White Paper

Cryogenic Experiments Using Simulant Fluids

Submitted by

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It is important to validate that simulant fluids can be representative of cryogenic applications, and that the validation of the numerical models using the data are applicable across the range of desired parameters. For example, it is of great technological interest to demonstrate the phase change phenomena associated with cryogenic fluids in low gravity (natural convection, nucleate boiling, film boiling, flow boiling, jet mixing, self-pressurization, Marangoni convection, heat pipes, etc.). However, experimentation using cryogens is very costly on existing low gravity platforms due to safety and physical limitations. The fluid physics community is therefore relying on using simulants as stand-ins for cryogens to obtain data in microgravity conditions. It has not been fully demonstrated this can be done, however. The objectives of this work would be to demonstrate the extent to which simulants can be used to model cryogens. The results can be used to streamline future ISS experiments so the resulting simulant microgravity data can be used with confidence to guide and fulfill NASA and aerospace industry cryogenic fluid management needs.

Dimensional analysis. To illustrate the complexities of scaling results, the example of using a simulant in place of a cryogen for flow boiling is discussed below. The heat transfer during flow boiling in a smooth tube is a function of many parameters, a subset of which are

$$\dot{q}'' = f\left(D, V_l, V_g, g, x, \Delta T_w, \Delta T_{sub}, \rho_l, \rho_g, \mu_l, \mu_g, \sigma, h_{fg}, k_l, k_v, c_p, \theta\right)$$

Dimensional analysis can be used to obtain the following non-dimensional groups:

$$Nu = f\left(Re, We, Bo, Fr, Ja, Ja_{sub}, Pr, \rho_l/\rho_g, \mu_l/\mu_g, k_l/k_v, x\right)$$

where

$$Nu = \frac{\dot{q}''D}{(T_w - T_b)k_l}, Re = \frac{\rho V D}{\mu}, We = \frac{\rho V^2 D}{\sigma}, Bo = \frac{g\left(\rho_l - \rho_g\right)D^2}{\sigma}, Fr = \frac{V^2}{Dg}, Ja_{sub} = \frac{c_p(T_{sat} - T_b)}{h_{fg}},$$

$$Ja = \frac{c_p(T_w - T_{sat})}{h_{fg}}, Pr = \frac{\mu c_p}{k}$$

and x=inlet quality. The Reynolds number accounts for turbulence in the flow while the Weber number accounts for instability at the liquid-vapor interface that leads to waves and drops. In microgravity, the Bond number is very small (surface tension dominates buoyancy) and the Froude number very large (inertia dominates body forces) so it is expected these can be neglected.

Suppose we wish to use FC-72 (n-perfluorohexane) as a simulant for microgravity flow boiling of a cryogen. To match the Reynolds and Weber numbers for the two fluids, it is easily shown that the diameter and mass flux ($G=\rho V$, kg/m^2-s) ratios must be $\frac{D_2}{D_1} = \frac{\rho_1}{\rho_2}\frac{\mu_2^2}{\mu_1^2}\frac{\sigma_1}{\sigma_2}$ and $\frac{G_2}{G_1} = \frac{\rho_2}{\rho_1}\frac{\mu_1}{\mu_2}\frac{\sigma_2}{\sigma_1}$. The subcooling Jakob number (Ja_{sub}) can be matched by varying the fluid inlet temperature, the Jakob number can be matched by varying the tube wall temperature, and the inlet flow quality x can be set by varying the heat input to the fluid in a preheater. The Prandtl number and property ratios are based on fluid properties, however, and cannot be manipulated.

