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THERMOMETRIC DETERMINATION OF OXIDANT-FUEL DISTRIBUTION WITHIN A ROCKET COMBUSTOR

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Cleveland, Ohio

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16. Abstract
Tungsten-rhenium alloy thermocouples were used to determine the distribution of hydrazine - nitrogen tetroxide products within a combustion chamber. Temperatures indicated by bare-wire thermocouples were a single-valued function of mixture ratio in part of the O/F range. Within this range, local composition could be estimated. The thermocouples also were used to determine changes in composition caused by induced mixing of products.

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SUMMARY

Tungsten-rhenium alloy thermocouples were used within a combustor to measure local temperatures and to estimate the propellant distribution as a function of radius and axial length. Hydrazine and nitrogen tetroxide propellants were injected through quadlet- or triplet-type elements into a 2-inch (5.1-cm) diameter chamber.

Temperatures indicated by bare-wire tungsten-rhenium alloy junctions were a single-valued function of oxidant-fuel weight ratio (O/F) from 0.5 to 4.5. Using an experimental temperature-O/F curve, mixture ratio was determined as a function of combustor length and radius.

The high-temperature thermocouples were also used to indicate changes in combustion gas mixing. It was possible to chart the improvement in gas uniformity resulting from placing wedges along the chamber walls to enhance mixing of combustion gases.

INTRODUCTION

The distribution of propellants within a rocket combustor is of interest to the engine designer with regard to maximizing performance and combustion stability and minimizing heat transferred to the chamber. Propellant distribution is usually measured in cold-flow tests using nonmiscible fluids (ref. 1). With combustion, this distribution can change considerably, especially with hypergolic propellants such as hydrazine and nitrogen tetroxide, which tend to repel each other at their interfaces (ref. 2). Clearly, an experimental method of determining local mixture ratios within the combustion chamber would be desirable.

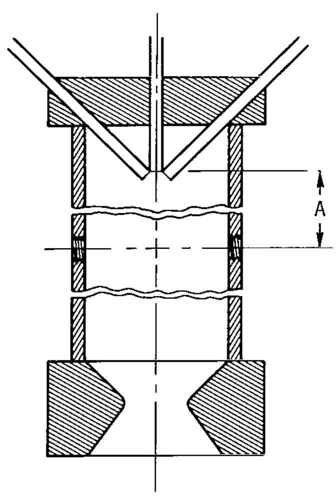
Preliminary measurements of temperature distribution within the combustion chamber using tungsten-rhenium alloy thermocouples (ref. 2) were consistent enough to warrant further studies. If the indicated thermocouple temperature was a function of mixture ratio, the thermovoltages at each location could be related to the local mixture ratio. This was done experimentally in the current study.

Bare-wire tungsten-rhenium alloy thermocouples were used to determine local variations in thermocouple temperature and the approximate propellant mixture ratio for several single-element quadlet and triplet injectors. Combustor pressure was approximately 20 atmospheres (2.02×10^{6} N/m^{2}). Overall oxidant-fuel weight ratios (O/F) were varied from 0.5 to 1.5 (fuel-rich to slightly fuel-lean). The effects of nonhomogeneous gases on performance is discussed.

APPARATUS AND PROCEDURE

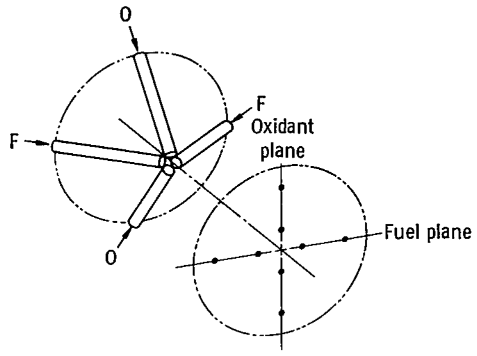
Uncooled, 2-inch (5.1-cm) diameter chambers contained four radially alined ports at each of seven axial locations for thermocouple placement (fig. 1). The thermocouple junctions extended 0.25 or 0.75 inch (0.64 or 1.91 cm) into the chamber at each location. Figure 2 shows the position of the thermocouples relative to each injector configuration tested. These positions corresponded to the maximum variations in mixture ratio as determined by thermocouple surveys and previous photographs (ref. 2).

