Metallized Gelled Propellants: Oxygen/RP–1/ Aluminum Rocket Engine Calorimeter Heat Transfer Measurements and Analysis

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Abstract

A set of analyses was conducted to determine the heat transfer characteristics of metallized gelled liquid propellants in a rocket engine. The analyses used the data from experiments conducted with a small 30- to 40-lbf thrust engine composed of a modular injector, igniter, chamber and nozzle. The fuels used were traditional liquid RP-1 and gelled RP-1 with 0-wt %, 5- wt%, and 55-wt% loadings of aluminum with silicon dioxide gellant, and gaseous oxygen as the oxidizer. Heat transfer was computed based on measurements using calorimeter rocket chamber and nozzle hardware with a total of 31 cooling channels. A gelled fuel coating formed in the 0-, 5- and 55-wt% engines, and the coating was composed of unburned gelled fuel and partially combusted RP-1. The coating caused a large decrease in calorimeter engine heat flux in the last half of the chamber for the 0- and 5-wt% RP-1/Al. This heat flux reduction effect was analyzed by comparing engine runs and the changes in the heat flux during a run as well as from run to run. Heat transfer and time-dependent heat flux analyses and interpretations are provided. The 5- and 55-wt% RP-1/Al fueled engines had the highest chamber heat fluxes, with the 5-wt% fuel having the highest throat flux. This result is counter to the predicted result, where the 55-wt% fuel has the highest combustion and throat temperature, and therefore implies that it would deliver the highest throat heat flux. The 5-wt% RP-1/Al produced the most influence on the engine heat transfer and the heat flux reduction was caused by the formation of a gelled propellant layer in the chamber and nozzle.

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Nomenclature

Al	Aluminum
Cstar	Characteristic velocity (m/s)
F	Fahrenheit degrees
Isp	Specific Impulse (lbf-s/lbm)
IRFNA	Inhibited Red Fuming Nitric Acid
K	Kelvin degrees
LRB	Liquid Rocket Booster
MMH	Monomethyl Hydrazine
O2	Oxygen
lbf	pound-force
Q/A	Heat flux (MW/m2)
RP-1	Rocket Propellant-1
SRB	Solid Rocket Booster
T	Temperature (K or F)
wt%	Weight Percent of Fuel Mass
0-wt% RP-1/Al	Gelled RP-1 (no metal)

Introduction

The heat transfer in rocket engines has always been a major design factor due to the extremely high temperature of rocket environments and the limits of existing materials. Engines using metallized gelled propellants will, typically, have higher operating temperatures and hence heat fluxes (Ref. 1) and therefore require additional design features to control or accommodate the higher engine heat flux and provide the needed engine lifetime. These features may include ablative liners, added nozzle coolant flow rates, oxidizer cooling, or simply thicker nozzle walls or more heat resistant nozzle materials (Ref. 2).

Heat transfer testing of the gelled propellants has been conducted in the past (Ref. 3), however, metallized gelled RP-1/Al rocket combustion had not been conducted. Therefore, a program was initiated to characterize the heat fluxes throughout the engine and to identify potential unique issues with heat flux distribution in the metallized gelled propellant engine. Metal combustion can potentially cause ignition time mismatches due to the multi-phase flow in the rocket engine, and the existence of an oxide coating on the metal particles. It was hoped that the analysis of the heat flux distribution would identify this ignition timing mismatch and the differences between the metallized gelled fuels and the baseline RP-1 combustion would clearly show this delay. Previous small scale flat flame burner testing to characterize RP-1/Al secondary ignition has been conducted, but this testing was conducted only at atmospheric pressure (Ref. 4).

Why Metallized Gelled Propellants?

Metallized gelled propellants have been studied analytically and experimentally for over 60 years (Ref. 5). The historical work has focused on the benefits of high specific impulse, high density, and safety (Ref. 3, 5-6). Current non-NASA uses for these propellants may lie in tactical and strategic missiles and aircraft ejection seats (Ref. 7-9). Extensive work has been conducted with metallized-gelled Earth-storable propellants, such as hydrazine (N2H4), Inhibited Red Fuming Nitric Acid (IRFNA), and monomethyl hydrazine (MMH). However, these propellants are not planned for use in future NASA launch vehicles. To explore the potential of metallized-gelled fuels, NASA chose to pursue the propellant combinations that were more suitable to its future plans in the Metallized Propellant Program (Ref. 1, 4, 10-24). This program, at the NASA Lewis Research Center, has been conducting experimental, analytical, and mission studies since 1987. This program has concentrated on O2/RP-1 and O2/H2 propellant combinations and the issues related to using these gelled propellants with metal particle additives. Gelled propellants such as H2 have also been investigated for their potential benefits in reducing boiloff, increasing density, and increasing the safety of space transfer and airbreathing aerospace vehicles. Several mission studies have indicated that O2/RP-1/Al can have

significant benefits by increasing propellant density. Figure 1 depicts the potential increases in payload enabled by high-density 55-wt% RP-1/Al for the Space Shuttle using a Liquid Rocket Booster. Testing was therefore conducted with O2/RP-1/Al propellants using gelled RP-1 with aluminum particles. The steady state heat flux profiles were presented in Ref. 1, the results of heat sink engine testing are summarized in Ref. 10, the overall testing lesson learned are documented in Ref. 24. More-detailed transient heat flux profiles and further analyses of the run-to-run heat flux changes in the metallized gelled rocket engines are presented in this paper.

Purpose of Experiments

Rocket performance and heat transfer experiments were conducted in this test program. Since no data were previously available for O2/RP-1/Al rocket combustion and heat transfer, rocket performance and temperature measurements were sought and obtained. During the combustion of the liquid fuel with metal particles, the two-phase flow creates a mismatch in the combustion time scale of the liquid droplets and the solid particles. The temperature measurements and the computed heat fluxes were envisioned so that some estimate might be made of the delay in ignition for the aluminum. Also, the deposition of gelled fuel on the chamber walls had been identified in previous heat sink engine testing (Refs. 1, 10, and 24) and its effects on engine heat flux were to be investigated. Both the baseline RP-1 propellants and the gelled RP-1 with three metal loadings, from the testing described in Refs. 1, 10, and 24, were used to compare the transient rocket engine heat flux profiles of the different combustion environments.

The combustion and heat transfer experiments were conducted with a small 30- to 40-lbf thrust engine composed of a modular injector, igniter, chamber and nozzle. The fuels used were traditional liquid RP-1 and gelled RP-1 with 0-wt %, 5- wt%, and 55-wt% loadings of aluminum with gaseous oxygen as the oxidizer. Three injectors were used during the testing: 1 was for the baseline O2/RP-1 tests and 2 for the gelled fuels. Heat flux computations based on temperature measurements were made using calorimeter rocket chamber and nozzle hardware with a total of 31 cooling channels. Each

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channel used a water flow to carry heat away from the chamber and the attached thermocouples and flow meters allowed measurements at each of the 31 stations that were used for heat flux computations. The heat fluxes were analyzed using techniques from Refs. 25 to 28. The details of the experimental setup, the engine hardware description and the fuel preparation are all discussed in Refs. 1, 10, and 24.

Analysis Methods

The engine heat fluxes for the different fuels were analyzed in multiple ways to discern the influence of the gelled layer that formed in the engine chamber and nozzle. There were several ways to present the data that were very useful: heat flux during a run and at different locations in the chamber, heat flux versus mixture ratio, and heat flux from run to run. These methods produced a picture of what was occurring in the chamber and nozzle and provided fodder for speculation about the extent and variability of the gelled protective layer.

Heat flux during a run, from run-to-run, and as a function of O/F

A series of 3-dimensional (3-D) plots of heat flux, time into the run, and the location in the chamber was created and a representative figures for the four fuels are presented the succeeding sections. The transient heat flux plots show a general form of an initial peak due to igniter and main propellants' combustion, a steady state region for the main propellants' combustion, and the engine shutdown. The initial peak shown in the flux in the nozzle is due to the added energy of the O2/H2 igniter. In Figure 2, the region from 9.0 to 9.6 seconds is the region where the O2/RP-1 rocket engine combustion and the heat flux have reached the steady state values. The peak heat flux occurred at station 28, 20.6 cm from the injector face, and just upstream of the nozzle throat.

