplifiers is related to the power, P_C, measured by the power sensor by a relation of the form

$$T_B = f_2(Z_B)[P_C + f_3(Z_B)] \qquad (6)$$

where f_2 and f_3 are vector functions of the source impedance Z_B and various amplifier constants.

The function f_2 accounts for the gain of the amplifier and the impedance difference between source and amplifier inputs. The function f_3 accounts for internal amplifier noise and for amplifier front end noise reflected back by the source-amplifier mismatch. This is a relatively small correction but important for proper amplifier calibration. Relation (6) is derived in Appendix 3.

The noise measuring system as characterized by relation (6) is calibrated by measuring noise power of several sources of known impedance and temperature. These include room temperature resistive, capacitive and inductive elements, an open and a short circuit element and a commercial calibrated white noise source. The white noise source used in these experiments has a temperature equivalent of 10,480 K ± 700 K and provides the primary means of determining the overall gain of the low noise amplifier.

2.2.4 Measurement Sequence

Prior to each data run, the vector impedance meter and power meter are initialized to specifications and the bandpass filter centering frequency is accurately set. The impedances and noise powers of the calibration sources are then measured.

For each data point in the run, the channel flow is allowed to reach equilibrium for at least 30 seconds as determined by both thermocouple and flow impedance measurements. Thermocouple and impedance measurements are made. Then the noise power at the transformer output is measured. The thermocouple and impedance measurements are then re-read.

When developed into a working temperature measurement system, this calibration and measurement procedure can be readily automated under computer control. Measurement of both noise power and interelectrode impedance guarantees that the calculated temperature is independent of the physical condition of the electrodes in the combustion environment. Long term calibration drift is then determined by straightforward electronic measurements.

2.3 Data Analysis

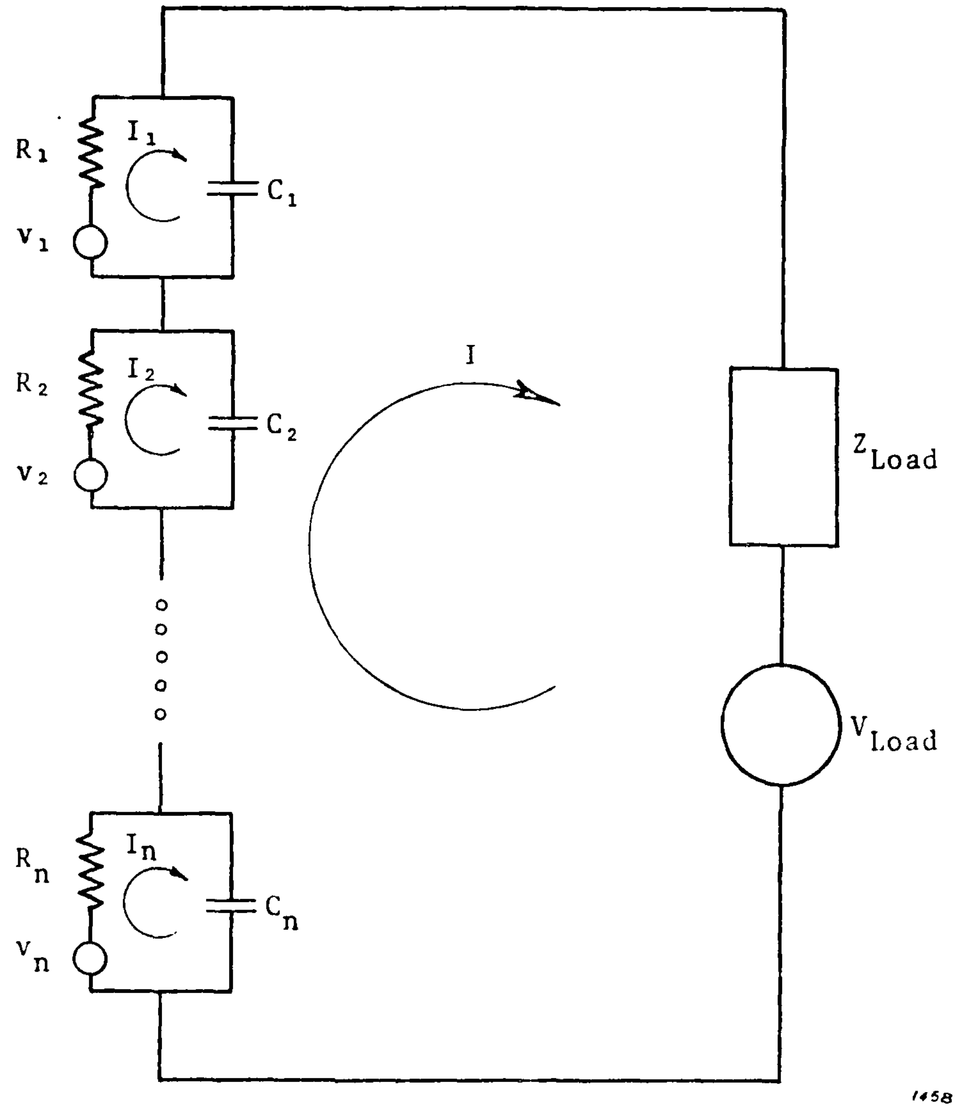
2.3.1 Response of Noise Thermometer to Cross Channel Flow Variation

