ANALYSIS AND TEST VERIFICATION OF TRANSITIONAL FLOW IN A DEWAR VENT

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ABSTRACT

The pressure of the cryogen within a Dewar determines the operating temperature since the cryogen is typically in a saturated state. Thus, the operating temperature of a Dewar is directly related to the ambient pressure external to the Dewar and the flow losses associated with venting cryogen. Given the low vapor pressures of some cryogens, such as solid hydrogen, the vent flow from Dewars used in space can enter the transitional and molecular flow regimes. In order to accurately predict the operating temperature within such Dewars, the analysis tool used to model the cryostat must account for free molecular and mixed flow losses as well as those for continuum flow.

As part of our analysis of Dewar designs for the James Webb Space Telescope Mid-Infrared Instrument (MIRI), we modified the continuum flow modeling capability of SINDA/FLUINT to accurately predict the pressure drop due to transitional and molecular flow in the MIRI Dewar vent line. This paper describes the modifications made to the flow loss computations within the analyzer and the testing conducted to verify these modifications.

1.0 INTRODUCTION

In the case of space telescopes that require cryogenically cooled detectors, accurately predicting cryogenic system performance is essential, since detector temperatures only slightly above optimum can result in severely degraded optical performance. One commercially available analytic software tool called SINDA/FLUINT has been used successfully to model the full thermodynamic performance of cryostats used in space. The flow regime of the venting cryogen from these previously modeled Dewars has been in the continuum range. Vent flow from some cryostats, however, and specifically those containing solid hydrogen, can be in the transitional and molecular flow regimes. Analytic correlations for computing line losses with continuum flow are inaccurate for these flow regimes. This paper describes the modifications made to the pressure loss computations within SINDA/FLUINT to account for transitional and molecular flow and the testing used to verify these modifications.

2.0 VENT FLOW FROM SPACE DEWARS

One technique for cooling detectors is to thermally couple the detector to the cryogen tank in a Dewar. The cryogen in this tank is maintained in a saturated state. The desired operating temperature is chosen to achieve optimum performance of the detector array. This temperature determines the cryogen to be used based on the range of associated saturation temperatures. For the case of the Near Infrared Camera and Multi-Object Spectrograph (NICMOS) that is currently on board the Hubble Space Telescope, solid nitrogen was used to maintain the detectors near 58 K[1]. Other space telescopes, including the Spitzer Space Telescope, the Cosmic Background Explorer (COBE) and the Infrared Astronomical Satellite (IRAS), have used liquid helium to achieve temperatures as low as 1.2 K[2,3,4].

2.1 Fixing the Cryogen Temperature

The temperature of the cryogen within its saturation range is determined by the pressure within the cryogen tank. This pressure is in turn determined by the line losses in the cryogen vapor venting to space with the absolute pressure near zero at the vent line port. Line losses are decreases in pressure due to friction and changes in flow momentum from valves, fittings, changes in line diameter and tube bends. In the case of space Dewars, the thermal analyst must also consider the losses associated with choking in the vent port. Line losses due to friction are proportional to the mass flow rate and line length and, with continuum flow, inversely proportional to the line diameter to the fourth power as shown in the Darcy equation.

$$\Delta p = \frac{f \rho L V^2}{2D} = \frac{128 \mu L \dot{m}}{\pi D^4} \qquad (1)$$

for laminar flow in a circular tube, where
Δp is the pressure drop through the tube,
f is the friction factor = $\frac{64}{\mathrm{Re}}$ for laminar flow,
$\mathrm{Re} = \frac{VD}{\mu}$ is the Reynolds number,
V is the fluid velocity,
D is the diameter of the vent line,
μ is the dynamic viscosity of the fluid,
ρ is the fluid density,
L is the length of the tube, and
$\dot{m}$ is the fluid mass flow rate.

The vent mass flow rate is dictated by the boil-off rate of the cryogen as a result of heat dissipation from the detector(s) and the parasitic heat leak into the cryogen tank through the Dewar insulation. Thus, with some knowledge about the heat load into the cryogen and thermodynamic properties of the cryogen, the operating temperature of the cryostat can be fixed by properly designing the vent line length and diameter.

2.2 Successes in Vent Line Design and Analysis

For NICMOS, a capillary tube 0.17 cm in internal diameter with a 1.65 m length was designed and tested to control the solid nitrogen cryogen to 57.5 K[1]. For SIRTF, where the thrust due to venting helium had to be minimized, opposing vent nozzles were used. The majority of the vent flow losses were in the nozzles[4], and the super-fluid helium bath temperature has been successfully controlled to a range of 1.20 to 1.25 K, depending on internal detector heat dissipation[5]. The vent nozzle design was based on analytic results from a SINDA/FLUINT model, and helium flow tests through the nozzle with room temperature helium gas proved the analysis correct to within the margin of error of the test results. In addition, flight performance has proven the accuracy of the analysis when extrapolated to flight temperatures.

