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Visco Jet Joule-Thomson Device Characterization Tests in Liquid Methane

John M. Jurns
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March 2009

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Abstract

Joule-Thomson (J-T) devices have been identified as critical components for Thermodynamic Vent Systems (TVS) planned for future space exploration missions. Lee Visco Jets (The Lee Company) (Ref. 4) are one type of J-T device that may be used for LCH_4 propellant systems. Visco Jets have been previously tested and characterized in LN_2 and LH_2 (Refs. 6 and 7), but have not been characterized in LOX or LCH_4. Previous Visco Jet tests with LH_2 resulted in clogging of the Visco Jet orifice under certain conditions. It has been postulated that this clogging was due to the presence of neon impurities in the LH_2 that solidified in the orifices. Visco Jets therefore require testing in LCH_4 to verify that they will not clog under normal operating conditions. This report describes a series of tests that were performed at the NASA Glenn Research Center to determine if Visco Jets would clog under normal operating conditions with LCH_4 propellant. Test results from this program indicate that no decrease in flow rate was observed for the Visco Jets tested, and that current equation used for predicting flow rate appears to under-predict actual flow at high Lohm ratings.

Introduction

Lee Visco Jets are one type of J-T device that may be used for LCH_4 tank internal pressure control and LCH_4 supply manifolds to Orbital Maneuvering System—Reaction Control System (OMS-RCS) thrusters. Visco Jets have been previously tested and characterized in LN_2 and LH_2, but have not been characterized in LOX or LCH_4. Previous Visco Jet tests with LH_2 resulted in clogging of the Visco Jet orifice under certain conditions (Ref. 1). It has been postulated that this clogging was due to the presence of neon impurities in the LH_2 that solidified in the orifices. Visco Jets therefore require testing in LCH_4 to verify that they will not clog under normal operating conditions.

One option for cryogenic propellant systems considered on future space exploration missions is a pressure fed system. Pressure fed systems may require tank pressures as high as 350 psi to feed engines (Ref. 2). Considering these high pressures and the degree of cryogenic propellant subcooling, a wide range of operating temperatures and pressures should be evaluated.

Test Objectives/Overview

Figure 1 shows a typical test run with LH_2 from 2002 tests using a 0.010 in. diameter orifice J-T device. Flow starts at 37 slpm and decreases to zero after 20 min. The standard LH_2 commodity specification does not list neon as an impurity, but Jurns (Ref. 1) had determined that impurities as small as parts per billion could potentially cause clogging. As methane is being considered for future propellant systems, it is important to determine whether or not Joule-Thomson devices also clog during expected normal operating conditions with liquid methane propellant.

The objective of these tests was to obtain long term (hour length test duration) mass flow data for typical size Visco Jets to detect evidence of clogging of the Visco Jet orifices by accretion from contaminates in the LCH_4 flow stream. The Visco Jets need to operate at typical tank operating pressures and temperatures. Representative size high flow (low Lohm rating) Visco Jets for cryogenic tank TVS applications and low flow (high Lohm rating) Visco Jets for OMS-RCS supply manifold applications were tested.

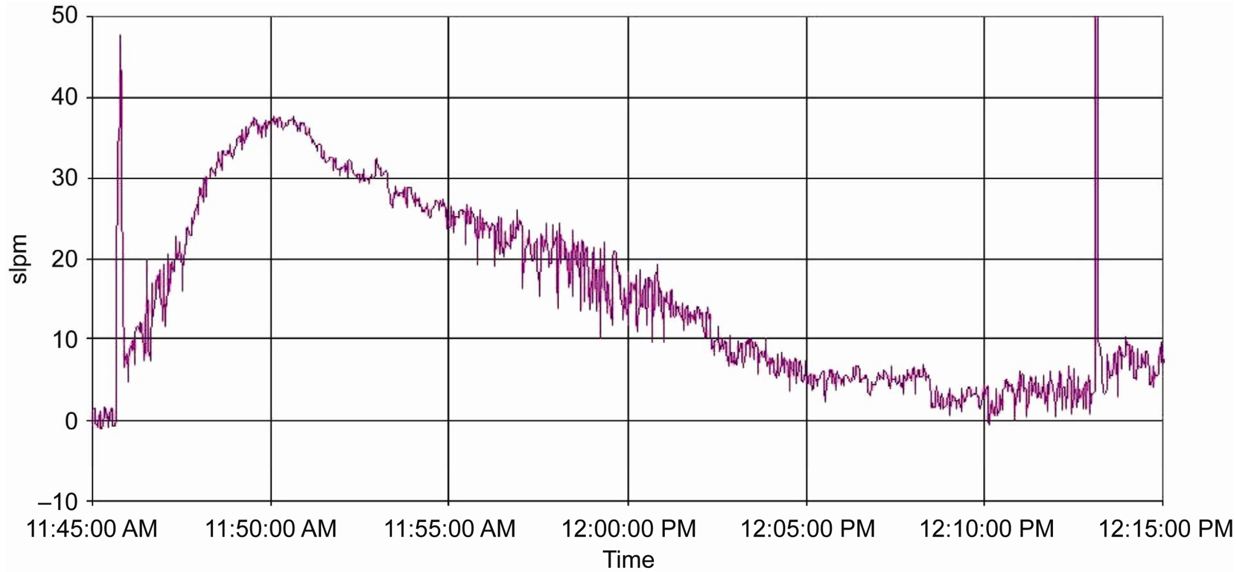

Figure 1.—Decrease in LH_2 flow through 0.010 in. diameter orifice, 2002 tests at NASA GRC.

