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Preliminary Heat Transfer Characteristics of RP-2 Fuel As Tested in the High Heat Flux Facility (Preprint)

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ABSTRACT

In recent years, Government and industry have both documented considerable interest in developing reusable, long-life, liquid hydrocarbon fueled rocket engines. However, in order to design an engine with these characteristics, a more complete understanding of the fuel's liquid-side fluid characteristics, while in engine regenerative-cooling channels, is needed. To add to this required understanding, experiments are currently being conducted at the Air Force Research Laboratory's High Heat Flux Facility (HHFF), located at Edwards AFB, CA. The HHFF is designed to explore many fuel related rocket engine design considerations (e.g., high aspect ratio cooling channels, various fuel thermal stability issues, material compatibility, heat transfer capability, effects related to dissolved oxygen or specific sulfur species contained within the fuel, etc.) Recently, the Air Force has been studying RP-2 (Ultra-Low Sulfur RP-1) in order to establish an accurate baseline for future experiments in the HHFF. These experiments were conducted using low overall heat transfer coefficients and wall temperatures. This paper will present and discuss the results of recent Air Force experiments at HHFF.

INTRODUCTION

With industry and government requirements pushing the envelope for longer life and more powerful engines, understanding the basic chemistry of the engine's fuel and how it reacts inside the engine's environment is essential. Currently, the industry standard fuel for liquid rocket engines is RP-1, a hydrocarbon blend that has been the standard fuel for the past fifty years. Experience has demonstrated that at relatively high temperatures ($\sim 700\text{-}900^\circ\text{F}$)³, RP-1 and other hydrocarbon fuels begin to decompose and chemically break down into "gummy" deposits that combine with other solids and attach themselves to wetted wall surfaces, causing disruptions and blockages of the flow. Along with flow obstruction, deposition on the wetted wall surfaces begins to act as micro-insulators on the cooling channel walls, which in turn raise the wall temperature to dangerous levels. This increase in wall temperature can lead to increased rates of further deposition on the wetted surface, eventually affecting the efficiency of fuel flow and life span of the engine itself with a possibility of catastrophic wall meltdown.

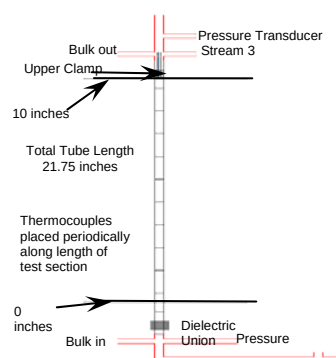
During the past three years, the Air Force has been working to develop a state-of-the-art facility for simulating cooling channels in hydrocarbon fueled rocket engines.¹ This paper is second in a series of papers that are documenting the design and usage of the facility. This paper discusses the first testing in the facility and examines the facility's overall characteristics. The HHFF became operational in October 2005. This facility, coupled with established heated tube facilities, such as the NASA Glenn Heated Tube Facility (HTF)³ and the Wright-Patterson AFB "Phoenix Rig" can now be used to conduct experiments to analyze fuel fluid-behavior, thermal decomposition, and fuel heat flux in a simulative rocket engine

environment, while safely using only small amounts of fuel. Facilities such as these are vital to understanding the behavior and thermal limits of rocket fuels.

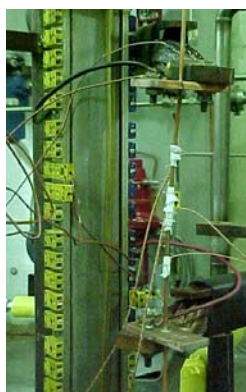
The High Heat Flux Facility design and operation differs from the existing facilities in both construction and heating elements. Both the NASA Glenn HTF and the Wright-Patterson Phoenix Rig use symmetrically heated cylindrical test sections. These test sections are resistively heated using electricity conducted through two bus bars located at the top and bottom of the test section, respectively. The HHFF at Edwards AFB uses an asymmetrically heated square test section. The HHFF test section design is more simulative of actual regenerative cooling channels in present day rocket engines. In addition to the square test section design, the HHFF uses a large conductive heat source, a "heater block", to asymmetrically heat the test section. This heater block is a copper block, approximately 4" x 4" x 12" containing up to 25 electrically controlled heater cartridges. The HHFF provides additional capabilities beyond other facilities by nature of its large experimental range capability. . HHFF can handle internal test section pressures of 4500 psi with flow rates of up to 450 ft/sec leading to heat fluxes of up to 100 BTU/in² sec.¹

