Design of a low gravity vane liquid acquisition device for cryogenic liquids using first principles modeling, CFD assessment, and scale model ground testing techniques

Mark Wollen, IES
Chris Ostoich, ATA

Presented By
Mark Wollen

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Abstract

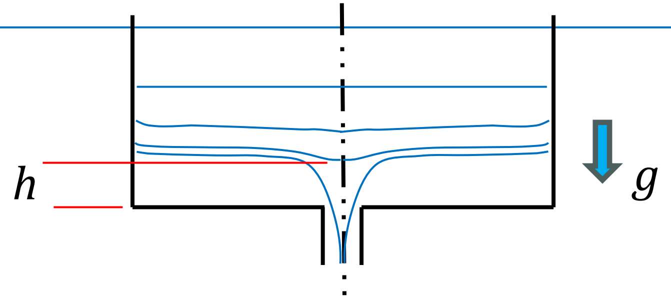
A methodology for designing a vane-type liquid acquisition device using a first-principles approach is described, followed by detailed modeling of device performance using CFD and scale model ground testing techniques. The work is motivated by the desire for a simple device to reduce vapor pullthrough residuals in cryogenic tanks when draining at fairly high flow rates in a low gravity (but not zero gravity) environment. The high flow rates, in addition to thermal management difficulties with cryogens, make a screen type retention device less suitable for this application. A smaller, partial contact, vane type device is better suited for this job; where the low gravity level is sufficient to generally locate the liquid towards the outlet, while the vane device takes advantage of surface tension to delay the surface dip formation caused by inertial forces of the accelerating liquid as it approaches the tank outlet. The "semi-quantitative" first principals approach provides insight into how gravitational, inertial, and surface tension forces interact in such a device, and allows general sizing and vane spacing of the device to be determined prior to extensive analytical effort. CFD and model test results are then used to fine-tune the design. The present effort uses STAR-CCM+ for the CFD analysis, although other codes with good liquid-vapor interface and surface tension modeling capabilities could also be used. Effects of thermal gradients due to any heat leakage to the vane structure is also considered, as this could adversely impact vane performance with cryogenic liquids.

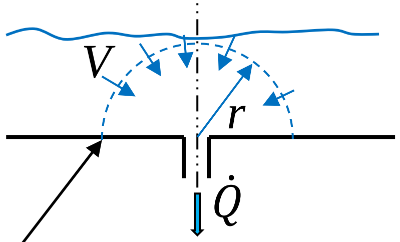
Vapor ingestion in a draining tank

- **Gravity** (body) forces settle liquid to aft region of tank and act to maintain a flat liquid surface
- **Inertial** forces increase near outlet and act to draw down the liquid surface
- At some level, **inertial forces overwhelm body forces**, a dip forms, and vapor is drawn down through the surrounding liquid and into the tank outlet

Classic analytical result by Lubin and Springer, Jol. of Fluid Mechanics, Sept 1967:

$$h = 0.69 \left[\frac{\dot{Q}^2}{g} \right]^{\frac{1}{5}}$$





Hemispherical surface of constant velocity around fluid sink

Froude number, in terms of volumetric flow rate

Or, normalizing with respect to some arbitrary length, l:

$$\frac{h}{l} = 0.69 \left[\frac{\dot{Q}^2}{g l^5} \right]^{\frac{1}{5}}$$

- **Extensively validated**
- **Extremely accurate over huge range of Froude number**
- **Ignores surface tension and viscosity**

A look at forces acting on dissimilar phases of fluid (e.g., a bubble)

Inertial forces acting on a roughly spherical bubble:

$$F_{inertia} \approx P_{dyn} \cdot A_x \approx \frac{1}{2}\rho_l V^2 \cdot \frac{\pi}{4} l^2$$

Gravity (buoyancy) forces acting on a roughly spherical bubble:

$$F_{gravity} \approx Density\ dif \cdot g \cdot Vol \approx (\rho_l - \rho_g) \cdot g \cdot \frac{1}{6}\pi l^3$$

Surface tension forces acting on a roughly spherical bubble:

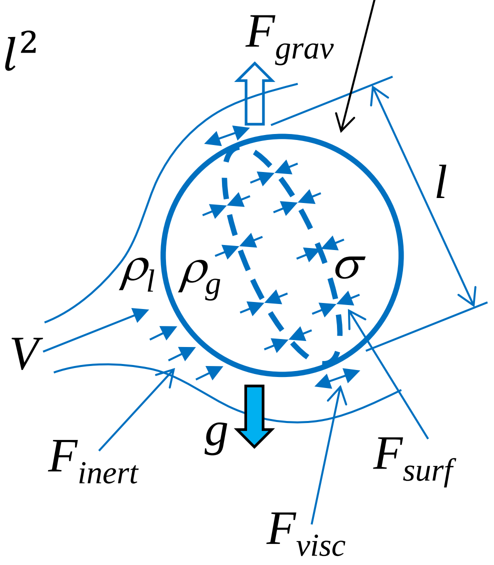
$$F_{surface} \approx surface\ tension \cdot circumf \approx \sigma \cdot \pi l$$

Viscous forces acting on a roughly spherical bubble:

$$F_{viscous} \approx viscosity \cdot vel\ grad \cdot A_x \approx \mu \cdot \frac{V}{l} \cdot \frac{\pi}{4} l^2$$

Note: $vel\ grad \approx \frac{V}{l}$ for estimating viscous force is arguably reasonable for laminar boundary layer around a sphere (Blasius, et.al.)