Test Requirements

Representative Visco Jet J-T devices were sized for expected cryogenic tank TVS applications and for cryogenic OMS-RCS manifold applications (Refs. 3 and 4). For cryogenic tank TVS applications, a propellant tank volume of between 60 and 120 ft^3 was considered. For this size tank, it was estimated that the Visco Jet would have to remove from 800 to 8,000 BTU/hr of incoming heat. This was calculated using the NASA Glenn ZBO CAT (Zero Boil off Cryogenic Analysis Tool) (Ref. 3). Considering a 10 percent duty cycle for the TVS system and a nominal 300 psi working pressure tank, this translated into an expected flow rate of approximately 0.0015 to 0.015 lb/sec of LCH_4. This assumes that all the methane is vaporized by the time it exits the TVS heat exchanger. For OMS-RCS manifold applications, NASA JSC indicated that a heat rejection requirement of approximately 20 BTU/hr could be expected for the current Lunar Surface Ascent Module (LSAM) LCH_4 OMS-RCS manifold design (Ref. 4). Assuming that there would be three Visco Jets operating, with a 50 percent duty cycle, the resulting requirements for any single Visco Jet would be to reject approximately 13 BTU/hr. This translated into an expected flow rate of approximately 2×10^{-5} lb/sec LCH_4.

Visco Jets were originally designed as a miniature hydraulic flow component using the multiple orifice concept to induce a pressure drop in a line. The resistance to flow in Visco Jets is measured in liquid ohms—or “Lohm”, a term coined by the manufacturer. This term has been included in an equation that predicts single phase liquid flow rates for many fluids (Ref. 5). The form of the equation is:

$$\dot{m} = \frac{10{,}000}{\text{Lohm}}\sqrt{S * \Delta P} \tag{1}$$

$\dot{m}$	Mass flow (lb/hr)
Lohm	Visco Jet Liquid Ω resistance
S	Methane Specific Gravity
ΔP	Pressure drop across Visco Jet (psid)

The Visco Jet multiple orifice design inherently reduces the onset of cavitation with hydraulic fluids. However, with cryogens stored at or near saturated conditions, it is inevitable that some flashing will occur, leading to a reduction in flow. Papell’s (Refs. 6 and 7) work resulted in an empirical factor to correct flow for cryogens based on the quality of the flow exiting the Visco Jet. The modified correlation was determined to be:

$$\dot{m} = k\frac{10{,}000}{\text{Lohm}}\sqrt{S * \Delta P}\left(1 - X\right) \tag{2}$$

k = Empirical constant (assume k = 1 for these tests)
X = Fluid quality

Exit flow fluid quality was calculated using isenthalpic expansion calculations:

$$\left(h_1\right)_{\text{upstream}} = X\left(h_g\right)_{\text{downstream}} + \left(1 - X\right)\left(h_1\right)_{\text{downstream}} \tag{3}$$

where h_t is inlet enthalpy, and h_g and h_l are saturated vapor and liquid enthalpies at the outlet pressure, respectively. The correction factor "k" was 1.0 for LN_2 (Ref. 6) and 0.9 for LH_2 (Ref. 7). As there is no published data for LCH_4, the correction factor was assumed to be 1.0.

Based on these expected flow rates, three Visco Jets were chosen with Lohm ratings of 8,200, 80,000, and 950,000 Lohms. We note that although these Visco Jets were chosen based on higher tank pressures, the CCL-7 test facility only had a maximum working pressure of 25 psia, so flow rates for these tests were lower. This limited the expected flow rates for the tests to between 7×10^{-6} to 8×10^{-4} lb/sec.

Test Matrix—Clogging Tests

The test matrix was based on the assumption that impurities in the LCH_4 would consist mainly of other hydrocarbons, carbon dioxide, and atmospheric gasses. Based on the premise of neon being the clogging mechanism in prior LH_2 tests (Ref. 1), the methane specification was examined to determine what impurity components have fusion temperatures in the operating range of the LCH_4 tank. Figure 2 shows that pentane (T_{fusion} = 245 °R) and butane (T_{fusion} = 258 °R) fall in the anticipated operating range of 15 to 300 psia. Considering methane in the tank is saturated, the most likely candidates to cause clogging