In similarity to the HTF, the HHFF uses oxygen-free grade copper walled test sections. Both HTF and HHFF operate under vacuum during experimentation, to prevent oxidation during testing. Copper, due to its highly conductive thermal properties is the industry standard for cooling channel wall material. However the use of copper presents a double-edged sword because copper oxidizes easily in an oxygen enriched environment and it freely reacts chemically with compounds contained within the fuels, mainly sulfur.

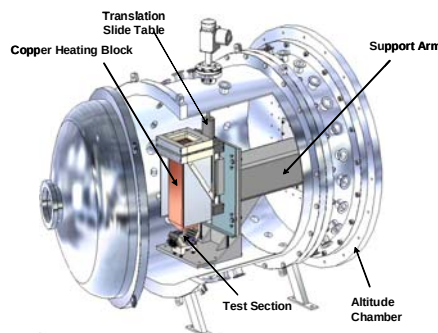
A major distinction between the Air Force's facility at Edwards AFB and the one at Wright-Patterson AFB is that the Wright-Patterson Phoenix Rig was constructed for testing jet fuel, typically JP-8. The turbine engine does not use fuel for cooling high temperature components, but rather uses air. Therefore copper tubes are not part of the principal design of cooling circuits within the turbine engine as they are in rocket engines. In aircraft powered by turbine engines, fuel is used as a heat sink, just as in rockets, but the heat source is different. In aircraft, fuel is the principal heat sink for all heat sources (e.g., electronics, avionics, some engine heat, etc.) The heat is added to the fuel as the fuel flows through a "radiator" style fuel-air heat exchanger. These aircraft heat exchangers are made of stainless steel or titanium². Therefore the Phoenix Rig at WPAFB was designed to use stainless steel tubing for its test section rather than copper. This material substitution eliminates the oxidation hazards associated with copper tubing and the experiments are operated in an ambient environment rather than in a vacuum. Even with these minor differences in construction and operation, all three facilities are producing data which in total is crucial to understanding fluid behavior and chemical interaction of newly developed fuels, and each facility offers a unique perspective and test range which produces complementary data.. Pictures of each facility are shown below in Figure 1.



Wright-Patterson AFB's
Phoenix Rig



NASA Glenn RSC's
Heated Tube Facility



Edwards AFB's
High Heat Flux Facility

Figure 1 : Pictures of Discussed Thermal Stability Test Rigs

To fully establish the newly constructed High Heat Flux Facility as a quality test apparatus, experiments were conducted using RP-2. This fuel was chosen for two reasons. First, even though RP-2 is a relatively new fuel, recent thermal stability data is available and the HHFF baseline experiments would help validate these results while providing initial results for the new facility. Secondly, RP-2 was chosen for the initial HHFF experiments due to RP-2's low sulfur content. One main goal of the HHFF is to evaluate how the presence of various sulfur species in fuel affects the copper-walled cooling channels. In accomplishing this type of test, it is essential that sulfur contamination within the facility plumbing remain as low as possible.

Even though the new facility is capable of producing high wall temperatures and high heat fluxes, it was determined that for the first round of testing all flow rates, pressures, and heat transfer rates should be kept lower to check for both repeatability of data collection as well as comparison of existing heat transfer data. This will help with establishing the facility's baseline characteristics, and the next set of data will begin to push the system's capability further.