Time series (or heat flux versus run number) and the heat flux versus O/F are the other two tools used to illustrate the heat flux variations in the data. The time series depicted any changes over the number of runs, such as the reduction in heat flux for runs with the same O/F, implying the formation of a gelled layer. A repeatable time

series would imply there was no significant degradation of the engine performance or heat flux over time. The heat flux versus O/F plots also showed whether there were runs at the same O/F that had substantially different heat fluxes, implying the formation of an insulating gelled propellant layer or metal oxide layer.

Results

The variation of the heat flux during a run exhibited some very predictable and some unpredictable effects in the metallized gelled rocket engines. Trends in the performance were sought with time series and the other time dependent methods to see if the rocket engine heat flux were changed over time. If changes were evident, then the formation and motion of the gelled propellant layer might be inferred. Overall the formation of the gelled layer seemed most evident during the 5- and 55-wt% RP-1/Al tests.

RP-1

Figure 2 shows the 3-D roller coaster plot of the RP-1 heat fluxes as a function of distance from the injector face and time during a run. The RP-1 cases were the most predictable, and exhibited a heat flux profile similar to the historic data base of past testing (Ref. 2). The heat fluxes in the chamber reached the steady state values quickly, and there were some small heat flux peaks that occurred near the injector at shutdown. During the firing, the steady state region was from 9.0 to 9.6 seconds. This region is where the engine steady state performance is reached (Refs. 1, 10, 24).

Figure 3 provides the time series of the RP-1 runs' peak nozzle heat flux. There appears in all cases to be a very repeatable trend with no degradation of the peak nozzle heat flux with run number. The runs from 882 to 900 are in the O/F range of 2.5 to 3.0 and the run numbers prior to 882 (873 to 881) have the O/F ratio range of 3.2 to 4.2. This accounts for the apparent drop in flux after run 882. Thus, all of the runs in the same range of O/F have very repeatable heat flux values.

The plot of peak flux versus O/F is provided in Figure 4. The values of the peak nozzle heat flux in the O/F range of 2.5 to 3.2

are repeatable and there seems to be no appreciable degradation in the heat flux over the set of runs. The heat flux peaks also follow very closely the general shape of the Isp plots of Ref. 1, implying that the Isp and the heat flux are correlated.

RP-1/Al: 0-wt%

In the 0-wt% RP-1/Al (gelled RP-1, with no metal) cases, the 3-D heat flux plot of Figure 5 shows a steady state heat flux is reached in the latter half of the chamber from 9.3 to 9.7 seconds. This timing of the steady state region is different from the RP-1 cases due to the minor changes in the test setup that were made for running the gelled fuels. The chamber heat flux can be discussed in terms of the first half of the chamber, which include stations 1 to 11 (at an average distance of 0.6 to 7.2 cm from the injector face), and stations 12 to 22 (7.8-14.2 cm from the injector face), the second half of the chamber. In the first half of the chamber the heat flux is slowly coming to a peak value, but never reaching a steady state value, while in the second half of the chamber, the flux is reaching steady state more quickly, but with a lower value. This phenomenon is further illustrated in Figures 5a and 5b. Figure 5a shows the 0-wt% RP-1/Al heat flux profiles at station 8 (5.3 cm from the injector face), each run at an O/F value near 2.0. In all cases, the flux profile has the same shape, and never reaches a steady state value.

Figure 5b compares the heat flux profiles at station 17 (11.0 cm from the injector face) for an O/F value near 2.0. A steady state heat flux value is reached in this section of the chamber. Because the heat flux is so much lower at station 17 than the flux reached at station 8, and this effect was not seen in the RP-1 cases, it was inferred that the gelled propellant layer had formed and reduced the chamber heat flux. This effect will be further discussed in the observations section.

The peak nozzle heat flux versus run number in Figure 6, and the heat flux values are very repeatable over the number of runs, implying no degradation of heat flux and no gelled layer in the throat. In Figure 6a, the peak heat fluxes are shown for an O/F of 2.0 only, and the figure depicts no appreciable changes in the

flux over the number of runs. This lack of change implies that the gelled propellant layer did not form in the throat with the 0-wt% rp-1/Al runs. This is corroborated by the inspection of the layer in the chamber and the converging section of the nozzle which was composed of a dark gray and pink gelled material, similar to the gelled 5-wt% RP-1/Al fuel. The gray color was caused by the combustion products and the unburned RP-1 gave it the pink color. This gelled layer was residing mainly in the chamber, and converging section, and was sufficiently soft and compliant to be swept off of the nozzle throat by the rocket combustion flow.

Figure 7 illustrates the peak nozzle flux versus O/F. At nearly all of the O/F values, a repeatable heat flux was delivered. The shape of the curve matches well with the Isp versus O/F plots of Ref. 1, implying a good correlation for the heat flux and Isp.

RP-1/Al: 5-wt%

The 3-D roller coaster plot for the 5-wt% RP-1/Al is provided in Figure 8. This plot, as with the others, has the initial heat flux peak for the igniter firing, and then the lower steady state value for the main propellant combustion. The peak nozzle flux reaches a value of 6.5 MW/m2. In the first half of the chamber, the flux reaches a peak value, but not a steady state value, and in the second half, the heat flux quickly reaches a steady state value, which is significantly lower than the peak value in the first half of the chamber. As with the 0-wt% cases, this discrepancy in the heat fluxes was caused by the formation of a gelled layer.

The heat fluxes at stations 8 and 17 also exhibit variations from run to run. Figures 8a and 8b, respectively, show the changes from run to run (with each run at an O/F of 2.0) in heat flux at these two stations, implying that the gelled layer with an insulating feature was growing from run to run. In the station 17 data (Figure 8b), the heat flux does not monotonically drop with each firing, but the overall trend is a drop in the heat flux with each successive run. This again implies the overall growth of the gelled layer.

The 5-wt% RP-1/Al peak nozzle heat flux data versus run number is shown in Figures

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9 and 9a. Figure 9 shows the complete data set, while figure 9a shows data only for O/F = 2.0. The Figure 9a time series for the 5-wt% fuel shows a marked reduction in heat flux for the later runs in the series. This heat flux reduction can be used to infer the gelled layer growth in the nozzle.

Figure 10 depicts the peak nozzle flux versus O/F. The data near an O/F of 2.0 shows a marked reduction in the heat flux. Comparing this data with the time series, it was found that the lowest heat flux value was for the first engine firing of the series, and may have had incomplete combustion and deposited an extensive layer in the engine. The succeeding runs however, show a noticeable reduction in heat flux as the runs proceeded. As with the previous results, the heat flux follows the results of Isp versus O/F and can be generally correlated with the Isp.

RP-1/Al 55-wt%

The 3-D plot of peak flux for the 55-wt% RP-1/Al is depicted in Figure 11, with a 6.3 MW/m^2 peak steady state flux at the nozzle. The chamber heat flux for these runs do not reach a steady state value, but they slowly decay during a run. This is likely due to the deposition of gelled fuel onto the walls of the chamber and nozzle, and the motion of the gelled layer. The mass flow rate and the Isp of the engine however, did reach a steady state value, making interpretation difficult. After the test firings, the engine was dismantled, and a highly non-uniform layer of gelled material lay in the chamber and on the nozzle walls. The heat flux drop over the length of the run was due to formation and motion of the gelled layer in the engine. There were some cases where a small amount of partially combusted metallized gelled propellant was ejected from the chamber, and there may have been a strong effect from the high metal loading of the gelled layer, due to the strong insulating character of the Al_2O_3 formed, and the non-uniform gelled layer of uncombusted 55-wt% RP-1/Al with other combustion products.

In the heat flux vs. run number of Figure 12, the 55-wt% fuel shows a wide variation of the heat flux vs. run number. Though some of this variation is due to the

Al_2O_3 coating that deposited on the engine throat surfaces (Ref. 1, 10, and 24), the identification of the heat flux reduction was possible, for the specific runs at the same O/F values. The heat flux for the O/F = 2.0 cases had a reduction of heat flux from run 1014 to 1017, though the Al_2O_3 metal coating was removed from the throat section after run 1013. This implies that though the coating was removed, some amount of Al_2O_3 remained attached to the converging section of the nozzle. The deposit was confirmed when the engine was dismantled.

