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FINAL REPORT

TURBULENCE IN A GASEOUS HYDROGEN - LIQUID OXYGEN ROCKET COMBUSTION CHAMBER

by

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TULANE UNIVERSITY

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16. Abstract

The intensity of turbulence and the Lagrangian correlation coefficient for a LOX-GH_2 rocket combustion chamber have been determined from experimental measurements of tracer gas diffusion. A combination of Taylor's turbulent diffusion theory and a numerical method for solving the conservation equations of fluid mechanics was used to calculate these quantities. Taylor's theory was extended to consider the inhomogeneity of the turbulence field in the axial direction of the combustion chamber, and an exponential function of the form $e^{-\alpha\tau}$ was used to represent the Lagrangian correlation coefficient.

The results indicate that the value of the intensity of turbulence reaches a maximum of 14% at a location about 7" downstream from the injector. The Lagrangian correlation coefficient associated with this value is given by the above exponential expression where $\alpha = 10{,}000\ sec^{-1}$.

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FORWARD

The research reported herein was performed by the Mechanical Engineering Department of Tulane University under NASA Grant NGR 19-002-030 from January 1974 through August 1975. The project manager was Dr. Richard J. Priem, Chemical Rockets Division, NASA Lewis Research Center.

ABSTRACT

The intensity of turbulence and the Lagrangian correlation coefficient for a LOX-GH_2 rocket combustion chamber have been determined from experimental measurements of tracer gas diffusion. A combination of Taylor's turbulent diffusion theory and a numerical method for solving the conservation equations of fluid mechanics was used to calculate these quantities. Taylor's theory was extended to consider the inhomogeneity of the turbulence field in the axial direction of the combustion chamber, and an exponential function of the form $e^{-\alpha\tau}$ was used to represent the Lagrangian correlation coefficient.

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SYMBOLS

Latin Characters

m	Mass concentration
R_L	Lagrangian correlation coefficient
r	Radial coordinate
$\overline{r^2}$	Mean square dispersion radius
T	The intensity of Turbulence
t	Diffusion time
u	Mean axial flow velocity
v	Radial velocity
Z	Axial coordinate from Propellant Injector

Greek Characters

α	Constant
Θ	Circumferential angle
τ	Difference in diffusion times

Indices

He	Helium
I	Helium injection location
S	Sample station
'	Fluctuating quantity

SUMMARY

The intensity of turbulence and the Lagrangian correlation coefficient in a LOX-GH_2 rocket combustion chamber have been determined experimentally using a small rocket engine operating at a nominal chamber pressure of 150 psia. The experimental method consisted of injecting a tracer gas at a point along the chamber centerline while taking samples along a diameter at a downstream station. Three sample stations were investigated. For each of the sample stations, several tracer gas injection points were used.

The gas samples were analyzed using a combination of weight analysis, Orsat analysis and gas chromatography to determine the tracer gas concentration profiles. The turbulence parameters were then calculated from the tracer gas concentration data using a combination of G. I. Taylor's turbulent diffusion theory and a numerical procedure developed by Rocketdyne for solving the conservation equations of fluid mechanics. Taylor's theory was extended to consider the inhomogeneity of the turbulence field in the axial direction of the combustion chamber. The Lagrangian correlation coefficient was represented by an exponential function of the form $e^{-\alpha\tau}$, where τ is the difference in dispersion times for an individual fluid particle and α is a constant.

The results indicate that the value of the intensity of turbulence reaches a maximum of 14% at a location about 7 inches downstream from the injector. The Lagrangian correlation coefficient associated with this value is given by the above exponential form where $\alpha = 10{,}000\ sec^{-1}$. This represents a relatively small degree of correlation in that the correlation will drop to above 10% in one inch of chamber length.

I. INTRODUCTION

Turbulent mixing is one of the most important physical processes occurring in a rocket combustion chamber. It influences the combustion process and therefore the performance of the rocket engine. In turbulent flow theory, the turbulent mixing of fuel and oxidizer is quantitatively expressed in terms of the intensity of turbulence and the Lagrangian correlation coefficient. At present there are very little data available regarding these quantities which can be used in the design and development of rocket engines.

For the past six years, a series of experiments has been conducted at Tulane University to determine the intensities of turbulence and the Lagrangian correlation coefficients in rocket combustion chambers using different combinations of fuel and oxidizer. The method used consisted of experimentally measuring the diffusion of a tracer gas. The intensity of turbulence and the Lagrangian correlation coefficient were calculated from the diffusion measurements using a combination of Taylor's [1] turbulent diffusion theory and a numerical procedure for solving the conservation equations of fluid mechanics. In the calculations, the turbulence field was assumed to be isotropic throughout the combustion chamber and homogeneous only in the radial and circumferential directions but not in the axial direction. The Lagrangian correlation coefficient was assumed to be an exponential function of the dispersion time. In earlier work, the intensities of turbulence and the Lagrangian correlation coefficients in the combustion chambers of a small LOX-heptane rocket [2] and a GOX-GH_2 rocket [3] were determined. The present work is the latest in the series of the experiments conducted.

The objective of the present work is to investigate the intensity of turbulence and the Lagrangian correlation coefficient in a liquid oxygen (LOX) and gaseous hydrogen (GH_2) rocket combustion chamber. These quantities were experimentally determined by a tracer gas diffusion method similar to that used in the earlier work. A combination of Taylor's turbulent diffusion theory and a numerical method [4] for solving the conservation equations of fluid mechanics was used to calculate the intensity of turbulence and the Lagrangian correlation coefficient.

II. DESCRIPTION OF EXPERIMENT

(1) Experimental Apparatus

A small rocket engine, as shown by Figure 1, using liquid oxygen and gaseous hydrogen and operating at a normal chamber pressure of 150 psia was used for the experiments. The propellants were injected in the form of co-axial jets from seven ports in the injector. Helium was used as the tracer gas and could be injected at various points along the centerline of the combustion chamber through the helium injection strut. A sample probe passing across the combustion chamber along a diameter was used to withdraw gas samples. This probe contained six sample ports and could be moved laterally across the chamber or rotated circumferentially about the chamber centerline. Further, the sample probe could be placed at several longitudinal stations.

The combustion chamber walls, the tracer gas injector and the sample probe are water-cooled.

(2) Experimental Procedure

An automatic timing device was used to fire the rocket engine and take the samples. About 1 1/2 seconds are required for the engine to reach equilibrium. During this time the sample lines were vented to the atmosphere and the helium tracer gas was injected so that equilibrium condition could be reached. Samples were withdrawn for about one second and collected in sample bottles for later analysis.

(3) Analysis of Samples

A method combining weight analysis, absorption methods and gas chromatography was used to analyze each sample containing water, oxygen, hydrogen and helium. More than 90% of the sample was water whose weight could not be determined either by absorption or by gas chromatography. Therefore, the sample bottle was weighed before the analysis, and again after the analysis had been completed and the bottle evacuated. This allowed the total weight of the sample to be determined.

Before the analysis was to begin, the sample bottle was charged with argon to a pressure of 20 psig at room temperature. With the pressure and temperature of the sample plus argon known, the mass of each component could be calculated using the volume fraction information from the gas analysis described below.