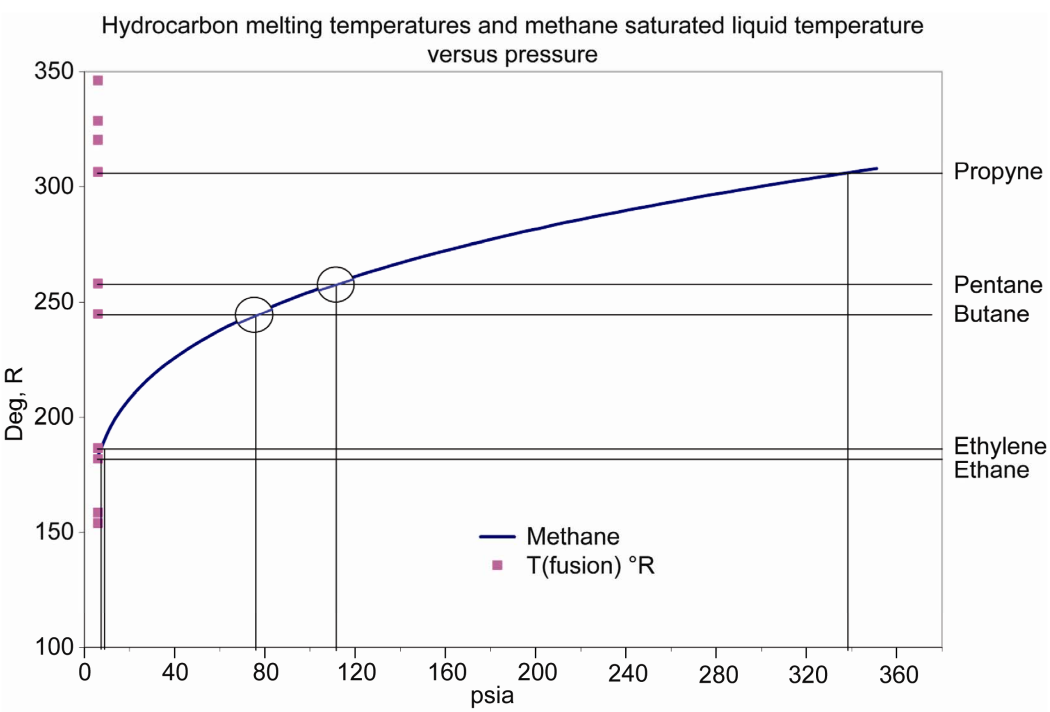

Figure 2.—Impurity components with fusion temperatures in LCH_4 operating range.

in the Visco Jet. Ethane (T_{fusion} = 182 °R) and Ethylene (T_{fusion} = 187 °R) may also cause clogging. Limitations on the maximum operating pressure of the CCL-7 dewar (25 psia) limit the range of impurities that can be investigated to Ethane and Ethylene. Future tests at a facility with higher pressure capabilities are planned to test for the presence of pentane and butane. Based on the temperatures that can be investigated, the test matrix in Table 1 was proposed.

TABLE 1.—TEST MATRIX FOR VISCO JET CLOGGING TESTS

Visco jet	Lohm rating	Tank pressure, (psia)	Bulk LCH_4 temperature, (°R)	Flow rate, (lb/hr)	Test fluid
VXLA 2500 820D	8,200	22	>187	3	LCH_4
VDCB 1825 800H	80,000	22	>187	0.3	LCH_4
VDLA 4316 950K	950,000	22	>187	0.03	LCH_4

Test Facility

CCL-7 is a small scale testing facility for concept and component testing (Ref. 8). In addition to component screening, the facility can perform propellant transfer, propellant conditioning (warming and sub-cooling), and vent flow tests. CCL-7 can safely handle 300 gal of LH_2 or LN_2, or 120 gal of LCH_4. Gaseous helium (GHe) and gaseous nitrogen (GN_2) are available on-site for use as pressurants.

For this test program, the Visco Jet hardware shown in Figure 3 was installed in one of the test facility dewars. Fluid supply and vent piping, and instrumentation lines pass through the lid of this dewar.