To illustrate how FC-72 (the proposed simulant for FBCE) can be used to simulate cryogen flows, assume saturated cryogens flow within a 1 cm diameter tube 100 K above the saturation temperature with G=100 kg/m^2-s. The fluid properties for three cryogens (LN_2 at 1 bar, LO_2 at 3 bar, and LH_2 at 3 bar) are listed in Table 1–the elevated pressure for LO_2 and LH_2 are representative of the pressures in cryogenic rocket engines. The test conditions for FC-72 needed to match the three cryogen flows are shown in Table 2. For LN_2, Re, We, and Ja, can be matched and the density and viscosity ratios are also quite close. It should be noted that although the mass flux of FC-72 is low (60 kg/m^2-s), the mass flow rate is much larger than FBCE can currently provide (40 g/s) due to the large tube diameter (6.6 cm). The wall temperature difference for FC-72 of 80°C needed to simulate flow of LN_2 into a tube at room temperature is close to the upper limit of the proposed experiment, so data in this regime may be limited. The Prandtl number for FC-

72 (12.4) is five times larger than for LN_2 (2.5)–this cannot be matched and will require simulation to investigate the dependence of Nu on Pr. LO_2 can also be simulated reasonably well with FC-72. The density ratio at 3 atm is off by 1.8, but the pressure in the FC-72 test section can be lowered to about 0.56 bar (T_{sat}=40°C) get them to match. As with LN_2, the tube diameter and mass flow rates are quite high. Quantum fluids like LH_2 cannot be simulated well using FC-72. The mass flow rate needs to be impractically high due to the very large Reynolds number, the wall-to-fluid temperature difference is large, and there is a large mismatch between the Prandtl number, density ratio, and viscosity ratio. In pool boiling studies, tank natural convection (due to residual gravity) may be also prove to be an important parameter. Since the relevant scaling parameters are the Gr or Ra numbers that depend on the characteristic length of the tank raised to the 3rd power, matching can easily be achieved through the ratios of the tank diameters. In summary, FC-72 can reasonably serve as a simulant for LN_2 and LO_2 within the limitations set by the experimental capabilities. FC-72 cannot be used to simulate LH_2 due to the large difference in fluid properties, but numerical simulations might be used once they are validated on other fluids.

Table 1: Properties of FC-72 and various cryogens at saturation.

	FC-72 (1 bar)	**LN_2 (1 bar)**	**LO_2 (3 bar)**	**LH_2 (3 bar)**
Liquid density (kg/m^3)	1680	806	1080	65
Vapor density (kg/m^3)	11	4.5	13	3.7
Liquid dynamic viscosity (mPa-s)	0.64	0.163	0.15	0.0096
Vapor dynamic viscosity (mPa-s)	0.013	0.0055	0.0065	0.0014
Thermal conductivity (W/m-K)	0.057	0.135	0.13	0.12
Liquid Heat capacity (J/kg-K)	1100	2045	1748	12200
Surface tension (mN/m)	10	8.9	10.3	1.3
Enthalpy of vaporization (kJ/kg)	88	199	200	410
Saturation temperature (K)	329	77	102	25

Table 2: Non-dimensional quantities for various cryogens in Table 1 flowing in a 1 cm ID tube at G=100 kg/m^2-s and 100 K superheat. The corresponding conditions for FC-72 are listed.

	LN_2 (1 bar) and FC-72		**LO_2 (3 bar) and FC-72**		**LH_2 (3 bar) and FC-72**	
	LN2	FC-72	LO2	FC-72	LH2	FC-72
Tube diameter (cm)	1	6.6	1	12	1	22
Mass flux, G (kg/m^2-s)	100	60	100	354	100	298
T_w-T_{sat} (K)	100	80	100	70	100	238
Mass flow rate (g/s)	7.8	204	7.8	403	7.8	11,322
Reynolds number	6130	6170	6670	6670	104,200	102,400
Weber number	14	14	9.0	9.0	1183	1163
Jakob number	1.0	1.0	0.87	0.87	3.0	3.0
Prandtl number	2.5	12.4	1.96	12.4	0.94	12.4
Density ratio (ρ_l/ρ_g)	179	153	85	153	18	153
Viscosity ratio (μ_l/μ_g)	30	49	23	49	7	49

Table 3: Thermal effusivity ratio for the cryogens in Table 1 vs. 316 stainless steel and sapphire.

	FC-72 (1 bar)	**LN_2 (1 bar)**	**LO_2 (3 bar)**	**LH_2 (3 bar)**
e_{316SS}/e_{fluid}	25	17	16	25
$e_{sapphire}/e_{fluid}$	27	18	17	28

Another parameter that needs to be matched for transient quenching of transfer lines is the wall-to-fluid thermal effusivity ratio, $e = \sqrt{\rho c k}$. The effusivity ratio between two wall materials (316 stainless steel and sapphire) and the cryogens is given in Table 3. The ratio between 316 stainless steel and FC-72 is about 50% higher than for LN_2 and LO_2 but matches that for LH_2. Simulation will thus be required to investigate the dependence on wall properties.