2.3 Space Dewar Venting Flow Regimes

The flow rates from Dewars used to cool detectors for space telescopes are small. In the case of NICMOS in a relatively warm near-Earth orbit, the mass flow rate was nominally 2.4 g/hr. For Spitzer, which is in a heliocentric drift-away orbit with an outer shell temperature of 35 K, the flow rate is 24 g/day. This corresponds to a Reynold's number of 15 for a 0.2 cm vent nozzle. Yet even at this flow rate, interactions between molecules of helium are sufficient to be considered continuum flow. The flow regime can be determined with the Knudsen number defined as,

$$Kn = \frac{v}{D} \cdot \left(\frac{\pi}{2RT} \right)^{1/2} \qquad (2)$$

where,
v is the kinematic viscosity of the cryogen,
R is the specific gas constant for helium, and
T is the cryogen temperature.

Barron[6] defines the flow regimes with,

$$\begin{array}{lll} Kn < 0.01, & \text{continuum flow,} & \\ 0.01 < Kn < 0.30, & \text{mixed, or transition flow, and} & (3) \\ 0.30 < Kn & \text{molecular flow.} & \end{array}$$

When a solid hydrogen Dewar was considered for cooling of the mid-infrared detector on the James Webb Space Telescope, Equations 2 and 3 were used to determine the flow regime. In this case, the temperature requirement for the cryogen tank of the Dewar was 6.65 K. At this temperature, the vapor pressure of saturated hydrogen is 0.72 Pa. With an expected cryogen tank heat load of 64 mW, the hydrogen mass flow rate would be 0.145 mg/sec. In order to achieve such a low pressure drop in the vent line, the vent tube would need to have a large diameter. Assuming a 3.8 cm diameter vent line and a 40 K vent port, these conditions would correspond to Kn = 4.3, or well into the molecular flow regime. Thus, flow losses associated with transitional and molecular flow needed to be taken into account.

3.0 TRANSITIONAL AND MOLECULAR FLOW

When the mean free path of the venting molecules approaches the diameter of the vent line, then collisions with the tube wall become more frequent than collisions with other molecules. In this regime, molecules have a finite velocity at the tube walls and thus molecular flow is often referred to as "slip" flow. For mixed, or transition flow, the mass flow rate in a circular tube is[7],

$$\dot{m} = \left(\frac{\pi D^4 \bar{p} \Delta p}{128 \mu L R T} \right) \left[1 + \frac{8\mu}{\bar{p} D} \left(\frac{\pi R T}{2} \right)^{1/2} \right] \qquad (4)$$

As the density of the cryogen decreases further, the flow becomes fully molecular, and the mass flow can be expressed as[8],

$$\dot{m} = \left(\frac{\pi}{18 R T} \right)^{1/2} \frac{D^3 \Delta p}{L} \qquad (5)$$

where,
$\bar{p}$ is the average pressure in the tube, and
Δp is the pressure difference at either end of the tube.

As one can see, the pressure drop for molecular flow is inversely proportional to the cube of the line diameter, as opposed to the fourth power for continuum flow. Thus, flow loss predictions with SINDA/FLUINT, which accounted only for continuum flow at the time, would have been inaccurate. SINDA/FLUINT, however, allows for manipulation of the flow loss calculations along with the compilation of user provided code, so Equations 4 and 5 were incorporated in the simulation of the MIRI vent line.

The magnitude of the losses in the MIRI vent line were to be so small that even small errors could result in large discrepancies in helium bath temperatures, thus a test to verify the modified predictions was deemed necessary.

4.0 FLOW TEST CONFIGURATION AND PROCEDURE

Vent line flow testing involved connecting a gaseous source through a representative vent line into a vacuum chamber with a large high-vacuum pumping capacity. Since hydrogen is a flammable gas, the test to verify molecular flow vent line predictions was conducted with room temperature helium. Four vent line configurations were tested: 1) a 3.48 cm (1.37 in) inside diameter (ID) by 0.61 m (24 in) long smooth-walled tube, 2) a 4.75 cm (1.87 in) ID by 0.61 m long smooth-walled tube, 3) a 3.5 cm (1.38 in) ID (this ID represents the smallest internal diameter of the corrugated tube) by 0.56 m (22 in) flexible corrugated tube, and 4) the flexible corrugated tube with a 5.1 cm (2 in) angle valve[9] with fittings. The various configurations are described in Figure 1 with pictures of the first and fourth configurations in Figures 2 and 3 respectively.