In early experiments, the noise thermometer electrodes were recessed in the channel walls and therefore measured a resistance-averaged temperature between the electrodes. Temperatures so measured fell considerably below the temperature measured by the reference thermocouple.

A thermocouple traverse of the channel indicated a substantial variation of temperature from the cooler walls to the hot core flow as shown in Figure 5.

The response of the noise thermometer to temperature and electrical conductivity variation between the sensing electrodes was modeled in a computer program. The gas between the electrodes was conceptually divided into many zones whose properties were assumed constant. Each zone was modeled by an ideal voltage source in series with a noise free resistance and in parallel with the capacitance of free space (Figure 6). This is the digitized representation of relations (3) and (4).

Calculations were made using the measured tempera-



$$I = \frac{\sum_{i=1}^{n} \frac{v_i}{(1+j\omega C_i R_i)} - v_{Load}}{Z_{Load} + \sum_{i=1}^{n} \frac{R_i}{1+j\omega C_i R_i}}$$

Figure 6. Circuit Representation of Hot Gas With a Distribution of Temperature and Conductivity

ture distribution. Electrical conductivity was assumed to vary with temperature according to an Arrhenius relation of the form

$$\sigma = k_1 e^{k_2 T} \tag{7}$$

where T is the temperature and σ is the electrical conductivity. The constants k_1 and k_2 were estimated from methane-air combustion data (Reference 7).

These calculations could not reproduce the observed variation of measured temperature with electrode separation. It was soon realized that the electrical conductivity of the combustion flow was being dominated by alumina contamination from the hot channel walls. This was confirmed by observing the interelectrode resistance under constant combustion conditions. Measured resistance approached ten thousand ohms when the walls were cool and decreased to a few thousand ohms as the wall temperature equilibrated.

To relate a resistance averaged temperature to the peak core flow temperature where the noise thermometer reading was taken, it would be necessary to measure interelectrode resistance variation across the channel for each data point. To circumvent this, the noise thermometer sensing electrodes were moved to a 10mm separation in the center of the channel. Here the temperature and conductivity variation was small and the resistance averaged temperature and peak core flow temperature were nearly identical. This electrode separation was used in all the data reported herein.

2.3.2 Correlation of Reference Temperature with Noise Temperature

The data presented in this section are from four runs with methane-oxygen and one run with propane-oxygen. These data cover a temperature range of 1500 K to 2100 K and are presented in Figure 7. The data are plotted against corresponding reference thermocouple measurements that have been adjusted upwards as a first order correction from the heat balance of the thermocouple element with its surroundings. The correction applied varies linearly from 4% at 1500 K to 7% at 2000 K.

It is emphasized that each data point represents a noise thermometer and thermocouple measurement which are taken totally independently of one another but are taken at essentially the same time under the same conditions.

