Heating Experiments for Flowability Improvement of Near-Freezing Aviation Fuel

Robert Friedman*
NASA Lewis Research Center, Cleveland, Ohio
and
Francis J. Stockemer†
Lockheed-California Company, Burbank, California

The experiments described were scale-model tests in an airplane wing-tank simulator. Fuel was chilled in the simulator to represent severe in-flight temperature environments. Flowability of the near-freezing fuel was enhanced by heating a portion of the fuel externally and recirculating the heated fuel back to the simulator tank. This setup simulated a system that used airplane engine heat rejection to heat fuel for advantageous use of future fuels with relaxed freezing-point specifications. The experiments demonstrated the feasibility and quantitative improvement of flowability. For example, at unheated conditions where unheated fuel would have 8.8% unpumpable solids, a practical rate of heating would reduce the unpumpable fuel to near 2.0%. Delayed heating, initiated only when the fuel reached a prescribed minimum temperature, was shown to be more efficient than continuous heating.

Introduction

TEMPERATURES in commercial aircraft wing tanks during long flights could, on occasion, approach the freezing-point limitations of aviation turbine fuels.[1] The likelihood of near-freezing fuel temperatures may increase in the future. Fuel-efficient routings at lower Mach numbers will reduce aerodynamic heating and increase the chilling heat transfer from the stored fuel. In addition, there is a gradual trend toward increasing fuel freezing points,[2] resulting from the economic advantages of this specificaton relaxation to meet changing product demands and poorer feedstock qualities.[3-8] Higher-freezing-point fuels would be acceptable for commercial aviation use if adequate margins between flight storage temperatures and freezing points (or other flowability parameters) are assured. An obvious means of maintaining these temperature margins is by heating the fuel in the aircraft tank. Several sources of heat rejection in the airframe-engine systems are potentially adaptable to fuel heating with minimal penalties.[7,9-11]

Experimental verification of the feasibility of fuel heating requires some understanding of the basic behavior of low-temperature fuel flow. Hydrocarbon fuels are complex mixtures. Phase change occurs over a range of temperatures, and the resulting two-phase mixture may retain more of its fluidity.[7,12] Isothermal fuel chilling tests have demonstrated that aviation turbine fuels are often partially or completely flowable at temperatures below the freezing point.[13,14] Fuel in an aircraft wing tank, however, is rarely isothermal. More representative testing employed wing-tank simulators to duplicate the internal temperature profiles expected in airplane flight environments.[1,15,16] Results of previous simulator tests demonstrated that flowability is influenced by the minimum fuel temperatures occurring near the chilled surfaces, temperatures which are often considerably below the fuel bulk temperatures.[15,17]

Presented as Paper 82-1234 at the AIAA/SAE/ASME 18th Joint Propulsion Conference, Cleveland, Ohio, June 21-23, 1982; received July 21, 1982; revision received Nov. 7, 1983. This paper is declared a work of the U.S. Government and therefore is in the public domain.

*Aerospace Engineer, Fuels Research Section. Member AIAA.
†Consultant (Retired). Member AIAA.

In the studies described here, a wing-tank simulator apparatus was operated with superimposed fuel heating. A portion of the fuel was withdrawn from the tank, heated in an external heat exchanger, and returned to the chilled tank. Tests employed two modes of heating: 1) delayed heating where the heating flow started only when the fuel reached a prescribed minimum temperature, and 2) continuous heating. Flowability was defined by holdup, the fraction of unpumpable fuel retained in the tank after otherwise complete withdrawal at the end of a test.

The fuel heating experiments involved a series of about 100 tests with five different fuels. To exaggerate flowability problems, selected tests were conducted with an experimental jet fuel having a higher freezing point than that of commercial Jet A. Results illustrate temperature histories and internal temperature gradients, as related to low-temperature fuel holdup. Comparisons of results from heated and unheated tests show the quantitative effects of fuel heating as a means of flowability improvement.

