

2006

Experimental study of the solidification of jet fuel flowing in a quartz duct

Lee Riehl
University of Dayton

Follow this and additional works at: https://ecommons.udayton.edu/graduate_theses

Recommended Citation

Riehl, Lee, "Experimental study of the solidification of jet fuel flowing in a quartz duct" (2006). *Graduate Theses and Dissertations*. 5173.

https://ecommons.udayton.edu/graduate_theses/5173

This Thesis is brought to you for free and open access by the Theses and Dissertations at eCommons. It has been accepted for inclusion in Graduate Theses and Dissertations by an authorized administrator of eCommons. For more information, please contact mschlangen1@udayton.edu, ecommons@udayton.edu.

**EXPERIMENTAL STUDY OF THE SOLIDIFICATION OF JET
FUEL FLOWING IN A QUARTZ DUCT**

Thesis

Submitted to

School of Engineering

UNIVERSITY OF DAYTON

In partial fulfillment of the requirement for the degree of
Master of Science in Mechanical Engineering

By

LEE RIEHL, 2Lt, ANG

School of Engineering

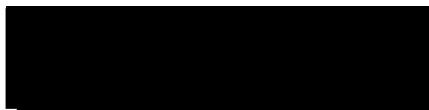
UNIVERSITY OF DAYTON

Dayton, Ohio

August 2006

Experimental Study of the Solidification of Jet Fuel Flowing in a Quartz Duct

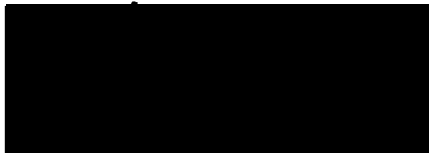
Approved by:



Jamie Ervin, Ph.D.
Professor, Mechanical and
Aerospace Engineering Department
Research Advisor & Committee Chair



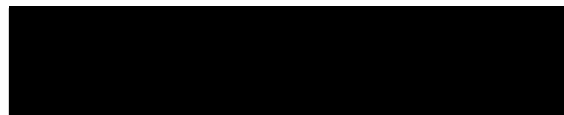
Vinod Jain, Ph.D.
Professor, Mechanical and
Aerospace Engineering Department
Committee Member



Kevin Hallinan, Ph.D.
Department Chair and Professor
Mechanical and Aerospace Engineering
Committee Member



Donald L. Moon, Ph.D.
Associate Dean
Graduate Engineering and Research
School of Engineering



Joseph E. Saliba, Ph.D., P.E.
Dean
School of Engineering

ABSTRACT

The problem of fuel freezing is a concern for both military and civilian aircraft. Aircraft that fly in Arctic regions or at high altitudes encounter low temperatures which may lead to fuel freezing. Frozen fuel can lead to problems in flight such as fuel trapped in fuel tanks as well as clogged filters, disabled valves, and potential fuel starvation of the engine. There are different fuels which can be used to address low temperature concerns. A specialty fuel currently used by the U.S. Air Force for high altitude flight is JPTS (Jet Propellant Thermally Stable). JPTS is costly and has limited availability. In addition, having different fuels available adds logistical difficulties as well as operational costs. One potential solution is the use of low cost additives which can improve fluidity at low temperature.

If the additive can be blended with an abundant low-cost fuel, it may be possible to only have one fuel on hand. It is necessary to better understand the freezing behavior of fuel in representative conditions, so that the additives can be screened in a meaningful way.

In this work, JP-8, JPTS, JP-8 with LTxxx and JP-8 with LTbbb were studied under low-temperature conditions flow through a quartz duct.

TABLE OF CONTENTS

ABSTRACT.....	iii
TABLE OF CONTENTS.....	iv
LIST OF FIGURES	v
CHAPTER 1: INTRODUCTION.....	1
CHAPTER 2: EXPERIMENTAL.....	4
2.1 APPARATUS	4
2.2 PROCEDURE.....	8
2.3 CONDITIONS	9
CHAPTER 3: RESULTS AND DISCUSSION.....	10
3.1 EXPERIMENTS WITH NEAT JP-8.....	10
3.1.1 Insulating Layer	19
3.1.2 Effects of Additives	24
3.1.2.1 Lower Temperatures	24
3.2 TEMPERATURE REDUCTION	38
3.2.1 JP-8 Lower Temperatures	38
3.2.2 JPTS Lower Temperatures.....	39
3.3 FISCHER-TROPSCH.....	47
CHAPTER 4: SUMMARY AND CONCLUSION	50
BIBLIOGRAPHY	55

LIST OF FIGURES

1. Temperature variation with altitude.....	1
2. Quartz duct image.....	5
3. Thermocouple arrangement.....	5
4. Layout of experimental equipment.....	7
5. Temperatures of fuel samples exiting the duct (60 ml/min).....	10
6. Image of JP-8 after 1 hour (60 ml/min flow rate) of flow.....	12
7. Image of JP-8 after 2.4 hours (60 ml/min flow rate) of flow.....	13
8. Image of JP-8 after 1 hour (120 ml/min flow rate) of flow.....	15
9. Image of JP-8 after 4.5 hours (120 ml/min flow rate) of flow.....	16
10. Temperature of JP-8 exiting the Duct (60 ml/min versus 120 ml/min)...	17
11. Image of solidifying JP-8 after 1 hour (250 ml/min).....	18
12. Image of solidifying JP-8 after 3.5 hours (250 ml/min).....	20
13. Chiller plate temperatures of JPTS (120 ml/min).....	21
14. Image of JPTS after 1.1 hours (120 ml/min).....	22
15. Image of JPTS after 3.9 hours (120 ml/min).....	23
16. Image of JPTS after 4 hours (60 ml/min).....	25
17. Image of JPTS after 4 hours (120 ml/min).....	26
18. Image of JPTS after 4 hours (250 ml/min).....	27
19. JP-8 + 4000mg/liter LTxxx (60 ml/min at 2 hours).....	29
20. JP-8 + 2000mg/liter LTxxx (60 ml/min at 2 hours).....	31
21. JP-8 + 4000mg/liter LTxxx (120 ml/min at 4 hours).....	32
22. JP-8 + 2000mg/liter LTxxx (120 ml/min at 4 hours).....	33

LIST OF FIGURES (Continued)

23.	JP-8 + 4000mg/liter LTxxx (250 ml/min at 4 hours).....	34
24.	JP-8 + 2000mg/liter LTxxx (250 ml/min at 4 hours).....	35
25.	JP-8 + 4000mg/liter LTbbb (60 ml/min at 4 hours).....	36
26.	JP-8 + 2000mg/liter LTbbb (60 ml/min at 4 hours).....	37
27.	JP-8 + 4000mg/liter LTbbb (120 ml/min at 4 hours).....	40
28.	JP-8 + 2000mg/liter LTbbb (120 ml/min at 4 hours).....	41
29.	JP-8 + 2000mg/liter LTbbb (250 ml/min at 4 hours).....	42
30.	JP-8 (120 ml/min at 2.5 hours).....	43
31.	JPTS (120 ml/min at 4 hours).....	44
32.	JP-8 + 4,000 mg/liter LTxxx (120 ml/min at 4 hours).....	45
33.	JP-8 + 4,000 mg/liter LTbbb (120 ml/min at 4 hours).....	46
34.	Fischer-Tropsch fuel (120 ml/min).....	48
35.	Thermocouple rakes (JPTS versus synthetic).....	49

CHAPTER 1

INTRODUCTION

The problem of fuel freezing is a concern for both military and civilian aircraft. Aircraft that fly in Arctic regions or at high altitudes encounter low temperatures due to both environmental conditions and reductions in temperature as higher altitudes are reached. For example, Figure 1 shows that the static air temperature decreases with increasing altitude between 0 and 10,000 meters. This behavior is important because -40C is the freeze point temperature of Jet A fuel, which is the commercial jet fuel used in the U.S.

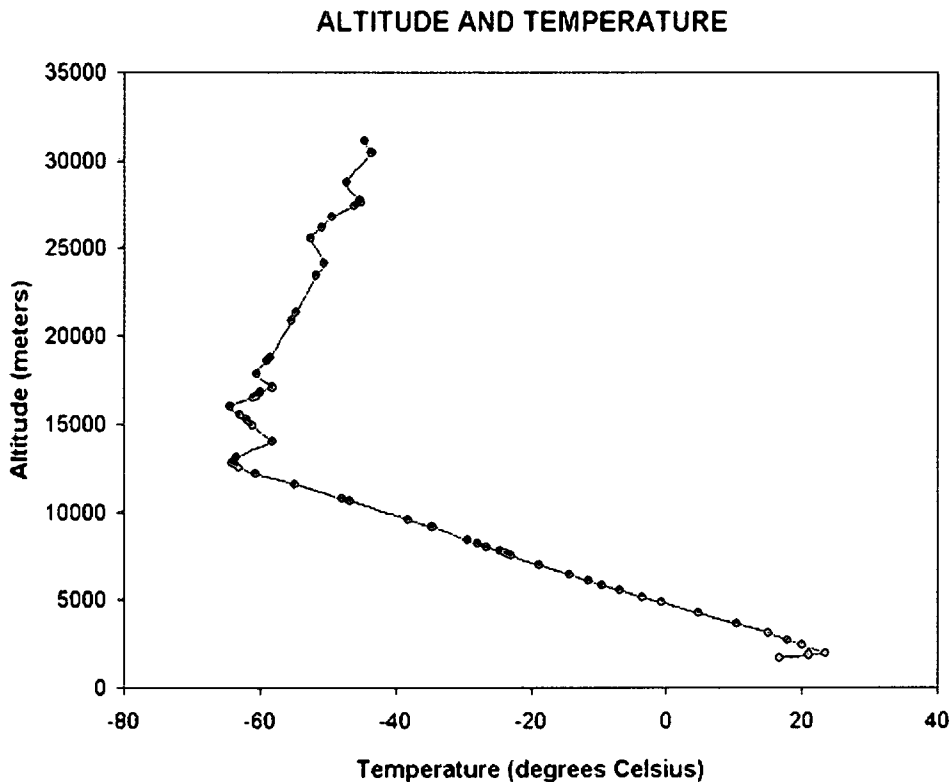


Figure 1. Temperature variation with altitude.

Frozen fuel can lead to problems in flight such as fuel trapped in fuel tanks as well as clogged filters, disabled valves, and potential fuel starvation of the engine. There are different of fuels which can be used to address low temperature concerns. A specialty fuel currently used by the U.S. Air Force for high altitude flight is JPTS (Jet Propellant Thermally Stable). Unfortunately, JPTS is costly and has limited availability. It may be desirable to have an alternative, less costly fuel.

One solution to this low-temperature issue is to have an additive that could be added to the fuel on site when the aircraft would likely encounter a situation where freezing is a risk. If the additive can be blended with an abundant low-cost fuel, it may be possible to only have one fuel on hand. There has been recent interest in creating new additives for jet fuel which enhance fluidity at low temperatures. It is necessary to better understand the freezing behavior of fuel under realistic conditions, so that the additives can be screened in a meaningful way.

Experiments have been performed on fuels at low temperatures.¹ This work made use of a tank (50.8 centimeters x 50.8 centimeters x 76.2 centimeters) fabricated from aluminum and included stringers. Fuel discharge and recirculation nozzles allowed for testing with and without recirculating fuel. The tank was chilled on the top and bottom and had thermocouples to monitor temperatures. Tests were conducted by chilling the external tank surfaces to a nearly constant temperature. Fuel was withdrawn by gravity flow. The remaining partially solidified fuel at the bottom of the tank was defined as holdup. In cases where there was little holdup, the remaining fuel in the tank was essentially solid. When there was a large fraction of holdup, entrapment of liquid fuel was more substantial. Solidification began along the bottom of the tank and then occurred

on the tank stringers. This test apparatus did not allow for images of fuel freezing during testing. In order to better understand fuel behavior under low temperature conditions, it is necessary to have images of the flow.

Leo and Meerwall² encountered problems photographing fuel as it was freezing due to fuel clouding as temperatures were lowered. Atkins and Ervin³ performed flow visualization studies of fuels at low temperatures by using polarized light to maximize the contrast between the liquid and solid phases. Polarized light eliminated the clouding problems associated with the work of Leo and Meerwall². The cell consisted of an aluminum tube with copper blocks mounted on the vertical sides, using liquid nitrogen for cooling. The front and back windows used vacuum insulated quartz chambers that prevented frosting of the quartz and insulated the cell. The work of Atkins and Ervin³ had high-quality optical images, but only of fuel in buoyancy driven flow with very low velocities. Higher flow velocities would better approximate the conditions encountered in many actual aircraft fuel tanks.

Although there has been work performed in this area, there is a need for further research. There is a need to study fuel freezing under forced flow conditions where optical images can be obtained. This information is necessary for more realistic modeling of actual fuel tanks and for enhancing the understanding of how jet fuel freezes.

CHAPTER 2

EXPERIMENTAL

2.1 APPARATUS

In order to study the effect of freezing temperatures on jet fuel and its flowability, a quartz duct (Figures 2 and 3) was fabricated. The rectangular duct (39.4 cm x 8.9 cm x 8.9 cm) was constructed of quartz because of its high optical quality and strength. Figures 2 and 3 show that the duct is separated into two compartments by a dividing plate similar to what might be encountered in some flow passages within a fuel tank. The dividing plate has two passages available for fuel flow. One passage is circular (2.5 cm diameter) and located at the dividing plate center while the other is rectangular (3.8 cm x 1.3 cm) at the plate bottom. The jet fuel flows into the duct through an inlet (1.3 cm diameter) located on one of the sidewalls. A deflector near the inlet reduces the inlet velocity of the fuel flow. In the absence of a deflector, the fuel entering through the inlet would simply pass through the circular opening on the dividing plate. It was presumed that this might result in inadequate mixing of the fuel and, hence would affect the solidification process. In addition, an outlet (1.3 cm diameter) was located at the opposite end of the chamber. Hollow aluminum plates were attached to both top and bottom surfaces. The plates were sealed on both open ends and allowed for threaded pipe fittings and mountings. These plates cooled the horizontal surfaces to the desired temperatures by passing cooled methanol through them. Thermally conductive grease was applied to ensure good thermal contact between the quartz duct and plates.

Well-insulated tubing (0.64 cm diameter) was used throughout the fuel system. A positive displacement pump pumped fuel from an insulated reservoir (5 liter capacity)

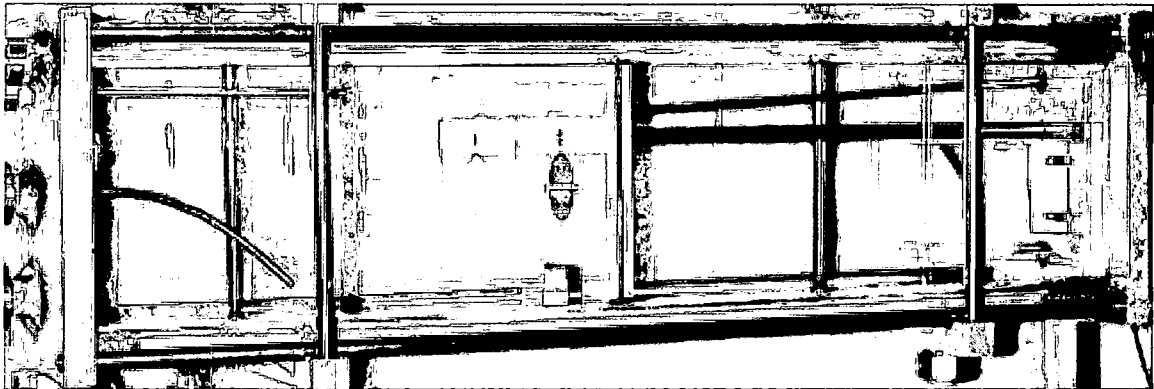


Figure 2. Quartz duct image.

