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GAS VELOCITY AND TEMPERATURE NEAR A LIQUID ROCKET INJECTOR FACE

by

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16. Abstract

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Average gas temperatures were found to be between 3100 (1700) and 3500°F (1950°C) and the average gas velocities between 550 (170) and 840 feet/second (260 m/sec).

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FORWARD

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ABSTRACT

The gas flow near the injector of a liquid propellant rocket was investigated by rapidly inserting butt-welded platinum-platinum rhodium thermocouples through the injector into the chamber. The transient responses of the thermocouples were analyzed to determine average gas temperatures and velocities. A method of fitting exponential curves to repeated measurements of the transient temperature at several positions near the injector face produced consistent results. Preliminary tests yielded gas flow directions and gas composition at the injector face.

Average gas temperatures were found to be between 3100 (1700) and 3500°F (1950°C) and the average gas velocities between 550 (170) and 840 feet/second (260 m/sec).

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SUMMARY

Average gas velocities and temperatures near the injector face of a liquid rocket engine were determined by means of a transient thermocouple experiment. The investigation, which was performed on a heptane-liquid oxygen rocket engine operating at 300 psia chamber pressure and approximately 250 pounds thrust, consisted of rapidly inserting butt-welded platinum-platinum 10% rhodium thermocouples through the injector face and into the chamber gases.

The recorded transient temperature responses of the thermocouples were analyzed by fitting a smooth exponential curve to each experimental trace. The parameters of the exponential curve were used to determine average gas temperature and wire heat transfer coefficient.

Average gas velocity was calculated by using a small wire Nusselt number relation, in which the gas properties were evaluated from gas composition data obtained in an auxilliary experiment. The gas flow directions were obtained by means of a directional erosion experiment.

Transient thermocouple measurements were made at four locations on the injector face. At each location, measurements were made .14 and .23 inches from the face.

The gas flow was found to spread radially across the injector from a location near the chamber wall. Average gas temperatures were found to be between 3100 and 3500°F and the average gas velocities between 550 and 840 ft/sec. Gas temperature and velocity measurements did not differ significantly at .14 and .23 inches from the injector face.

Fluctuations of heat transfer were observed to occur at rates of approximately 50 and 270-290 hertz. These fluctuations can be represented by variations in gas temperature of the order of ±1000°F.

The O/F ratio at the injector was found to be close to the overall engine O/F ratio, rather than a higher value predicted by a drop vaporization-combustion model.

INTRODUCTION

The prediction of heat transfer rates to a rocket injector from hot chamber gases requires knowledge of the nature of the gas flow near the face of the injector. Few investigations of injector face conditions had been previously performed, and the gas temperature, velocity, composition, and flow direction were unknown.

In the work reported herein, flow conditions near the injector were determined for a small heptane-liquid oxygen rocket engine. The rocket operated at approximately 300 psia chamber pressure and 250 pounds thrust, and a like-on-like impingement injector was used.

Average gas temperatures and velocities were determined by means of a transient thermocouple experiment, in which small thermocouples were rapidly inserted through the injector into the gas near the injector face. The recorded transient temperature responses of the thermocouples were analyzed for average gas temperature and velocity by a method described in this report.

Gas composition and flow direction were determined in the course of this work in supporting auxilliary experiments.

SYMBOLS

b	quartz coating correction term
c_p	specific heat of thermocouple wire
d	thermocouple diameter
h	convective heat transfer coefficient
k_f	thermal conductivity of gas
Nu	Nusselt number
Pr	Prandtl number
$Q_{chem.}$	chemical heat transfer source
$Q_{cond.}$	conduction through thermocouple leads
$Q_{gas\ rad.}$	thermal radiation from gas
$Q_{wire\ rad.}$	thermal radiation from wire
r	radius of thermocouple
Re	Reynolds number
T	thermocouple temperature
T_i	initial thermocouple temperature
T_g	gas temperature
t	time
Δt	time increment
α	absorbtivity of thermocouple wire
μ	gas viscosity
ρ	density of thermocouple wire
$\bar{\rho}$	density of gas
τ	thermocouple time constant

APPARATUS AND TEST PROCEDURE

A schematic of the thermocouple experiment is shown in Figure 1. The rocket engine operated at a nominal chamber pressure of 300 psia and burned liquid oxygen and heptane at an oxidizer/fuel ratio of 1.8. A like-on-like injector, as shown in Figure 2, was used.

Platinum-platinum 10% rhodium thermocouples of .010 and .020 inch diameter were used in the experiment. The thermocouples were butt-welded and closely approximated a continuous cylinder. A coating of quartz approximately .0005" thick was applied to the thermocouples to reduce the effect of catalytic heating.

Each thermocouple was formed into a "U" shape with the junction located on a leg of the "U". The junctions were located on the legs in order to minimize mutual flow interference between the thermocouples. Flow interference was also minimized by proper orientation of the thermocouples in the chamber using knowledge of the gas flow direction obtained in separate experiments described below. Full insertion of the thermocouple probes was achieved between 5 to 7 milliseconds by means of an air cylinder. Provision was made to allow testing at several positions on the injector face, as well as at different distances from the injector face.