Apparatus and Procedure

The experimental apparatus consisted of a wing-tank simulator with discharge, chilling, and heating systems (Fig. 1). The tank was an aluminum box, 51-cm high internally with a rectangular cross-section measuring 76 by 51 cm. Nominal tank volume was 0.193 m^3. Heat exchanger plates bonded to the outside of the tank chilled the upper and lower surfaces of the tank, which were internally stringer-reinforced. External insulation of the tank confined the heat transfer from the fuel to the upper and lower surfaces. Fuel was withdrawn from the tank through an opening at a bottom corner surrounded by an open top "surge box." The discharge system consisted of a centrifugal pump mounted below the simulator tank in order to pump fuel to a weighing tank installed on a manual beam balance. The chilling system supplied cold methanol to the chilled tank surfaces, using a closed loop system with temperature and flow controls for programmed rates of chilling. For fuel heating, a portion of the fuel could be pumped through an external heat exchanger. Heated fuel then returned to the simulator tank through a perforated recirculation distributor at the bottom of the tank. Lubricating oil heated by an electrical cartridge heater furnished the energy to the hot side of the fuel heat exchanger. Heating rates were usually

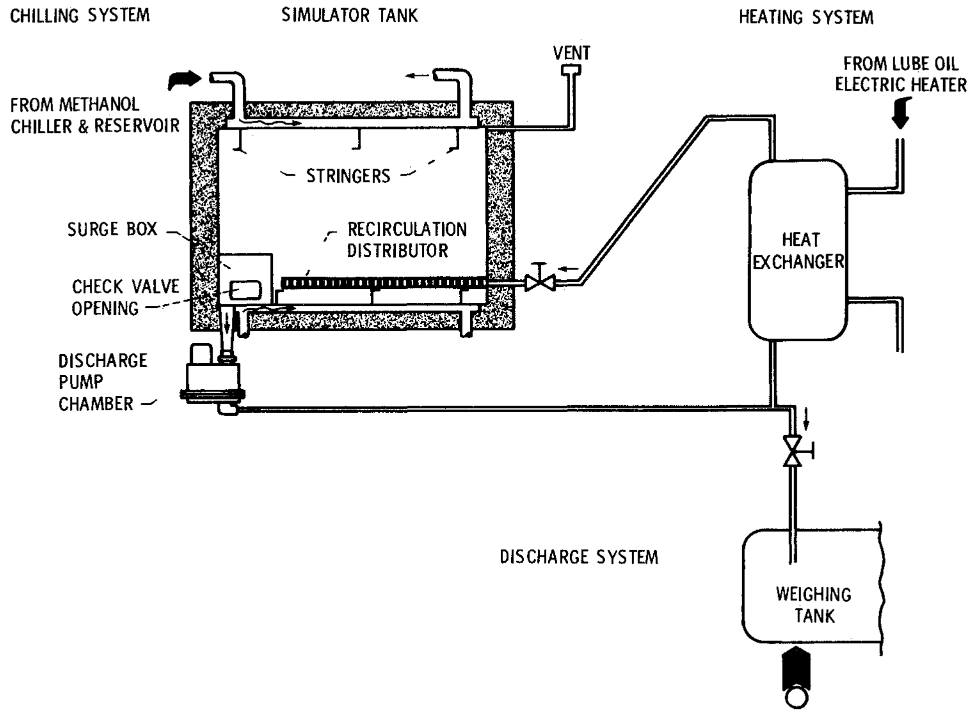

Fig 1 Schematic of apparatus

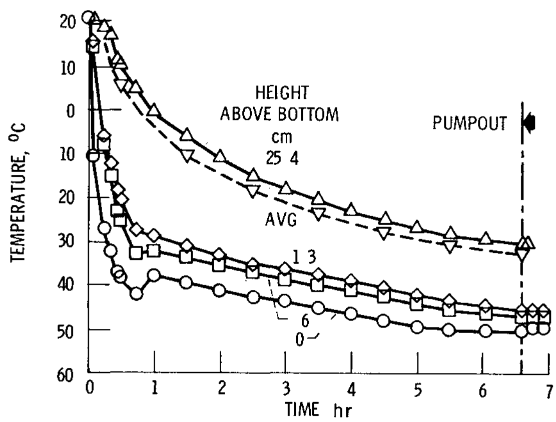

Fig 2 Temperature histories in simulator tank for unheated cold day baseline test (No 210)

controlled by the amount of heating of the lubricating oil, although the recirculating fuel flow could be varied as well