In Figure 13, the heat flux versus O/F shows a peak near an O/F of 1.8 to 2.0 and the lower flux values near the peak imply the Al_2O_3 deposition reduced the engine heat fluxes, as discussed previously in the 55-wt% heat flux versus run number plots.

Observations

The gelled layer, while deposited throughout the chamber during the 0-, 5-, and 55-wt% metallized gelled RP-1/Al tests, was more influential in reducing the heat fluxes in the latter part of the chamber, and reduced the heat flux by up to a factor of two over the first half of the chamber. The layer's insulating ability was most evident in the 0- and 5-wt% cases, creating a relatively thick but uneven layer, while the layer was thinner and very non-uniform in the 55-wt% cases.

The formation of the layer occurred in several steps. As the gelled fuel is injected into the chamber, the O2 gas streams impinging on the gelled fuel stream causes a ligand structure to form. This was evident from past testing (Ref. 14). Some of the propellant, rather than undergoing combustion, will deposit on the chamber walls. An intense combustion environment occurs in the chamber, but the gelled fuel is not completely atomized and therefore not consumed. Additional shear stress would be needed to completely atomize the propellants, and improved injector designs can deliver this increased shear stress. After the gel has deposited on the walls, some of this propellant vaporizes, and further contributes to the combustion process, but some of it remains on the walls. The grayish color of the layer implies that in the 5- and 55-wt% cases, the layer is partially composed on metal particles, and the

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gelled nature of the layer implies that the silicon dioxide gellant was a large fraction of the gelled layer. The viscosity of the gelled layer was significantly higher than the gelled fuels demonstrating that the RP-1 fuel volatiles had evaporated from the gelled fuel that was deposited on the walls. These observations are all qualitative, based on visual inspection of the layer.

In addition, some of the changes in the heat flux from run to run can be explained by motion of the gelled layer in the chamber. After a test series, inspection of the chamber and nozzle was conducted. In most cases, the gelled layer was not completely uniform over the chamber and nozzle surfaces. This motion of the gelled layer may account for the run to run changes in heat flux noted in all of the gelled propellant engine tests.

With the 5-wt% cases, the heat flux at station 17 exhibits possible evidence of this layer motion. The heat flux had an overall trend of dropping as the number of runs increases, but there were single runs where the heat flux increased, and on the next run, returned to the trend of reduction in the flux. After these tests, the inspection of the engine showed that the gelled layer was somewhat lumpy and uneven, suggesting motion in the chamber from run to run. In the 55-wt% cases, the gelled layer was distributed very unevenly in the chamber, and had an almost clear color, with some distinctly grayish gelled propellant patches distributed over injector face, chamber wall, and nozzle surface. The layer produced in this case was generally very thin and showed a propensity for gravitational settling into the "bottom" or lowest part of the chamber. Based on these observations, motion of the gelled layer did occur.

With the 55-wt% cases, the highest chamber heat fluxes were created. The 5-wt% RP-1/Al fuel delivered the highest peak nozzle heat flux at 6.5 MW/m2, but 55-wt% fuel had nearly the same peak nozzle flux at 6.3 MW/m2. It was thought that the 55-wt% fuel would deliver a higher heat flux due to the higher metal content of the fuel. Due to the unusually high N2 flow rates in the engine (Ref. 1), the predicted combustion and nozzle temperatures may have been lower than expected.

Other contributors to gelled layer

With each of the metallized gelled fuels, the mass flow rate exhibits small peaks at ignition and shutdown, and an example of this is shown in Figure 14. During a typical run, the fuel flow is turned on first, and the O2 is turned on 0.1 to 0.2 seconds later. This is done to prevent possible oxygen burning of the metal surfaces. After the O2 is turned on, and the main propellants' ignition occurs, the mass flow rate of the fuel drops slightly, owing to the increase in chamber pressure. The delta P across the injector was reduced and therefore the mass flow rate dropped after the engine main propellants ignited. At shutdown, the O2 was shut off first, then the metallized gelled fuel. As the chamber pressure drops, the fuel experiences less backpressure, and the flow rate increases, causing a second peak. This additional partially combusted propellants may contribute to the gelled layer.

Conclusions

Heat transfer characteristics for RP-1 and three metallized gelled propellants (0-, 5-, and 55-wt% RP-1/Al) were analyzed, using data from a small scale, 30- to 40-lbf thrust rocket engine with 31 water coolant channels. Gelled fuel, sprayed onto the chamber walls, created a layer composed of gellant, unburned fuel, and other combustion products. Heat flux analyses were conducted to calculate the influence of the gelled layer that formed in the chamber. Analyses that provided insight into the engine heat transfer and the formation of the gelled layer are the variation of heat flux with the O/F, with location in the engine, with time during a run, and from run to run.

Time dependent, run to run heat flux analyses showed that the RP-1 engine heat flux did not change appreciably over the series of test firings conducted at the same O/F values. The metallized gelled propellants, however, created significant variations in the chamber and nozzle heat fluxes. With the 0- and 5-wt% RP-1/Al cases, the heat flux in the first half of the chamber was substantially higher than the flux in the latter half. The nozzle heat fluxes for the 0-wt% cases did not change significantly from run to run (at the same O/F value), implying that the gelled layer did not remain in the nozzle throat

region. The 5-wt% cases showed a reduction in nozzle heat flux over a series of runs, showing that this gelled layer was more persistent, even in the nozzle region. A slow reduction in the peak nozzle heat flux occurred over the total number of firings with the 5-wt% RP-1/Al tests.

The highest chamber heat fluxes occurred in the 55-wt% RP-1/Al cases, though the heat flux in the chamber never reached a steady state value during a test. The drop in chamber flux during a run was unexpected, as the mass flow rate was steady during the runs, and the engine combustion and Isp remained steady.

Concluding Remarks

This heat flux measurements led to the link between a gelled layer deposited in the rocket engine and the unusual heat flux results. The gelled layers in the 0-, 5-, and 55-wt% RP-1/Al tests created significant heat flux variations in the chamber and nozzle, and will require more detailed analyses to fully interpret them. The gelled layer can be modeled as relatively thick (1 to 5 mm) for the 0- and 5-wt% cases, while it was thinner and more non-uniform for the 55-wt% tests.

Additional analyses of heat transfer coefficients, correlation coefficients, and ignition delay can be conducted. Ignition delay was not clearly noted in the data presented, and the influence of the gelled layer may have masked some of the occurrences of the delay. .