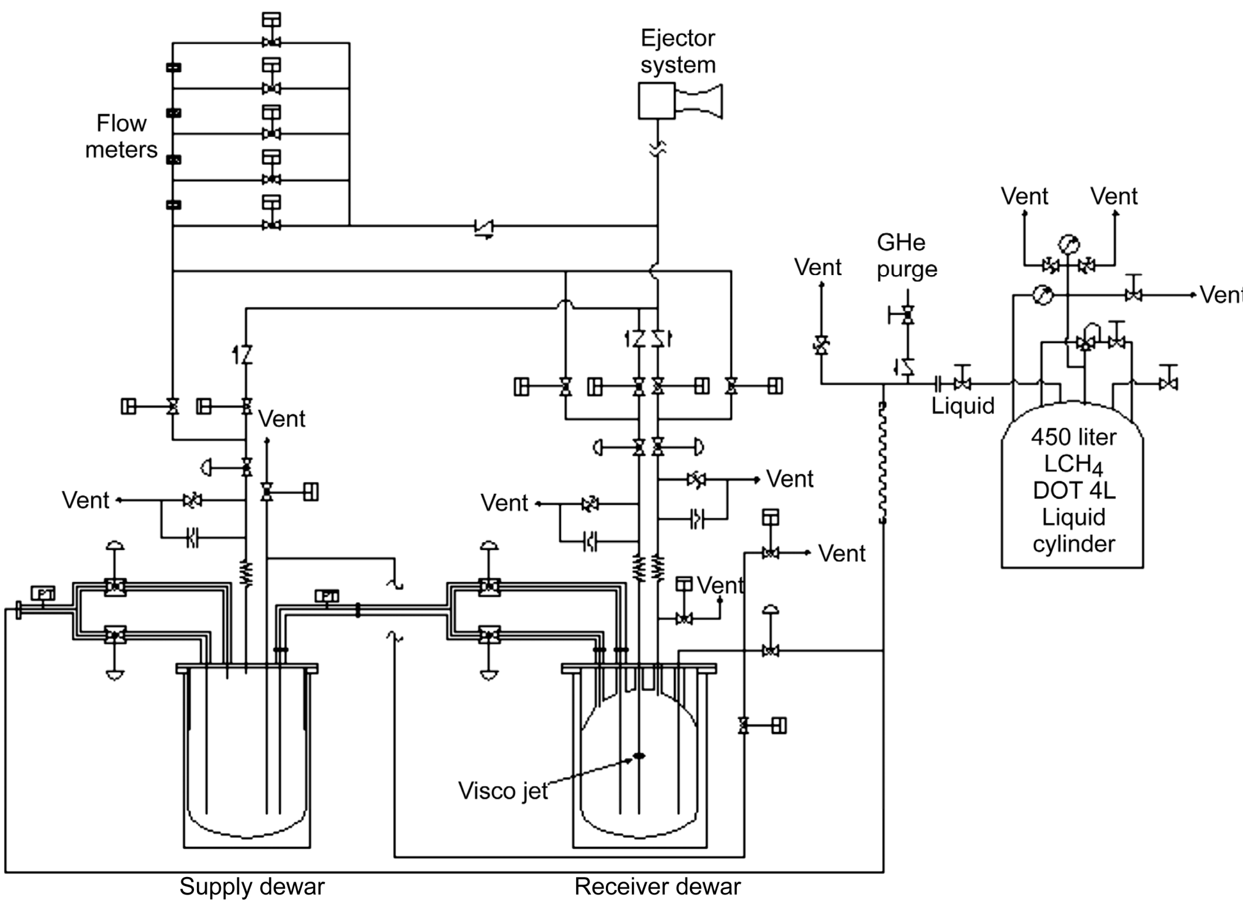

Figure 3.—CCL-7 Test facility simplified system schematic diagram.

The diameter of this dewar was 22 in. An instrument rake equipped with silicon diodes provides temperature measurements and liquid level indication. The dewar was 42 in. deep, has an internal volume of 8.1 ft^3, and has a working pressure of 25 psia. A window in the sidewall was located 22 in. from the bottom of the dewar.

Instrumentation/Data Acquisition

CCL-7 utilizes a PC computer based data collection system. Up to 320 channels of data can be collected at a nominal rate of 1 Hz. Many of the facility channels are pre-configured for standard instruments including thermocouples, pressure transducers, and silicon diodes. Interlocks, alarms and shutdowns protect the research hardware and the facility. Operator controlled open-loop processes are used to provide flexibility.

Test Hardware Configuration

Visco Jets tested were installed inside the test dewar as shown in Figure 4. The inlet to the Visco Jet was immersed in the liquid methane, and was located approximately 11.4 in. below the bottom of the dewar. The liquid inlet line to the Visco Jet was located approximately 3 in. above the bottom of the dewar. Silicon diode temperature sensors were located in the tubing immediately upstream and downstream of the Visco Jet. Inlet pressure was measured using the pressure transducer that measures ullage pressure. Outlet pressure was measured using a pressure transducer in the downstream piping located where the outlet line exits the dewar. Liquid methane flowing through the Visco Jet and out of the dewar was vaporized downstream of the dewar, and the gaseous methane flowrate was measured using mass flow meters.

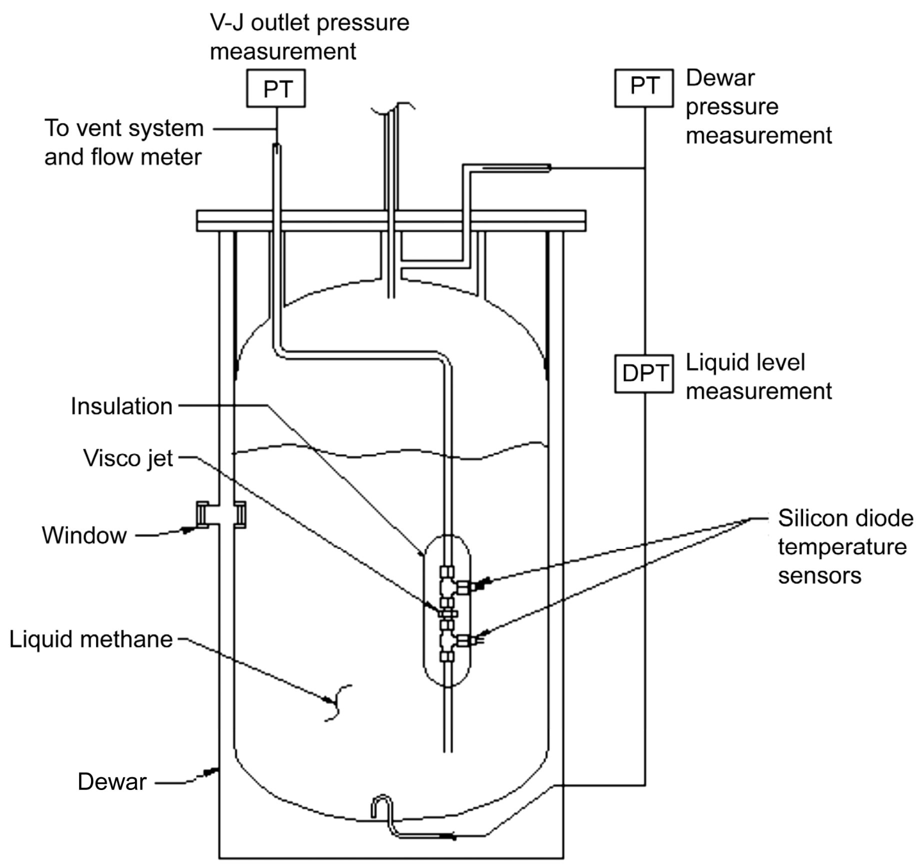

Figure 4.—Schematic of Visco Jet in test dewar.