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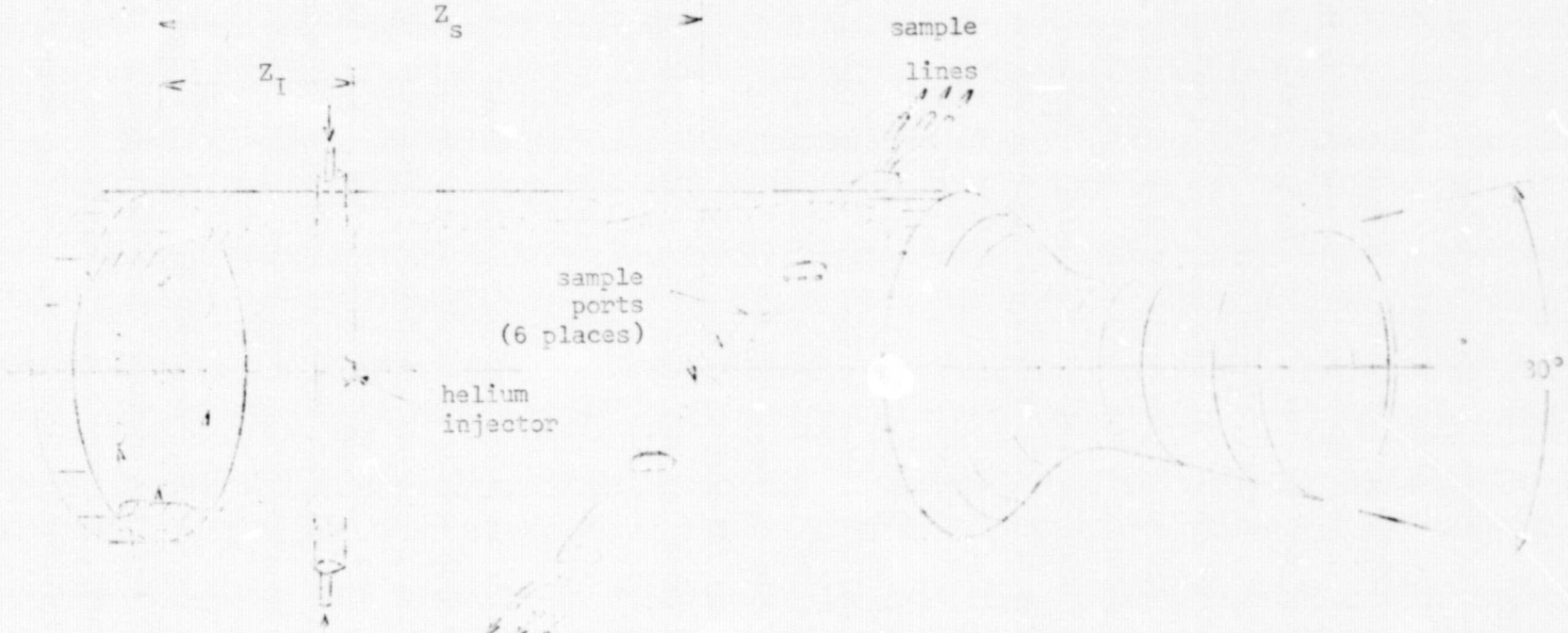
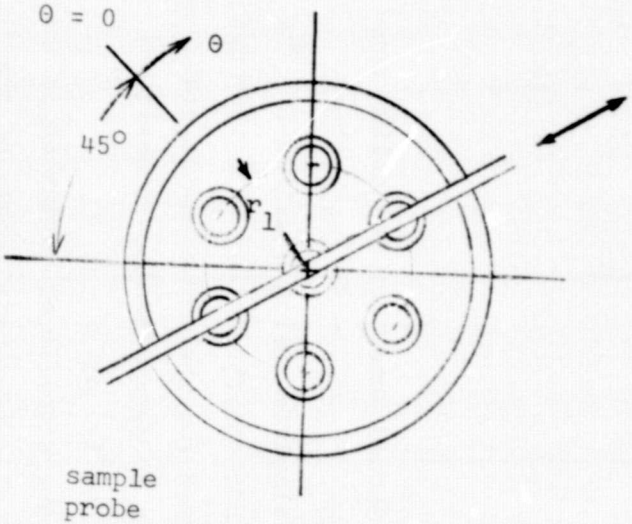


(a) The Rocket Engine

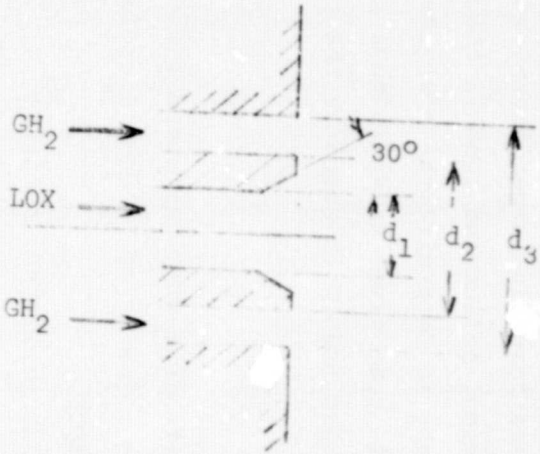
Chamber dia. = 2.34 in
(5.94 cm)
Throat dia. = 1.00 in
(2.54 cm)
Exit dia. = 2.00 in (5.08 cm)
Mass flow rate LOX = .47 lb/sec
(.21 Kg/sec)
Mass flow rate GH_2 = .086 lb/sec
(.038 Kg/sec)

Figure 1
Experimental Configuration



r_1 = 0.80 in (2.03 cm)

(b) Propellant Injector



d_1 = 0.063 in (0.16 cm)

d_2 = 0.188 in (0.50 cm)

d_3 = 0.218 in (0.55 cm)

(c) Typical Propellant Injector Element

Figure 1 Experimental Configuration (concluded)

The volume fraction of oxygen and most of hydrogen were measured by selective absorption using an Orsat analyzer. The absorption method was used because it was well suited for analyzing these gases in large concentrations.

The remaining sample which contained argon, helium and a small amount of hydrogen was analyzed using gas chromatography to determine the concentration of helium and hydrogen in a manner similar to that given by Villalobos and Nuss[5]. A Linde 5A molecular sieve colume was used with argon as the carrier gas.

(4) Experimental Data

Gas samples were taken from three longitudinal stations along the combustion chamber. For each of these stations a series of helium injection points along the chamber centerline were investigated.

A typical helium concentration profile is presented in Figure 2. The experimental data show considerable scatter, a point which will be discussed later in the report. A "best fit" symmetrical curve was drawn by hand through the data points to represent the helium concentration distribution. The mean square dispersion radius $\overline{r^2}$ of the spread of the helium tracer gas at a sample station was obtained from the helium concentration distribution according to the relation

$$\overline{r^2} = \frac{\int_0^\infty m_{He} r^3 dr}{\int_0^\infty m_{He} r dr} \qquad (1)$$

that is, by taking the zero moment and the second moment of the helium concentration distribution at the sample station. For each of the helium concentration profiles, a value of $\overline{r^2}$ was calculated using Equation 1. The values of $\overline{r^2}$ as a function of the distance between the helium injection point and the sample station are plotted in Figure 3 for the three sample stations investigated. These results were used later to determine the intensity of turbulence and the Lagrangian correlation coefficient.

The experimental results did not show any significant variation in the spread of the helium concentration with the circumferential angle of the sample probe. This shows that the assumption of the circumferential homogeneity of turbulence in the combustion chamber is satisfactory.