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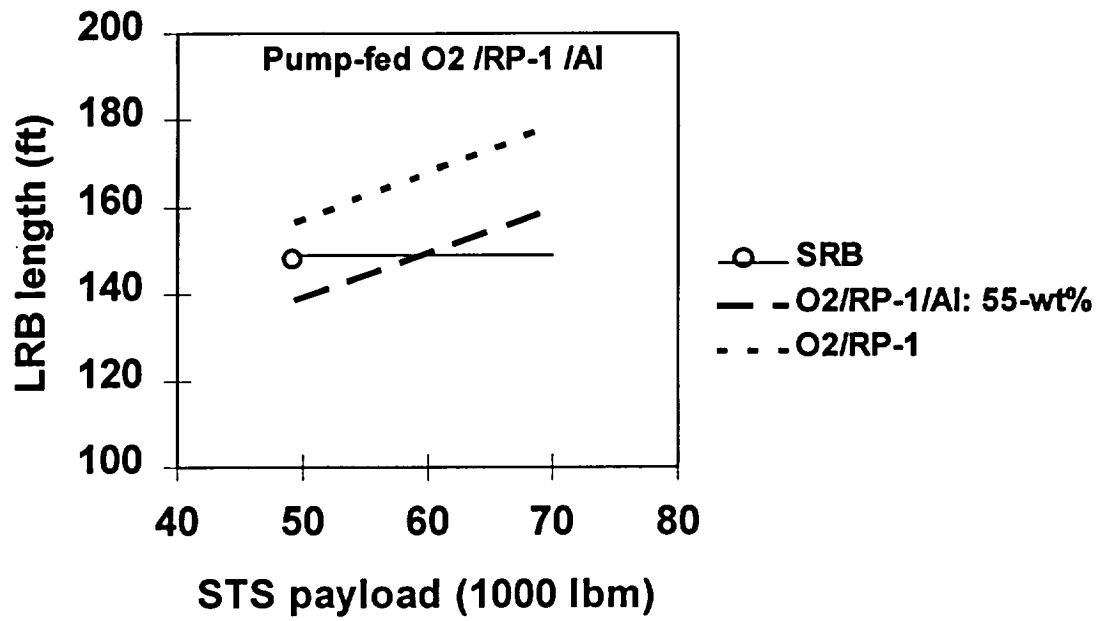
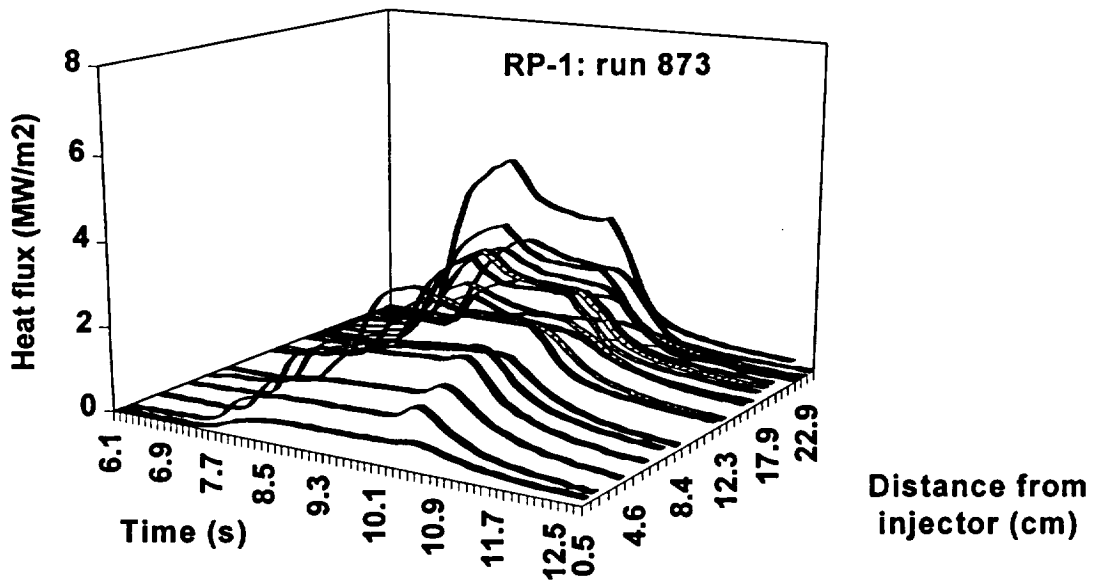Figure 1. O_2/RP-1/Al Booster Length vs. Payload
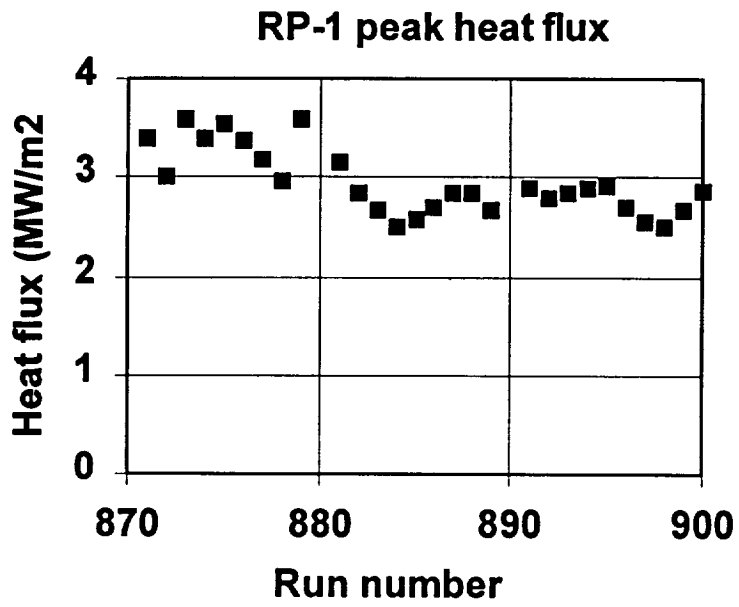

Figure 2. O_2/RP-1 3-D Transient Heat Flux

RP-1 peak heat flux

Figure 3. O$_2$/RP-1 Peak Heat Flux vs. Run Number

RP-1 peak heat flux: O/F = 2.5
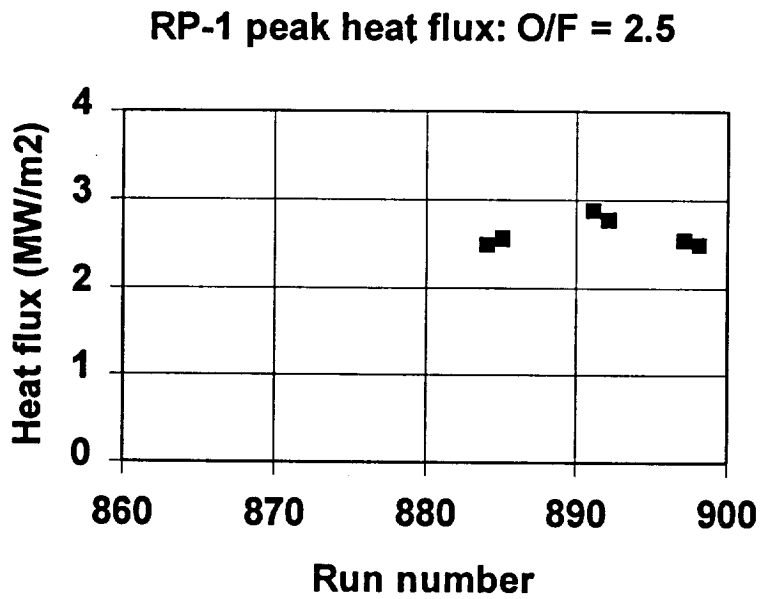
Figure 3a. O$_2$/RP-1 Peak Heat Flux vs. Run Number. O/F = 2.5

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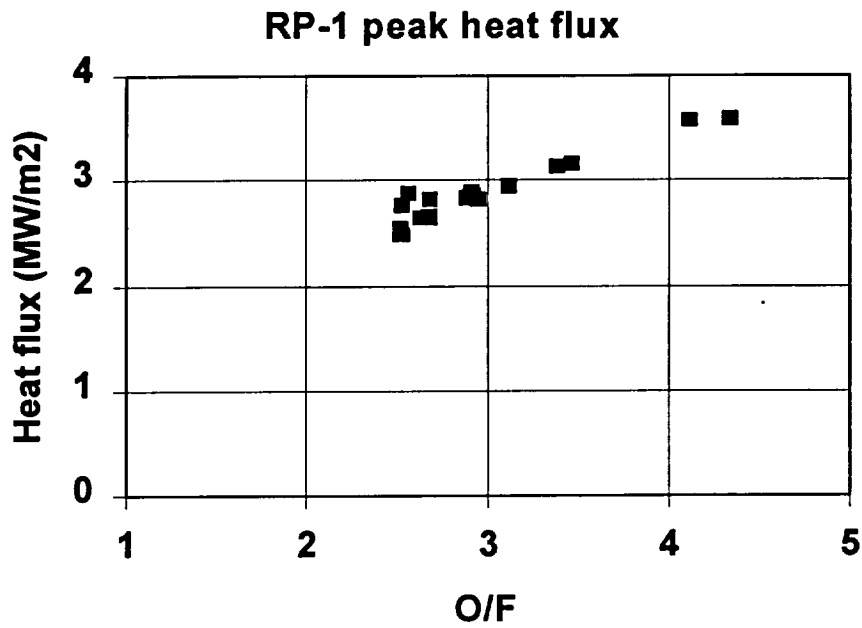
RP-1 peak heat flux