Test Procedure

Tests were conducted at two fluid conditions. The first test condition was with LCH_4 fluid temperature at approximately NBP conditions (200 to 203 °R). The second test condition was with LCH_4 fluid temperature subcooled to approximately 182 to 190 °R. The procedure for NBP temperature liquid was as follows:

1. CCL-7 test dewar was filled with LCH_4 to above the Visco Jet
2. The dewar was pressurized to approximately 22 psia with GHe
3. Outlet valve downstream of Visco Jet was opened allowing flow through the Visco Jet
4. Record inlet and outlet temperatures and pressures

Downstream pressure was controlled by using an open loop proportional valve between the Visco Jet outlet line and the facility air ejectors.

Tests for the sub-cooled LCH_4 were conducted in the same manner, except the liquid was chilled by reducing the ullage pressure in the test dewar by venting through the air ejectors. This reduction in pressure caused the liquid to boil, thereby reducing the fluid temperature. Once the desired fluid temperature was achieved, the vent valve was closed, and the dewar pressurized as before.

Test Results/Observations

Tests were performed between October 2006 and January 2007. A summary of tests is shown in Table 2. Measured flow rates from test facility flow meters and calculated flow rates per Equation (2) are shown in Figures 5 to 11 for each of the Visco Jets tested. As there is no previous published data on LCH_4 flows through Visco Jets, flow rates calculated from Equation (2) assume a correction factor of $k = 1$.

TABLE 2.—TEST RESULTS FOR VISCO JET CLOGGING TESTS

Figure	Data file	Visco jet	LCH_4 condition	Bulk liquid temperature, (R)	VJ outlet temperature, (R)	Average measured, (slpm)	Calculated flow, (slpm)
5	CCL7_12.20.06	8200	saturated	203.2	191.5	32.158	28.953
6	CCL7_12.21.06	8200	subcooled	189.6	190.3	32.236	30.721
7	CCL7_12.13.06	80000	saturated	202.5	174.7	4.901	3.303
8	CCL7_12.14.06	80000	saturated	202.0	174.3	4.691	3.325
9	CCL7_12.15.06	80000	subcooled	181.5	174.7	4.660	3.649
10	CCL7_01.05.07	950000	saturated	200.1	201.8	1.087	0.316
11	CCL7_01.08.07	950000	saturated	199.6	210.8	0.549	0.314
11	CCL7_01.08.07	950000	subcooled	189.3	197.5	0.524	0.317

It was noted that for all size Visco Jets and fluid conditions, there was no decrease in flow rate over the time period tested (approximately 1 hr). The modified Lee equation appeared to under-predict flow, especially for high Lohm rated Visco Jets. This under-prediction trend was opposite of previously reported results with LN_2 and LH_2 by Papell et al. (Refs. 5 and 6). However, Papell used a correction factor "*k*" of 0.9 to improve correlation of LH_2 data. As these tests are the first known results with LCH_4, perhaps a fluid specific correction factor for methane could be utilized. Adjusting the mass flow predictions to fit the data would result in correction factors of 1.1 to 1.8 (the correction factor increased with increasing Lohm rating).

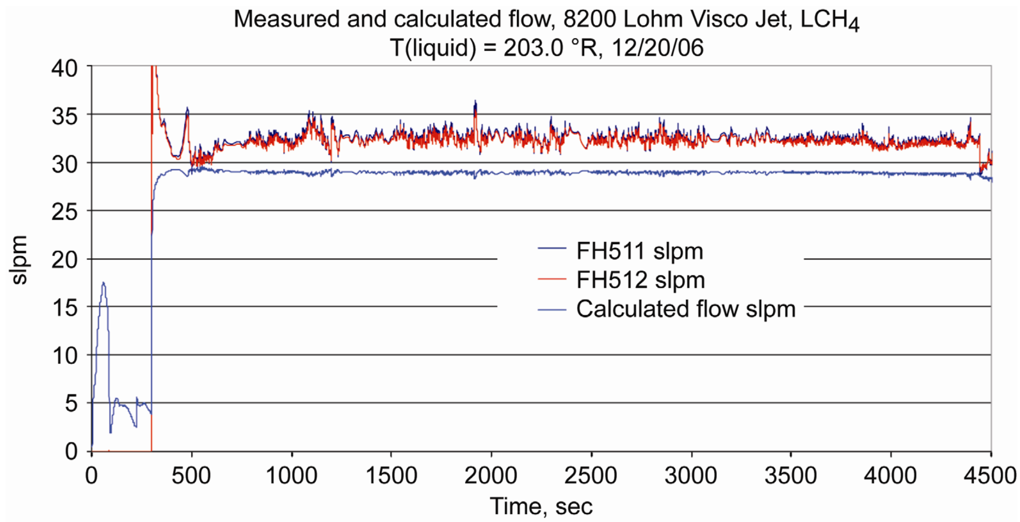

Figure 5.—Plot of flow rate versus time, 8,200 Lohm Visco Jet, T(liquid) = 203.2 °R.