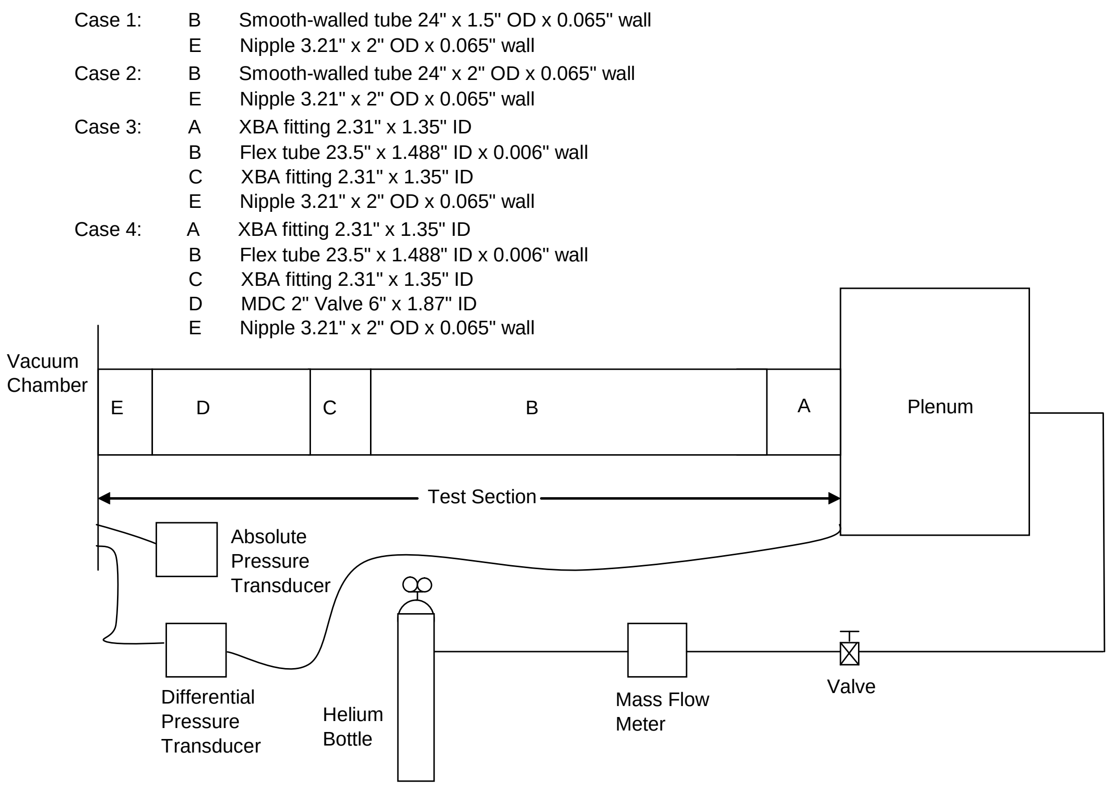

Figure 1. Molecular Flow Test Configuration

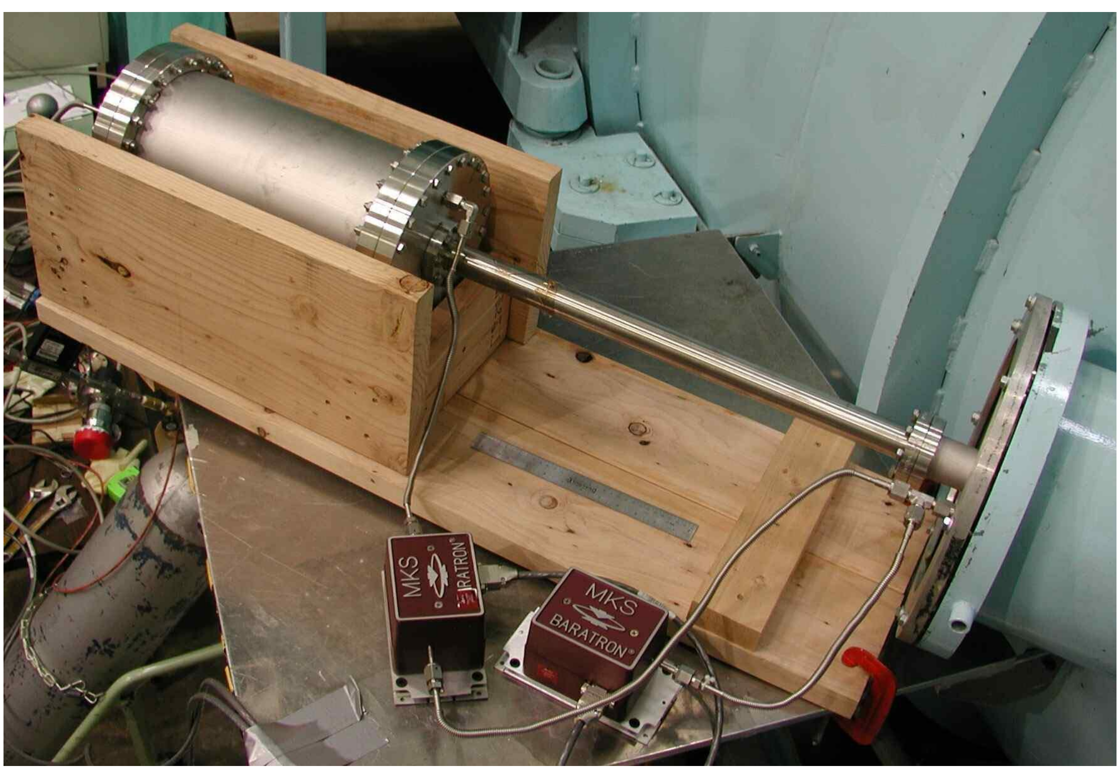

Figure 2. Molecular Flow Test Set-up with 3.48 cm ID Smooth-Walled Tube

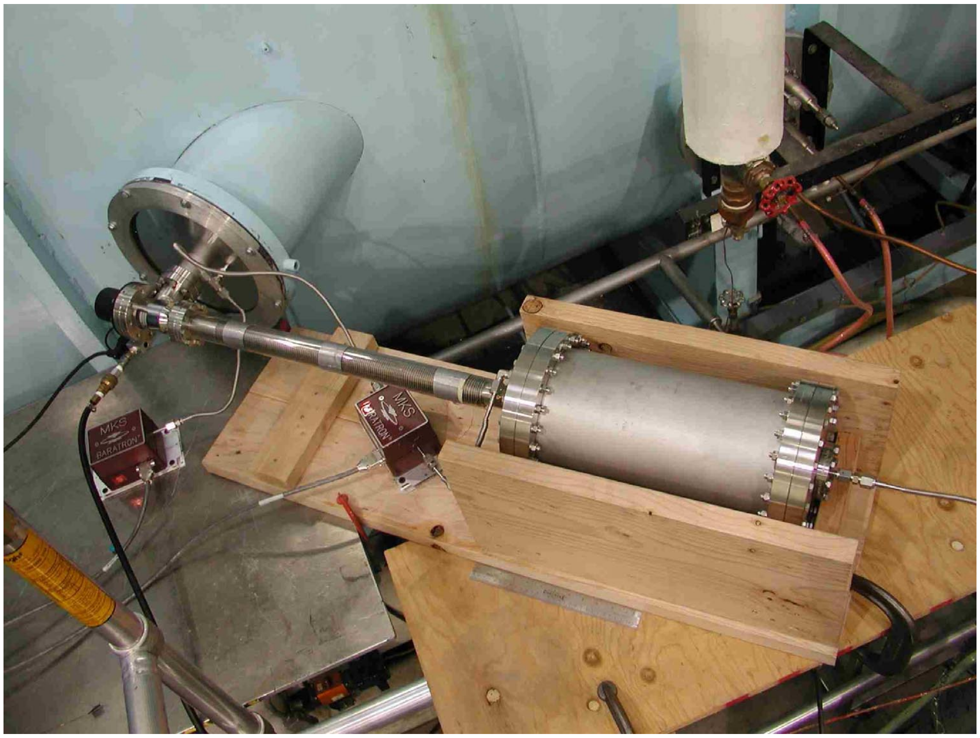

Figure 3. Molecular Flow Test Set-up with 3.5 cm ID Corrugated Tube and 5.1 cm Valve

Helium at room temperature was supplied through a mass flow meter and a needle valve to a plenum 40.6 cm in length and 19.7 cm in diameter. The mass flow meter had an accuracy of 0.03 mg/sec[10]. The plenum allowed for any entrance effects into the test section. The pressure drop across the test section was measured with a 133 Pa (1.0 torr) full scale differential pressure transducer with an accuracy of 0.16 Pa[11], and the pressure at the vacuum chamber interface was measured with a 133 Pa full scale absolute transducer with an accuracy of 0.16 Pa[12]. The vacuum chamber has two diffusion pumps each with a rated capacity of 32,000 l/sec of air, or 35 torr-l/sec.

Once the pressure in the vacuum chamber had been reduced to less that 1 x 10^{-4} Pa, the needle valve was opened to achieve a flow rate near 0.1 mg/sec. After all sensors had stabilized, measurements were recorded and the flow rate increased by increments of 0.1 mg/sec up to a flow rate of 0.5 mg/sec. Data were then recorded in increments of 1 mg/sec up to a flow rate of 7 mg/sec. The vacuum chamber pumps were unable to hold the chamber pressure steady above this flow rate. This procedure was conducted a second time for each manifold configuration.

5.0 TEST RESULTS

Results of this testing are shown in Figures 4 through 9. Figure 4 shows the measured inlet pressure to the test section as a function of mass flow rate, with error bars, through the manifold for the configuration with only a 3.48 cm (1.37 in) ID smooth wall tube. Also shown in the plot are predictions made with a SINDA/FLUINT model with and without the modifications for transitional and molecular flow. Figure 5 shows the predicted Knudsen number at intervals along the test vent line for the lowest and highest test flow rates from Figure 4 (0.1 and 7 mg/sec respectively).