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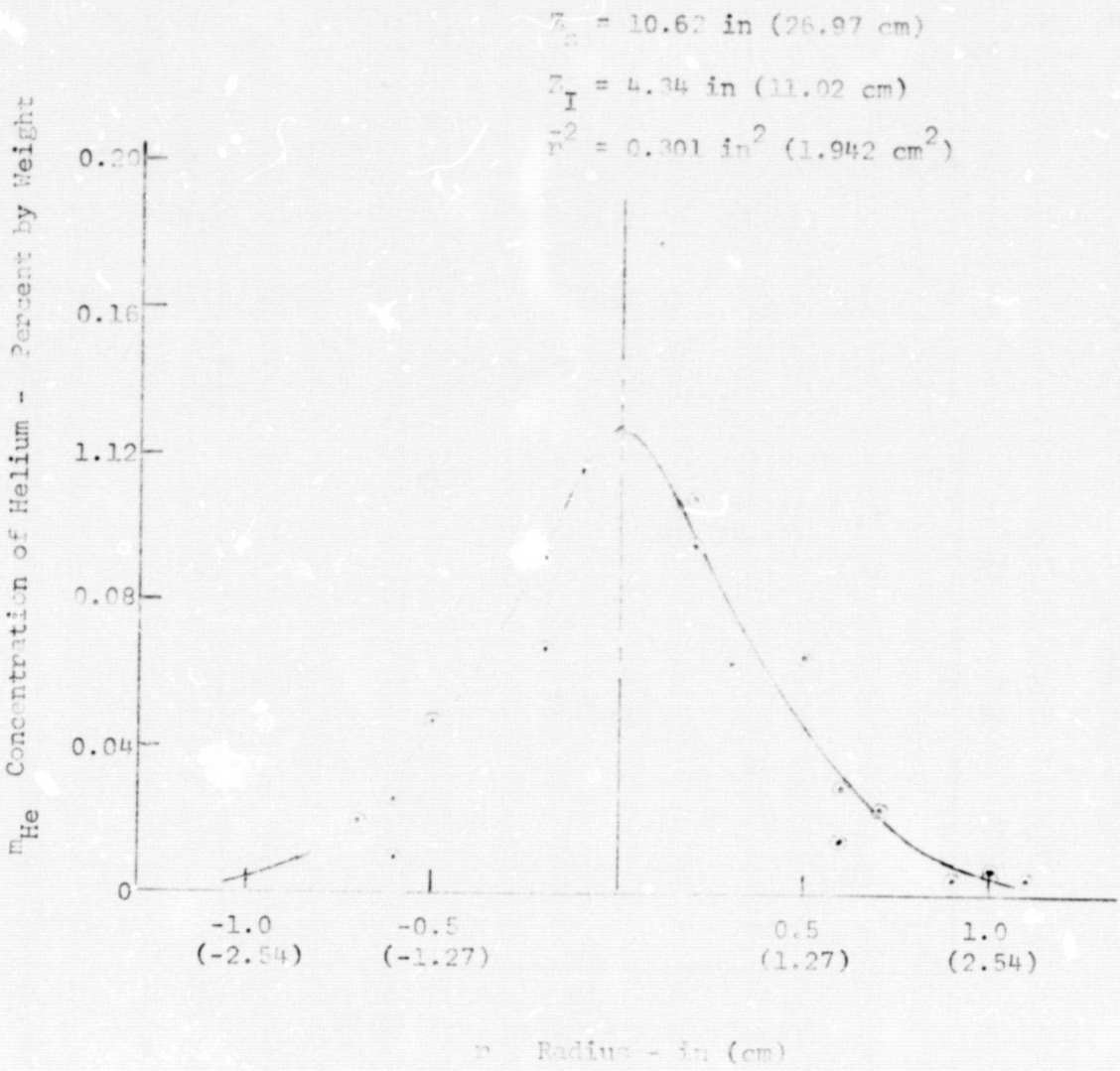


Figure 2 Typical Experimental Helium Concentration Profile

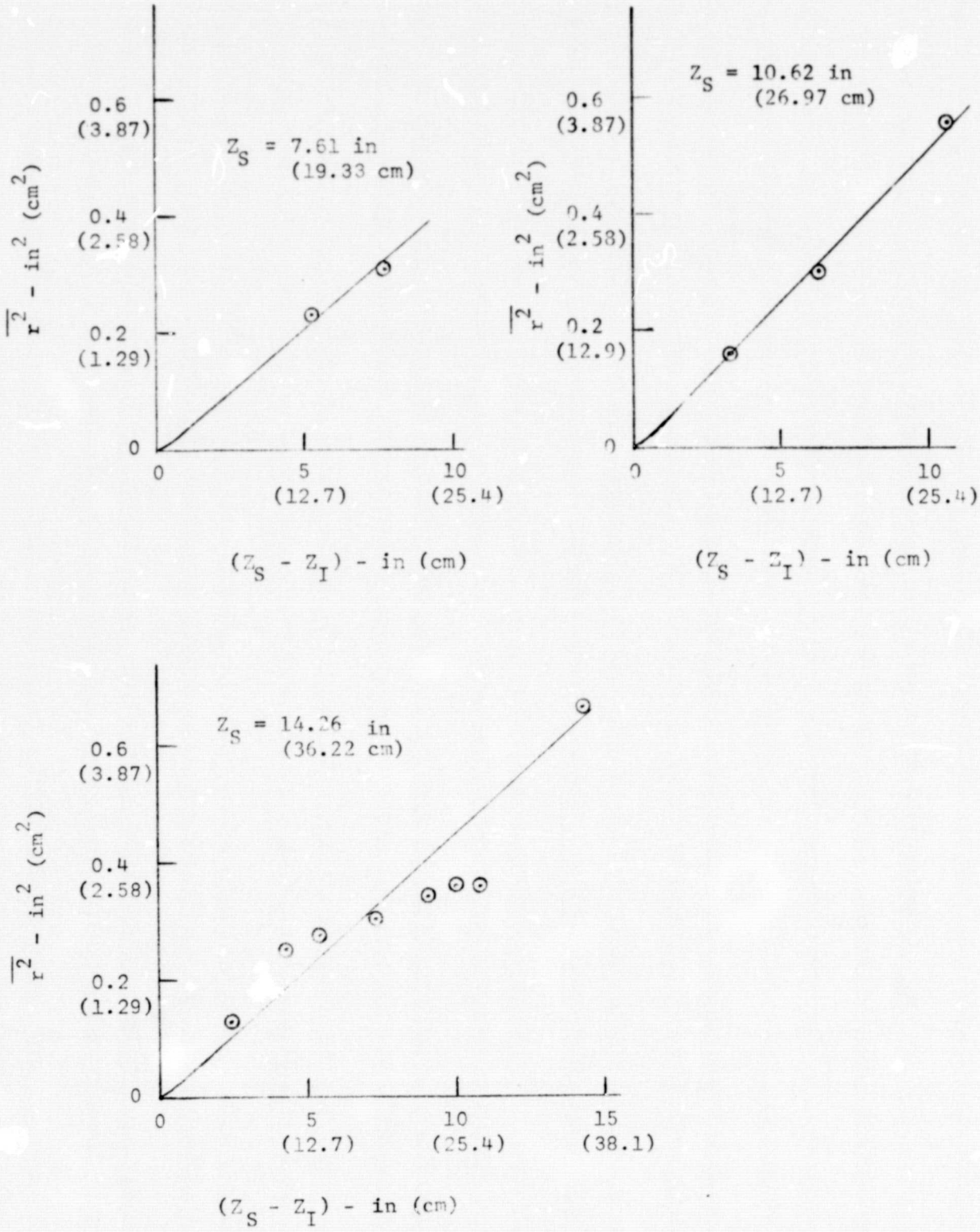


Figure 3 - Experimental Mean Square Dispersion Radii

III. ANALYSIS OF THE EXPERIMENTAL RESULTS

(1) Steady State Assumption

As was mentioned earlier in this report, the data exhibits considerable scatter. An accuracy analysis has been performed and it indicated that the scatter in the data should be an order of magnitude less than was observed. Also, all of the steps in the sample gathering and analysis procedure have been thoroughly checked. It has been concluded that the scatter in the data represent a true measure of the variation present in the combustion chamber. Since the sample time was about one second in duration this would indicate some type of very low frequency instability. It might even mean that the steady state burning pattern in the chamber is in some way dependent on the ignition history.