Two basic types of injection elements were tested in the combustor and are referred to herein as quadlet or triplet types. Fuel and oxidizer entered either opposite or adjacent 0.067-inch (0.17-cm) diameter tubes in the quadlet element. In the triplet element, outer 0.067-inch (0.17-cm) diameter fuel jets impinged on an 0.095-inch (0.242-cm) diameter center jet containing the oxidizer. In all elements, the tubes extended nearly to

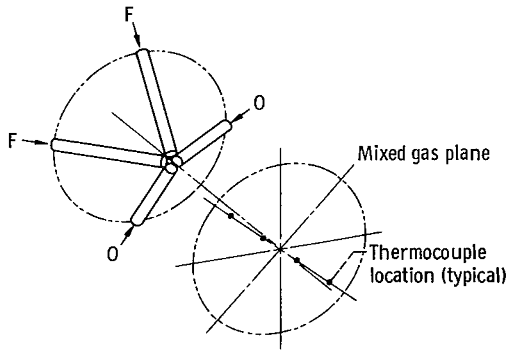


Thermocouple distance from injector, A	
in.	cm
1	2.5
2	5.1
3	7.6
6	15.2
8	20.3
12	30.5
18	45.7

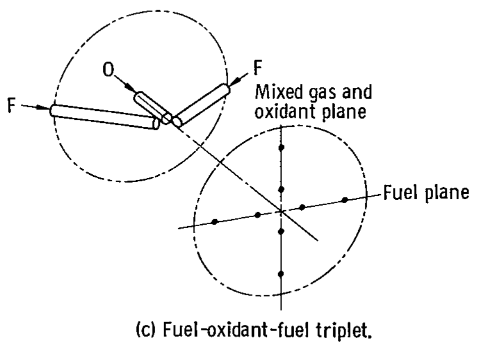
Figure 1. - Single-element combustor, quadlet or triplet injection. Chamber diameter, 2 inches (5.1 cm); nozzle throat diameter, 0.645 inch (1.64 cm); combustor length, 22 inches (55.8 cm).



(a) Like-on-like impinging quadlet.



(b) Unlike-impinging quadlet.



(c) Fuel-oxidant-fuel triplet.

Figure 2. - Thermocouple locations for injector configurations studied.

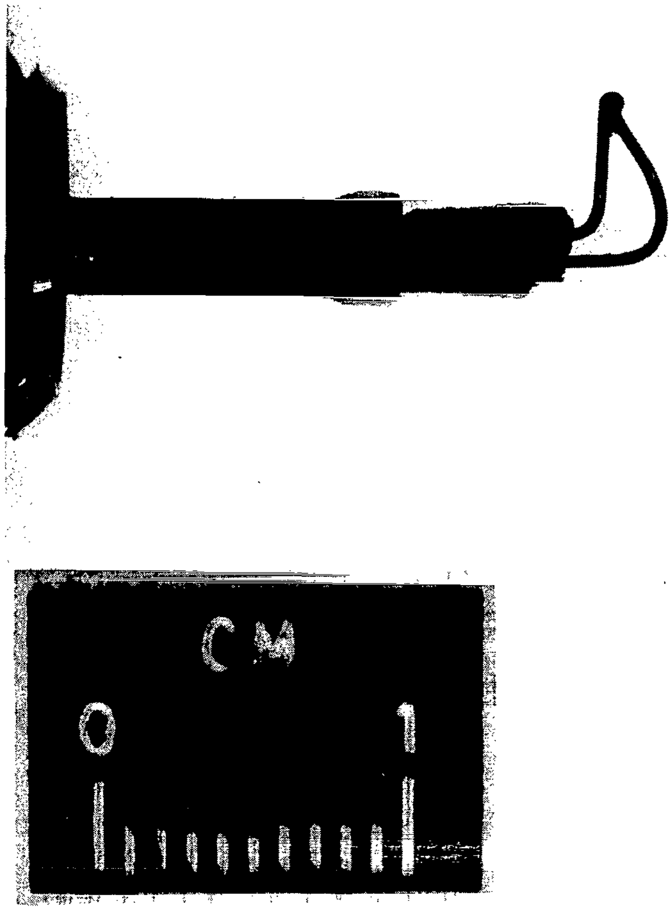


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Figure 3. - Tungsten/tungsten-26-percent-rhenium-alloy thermocouple. Diameter of wires, 0.015 inch (0.038 cm).

the impingement point, and were flow-checked with water to ensure symmetrical propellant flows.

Tungsten/tungsten-26-percent-rhenium wires with diameters of 0.015 inch (0.038 cm) or 0.030 inch (0.076 cm) were used to form the thermocouple configurations, as shown in figure 3. Wires extended approximately 10 wire diameters beyond the alumina insulator in order to minimize conductive losses.