Figure 4. O_2/RP-1 Peak Heat Flux vs. O/F
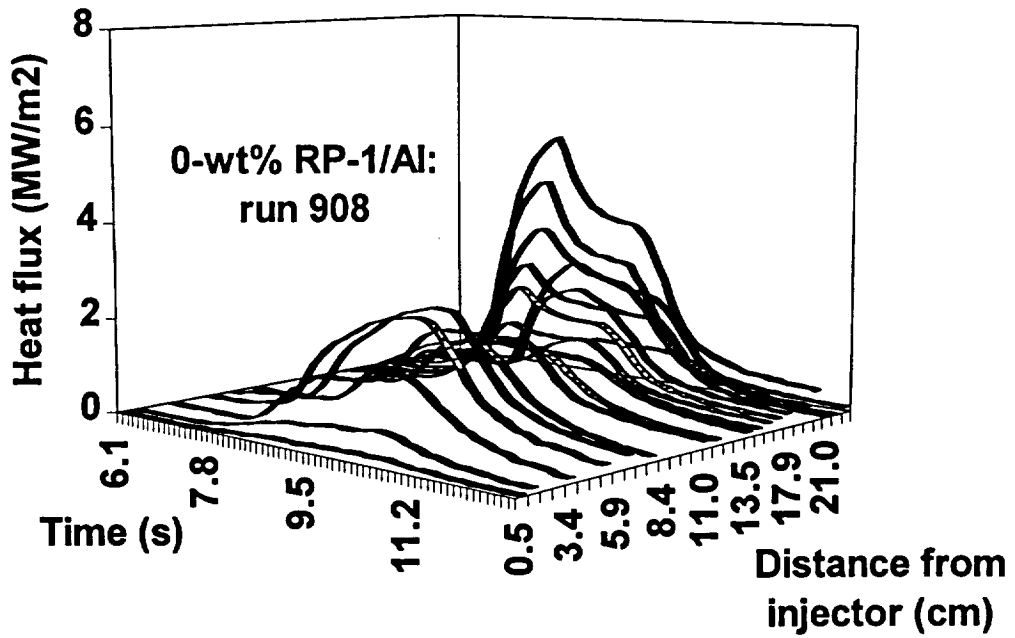
Figure 5. O_2/RP-1/Al - 0-wt% Al: 3-D Transient Heat Flux

0-wt% RP-1/Al: station 8, O/F = 2.0
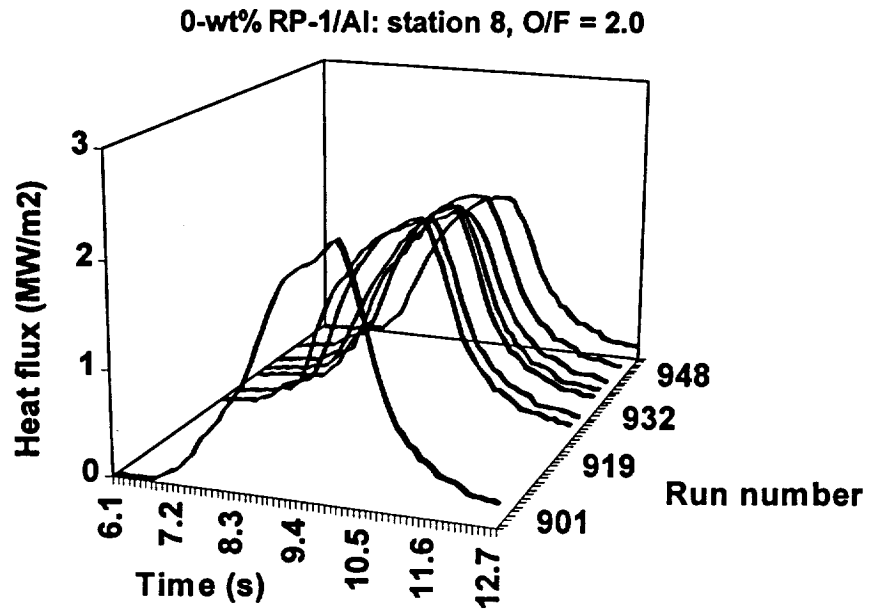
Figure 5a. O_2/RP-1/Al - 0-wt% Al: Transient Heat Flux - station 8

0-wt% RP-1/Al: station 17, O/F = 2.0
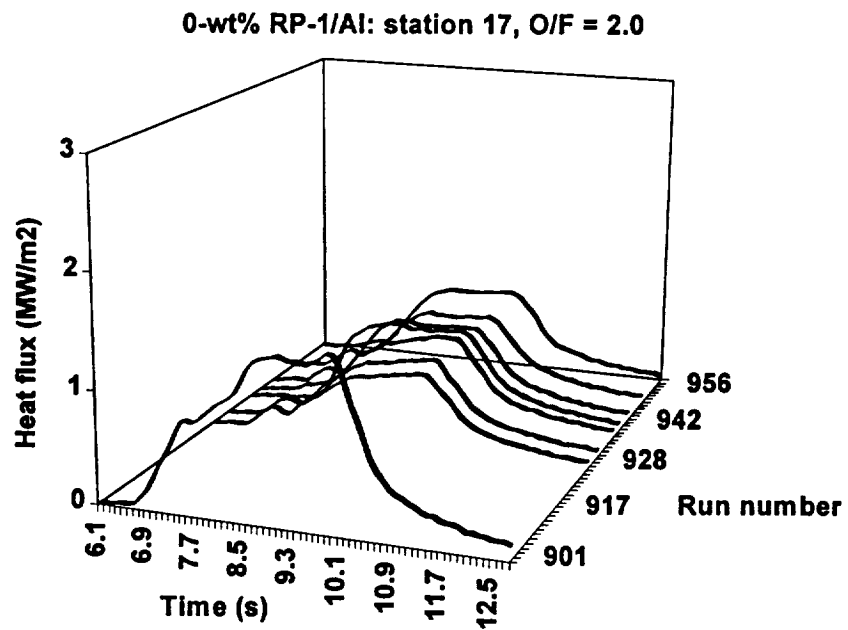
Figure 5b. O_2/RP-1/Al - 0-wt% Al: Transient Heat Flux - station 17

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0-wt% RP-1/Al: peak heat flux
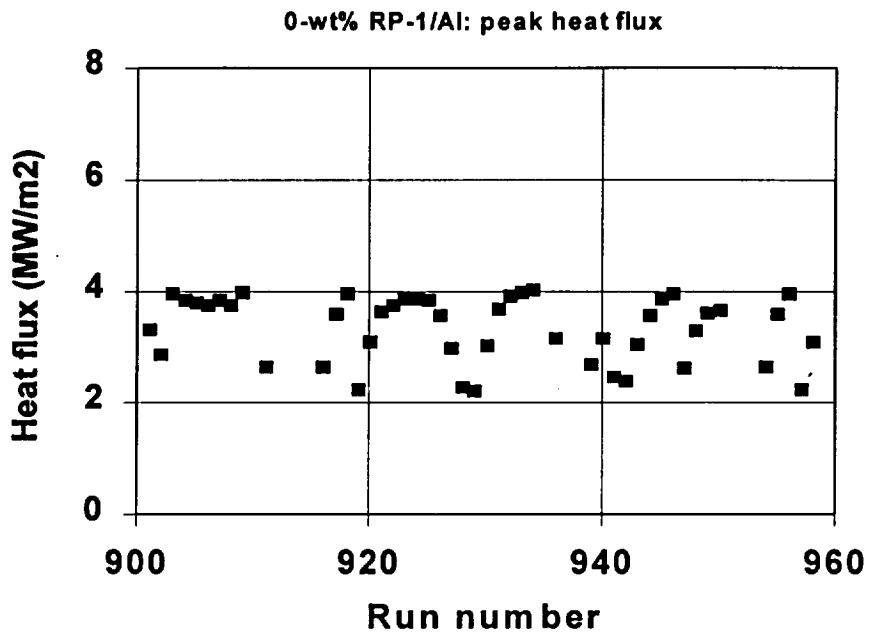
Figure 6. O$_2$/RP-1/Al - 0-wt% Al: Peak Heat Flux vs. Run Number

