

Validation of a Multiphase Computational Fluid Dynamics Model for Vapor Pull-Through in Normal and Low Gravity

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On-orbit fluid transfer such as refueling of propellant tanks and life-support systems can enable long-duration space missions. For safe and efficient liquid transfer operations, prior knowledge of liquid positioning and liquid-vapor interface behavior while draining in a reduced-gravity environment is required. Numerical models capable of predicting vapor ingestion (or vapor pull-through) can be used to design liquid transfer operations while reducing liquid residuals, mission risk and settling thrust required to prevent vapor ingestion. An experimental program conducted in the 2.2 Second Drop Tower facility at NASA Lewis Research Center in 1969 investigated the vapor ingestion phenomenon for a range of outflow rates and tank sizes providing a database for validation. This study presents a Computational Fluid Dynamics model capable of accurately predicting the vapor ingestion using the Volume-of-Fluid multiphase solver in commercial code STAR-CCM+. A description of the experimental setup and general trends from similar studies are presented. Comparisons of the numerical prediction and test data in normal and low gravity show good agreement and give confidence in pursuing design of full-scale propellant transfer systems.

Nomenclature

g	=	gravitational acceleration, 9.81 m/s ²
h	=	liquid-vapor interface height, cm
Q	=	volumetric flow rate, m ³ /s
R	=	tank radius, cm
r	=	outlet radius, cm
V	=	velocity, m/s
We	=	Weber number

Greek

β	=	specific surface tension, σ/ρ , m ³ /s ²
μ	=	dynamic viscosity, Pa-s
ρ	=	density, kg/m ³
σ	=	surface tension, N/m

Subscripts

cr	=	critical
i	=	initial
o	=	outlet
vi	=	vapor ingestion

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I. Introduction

On-orbit cryogenic liquid propellant transfer capabilities can enable cost-effective solutions for space exploration. For example, future deep space missions may utilize propellant depots for refueling to sustain long-duration human and science exploration activities. However, many challenges exist with liquid transfer in a microgravity environment. These challenges include: knowledge of the liquid position in the source tank, behavior of the liquid-vapor interface while draining at a reduced-gravity level, chilldown of the receiver tank, knowledge of source and receiver tank thermodynamic states for a pressure-fed transfer, coupling hardware design and leakage, etc. This study focuses on the behavior of the liquid-vapor interface while draining, and more specifically vapor ingestion (or vapor pull-through). Vapor pull-through is important to understand for designing propellant transfer systems and engine operation. Vapor entrainment while operating an engine or refueling a propellant depot or can lead to failure of the system. For pressure-fed tank-to-tank transfer, vapor entrainment can equalize the pressure between the tanks and stop the transfer. Vapor pull-through is of less risk for in-space engine operation than refueling because firing the engine provides significant settling force to the liquid. Contrary, propellant transfer is subject to reduced-gravity where vapor pull-through will occur at higher fill levels due to the curvature of the liquid-vapor interface at low Bond numbers.

For pressure fed on-orbit refueling, conditioning the source and receiver tanks requires thermodynamic considerations as well as mass gauging. In microgravity, the liquid can easily become unsettled from the tank drain. Therefore, a liquid acquisition device (which adds weight) or some other method must be used to drain liquid from the tank. Settling thrusters such as reaction control system (RCS) thrusters or propulsive vents can be used to apply a small force to settle the propellant aft such that the tank drain remains covered with liquid throughout the duration of the transfer. If the settling thrusters use non-cryogen propellant to settle, extra tanks are required thus adding weight to the spacecraft. The settling thrusters could use the cryogenic propellant itself, but this reduces efficiency and is considered wasted propellant that could have been transferred. To evaluate on-orbit propellant transfer efficiency, the liquid residual remaining in the tank and mass used for settling must be considered. Once vapor pull-through occurs, the residual liquid in the tank is untransferable and adds to the overall wasted propellant. Employing Computational Fluid Dynamics (CFD) models to predict in-space cryogenic propellant transfer can reduce cost and mission risk. CFD models can be used to design hardware and concept of operations for transfer vehicles, thereby reducing system and propellant mass. However, these CFD models must be validated to experimental data in relevant conditions.

Vapor pull-through and in-space propellant transfer/depot concepts have been extensively studied in literature for decades. Several fundamental vapor pull-through studies were conducted during the Apollo era. Nussle et al. [1] showed that the amount of liquid drained prior to vapor ingestion is a strong function of outflow velocity, and that baffling the pressurant inlet at the top of the tank mitigated direct impingement on the interface reducing liquid residuals. In Ref. [2], it is shown that the distortion of the liquid-vapor interface during outflow is correlated to the Weber number. Abdalla and Berenyi [3, 4] conducted experiments in the 2.2 Second Drop Tower facility at NASA Lewis Research Center investigating vapor ingestion in normal and low gravity, providing a sufficient database for model validation. Ref. [3] characterized cylindrical flat-bottomed tanks while Ref. [4] characterized cylindrical hemispherically-bottomed tanks by correlating liquid residuals to Froude number in normal gravity and Weber number in low gravity.