Roughly spherical bubble, l ~ d



Note that:

F_{inert} - Disruptive

F_{grav} , F_{surf} – Cohesive

F_{visc} - Can be either (delaying either disruptive or cohesive progression)

Note that above apply to either a vapor bubble or a liquid droplet

Derivation of magnitude-meaningful dimensionless groups

Froude number: $$Fr = \frac{F_{inertia}}{F_{gravity}} = \frac{\frac{1}{2}\rho_l V^2 \frac{\pi}{4} l^2}{(\rho_l - \rho_g) g \frac{1}{6}\pi l^3} = \frac{3}{4}\frac{V^2}{g\left(1 - \frac{\rho_g}{\rho_l}\right) l}$$

- If Fr>>1, inertial forces dominate over gravitational forces
- Etc. for below

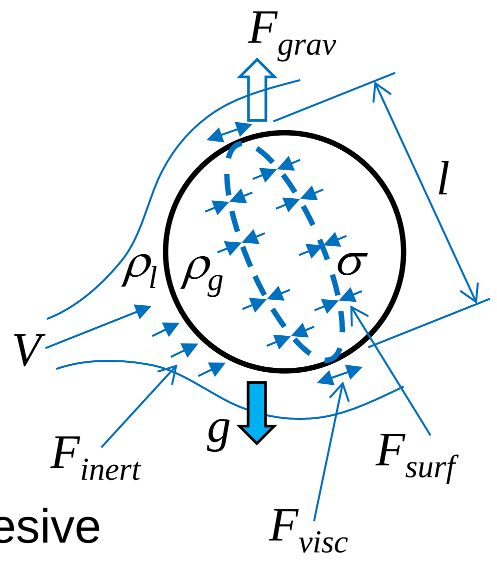
Bond number: $$Bo = \frac{F_{gravity}}{F_{surface}} = \frac{(\rho_l - \rho_g) g \frac{1}{6}\pi l^3}{\sigma \pi l} = \frac{1}{6}\frac{\rho_l\left(1 - \frac{\rho_g}{\rho_l}\right) g\, l^2}{\sigma}$$

Reynolds number: $$Re = \frac{F_{inertia}}{F_{viscous}} = \frac{\frac{1}{2}\rho_l V^2 \frac{\pi}{4} l^2}{\mu \frac{V}{l}\frac{\pi}{4} l^2} = \frac{1}{2}\frac{\rho_l V\, l}{\mu}$$

Weber number: $$We = \frac{F_{inertia}}{F_{surface}} = \frac{\frac{1}{2}\rho_l V^2 \frac{\pi}{4} l^2}{\sigma \pi l} = \frac{1}{8}\frac{\rho_l V^2 l}{\sigma}$$

Weber number redundant: $We = Bo \cdot Fr$

(But still useful for assessment of relative forces)



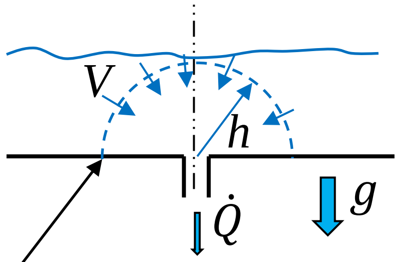
F_{inert} - Disruptive
F_{grav} , F_{surf} – Cohesive
F_{visc} - Can be either

When any of these groups are near 1, relative forces roughly balance

Relative fluid forces in a draining tank

- **Let's apply the relative force balance technique to a draining tank**

$$V = \frac{\dot{Q}}{2\pi h^2}$$

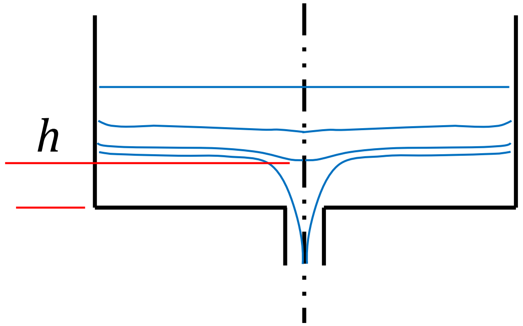


Hemispherical surface of constant velocity around fluid sink

$$F_{inertia} \approx P_{dyn} \cdot A_x \approx \frac{1}{2}\rho_l V^2 \cdot 2\pi h^2 = \frac{1}{2}\rho_l \left(\frac{\dot{Q}}{2\pi h^2}\right)^2 \cdot 2\pi h^2 = \frac{1}{4\pi}\rho_l \frac{\dot{Q}^2}{h^2}$$

$$F_{gravity} \approx Density \cdot g \cdot Vol \approx \rho_l \cdot g \cdot \frac{2}{3}\pi h^3$$

$$Fr = \frac{F_{inertia}}{F_{gravity}} = \frac{\frac{1}{4\pi}\rho_l \frac{\dot{Q}^2}{h^2}}{\rho_l \cdot g \cdot \frac{2}{3}\pi h^3} = \frac{3}{8\pi^2}\frac{\dot{Q}^2}{g\, h^5}$$



Set Fr = 1 and solve for h:

$$h = \left[\frac{3}{8\pi^2}\frac{\dot{Q}^2}{g}\right]^{\frac{1}{5}} = 0.52\left[\frac{\dot{Q}^2}{g}\right]^{\frac{1}{5}}$$

Compare our order-of-magnitude result with previous Lubin and Springer result

Normalize with respect to arbitrary length, *l*

$$\frac{h}{l} = 0.52\left[\frac{\dot{Q}^2}{g l^5}\right]^{\frac{1}{5}}$$

OoM result

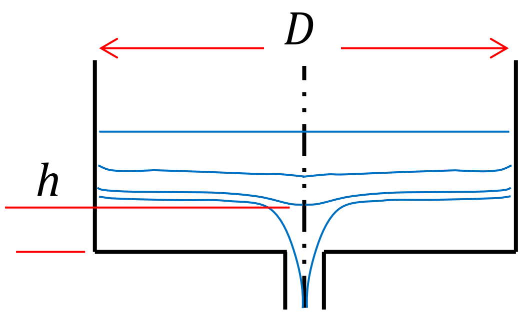
$$\frac{h}{l} = 0.69\left[\frac{\dot{Q}^2}{g l^5}\right]^{\frac{1}{5}}$$