Thermocouple voltages were recorded as a function of run time, and the values were read after they became constant within 5 percent. This response time required approximately 0.3 to 0.6 second of combustor operation. Where the thermocouple junctions were coated with zirconium oxide, response times increased to 1.1 seconds. Steady-state values of thermovoltage were used for all measurements.

Published values of millivolt output against temperature for tungsten-rhenium wire do not extend higher than 2600 K (ref. 3). The millivolt-temperature curve was there-

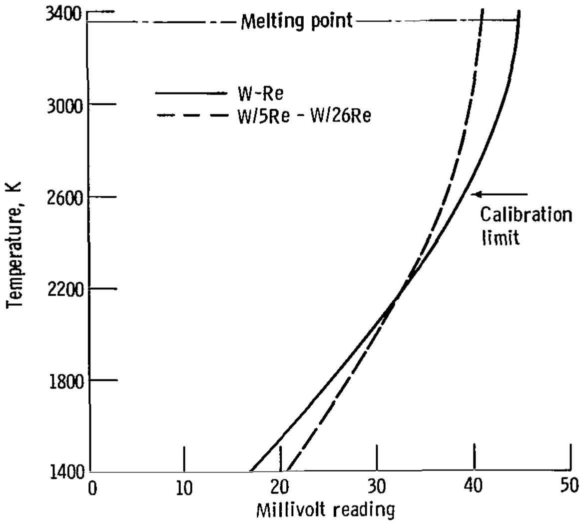


Figure 4. - Tungsten-rhenium thermocouple alloy calibration.

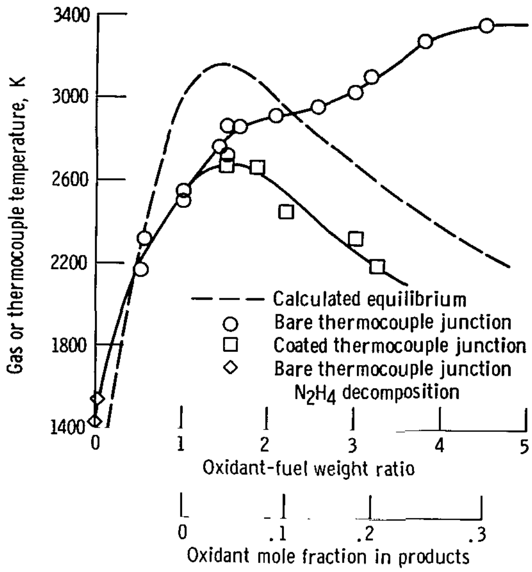


Figure 5. - Calculated gas temperature and measured thermocouple temperature as function of oxidant-fuel weight ratio.

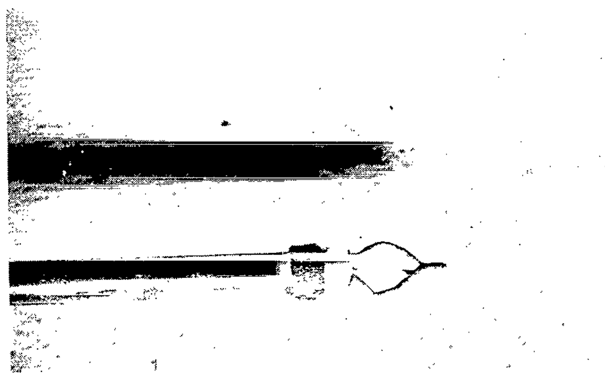
fore extended, using the junction melting point of 3360 K with the highest observed voltage of 45 millivolts for the limiting value on the curve (fig. 4). Limited data were also taken with tungsten/5-percent rhenium - tungsten/26-percent rhenium, with a similarly constructed millivolt-temperature curve shown as the dashed line in figure 4. Thermocouple erosion and breakage was not noticeably dependent on wire type.

Figure 5 shows the relation of oxidant-fuel weight ratio to the indicated thermocouple temperature and calculated gas temperature. The indicated thermocouple temperatures were measured 18 inches (45.7 cm) downstream from the injector in the center of the chamber using the high-performance, like-on-like quadlet injector.