Gas flow directions were determined by allowing small copper projections which protruded from the injector face to directionally erode during the rocket firing. The leading edges of the projections were shiny where some of the copper had been melted away and the

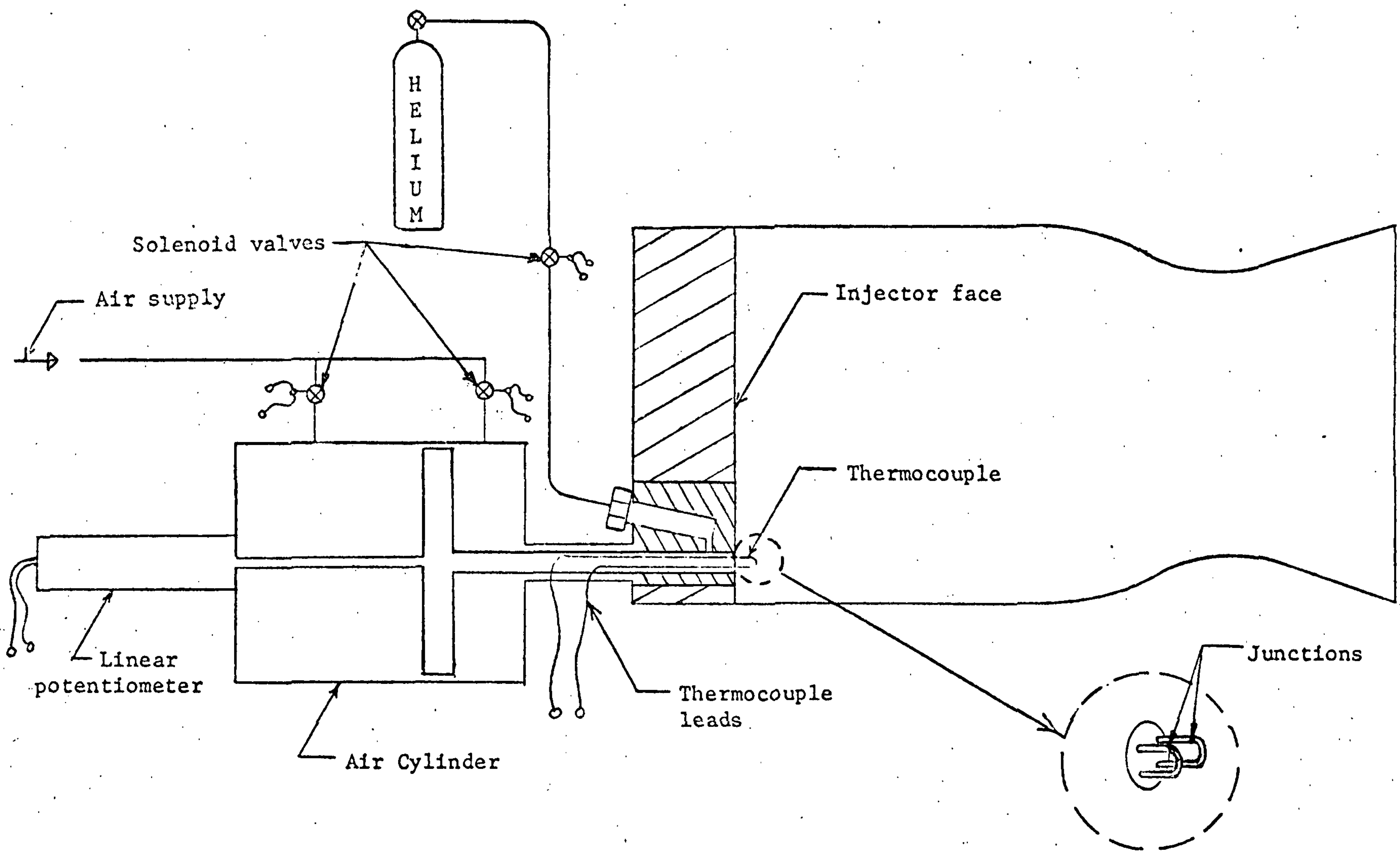


Figure 1. Schematic For Thermocouple Experiment

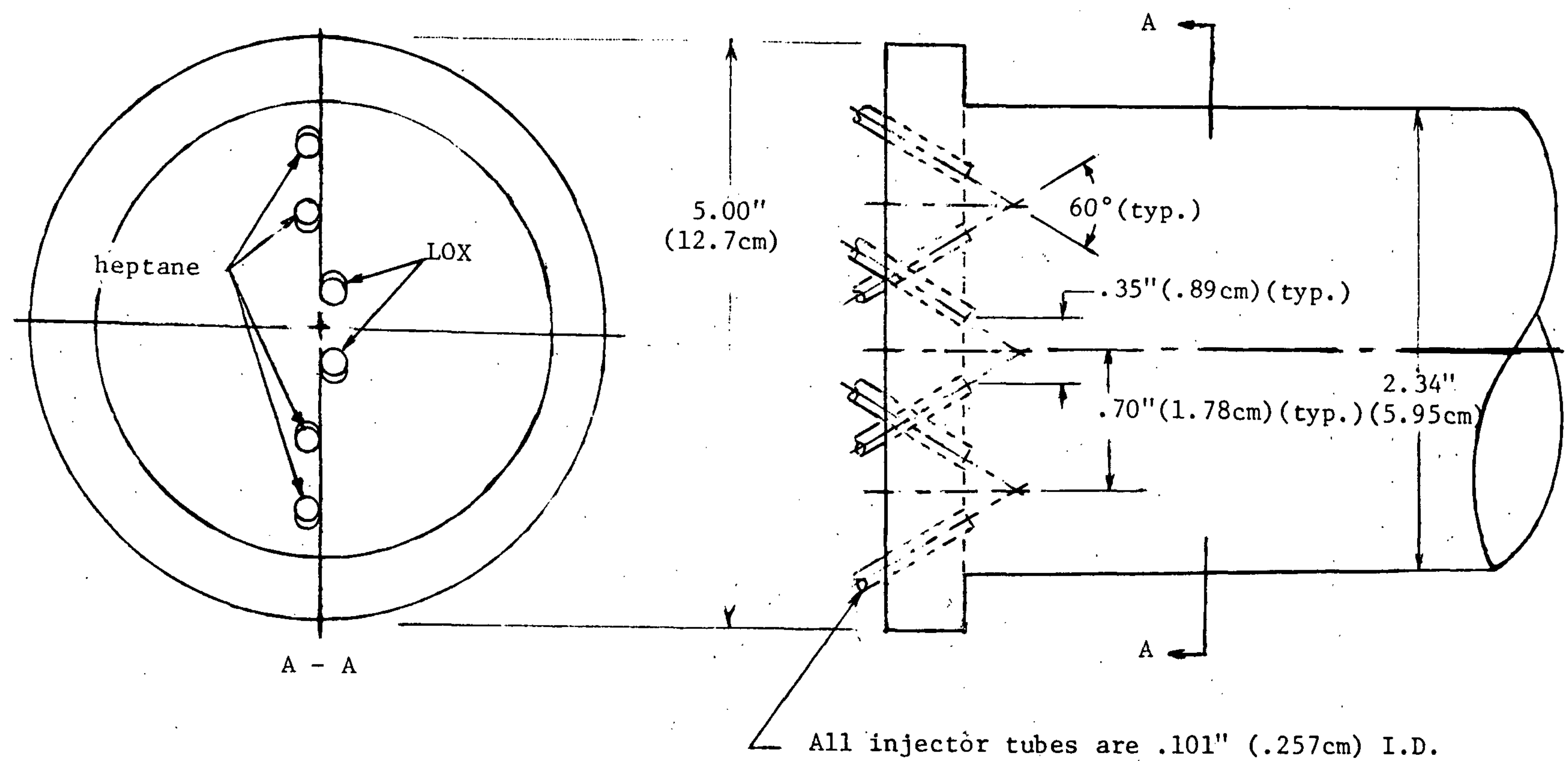


Figure 2. Injector

sheltered trailing region was black with soot deposits and unmelted. Flow directions consistent with the erosion experiment results were also obtained by releasing helium at a port on the injector and withdrawing gas samples at several positions around the helium injection port. The samples were analyzed for helium content by means of a gas chromatograph,and the sample position of maximum helium content was considered to lie directly downstream of the helium injection port.