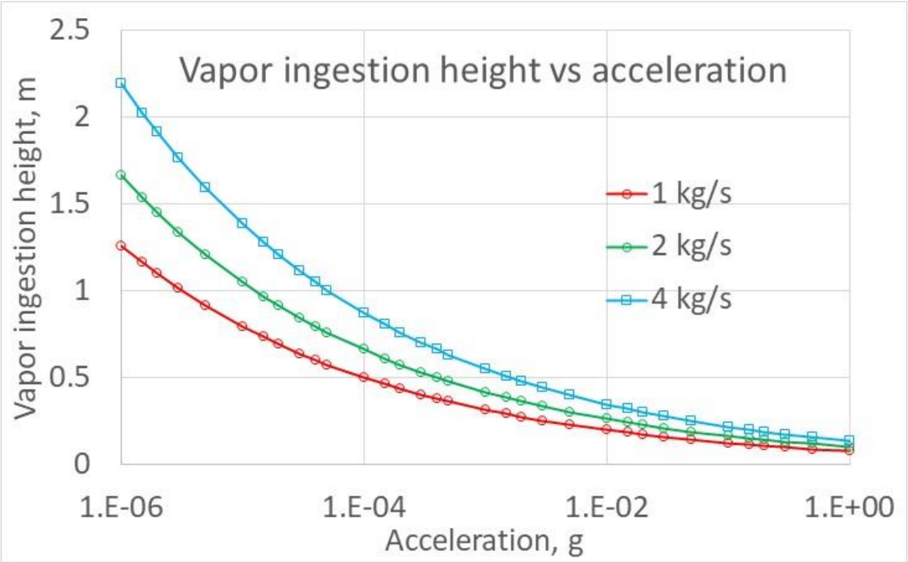
"Exact" result

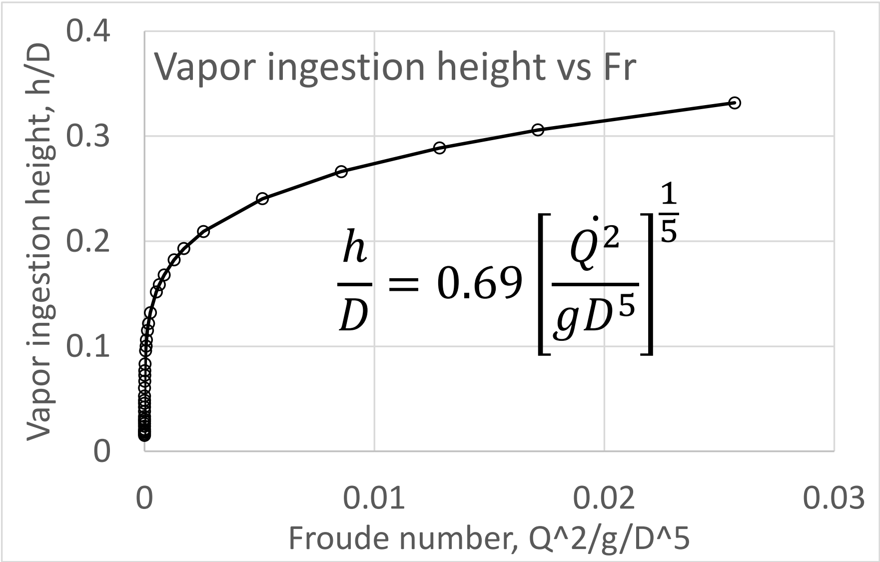
Lubin and Springer results for a 2.8 m diameter liquid hydrogen tank, 1 – 4 kg/s flow rate, and 10^{-6} – 1 g acceleration

$$\frac{h}{D} = 0.69\left[\frac{\dot{Q}^2}{gD^5}\right]^{\frac{1}{5}}$$

Where: $$Fr' = \frac{\dot{Q}^2}{gD^5}$$







- Low vapor ingestion residuals at typical main engine acceleration levels (~ 1 g)
- Residuals become very large if attempting to extract liquid at milli-g levels (e.g. in-space chill-down conditioning or propellant transfer)

Above correlation ignores surface tension and viscous effects

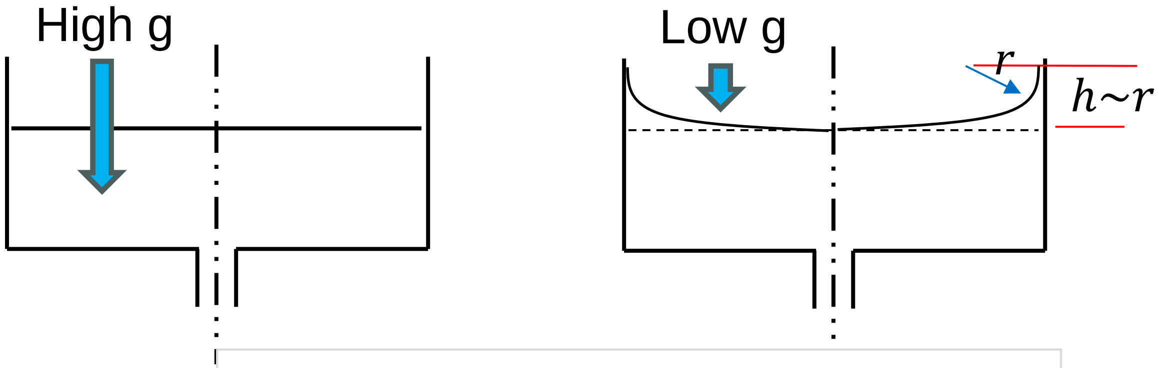
Surface tension effects at low gravity levels

- At very low gravity levels, surface tension forces might become significant…
- What does surface tension do, **prior to** draining?