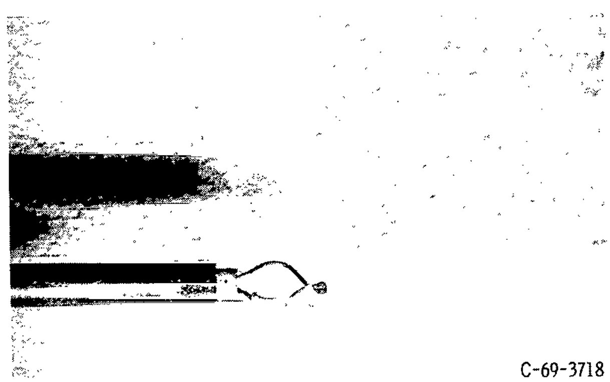
Bare-wire thermocouple junctions indicated an increasing temperature with increasing oxidant mole fraction until their melting point was reached at an O/F of 4.5. In oxidant-rich gases, the apparent reaction of the junction with excess oxidant reduced its size rapidly during the steady-state portion of the run. Between the stoichiometric O/F (1.43) and 4.5, thermocouple temperatures deviated increasingly from theoretical, and were a single-valued function of O/F. When the junctions were protected from oxidating gases with approximately 0.005 inch (0.013 cm) of zirconium oxide, thermocouple temperatures decreased with O/F values higher than stoichiometric, as predicted by the thermochemical data.

The coated-wire tests imply that the oxidizing environment caused the bare-wire junctions to indicate higher-than-theoretical gas temperatures at high oxidant-fuel mixture ratios. The mechanism causing this has not been resolved, but heat released from

(a) Before run.



(b) After 0.3 second.



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(c) After 1.4 seconds.

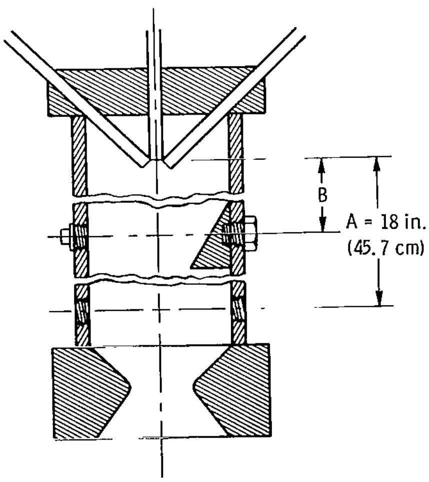
Figure 6. - Tungsten/tungsten-26-percent-rhenium-alloy thermocouple showing deterioration of flame-sprayed zirconium oxide coating after 0.3 and 1.4 seconds of combustor operation.

the oxidizing junction is implied. Regardless of the cause, the reproducibility of the bare-wire calibration meets the requirements of this study.

Coated thermocouples were unsatisfactory since (1) the calibration curve produced double-valued mixture ratios for every indicated temperature and (2) the coating was weak and could not withstand temperature cycling from run to run. Small cracks appeared in the coating, exposing the metal surface; and indicated temperatures increased to those of bare-wire junctions (fig. 6).

Temperatures indicated by the bare-wire thermocouples offer a unique opportunity to define fuel-rich and oxidant-rich zones within the combustor in the O/F range of 0.5 to 4.5. Beyond these limits there is a possibility of double-valued readings. Fuel-rich gases will approach the decomposition temperature of hydrazine (1465 K) as calculated in reference 2. Oxidant-rich gases eventually will approach the temperature of saturated vapor at 20 atmospheres (373 K). The thermocouple temperature - O/F curve in figure 5 will therefore not be applicable to gases very close to the injector because of the wide range in O/F mixtures which exist there.

One method of improving combustor performance from poorly distributed propellants is to enhance gas-phase mixing. This was done in the current study by placing copper wedges on the walls of the chamber, as shown in figure 7. Four to seven wedges were used to improve performance and mix the gases. The thermocouples were used to indicate the changes in the gas profile due to mixing.



Wedge distance from injector, B, in.	Wedge distance from injector, B, cm	Axial location, θ, deg
1	2.5	0
2	5.1	90
3	7.6	180
6	15.2	270
8	20.3	0
12	30.5	90
18	45.7	180

Figure 7. - Induced gas-phase mixing using copper wedges along walls. Four or seven wedges; thermocouple distance from injector, 18 inches (45.7 cm).

RESULTS AND DISCUSSION

Steady-state temperatures of the bare-wire thermocouple junctions were measured at three overall oxidant-fuel weight ratios using quadlet and triplet injector elements (figs. 8 to 10). Generally, thermocouple temperatures varied between 1400 and 3360 K, or from the decomposition temperature in fuel zones to the melting temperature of tungsten-rhenium alloy at an O/F of 4.5 or higher. When close to the point of liquid oxidant injection, thermocouples registered a temperature of 470 K, or almost 100 K above the saturated N_2O_4-NO_2 vapor temperature.