Raco et al. [5] showed that adding dielectrophoretic baffling to a cylindrical tank can successfully delay vapor pull-through in low gravity but has no effect in normal gravity. Symons [6] studied the effect of various baffle geometries on liquid residuals in low gravity, showing a reduction of 10% to 60% depending on baffle geometry and outflow velocity. More recently, Yang et al. [7] reported that swirling liquid due to spacecraft roll maneuvering causes vapor pull-through to occur earlier than liquid that is initially quiescent using CFD simulations of the Ares I upper stage spacecraft. The authors also showed the addition of anti-vortex baffling can mitigate the swirling motion and delay vapor pull-through. Similarly, Kinefuchi et al. [8] compared numerical and experimental vapor pull-through results with a circular baffle above the tank drain.

Wood and Trucks [9] presented a concept for an orbital fluid transfer experiment in 1969. The authors highlighted the need for an on-orbit demonstration to eliminate gaps in understanding of cryogenic transfer. Decades later, Chato [10, 11] summarized issues relating to deep space refueling architectures including long term storage of cryogens, pressure control, mass gauging, liquid acquisition, and fluid transfer. The author concluded that an orbital demonstration is likely required to develop these technologies.

This paper presents CFD model predictions of vapor pull-through and liquid residuals at several outflow velocities for a cylindrical flat-bottomed tank. Descriptions of the vapor ingestion phenomenon and test procedure from the experiment used for validation are provided. Finally, the computational model is defined and the CFD model predictions are compared with the test data. Methods to delay vapor pull-through and reduce liquid residuals are discussed.

II. Vapor Ingestion Phenomenon

The vapor ingestion phenomenon is illustrated in Fig. 1 from Ref. [3]. For both normal and low gravity, centerline interface height is plotted as a function of time indicating a constant interface velocity followed by rapid acceleration to the outlet. For normal gravity, the interface remains relatively flat until it reaches the critical height, h_{cr} , where the interface is at the incipience of vapor ingestion. The critical height is identified by a dip forming on the interface centerline and the interface displacement-time curve deviates from a linear slope. Shortly after, the interface accelerates toward the drain and vapor is ingested. The interface away from the drain remains relatively flat under normal gravity, and the height of the interface at this location is defined as the vapor ingestion height, h_{vi} .

In a low gravity environment, the interface is curved at the initiation of draining where the shape is determined by the combination of the surface tension force, contact angle, and gravity force. During draining, the interface distorts while the centerline drains at a constant velocity. The height of the interface centerline at the incipience of vapor ingestion is the critical height, h_{cr} . Since the interface away from the drain is curved a vapor ingestion height cannot be defined, so the phenomenon in low gravity is exclusively characterized by the critical height.

The authors of Ref. [3] primarily focused on reporting critical height and vapor ingestion height, which gives quantitative values for validation. However, the remaining liquid in the tank, or liquid residual, is more valuable for validation. Predicting liquid residuals requires accurate reconstruction of the liquid-vapor interface at a reduced gravity level. As the gravity force is reduced, the interface becomes more curved yielding a larger liquid residual.

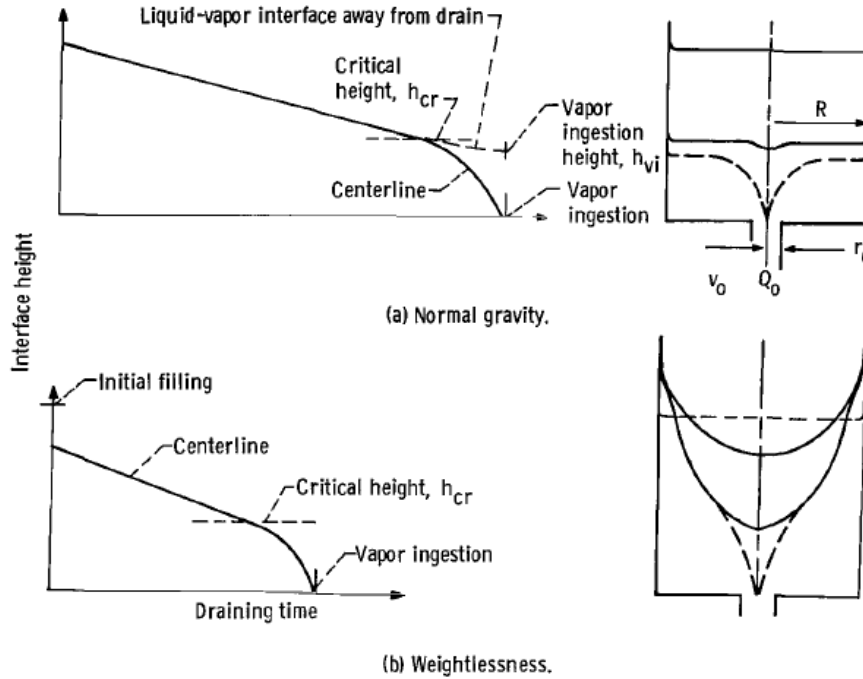


Fig. 1 Vapor ingestion or vapor pull-through phenomenon, reprinted from Ref. [3].

III. Experimental Overview

The experiment performed by Abdalla and Berenyi [3] in 1969 used acrylic plastic, cylindrical flat-bottomed tanks with a central outlet. A baffle was placed near the top of the tank to mitigate interface impingement from the injected pressurant gas shown in Fig. 2. Two tanks at 2 and 4 centimeters in radius were used. Each tank was tested with an outlet radius of 1/10 and 1/20 of the tank radii. The outlet length was at least 10 times the outlet radius. The tanks length-to-diameter ranged from 1.5 to 4 depending on fill height, where the nominal fill height was 2 times the tank radius. Outflow velocities ranged from 2 to 95 m/s for both normal gravity and low gravity.