The rocket firing was controlled by an automatic sequencing device which, upon the firing signal, ignited the rocket propellants and started helium cooling gas flow around the thermocouples. After approximately 1 1/2 seconds, which was the time required for the rocket to reach steady state operating conditions, the helium cooling gas flow was stopped and the thermocouple probe was inserted. The transient temperature responses of the inserted thermocouples were recorded on an oscillograph. A typical data trace is shown in Figure 3.

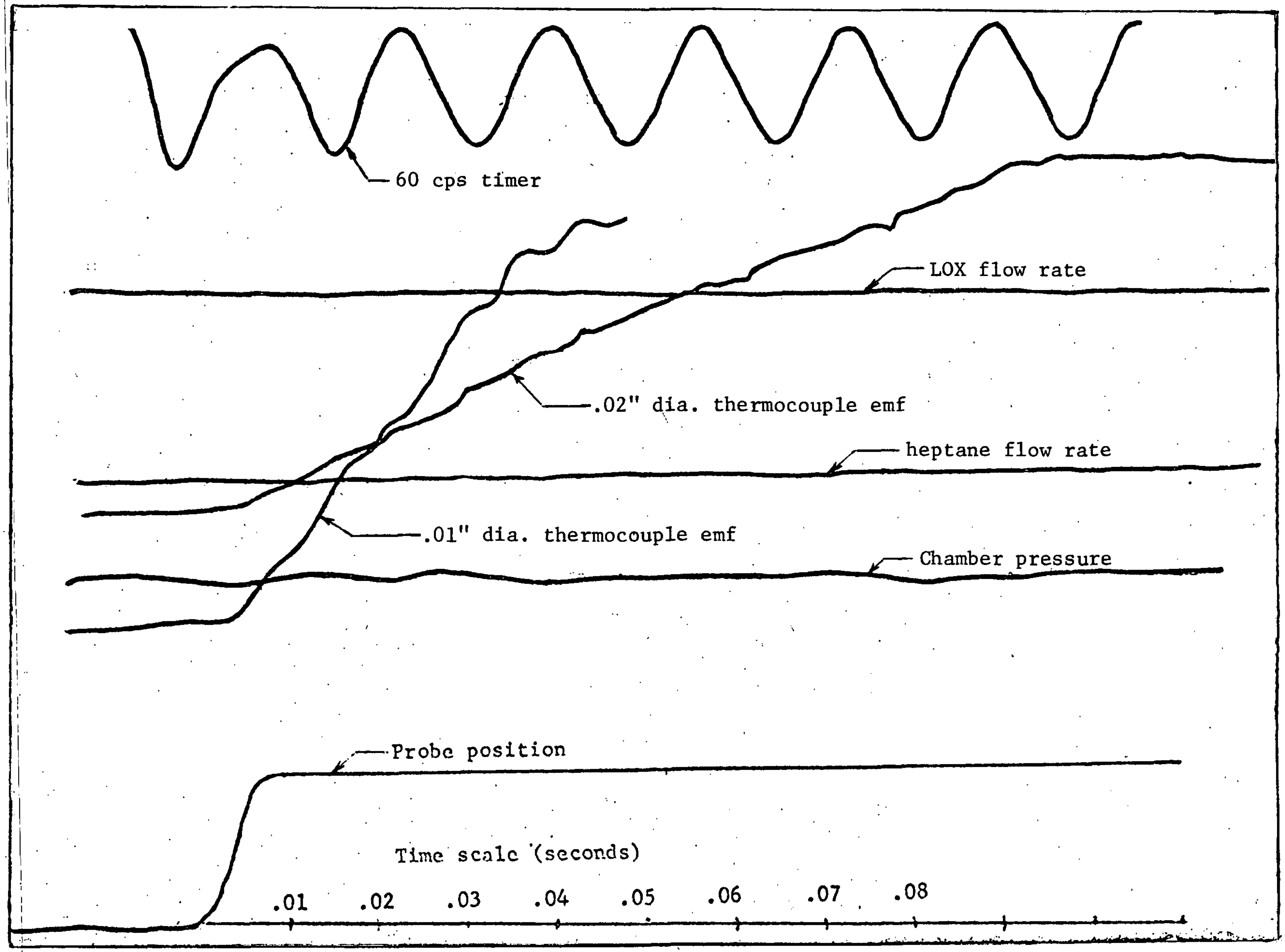


Figure 3. Typical Data Trace

ANALYTICAL METHOD

The emf traces obtained in the thermocouple experiment described above were analyzed to determine average gas velocity and temperature. This analysis was performed by developing an idealized model for the thermocouple in the gas flow and fitting an exponential curve to the transient temperature data traces.