Like-On-Like Quadlet

Maximum thermocouple temperatures within the chamber shifted from the fuel-injected plane of the chamber at low metered O/F to the oxidant-injected plane at high metered O/F, as shown in figures 8(a) to (c). Stoichiometric proportions of fuel and oxidizer at an O/F of 1.43 also shifted in location within the chamber, ranging from the fuel-injected sides at an overall O/F of 0.53 to the oxidant-injected sides at an O/F of 1.1 and back to the fuel-injected sides at an O/F of 1.51. Cool liquid oxidant controlled thermocouple temperatures close to the injector on the oxidant-injected sides. For these temperatures, the approximate O/F scale obviously could not be used.

The impinging streams of hydrazine and nitrogen tetroxide are of equal diameters, so their momentum will be equal at an O/F of 1.22. This condition should provide for optimum distribution of propellants and their products. The intermediate O/F data were taken at an O/F of 1.1 and appear to show the best mixing and flattest temperature profile when the like-on-like quadlet is used.

Unlike-Impinging Quadlet

Thermocouple temperature profiles are completely changed when the unlike-impinging quadlet is used (fig. 9). Temperatures are low and quite uniform at the low O/F condition, but show a steep gradient across the chamber at O/F values of 1.1 and 1.41. This radial gradient confirms the marked separation of fuel-rich and oxidant-rich gases within the chamber that was observed in photographs of this injector which were reported in the film supplement to reference 2 (NASA film C-258). Oxidizer-rich gases remain on one side of the chamber, and fuel-rich gases remain on the other side. Even 18 inches downstream, the temperature gradient across the chamber at the higher O/F