EXPERIMENTAL SET-UP

Prior to beginning any of the experiments, all test sections were thoroughly cleaned, assembled, and hydrostatically leak checked with isopropanol. Each test section was washed with isopropanol and nitrogen dried, then lubricated and assembled with vacuum compatible high temperature lubricant. Fuel was then pumped into the bladder accumulator tanks (shown in Figure 2) and the weight of fuel loaded was recorded in the facility log. The entire facility was inspected for any leaks and other potential hazards, and the cleaned test section was installed in the altitude chamber. The chamber was wiped clean of any oil residues and the door was lubed with vacuum grease and sealed shut. Finally, a "roughing" pump was activated the night before testing to pump down the chamber to approximately 2.5×10^{-2} torr for the next morning. At this point the facility was ready for testing.



Figure 2: Bladder Accumulator Tanks

Experimental parameters for the RP-2 tests mandated low wall temperatures in order to monitor fluid flow and facility behavior without the risk of coking the inside of the test section. To achieve these values, three target heater block temperatures were used, 550°F, 650°F, and 750°F. After each test, the fuel tested was analyzed using GCMS to verify cleanliness and composition. All experimental sets were

analyzed identically and no deviation from the pre-test fuel parameters was found. To help maintain a constant inlet fuel temperature, the HHFF's preheater heat exchanger was utilized during all experiments.¹ This component is located just up-stream of the test section and had a set point of 100°F. Due to heat losses through the facility plumbing, the inlet temperature for the test section averaged approximately 89°F for each experiment.

Two experimental sets of the temperature ranges were conducted to validate facility repeatability. Experiments 1, 2, 4, and 5 were five minutes in duration, while Experiments 3 and 6 were twenty minutes in duration. The twenty minute experimental tests were conducted to ensure test duration did not alter the test results due to some, as yet undiscovered, secondary effects that most new facilities seem to experience as they become operational. The data showed that increasing the test duration by a factor of four did not reveal any deviation in results from any facility secondary effects. Each experiment revealed that the facility could maintain the heater block temperature within 40°F of the target temperature. Furthermore the data showed that the mass flow rate of fuel being tested fluctuated within 1% of the set point; which is determined to be an acceptable value. The average experimental values are presented in Table1.

Experiment #	Average Heater Block Temperature (°F)	Average Wall Temperature (°F)	Average Mass Flow Rate (lb/min)
1	541.2	257.8	1.01
2	669.5	304.7	1.01
3	799.9	323.5	0.99
4	539.8	272.7	1.02
5	653.8	281.8	0.94
6	725.7	304.8	0.86

Table 1: Experimental Parameters For HHFF Initial Testing

RESULTS AND DISCUSSIONS

Since the High Heat Flux Facility is newly established, initial tests were conducted in a rather simplistic form to perform a general checkout of the facility. It was determined that general checkout should be performed prior to conducting any in-depth experiments without full confidence in the HHFF's basic operation and not adding any errors or unknowns to a more complex experiment. At this point, the first data has only been cursorily examined using average values of qualified data points. Data points were qualified visually from a plot constructed by graphing the test section outside wall thermocouples (located in the cradle)¹ as a function of time. This qualification was required because it was noted throughout the experiments, that several of the thermocouples did not make complete contact with the test specimens, therefore they did not track temperature measurements accurately. As seen in Figure 3, there is a significant visual difference between the thermocouples that made good thermal contact and those that did not. The thermocouples that made contact with the test section had a large temperature jump within the first 15 to 20 seconds after contact was initiated between the heater block and the test section, whereas the thermocouples with poor test section contact remained unchanged throughout the duration of the experiment.