For the analysis, the thermocouple is modeled as a right circular cylinder projecting from a cool wall into a crossflow. The convective heat transfer coefficient of the wire and the gas temperature are assumed to be constant with time and position. The temperature at any cross section of the thermocouple is assumed to be uniform although the wire temperature may vary with distance from the injector. An energy balance on the thermocouple model includes heat transferred to the wire due to convection, conduction through the leads, radiation from the wire and from the gas, and chemical dissociation. The energy equation is

$$r\rho c_p\dot{T} + 2h(T - T_g) + Q_{wire\ rad.} - \alpha\, Q_{gas\ rad.} + Q_{cond} - Q_{chem} = 0 \qquad (1)$$

where r is the thermocouple radius, ρ and c_p are the thermocouple density and specific heat, respectively; T is the thermocouple temperature and T_g is the gas temperature, h is the convective heat transfer coefficient, and the Q's are the various non-convective sources of heat transfer noted above. These non-convective contributions were found to be small in comparision with convection [1] so that the energy equation becomes

$$r\rho c_p\dot{T} + 2h(T - T_g) = 0 . \tag{2}$$

The quartz coating of the thermocouple wires acts as thermal insulation and affects the assumption that the temperature of the wire at any cross section is uniform. From an energy balance across the quartz coating and the assumption that the mass of the quartz is small in comparison with the wire mass, a correction to equation (2) is found to be[1]

$$r\rho c_p\dot{T} + \frac{2h}{(1 + b)} (T - T_g) = 0 . \tag{3}$$

For the larger .02" dia. thermocouples, b was found to be approximately .055. As will be discussed later, data from the .01" dia. thermocouples were not used.

The equation for the temperature of a cylinder instantaneously thrust into a constant thermal environment is

$$(T - T_i) = (T_g - T_i)\ (1 - e^{-t/\tau}) \tag{4}$$

where $\tau = r\rho c_p(1 + b)/2h$ and T_i is the initial temperature of the thermocouple. It was desired to fit a curve of the form of equation (4) to the experimental data. Giedt[2] has shown that for the constant environment, the difference between two successive thermocouple temperatures separated by a time increment Δt is

$$T_{t + \Delta t} - T_t = (T_g - T_i)e^{-t/\tau}\ (1 - e^{-\Delta t/\tau}) . \tag{5}$$

He then showed that if the exponential response is divided into many equal time increments of size Δt, successive temperature differences are related only to $e^{-t/\tau}$ because Δt is constant. Therefore, in order to relate the model to the experimental temperature data, successive temperature differences are measured from the data