This apparatus represented a 1/100 scale volume element of an outer wing tank of a wide bodied commercial airplane [17] It was full scale in the vertical dimension The tank provided the experimental conditions to simulate the expected environment during a long range flight where fuel is chilled through heat loss to the atmosphere through the upper and lower wing surfaces This simulator used since 1978 for a variety of low temperature flowability experiments has been described in more detail in Refs 15, 18, and 19

Most of the tests discussed in this paper were conducted with an experimental fuel, designated LFP 14 This fuel is a kerosine that met all the specifications of commercial aviation turbine fuel Jet A, except that its freezing point −33 C was higher The freezing point is actually the melting temperature at which wax or solid crystals are observed to disappear In the case of Jet A the required maximum freezing point is −40 C Some comparisons are given to test results with a reference Jet A fuel designated as LFP 11, with a freezing point of −46 C

Testing always began with a full fuel tank (155 to 160 kg load) Fuel loading temperatures varied with ambient con ditions but initially all the fuel in the tank was at a uniform temperature A programmed rate of chilling reduced the fuel temperature as a function of test time Since the fuel would chill more rapidly near the surfaces than at the center internal temperature gradients were created During the test internal and surface temperatures were measured and recorded At the conclusion of a test the discharge pump withdrew fuel to the weighing tank at a nominal rate of 0 010 m^3/min requiring about 20 min to empty the simulator tank Flowability was defined by holdup, the mass ratio of unpumpable fuel remaining in the tank as compared to the original load Completely flowable fuel has zero holdup and at warm conditions all the fuel could be recovered within the precision of the weighing balance about 0 1 kg For tests with fuel heating the recirculating heating fuel flow was at a nominal rate of 0 003 m^3/min Heat input to the fuel was calculated from the recirculation flow rate and the temperature rise of the recirculating fuel

Fuel Heating Test Results

Baseline, Unheated Tests

Figure 2 shows temperature histories at several vertical heights in the center of the tank for a test where the ex perimental fuel, LFP 14, was chilled for nearly 7 hours wihout fuel heating This test served as a reference baseline for comparison with fuel heating tests The skin temperature (surface chilling)schedule of the simulator was based ap proximately on the environment expected for a long range commercial flight on an extremely cold day (0 3% probability) The derivation of the extremely cold day flight temperature schedule is discussed in Ref 20 and its adap tation to simulator testing is further discussed in Ref 18

Figure 2 shows fuel temperatures measured at the inside surface of the bottom skin (0 cm) and at heights of 0 6, 1 3 and 25 4 cm above the lower surface The 0 6 and 1 3 cm measurements are fuel temperatures closest to the lower surface The 25 4 cm measurement is at the vertical center of the tank Figure 2 also includes the average fuel temperature history calculated from graphical integration of the time dependent temperature height profiles

The skin temperature schedule for the baseline test was a rapid chilling during the first hour, followed by slower but continued chilling thereafter The bottom skin temperature reversal near 1 h shown in Fig 2 was caused by overshoot of the controller response but this perturbation had no influence on subsequent temperature behavior. The temperatures nearest to the lower surface decreased almost in concert with the skin temperature decrease, but the center temperature responded much more slowly The average fuel temperature decreased at the same rate as the center temperature remaining within 3 C of the center temperature throughout Pumpout for holdup measurements was started at 6 6 h and completed before 7 h elapsed time

Figure 3 shows the internal temperature gradients at the center of the tank at 6 6 h elapsed time for the test illustrated in Fig 2 The illustrated temperature profile is typical of those observed in the simulator apparatus The bulk temperature was nearly uniform at a temperature about 3 C above the freezing point but some of the fuel near the surfaces was below the freezing point Previous wing tank analyses[16] showed that for chilling most heat transfer is by convection through the upper surface In the Fig 3 example the upper surface was not completely wetted by fuel If the top were completely wetted the upper temperature gradient would be greater (narrower boundary layer height) At the lower surface, a stagnant conduction zone formed The heat transfer and temperature gradient were small at this surface and the gradient occurred over a larger boundary layer occupying about 20% of the tank height Upon pumpout, this test yielded a holdup of 8 8 mass % unpumpable fuel These solids obviously originated in the near surface zones predominately at the bottom