The experiment was conducted in the 2.2 Second Drop Tower at NASA Lewis Research Center (now NASA Glenn Research Center). The drop tower can provide 2.2 seconds of microgravity by allowing the test article to free fall for 24 meters. The test article is encapsulated in a drag shield to minimize aerodynamic forces and is decelerated by an airbag at the bottom of the tower.

The flow schematic of the entire experimental system is shown in Fig. 3. Draining was achieved by pressurizing the ullage for a specified outflow condition. No pressurization data were given, and the outflow velocities were assumed constant. The authors state that for the drop tower operation, the solenoid opened once the interface centerline reached its low point. However, in a separate section of the paper the solenoid was opened at a set time for each drop which might not have been the low point for every case considered. This was done since there was not enough time within the 2.2 second drop to let the interface completely equilibrate. A high-speed camera measured the interface height as a function of time and the resulting outflow velocity and pertinent heights were computed thereafter. In addition, the residual liquid (undrained liquid) in the tank at the time of vapor pull-through was also reported.

Three working fluids were considered to determine the dependence of the critical and vapor ingestion heights on fluid properties listed in Table 1. The viscosity ranged from 0.0007 to 0.0154 Pa-s and surface tension ranged from 0.0186 to 0.0269 N/m.

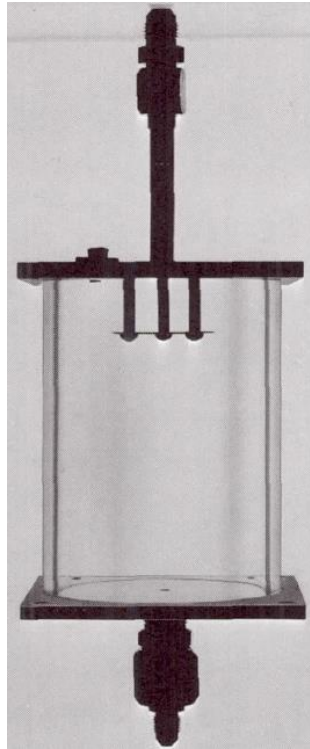


Fig. 2 Experimental test tank, reprinted from Ref. [3].

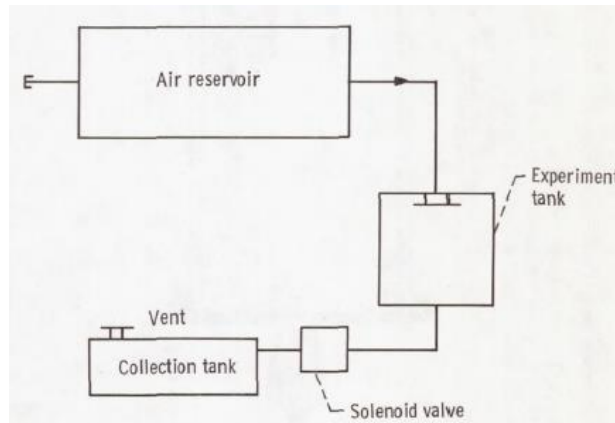


Fig. 3 Experimental flow schematic, reprinted from Ref. [3].

Table 1 Test liquid properties at 20°C

Liquid	Surface Tension, σ , N/m	Density, ρ , kg/m ³	Viscosity, μ , Pa-s
Ethanol	0.0223	789	0.0012
Trichloro-trifluoro-ethane	0.0186	1580	0.0007
60 Ethanol - 40 Glycerol (% by volume)	0.0269	988	0.0154

IV. Computational Model

Commercial CFD code STAR-CCM+ version 2402 [12] was used to model the experiment. The model geometry and spatial boundary conditions are detailed in Fig. 4, and the computational mesh is shown in Fig. 5. A length-to-diameter of 3 was chosen so that the pressure outlet set to ambient conditions was far enough away from the interface to have no effect. The mass flow rate was specified at the drain outlet based on the outflow velocity and liquid density reported in Ref. [3]. The problem was solved using a 2D-axisymmetric transient analysis with a time step of 0.001 seconds and the Volume-of-Fluid (VOF) multiphase solver. The surface tension force was modeled via Brackbill et al. [13] with a contact angle for ethanol of zero degrees, just as it is with cryogenics. The low gravity cases used a gravitational acceleration of 0.001g. The Realizable K-Epsilon Two-Layer turbulence model was used for all cases since the smallest outflow velocity considered was in the turbulent regime. The default initial conditions for the turbulence model were used and the initial velocity was set to zero. Both liquid and vapor phases were considered incompressible with constant material properties at room temperature.