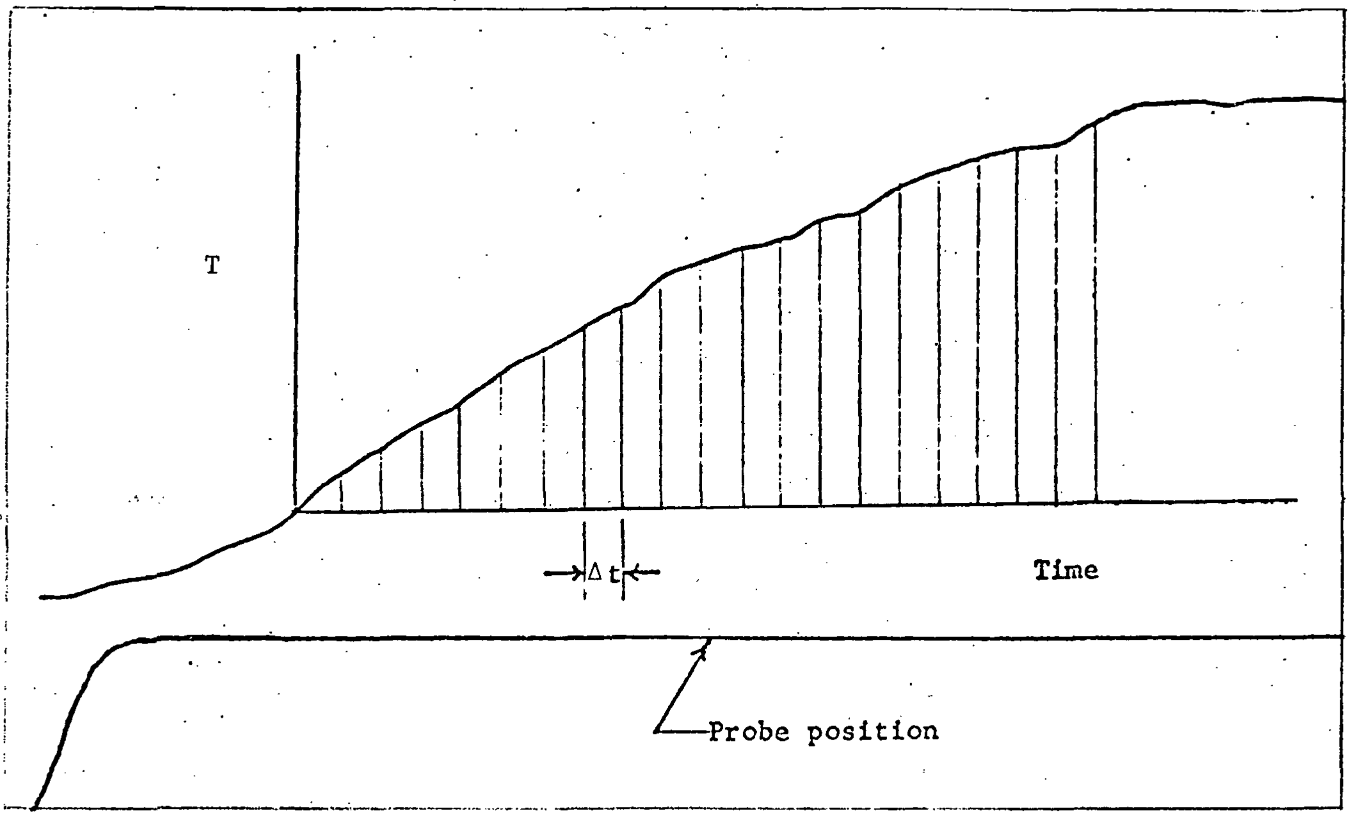


Figure 4. Data Analysis

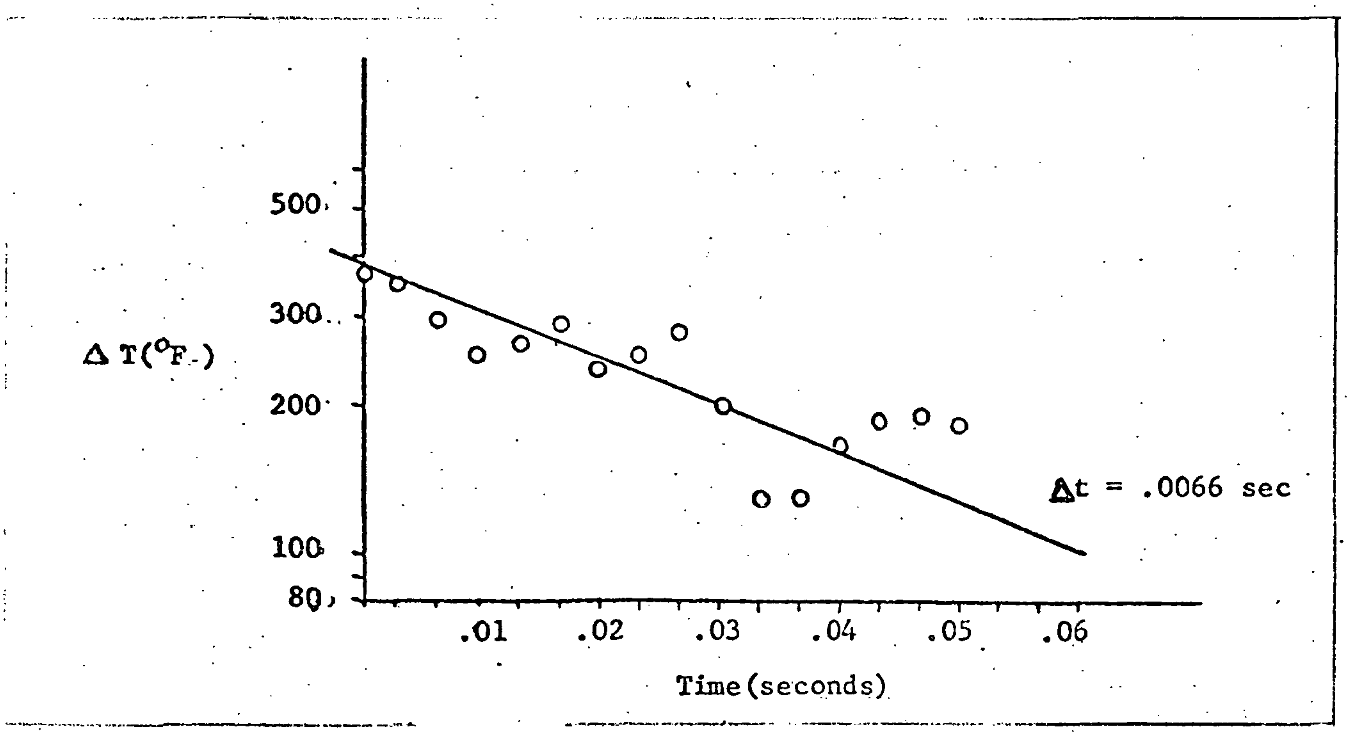


Figure 5. Time Constant Determination

traces at constant values of Δt as illustrated in Figure 4. These quantities are then plotted on semilog paper as shown by Figure 5. A straight line is fitted to the plotted points and the slope of this straight line is the reciprocal of the average time constant for the thermocouple. From this value, an average heat transfer coefficient for the wire can be calculated from the definition of the time constant. Equation (4) is solved for T_g, and a T_g value is calculated for each measuring time. The arithmetic average of the calculated T_g values is taken to be the average gas temperature.

The gas velocity required to produce the measured average heat transfer coefficient is calculated from knowledge of the gas composition and temperature by using a relation according to Moffat[3] for convective heat transfer to small wires,

$$Nu = .49\, Re^{.5}\, Pr^{.33} \quad . \tag{6}$$

This expression is valid for small wires between .0085 and .055 inch diameter and Reynolds numbers between 100 and 100,000. All gas properties are evaluated at the temperature of the gas, and these properties can be calculated by methods described by Barrere, et al[4]. Gas velocity is calculated by rearranging eq. (6) as follows

$$V = \left(\frac{hd}{k_f}\,\frac{Pr^{-.33}}{.49}\right)^2 \frac{\mu}{\bar{\rho} d} \tag{7}$$