The propane-oxygen data is offset from the methane-oxygen data in Figure 7 and this is tentatively attributed

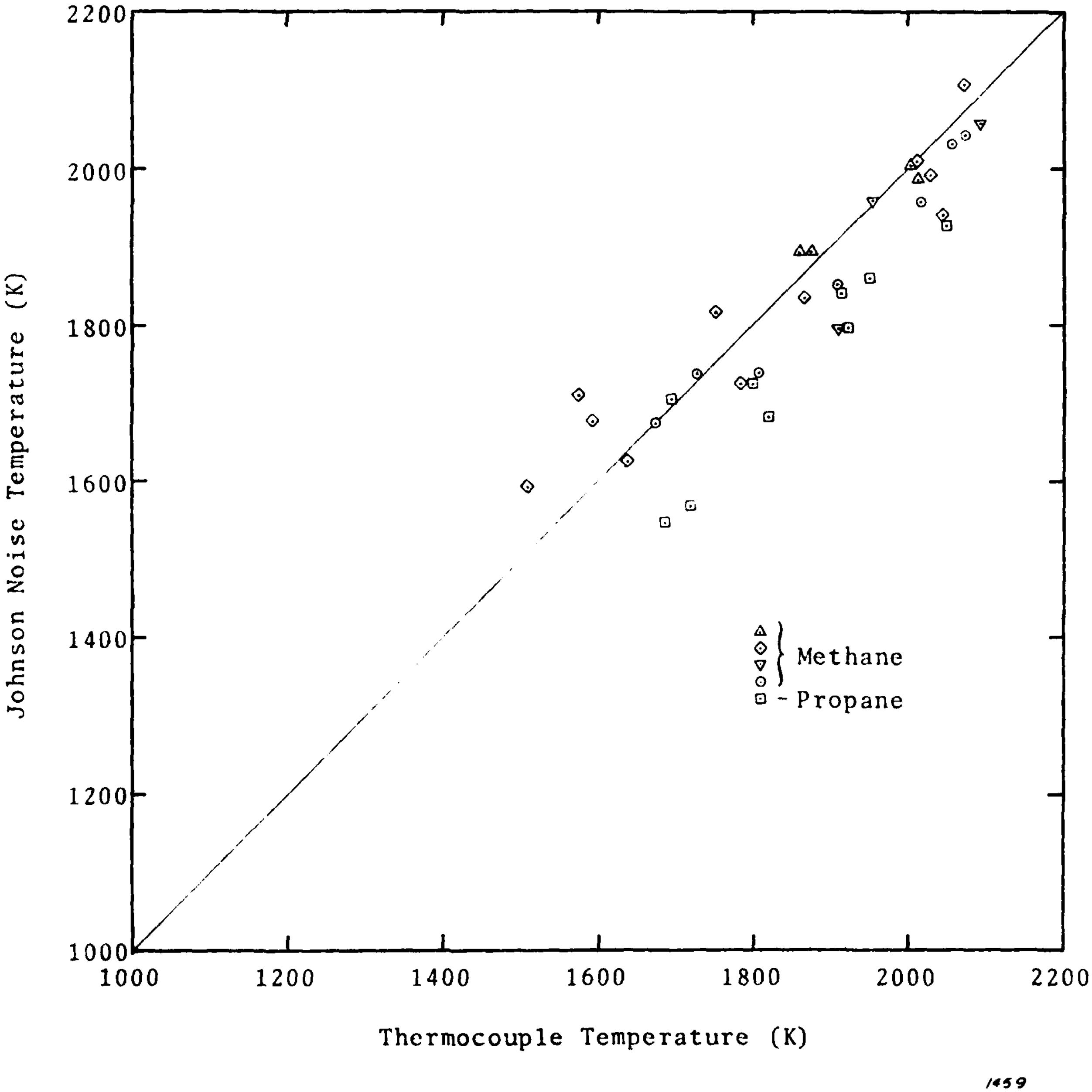


Figure 7. Correlation of Johnson Noise Temperature With First-Order Corrected Thermocouple Temperature

to differences in the estimated thermocouple correction.

The corrected thermocouple readings are estimated to be within ±3% of true temperature. Most of this error arises from the assumptions and estimates made in the heat balance to determine the thermocouple correction.

The amplifier constants and calibrated source characteristics used in the calculation of noise temperature are the same for all runs. They were chosen to give the best overall fit of data within the manufacturers specified accuracy. The values used are given in Table 3 along with other experimental conditions.

The noise temperature data are estimated to be within ±5% of true temperature. A major source of this discrepancy arises from the accuracy to which the calibrated noise source is known. Manufacturers specification is 10480 K ± 700 K. This calibrated source along with the other room temperature calibration sources are the primary means of determining the gain of the noise measurement system. The tolerance of the white noise source can be tightened to ±200 K with special calibration procedures.