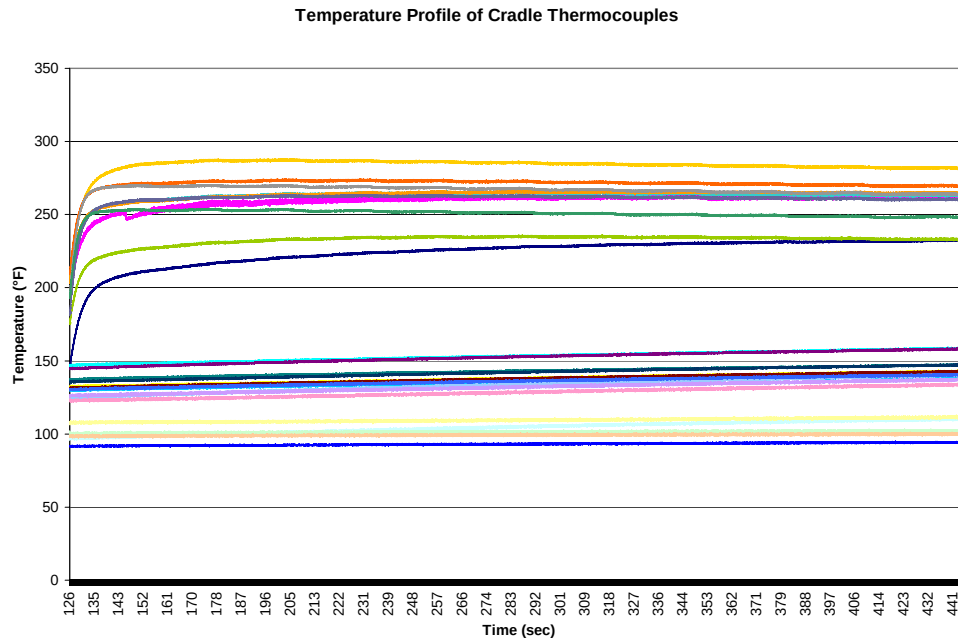


Figure 3 : Visual Qualification of Test Section Thermocouple Values

In order to establish the transient time for each experimental set, all qualified thermocouple values were graphed according to time. A noticeable slope change occurs between the sudden initial (transient) temperature increase and the slower, more gradual “steady state” temperature increase. A tangent line was drawn to each curve, transient and steady-state respectively, as representatives of slope. Where the two tangent lines intersected, a vertical line was placed to indicate the time step of the transition to steady-state. The graph used for Experiment 1 is shown below. (Figure 4)

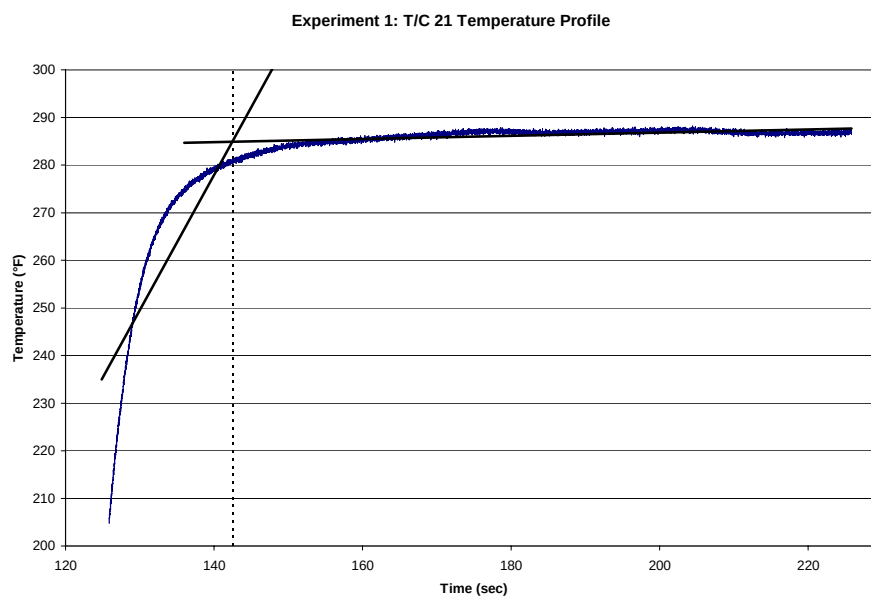


Figure 4 : Transient Time for Experiment 1

After establishing transient time for each experiment, the average heat transfer coefficient (h), heat flux (q), Reynolds Number (Re), Peclet Number (Pe), and Prantl Number (Pr) were calculated. Using these calculated values (Figure 5), an experimental Nusselt Number was determined. Since each experimental Reynolds Number was in the transition range ($1000 < Re < 2300$) and the calculated Peclet Number was greater than 100, the Seban and Shimazaki Correlation was deemed the best fit for the data. (Figure 6)