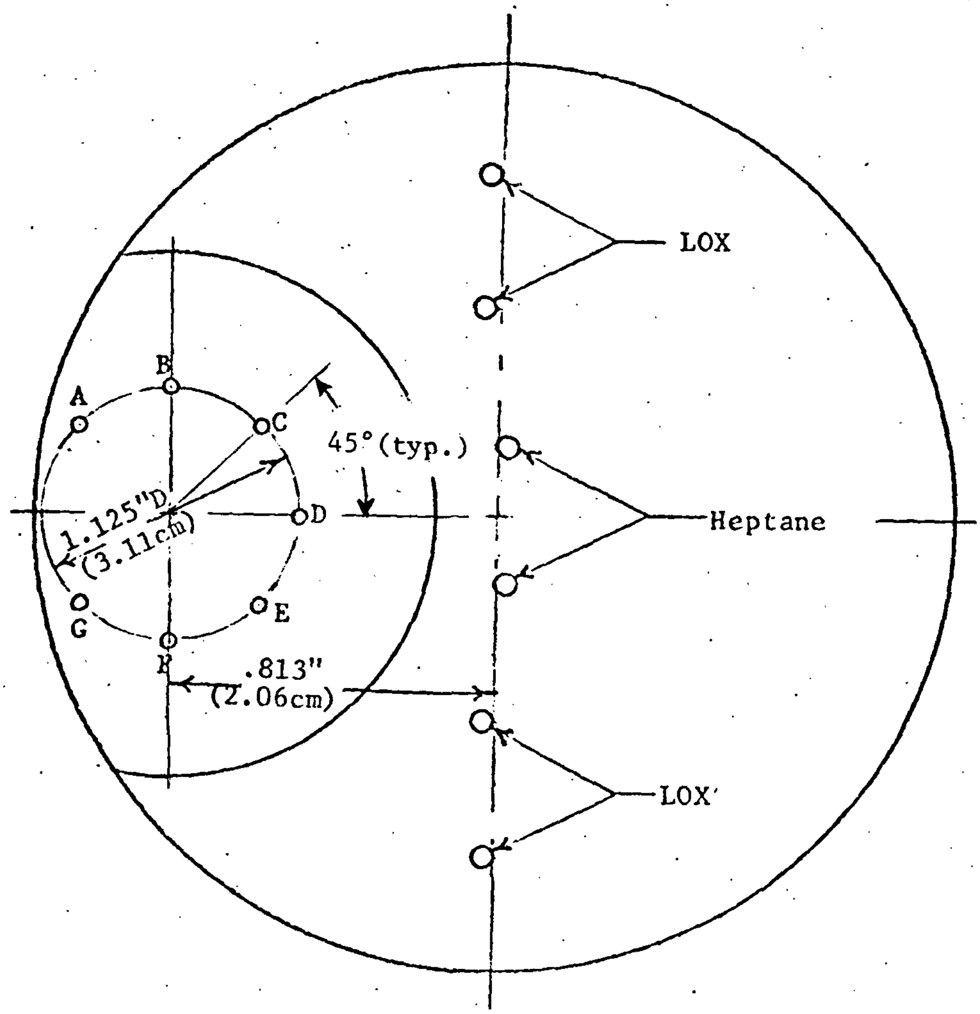
where k_f, μ, and $\bar{\rho}$ are the conductivity, viscosity and density of the gas, respectively.

RESULTS AND DISCUSSION

Transient thermocouple measurements were made near the injector face at positions which corresponded to gas sampling positions B, D, E and F in Figure 6. The measured wire heat transfer coefficients and gas temperatures for each run are tabulated in Table 1. Figure 7 presents the arithmetic averages of values of gas temperature, wire heat transfer coefficient, and gas velocity for each measurement position. The transient thermocouple measurements were made at .14 and .23 inches from the injector. These measurements showed little difference between the average heat transfer conditions at these two distances from the injector face, and the average values shown were obtained using data for both distances.

The wire heat transfer coefficients and gas temperature values were fairly repeatable at each measuring position on the injector. All heat transfer coefficient measurements except two were within 20% of the arithmetic mean for that position. Two measurements were greater: one was 38 and the other 46%. Only two gas temperature measurements were not within 390°F of the average temperatures for each position, one of which was 890° higher than the mean, the other being 510°F below the mean.

Only the data traces of the .02 inch diameter thermocouples were used in the analysis because of large fluctuations of the heat transfer conditions. The useful life of the .01 inch thermocouples was about