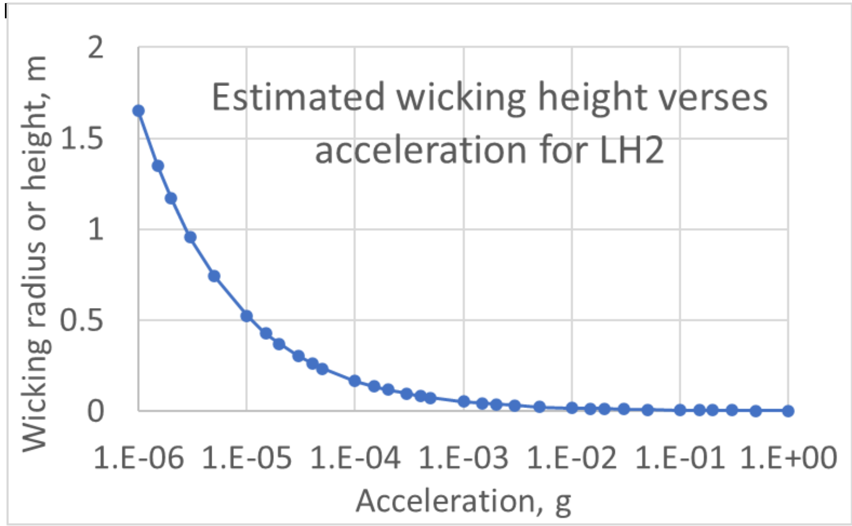
Order of magnitude force balance between gravity and surface tension:

$$Bo = \frac{F_{gravity}}{F_{surface}} = \frac{\Delta P_{gravity}}{\Delta P_{surface}} = \frac{\rho_l g\, r}{\sigma/r} = \frac{\rho_l\, g\, r^2}{\sigma}$$

$$Bo \equiv 1 \Rightarrow r = \sqrt{\frac{\sigma}{\rho_l\, g}}$$



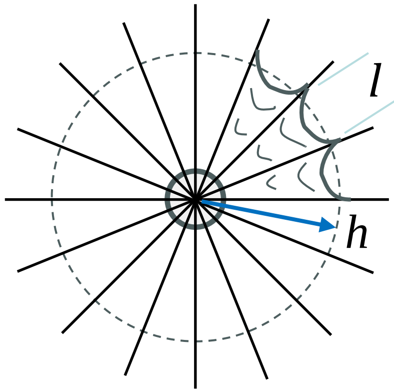
- Above 10-3 g - Relatively flat surface for a large tank
- Below 10-4 g – Wicking up wall approaches 1 meter
- In agreement with more sophisticated analytical models

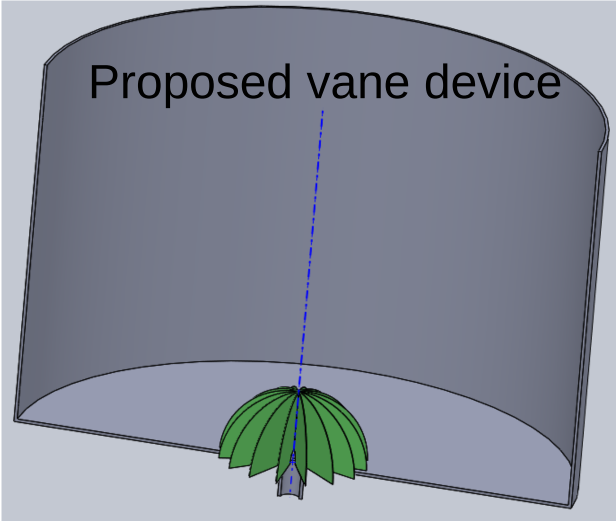


Surface tension effects at low gravity levels

- Can surface tension be used to help liquid extraction, while draining?
- Consider radial vanes over outlet

Top view of vanes showing gap, l, at distance, h, from outlet





Vane gap at 45 deg off-axis:

$$l_{vane\ act} = h\frac{2\pi}{N}\sin\left(\frac{\pi}{4}\right)$$

Order of magnitude force balance between inertia and surface tension:

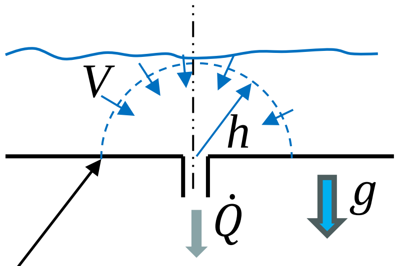
$$We = \frac{F_{inertia}}{F_{surface}} = \frac{Dyn\ Press \cdot A_x}{surf\ tens\ \Delta P \cdot A_x} = \frac{\frac{1}{2}\rho_l V^2 \cdot l^2}{\frac{\sigma}{l/2} \cdot l^2} = \frac{1}{4}\frac{\rho_l V^2 l}{\sigma}$$

Set $We \equiv 1$ and solve for l:

$$l = \frac{4\sigma}{\rho_l V^2}$$

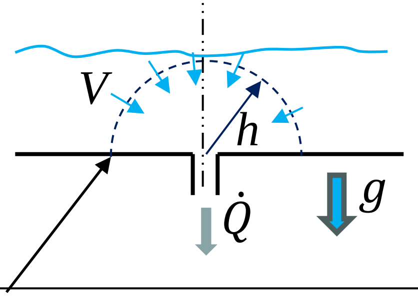
Invoke hemispherical surface to obtain V

$$V = \frac{\dot{Q}}{2\pi h^2}$$



Hemispherical surface of constant velocity around fluid sink

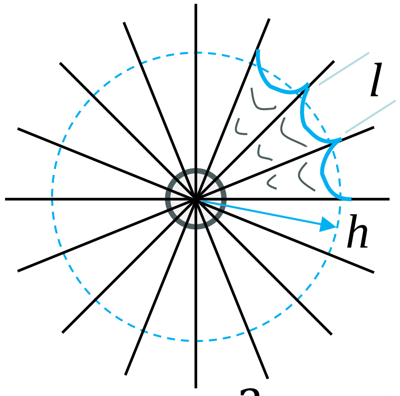
Results of order of magnitude vane sizing analysis