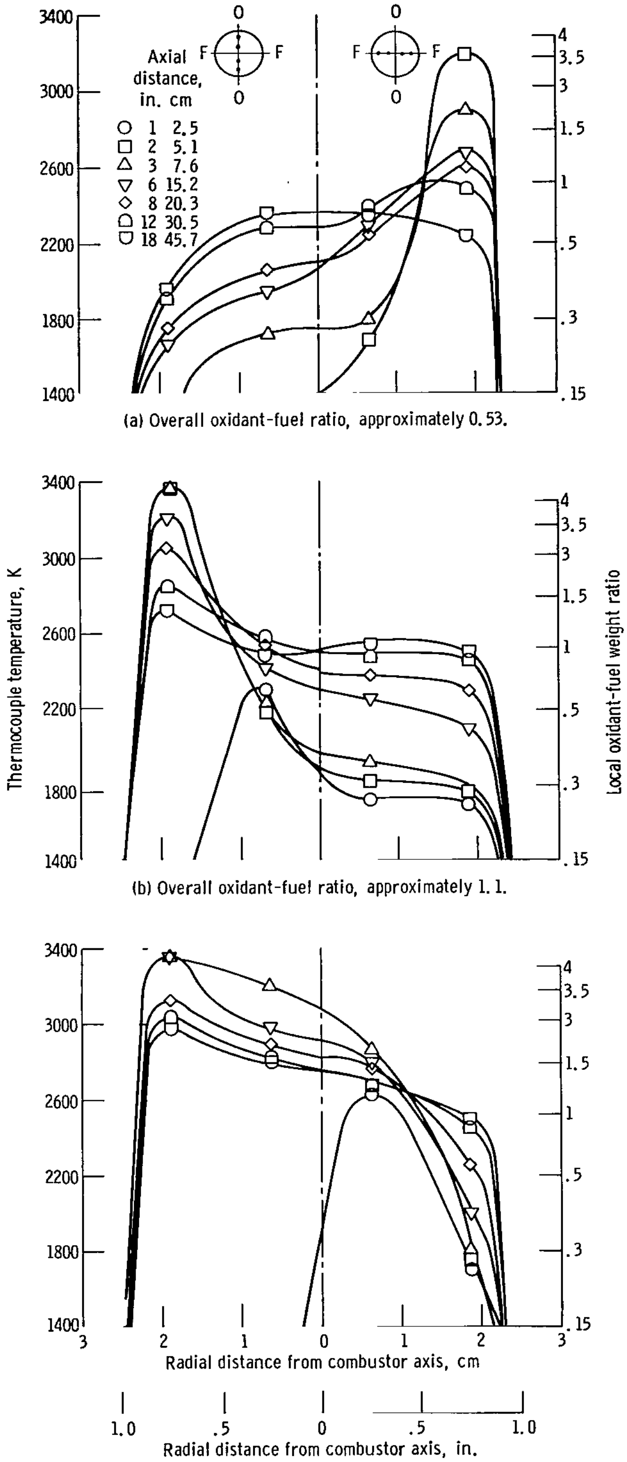
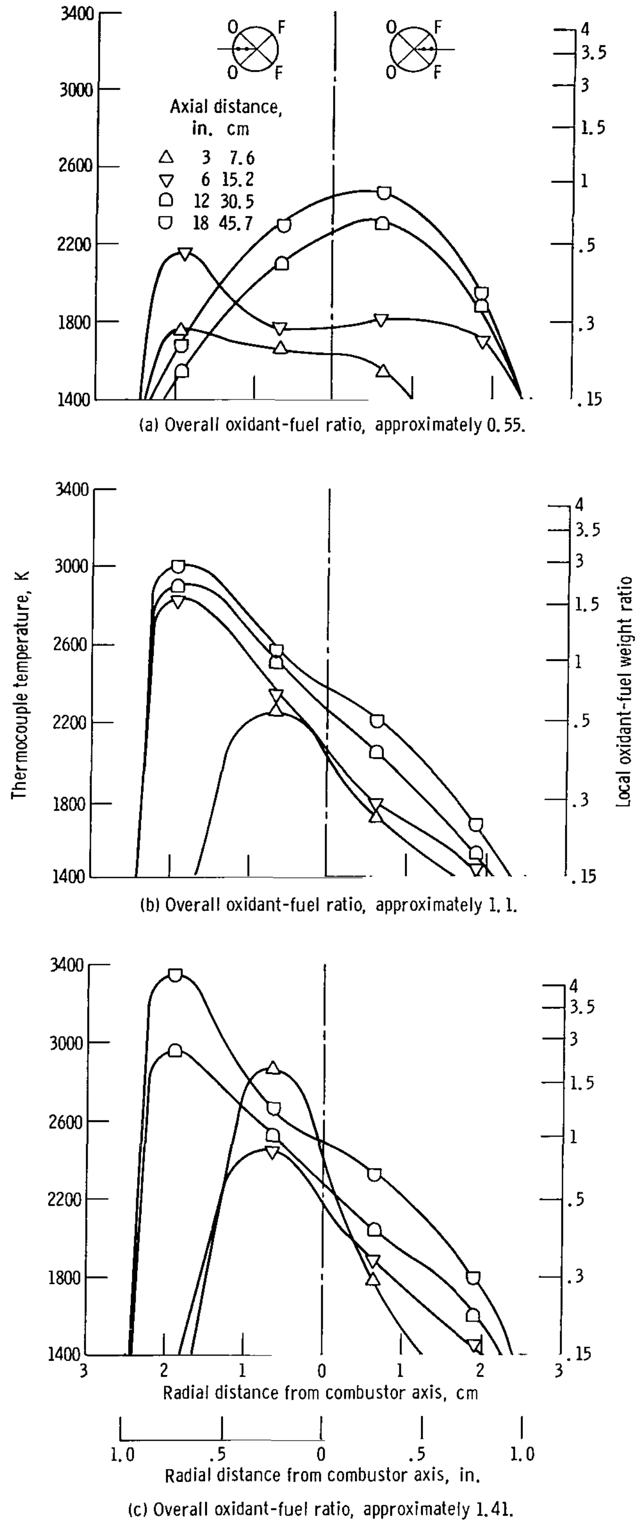


Figure 8. - Bare-wire junction temperatures and local oxidant-fuel ratios within combustor using like-on-like impinging quadlet.

