

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 low-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 Glenn Research Center 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

h	=	liquid-vapor interface height
R	=	tank radius
r	=	outlet radius
V	=	velocity

Greek

σ	=	surface tension
ρ	=	density
μ	=	dynamic viscosity
β	=	specific surface tension

Subscripts

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

I. Introduction

On-orbit fluid transfer capabilities can enable cost-effective solutions for space exploration. For example, future space missions can utilize propellant depots to sustain long-duration human and science exploration activities. However, many challenges exist with liquid transfer in a low-gravity environment. This includes: prior 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, etc. This study focuses on the behavior of the liquid-vapor interface while draining, or more specifically the vapor ingestion, or vapor pull-through, phenomenon.

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Several studies on this phenomenon 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. Gluck et al. [3] and Lubin and Hurwitz [4] both correlated the vapor ingestion height to the Froude number using experiments conducted in normal gravity. Last, Abdalla and Berenyi [5, 6] 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. This study presents Computational Fluid Dynamics (CFD) model predictions of vapor ingestion at several outflow velocities. 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.

II. Vapor Ingestion Phenomenon

The vapor ingestion phenomenon is illustrated in Fig. 1 from Ref. [5]. 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 displacement-time curve deviates from a linear slope. Shortly after, the interface accelerates toward the drain and vapor is ingested. At this time, the interface away from the drain remains relatively flat, and the height of the interface at this location is 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 surface tension force and contact angle of the fluid. 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. 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.

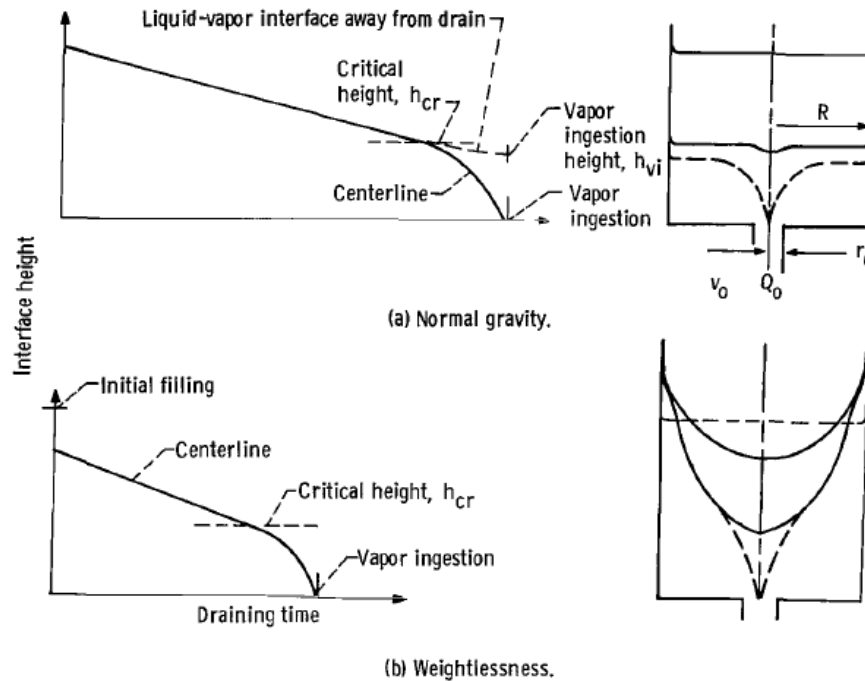


Fig. 1 Vapor ingestion or pull-through phenomenon, reprinted from Ref. [5].

III. Experimental Overview

The experiment performed by Abdalla and Berenyi [5] used acrylic plastic, cylindrical flat-bottomed tanks with a baffle to mitigate interface impingement shown in Fig. 2. The top and bottom plates were made of stainless steel. 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 rates ranged from 200 to 2000 cm/s for both normal gravity and low gravity ($<0.001 \text{ m/s}^2$).

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.

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.