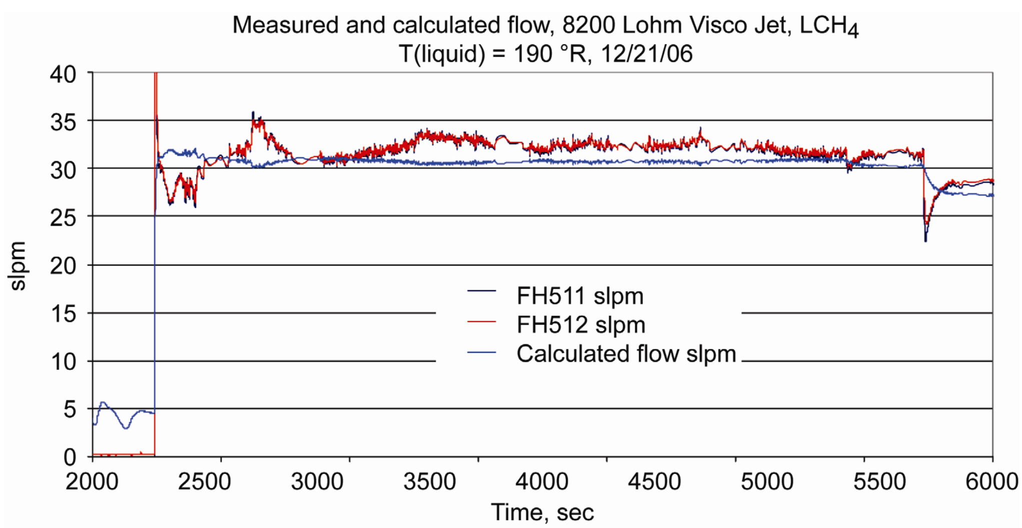

Figure 6.—Plot of flow rate versus time, 8,200 Lohm Visco Jet, T(liquid) = 190 °R.

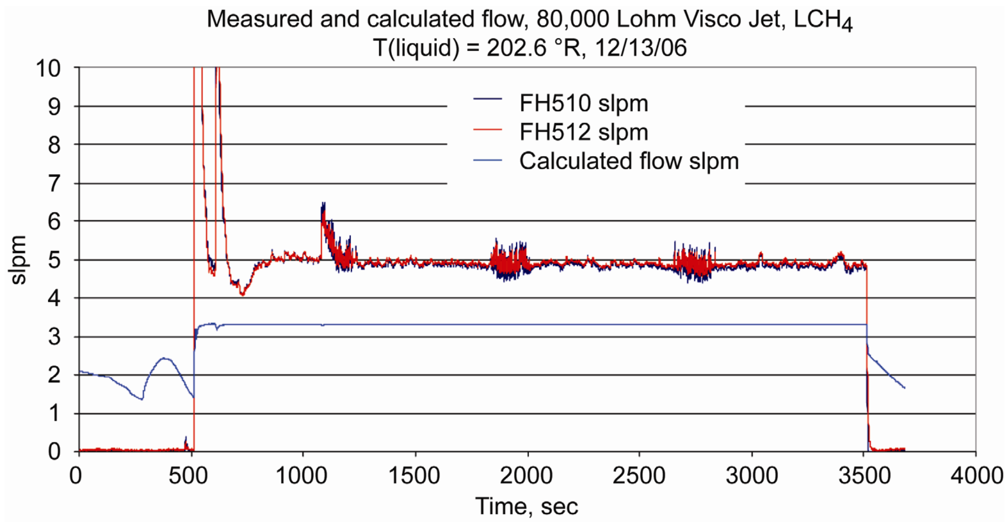

Figure 7.—Plot of flow rate versus time, 80,000 Lohm Visco Jet, T(liquid) = 202.6 °R.

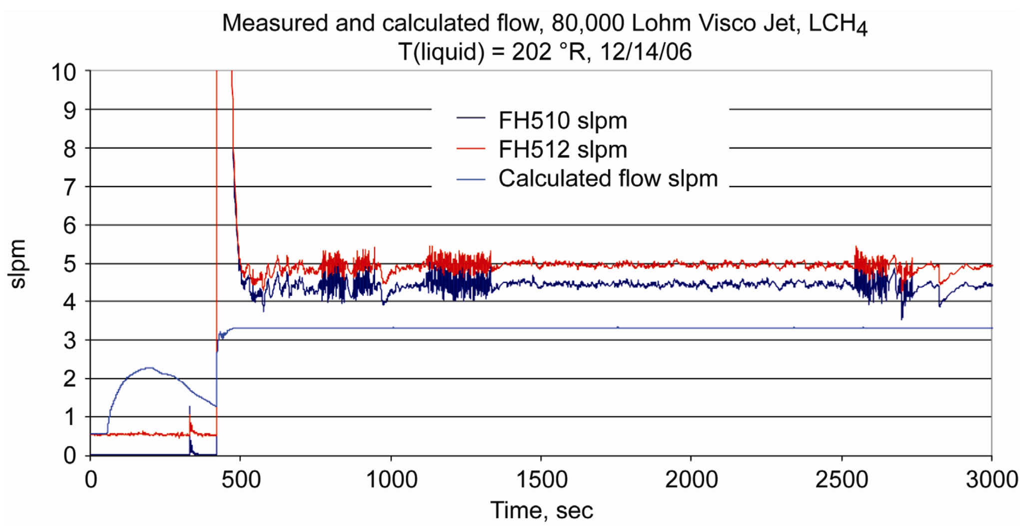

Figure 8.—Plot of flow rate versus time, 80,000 Lohm Visco Jet, T(liquid) = 202 °R.