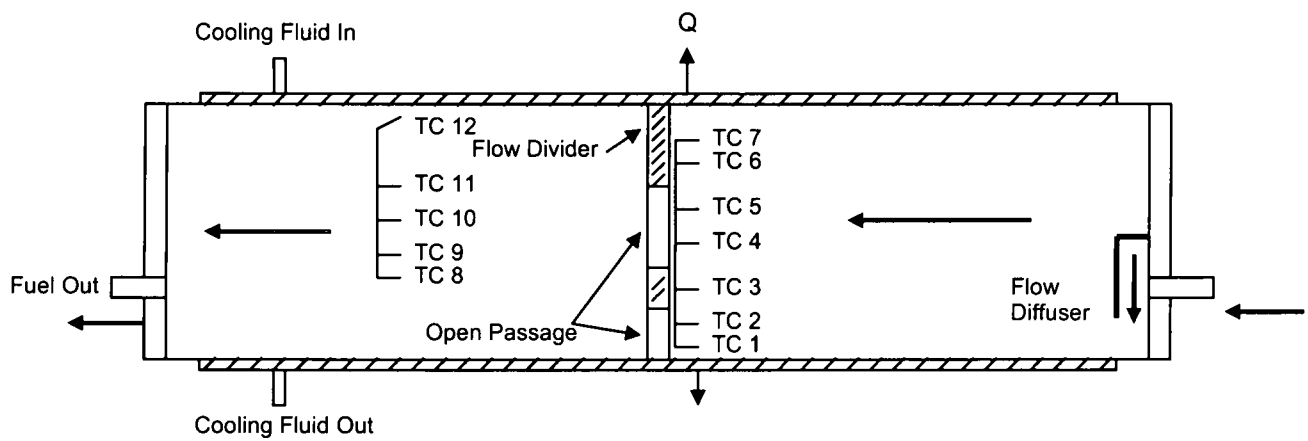


Figure 3. Thermocouple arrangement.

through the duct. A flow meter was installed at the pump outlet to monitor the fuel flow rate. A coil-type heat exchanger was used to cool the fuel before entering the duct. Fuel exited the duct through the outlet and passed through the insulated tubing back to the reservoir.

The entire quartz duct was placed in an environmental chamber (Cincinnati Sub-Zero, Model 152-1, temperature stability of plus or minus 1C) to simulate the low temperature conditions existing in high altitude flight. The chamber temperature was also monitored with a thermocouple.

A chiller (Neslab ULT 95) was used to cool and pump methanol through the hollow plates on the top and bottom of the quartz duct. This unit was capable of maintaining temperature stability within $\pm 0.2^{\circ}\text{C}$. The actual temperature of the methanol was measured by the chiller as well as by thermocouples located at the entrance and exit from the hollow plates. The mass flow rate of the chiller was 1.3 kg/min at -65°C . All lines carrying methanol were well insulated, and the temperature of the methanol entering and leaving the chiller plates was measured using thermocouples. The temperatures of the top and the bottom walls of the duct were recorded and later used as the boundary conditions for CFD calculations. A pressure transducer measured the pressure differential between inlet and outlet of the duct. All data was recorded using a data acquisition system once every minute. Figure 4 shows the arrangement of all test equipment.

Calibrated (Type T) thermocouples were placed at discrete locations inside the duct where large temperature gradients were expected. As shown in Figure 3, a vertical thermocouple rake supporting seven thermocouples at different heights was located near

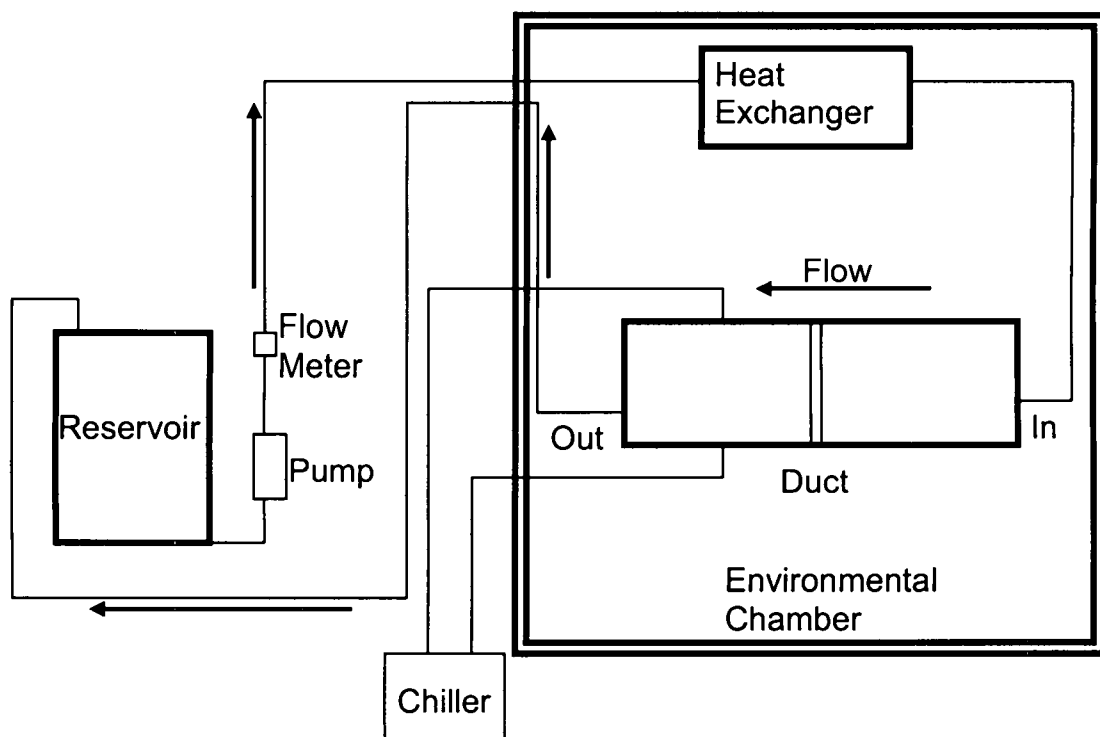


Figure 4. Layout of the experimental equipment.

the flow divider. Another thermocouple rake supporting five thermocouples measured temperatures on the other side of the dividing plate and near the center of a compartment of the duct. Thus, the temperature measurements on both sides of the flow divider are recorded. Thermocouples were installed in the fuel lines entering and exiting the duct.

Lighting for the quartz duct consists of an optical fiber panel that illuminates the entire cell uniformly. Polarizing filters were installed on the front and rear windows of the duct to maximize the contrast between the solid and liquid fuel as cross polarization eliminates light transmittance through the liquid fuel. A high resolution digital camera (Sony DKC-ST5, 4 Mega-Pixel) equipped with a zoom lens (Sony VCL1205B) was used to record images every 30 minutes.

Great care was used when assembling the quartz duct and associated equipment to avoid contaminants. The quartz duct and all the associated equipment were initially cleaned with acetone and then rinsed with JP-8 before assembly. The fuel lines and quartz duct were then flushed with the fuel to be tested thoroughly when the quartz duct was reassembled and when the fuel was changed. The fuel blocked the 60 micron filters located at the pump outlet on a regular basis, so the filters were changed on a regular interval before the fuel flow was restricted.

2.2 PROCEDURE

Experiments were initiated by ensuring that there was no trapped air in the quartz duct that might interfere with the heat transfer to the liquid. When air was found, it was bled off using the bleed ports at the top of the duct. The fuel level was then checked to ensure that the appropriate fuel volume was present. If there was a leak, the total mass of fuel in the reservoir would be decreased causing the bulk fuel temperature of the fuel in the reservoir to fall. The fuel entering the quartz duct would then have a reduced temperature which is undesirable. The chamber was purged with gaseous nitrogen before the experiment began to ensure a moisture-free environment existed. Without the nitrogen purge, frost would form on all surfaces of the quartz duct, making imaging impossible. This also ensured that the environment surrounding the quartz duct remained constant between different experiments. The fuel pump was then started and the volumetric flow measured with the flow meter. The chamber was then set to the desired temperature and allowed to cool. Simultaneously, the chiller was started with the data acquisition. The light panel provided no significant heating of the duct. The lack of

heating was important since the light panel was held against the back of the quartz duct and could be left for long periods.

2.3 CONDITIONS

Each fuel was subjected to the same temperature conditions imposed by the environmental chamber (-48C) and chiller plates (-65C). The environmental chamber temperature was chosen to keep JP-8 with a freeze point of -48C from freezing in the fuel lines. The chiller temperature was selected to keep the difference between sides on the duct from becoming too large, possibly cracking the quartz. Each fuel was run for three different volumetric flow rates; 60 ml/min, 120 ml/min, and 250 ml/min. After these tests were completed, three of the fuels were re-evaluated at 120 ml/min, but with lower environmental chamber (-53C) and chiller (-75C) temperatures. The environmental chamber temperature was chosen to keep JPTS (freeze point of -53C) from freezing in the fuel lines. The chiller temperature was selected to keep the temperature difference on the sides from becoming large enough to crack the quartz.

Pictures were taken with several different cameras and included a high resolution Sony STC and a Kodak DX6340.

CHAPTER 3

RESULTS AND DISCUSSION

In the experiments, the data acquisition system (DaqView) recorded the thermocouple temperatures every 60 seconds to ensure adequate data was available for each experiment. Every 30 minutes a picture was taken of the duct, so that runs at different conditions could be compared. Figure 5 shows that JPTS temperatures changed slightly faster than the additized JP-8 due to the differences in thermal properties of between the fuels.

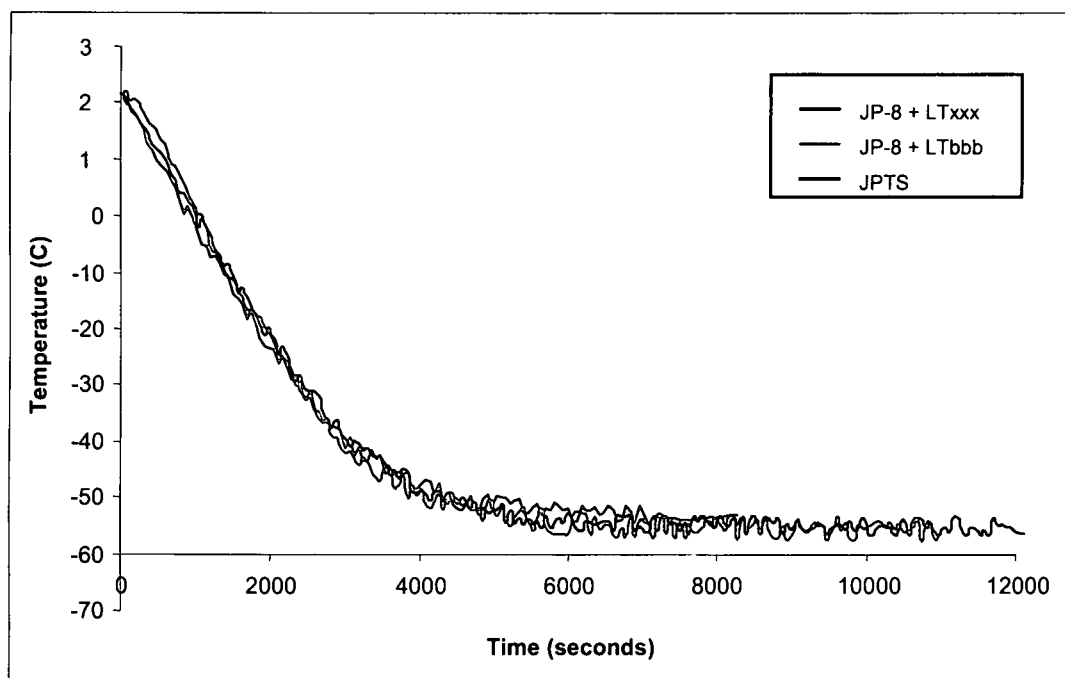


Figure 5. Temperatures of fuel samples exiting the duct (60 ml/min).

3.1 EXPERIMENTS WITH NEAT JP-8

JP-8 was tested as a reference fuel. This fuel is currently used by the Air Force in the majority of flight operations. The measured freeze point of -48C was the lowest of any fuel tested here.

With an inlet flow rate of 60 ml/min, the bulk fuel temperature was the lowest. In addition the accumulation of solidified fuel was the greater for this flow rate. (Figure 3 shows the thermocouple locations within the duct.) Within one hour of starting the experiment, solid formation was visible on the lower surface of the duct as shown by the image of Figure 6. The temperature of thermocouple 1 (TC1) of Figure 3 was -53C which is below the freeze point of -48C for this JP-8 sample. At this time, the amount of accumulation was minimal, but uniformly distributed from the front to the back window of the duct demonstrating that the experiment was two dimensional. After 2.4 hours, the experiment had to be terminated due to a blocked outlet. As shown in Figure 7, solid formation was extensive and rapid. At this time the temperature of TC1 had decreased to -62C, which is the steady-state temperature for that thermocouple. On the left side of the duct, crystals were observed floating in the fuel in the flow path. This suggests that either the solids are forming in the flowing fuel as the temperature decreases below the freeze point or the solids are loosely adhered to the cooled surfaces. As would be expected, the least amount of solidification occurs on the right hand side of the duct due to higher temperatures. As the fuel flows from left to right, the temperature of the fuel decreases as the chiller plates remove heat. The exit is blocked in Figure 7. The temperature increased from the bottom to the top and from right to left resulting in increased solid growth in areas of lower temperature. Solids are floating in the left side due to lower

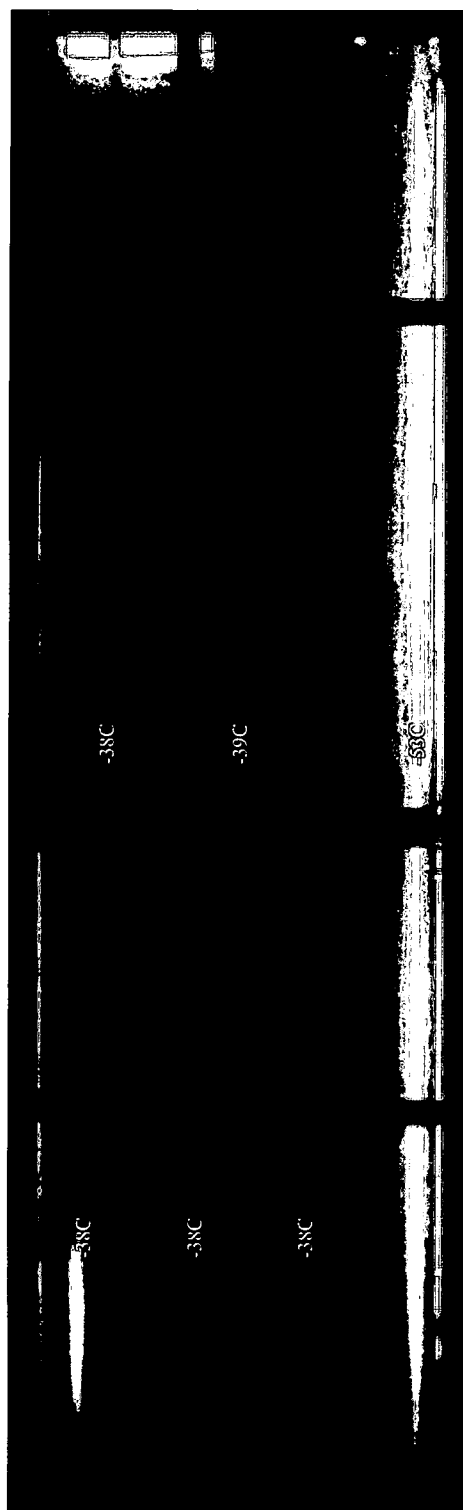


Figure 6. Image of JP-8 after 1 hour (60 ml/min flow rate) of flow.