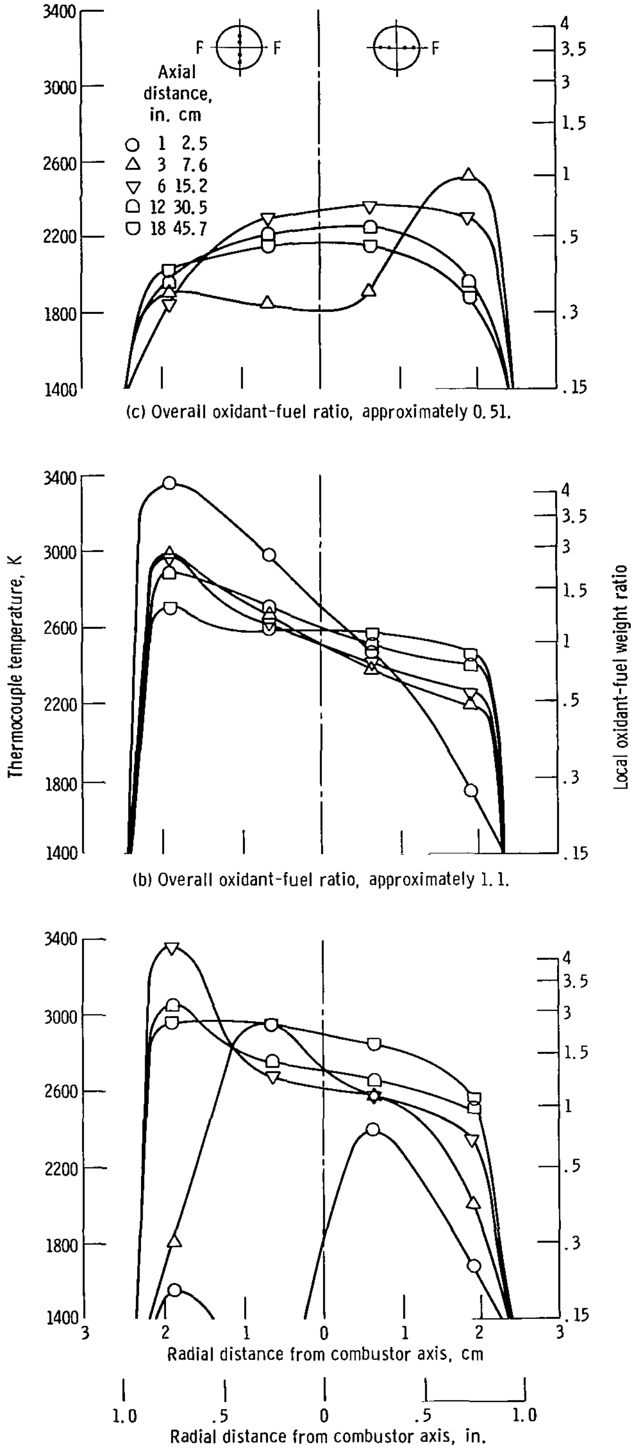


(a) Overall oxidant-fuel ratio, approximately 0.55.

(b) Overall oxidant-fuel ratio, approximately 1.1.

(c) Overall oxidant-fuel ratio, approximately 1.41.

Figure 9. - Bare-wire junction temperatures and local oxidant-fuel ratios within combustor using unlike impinging quadlet.



(c) Overall oxidant-fuel ratio, approximately 0.51.

(b) Overall oxidant-fuel ratio, approximately 1.1.

(c) Overall oxidant-fuel ratio, approximately 1.5.

Figure 10. - Bare-wire junction temperatures and local oxidant-fuel ratios within combustor using fuel-oxidant-fuel triplet.

values was 1300 to 1500 K, corresponding to local O/F ratios which varied from 0.5 to 4 or more.

Fuel-Oxidant-Fuel Triplet

The triplet element showed the best distribution of thermocouple temperature with overall O/F, distance from the injector, and radius (fig. 10). Temperature within 6 inches (15.25 cm) of the injector showed some effects of local changes in O/F.

The diameter of the center oxidant stream was sized so that its area equaled that of the two impinging fuel streams. Hence, the stream momentums were balanced at an overall O/F of 1.22. Again, intermediate O/F data were taken close to this value, and the thermocouple temperature was 2575 K ±125 K over most of the chamber width close to the nozzle. These temperature limits corresponded to indicated O/F mixtures which ranged from 0.85 to 1.3.

It is shown in reference 4 that complete mixing is not a necessary condition to attaining high performance. Thus, a variation in O/F of less than 2 to 1 across the chamber did not significantly reduce the performance. However, in the case of the unlike-impinging quadlet, the O/F variation close to the nozzle was greater than 10 to 1, which degraded performance as much as 7 percent. The same magnitude of O/F variation was obtained with the like-on-like impinging quadlet in only 6 inches (15.25 cm) of chamber length, or in less than 3 inches (7.62 cm) with the fuel-oxidant-fuel triplet.

Turbulent Mixing

The thermocouple temperature data on the three injection systems in figures 8 to 10 show the persistence of nonhomogeneous gases within the combustion chamber once they are formed.

Using the thermocouples as indicators of O/F distribution, the degree of mixing induced by obstructions along the chamber walls could be determined. The obstructions were in the form of wedges, with a length to maximum thickness ratio of 2 to 1, and they were installed in a spiral arrangement along the walls (fig. 7).