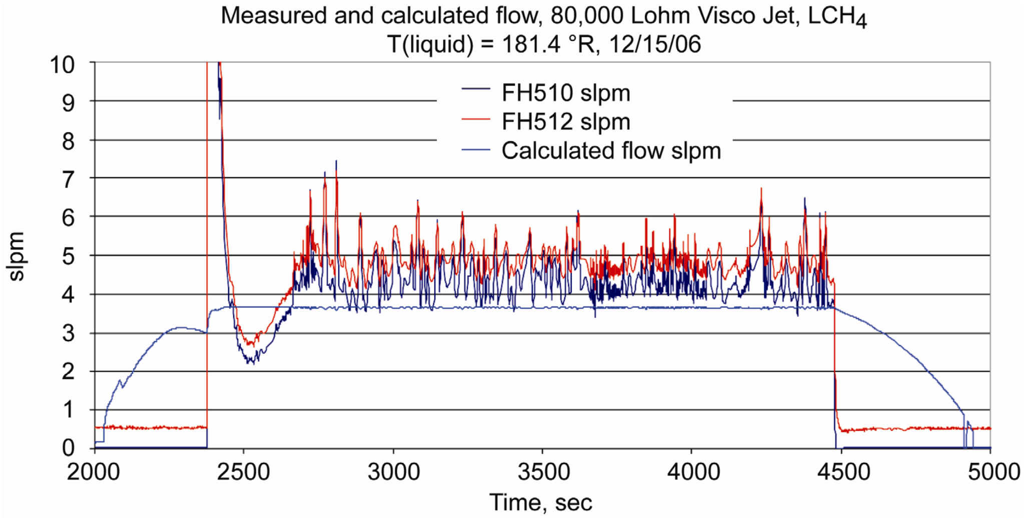

Figure 9.—Plot of flow rate versus time, 80,000 Lohm Visco Jet, T(liquid) = 181.4 °R.

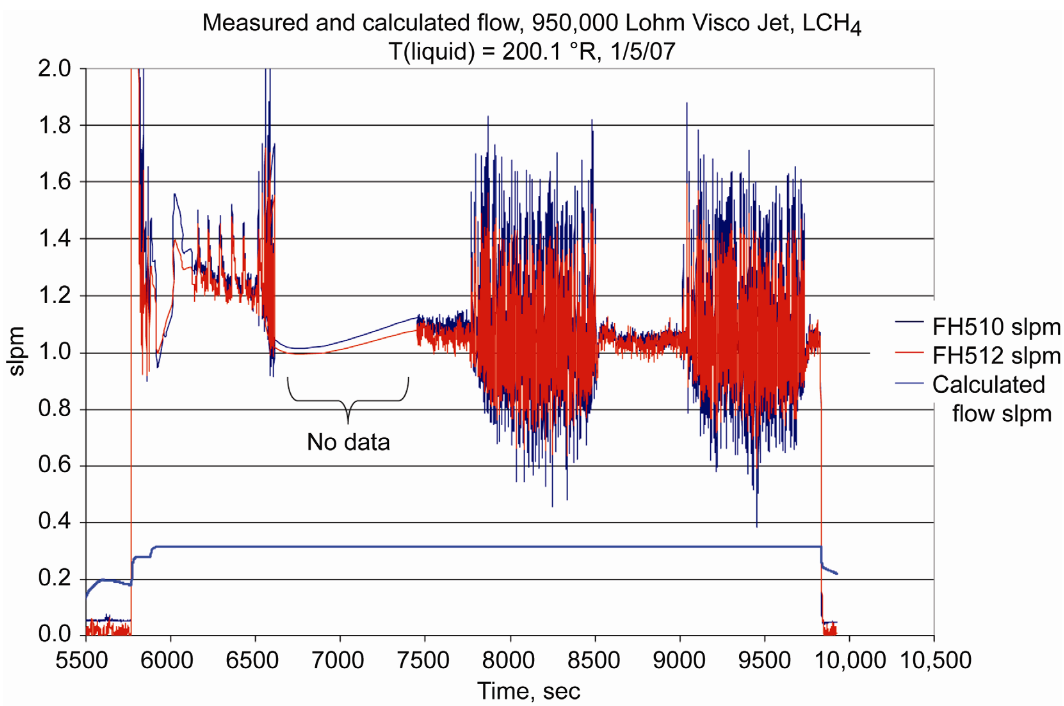

Figure 10.—Plot of flow rate versus time, 950,000 Lohm Visco Jet, T(liquid) = 200.1 °R.