Experiment	Heat Flux (BTU/in ² -sec)	Reynolds Number	Prantl Number	Peclet Number	Heat Transfer coefficient (experimental) (BTU/ft-hr-°F)	Heat Transfer coefficient (from S&S Correlation) (BTU/ft-hr-°F)
1	4.77	1725.09	149.36	2.58×10^5	146.29	168.39
2	3.57	1712.19	149.36	2.56×10^5	71.94	167.4
3	6.81	1697.66	149.36	2.54×10^5	154.61	166.27
4	4.82	1745.96	149.36	2.61×10^5	132.61	170.01
5	4.80	1592.92	149.36	2.34×10^5	121.60	158.09
6	5.32	1466.73	149.36	2.19×10^5	118.94	148.09

Figure 5 : Calculated Values for Initial HHFF Experiments

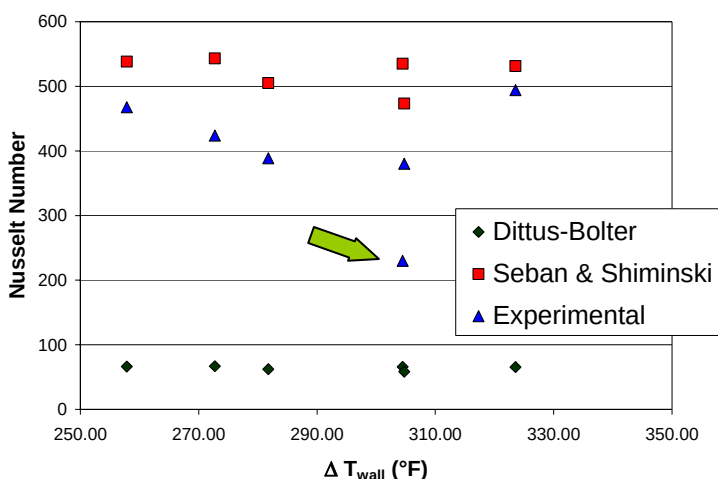


Figure 6 : Nusselt Numbers from Initial Heat Transfer Experiments

For a known comparison, the Dittus-Bolter Correlation was also calculated; however, as it is clearly seen, Dittus-Bolter is not a good correlation for these experiments since the Reynolds Number is below the normal Dittus-Bolter range. The Seban & Shiminski Correlation seen above is plotted as a function of the average wall temperature along the length of the test section.

During the analysis of the data, it was noted that one particular data point did not seem to follow the trend. This data set is from Experiment 2 (shown with the green arrows), and is seen in Figure 7 (heat flux as a function of wall temperature) and Figure 8 (Wall temperature as a function of heater block temperature) as well. Since all the data analysis is still preliminary, it is currently unknown as to why this data set is different. The hypothesis at this time is that some deposition occurred within the test section during the experiment leading to lower heat flux and higher wall temperature. However, if a large amount of build up had occurred in the test section it should have been noted through a decrease in the flow rate and an increase in the pressure drop across the test section and neither of these observations were

noted during testing. Further studies into this result are required to determine the exact cause of the outlier.