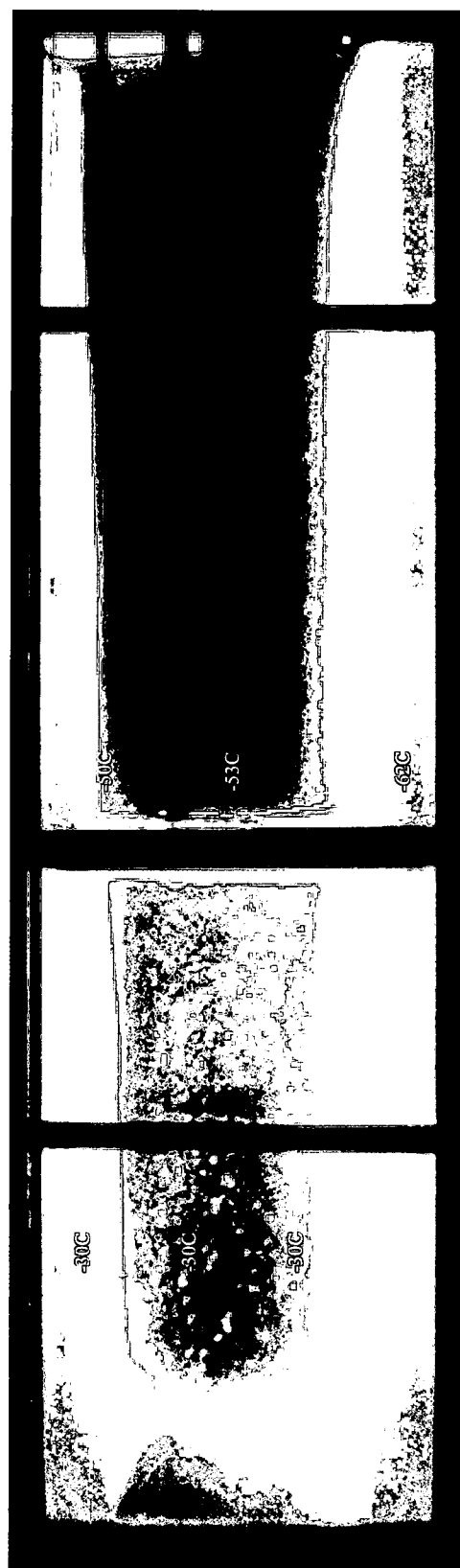


Figure 7. Image of JP-8 after 2.4 hours (60 ml/min flow rate) of flow.

temperatures. This was also experienced by Atkins³ in an optical cell with low flow velocities.

The flow rate was increased to 120 ml/min in order to study the effects of greater velocities while all other experimental conditions remained the same. It was hypothesized that increased flow rate should have the effect of reducing the temperature of the bulk fuel, resulting in reduced solid formation.

At the same point in both experiments the largest temperature difference was noted at TC12, at 5°C warmer with a flow of 120 ml/min. At TC1, the temperature difference was less than 1°C. These two thermocouples demonstrate the most extreme difference between the two experiments. In the case of 120 ml/min, before 1 hour, the rate at which solids form is approximately the same with only a thin layer on the cooled surfaces, as shown in Figure 8. However, as the experiment progressed, the rate of solid formation was greatly reduced from that experienced with 60 ml/min. The experiment was terminated due to a lack of further growth at 4.5 hours. With the higher flow rate, the solid formation appeared smoother and more tightly packed on the surface (Figure 9). There were no solids floating in the fuel, and the exit never became restricted. The absence of solids floating in the duct may have been due to the difference in the temperature gradient within the duct between experiments. Figure 10 shows the cooling of fuel flowing at 60 ml/min compared to the cooling of fuel flowing at a flow rate of 120 ml/min, measured from the outlet of the duct.

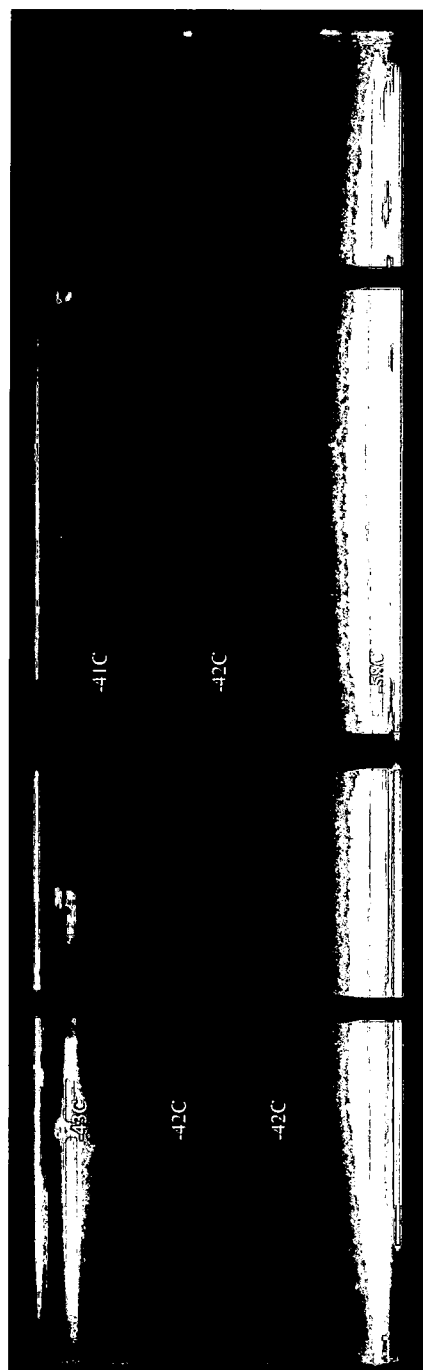


Figure 8. Image of JP-8 after 1 hour (120 ml/min flow rate) of flow.

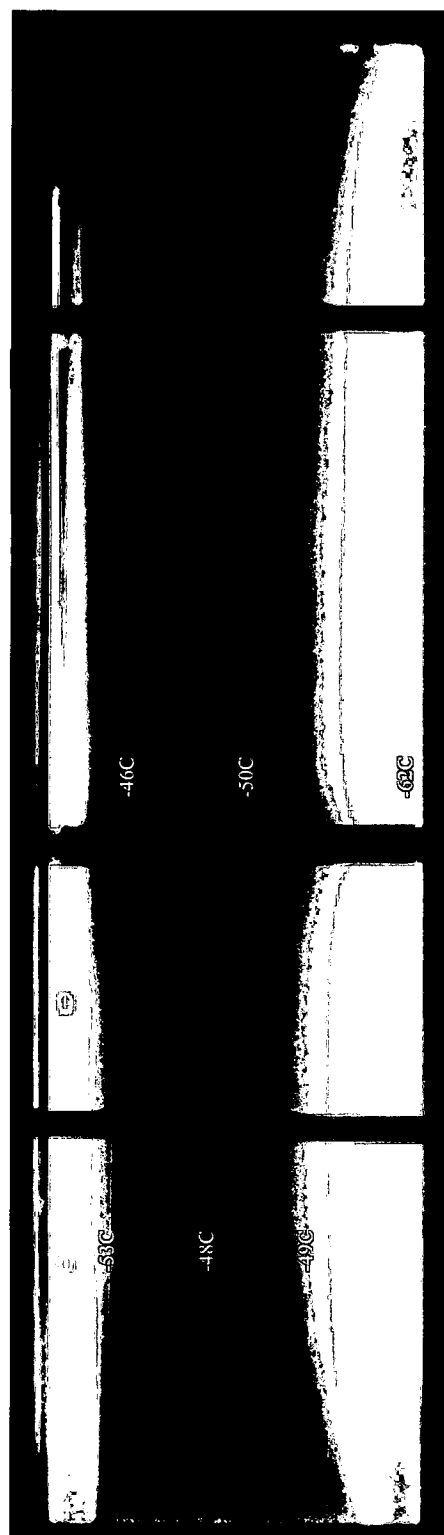


Figure 9. Image of JP-8 after 4.5 hours (120 ml/min flow rate) of flow.

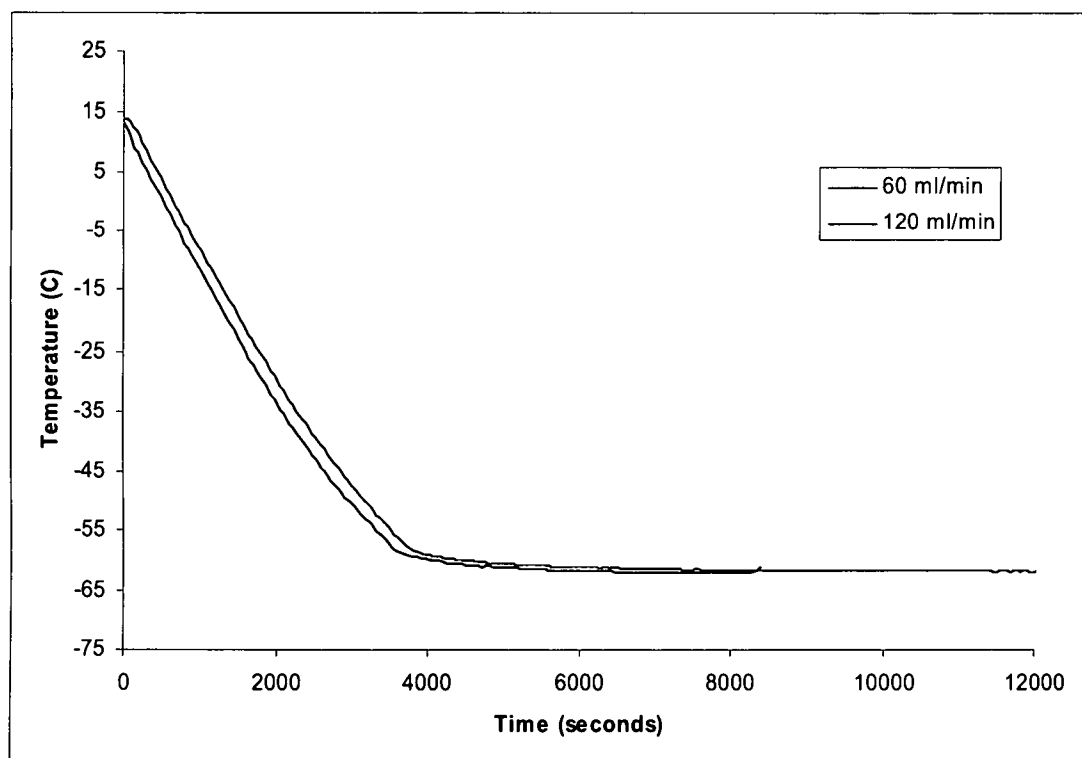


Figure 10. Temperature of JP-8 exiting the duct (60 ml/min versus 120 ml/min).

With a flow rate of 250 ml/min the duct had a significantly greater temperature gradient. The temperature at TC1 in this case was -61 °C, the same as for the 120 ml/min experiment and within a degree of the 60 ml/min experiment. When compared to 60 ml/min, TC12 was 14 °C warmer at the same time of 2.4 hours. This represents the extreme difference, but all thermocouples were warmer until near the top and bottom surfaces. As seen in Figure 11, solid formation is the same as both 60 ml/min and 120 ml/min. The temperature of the fuel exiting the wing was -47 °C, higher than the previous runs by 2 °C. After the experiment was run for 1 hour, solid formation had just started to occur on the cooled surfaces. The accumulation rate slowed significantly after 1

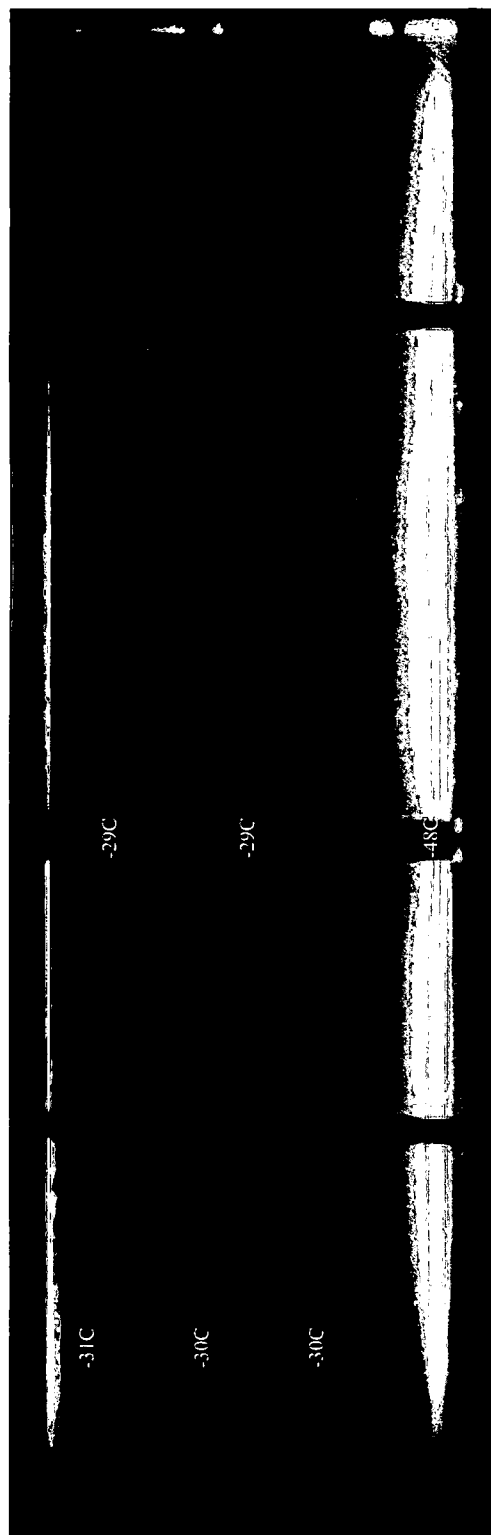


Figure 11. Image of solidifying JP-8 after 1 hour (250 ml/min).

hour, more than either of the two previous runs as shown in Figure 12. The appearance of the solids appeared smoother, as with 120 ml/min, and there were no solids floating in the liquid fuel. There was no flow restriction and the exit was visibly clear and free. The same trend continued as with the 120 ml/min experiment, but with increasing effects.

3.1.1 Insulating Layer

It is often believed that a freezing layer of fuel actually insulates the bulk fuel at the center of the tank and prevents further freezing. Even though the air surrounding the wing, and therefore the fuel tank, may be below the freezing temperature of the fuel, the majority of the fuel in the tank would be protected from freezing.

If the solidified fuel insulates and slows freezing, it should be evident from the heat transfer rate from the chiller plates. The temperature of the methanol used to cool the top and bottom surfaces was measured as it entered one chiller plate and again as it exited the other chiller plate. If the amount of energy gained by the methanol is reduced with time then it would be reasonable to assume that there may be some insulating effects associated with the frozen layer. However if the difference in temperature between the methanol entering and exiting stays the same or increases then it would be reasonable to assume that the frozen layer conducts rather than insulates. Figure 13 shows the transient temperature of the methanol entering the chiller plates relative to the methanol exiting the chiller plates. The graph shows that the temperatures entering and exiting are roughly equal, changing no more than 1 degree in 2.8 hours. (The time selected to start this comparison was the point where the chiller reached the set point value of -75 °C. The time chosen for the end of this comparison was the point where the experiment was



Figure 12. Image of solidifying JP-8 after 3.5 hours (250 ml/min).