0-wt% RP-1/Al: peak flux, O/F = 2.0
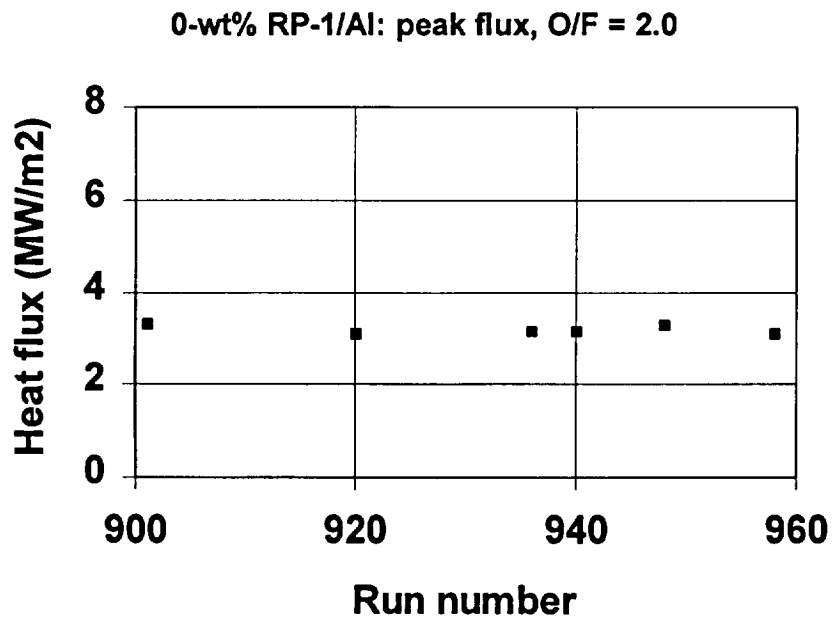
Figure 6a. O$_2$/RP-1/Al - 0-wt% Al: Peak Heat Flux vs. Run Number - O/F = 2.0

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0-wt% RP-1/Al: peak heat flux
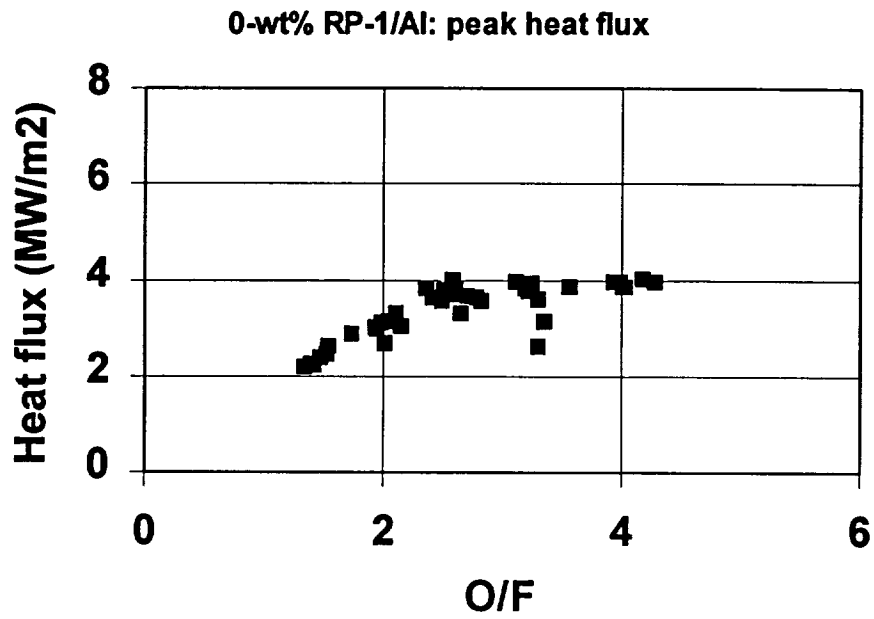
Figure 7. O_2/RP-1/Al - 0-wt% Al: Peak Heat Flux vs. O/F

5-wt% RP-1/Al: run 986
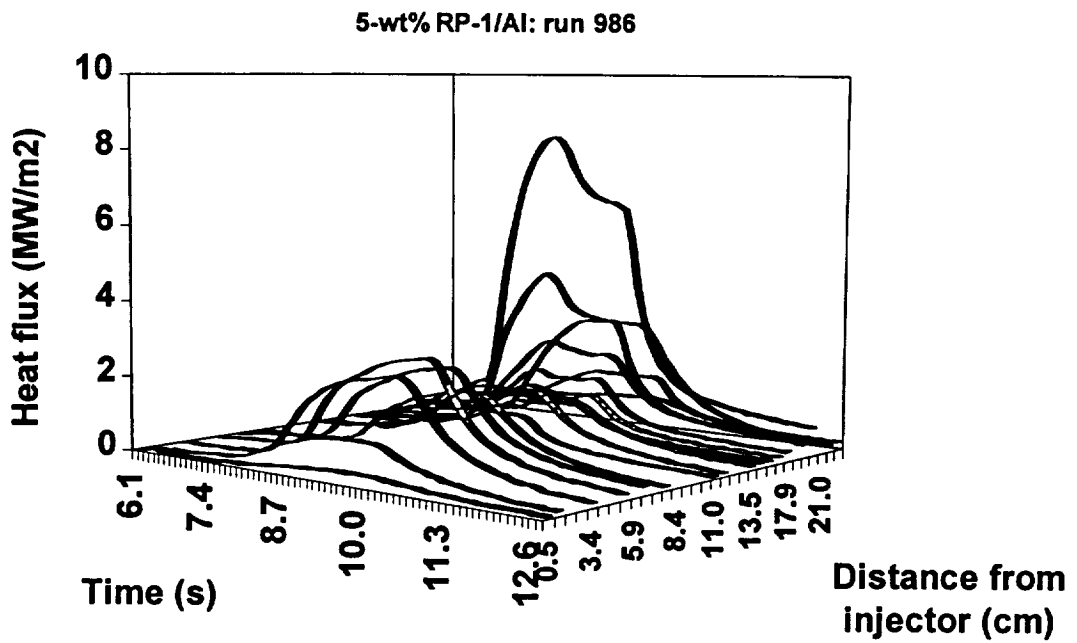
Figure 8. O_2/RP-1/Al - 5-wt% Al: 3-D Transient Heat Flux

5-wt% RP-1/Al: station 8, O/F = 2.0
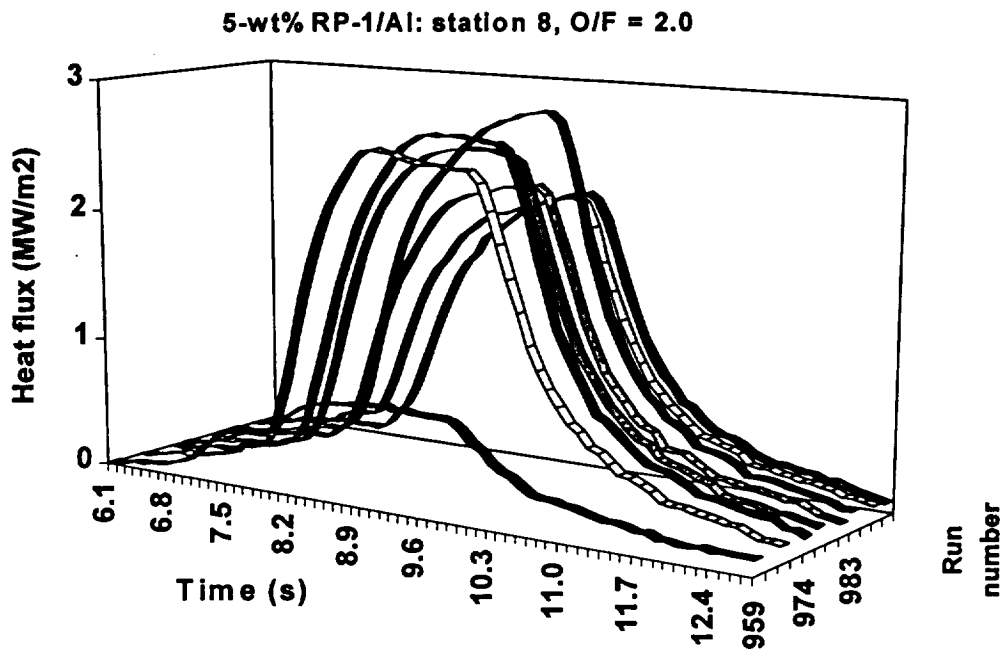
Figure 8a. O_2/RP-1/Al - 5-wt% Al: Transient Heat Flux - station 8
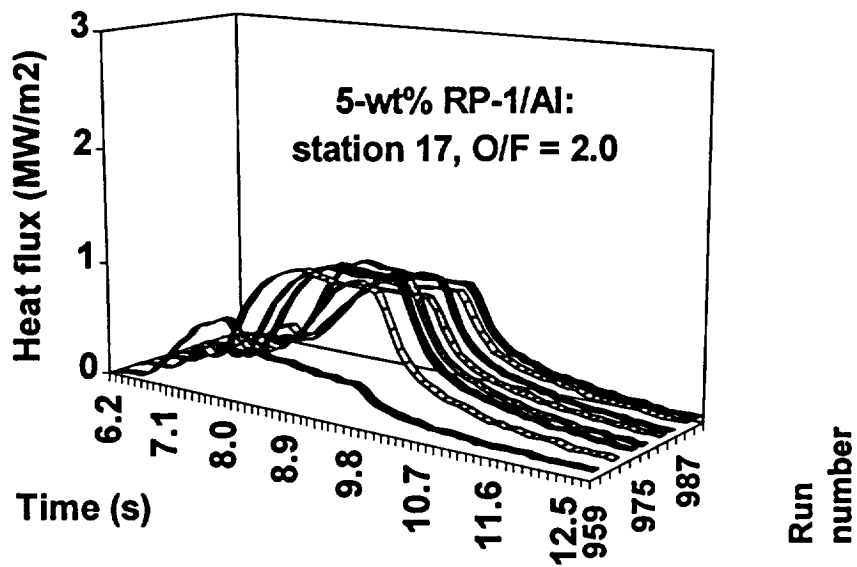
Figure 8b. O_2/RP-1/Al - 5-wt% Al: Transient Heat Flux - station 17