Hemispherical surface of constant velocity around fluid sink

$$V = \frac{\dot{Q}}{2\pi h^2} \qquad l = \frac{4\sigma}{\rho_l V^2}$$

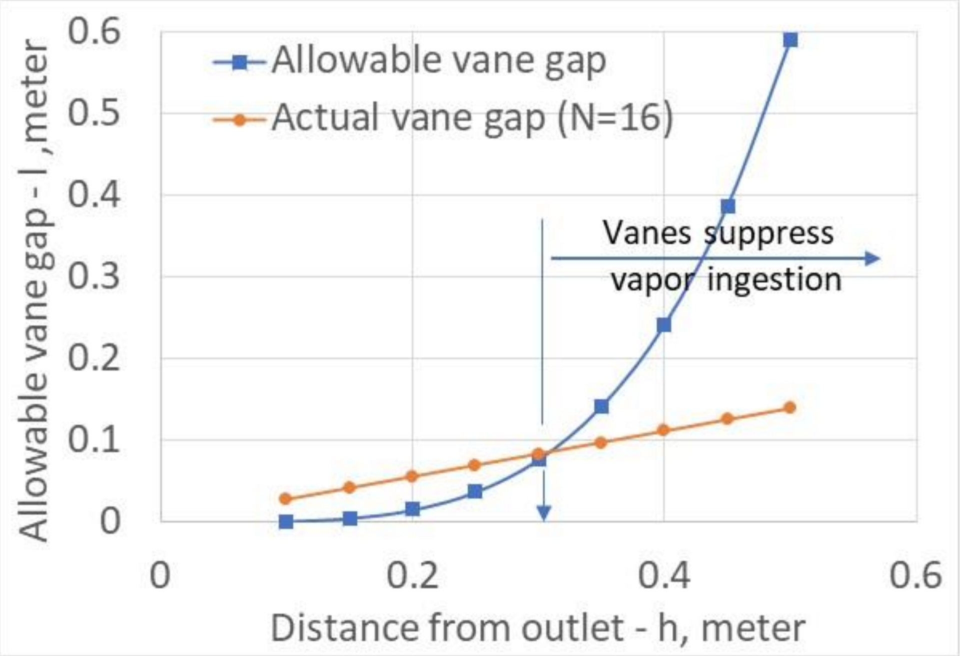
Top view of vanes showing gap, l, at distance, h, from outlet



$$l_{vane\ act} = h\frac{2\pi}{N}\sin\left(\frac{\pi}{4}\right)$$

Desired We:	1	# vanes N:	16
Distance from outlet	Local velocity	Allowable vane gap	Actual vane gap
m	m/s	m	m
0.1	0.33719	0.00094	0.02777
0.15	0.14986	0.00478	0.04165
0.2	0.08430	0.01511	0.05554
0.25	0.05395	0.03688	0.06942
0.3	0.03747	0.07647	0.08330
0.35	0.02753	0.14168	0.09719
0.4	0.02107	0.24169	0.11107
0.45	0.01665	0.38715	0.12496
0.5	0.01349	0.59007	0.13884

Results for LH2 (σ = 0.0019 N/m, ρ = 70.8 kg/m3) draining at 1.5 kg/s

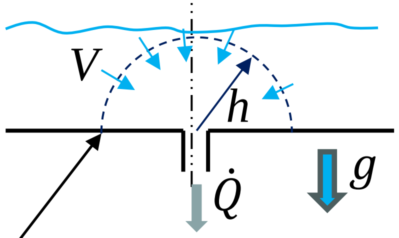


- For radial vanes, actual gap increases linearly with distance from outlet
- Allowable gap increases with 4th power of distance from outlet

- Shown vane design should allow tank to be drained to h < 0.3 m
- Lubin and Springer result (without vanes) is 1 - 1.5 m for 10^{-5} – 10^{-6} g

Alternate We derivation for vane sizing analysis

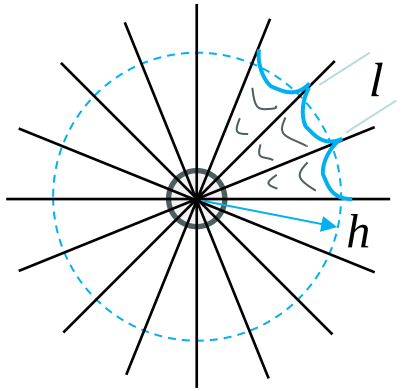
- We can also write We in terms of a total volumetric flow rate, as we did with Fr, and use vane gap relationship to put everything in terms of h



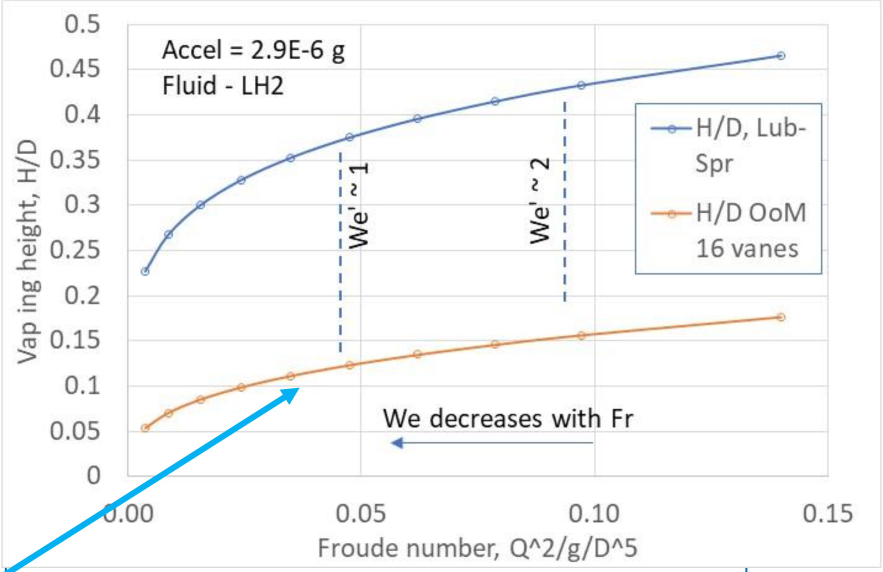
Hemispherical surface of constant velocity around fluid sink

$$V = \frac{\dot{Q}}{2\pi h^2}$$

$$l = h\frac{2\pi}{N}\sin\left(\frac{\pi}{4}\right)$$



$$We = \frac{F_{inertia}}{F_{surface}} = \frac{1}{4}\frac{\rho_l V^2 l}{\sigma} = \frac{1}{4}\frac{\rho_l \left(\frac{\dot{Q}}{2\pi h^2}\right)^2 h\frac{2\pi}{N}\sin\left(\frac{\pi}{4}\right)}{\sigma} = \frac{\sin\left(\frac{\pi}{4}\right)}{8\pi N}\frac{\rho_l \dot{Q}^2}{\sigma h^3}$$