Tests with Heat Addition

Fuel Heating Modes

There were two modes of heat addition delayed and continuous (Fig 4) For delayed heating the recirculation line to the tank was closed until the bulk fuel reached a predetermined temperature margin above the freezing point Then the recirculation flow valve was opened to provide fuel heating until the pumpout time During the early part of the test, the lubricating oil heat transfer fluid was preheated to about 110 to 120 C When the recirculating fuel flow initiated heat transfer there was a rapid surge of thermal energy from the sensible heat of the heat transfer fluid In Fig 4, the delayed heating schedule at first had a peak heating rate or power well over 3 kW, but the heating rate decreased rapidly to around 700 W as the heat transfer fluid reached equilibrium temperatures of 0 to 10 C For continuous heating fuel recirculation and heating were initiated shortly (about 0 1 h) after the start of the chilldown and heating power was nearly constant until the pumpout time The continuous heating schedule in Fig 4 is typical for a low rate of fuel heating

Temperature Histories

Figure 5 shows temperature histories at several vertical heights in the center of the tank for a test where the LFP 14 fuel was heated by delayed heating Surface temperatures were chilled according to the baseline temperature schedule Delayed heating (the schedule shown in Fig 4) was initiated when the thermocouple at the vertical center of tank reached −25 C (4 3 h) Temperature locations in Fig 5 correspond to those in Fig 2 The 0 cm (lower surface) temperatures were slightly warmer than those of the baseline schedule of Fig 2, due to inaccuracies of the chilling system controller The vertical center temperature responded immediately and rapidly to the heating, increasing with time and reaching − 16 5 C at 6 6 h (pumpout) For the unheated, baseline test at the corresponding time, this temperature was − 30 5 C The temperatures at the two stations nearest the lower surface also increased when heating was superimposed but to a lesser degree than those at the center At the 0 6 cm height for example heating increased the temperature at 6 6 h to − 40 C

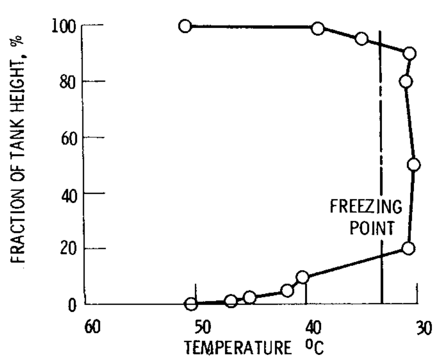

Fig 3 Temperature profile at center of simulator tank at 6 6 h for baseline test

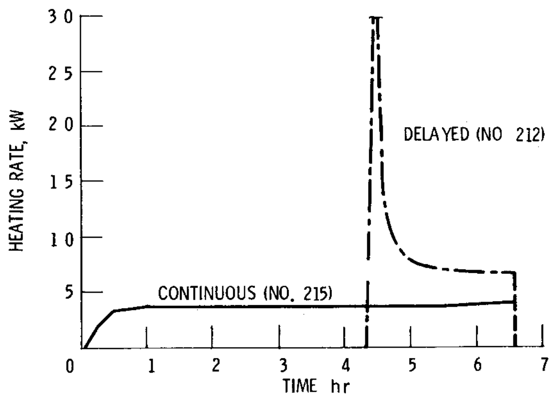

Fig 4 Examples of fuel heating schedules

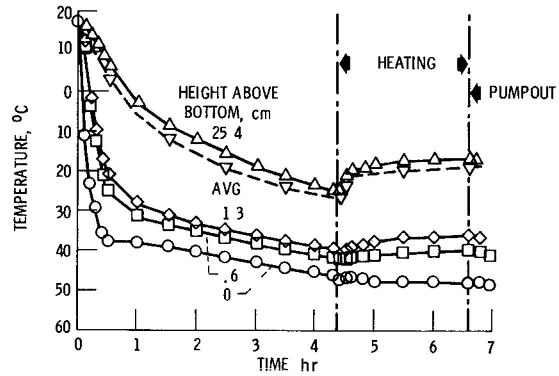

Fig 5 Temperature histories in simulator tank for delayed heating test (No 212)