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5-wt% RP-1/Al: peak heat flux
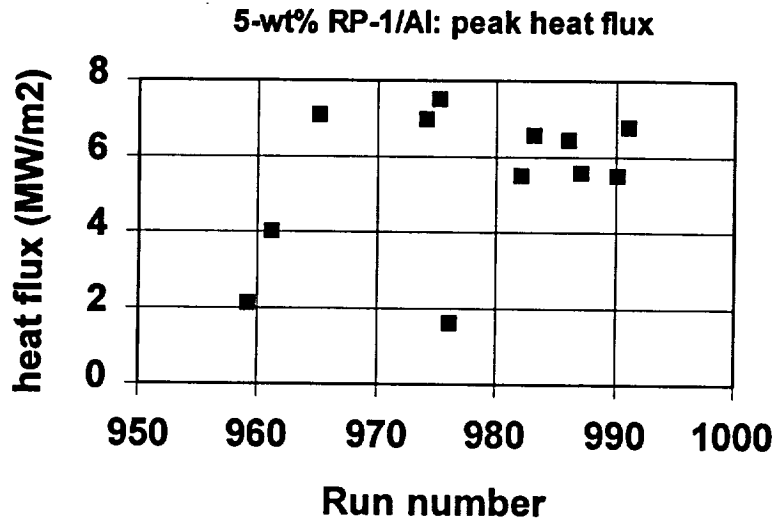
Figure 9. O$_2$/RP-1/Al - 5-wt% Al: Peak Heat Flux vs. Run Number

5-wt% RP-1/Al, O/F = 2.0
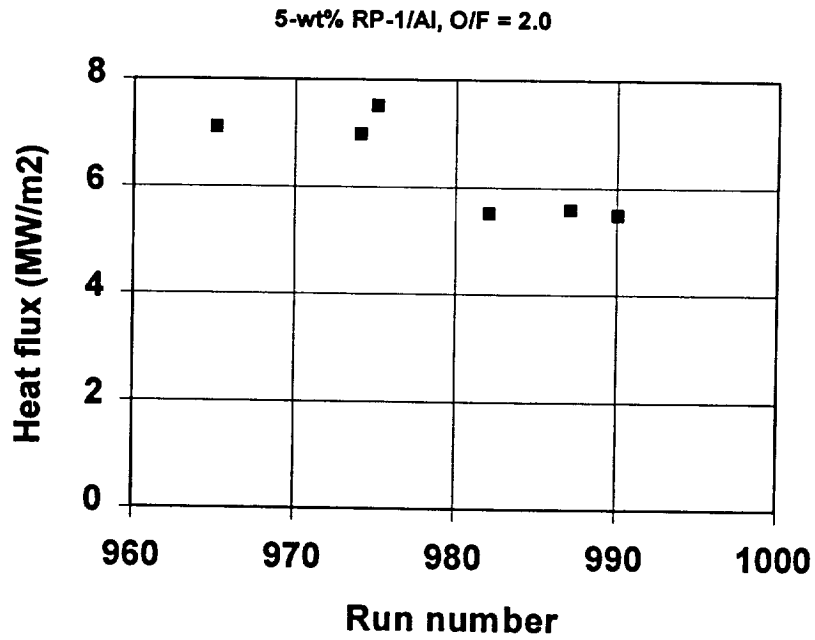
Figure 9a. O$_2$/RP-1/Al - 5-wt% Al: Peak Heat Flux vs. Run Number: O/F = 2.0 only

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5-wt% RP-1/Al: peak heat flux
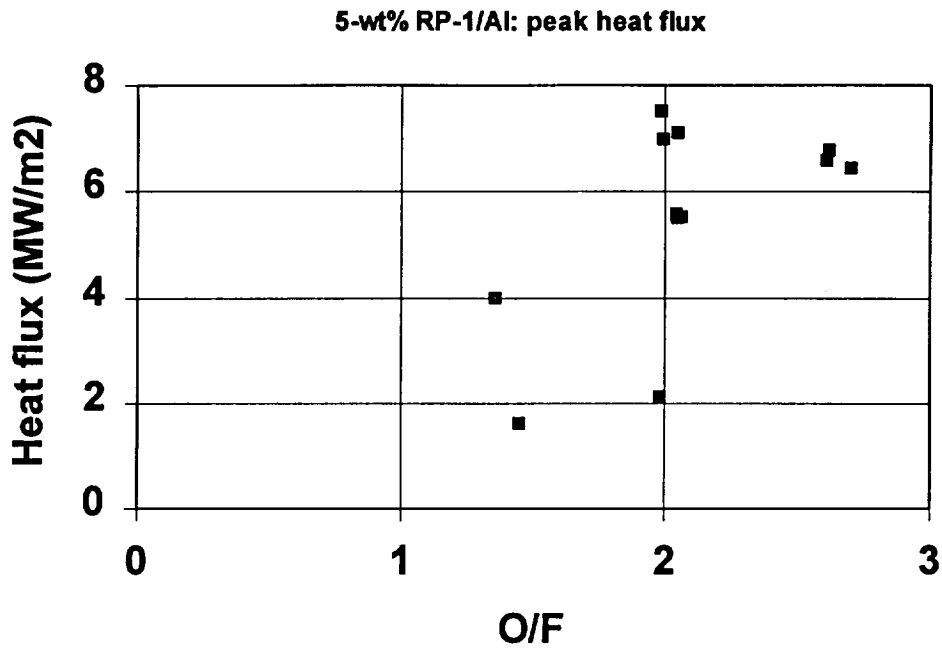
Figure 10. O_2/RP-1/Al - 5-wt% Al: Peak Heat Flux vs. O/F