The results of using these wedges to improve mixing within the chamber are shown in figure 11. The unlike-impinging quadlet was used because of its poor performance and corresponding large temperature gradient across the chamber. With four wedges (fig. 7) the temperature extremes were reduced considerably. With seven wedges along the walls, temperatures became as uniform as they are when either the like-on-like imping-

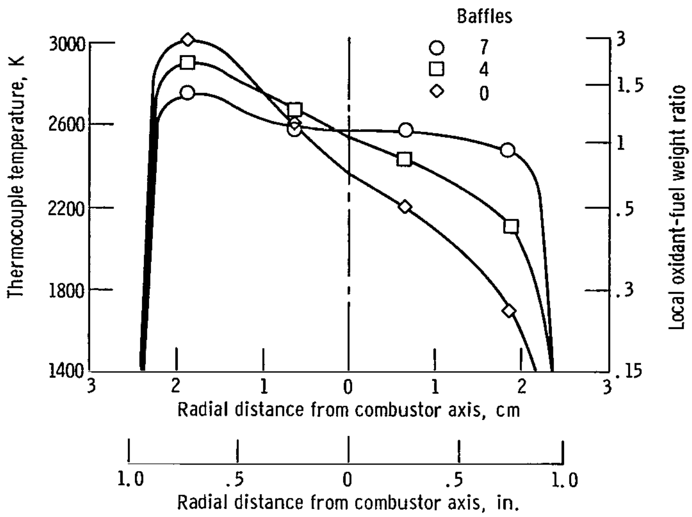


Figure 11. - Effect of induced turbulent mixing on thermocouple junction within combustor using unlike-impinging quadlet. Overall oxidant-fuel ratio, approximately 1.1.

ing quadlet or the fuel-oxidant-fuel triplet is used. The corresponding improvement in performance was approximately 7 percent.

The tests on turbulent mixing show the effectiveness of using thermocouples to detect changes within the combustor that will affect performance. Thermocouple temperatures also provide a sensitive indication of the combustion gas composition within the chamber. No attempt was made to record thermocouple temperatures close to the chamber walls since there are transient effects of the heat-sink, stainless-steel walls. Cooled hardware would permit steady-state measurements close to the walls, which, if calibrated, could be related to the gas composition.

CONCLUDING REMARKS

Although there has been considerable work done on cold flow studies of injector elements (refs. 1, 5, 6, and 7) only the two-on-two element and two-on-one element reported in reference 5 were similar to the quadlet and triplet elements used in this study.

Based on reference 5, optimum distribution of the quadlet should occur at an O/F of 1.22, where stream momentums are balanced. Typical weight ratios 8 inches (20.3 cm) downstream and 0.75 inch (1.9 cm) from the combustor axis varied from approximately 0.8 to 1.2 in the cold flow study, compared to a range from 0.7 to 3.0 in this study. The two-on-one element in reference 5 produced an optimum cold-flow distribution at a weight ratio of 1.87 for the conditions of this study.

The optimum distribution of propellants for the triplet element in this study appeared to be closer to the intermediate O/F of 1.1. The wide difference in O/F for optimum distribution between cold flow and combustion data may in part be due to whether fuel or oxidizer is in the center, the extent of interfacial reactions, and the length-to-diameter ratio of the tubes in the injector element.

SUMMARY OF RESULTS

Tungsten-rhenium alloy thermocouples were used to map the distribution of propellants within a single-element N_2H_4-N_2O_4 combustion chamber. Bare-wire thermocouple junctions provided a semiquantitative measure of mixing and reaction as a function of downstream distance from the injector. Principal results with several types of injector elements were as follows:

1. Tungsten-rhenium alloy thermocouples provided a simple and economical means of determining the propellant distribution, degree of mixing, and extent of reaction within an operating combustor.
2. Indicated thermocouple temperatures with an unlike-impinging quadlet showed poor downstream mixing and extreme variations in mixture ratio across the chamber. Performance from the unlike-impinging quadlet was as much as 7 percent lower than the other injectors tested.
3. Placing wedges along the chamber walls improved mixing in the low-performance combustor and increased performance. Seven wedges, arranged in a spiral fashion on the chamber walls, provided a relatively flat temperature profile across the chamber. Performance of the unlike-impinging quadlet then approached that of the best injectors tested.
4. Best mixing and shortest reaction length between the N_2H_4 and N_2O_4 occurred with a fuel-oxidant-fuel triplet element and with a like-on-like impinging quadlet with equal stream momentum.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, October 10, 1969,
722-03.

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