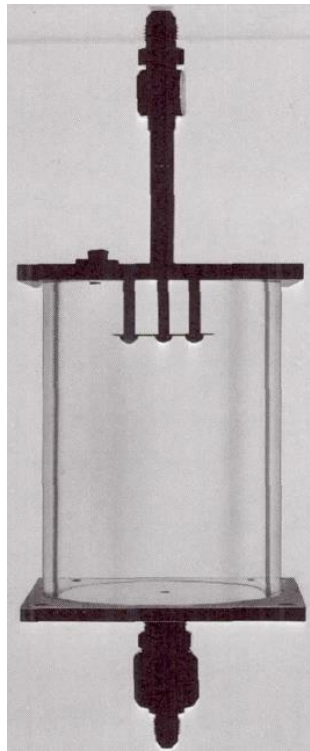


Fig. 2 Experimental test tank, reprinted from Ref. [5].

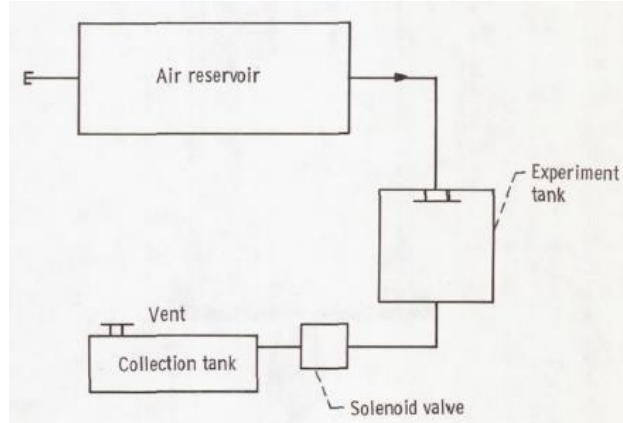


Fig. 3 Experimental flow schematic, reprinted from Ref. [5].

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

The model geometry and spatial boundary conditions are presented in Fig. 4. 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. [5]. 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 low gravity cases used a gravitational acceleration of 0.001 m/s². 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.