55-wt%: run 1019
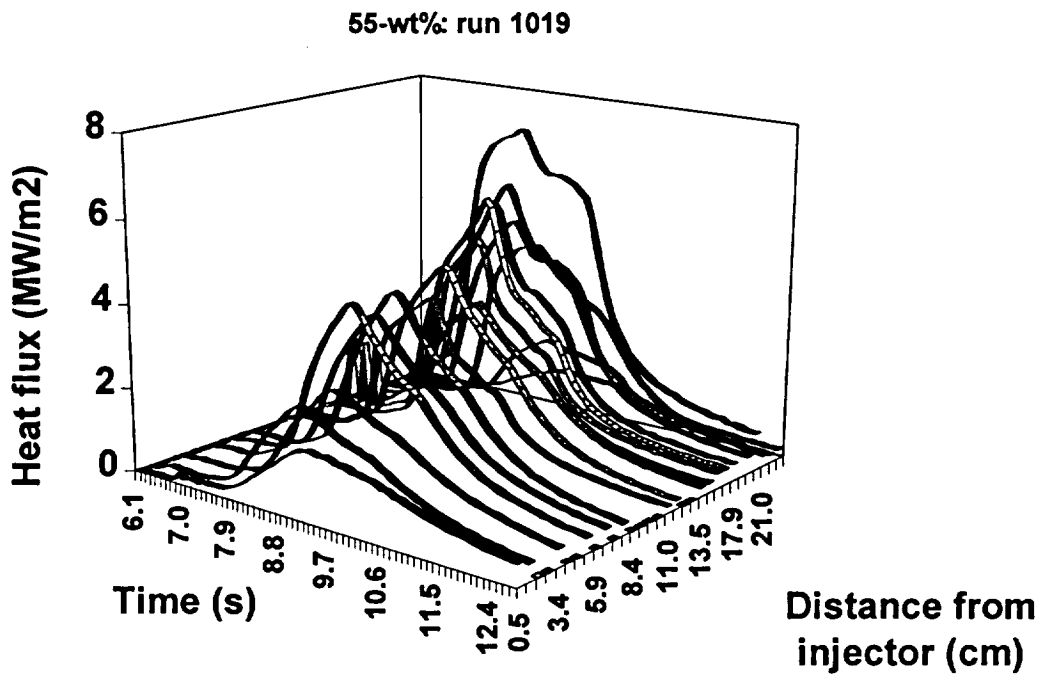
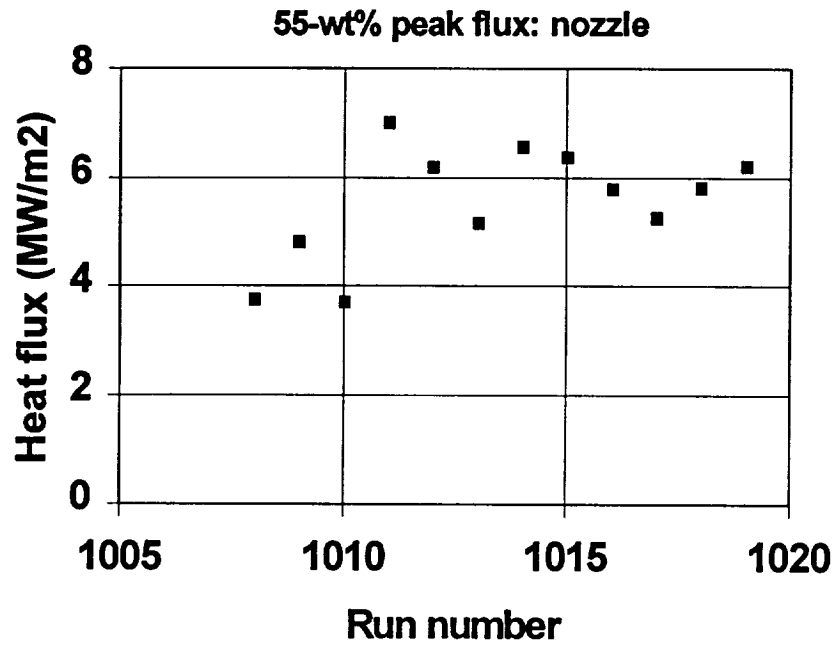Figure 11. O_2/RP-1/Al - 55-wt% Al: 3-D Transient Heat Flux

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Figure 12. O_2/RP-1/Al - 55-wt% Al: Peak Heat Flux vs. Run Number
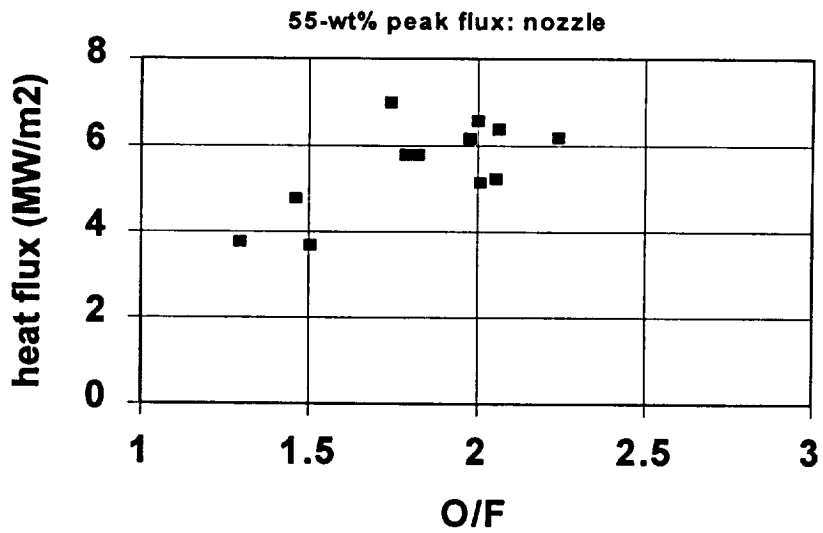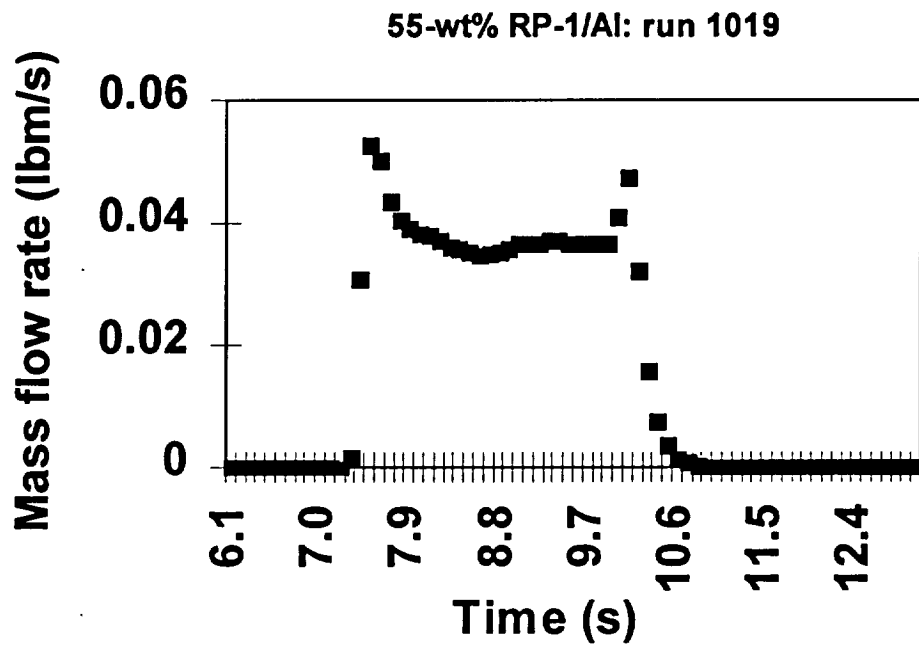

Figure 13. O_2/RP-1/Al - 55-wt% Al: Peak Heat Flux vs. O/F

Figure 14. O_2/RP-1/Al - 55-wt% Al: Mass Flow Rate vs. Time

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13. ABSTRACT (Maximum 200 words)

A set of analyses was conducted to determine the heat transfer characteristics of metallized gelled liquid propellants in a rocket engine. The analyses used the data from experiments conducted with a small 30- to 40-lbf thrust engine composed of a modular injector, igniter, chamber and nozzle. The fuels used were traditional liquid RP-1 and gelled RP-1 with 0-wt %, 5-wt%, and 55-wt% loadings of aluminum with silicon dioxide gellant, and gaseous oxygen as the oxidizer. Heat transfer was computed based on measurements using calorimeter rocket chamber and nozzle hardware with a total of 31 cooling channels. A gelled fuel coating formed in the 0-, 5- and 55-wt% engines, and the coating was composed of unburned gelled fuel and partially combusted RP-1. The coating caused a large decrease in calorimeter engine heat flux in the last half of the chamber for the 0- and 5-wt% RP-1/Al. This heat flux reduction effect was analyzed by comparing engine runs and the changes in the heat flux during a run as well as from run to run. Heat transfer and time-dependent heat flux analyses and interpretations are provided. The 5- and 55-wt% RP-1/Al fueled engines had the highest chamber heat fluxes, with the 5-wt% fuel having the highest throat flux. This result is counter to the predicted result, where the 55 wt% fuel has the highest combustion and throat temperature, and therefore implies that it would deliver the highest throat heat flux. The 5-wt% RP-1/Al produced the most influence on the engine heat transfer and the heat flux reduction was caused by the formation of a gelled propellant layer in the chamber and nozzle.

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Gelled propellants; Heat transfer rocket engine; Metallized fuels; Metal combustion; Gellants

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