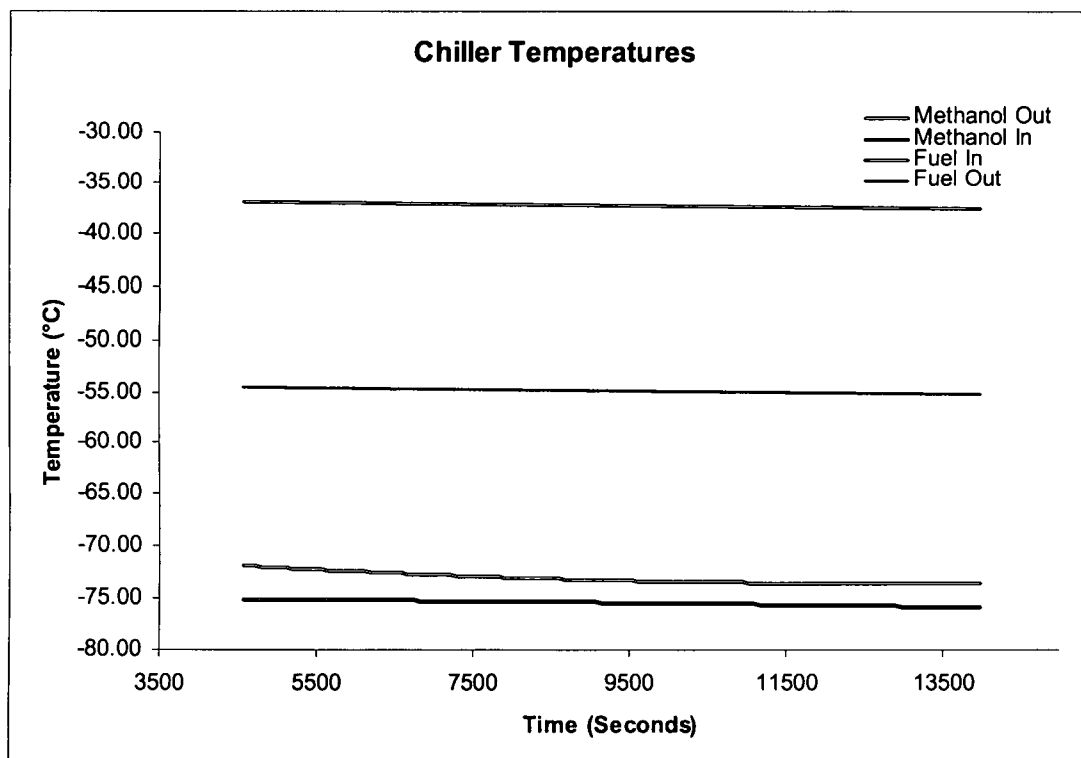


Figure 13. Chiller plate temperatures using JPTS (120 ml/min).

terminated.) Figures 14 and 15 shows that there is a significant increase in solid accumulation, but the inlet temperature versus outlet temperature of the methanol indicates that there is no large reduction in temperature difference with solidification. This indicates that the heat transferred by the methanol is not influenced to any large extent by any insulating effects of solid formation. The evidence from these experiments suggests that the solidified fuel conducts rather than insulates, or is at least a poor insulator.

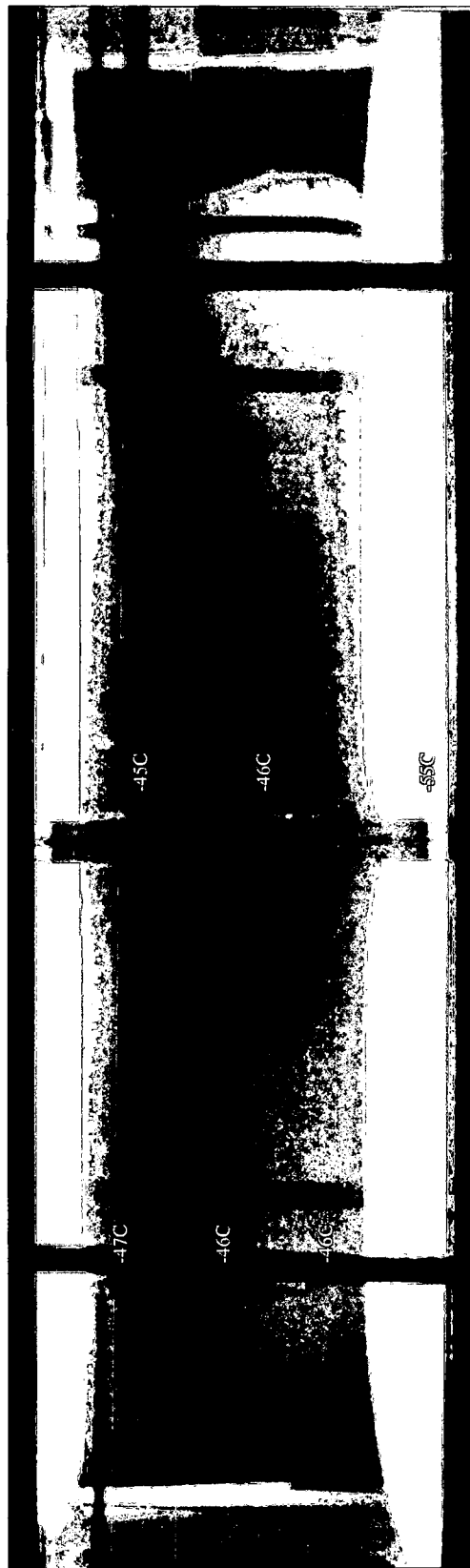


Figure 14. Image of JPTS after 1.1 hours (120 ml/min).

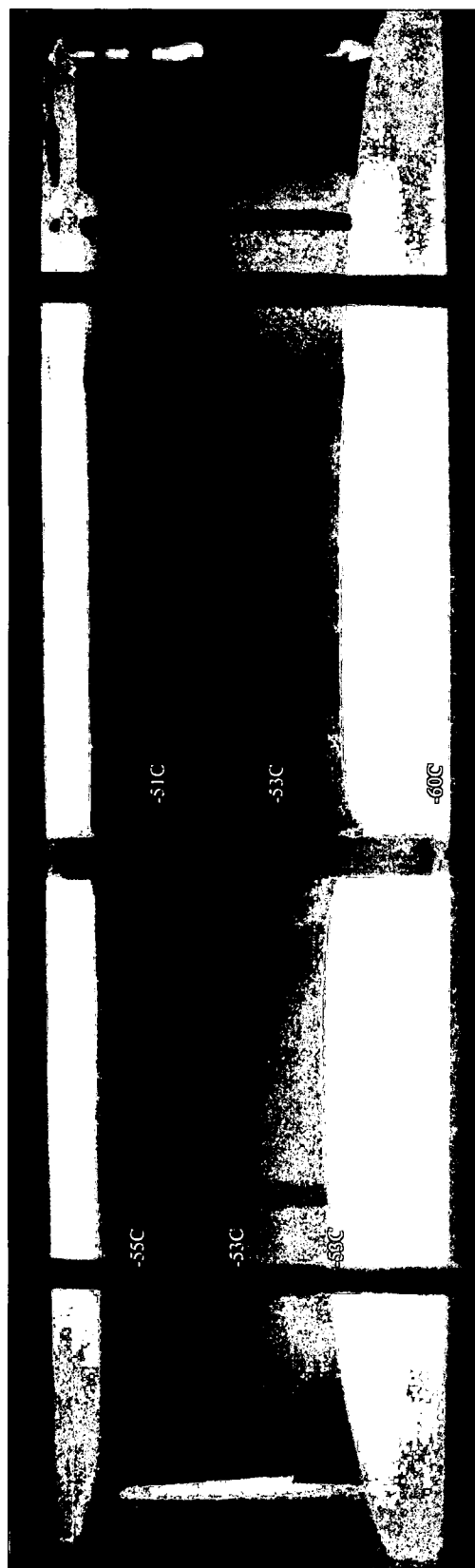


Figure 15. Image of JPTS after 3.9 hours (120 ml/min).

3.1.2 Effects of Additives

Additives designed to improve the low-temperature flow properties of JP-8 were tested and compared to the same JP-8 sample without additives and JPTS. The conditions of testing were maintained to permit accurate comparisons.

JPTS was chosen as the reference for comparison with JP-8 and JP-8 with additives since JPTS is a low temperature specialty fuel. Figures 16 through 18 show JPTS at the end of each experiment for the three different flow rates. Under all flow conditions, the exit never became restricted. As expected due to lower temperatures resulting from increased residence times, more solid formation was experienced with lower flow rates. Temperature gradients became larger as flow rates were increased, as experienced with JP-8. The crystals appeared as long, finger-like extensions that seemed to not be densely packed. The frozen fuel first appeared on the bottom surface, where the chiller plate contacted the quartz. Frozen fuel continued to grow on this surface before any was observed on the upper surface. The thermocouples throughout the wing indicated cooler temperatures at the bottom, due to the cooler denser fuel collecting at the bottom while the warmer less dense fuel moved to the top due to buoyancy effects. Each experiment was terminated as the growth slowed to the point that any additional accumulation was imperceptible. The low amount of solid formation was due to the low freeze point of JPTS (-53 °C).

3.1.2.1 Lower Temperatures

The temperature of the chiller was lowered to -75°C and the environmental chamber decreased to -53 °C, in order to further compare the effects of additives. Figure

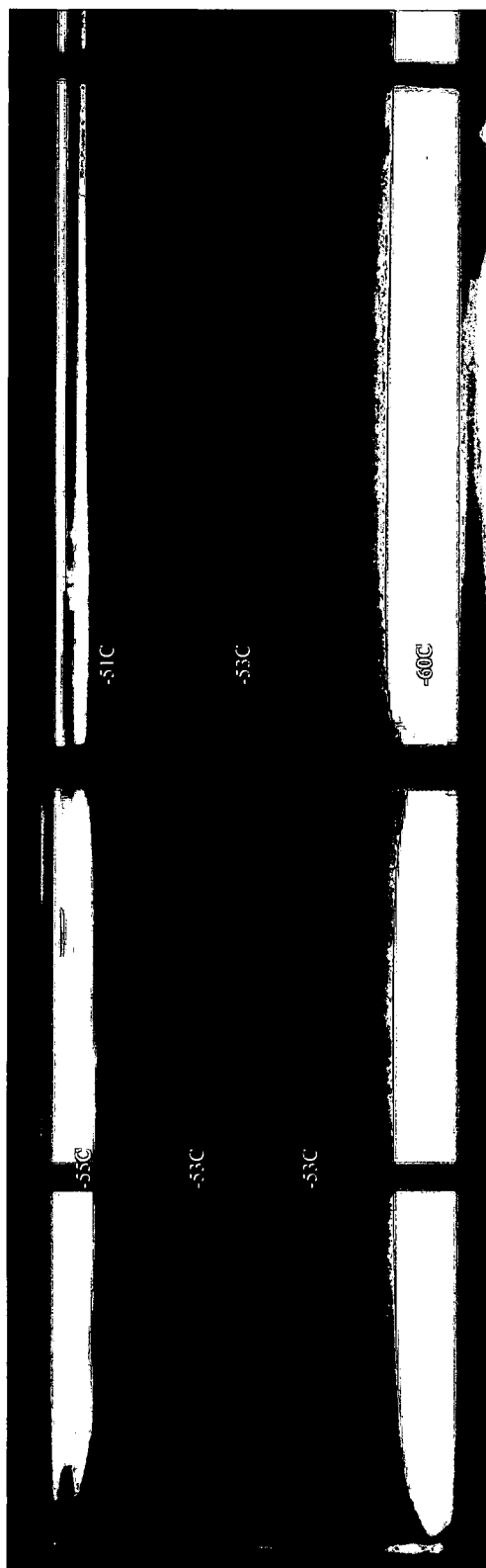


Figure 16. Image of JPTS after 4 hours (60 ml/min).

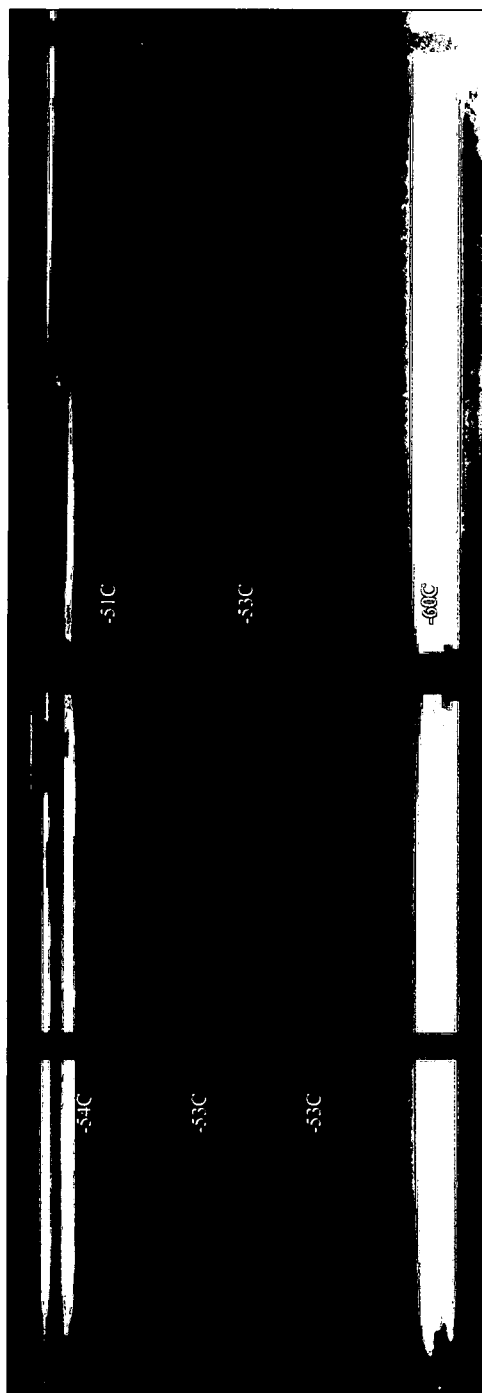


Figure 17. Image of JPTS after 4 hours (120 ml/min).

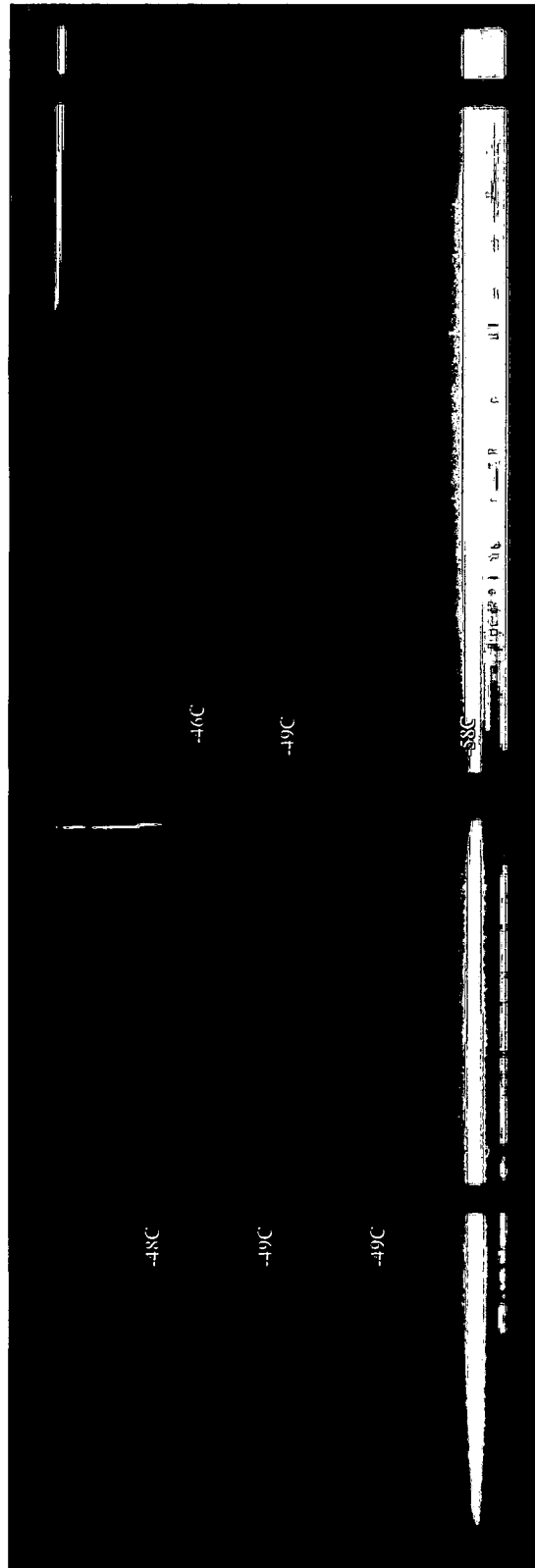


Figure 18. Image of JPTS after 4 hours (250 ml/min).