Note similarity to correlation with Fr (where gravity dominates, rather than surface tension)

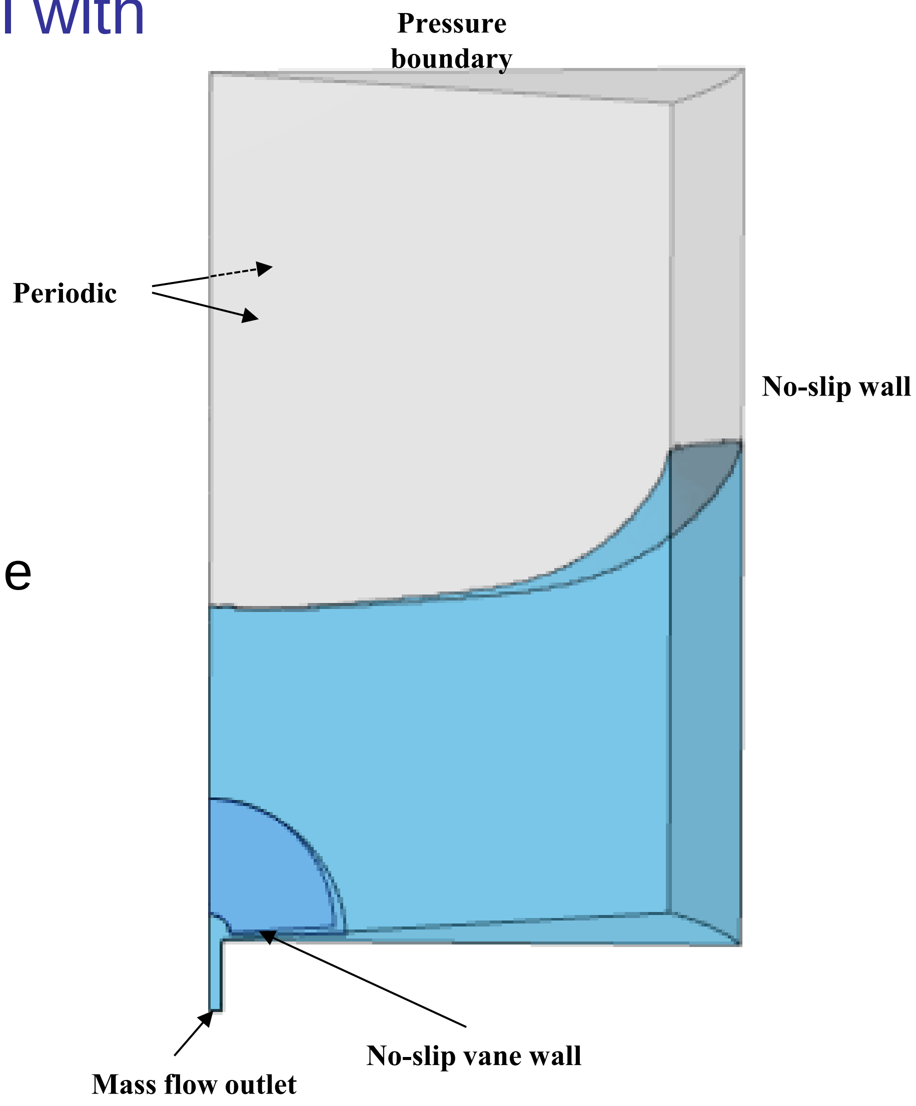
Set $We \equiv 1$ and solve for h: $h = \sqrt[3]{\frac{1}{8}\frac{\sin\left(\frac{\pi}{2}\right)}{N\pi}\frac{\rho\dot{Q}^2}{\sigma}}$

And normalize with respect to (arbitrary) length scale D: $\frac{h}{D} = \sqrt[3]{\frac{1}{8}\frac{\sin\left(\frac{\pi}{2}\right)}{N\pi}} \cdot (We')^{\left(\frac{1}{3}\right)}$

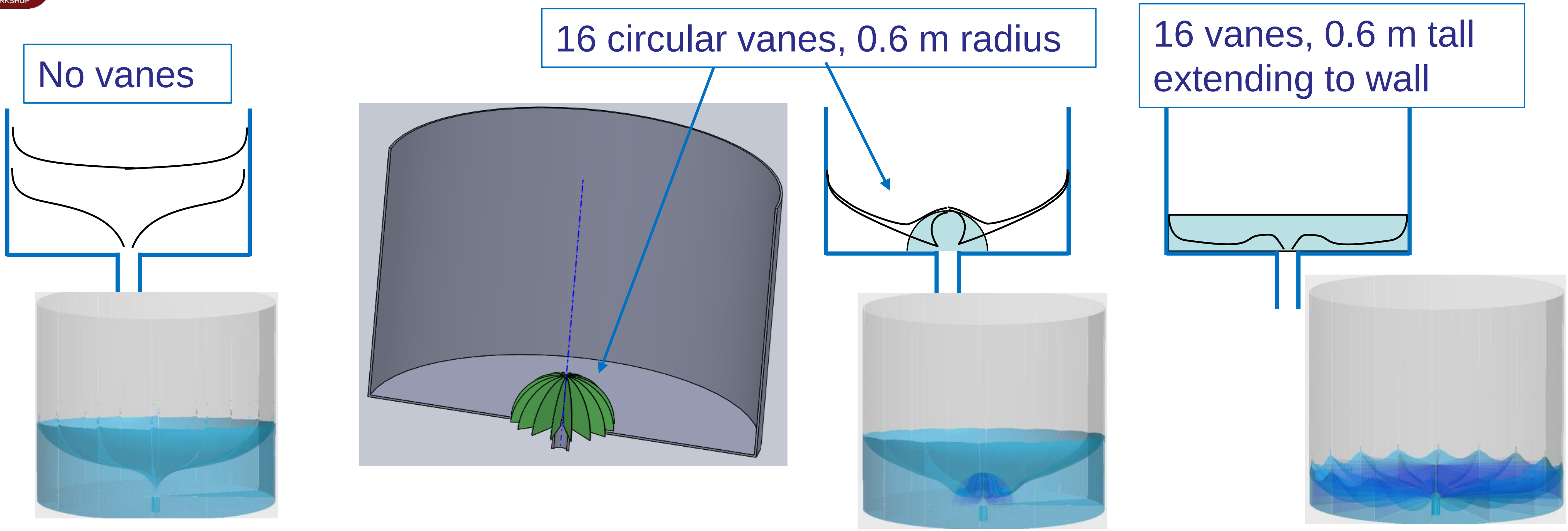
Where: $We' = \frac{\rho\dot{Q}^2}{\sigma D^3}$