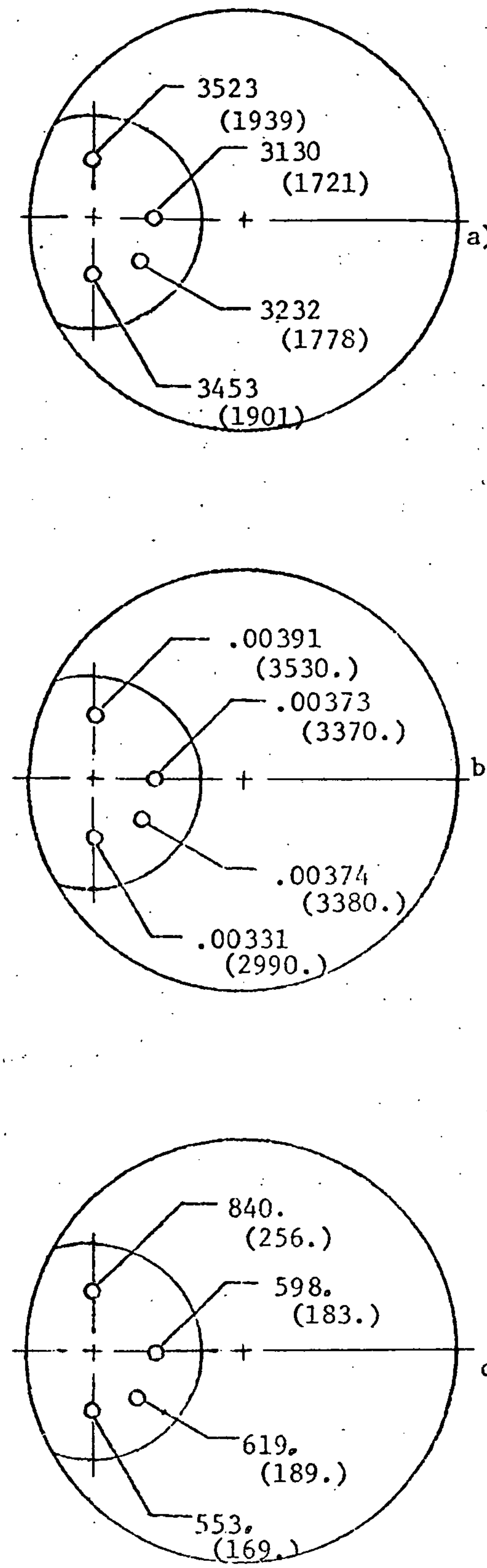
Note: Twice Full Scale

Figure 6. Gas Sample Positions

Table 1. Average Gas Temperature and Heat Transfer Coefficient

Position	distance from injector face in.	$T_{g_{avg}}$ °F(°C)	$h_{1_{avg}}$ BTU/in^{2}sec°F (watts/m^2°K)
B	.23	4421 (2438)	0.00367 (3320.)
	.14	3621 (1994)	0.00388 (3510.)
	.23	3020 (1660)	0.00586 (5290.)
	.23	3154 (1734)	0.00369 (3340.)
	.14 & .23*	3364 (1850)	0.00402 (3630.)
	.14	3557 (1958)	0.00238 (2250.)
D	.14	3520 (1938)	0.00379 (3420.)
	.23	2850 (1566)	0.00361 (3260.)
	.14	3021 (1661)	0.00378 (3420.)
E	.23	3044 (1673)	0.00383 (3460.)
	.14 & .23*	3405 (1874)	0.00365 (3300.)
F	.14	3509 (1934)	0.00379 (3420.)
	.14	3316 (1824)	0.00332 (3000.)
	.23	3500 (1927)	0.00248 (2240.)
	.23	3420 (1882)	0.00363 (3280.)

*Two .020" dia. thermocouples on probe with junctions at different heights. Results were essentially same for both thermocouples.



a) Average Gas Temperatures
°F(°C)

b) Average Heat Transfer Coefficients
For Large Wire
BTU/in^2-sec°R (watts/m^2°K)

c) Average Gas Velocity
ft/sec (m/sec)

Figure 7. Results

.03 seconds, and the 50 hertz fluctuations of the heat transfer rate discussed below were of too long a period to permit average values to be determined using the .01 inch thermocouple.

Irregular heat transfer rate fluctuations of approximately 50 and also 270-290 hertz were sensed by the thermocouples. It is believed that the 50 hertz fluctuations are a result of propellant feed system instabilities, while the origin of the 270-290 hertz fluctuations is unknown. Undoubtedly the fluctuations in heat transfer rate are caused by variations in both gas temperature and wire heat transfer coefficient; however, these effects cannot be separated by the method of analysis used. The effective gas temperature fluctuations required to produce the observed fluctuations in the thermocouple response curves were calculated assuming that the heat transfer coefficient remains constant and equal to the measured average value. Maximum and minimum slope measurements were made from four transient temperature data curves, and equation (3) was used to determine maximum and minimum effective gas temperatures. The resulting extremes of effective gas temperature fluctuations were found to be approximately ±1000°F about the mean gas temperature.

There is reason to believe that the actual gas temperature variations were also of the order of ±1000°F. At times, the emf trace of the .01 inch diameter thermocouple attained zero and negative slopes. The thermocouple temperature when zero slope is attained should be close to the temperature of the gas. The lowest temperature at which this was observed was 2400°F which is approximately 1000°F below the measured average.

It was originally intended that the data be analyzed for instantaneous gas temperature and velocity by a two thermocouple method described by Giedt[2] and Tschang[5]. For this reason, two thermocouples, each of different thermal mass, were inserted simultaneously at positions separated by less than .08 inch. However, meaningful results could not be obtained. The reason for this is believed to be that the two thermocouples did not always experience identical instantaneous heat transfer conditions, so that an assumption basic to the two thermocouple analytical model was violated.

An analysis of the differences between the instantaneous heat transfer rate sensed simultaneously by the two thermocouples was performed by comparing the fluctuations of the two temperature responses. Abrupt slope changes in one trace were noted and corresponding simultaneous abrupt slope changes were sought in the other. For approximately 10% of the oscillations, no corresponding changes in the other trace appeared. Of the oscillations which occurred simultaneously in each data trace, it is not known to what degree the magnitude of the respective oscillations corresponded, but it is believed from observation of the traces that the simultaneous fluctuation sensed by each thermocouple were sometimes of different magnitude.

The gas composition was required for calculation of the gas velocity from the wire heat transfer coefficient. Gas samples were taken on the injector face at all of the positions shown in Figure 6, and anlyzed using the analysis system described by Partus[6]. The average gas composition measurement results are presented in Table 2.

Table 2. Average Measured Gas Composition

(Percent by Volume)

Position	CO_2	O_2	CO	H_2	H_2O*
A	7.7	1.2	34.6	25.5	31.0
B	8.8	6.0	29.8	22.9	32.0
C	6.4	3.0	33.7	29.3	27.5
D	5.0	4.8	35.0	31.1	24.7
E	6.8	4.0	33.2	27.8	29.8
F	5.7	2.1	34.0	30.5	27.7
G	7.3	2.4	32.8	31.8	27.8

*Percent H_2O estimated after Partus.[6]

The injector face region was more fuel-rich than was expected. The O/F ratio as determined from the samples taken from the injector face was about 2.1 which is much lower than the value predicted by a one dimensional vaporization and combustion model[7]. This measured O/F ratio is close to the overall engine O/F ratio of 1.8. This is believed to be due to the folded-distance effect of recirculation, which causes combustion products to travel downstream and then return to the injector, giving the reactants more time to achieve complete combustion. Also, recirculation may selectively return a higher proportion of lighter fuel droplets than liquid oxygen droplets to the injector, causing a more fuel-rich region at the injector face.