17 shows JPTS flowing at 120 ml/min under these conditions. The exit never became restricted and the experiment was terminated when there was no observable increase in accumulation. The amount of solidification was appreciably increased as shown in Figures 15 and 17 due to the decreased temperature.

JP-8

Figure 16 compared to Figure 7 shows the dramatic difference between JP-8 and JPTS. With a flow rate of 60 ml/min after 2.4 hours, the JP-8 experiment was terminated due to restricted flow from the duct. The JPTS never experienced a flow restriction and the experiment was terminated only because no additional buildup was experienced. With JP-8, solids were observed floating in the liquid fuel at a flow rate of 60 ml/min and was not experienced with JPTS. The appearance of the crystal microstructure was also different. The JP-8 did not have the finger-like projections; instead it appeared more densely packed. The temperature distribution between the two tests was essentially the same, and the temperature of the bulk fuel entering and exiting the duct was equivalent.

JP-8 + LTxxx

JP-8 with the LTxxx additive was tested for comparison with the other fuels. The initial solid formation on the cooled surfaces occurred at the same time and conditions as with JPTS and JP-8. Crystal growth was similar to that of JPTS, and under the flow rate of 60 ml/min, the exit never became restricted. The crystals appeared different than either JP-8 or JPTS. Also noted was a large increase in crystals in the liquid fuel, more so than with JP-8. This may suggest the crystals are not bonded tightly with each other and may be easily moved. The growth formed in approximately the same rate as with JPTS. Figure 19 illustrates that when the LTxxx additive was added to JP-8 at the concentration of

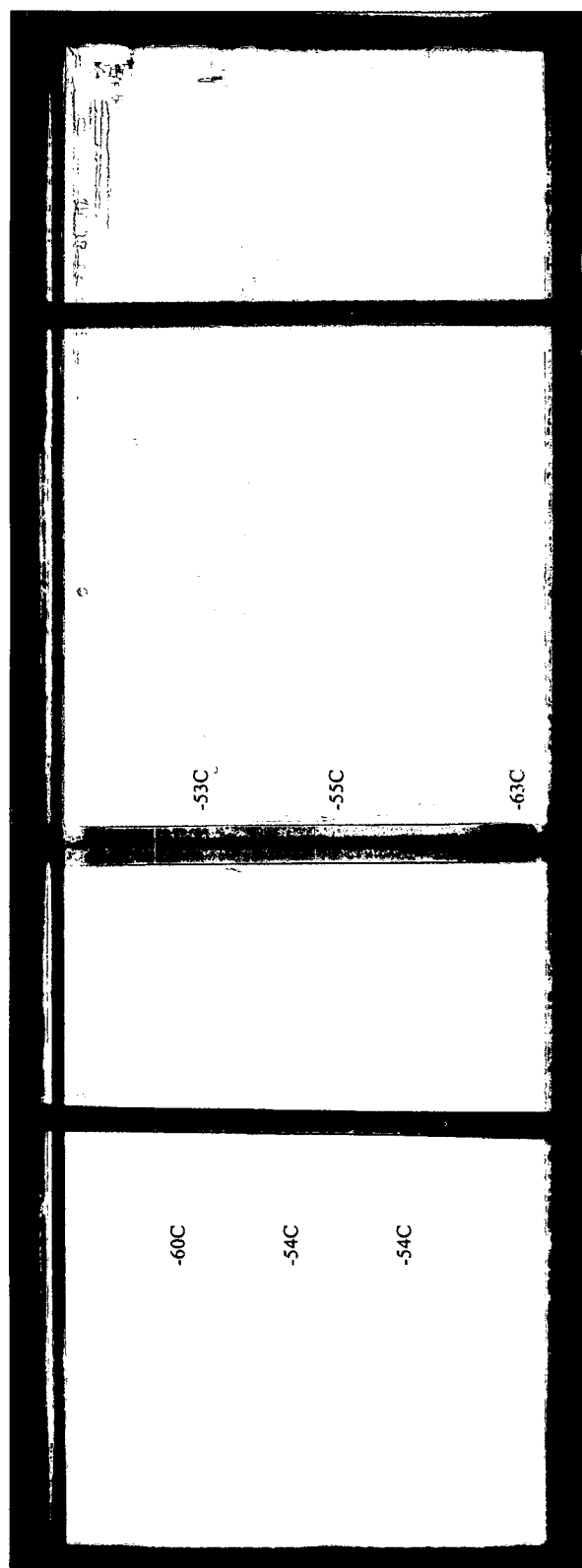


Figure 19. JP-8 + 4000mg/liter LTxxx (60 ml/min at 2 hours).

4000 mg/liter, the low temperature performance was essentially equal to that of JPTS and was much improved over that of JP-8 alone.

Figure 20 shows that as the concentration was decreased to 2000 mg/liter, the effectiveness of the LTxxx additive was slightly degraded. The solid formation was slightly increased, but the exit was never blocked. The solid formation was higher than that of JPTS or JP-8 + 4000 mg/liter LTxxx but much less than that with neat JP-8. The amount of solids floating in the liquid fuel was significantly reduced, which may be significant as solids could potentially restrict flow in filters and lines. Figures 21 and 22 show that as the flow is increased, the solids floating in the liquid fuel are greatly reduced and almost non-existent with just a few particles. The build-up of solids with a flow of 120 ml/min for both 4,000 mg/liter and 2,000 mg/liter of LTxxx showed similar reduction in solid formation as with previous fuels. However, the lower concentration seemed to be as effective as the higher concentration in this example. Increasing the flow rate to 250 ml/min showed almost no accumulation with both concentrations with this additive (Figures 23 and 24). The results for the 250 mg/liter flow rate showed the same solidification with both concentrations as JPTS for these conditions.

JP-8 + LTbbb

JP-8 with the LTbbb additive was then tested and compared with JPTS, JP-8 and with JP-8 with the LTxxx additive. Similar results were obtained for the LTbbb additive in full concentration with respect to total solid buildup. As shown in Figure 26, the darker areas, top and bottom were solid accumulation. Visual images were much harder to obtain with this additive due to extensive clouding. The clouding was thought to be due

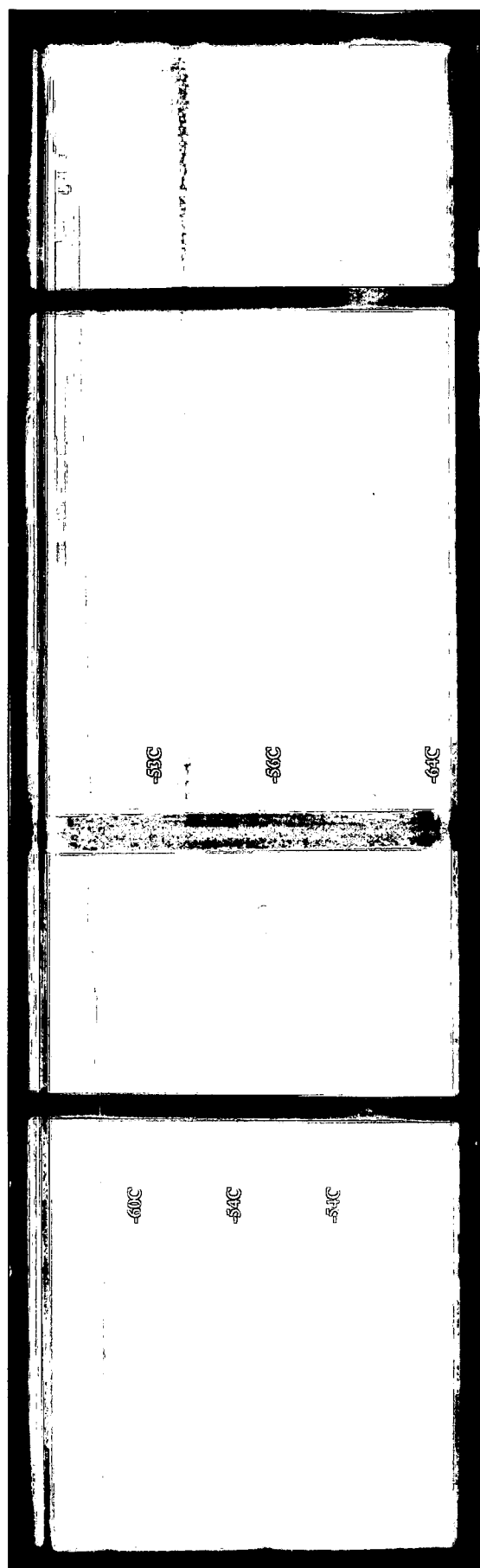


Figure 20. JP-8 + 2000mg/liter LTxxx (60 ml/min at 2 hours).

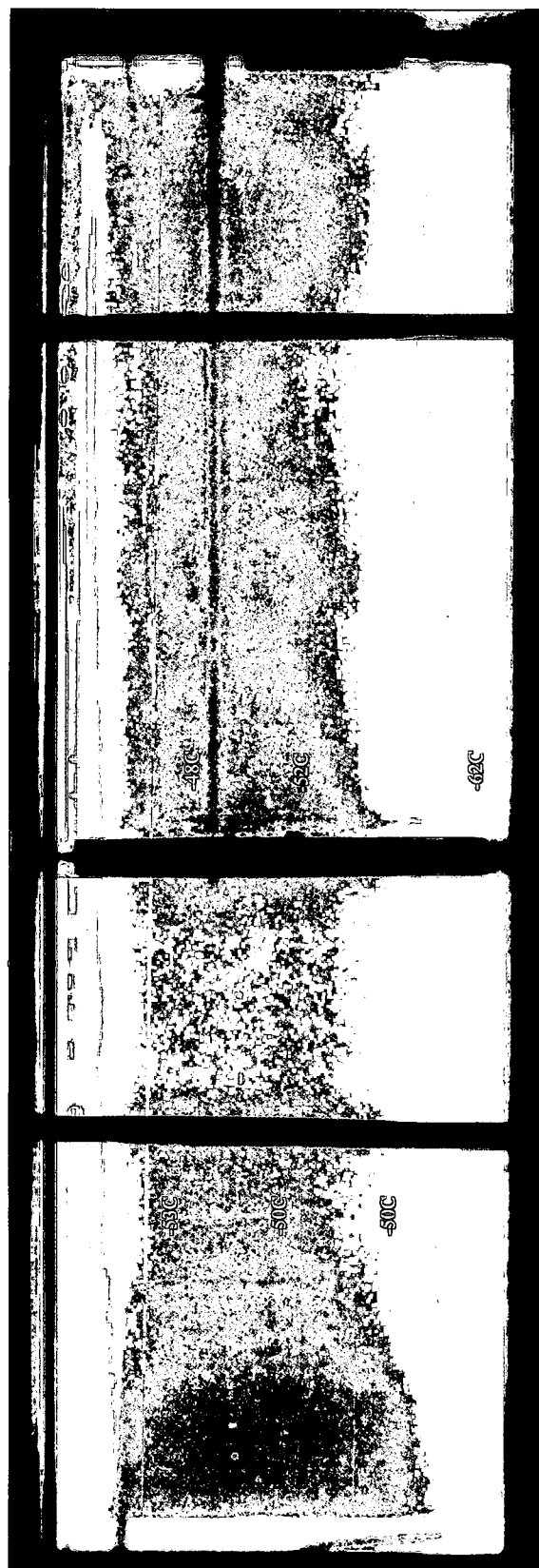


Figure 21. JP-8 + 4000mg/liter LTxxx (120 ml/min at 4 hours).

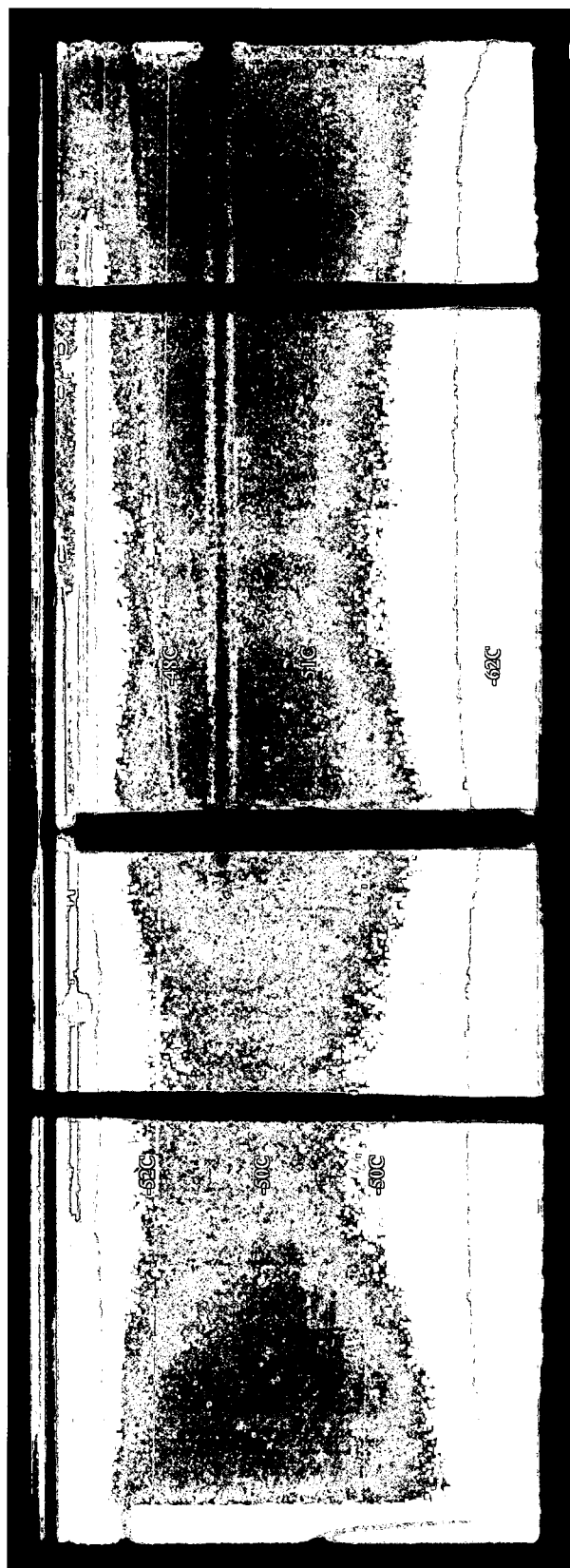


Figure 22. JP-8 + 2000mg/liter LTxxx (120 ml/min at 4 hours).

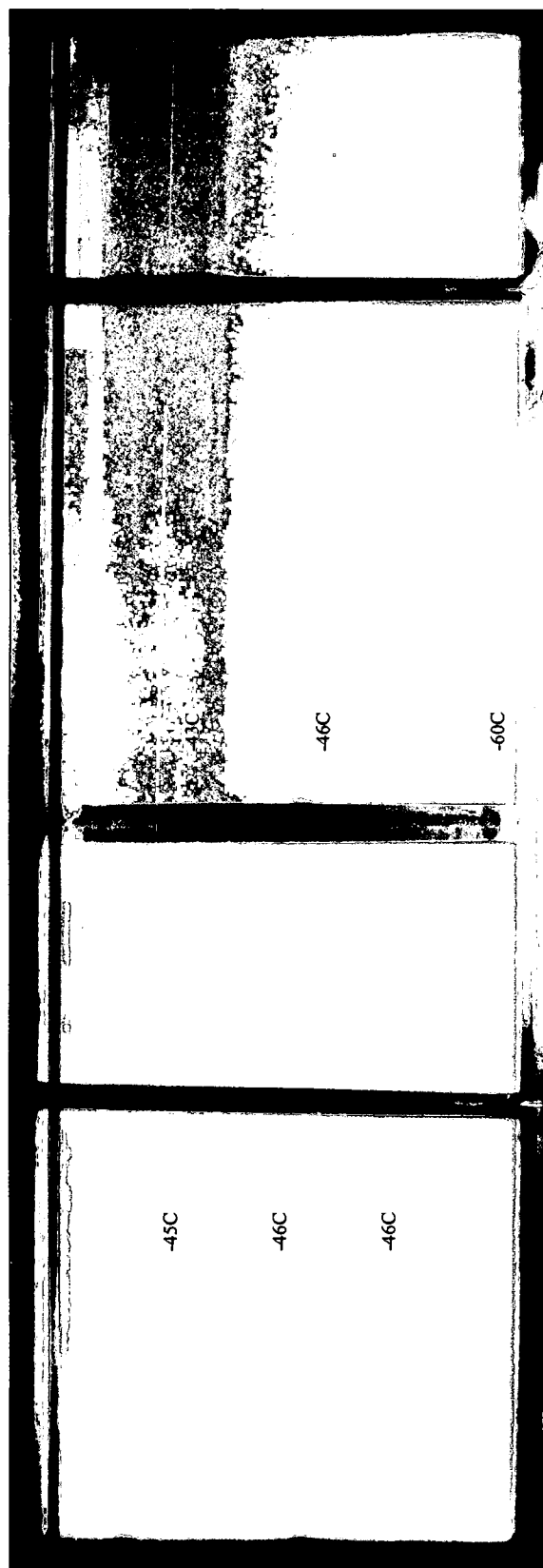


Figure 23. JP-8 + 4000mg/liter LTxxx (250 ml/min at 4 hours).