A second major source of error are the readings of the meter movements of the vector impedance meter and

Other	Electrode Separation	12.7 mm	
	Working Frequency	10.7 MHz	
Noise Measurement System	Δf = .3 MHz		
	G = 93.2 db (overall input/output gain)		
	T_L = 148 K (independently measured apparent low noise amplifier temperature)		
	P_a = 4.35 μW		
		Magnitude	Phase
	A/Z_T	7.3×10^{-3}	10°
	Z_L	54	-3
Calibration Source	50 ohm	51	1
	75 ohm	76.3	0
	600 ohm	593	-14
	Short cct	0	0
	Open cct	10^6	0
	Capacitive	185	-90
	Inductive	-	-
	Calibration Noise Source	49.8	.5
Impedance Transformer	a_{11}	79.3	90.3
	a_{22}	40.3	-81.5
	$-a_{12}^2$	2.78×10^5	7.0

Typical Noise Measurement System,

Calibration Source and Experimental Data

Table 3

power meter. When the meters are carefully adjusted to specifications they can be read to within 1%. In the present experiments, however, the meters fluctuated as much as 5% about a mean as a result of combustion flow variations. When these fluctuations persisted several readings were taken and averaged.

3.0 Concluding Remarks and Recommendations

Within the limitations of the reference thermocouple and the Johnson noise impedance matching transformer, these experiments demonstrated that direct Johnson noise thermometry can be used to measure temperature in combustion processes. The temperatures measured by the Johnson noise thermometer are estimated to be within ±5% of the true temperature. The experiments should be extended with the following improvements

* include a broad band impedance matching transformer to permit a wider range of working frequencies (for example 500 kHz to 50 MHz).

* use of a reference thermocouple that minimizes sheath radiation losses to the walls and conduction losses in the lead wires.

* thicker channel walls to reduce temperature gradients across the channel.

* use of more Johnson noise calibration sources with higher calibration tolerances.

* automatic readout of thermocouple, Johnson noise power and impedance to minimize errors arising

from flow fluctuations.

With the above improvements the Johnson noise and thermocouple temperatures are expected to be within ±2% of true temperature in the absence of contaminating sources of noise which would affect the noise thermometer readings.

The ultimate objective of our research with direct noise thermometry is to make transient temperature measurements in hostile environments such as shock tubes and gun barrels. Artec believes that transient temperature measurements can be made using the following methods.

* use of a broad band impedance matching transformer.

* oscilloscope readout of the output of a Schottky diode noise power sensor.

* determination of transient impedance by use of a low amplitude, high frequency current source and by monitoring voltage across the electrodes. This would be done either at a slightly different frequency or alternately by fast switching with the noise power measurements.

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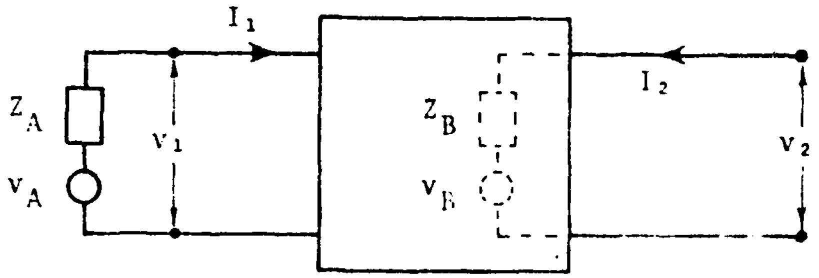
Appendix 2. Calculation of True Temperature, T_A From Measured Transformed Temperature, T_B

The impedance matching transformer is represented as a linear passive network



$$v_1 = a_{11}I_1 + a_{12}I_2$$

$$v_2 = a_{21}I_1 + a_{22}I_2$$

The output impedance Z_B can be expressed in terms of the input impedance and transfer coefficients

as $$Z_B = a_{22} - \frac{a_{12}a_{21}}{Z_A - a_{11}}$$

or $$Z_A = -a_{11} - \frac{a_{12}a_{21}}{Z_B - a_{22}}$$

where $a_{12}=a_{21}$ by Kirchoff's Reciprocity Theorem

also $v_1 = v_A - Z_A I_1$

using $v_2 = a_{21}I_1 + a_{22}I_2$

so $v_2 = \frac{a_{21}}{Z_A+a_{11}} v_A + Z_B I_2 = v_B + Z_B I_2$

thus $v_B = \frac{a_{21}}{Z_A+a_{11}} v_A$

using $v_A^2 = 4R_A k T_A \Delta f$ where k = Boltzmann's constant
Δf = bandwidth