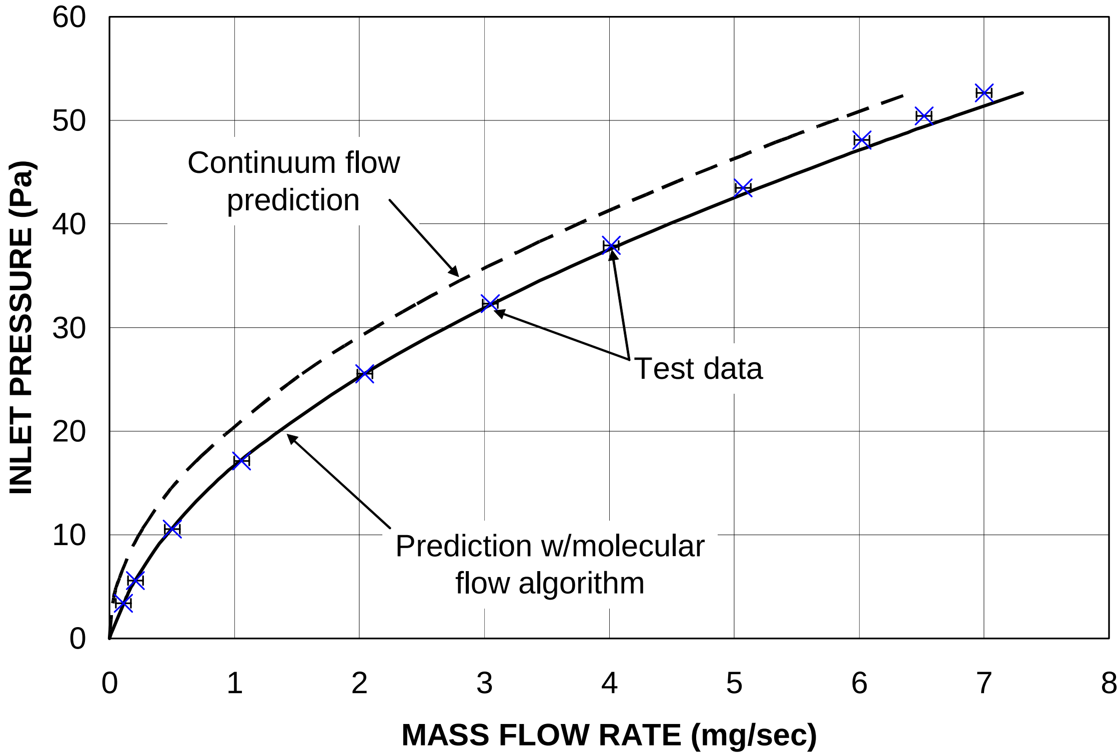

Figure 4. Predicted 3.48 cm ID Smooth-Walled Tube Performance and Test Data

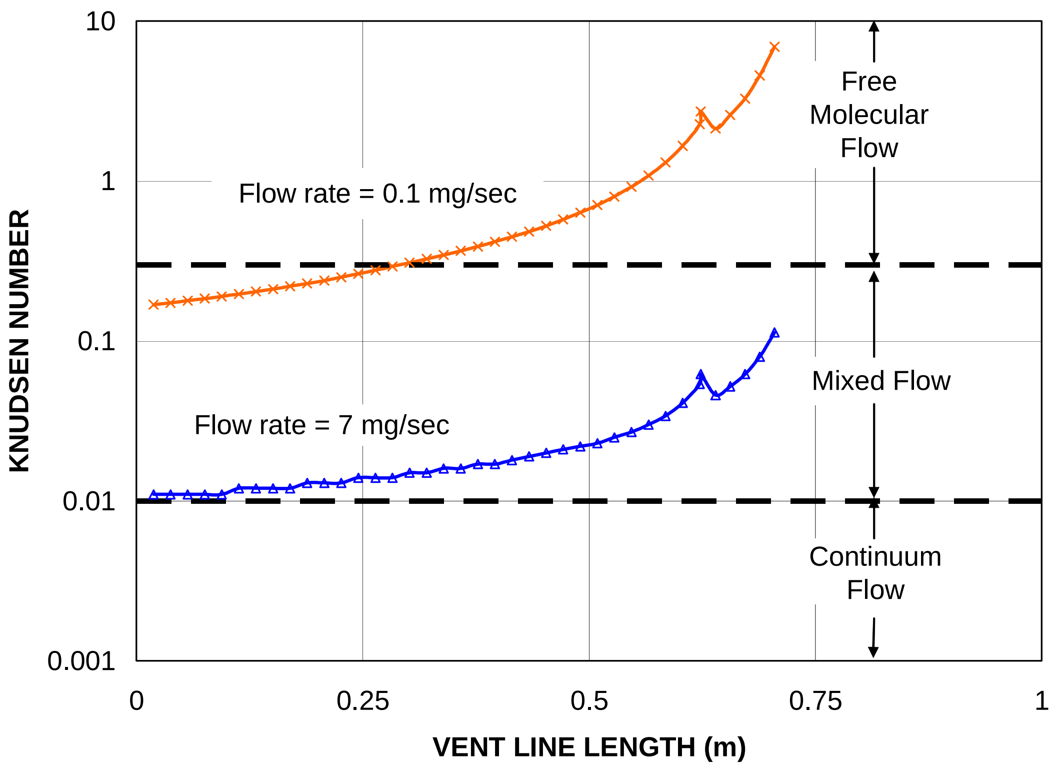

Figure 5. Predicted Flow Regime inside 3.48 cm ID Smooth-Walled Tube

Figures 6, 7 and 8 show the test results and predicted conditions within the manifold for the other three manifold configurations. Figure 9 shows the predicted Knudsen numbers for the configuration with flex line and valve for the lowest and highest flow rate cases from Figure 8.