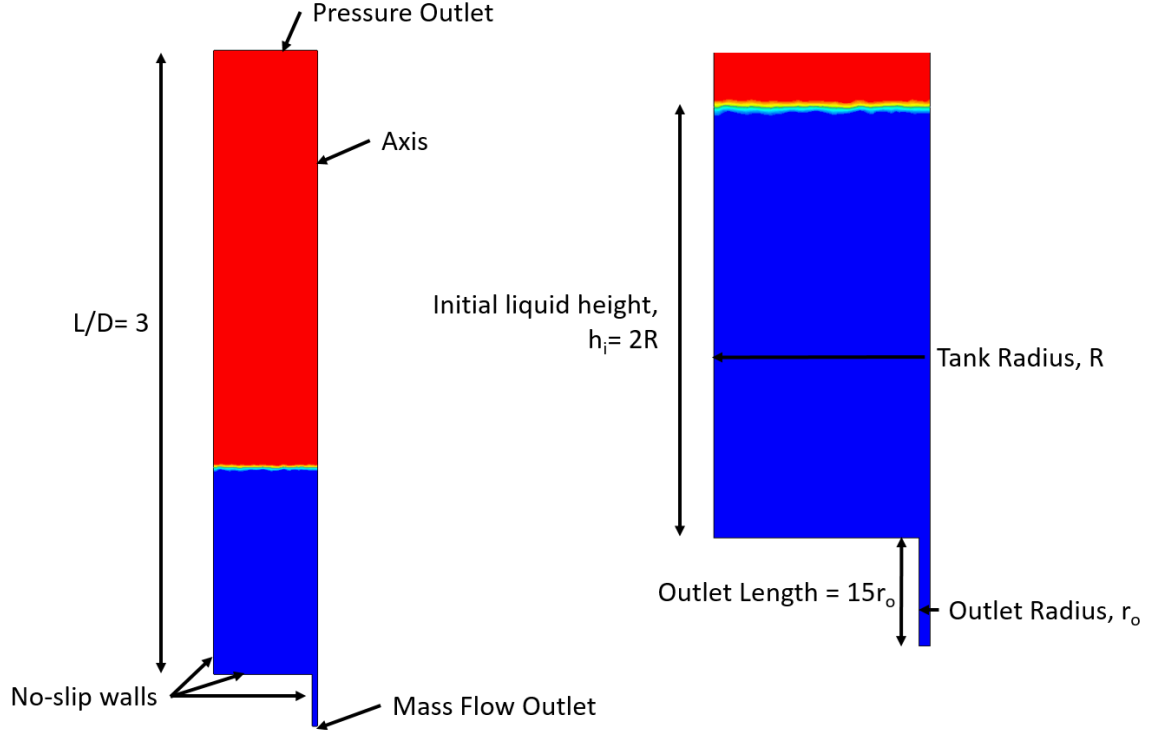


Fig. 4 Model geometry and boundary conditions.

V. Results and Discussion

Interface displacement-time draining curves were only reported for the 2 cm tank radius, 0.1 cm outlet radius for three outflow velocities using ethanol. 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.

The outflow velocities that were simulated are listed in Table 2. The three cases with experimental draining curves available were considered, and a ~ 200 cm/s condition to cover the entire range of outflow velocities tested in the experiment. Each outflow velocity was run in normal and low gravity.

Table 2 CFD case summary

Outflow Velocity, V_o (cm/s)	Tank Radius, R (cm)	Outlet Radius, r_o (cm)	Liquid
201.7	2.0	0.2	Ethanol
1008	2.0	0.1	Ethanol
1688	2.0	0.1	Ethanol
2080	2.0	0.1	Ethanol

A comparison of the draining curves for normal and low gravity are shown in Fig. 5 and Fig. 6, respectively. The experimentally determined 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 well to the experiment. For the low gravity cases, draining was initiated after 0.4 seconds of simulation time to allow the interface centerline to reach its low point. Tabulated values of the critical and vapor ingestion heights are given in Table 3 for normal gravity and Table 4 for low gravity. Last, a qualitative comparison of the vapor ingestion phenomenon is shown in Fig. 7 for normal gravity and Fig. 8 for low gravity.

In the final manuscript, more details of the model will be provided. In addition, results will be compared to correlations developed and presented in the experimental reports. Last, a full 3D analysis will be provided.