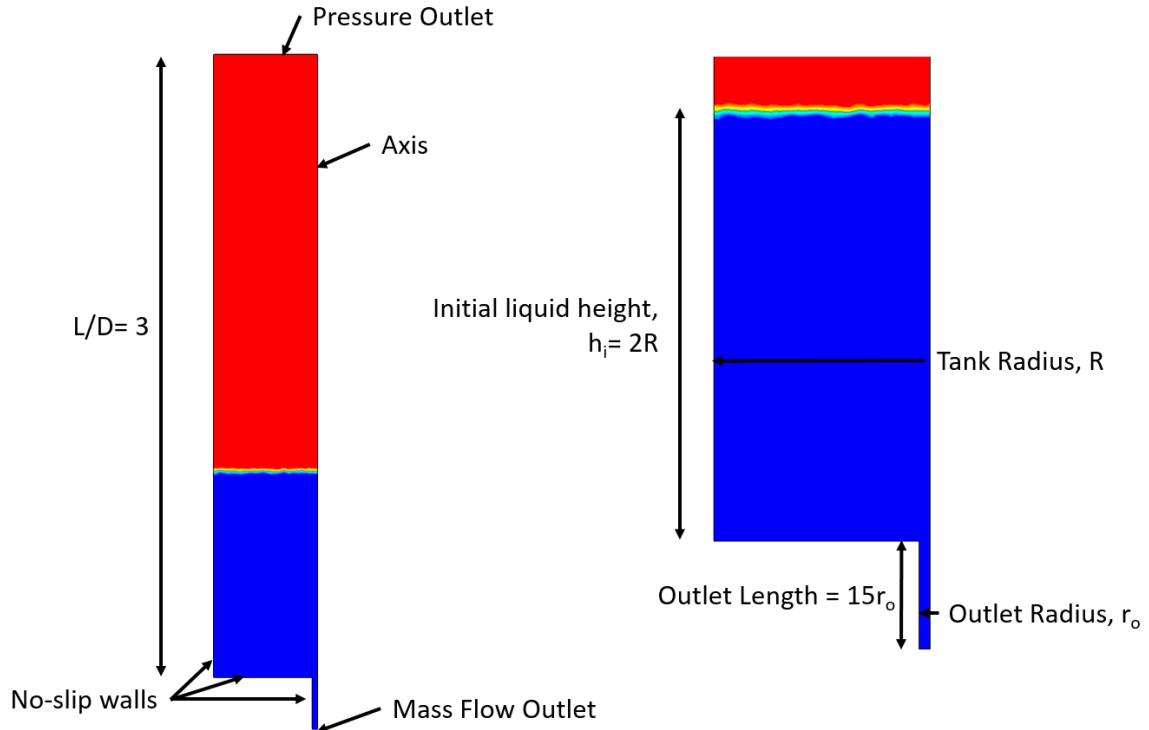


Fig. 4 Model geometry and boundary conditions.

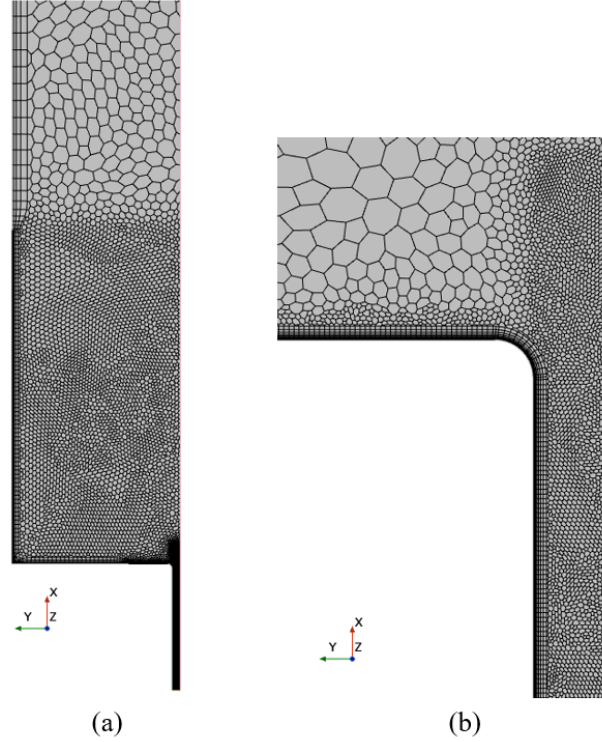


Fig. 5 Computational mesh of (a) tank bottom and (b) outlet pipe.

V. Results and Discussion

Interface displacement-time draining curves were reported for only three outflow velocities with the 2 cm tank radius, 0.1 cm outlet radius using ethanol as the working fluid. The critical heights and vapor ingestion heights were indicated on the draining curves for both gravitational environments. For the remainder of the cases, the vapor ingestion height was reported as a function of outflow velocity for normal gravity, and the critical height was reported as a function of outflow velocity for low gravity. No tabular data were provided so the experimental data were digitized from the original NASA technical note. In addition, liquid residuals were reported as a function of Weber number for the low gravity experiments to highlight dependence on surface tension force and outflow rate. Weber number is given in Eq. (1), where Q_o is the outlet volumetric flow rate, β is the specific surface tension, and R is the tank radius. Note that this unconventional form of Weber number was used in Ref. [3].

$$We = \frac{Q_o^2}{\beta R^3} \quad (1)$$

The outflow velocities that were considered for simulation are listed in Table 2. The three cases with experimental draining curves available were considered (10.08, 16.88, 20.80 m/s), and four more cases at 2, 25, 35, and 55 m/s were simulated to cover the entire range of outflow velocities tested in the experiment. Each outflow velocity was run in normal and low gravity. All cases used ethanol as the working fluid, tank radius of 2 cm, and outlet radius 0.1 cm, except the 2 m/s case used an outlet radius of 0.2 cm.