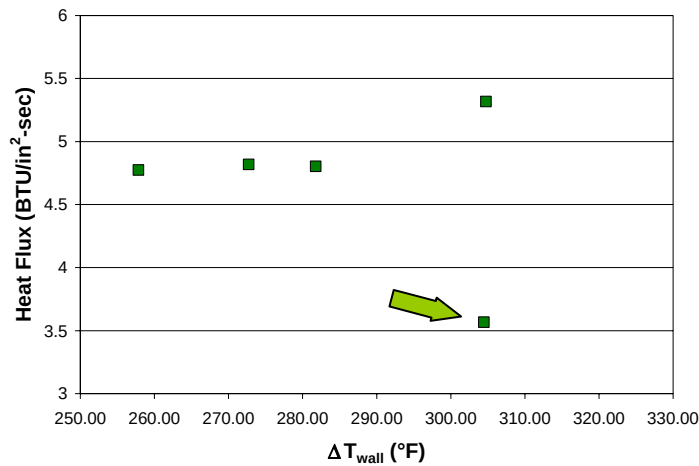


Figure 7 : Heat Flux as a Function of Wall Temperature

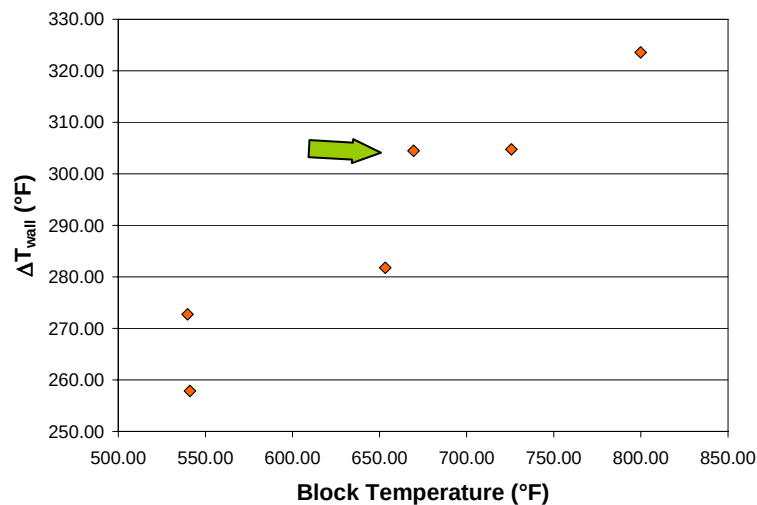


Figure 8 : Wall Temperature as a Function of Block Temperature

As stated previously, one reason for the use of RP-2 as the test fuel and the lower heating parameters was to conduct a comparison between known RP-2 thermal stability data collected at other facilities, principally NASA Glenn's Heated Tube Facility, and the results collected at the HHFF. Other than the similar heat flux measurements obtained, no further comparisons can be made at this time. The majority of data published for RP-2 reports incredibly low deposition and sulfur content. This type of analysis remains to be accomplished for the HHFF test sections.

SUMMARY AND CONCLUSIONS

With the Air Force's new thermal stability test facility up and operational, initial testing was conducted to start in the establishment of a reliable baseline for future use. For these experiments RP-2 was chosen due to recent availability of its thermal stability data as well as its low sulfur content. Six experiments were conducted using three repeated temperatures over an 800 degree heater block range. Experimental procedures were established to ensure minimal thermal deposition would occur within the test specimen during testing. All experiments were successfully carried out and demonstrated that the HHFF is capable of obtaining repeatable heat transfer results.

In analyzing the experimental results, it was determined that the flow was in the transition range from the calculated Reynolds' Number, therefore the Seban & Shiminski Nusselt Number Correlation was an approximate fit for the data collected. All but one of these numbers were within 30% of the experimental values. In addition to the Nusselt Numbers, the heat flux values calculated were similar to previously reported values from NASA Glenn, on the average of 5 BTU/in²-sec. Further studies into the outlying data series and physical examination of the test sections from the HHFF experiments are required. The HHFF facility at EAFB is expected to grow in test capability through a continued establishment of its baseline with advances made thereto.

FUTURE WORK

Future research planned for the HHFF includes completing the initial analysis and baseline establishment begun here, along with conducting further detailed testing to determine: (a) the effects of dissolved oxygen on the fuel behavior and decomposition, (b) the best alternative fuel and material candidates for engine design consideration under typical thermally stressful engine environments, (c) the effects of surface finish on cooling channel operation, and (d) the effects of sulfur species and amounts on the fuel behavior.

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