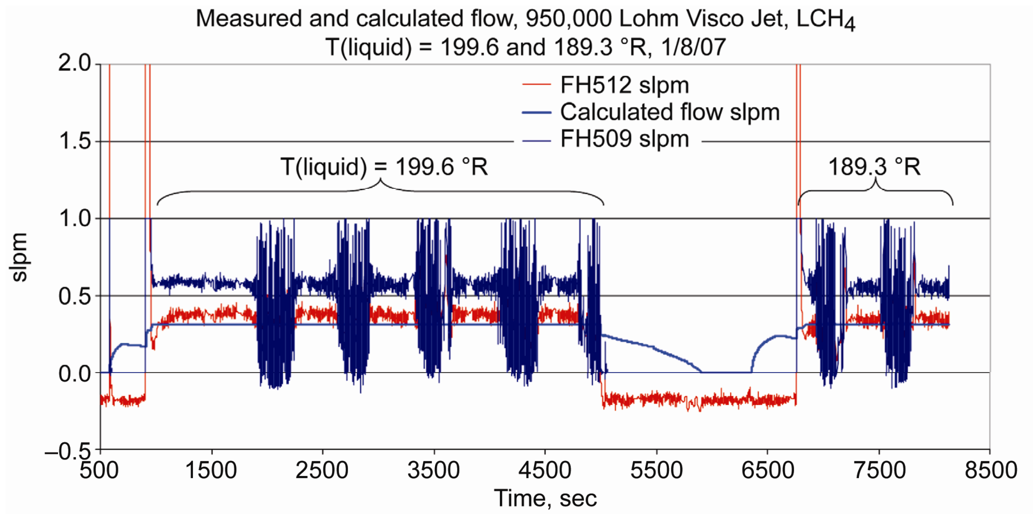

Figure 11.—Plot of flow rate versus time, 950,000 Lohm Visco Jet, T(liquid) = 199.6 and 189.3 °R.

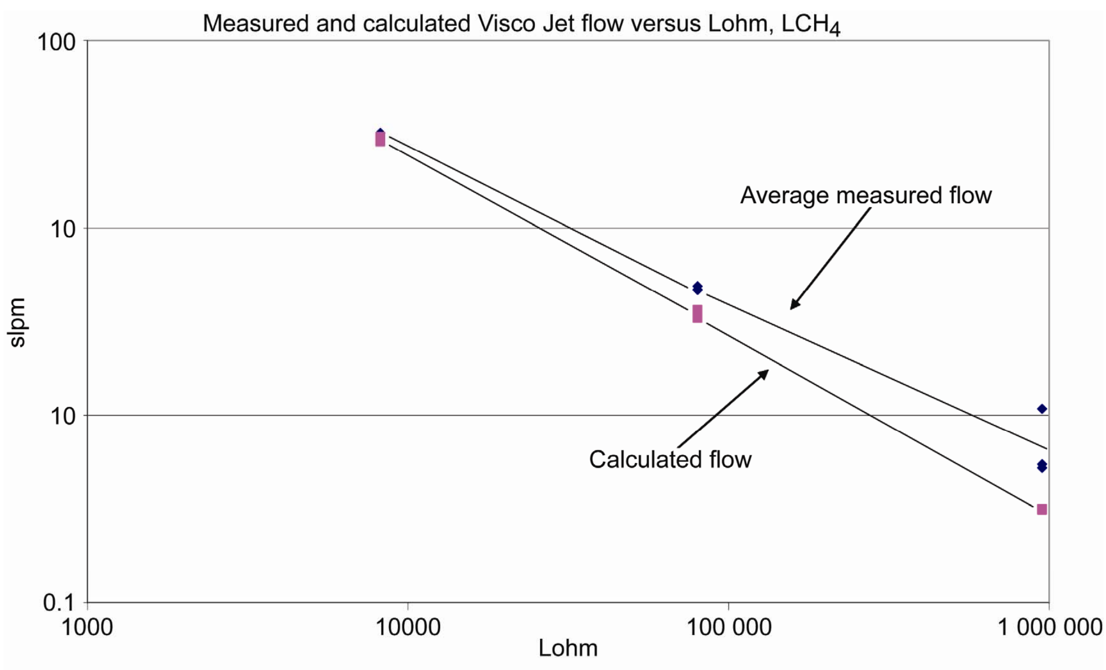

Figure 12.—log-log plot of calculated and measured Visco Jet flow rate versus Lohm rating.

Papell also proposed reducing the flow rate using a quality term as shown in Equation (2) based on phase change of the fluid within the Visco Jet body. For high Lohm rating Visco Jets, periodic flow instabilities were noted. The reason for this is yet to be determined, but may be due to phase change of the methane in the body of the Visco Jet as per Papell's conjecture. Finally, it was noted that the low flow (high Lohm rating) outlet temperatures did not track saturation temperatures. It was suspect that the outlet line was not insulated sufficiently to prevent influence from ambient conditions at outlet. Also, after reviewing test data, it was noted that the outlet Visco Jet diode was in vapor ullage during January 8, 2007 tests, which would account for the outlet temperatures tracking more closely with vapor ullage temperatures. It was previously mentioned that the flow rate was calculated using Equation (2), which included a quality term as shown in Equation (3). This quality term was calculated based on calculating downstream enthalpy from the downstream temperature. As these temperatures were suspect for high Lohm rated Visco Jets, this may have introduced errors in the flow calculations. Quality correction factors for low Lohm rating Visco Jet tests ranged from 0.9 to 0.98. Based on this, there may have been errors that would over-predict flow rates by as much as 10 percent for the high Lohm rating Visco Jets. However, although the outlet temperatures appeared to be masked by test conditions for some of the low flow tests, it was noted that the results were consistent across all tests—i.e., that the *Visco Jets did not clog*, and flow rates remained constant over the length of test.

Conclusions

- For all test conditions and Visco Jets tested, no decrease in flow rate was observed
- Subcooling liquid below T(fusion) of ethane and ethylene had no affect on results
- The modified Lee equation appears to under-predict actual flow at high Lohm ratings—result were counterintuitive to expected results, analysis is on-going
- For low pressure LCH_4 (test pressures <25 psia) Visco Jet clogging is not a concern

Future work includes Visco Jet testing LCH_4 at NASA GRC SMIRF test facility at higher (250 psia) pressures (planned tests for 2009). These Visco Jet tests will address other potential contaminants—Pentane & Butane.

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13. SUPPLEMENTARY NOTES

14. ABSTRACT
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