$$v_B^2 = \left|\frac{a_{21}}{Z_A+a_{11}}\right|^2 4R_A k T_A \Delta f$$

using $Z_B = a_{22} - \frac{a_{12}a_{21}}{Z_A+a_1}$

and noting that $R_A = R_e\left[-a_{11} - \frac{{a_{12}}^2}{Z_B+a_{22}}\right]$

$$v_B^2 = \left|\frac{Z_B-a_{22}}{a_{12}}\right|^2 4\mathrm{Re}\left[-a_{11} - \frac{{a_{12}}^2}{Z_B-a_{22}}\right]$$

$$= 4R_B k T_B B$$

Rearranging

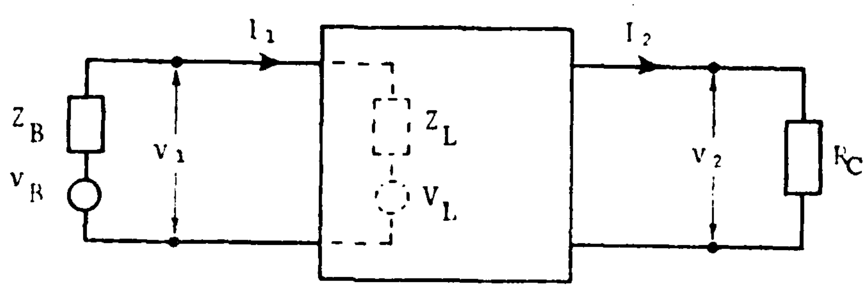
$$T_A = T_B \left\{\frac{(a_{12})^2 \mathrm{Re}(Z_B)}{\mathrm{Re}[-a_{11}|Z_B-a_{22}|^2 - {a_{12}}^2 (Z_B-a_{22})^*]}\right\}$$

which is of the form

$$T_A = f_1(Z_B) T_B$$

Appendix 3. Calculation of Temperature, T_B From Measured Noise Power, P_C

The noise measurement system is represented as a linear active network



$$v_1 = a_{11}I_1 + a_{12}I_2 + a_{13}$$

$$v_2 = a_{21}I_1 + a_{22}I_2 + a_{23}$$

the power meter is a constant load

therefore

$$I_2 = \frac{v_2}{R_C}$$

v_1 is independent of I_2 by experiment

therefore

$$a_{12} = 0$$

rewrite as $v_1 = Z_L I_1 + v_L$

$$v_2 = Z_T I_1 + Av_L + v_a$$

where $Z_L = a_{11}$

$$v_L = a_{13}$$

$$Z_T = \frac{a_{21}}{\left[1-\frac{a_{22}}{R_C}\right]}$$

$$Av_L + v_a = \frac{a_{23}}{\left[1-\frac{a_{22}}{R_C}\right]}$$

$$I_1 = \frac{v_B - v_L}{Z_B + Z_L}$$

$$P_C = \frac{\overline{v}_2^{\,2}}{R_C} \quad \text{and} \quad \overline{v}_B^{\,2} = 4R_B k T_B \Delta f$$

$$\overline{v}_L^{\,2} = 4R_L k T_L \Delta f$$

$$P_C = \frac{4R_B k T_B \Delta f}{R_C}\left|\frac{Z_T}{Z_B+Z_T}\right|^2 + \frac{4R_L k T_L \Delta f}{R_C}\left|\frac{Z_T}{Z_B+Z_L} - A\right|^2 + \frac{\overline{v}_a^{\,2}}{R_C}$$

set $G = \frac{|Z_T|^2}{R_C R_L}$ and $P_a = \frac{\overline{v}_a^{\,2}}{R_C}$

$$P_C = \frac{4R_B R_L k T_B \Delta f G}{|Z_B+Z_L|^2} + 4R_L^2 k T_L \Delta f G\left|\frac{1}{Z_B+Z_L} - \frac{A}{Z_T}\right|^2 + P_a$$

which is of the form

$$T_B = f_2(Z_B)[P_C + f_3(Z_B)]$$