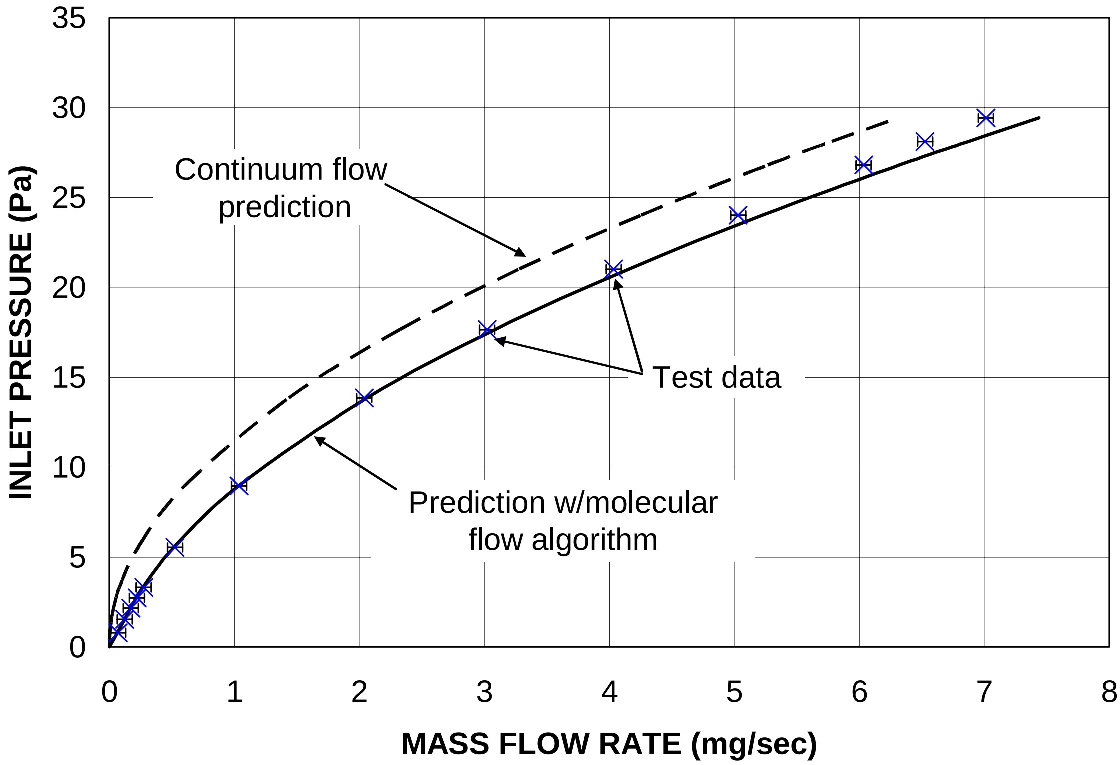

Figure 6. Predicted 4.75 cm ID Smooth-Walled Tube Performance and Test Data

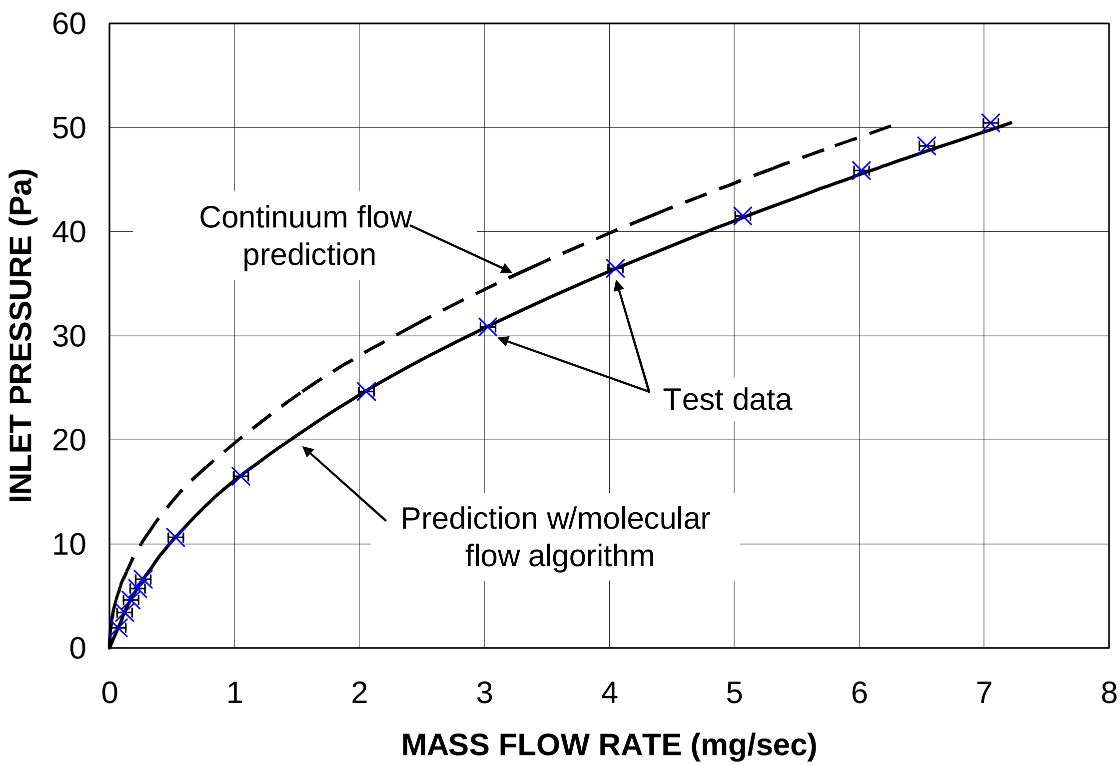

Figure 7. Predicted 3.5 cm ID