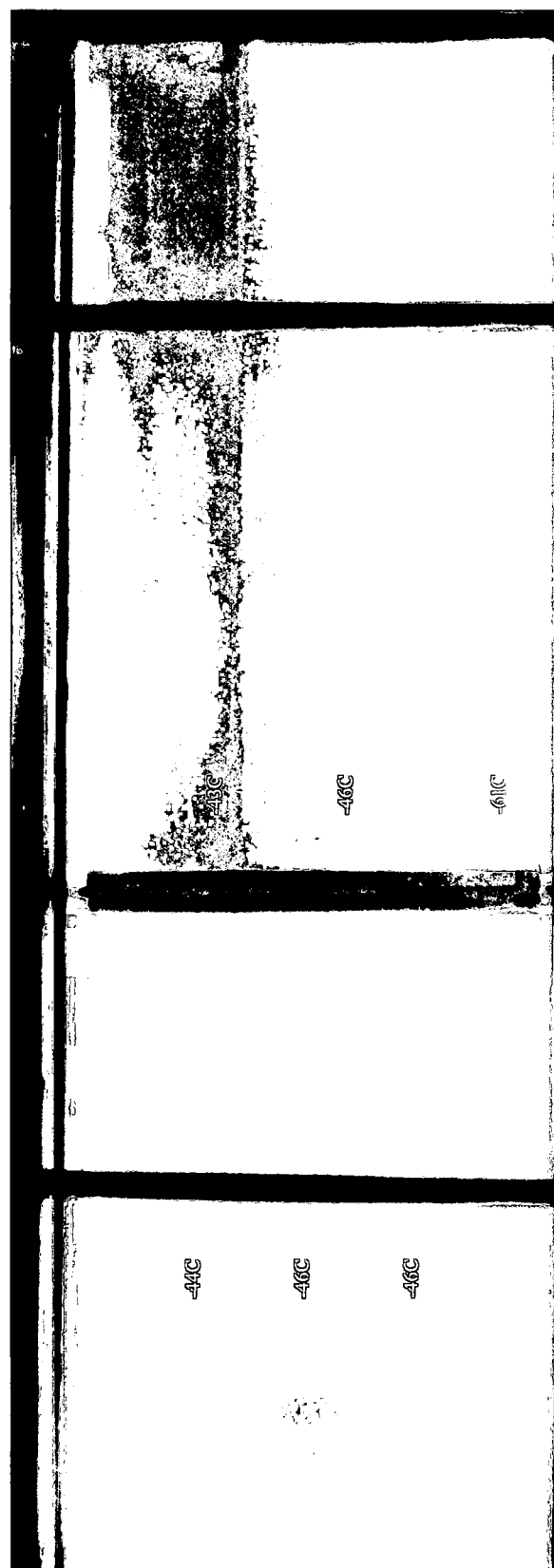


Figure 24. JP-8 + 2000mg/liter LTxxx (250 ml/min at 4 hours).

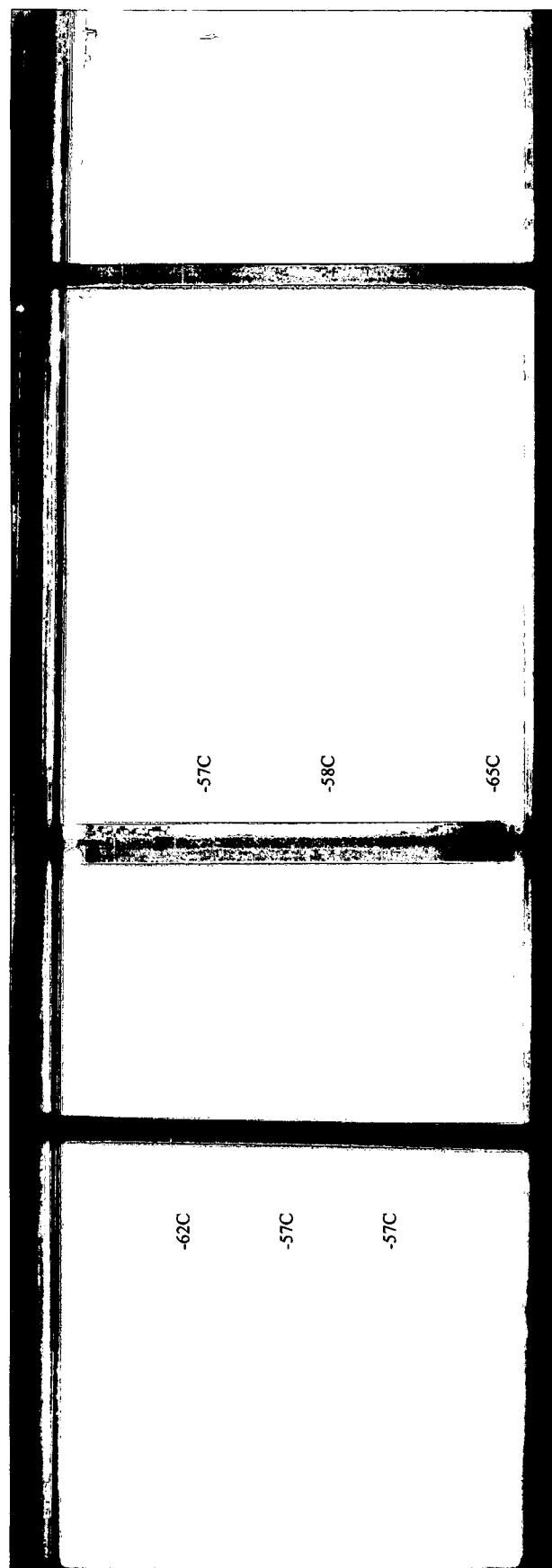


Figure 25. JP-8 + 4000mg/liter LTbb (60 ml/min at 4 hours).

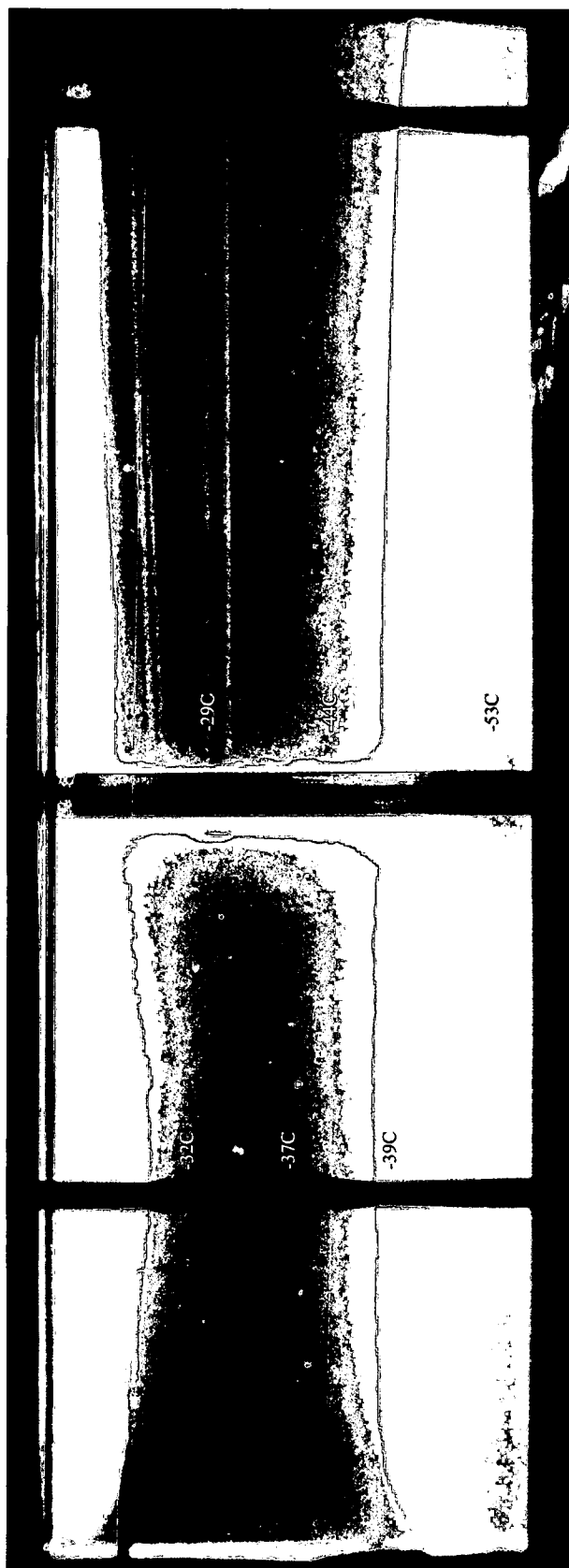


Figure 26. JP-8 + 2000mg/liter LTbb (60 ml/min at 4 hours).

to small crystals floating in the fuel³. The exit never became blocked and the experiment was terminated when no further solid formation was noticed. When compared to JPTS or LTxxx, LTbbb in a 4000mg/liter concentration appeared to be equal in terms of solid accumulation.

However, when the concentration is decreased to 2,000 mg/liter in Figure 26 the results were closer to that of JP-8 in (Figure 8). The experiment was terminated when further solid fuel accumulation seemed to have diminished. The volume of solids in the duct upon termination was far in excess of that of JP-8 + LTxxx and that of JPTS. The cloudy appearance of JP-8 + LTbbb at 4,000 mg/liter was not encountered with the lower concentration.

3.2 TEMPERATURE REDUCTION

The temperatures for both the environmental chamber and chiller were both reduced to further distinguish JPTS from the additized JP-8. The environmental chamber was set at -53 °C which is the freeze point of JPTS. The chiller was set to -75 °C. The chiller's temperature was chosen to avoid freezing in the fuel lines and the chiller temperature was chosen to avoid having to great of a temperature difference that might crack the quartz.

3.2.1 JP-8 Lower Temperatures

With the lower temperature conditions, JP-8 solidified at approximately the same rate that it did with a flow rate of 60 ml/min and the lower temperatures of -48 °C for the environmental chamber and -65 °C for the chiller. The exit appeared to be completely blocked at 2.5 hours, but flow was never restricted. The solidification was very rapid and had the same appearance as it did in the previous experiment with the warmer

temperatures and the same flow rate. When compared to Figure 8, with lower temperatures and the same flow rate, the difference in solidification rate is apparent.

3.2.2 JPTS Lower Temperatures

JPTS showed a large increase in solidification (Figure 31), compared to Figure 16 which shows JPTS with the same flow but under lower temperature conditions. The flow never became restricted and the solid growth appeared as long thin needle-like projections as with the earlier experiments. The exit always appeared to be clear, in contrast with JP-8 with the same conditions. This experiment was terminated when the growth appeared to have stopped.

JP-8 with the LTxxx additive in 4,000 mg/liter showed more solidification than JPTS and had a different point of accumulation as shown in Figure 32. The right side of the duct had about the same volume of solid formation as with JPTS, but forms higher amounts toward the flow divider and reduced at the inlet. The left side shows more build-up than with JPTS, but again builds more toward the flow divider and then tapers off towards the exit. The exit always appeared to be clear, and the flow never became restricted.

JP-8 with the LTbbb additive in 4,000 mg/liter showed about the same solidification as JPTS, having slightly more accumulation at the bottom surface and slightly less on the top as shown in Figure 33. In the previous experiments with this additive, with a flow rate of 60 ml/min the fuel within the duct became clouded. As the flow rate was increased the clouding went away suggesting the higher temperatures within the duct may have caused it. This experiment suggests that this may not be the case since the temperatures with the lower environmental chamber and chiller

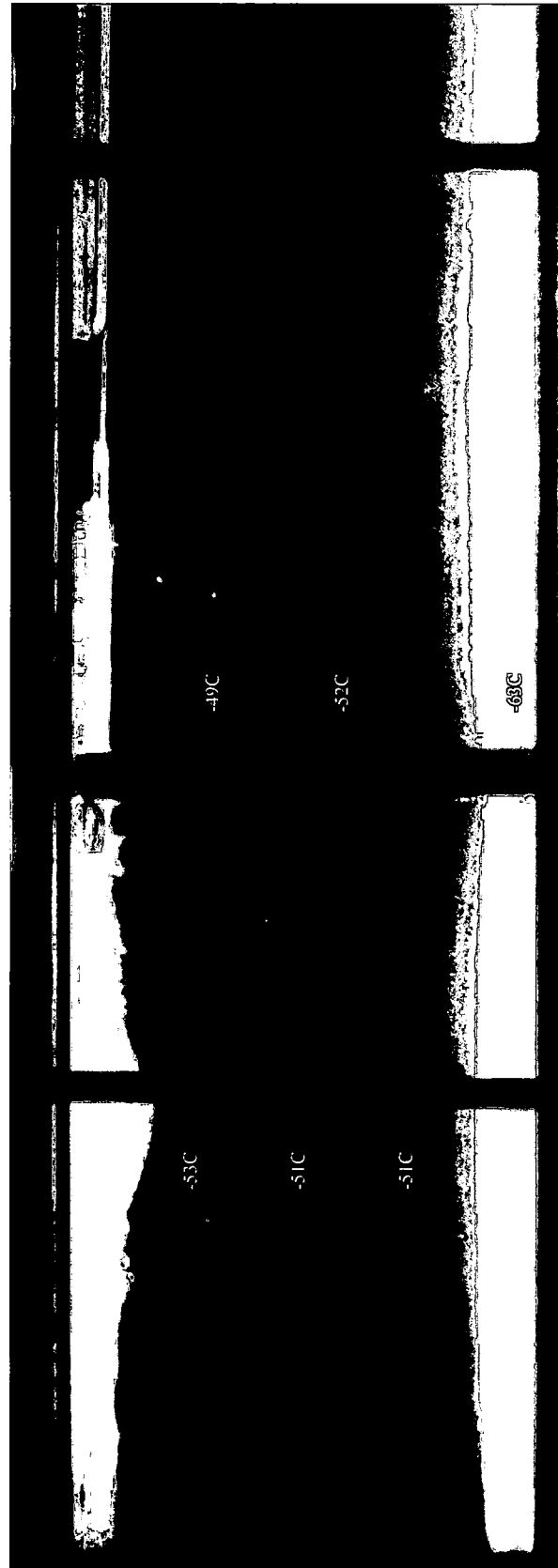


Figure 27. JP-8 + 4000mg/liter LTbb (120 ml/min at 4 hours).



Figure 28. JP-8 + 2000mg/liter LTbb (120 ml/min at 4 hours).