FBCE utilization. Suppose it is desired to use FBCE hardware to simulate cryogenic flow boiling. Modules that can be used with little or no modification include the Fluid Systems Modules (Upper and Lower), Bulk Heater Module, Remote Data Acquisition Modules, and the associated hardware including SAMS. The existing FBCE camera is capable of 2000 fps and may be reutilized. Void fraction sensors could be added before and after the test section. Since the FBCE pump can only provide 40 g/s, data at equivalent flow conditions for cryogens will be similarly limited. The pump flow rate, preheater power (currently 1540 W), and condenser will be increased to the maximum feasible so cryogenic quenching data under more realistic conditions can be obtained. Limitations on the heater temperature will put a limit on the Jakob number that can be attained.

ZBOT utilization. The Zero-Boil-Off Tank experimental hardware and diagnostics can be used to study self-pressurization, pool boiling during self-pressurization caused by localized hotspots, depressurization by subcooled liquid jet mixing, and cavitation during depressurization. The experimental rig provides a transparent optical quality test cell that can accommodate any low boiling point phase change fluid. The tank is isolated in a temperature controlled vacuum jacket. It is equipped with wall mounted strip heaters used for self-pressurization and a thermally controlled jet flow supported by a Fluid System Unit and a screened Liquid Acquisition Device (LAD) that ensures only liquid is extracted, thermally conditioned and pumped back into the tank during depressurization cycles. A bellowed reservoir and membrane contactor unit allow for degassing the fluid as needed. The ZBOT diagnostic rig can provide white light imaging, Particle Imaging Velocimetry (PIV), and a full field Quantum Dot Thermometry (QDT). There are limitations on the heater and camera that may need to be upgraded for boiling studies.

Parallel cryogenic implementation. A parallel cryogenic implementation could be made either external to the International Space Station or as a free flying payload that is scaled to the FBCE and ZBOT utilizations (or other utilizations) via the non-dimensional numbers shown above for flow boiling and other non-dimensional numbers for ZBOT that will be mostly similar to the ones listed for FBCE but may also additionally include the Grashof (Gr), Fourier (Fo), and Euler (Eu) or Cavitation (Cn) numbers. While such options have been proposed in the past, including the collaborative activity FROST (Bruns, 2020) between NASA and DLR, the experiment did not go the final step of scaling between other simulant fluid based orbital experiments and ultimately were not funded. It should be possible to include both storage and transfer operations in a cryogenic fluid experiment implementation with visualization both in the transfer line and in a receiver tank as was proposed on FROST. Similar instrumentation would be required on the cryogenic system as the simulant fluid systems, including temperature, pressures, mass flow (void fraction), quantity, and imaging sensors. The imaging system frame rates may be somewhat limited due to data rates if a free flying implementation was chosen. While the storage durations in the receiver tank will be limited due to heating to allow the visualization, the science benefit of the visualization is of utmost importance to understanding what is going on in the experiment. It is important to realize that the system will not be of large scale and comparison with other experiments, such as the recently funded STMD Tipping Point demonstrations (2) would provide the necessary scaling analysis between this experiment implementation and large flight applications.

Computational and Numerical Aspects. The systems should be sized such that the non-dimensional overlap is present, but at only a fraction of the full operational band of the system. This allows for wider extension of the models and validation as well as cross validation between the two experiments and those models. Cross validation would be focused on key overlaps in the experiments and predetermined non-dimensional numbers. It will not be possible to match all non-dimensional numbers and as such, it will be key to extrapolate from the validated models that can numerically cross size scale and fluid types to gather information from these other non-dimensional numbers.

Conclusions. The integrated effort of simulant and cryogenic experimental systems can allow for the results that are more than a sum of the parts. By validating the assumption of scalability, the results from ISS experiments can be more freely and widely used in the development of NASA and Industry Exploration missions.

References:

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