Flexible Corrugated Tube Performance and Test Data

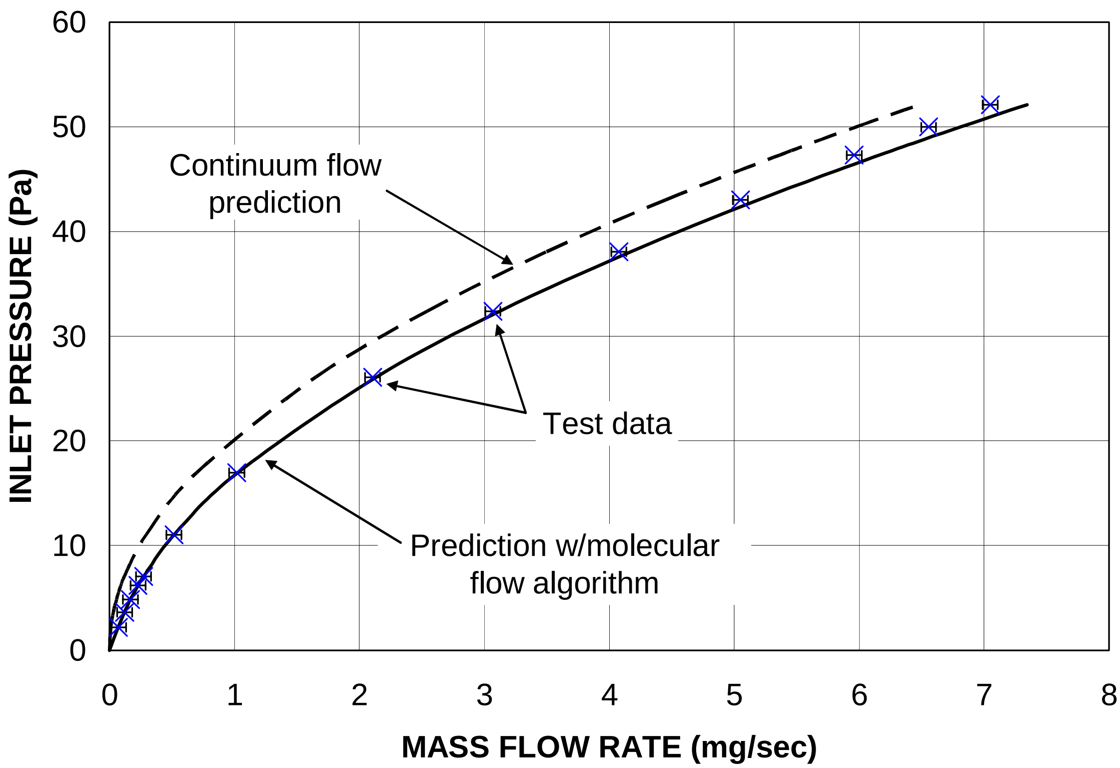

Figure 8. Predicted 3.5 cm Flexible Corrugated Tube with 5.1 cm Valve Performance and Test Data