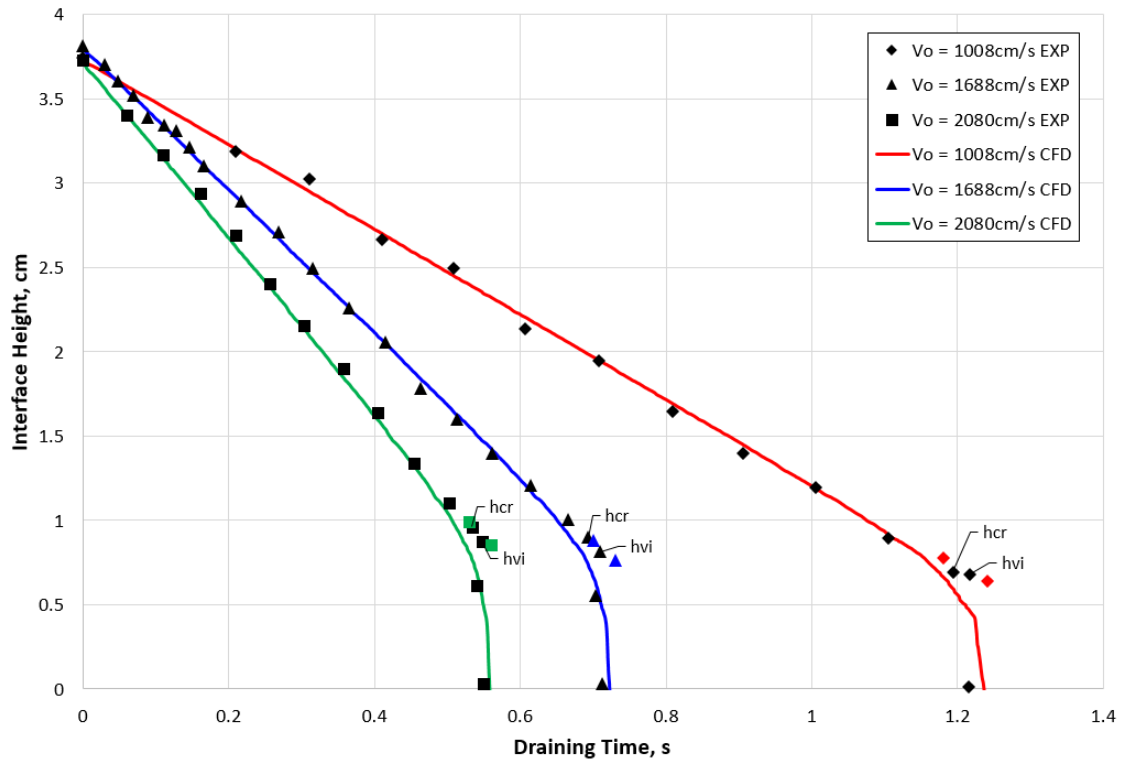


Fig. 5 Draining curve comparison, $R = 2$ cm, $r_o = 0.1$ cm, normal gravity, ethanol.