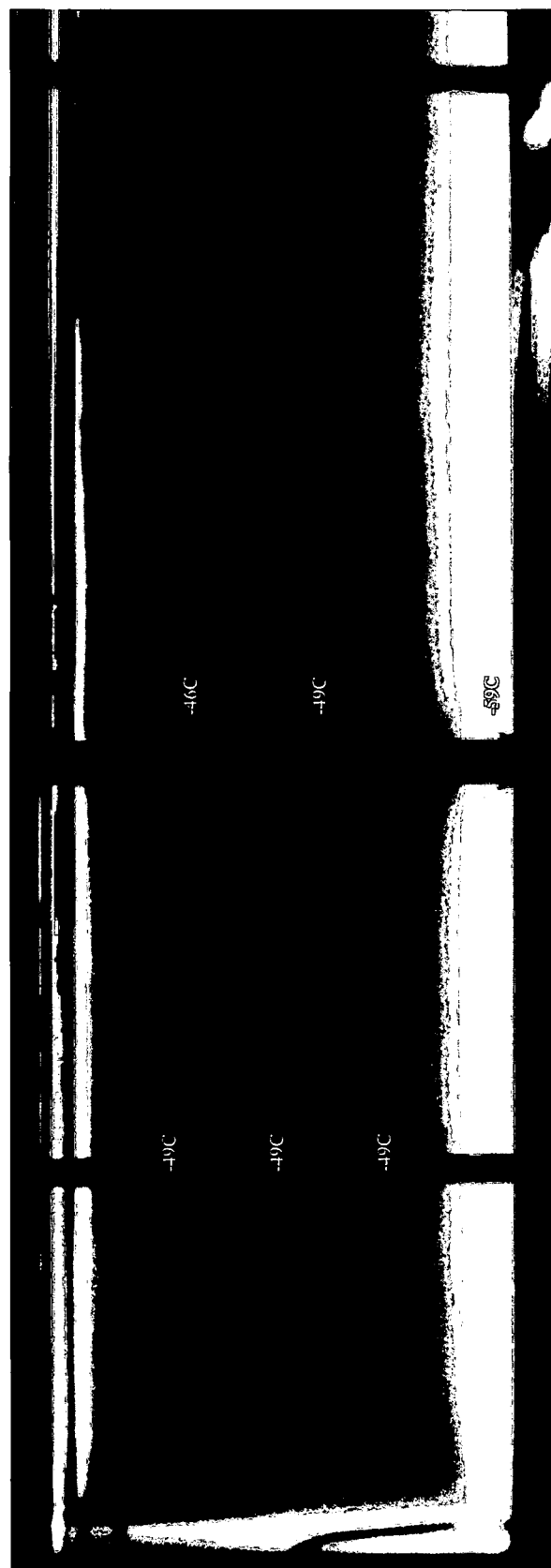


Figure 29. JP-8 + 2000mg/liter LTbb (250 ml/min at 4 hours).

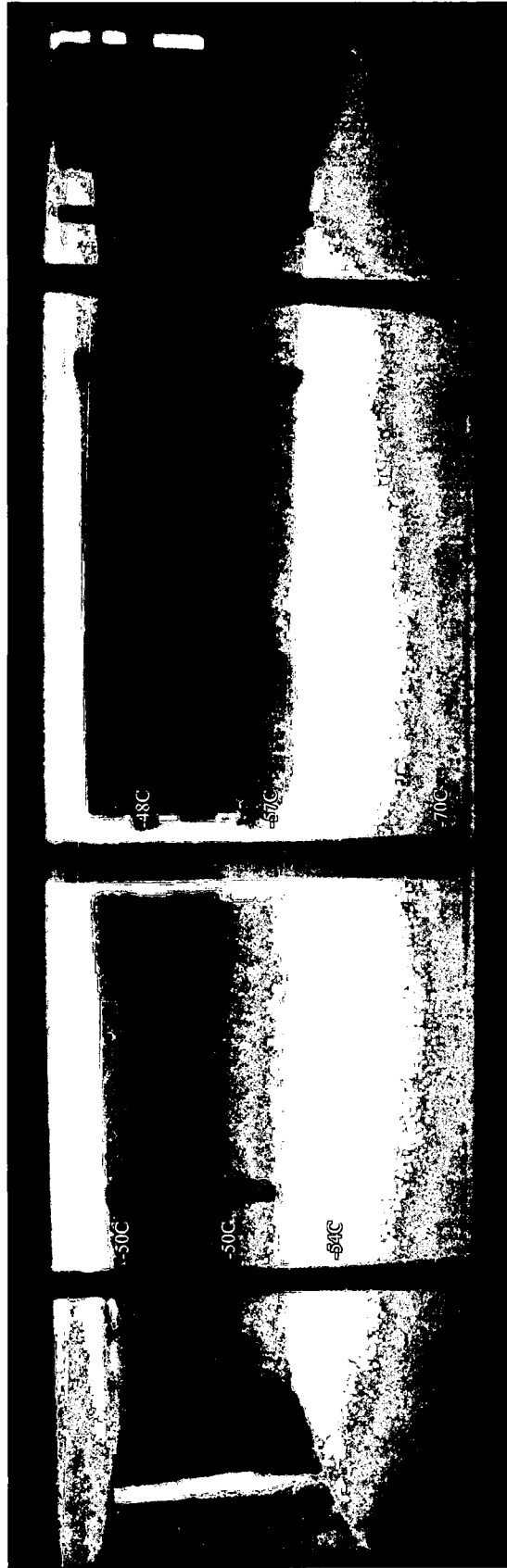


Figure 30. JP-8 (120 ml/min at 2.5 hours).

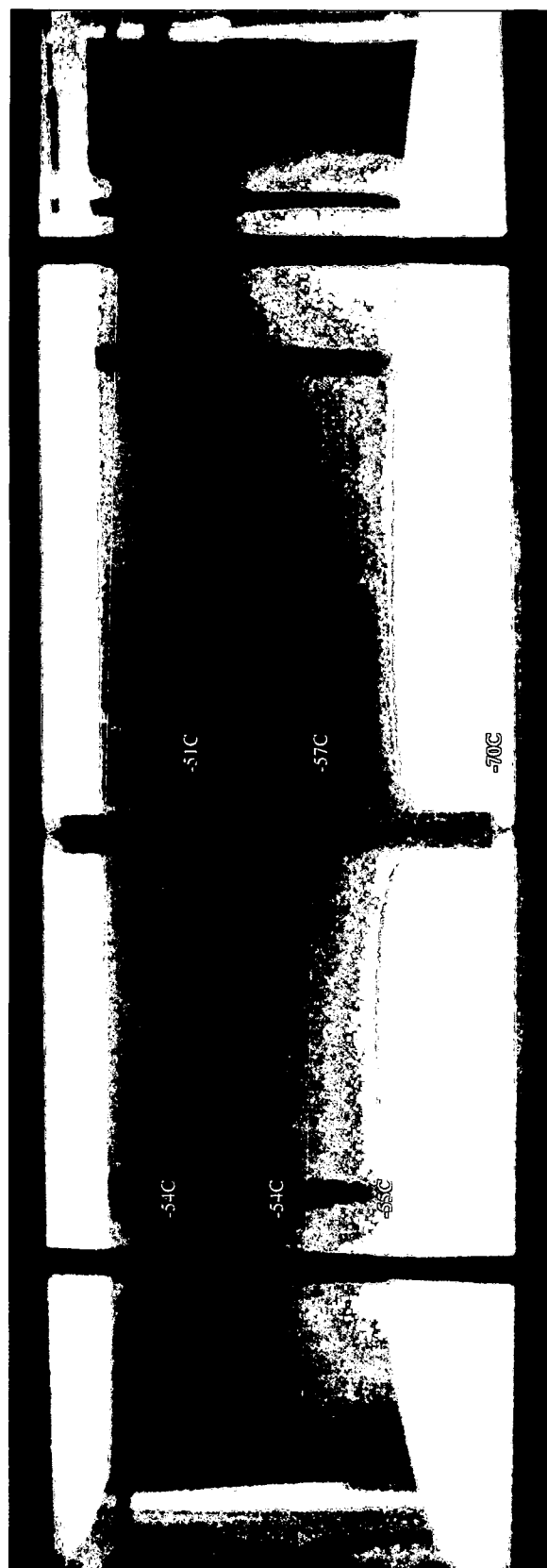


Figure 31. JPTS (120 ml/min at 4 hours).

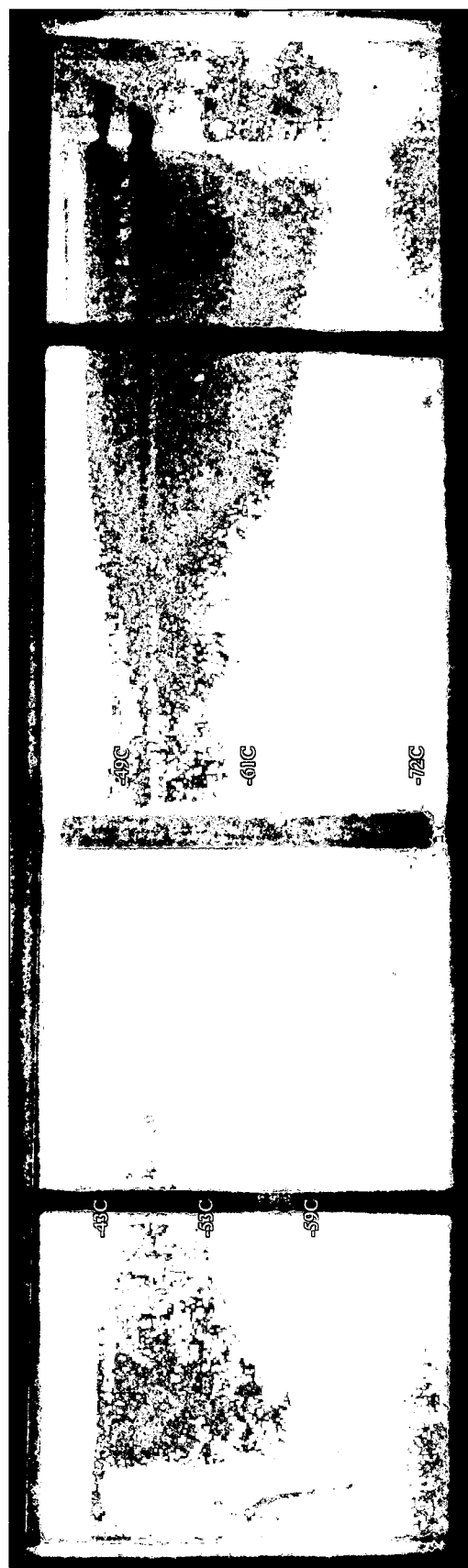


Figure 32. JP-8 + 4,000 mg/liter LTxxx (120 ml/min at 4 hours).

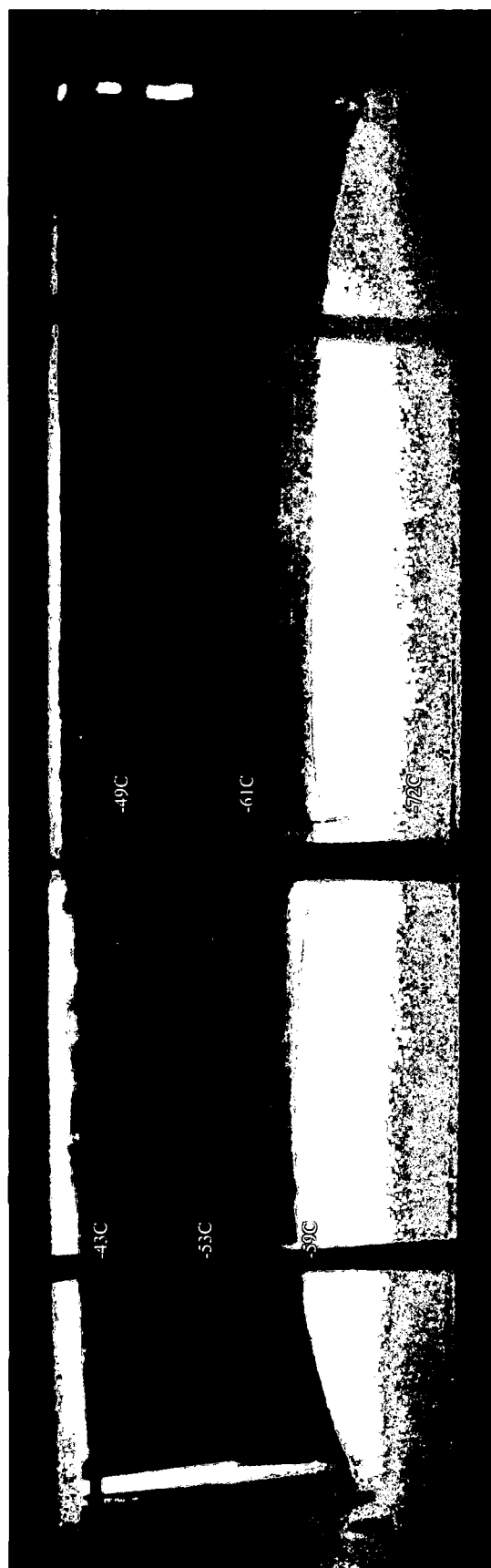


Figure 33. JP-8 + 4,000 mg/liter LTbbb (120 ml/min at 4 hours).

temperatures and 120 ml/min were lower than the previous experiment with the higher temperatures and 60 ml/min flow rate.

3.3 FISCHER-TROPSCH

A synthetic fuel was also chosen for comparison under the same conditions. As shown in Figure 34 the Fischer-Tropsch synthetic fuel performed at least as well as JPTS, and any of the additized JP-8. The synthetic fuel appeared to be clearer out of the barrel, and did not plug the fuel filters in the same manner as all the other fuels. The Fischer-Tropsch fuel has slightly different thermal properties from JP-8. The thermocouple rake showed temperatures somewhat cooler at every point, with the magnitude of the temperature difference growing toward the center of the duct. At steady-state, the temperature of TC1 was only lower by 1 °C, but TC 11 was lower by 8 °C, as shown in Figure 35.

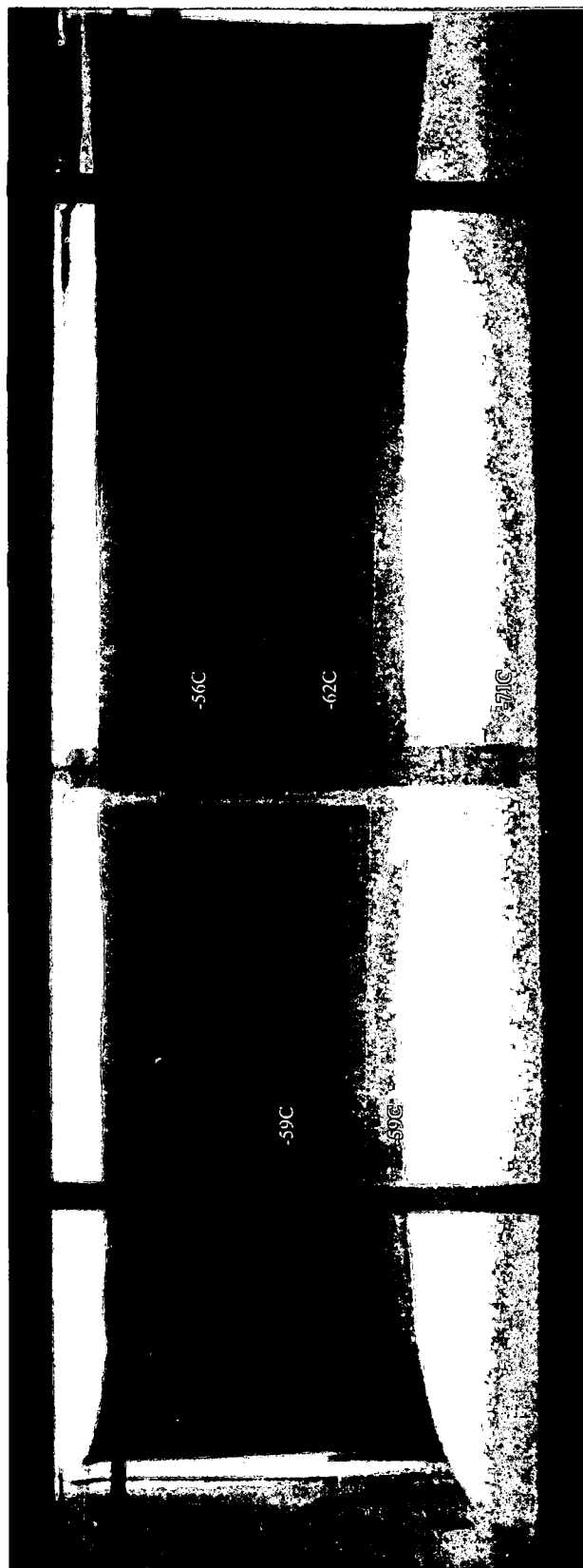


Figure 34. Fischer-Tropsch fuel (120 ml/min).