A basic assumption of the analysis herein is that a time average of the diffusion of the tracer gas can be obtained by averaging measurements from several different runs. This is equivalent to assuming steady state turbulent flow as opposed to non-steady flow.

(2) Equations of the Turbulent Diffusion

In analyzing turbulent diffusion, G. I. Taylor used the Lagrangian approach by considering the path of a marked fluid particle during its motion through the flow field, and developed an equation relating the displacement of the particle to the turbulent velocity. This formulation was based on the assumption that the turbulence was isotropic and homogeneous throughout the flow field.

For the present work, Taylor's turbulent diffusion theory was employed to analyze the turbulent diffusion in the combustion chamber. However, the original assumption was extended to consider that the turbulence field was inhomogeneous in the axial direction. Based on this assumption, the equation for the mean square dispersion radius $\overline{r^2}$ in the cylindrical coordinates can be written as

$$\overline{r^2} = 4 \int_0^t dt' \int_0^{t'} R_L(\tau) \sqrt{\overline{v'^2}\,(t')} \sqrt{\overline{v'^2}\,(t'')}\, dt'' \qquad (2)$$

where t' and t'' are two dispersion times of the same fluid particle and $\tau = t'' - t'$. The Lagrangian correlation coefficient $R_L(\tau)$ in the equation is defined as

$$R_L(\tau) = \frac{\overline{v'(t')\, v'(t'')}}{\sqrt{\overline{v'^2}\,(t')}\sqrt{\overline{v'^2}\,(t'')}} \qquad (3)$$

In order to solve Equation 2, it is necessary that the Lagrangian correlation coefficient be represented by a suitable function. Measurements of turbulent flows by many researchers [6] have shown that the Lagrangian correlation coefficient can for many situations be represented by an exponential function. In particular, Taylor also used an exponential function in his formulation. For the present work, the Lagrangian correlation coefficient was approximated by the form

$$R_L(\tau) = e^{-\alpha\tau} \qquad (4)$$

where α is a constant.

The variables $\overline{r^2}$, R_L and $\sqrt{\overline{v'^2}}$ in Equation 2 are functions of the dispersion time. Since the flow in the combustion chamber is considered to be steady, the dispersion time, t, required for a fluid particle to travel an axial distance from the point of release, Z_I, to any point of interest, Z is related to the axial coordinate by the expression

$$t = \int_{Z_I}^{Z} \frac{dZ}{\bar{u}(Z)} \qquad (5)$$

where $\bar{u}$ is the mean axial flow velocity. Therefore the variables mentioned above are also functions of Z.

The mean axial flow velocity was not measured in the experiment but was calculated analytically by the numerical method of the CICM computer program developed by Rocketdyne[4]. The calculated results of the mean axial flow velocity are presented in Figure 4.

(3) Determination of the Turbulence Parameters

Using the experimental values for the mean square dispersion radii (Figure 3), Equation 2 can now be solved for the root mean square (rms)

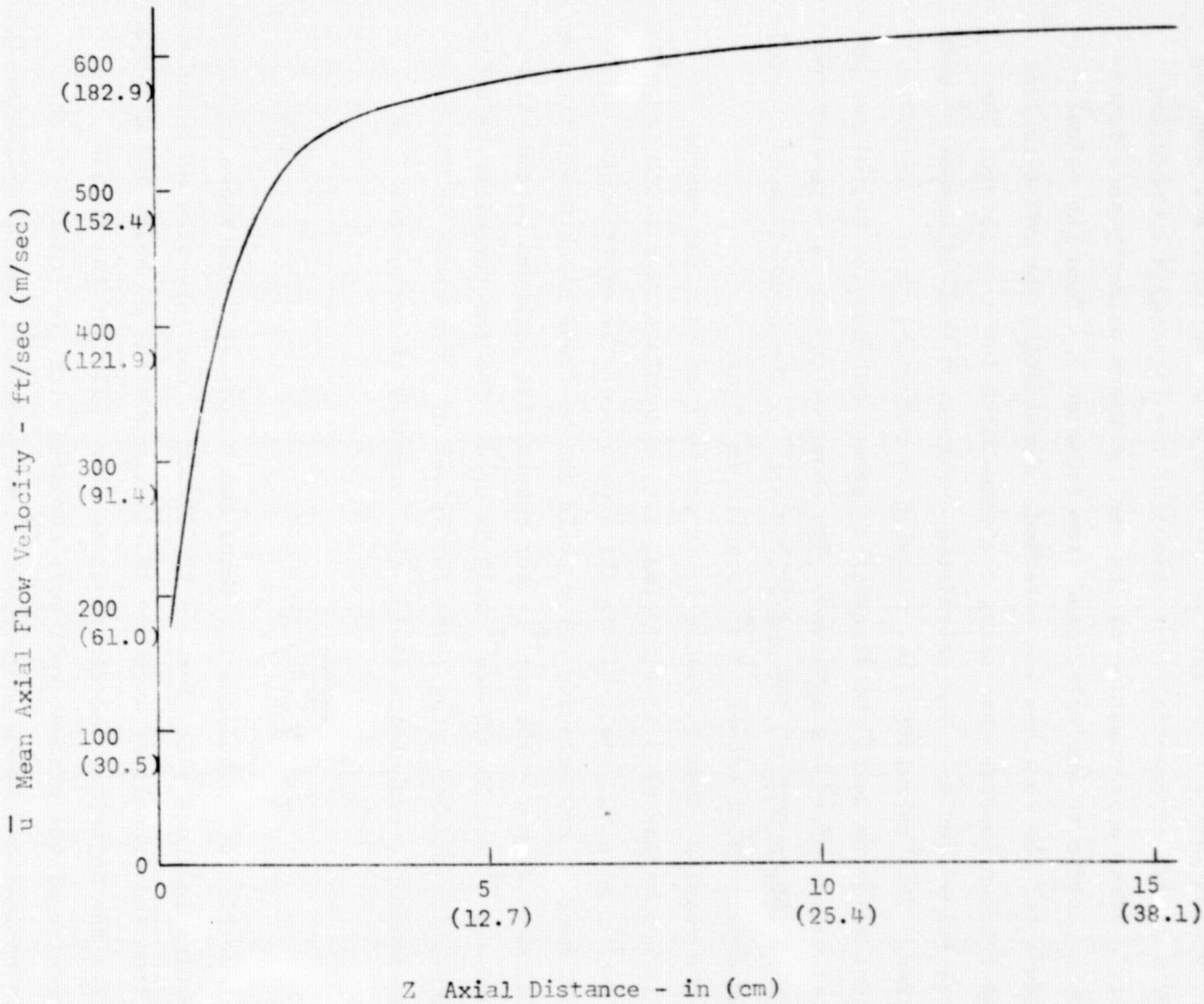


Figure 4 Mean Axial Flow Velocity

turbulent velocity using a numerical method. The calculation procedure is given below.

With the mean square dispersion radius as a known variable and assuming a value for α in the exponential expression for the Lagrangian correlation coefficient, a first approximation of the rms turbulent velocity as a function of the z coordinate was calculated from Equation 2. Then the calculation procedure for the equation was reversed. Considering the rms turbulent velocity as a known function and using the same value for α as before, the equation was solved for $\overline{r^2}$. The calculated and experimental values of $\overline{r^2}$ were then compared. This calculation was repeated by adjusting the values of the rms turbulent velocity until satisfactory agreement between the calculated and experimental values of $\overline{r^2}$ was achieved. The above calculations were performed for α equal to 100, 4,000, 10,000 and 20,000 sec^{-1}. The comparison of the calculated and experimental values of $\overline{r^2}$ is shown in Figure 5.