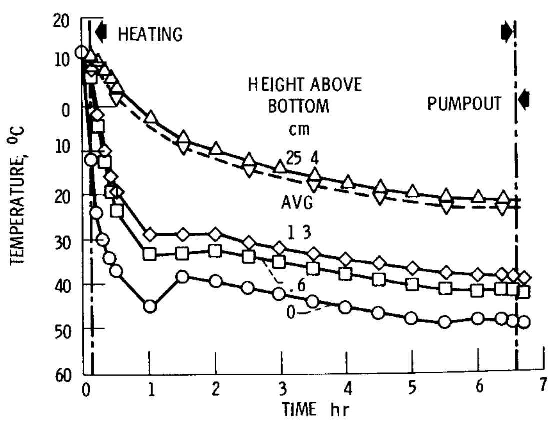

Fig 6 Temperature histories in simulator tank for continuous heating test (No 215)

compared to a baseline value of −47 C The delayed heating improved flowability reducing holdup from the baseline 8 8 mass % to 2 5%, but it did not restore complete flowability (zero holdup)

Figure 6 shows temperature histories for a test where the fuel was heated continuously Again the test maintained a chilldown schedule of surface temperatures, duplicating as far as possible the baseline test This test incorporated the nominal 370 W heating rate schedule that is illustrated in Fig 4 The effect of continuous heating on the fuel temperature is less apparent than that of delayed heating because temperatures decreased throughout the test Nevertheless a comparison with the baseline test temperatures shows that temperatures did increase with the continuous heating At the 6 6 h pumpout time, the vertical center temperature was −20 5°C compared to −30 5 C for the baseline test At the same time, the 0 6 cm temperature was −41 5 C compared to −47 C for the baseline test Flowability improved with holdup reduced from the baseline 8 8 mass % to 3 1%

Figure 7 shows the internal temperature gradients at the center of the tank at 6 6 h elapsed time for the continuous heating test illustrated in Fig 6 The profile resembles that of the baseline (Fig 3) with a nearly uniform temperature over the bulk of the fuel The profile shows that heating is most effective in raising the bulk temperature of the fuel as compared to the baseline example However since the surfaces were maintained at about −50 C for both the baseline and heated tests, a small volume of fuel near the surfaces remained below the freezing point even for heated fuel Thus the reduction but not complete elimination of unpumpable holdup by heating is not surprising

Discussion of Results

Effect of Fuel Heating on Flowability

Table 1 is a summary of the results of selected tests giving heating rates, average fuel temperatures at pumpout and holdups Tests are identified by the test numbers by the experimental program and if applicable by the illustrative figures in this paper Heated tests include one delayed heating test and four continuous heating tests with a range of heating rates Two unheated baseline tests are also included The cold day test (No 210) is the baseline test described in this paper and used as a reference for all the heated tests The other unheated test was a special warm day test with surface temperatures always above −33 C Comparison of the holdup results of this test and the heated test No 215 demonstrated that the heated test with cold boundaries could not achieve the zero holdup of the warm day test although average fuel temperatures were about equal for the two tests

The measured fuel heating rates in Table 1 are the differences between the average heated fuel power (enthalpy/time) and the corresponding values for the unheated baseline test Enthalpies were computed from the temperature histories and estimated fuel thermodynamic and transport properties at low temperatures Table 1 also lists a second heating rate, the power supplied calculated from the temperature rise of the recirculating fuel For tests with a low rate of continuous heating (No 215) or short duration delayed heating the power supplied and measured fuel heating rates are nearly the same The fuel heating is in fact slightly greater than the power supplied for test No 212 only because of a small mismatch in the duplication of the baseline skin temperature schedule At higher rates of fuel heating however, the power supplied became greater than the measured fuel heating rate Apparently an increasing portion of the heating power supplied was rejected to the chilling system and was unavailable for fuel heating For example, to increase the fuel heating rate by 45 W (No 217 compared to No 216) required an increase of about 300 W of heating power This decreasing effectiveness of higher rate fuel heating under realistic heat transfer conditions is a factor to be considered in the determination of practical requirements for fuel heating systems