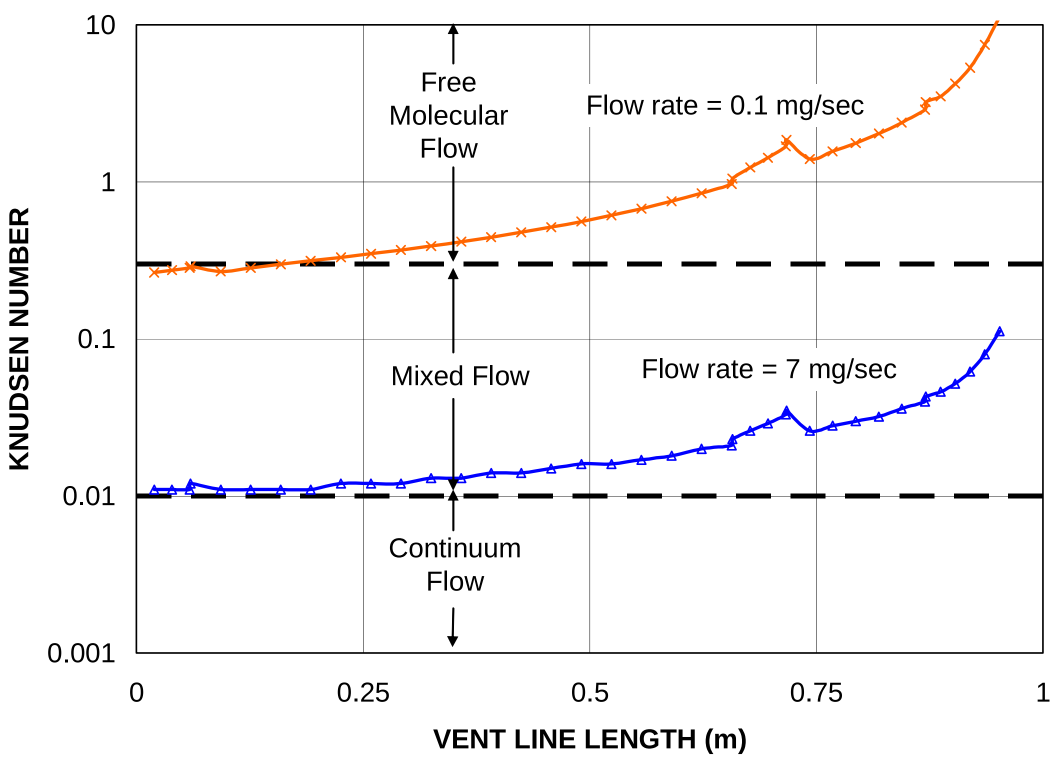

Figure 9. Predicted Flow Regime inside 3.5 cm ID Corrugated Tube with 5.1 cm Valve

6.0 DISCUSSION

For each of the test configurations, the predicted pressure drop through the vent line matched test data to within the experimental accuracy below a flow rate of about 4 mg/sec, and within a few error bar multiples between 4 and 7 mg/sec. In all cases, the model with the molecular flow algorithm matches the test data much better than that considering continuum flow alone.

For the higher flow rate cases, the upstream pressure required to achieve a given flow rate was slightly greater than expected. Because this behavior was present in each of the vent line configurations, the effect is unlikely the result of increased tortuousity in flow due to corrugations and the valve. This verifies that flow losses due to momentum changes become negligible at these flow rates (since none were accounted for in the models).

As can be seen from Figures 4 and 5 and also in Figures 8 and 9, a greater deviation in the predicted pressure drop from the test data occurs when a greater percentage of flow is in the mixed flow regime. A correction factor for flow in the mixed region may be appropriate. When the onset of mixed flow was assumed to occur at a Knudsen number of 0.015 rather than 0.01, the predictions matched the test data much more closely than the original predictions for the cases with line diameters near 3.5 cm. The improvement in predictions due to this modification was less evident, however, for the case with a 4.75 cm ID. Thus an investigation with a greater variety of configurations would likely be necessary to resolve this discrepancy.

7.0 CONCLUSIONS

Testing with helium flow through a representative vent line into a vacuum chamber has verified the capability to simulate molecular and mixed flow losses with a commercially available thermal/thermodynamic modeling tool, SINDA/FLUINT. This work demonstrates the ability of analysts to predict the performance, and more specifically the operating temperature, of Dewars operated in space, even in mixed and molecular flow regimes. Since the completion of this work, the capability to model mixed and molecular flow has been added as a standard feature in SINDA/FLUINT.

8.0 REFERENCES

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