The results of the erosion flow direction experiments and helium tracer gas experiments indicate that the flow is of a recirculatory nature. The flow direction experiments showed that gas flow near the injector face spreads radially from an area near the wall as shown on Figure 8. However, from the helium tracer gas experiments helium injected on the injector face was detected in samples taken on the injector face at a location which was upstream of the injection port. This was true whether the injection port and sample port were both on the same side or on opposite sides of the line of propellant injectors, indicating that the helium may have been returned to the injector face by recirculatory flow. The pattern of the injector face flow is believed to be caused by the deflection of sheets of LOX by the circular wall of the chamber. The like-on-like injectors tend to form flat sheets of droplets which are perpendicular to the

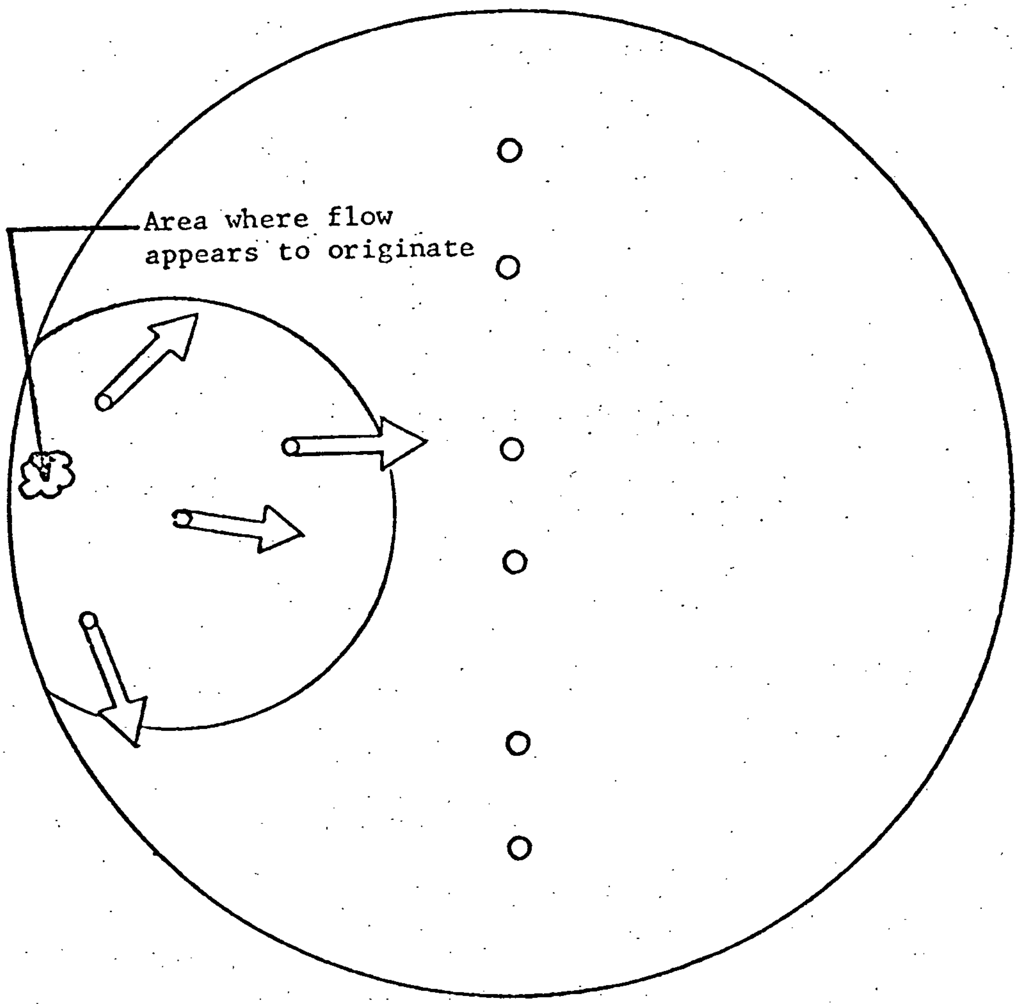


Figure 8. Measured Flow Directions

line joining the injection ports. The sheets are fan shaped with the vertex at the injector and will spread radially outward into the chamber until the walls are contacted. Because of the angle of incidence of the liquid oxygen on the wall, the oxygen sheets are deflected toward the fuel sheet. This would tend to induce a recirculation of flow which would appear on the surface of the injector face as flow spreading radially from a position near the chamber wall.

The directions of flow were interestingly verified during the experiment in two ways. The helium injection port originally had a copper cap to deflect the helium flow parallel to the injector face. During one firing, the cap melted and copper droplets were deposited on the surface of the injector. The direction of flow indicated by the copper deposit was close to that determined by the helium tracer experiment.

Occasionally the legs of the thermocouple survived the firing. For these runs the legs were bent over by the flow in the direction determined by the erosion experiments.

CONCLUSIONS

1. Average gas temperatures and velocities near the injector face of a steady state heptane-liquid oxygen rocket engine were determined by means of a transient thermocouple experiment.

2. The average gas temperatures near the injector were found to range between 3100 (1700) and 3500°F (1900°C), and the average velocities between 550 (170) and 840 feet per second (250 m/sec).

3. Fluctuations of heat transfer rate were observed to occur at rates of approximately 50 and 270-290 hertz. These fluctuations can be represented by large variations of effective gas temperature of the order of ±1000°F (±540°C).

4. The O/F ratio at the injector was found to be close to the overall engine O/F ratio, rather than the higher value predicted by a drop vaporization-combustion model.

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