Transient tank draining CFD models created in STAR-CCM+

- STAR-CCM+ used to simulate tank draining model with 1/16th periodicity
  - Laminar
  - Volume of Fluids multiphase model
  - Segregated solution approach
  - Thermal effects neglected
- Boundary conditions
  - Tank walls and vanes were non-slip with 0° contact angle
  - Outlet closed while liquid reached steady wicking height
  - Constant pressure boundary at domain top
- Static 1.2 M trim cell mesh
  - Fine static mesh to resolve VOF interface

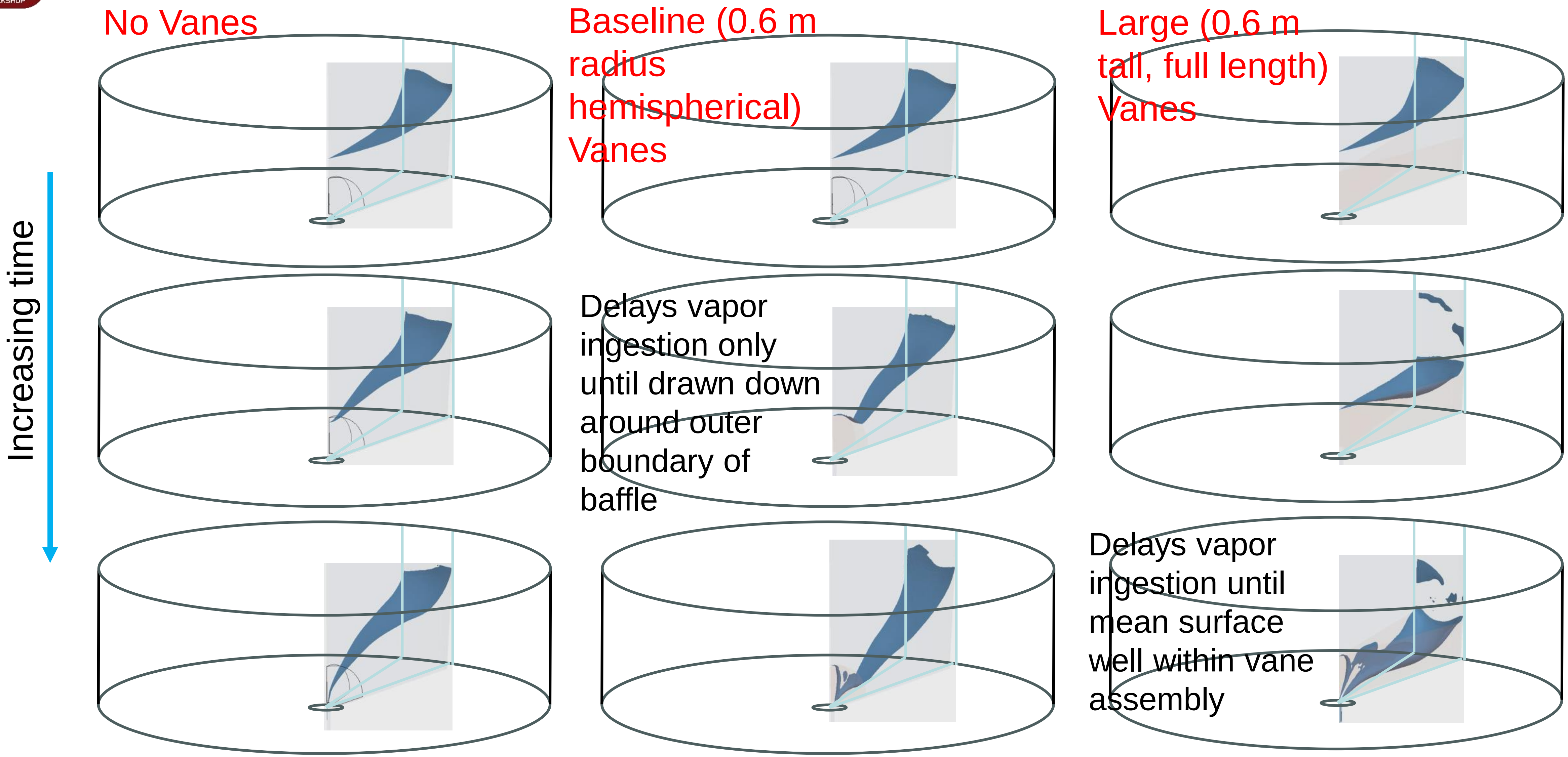


Vane configurations modeled with CFD



- CFD results identified a design detail not immediately obvious from simple OoM approach
  - Vanes must extend beyond critical radius for most efficient propellant acquisition
  - Effect magnified for flat bottomed tank, effect likely not as severe for reasonably deep elliptical or spherical aft bulkhead