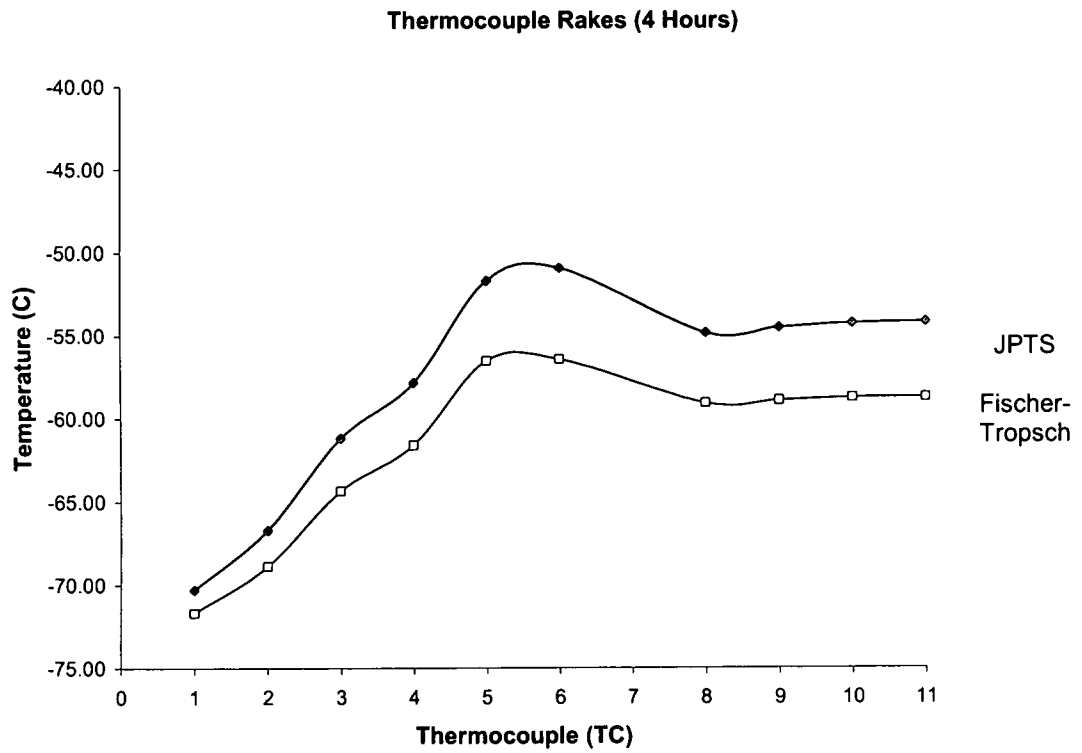


Figure 35. Thermocouple rakes (JPTS versus Fischer-Tropsch).

CHAPTER 4

SUMMARY AND CONCLUSION

The purpose of this research was to determine the effectiveness of low temperature fuel additives in lowering the freeze point and reducing buildup of solids in the fuel tank. To accomplish and test this, quartz duct was cooled in an environmental chamber with chiller plates to permit the collection of optical images for calibration and comparative studies. It was observed that the additives studied enhanced the low temperature properties of fuel.

Temperatures were recorded as a function of time. The data acquisition system (DaqView) recorded the thermocouple temperatures every 60 seconds to ensure adequate data was available for each experiment. This was done to provide a point by point comparison of different additives; therefore every experiment was controlled to have the same conditions. JP-8 was tested as a reference to compare other fuels to. This fuel is currently used by the Air Force in the majority of flight operations. The freeze point of -48°C was the lowest of any fuel tested. It was observed that the flow rate of the fuel through the quartz duct correlated directly with lower temperatures and more solidification. At the same point in time with both experiments, the largest temperature difference was noted at TC12, at 5°C warmer with a flow of 120 ml/min. At TC1, the temperature difference was less than 1°C .

In the case of 120 ml/min, before 1 hour the rate at which solids form is approximately the same as with 60 ml/min with only a light frosting on the cooled surfaces, as shown in Figure 7. However as the experiment progressed the rate of solid

formation was greatly reduced from that experienced with 60 ml/min. The experiment was terminated due to a lack of further growth at 4.5 hours.

It is commonly believed that a frozen layer of fuel actually insulates the bulk fuel at the center of the tank and prevents further freezing of fuel. Even though the air surrounding the wing, and therefore the fuel tank, may be below the freezing temperature of the fuel, the majority of the fuel in the tank would be safe from freezing conditions. The evidence of these experiments suggests that the frozen fuel conducts rather than insulates, or is at least a poor insulator.

Additives designed to improve low temperature properties of JP-8 were tested and compared to the JP-8 without additives and JPTS. The conditions were kept the same to allow for accurate comparisons. JPTS was chosen as a reference to compare JP-8 and all JP-8 with additives to since it is a low temperature specialty fuel. The thermocouples throughout the wing indicated cooler temperatures at the bottom, probably due to the cooler more dense fuel collecting at the bottom while the warmer less dense fuel moved to the top due to buoyancy effects. Each experiment was terminated as the growth slowed to the point that any additional accumulation was imperceptible. The low amount of solid formation was due to the lower freeze point of JPTS of -53 °C. As the temperature was decreased ,the amount of build-up was appreciably increased as shown in Figures 14 and 16.

There is a dramatic difference between JP-8 and JPTS. With a flow of 60 ml/min, after 2.4 hours the JP-8 experiment. This was terminated due to restricted flow out of the duct. The JPTS never experienced a flow restriction of any kind, and the experiment was terminated only because no additional buildup was experienced. The temperature

accumulation between the two tests was practically the same, and the temperature of the bulk fuel in and out of the duct was equivalent.

JP-8 with the LTxxx additive was tested for comparison with the other fuels. The initial solid formation on the cooled surfaces occurred at the same time and conditions as with JPTS and JP-8. This suggests the crystals are not bonded strongly with each other and may be easily moved. The crystal structures formed in approximately the same rate as with JPTS. When the LTxxx additive was added to JP-8 at the concentration of 4000 mg/liter the low temperature performance roughly equaled that of JPTS and was much better than that of JP-8. When the concentration was decreased to 2000 mg/liter, the effectiveness of the LTxxx additive was degraded. The solid formation was slightly higher than that of JPTS or JP-8 + 4000 mg/liter LTxxx but much improved over that of JP-8. When the flow is increased, the solids floating in the liquid fuel is greatly reduced.

JP-8 with the LTbbb additive was tested and compared with JPTS, JP-8 and with JP-8 with the LTxxx additive. Similar results were obtained for the LTbbb additive in full concentration with respect to total solid buildup. Visual images were much harder to obtain with this additive due to extensive clouding. The clouding was thought to be small crystals floating in the fuel³. When compared to JPTS or LTxxx, LTbbb in a 4000mg/liter concentration appeared to be equal in terms of solid build-up.

However when the concentration is decreased to 2,000 mg/liter, the volume of solids in the duct upon termination was far in excess of that of JP-8 + LTxxx and that of JPTS. The cloudy appearance of JP-8 + LTbbb at 4,000 mg/liter was not encountered at a concentration of 2000 mg/liter.

The temperatures for both the environmental chamber and chiller were both reduced to further distinguish the behavior JPTS from that of the additives. With the lower temperature conditions, JP-8 solidified at approximately the same rate that it did with a flow rate of 60 ml/min and the lower temperatures of -48 °C for the environmental chamber and -65 °C for the chiller. With lower temperatures and the same flow rate, JP-8 with the LTxxx additive in 4,000 mg/liter showed more solidification than JPTS. The right side of the duct had about the same volume of solid formation as with JPTS, but forms higher amounts toward the flow divider and reduced at the inlet. The left side shows more build-up than with JPTS, but again builds more toward the flow divider and then tapers off towards the exit. The exit always appeared to be clear, and the flow never became restricted. JP-8 with the LTbbb additive in 4,000 mg/liter showed about the same solidification as JPTS. In the previous experiments with this additive, with a flow rate of 60 ml/min the fuel within the duct became clouded.

A synthetic fuel was also chosen for comparison under the same conditions. The Fischer-Tropsch synthetic fuel performed at least as well as JPTS, and any of the additized JP-8. The Fischer-Tropsch fuel had slightly different thermal properties.

The additives tested showed that they lowered the cloud point and improved the low temperature characteristics of JP-8.

BIBLIOGRAPHY

- (1) Stockemer, Francis J. "Experimental Study of Low Temperature Behavior of Aviation Turbine Fuels in a wing Tank Model", 1979 NASA-Lewis Research Center.
- (2) Leo, A., and Meerwall, E. von, "Fuel Holdup and Component Diffusivity in a cooled Cylindrical Tank," *Journal of Aircraft*, Vol. 26, No. 5, 1989, pp. 465-469.
- (3) Atkins, D. L., and Ervin, J. S., "Freezing of Jet Fuel within a Buoyancy-Driven Flow in a Rectangular Optical Cell," *Energy & Fuels*, Vol. 15, No. 5, 2001, pp. 1233-1240.
- (4) (http://www.classzone.com/books/earth_science/terc/content/investigations/es1702/es1702page05.cfm)
- (5) Van Winkle, T.L., Affens, W.A., Beal, E.J., Mushrush, G.W., Hazlett, R.N., and DeGuzman, J., "Determination of liquid and solid phase composition in partially frozen middle distillate fuels," *Fuel*, Vol. 66, 1987, pp. 947-953.
- (6) Lewtas, K., Tack, R.D., Beiny, D.H.M., and Mullin, J.W., "Wax Crystallization in Diesel Fuel: Habit Modification and the Growth of n-Alkane Crystals," *Advances in Industrial Crystallization*; Garside, J., Davey, R. J. and Jones, A. G., Ed.; Butterworth Heinemann: Oxford, 1991, pp. 166-179.
- (7) Grosjean, D. F., "Efforts to Advance Fuel-System Ice-Inhibitor (FSII) Technology," Prepared under contract for the Air Force Research Laboratory, Propulsion Directorate, Wright-Patterson Air Force Base, OH, 18 September 1998.
- (8) Langer, G., "JP-4 Fuel System Icing," Wright Air Development Division (WADD), Wright-Patterson Air Force Base, OH, 1960.
- (9) Anderson, S. D., Rubey, W. A., and Striebich, R., "Measurement of Dissolved and Total Water Content in Advanced Turbine Engine Fuels with a Gas-Liquid Chromatographic OTC Technique," 6th International Conference on Stability and Handling of Liquid Fuels, Vancouver, B. C., Canada, October 13-17, 1997.
- (10) "Aviation Fuels Technical Review (FTR-3)," Chevron Products Company, URL: <http://www.chevron.com/prodserv/fuels/bulletin/aviationfuel> [cited March 2004].

- (11) "Viscosity of Liquid; Organic Compounds," Chemical Properties Handbook [online], URL: <http://www.knovel.com> [cited March 2004].
- (12) Atkins, D. L., Ervin, J. S., Vangsness M., Obringer C., "Flow Visualization of the Freezing of Jet Fuel," 7th International Conference on Stability and Handling of Liquid Fuels, Graz, Austria, September 24-29, 2000.
- (13) Wilcox, David C., Basic Fluid Mechanics, DCW Industries: La Cañada, California, 1997.
- (14) Hanson, F. V., "Production of High Density Aviation Fuels Via Novel Zeolite Catalyst Routes," Air Force Research Lab., Technical Rept. WRDC-TR-89-2097, 1989.
- (15) Belousov, A. I., Bushueva, E. M., and Rudyakov, D. G., "Low-Temperature Filterability of T-6 Jet Fuel," Chemistry and Technology of Fuels and Oils (English translation of Khimiya i Tekhnologiya Topliv i Masel), Vol. 20, No. 1-2, 1984, pp. 79-80.
- (16) Gorenkov, A. F., Lifanova, T. A., Klyuchko, I. G., and Saleev, V. A., "Viscosity-Temperature Properties of Jet Fuels," Chemistry and Technology of Fuels and Oils (English translation of Khimiya i Tekhnologiya Topliv i Masel), Vol. 19, No. 5-6, 1983, pp. 297-299.
- (17) Mitin, M. B., Lyashenko, B. N., Karpov, V. A., Goncharov, L. A., and Kutuzova, O. V., "Viscosity Characteristics of T-6 Jet Fuel at Low Temperatures," Chemistry and Technology of Fuels and Oils (English translation of Khimiya i Tekhnologiya Topliv i Masel), Vol. 24, No. 5-6, 1989, pp. 219-221.
- (18) Stockemer, F. J., "Experimental Study of Low Temperature Behavior of Aviation Turbine Fuels in a Wing Tank Model," NASA CR-159615, 1979.
- (19) "Handbook of Aviation Fuel Properties," Coordinating Research Council Technical Report 635, Atlanta, Georgia, 2004.
- (20) Zabarnick, S.; Widmor, N. "Studies of Jet Fuel Freezing by Differential Scanning Calorimetry," Energy & Fuels, Vol. 15, 2001, pp 1447-1453.
- (21) Yarbrough, D. W., and Kuan C. E., "The Thermal Conductivity of Solid N-Eicosane, N-Octadecane, N-Heptadecane, N-Pentadecane, and N-Tetradecane," Thermal Conductivity 17, Plenum Press, New York, 1983, pp. 265-274.

R002592731

- (22) "Thermal Conductivity of Liquid; Organic Compounds", Chemical Properties Handbook (online), URL: <http://www.knovel.com> [cited March, 2001].
- (23) "Handbook of Aviation Fuel Properties," CRC Report No. 530, Coordinating Research Council, Atlanta, Georgia, May, 1988.
- (24) Desmarais, L. A., and Tolle, F. F., "Fuel Freeze Point Investigations," AFRL Report No. AFWAL-TR-84-2049, Air Force Research Laboratory, Wright-Patterson Air Force Base, Ohio, July, 1984.
- (25) McConnell, P. M., Owens, S. F., and Kamin, R.A., "Prediction of Fuel Freezing in Airplane Fuel Tanks of Arbitrary Geometry – Part 2," Aircraft Engineering, Vol. 58, No. 10, 1986, pp. 2-7.
- (26) McConnell, P. M., Owens, S. F., and Kamin, R.A., "Prediction of Fuel Freezing in Airplane Fuel Tanks of Arbitrary Geometry – Part 1," Aircraft Engineering, Vol. 58, No. 9, 1986, pp. 20-23.
- (27) Widmor, N, Ervin, J.S., Zabarnick, S., and Vangsness, M., "Studies of Jet Fuel Freezing by Differential Scanning Calorimetry and Cold-Stage Microscopy," ASME Journal of Engineering for Gas Turbines and Power, Vol. 125, No. 1, 2003, pp. 34-39.
- (28) Ervin, J. S., Zabarnick, S., Binns, E., Dieterle, G., Davis, D., and Obringer, C., "Investigation of the Use of JP-8+100 with Cold Flow Enhancer Additives as a Low-Cost Replacement for JPTS," Energy & Fuels, Vol. 13, 1999, pp. 1246-1251.
- (29) "Low Temperature Behavior of Fuels in Simulated Aircraft Tanks," CRC Report No. 532, Coordinating Research Council, Atlanta, Georgia, May, 1983.
- (30) Van Winkle, T.L., Affens, W.A., Beal, E.J., Mushrush, G.W., Hazlett, R.N., and DeGuzman, J., "Determination of liquid and solid phase composition in partially frozen middle distillate fuels," Fuel, Vol. 66, 1987, pp. 947-953.