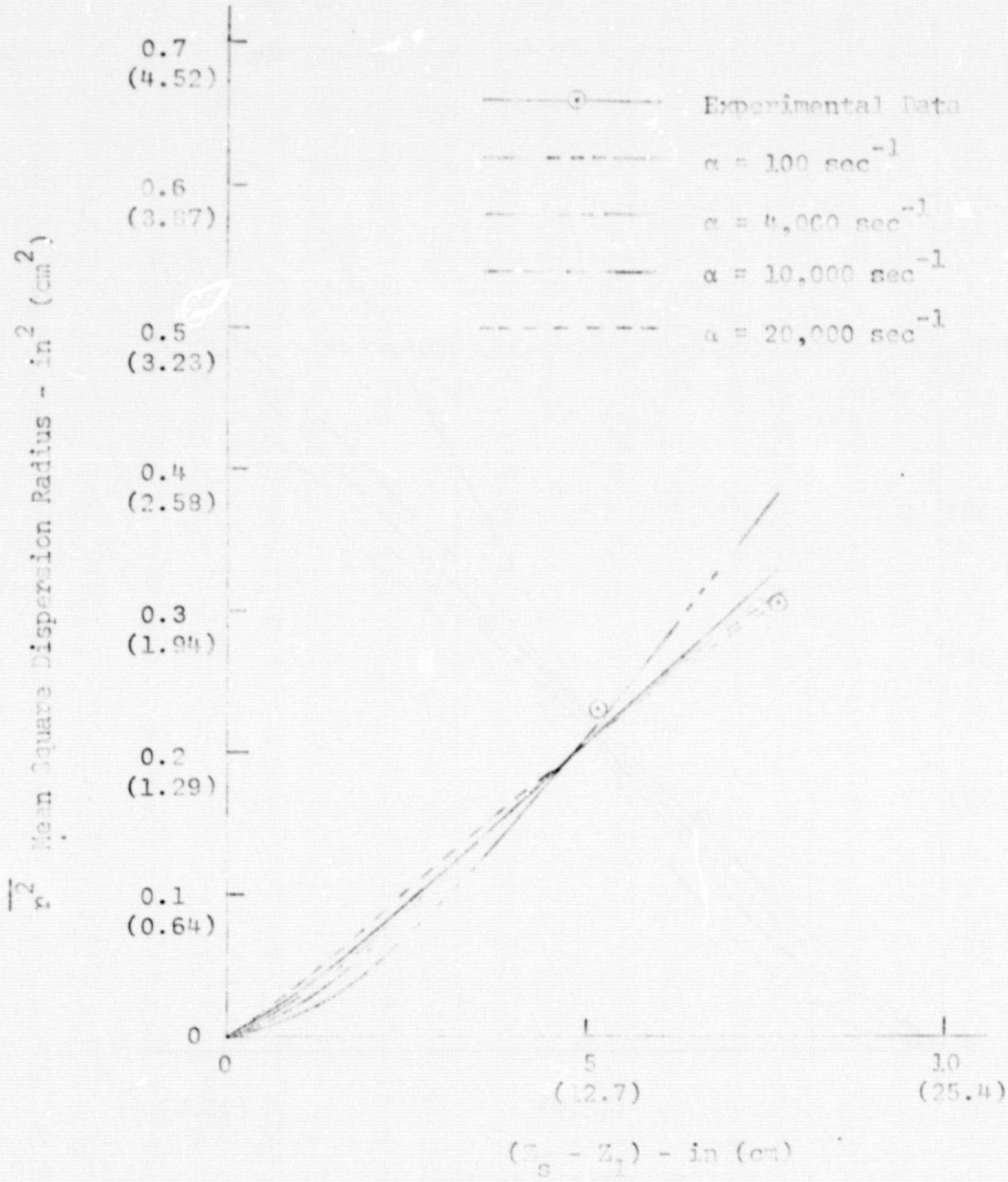
From the results shown in Figure 5, it can be seen that the curves for the three larger values of α investigated, i.e. α equals either 4,000, 10,000 or 20,000 sec^{-1}, give agreement within the accuracy of the experimental data. On the other hand, a rms velocity curve could not be found which would fit the experimental data when α = 100 sec^{-1}. For comparative purposes herein values of α = 4,000 sec^{-1} and 10,000 sec^{-1} will be used. The rms turbulent velocity for the combustion chamber using these two values of α are shown in Figure 6.

For an isotropic turbulence field, the intensity of turbulence T is defined as

$$T = \sqrt{\overline{v'^2}} \Big/ \overline{u} \qquad (6)$$

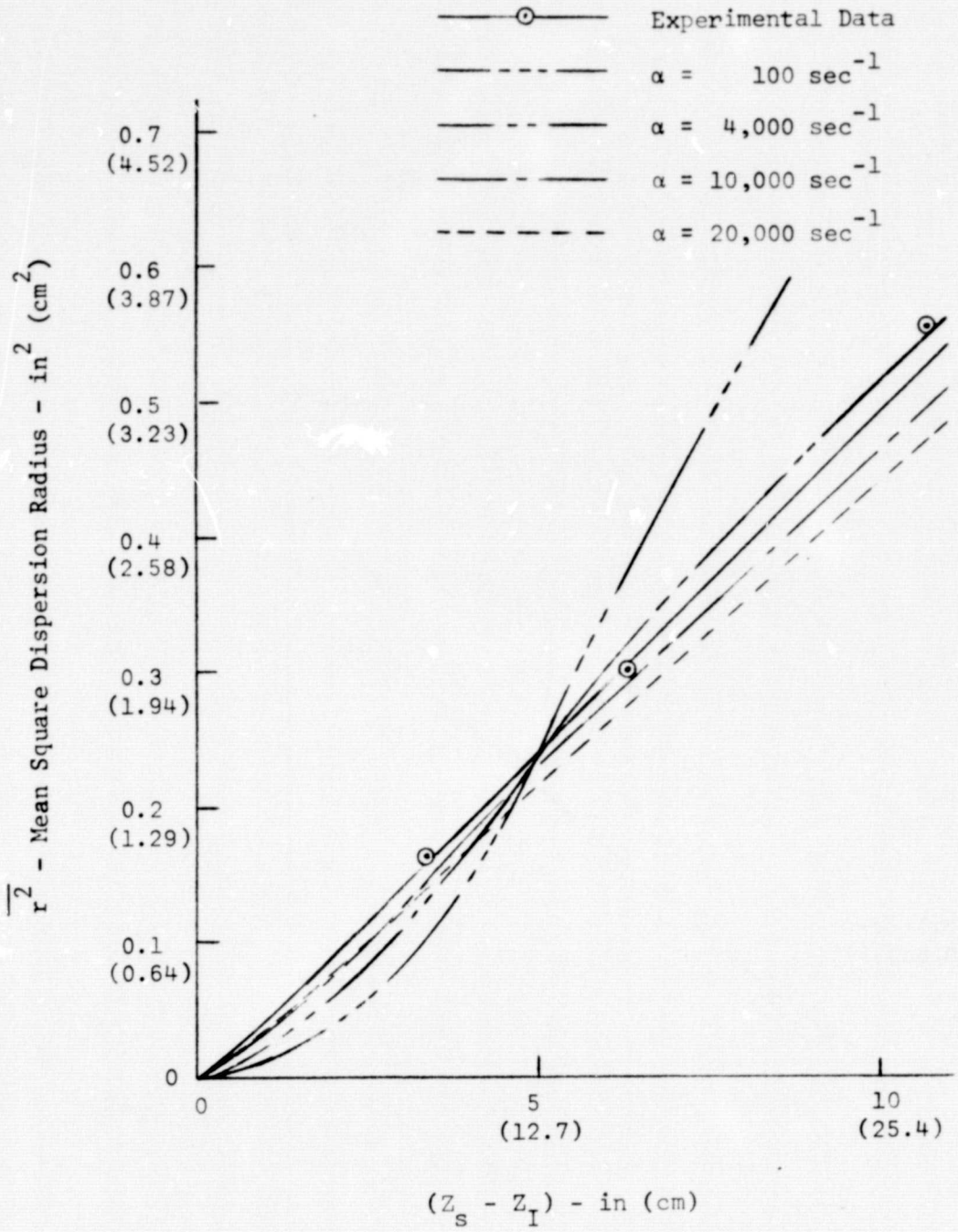
and the intensities of turbulence for these two values of α are shown on Figure 7. The results indicate that, for α = 10,000 sec^{-1}, the intensity of turbulence increases from the propellant injector to a maximum value of about 14% at about 7 inches from the injector, and decreases to about 11% near the nozzle.