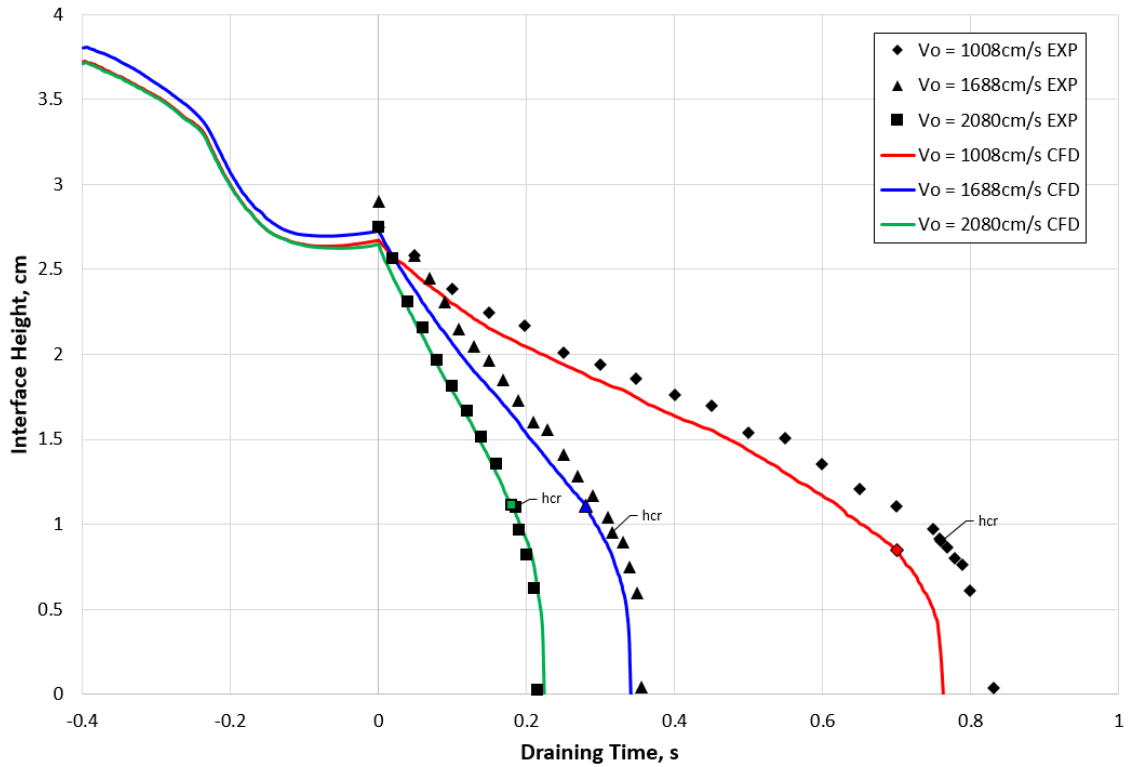


Fig. 6 Draining curve comparison, $R = 2$ cm, $r_o = 0.1$ cm, low gravity, ethanol.

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

V₀, cm/s	h_{cr} EXP	h_{cr} CFD	h_{vi} EXP	h_{vi} CFD
201.7	NR*	0.70	0.45	0.55
1008	0.69	0.78	0.68	0.64
1688	0.90	0.88	0.82	0.76
2080	0.96	0.99	0.88	0.86

*NR=not reported

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

V₀, cm/s	h_{cr} EXP	h_{cr} CFD
201.7	0.75	0.78
1008	0.90	0.84
1688	0.95	1.11
2080	1.10	1.11

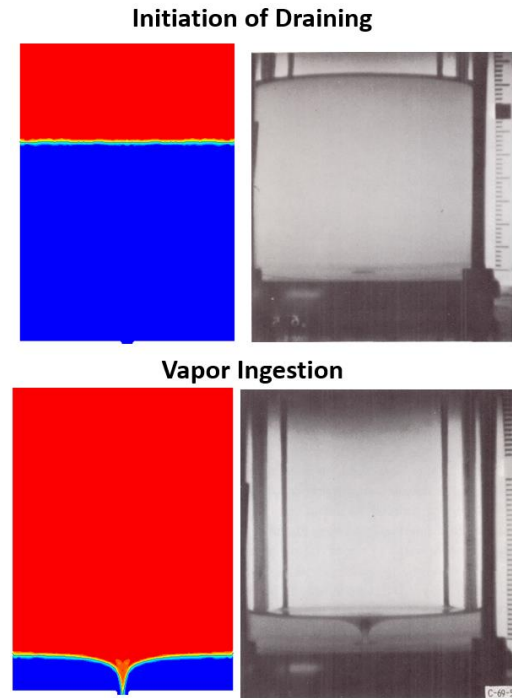


Fig. 7 Qualitative comparison of vapor ingestion phenomenon in normal gravity.

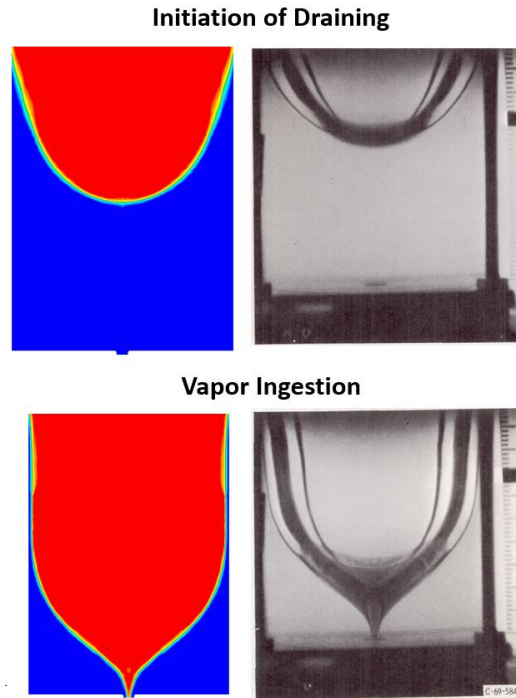


Fig. 8 Qualitative comparison of vapor ingestion phenomenon in low gravity.

VI. Conclusions

In the final paper, a comparison of residual liquid mass at vapor pull-through will be presented and discussed. In addition, the effect of an initial liquid swirl velocity on vapor pull-through will be presented.

Acknowledgments

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