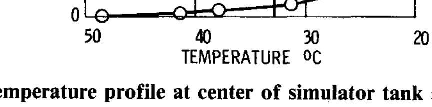

Fig 7 Temperature profile at center of simulator tank at 6 6 h for continuous heating test

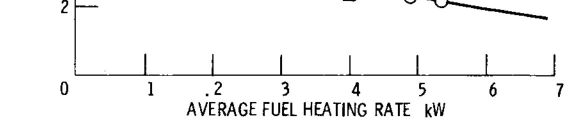

Fig 8 Improvement of fuel flowability by heating

Table 1 Summary of selected test results

Test identification	Type	Fuel heating rate, W: Measured (referenced to No 210)	Fuel heating rate, W: Power supplied	Average fuel temperature at pumpout C	Holdup mass %
210 (Figs 2 3)	Baseline cold day	—	0	−32 6	8 8
213	Baseline warm day	[a]	0	−22 1	0
212 (Fig 5)	Delayed heating	325[b]	305	−18 1	2 5
215 (Figs 6 7)	Continuous heating	345	360	−22 6	3 1
221	Continuous heating	400	575	−16 9	2 4
216	Continuous heating	490	765	−17 0	2 3
217	Continuous heating	535	1070	−15 4	2 2

[a] Not applicable [b] Rates shown are averaged over the entire test period During the actual 2 3 h delayed heating period average fuel heating was 910 W

Figure 8 is a plot of the Table 1 information showing the effect of heating on holdup The curve is drawn through the baseline and three continuous heating test results shown by circles Figure 8 illustrates the diminishing improvement of flowability by increased heating and demonstrates that holdup may not be reduced much below 2% by even large rates of fuel heating

The heated fuel was returned to the tank through a per forated distributor tube at the bottom of the tank The tube rested on the stringer supports about 7 to 8 cm above the bottom Since results showed that almost all of the heating occurred in the central part of the tank it was felt that flowability would be improved by greater penetration of heated fuel toward the chilled surfaces Ref 19 describes three distributor designs that attempted to improve the boundary layer heating Two designs used tube extensions to divert the heated flow directly on the bottom surface The test result in Fig 8 shown by a square point is typical for one of the alternative designs (No 2) Flowability gains were noted, but they were comparatively minor For the example shown, holdup was reduced about 0 3 mass % below the curve representing the standard design results

Delayed heating may be a technique promising more flowability improvements than those through design changes The test result in Fig 8 for delayed heating shown by a diamond point indicates holdup at about 0 7 mass % below the curve representing the continuous heating results The delayed heating power in Fig 8 and in Table 1 was calculated as an average for the 6 6 h test although heating was applied only over a portion of the time Continuous heating has an inherent inefficiency in that energy is supplied (and rejected to the environment) during early parts of the test when the fuel is relatively warm

Correlations of Heated and Unheated Flowability

Previous studies have suggested some empirical correlations of holdup results that are useful for prescribing test con ditions or comparing results [17] Two correlations are discussed here in relation to the comparison of the results of heated and unheated fuel tests

Boundary Layer Temperature

For all the tests baseline or heated, subfreezing tem peratures existed only in the fuel volumes near the chilled tank surfaces Figure 9 presents the results of test data plotted as holdup as a function of the temperature measured at 0 6 cm above the bottom center of the simulator tank This is the closest fuel temperature measurement to the lower surface The test results used for the correlations are taken from a larger group of experimental tests than those included in Table 1 For the experimental fuel LFP 14 results of 18 tests are plotted including unheated tests and additional tests at heated conditions In addition another group of 14 test results are also shown for the reference Jet A fuel LFP 11

Separate curves are fit to the data for each fuel in Fig 9 Zero holdup is approached near the freezing points (−33 C for LFP 14 and −46 C for LFP 11) The data for the heated tests have a very limited range of variation, but they are reasonably well represented by the curves established for the results of the unheated tests This implies that the principal effect of flowability improvement by heating lies in the in crease of the boundary layer temperature