The results of the present work were compared with the results of the previous investigations using LOX-heptane[2] and GOX-GH_2[3] as propellants. The three combustion chambers were identical except for the propellant combination and injector used. Figure 8 shows a comparison of the intensity of turbulence for these cases. Since the intensity of turbulence is dependent on the value of α, any comparison should be made using the same value of α. Since a value of α = 4,000 sec^{-1} gave satisfactory agreement with experimental data for each of



(a) Z_s = 7.61 in (19.37 cm)

Figure 5. Comparison of Experimental and Calculated Mean Square Dispersion Radius



(b) Z_s = 10.62 in (26.97 cm)

Figure 5 Comparison of Experimental and Calculated Mean Square Dispersion Radius (continued)

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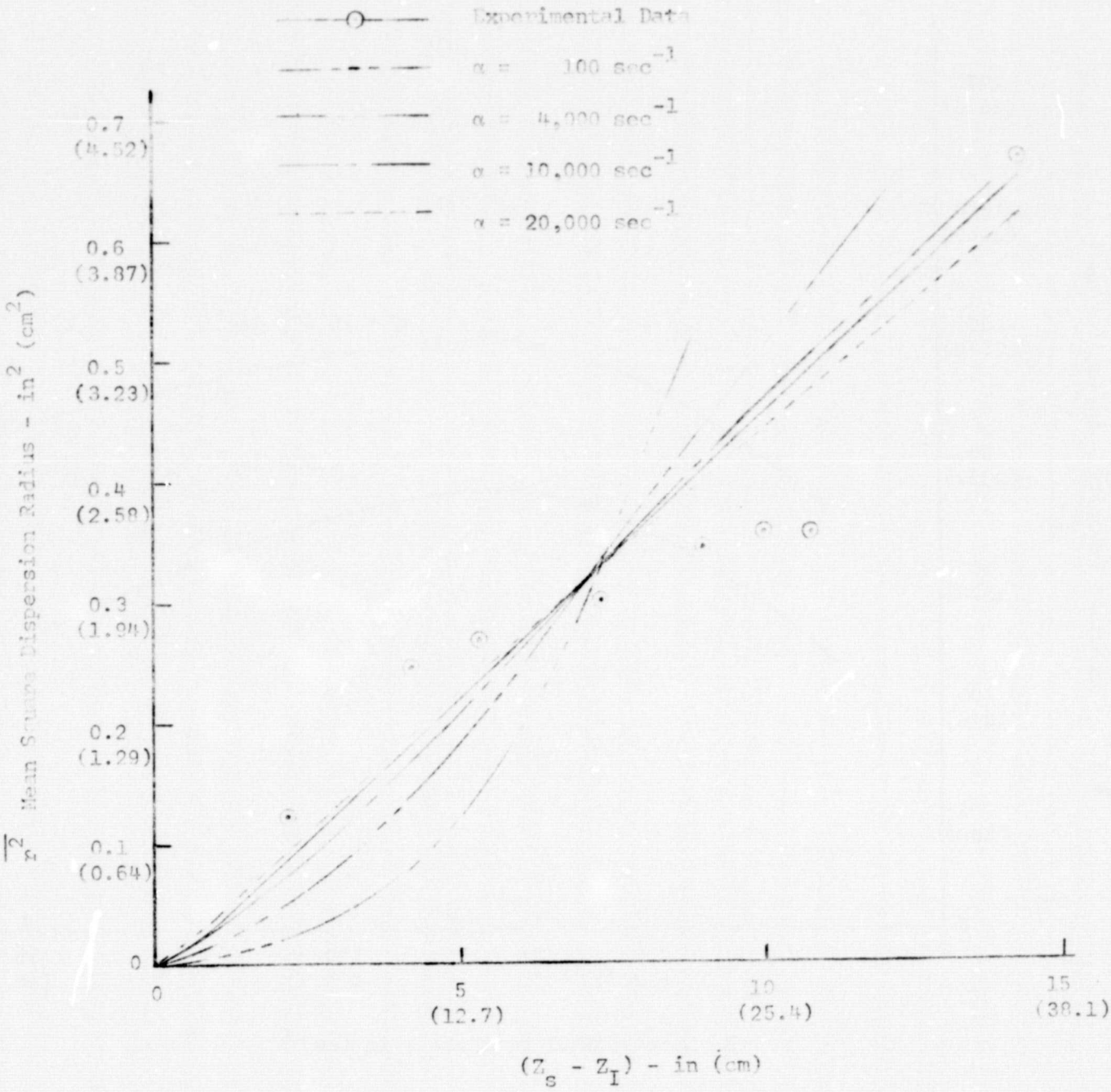

(c) Z_s = 14.26 in (36.2 cm)

Figure 5 Comparison of Experimental and Calculated Mean Square Dispersion Radius (concluded)