Table 2 CFD case summary

Outflow Velocity, V_o (m/s)	Tank Radius, R (cm)	Outlet Radius, r_o (cm)	Liquid
2	2.0	0.2	Ethanol
10.08	2.0	0.1	Ethanol
16.88	2.0	0.1	Ethanol
20.80	2.0	0.1	Ethanol
25	2.0	0.1	Ethanol
35	2.0	0.1	Ethanol
55	2.0	0.1	Ethanol

A. Draining Curves

A comparison of the draining curves for normal and low gravity are shown in Fig. 6 and Fig. 7, respectively. The experimentally measured critical heights and vapor ingestion heights are indicated by the tailed symbols while the corresponding CFD values are shown by the colored markers. In all cases, the CFD prediction compares reasonably well to the experiment.

For the low gravity cases, draining was initiated after 0.4 seconds of simulation time with no flow to allow the interface centerline to reach its low point while equilibrating. After running the simulations, it was observed that 0.4 seconds results in the interface “rebounding” upward; however, this is a negligible effect on the final vapor ingestion heights and liquid residuals. It was also observed that the initial interface centerline heights ($t = 0$ s) for the CFD cases were slightly lower than the experimental measurements. This could be due to erroneous initial fill levels or that the draining was initiated at slightly different times during the liquid-vapor interface equilibration in the experiment. This resulted in an under-prediction of liquid-vapor interface height for the two slowest draining velocities shown in Fig. 7. Future work could include re-running these simulations so that the initial heights are equivalent.

Tabulated values of the critical heights and vapor ingestion heights are given in Table 3 for normal gravity and Table 4 for low gravity. Note that all heights reported are in cm, and only the four slowest velocities are reported. A qualitative comparison of the vapor ingestion phenomenon is shown in Fig. 8 for normal gravity and Fig. 9 for low gravity. The CFD volume fraction contours are on the left (blue is liquid, red is vapor), and still images from the experimental video are shown on the right. The qualitative comparisons show the predicted interface shapes are in excellent agreement with the experiment. Last, a comparison between the nominal 2D-axisymmetric model and a full 3D model is given in Fig. 10, highlighting there are no 3D effects for this simulation and 2D-axisymmetric is a good assumption.

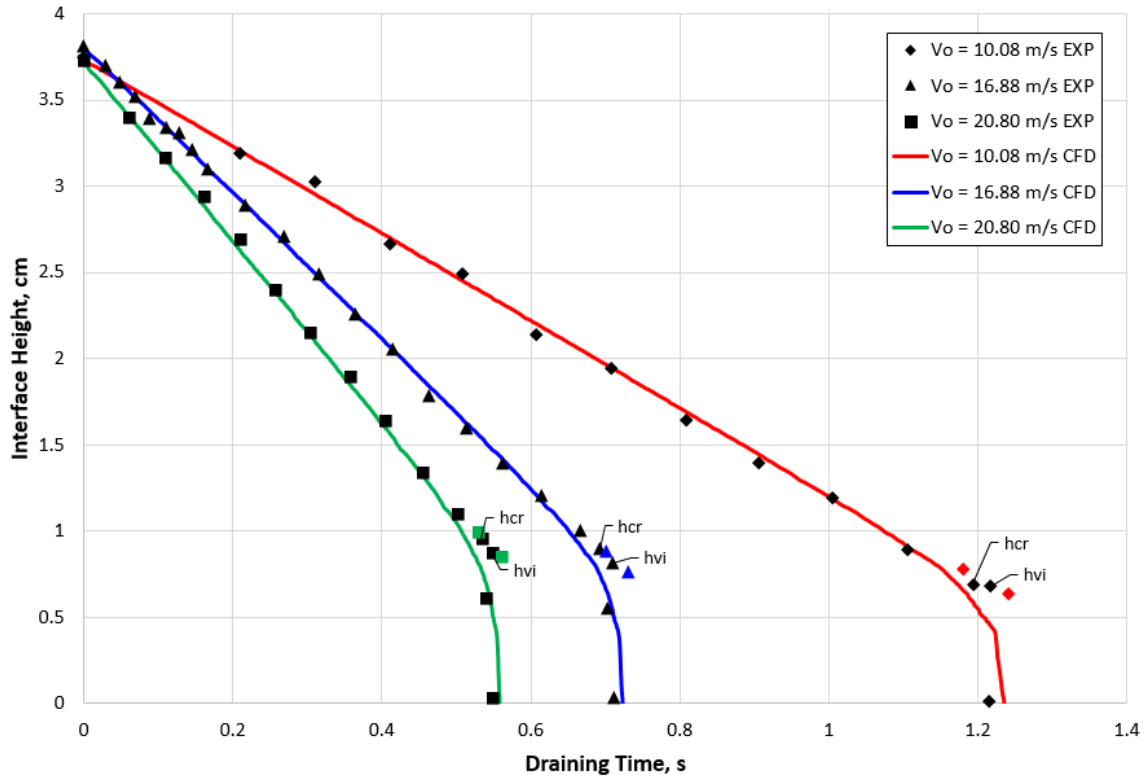


Fig. 6 Draining curve comparison, $R = 2$ cm, $r_o = 0.1$ cm, normal gravity, ethanol.