Fraction of Volume Below Solid Index

As noted in the typical temperature profiles (Figs 3 and 7) only a small volume of the tank is occupied by fuel below the freezing point This volume fraction is readily calculated from the temperature profile at the time of pumpout and the physical dimensions of the tank For the purposes of correlation best results are obtained if holdup is related to the volume fraction occupied by a fuel having a temperature below a characteristic temperature called the solid index In this study the solid index is simply the mean of the freezing point and the pour point The pour point is the lowest tem perature at which the fuel will flow when inverted in a standard cup apparatus The solid index is −34 C for LFP 14 −49 C for LFP 11

Figure 10 presents the results of test data plotted as holdup as a function of the fraction of volume occupied by fuel with temperatures below the solid index A single curve gives a reasonable fit to the data obtained from heated and unheated tests for both fuels As expected holdup approaches zero as values of the correlating parameter approach zero The best fit curve has a slope of approximately 0 7, suggesting that approximately 70% of the fuel in the subfreezing volume is unpumpable holdup This type of correlation produces a universal curve applicable to many fuels if characterized to the extent that freezing and pour points are known Since the heated fuel test results can be correlated with the unheated

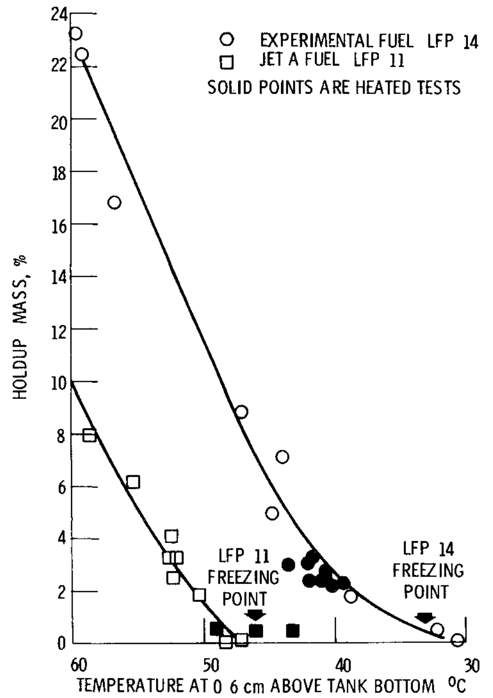

Fig 9 Correlation of flowability by boundary layer temperature

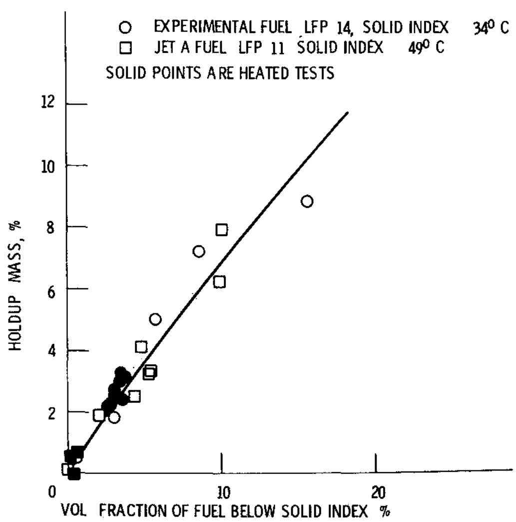

Fig 10 Correlation of flowability by volume fraction of fuel at subfreezing conditions

test results the effect of heating in improving flowability can be alternatively viewed as a reduction in the subfreezing zone volume

Concluding Remarks

Results of tests on an experimental jet fuel with a −33 C freezing point in a chilled aircraft wing tank simulator with superimposed fuel heating indicate that fuel heating is feasible and improves flowability Heated test results correlate well with boundary layer temperature or freezing zone volume correlations developed for unheated test data

Delayed fuel heating, with initiation occurring when the fuel reaches a prescribed low temperature limit, was shown to be more efficient than continuous heating While the degree of flow improvement can be enhanced by greater heating rates, high heating rates become less effective because an increasing portion of the heat supplied is not transferred to the fuel but is rejected to the environment (simulator chilling system) instead In addition, some subfreezing fuel is always retained near the cold surfaces of the simulator tank even under high heating rate conditions Thus even the highest heating rates did not completely restore flowability, as measured by a zero holdup of unpumpable fuel upon with drawal The limiting fraction of unpumpable fuel, about 2 mass % holdup may be recoverable however under flight conditions during descent