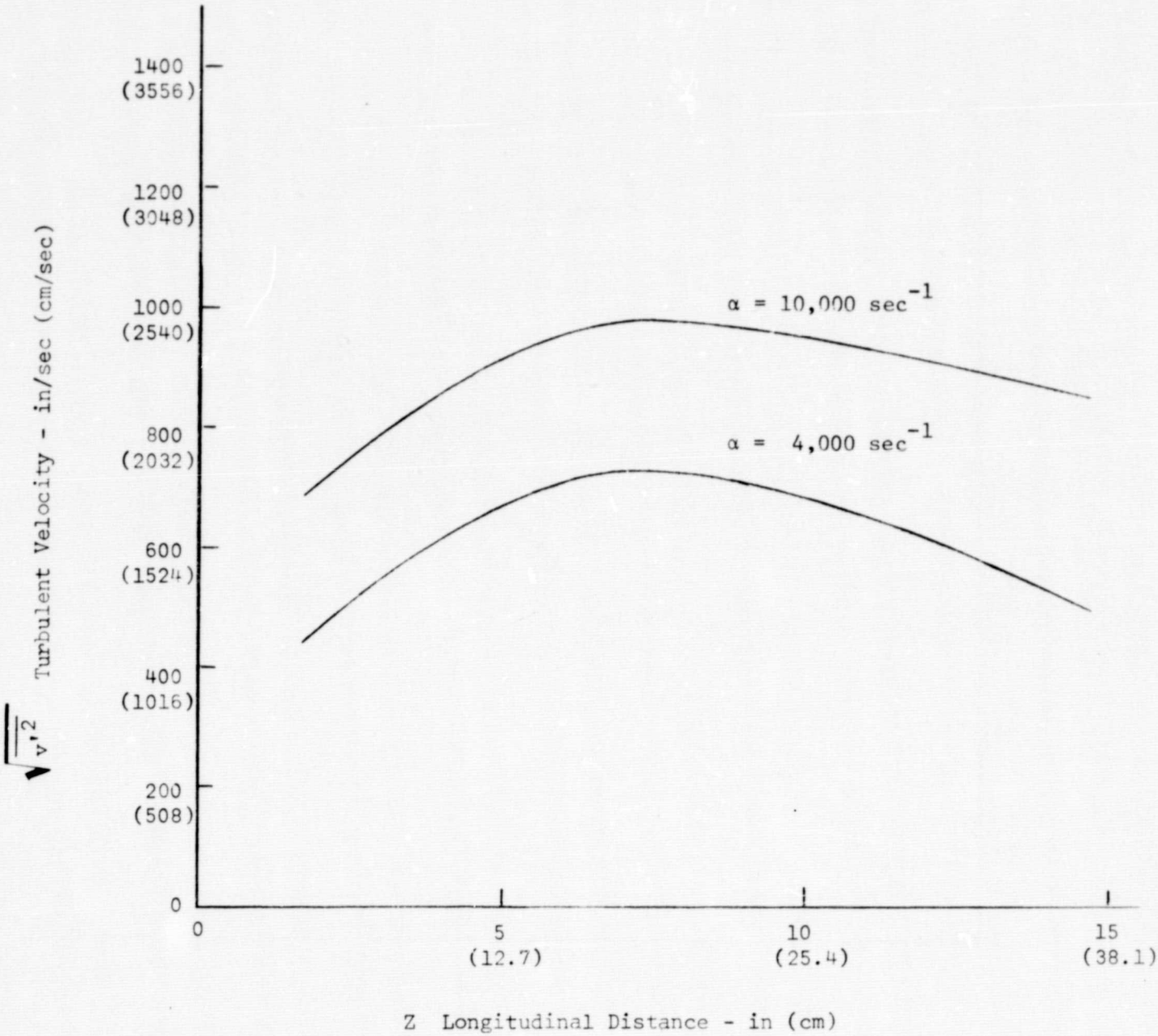

Figure 6 - Root Mean Square Turbulent Velocity

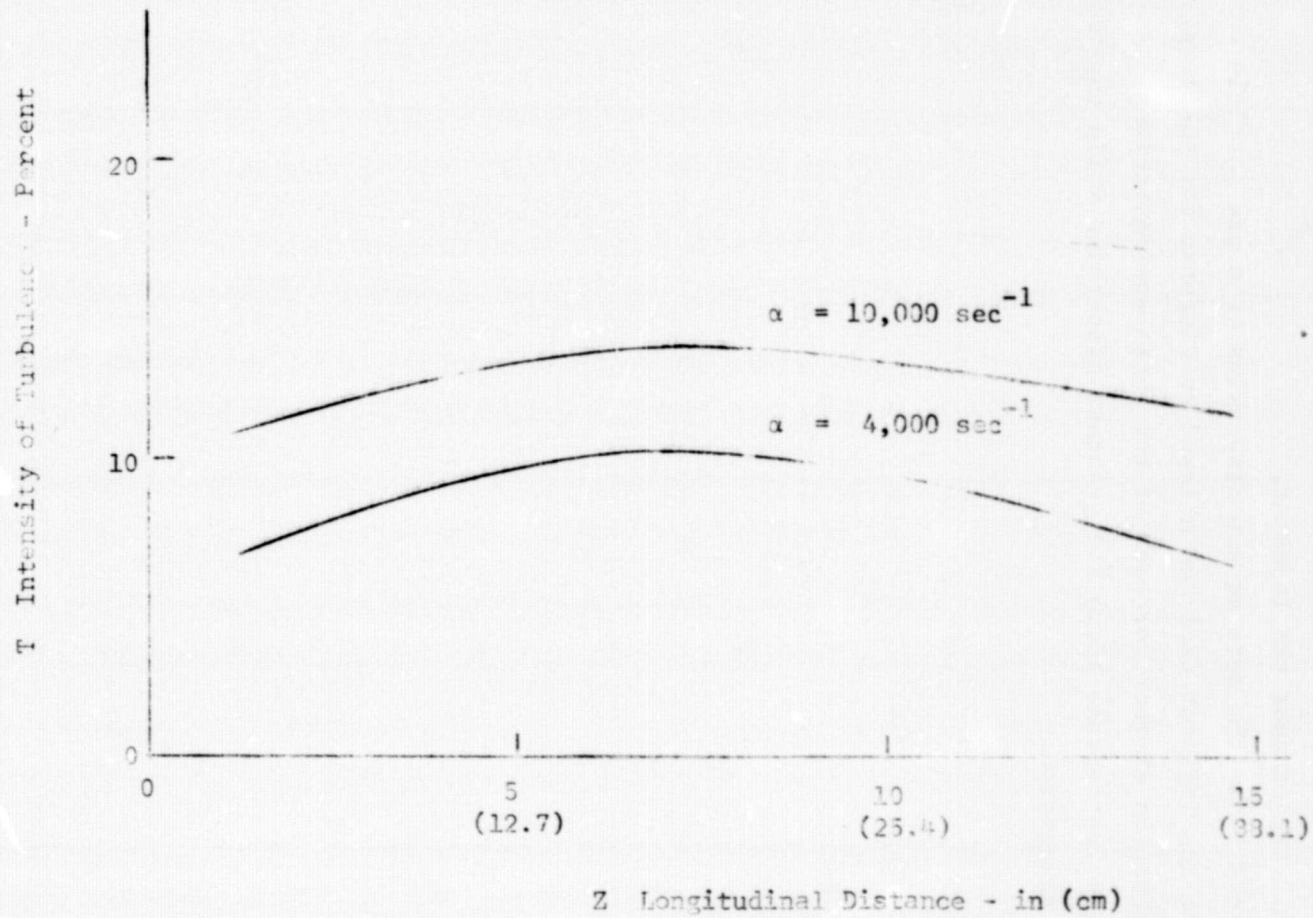

Figure 7 Intensity of Turbulence

the three configurations this value was used for comparative purposes in Figure 8. As can be seen the intensity of turbulence is greatest for the LOX-heptane configuration and is least for the GOX-GH_2 configuration except in one small region near the injector.

Figure 9 shows the mean square dispersion of a gas particle which is released at the injector face and allowed to disperse for the complete length of the combustion chamber for each of the three configurations. As would be expected the LOX-heptane shows the greatest dispersion while the GOX-GH_2 has the least dispersion.