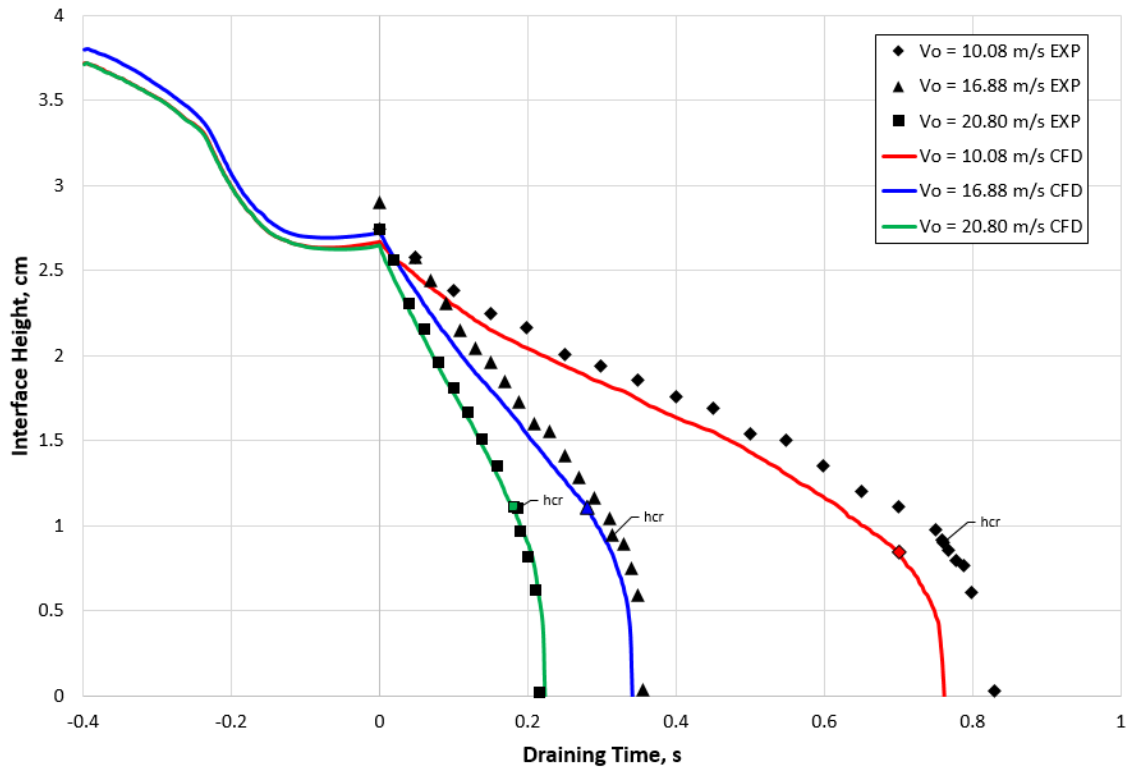


Fig. 7 Draining curve comparison, $R = 2$ cm, $r_o = 0.1$ cm, low gravity, ethanol.

Table 3 Comparison of critical and vapor ingestion heights in normal gravity (all heights in cm)

V_o , m/s	h_{cr} EXP	h_{cr} CFD	% error	h_{vi} EXP	h_{vi} CFD	% error
2	NR*	0.70	-	0.45	0.55	22.2
10.08	0.69	0.78	12.4	0.68	0.64	6.4
16.88	0.90	0.88	1.9	0.82	0.76	6.2
20.80	0.96	0.99	3.3	0.88	0.86	2.3

*NR=not reported

Table 4 Comparison of critical heights in low gravity (all heights in cm)

V_o , m/s	h_{cr} EXP	h_{cr} CFD	% error
2	0.75	0.78	4.0
10.08	0.90	0.84	6.0
16.88	0.95	1.11	15.9
20.80	1.10	1.11	1.1

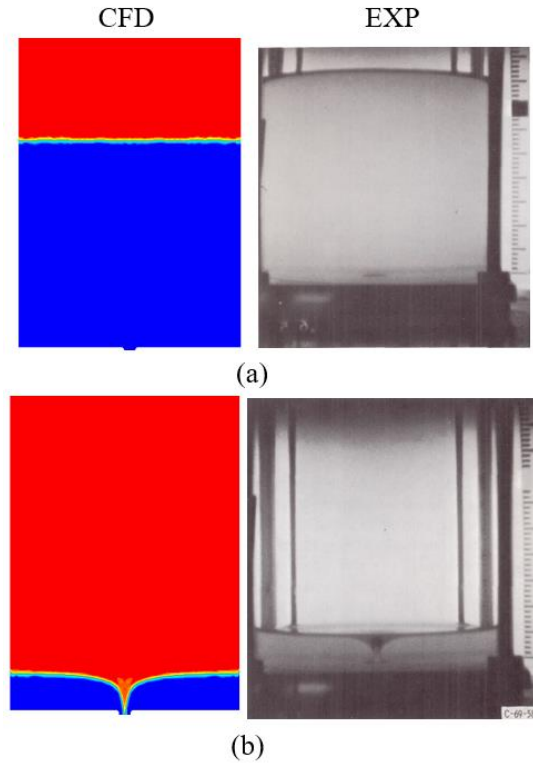


Fig. 8 Qualitative comparison of (a) initiation of draining, and (b) vapor pull-through in normal gravity for $V_o = 10.08$ m/s [3].