For practical considerations delayed heating may be most useful for minimizing performance penalties in heating systems which require diversion of engine thrust, such as electrical heating Delayed heating however, may be difficult to program or control whether manually or automatically Continuous heating can be simple and easy to measure and control It may be best suited, however for low penalty heating systems such as engine waste heat rejection The serious consideration of any fuel heating system of course requires further study of trade offs between possible fuel retention and the economic complexity of a heating system

Acknowledgments

The experimental studies were conducted at the Lockheed California Co , Rye Canyon Laboratories Valencia Calif under NASA Contract NAS 3 21977 The contributions of the test engineer, Mr Ronald L Deane are gratefully acknowledged The authors are also indebted to the Coor dinating Research Council Inc and Mr Jack A Bert of Chevron Research Company for an unpublished work suggesting the use of the solid (solidification) index

References

[1]Thomas I , Broadened Jet Fuel Specifications: Their Effect upon Commercial Airplane Design and Operation *Shell Aviation News* No 450 1978 pp 32 35

[2]Friedman, R Recent Trends in Aviation Turbine Fuel Properties NASA Technical Paper 2056 Oct 1982

[3]Robertson A G and Williams R E , Jet Fuel Specifications: The Need for Change *Shell Aviation News* No 435 1976 pp 10 13

[4]Dukek, W G and Longwell, J P , Alternative Hydrocarbon Fuels for Aviation ' *Exxon Air World* Vol 29 No 4 1977 pp 92 96

[5]Churchill, A V Delaney C L and Lander H. R Future Aviation Turbine Fuels *Journal of Aircraft* Vol 15 Nov 1978 pp 731 734

[6]Longwell J P and Grobman J , Alternative Aircraft Fuels *Journal of Engineering for Power* Vol 101 1979 pp 155 161

[7]Friedman R High Freezing Point Fuels Used for Aviation Turbine Engines, ASME Paper 79 GT 141, March 1979

[8]Strauss K H , Future U S Jet Fuel—A Refiner s Viewpoint AIAA Paper 81 0770 May 1981

[9]Pasion A J Design and Evaluation of Aircraft Heat Source Systems for Use with High Freezing Point Fuels NASA CR 159568 May 1979

[10]Stewart, W L , Nored D L Grobman, J. S , Feiler C E and Petrash D A Preparing Aircraft Propulsion for a New Era in Energy and the Environment *Astronautics & Aeronautics* Vol 18 No 1 Jan 1980 pp 18 31 37

[11]Grobman, J. and Reck, G M The Impact of Fuels on Aircraft Technology Through the Year 2000 AIAA Paper 80 0896 May 1980

[12]Smith, M , *Aviation Fuels* Foulis Henley on Thames U K 1970 pp. 268 282

[13]Ford P T and Robertson A G Jet Fuels—Redefining the Low Temperature Requirements *Shell Aviation News* No 441 1977 pp 22 26

[14]Lewis A Future Aviation Fuels—the Petroleum Industry Responds to the Challenge SAE Paper 800769 May 1980

[15]Stockemer F J , Experimental Study of Low Temperature Behavior of Aviation Turbine Fuels in a Wing Tank Model ' NASA CR 159615 1979

[16]McConnell, P M Massmann, L A , Peterson, G N and Tolle F F Operational Effects of Increased Freeze Point Fuels Air Force Aero Propulsion Lab AFWAL TR 82 2067 Aug 1982

[17]Friedman R and Stockemer F J Temperature and Flow Measurements on Near Freezing Aviation Fuels in a Wing Tank Model ASME Paper 80 GT 63 March 1980

[18]Stockemer, F J , Experimental Study of Fuel Heating at Low Temperatures in a Wing Tank Model NASA CR 165391 Aug 1981

[19]Stockemer F J and Deane R L Additional Experiments on Flowability Improvements of Aviation Fuels at Low Temperature NASA CR 167912 Aug 1982

[20]Pasion A J and Thomas I , Preliminary Analysis of Aircraft Fuel Systems for Use with Broadened Specification Fuels NASA CR 135198 1977