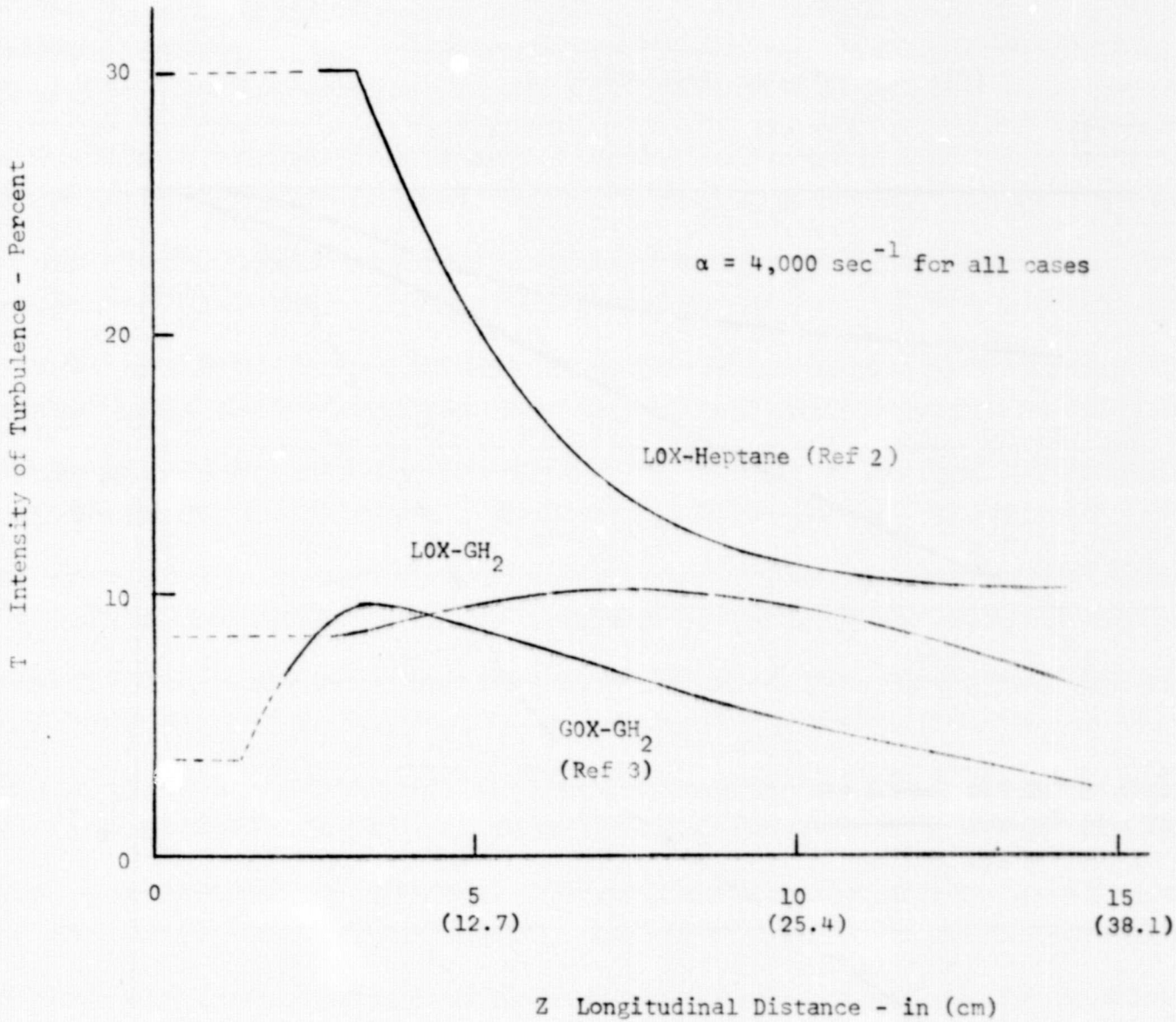

Figure 8 Comparison of Intensity of Turbulence

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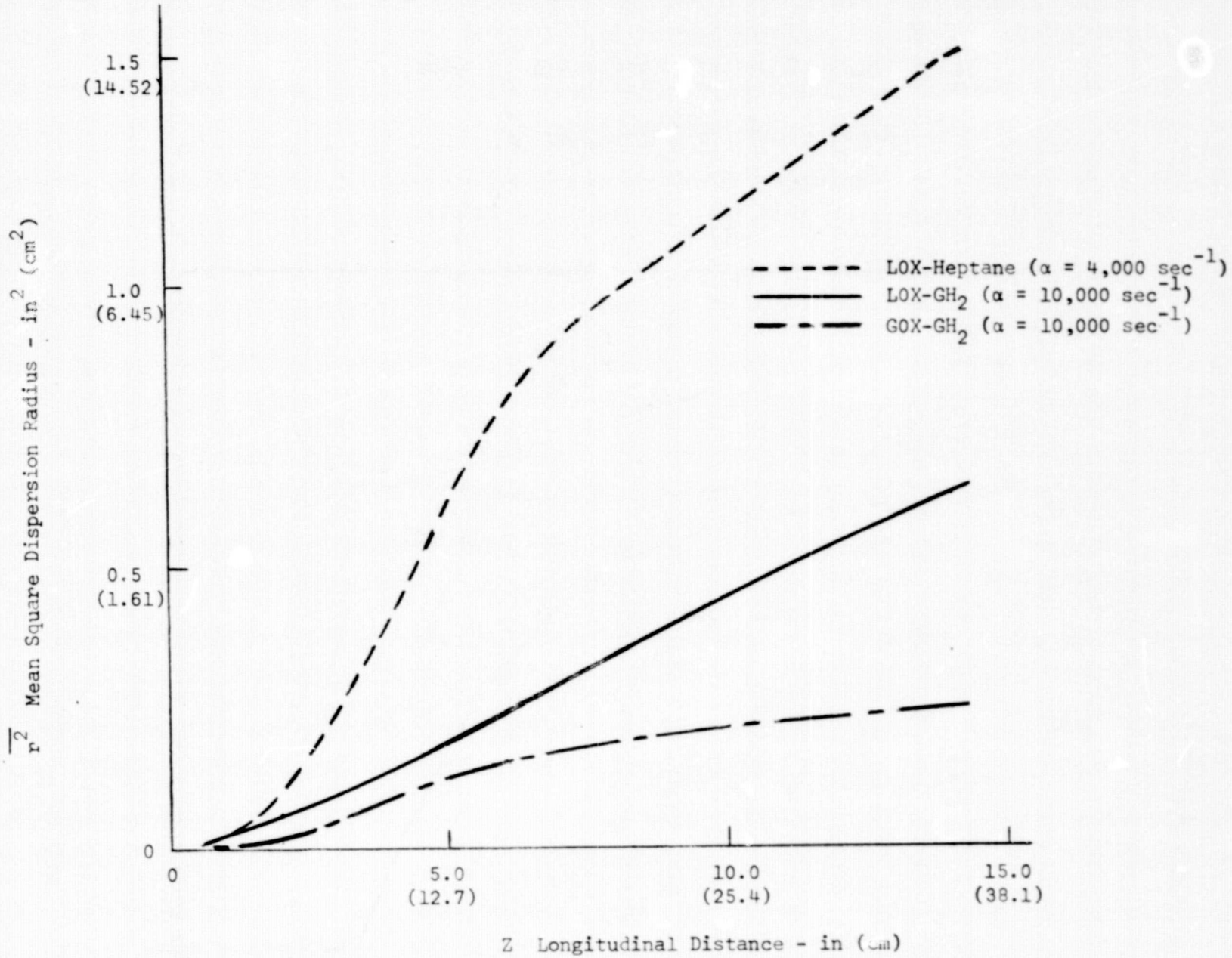

Figure 9 Mean Sqaure Dispersion Radius for Complete Combustion Chamber

CONCLUSIONS

The diffusion of a tracer gas in a LOX-GH_2 rocket combustion chamber has been measured, and the data analyzed using Taylor's turbulent diffusion theory to determine the intensity of turbulence and the Lagrangian correlation coefficient. The results show that the intensity of turbulence reaches a maximum about 7" downstream of the injector and decreases only slightly to about 12% just upstream of the nozzle. The Lagrangian correlation coefficient can be represented by an exponential function of the form $e^{-\alpha\tau}$ where $\tau = 10{,}000\ sec^{-1}$.

Among the three rocket combustion chambers investigated in the series of experiments at Tulane, the LOX-heptane rocket using a like-on-like injector produces the highest intensity of turbulence. For the LOX-GH_2 and GOX-GH_2 rockets using coaxial injectors, the maximum intensities of turbulence show only a small difference: 15% for the GOX-GH_2 rocket and 14% for the LOX-GH_2 rocket, although the overall turbulence in the GOX-GH_2 rocket was considerably less than in the LOX-GH_2 rocket. Furthermore, the maximum intensity of turbulence occurred farther downstream from the injector in the LOX-GH_2 rocket than that in the GOX-GH_2 rocket.

Scattering of the helium concentration data persistently occurred throughout the experiments using GOX-GH_2 and LOX-GH_2 propellants, despite efforts to improve the accuracy of the data. The scattering is believed to be due to an instability of the flow in the combustion chambers.

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