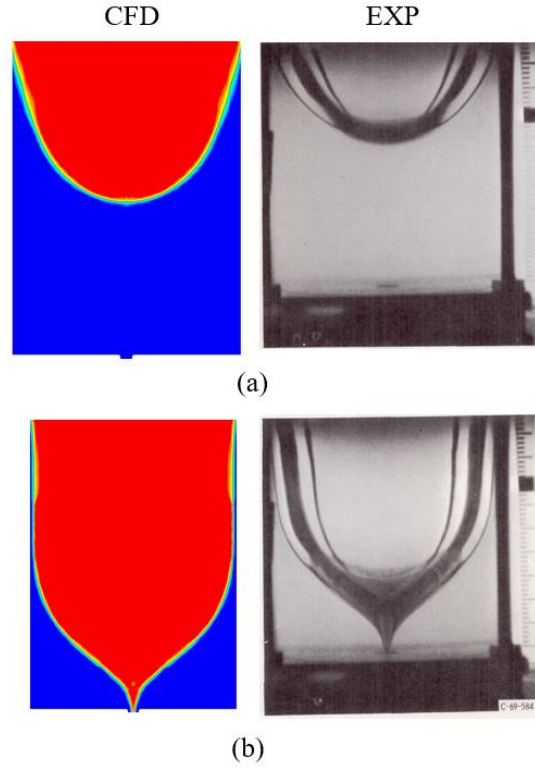


Fig. 9 Qualitative comparison of (a) initiation of draining, and (b) vapor pull-through in low gravity for $V_o = 10.08$ m/s [3].

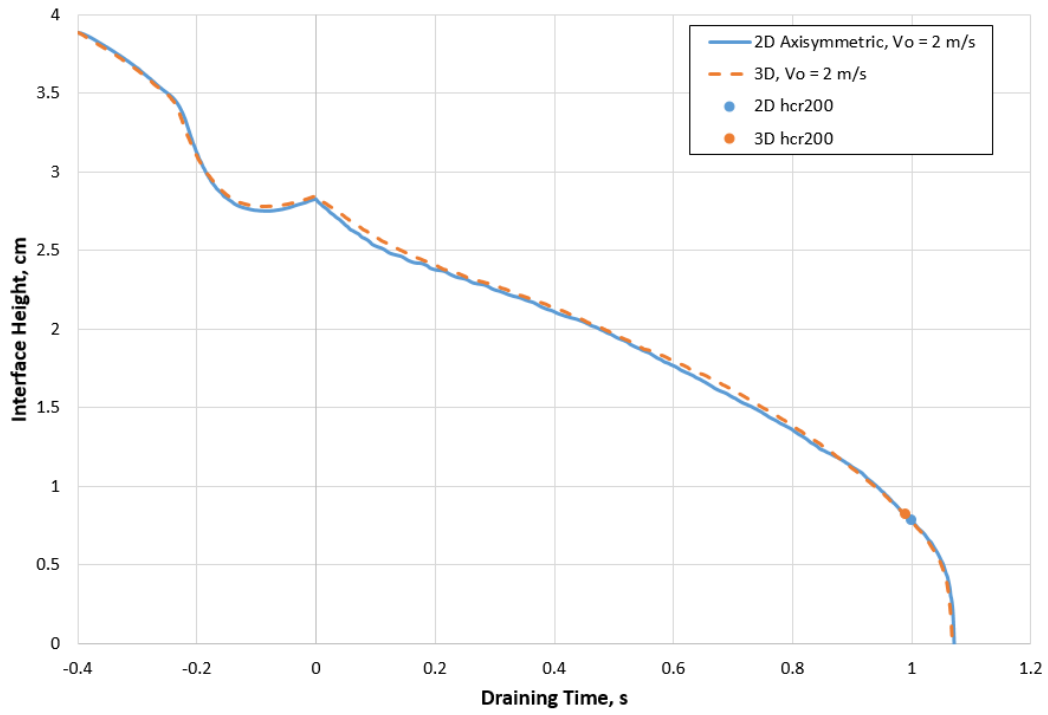


Fig. 10 Comparison between 2D-axisymmetric and full 3D CFD models.

B. Liquid Residuals in Low Gravity

For in-space propellant transfer, the most important performance parameter is the quantity of residual liquid in the tank at the time of vapor pull-through. This quantity is the untransferable propellant that is wasted and reduces efficiency of the system. As the gravity force is reduced, the residual liquid quantity increases. Similarly, as the outlet flow rate increases, the residual liquid increases. However, there exists a “critical” flow rate in which above it the residuals remain constant. This can be observed in Fig. 11, where the non-dimensional residual fraction is plotted against Weber number. The experimental results show the residuals begin leveling off around $We = 27$, corresponding to an outflow velocity of 25 m/s. Outflow velocities above this point yield constant residual values.

The CFD predictions agree well with the experimentally measured values, especially below the critical outflow velocity. Above this, the CFD results slightly under-predict the liquid residuals but still captures the asymptotic effect. One possible explanation for the discrepancy is the gravitational force used in the CFD model may not be the same as what was experienced by the test article in the drop tower tests. In Ref. [3], the authors estimated the net body force on the test article to be $10^{-5}g$. In 1969, accelerometers were not regularly implemented so an estimate was provided. Current operators of the 2.2 Second Drop Tower state that the lowest gravitational force achievable is between 0.0001g and 0.001g. Therefore, it is likely the gravitational force used in the CFD model was too high (0.001g), yielding lower residuals compared to the experiment. Another explanation is that at higher velocities, the interface becomes smeared near the outlet reducing the accuracy of the VOF model. This inaccuracy could be mitigated by using an adaptive time step or manually reducing the time step as the interface approaches the outlet.

As stated earlier, liquid residuals define the efficiency of a microgravity propellant transfer. Fig. 11 highlights the percentage of liquid that would be successfully transferred at these conditions. Only 60% of the initial liquid is transferred at the lowest outlet velocity ($We = 2.5$), diminishing to 30% at high velocities ($We > 27$). Note that Ref. [3] shows the percentage of liquid drained prior to vapor pull-through is greater than 60% for all outflow velocities in normal gravity (residual fractions all less than 0.4). This highlights the drastic effect microgravity has on liquid residuals. To make in-space propellant transfer viable, efficiencies much higher than this configuration must be attained. Methods to delay vapor pull-through and decrease liquid residuals could include: 1) increase settling acceleration, 2) decrease flow rate, and 3) baffling structures to redirect the flow near the tank drain [5-8].

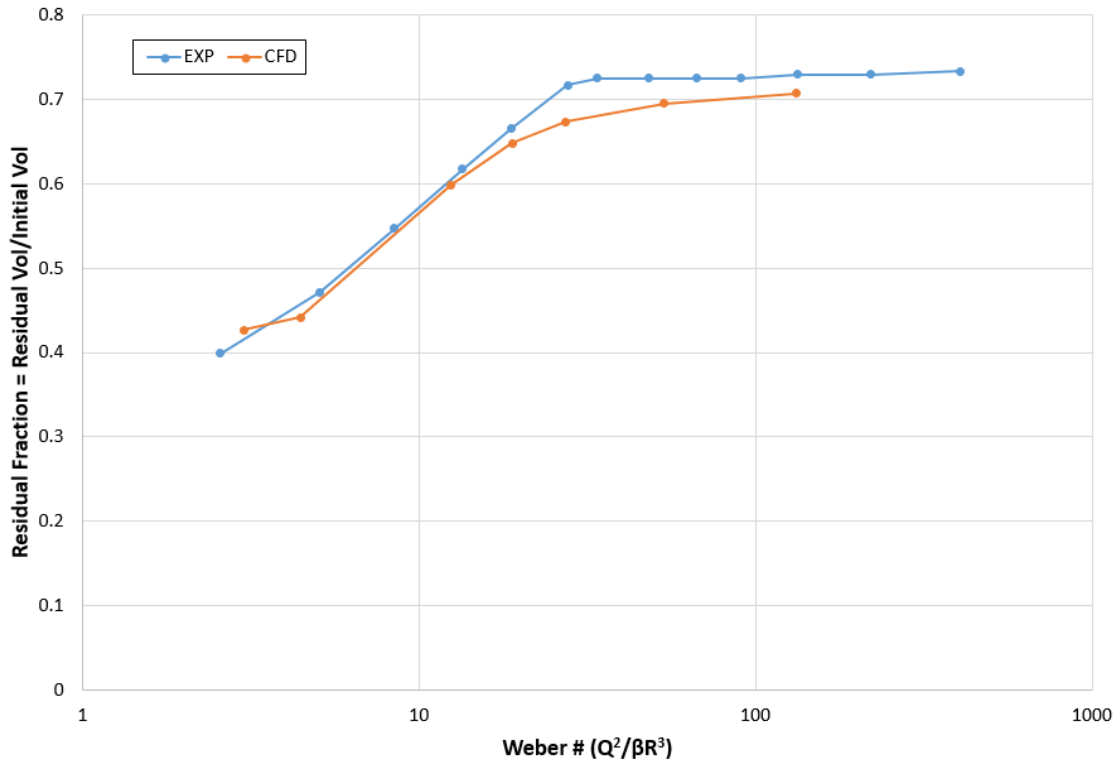


Fig. 11 Comparison of liquid residuals due to vapor pull-through.

VI. Conclusions

A computational fluid dynamics (CFD) validation study was performed for predicting vapor pull-through of a cylindrical flat-bottomed tank draining in normal and low gravity. The CFD model used the Volume-of-Fluid two-phase flow solver in commercial CFD code STAR-CCM+. An experiment by Abdalla and Berenyi [3] was selected for model validation where low gravity tank drain tests were conducted in the 2.2 Second Drop Tower at NASA Lewis Research Center (now NASA Glenn Research Center). CFD simulations were run for outlet velocities ranging from 2 to 55 m/s. The liquid-vapor interface centerline height predicted by the CFD model compared well to the experiment for all velocities considered. Critical heights and vapor ingestion heights were predicted within 25%, with most predictions accurate within 10%. CFD results showed a strong comparison to liquid residuals, capturing the asymptotic trend with respect to outflow velocity. The CFD slightly under-predicted the liquid residuals at high velocities, likely due to uncertainty in the gravitational acceleration observed in the experiment. Experimental and CFD data show that only 30 to 60% of the initial liquid is successfully drained under test conditions. To make in-space propellant transfer realizable, efficiencies must increase by employing methods to delay vapor pull-through and reduce liquid residuals. These methods may include increasing settling acceleration, decreasing flow rate, and/or implementing internal tank structures designed to delay vapor pull-through.

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