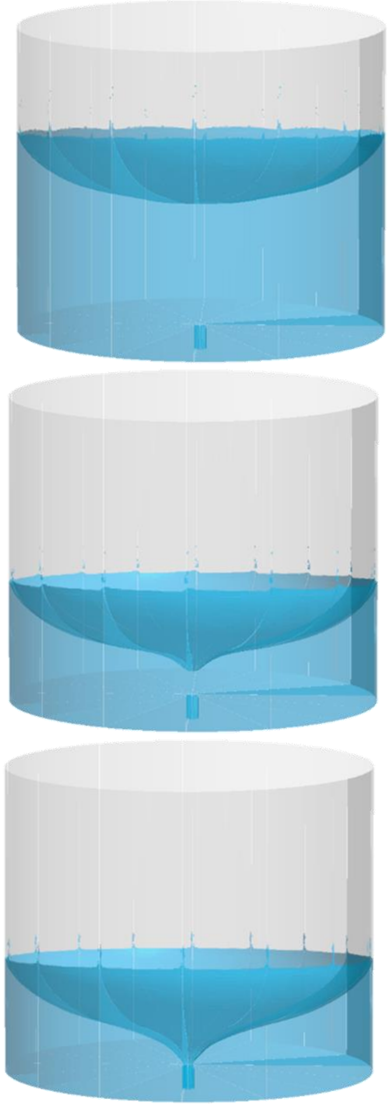
Comparison of results with CFD



Comparison of results with CFD

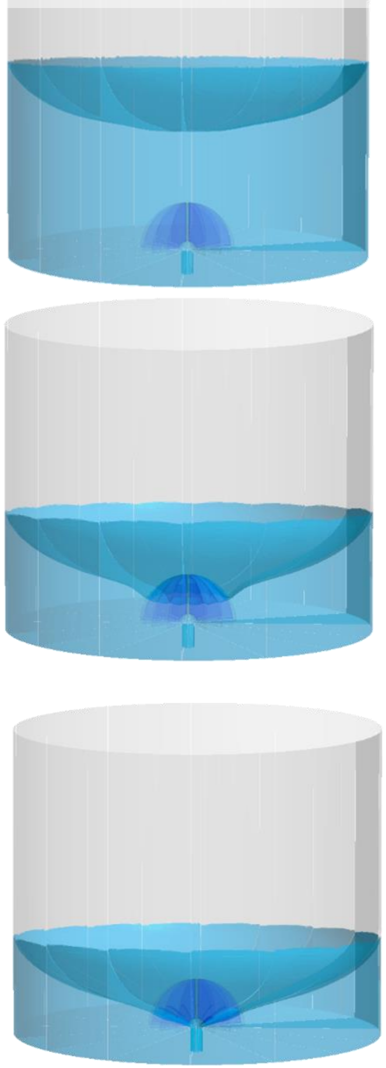
Increasing time

No Vanes

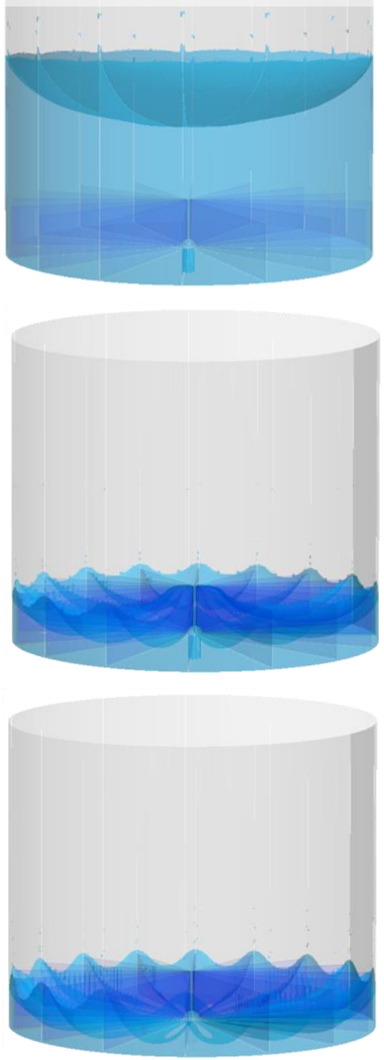


Delays vapor ingestion only until drawn down around outer boundary of baffle

Baseline Vanes
(0.6 m radius hemispherical)



Large Vanes
(0.6 m tall, full length)



Delays vapor ingestion until mean surface well within vane assembly

Comparison of analysis with subscale test data

Dimensional analysis used to size experiment with water to simultaneously match full scale and model Froude and Bond (or Weber) numbers

$$Bo_m = Bo_{fs}$$

$$\left.\frac{\rho_l\, g\, l^2}{\sigma}\right)_m = \left.\frac{\rho_l\, g\, l^2}{\sigma}\right)_{fs}$$

Eq. 1

$$\frac{l_m}{l_{fs}} = \sqrt{\left(\frac{\rho_{fs}}{\rho_m}\right)\left(\frac{g_{fs}}{g_m}\right)\left(\frac{\sigma_m}{\sigma_{fs}}\right)}$$

Bond number match sets model scale size

$$Fr_m = Fr_{fs}$$

$$\left.\frac{V^2}{gl}\right)_m = \left.\frac{V^2}{gl}\right)_{fs}$$

Eq. 2

$$V_m = V_{fs}\sqrt{\left(\frac{g_m}{g_{fs}}\right)\left(\frac{l_m}{l_{fs}}\right)}$$

Froude number match sets model flow velocity

Plugging numbers into Eq. 1, we find that LH2 at 2.9x10^{-6} g can be simulated with water at 1 g if: $\frac{l_m}{l_{fs}} = \frac{1}{350}$

Then, to simulate LH2 flowing at 1.41 kg/s through a 0.15 m outlet at 2.9x10^{-6} g, Eq. 2 gives: $V_m = 35\, {}^{m}/_{s}$ (water)

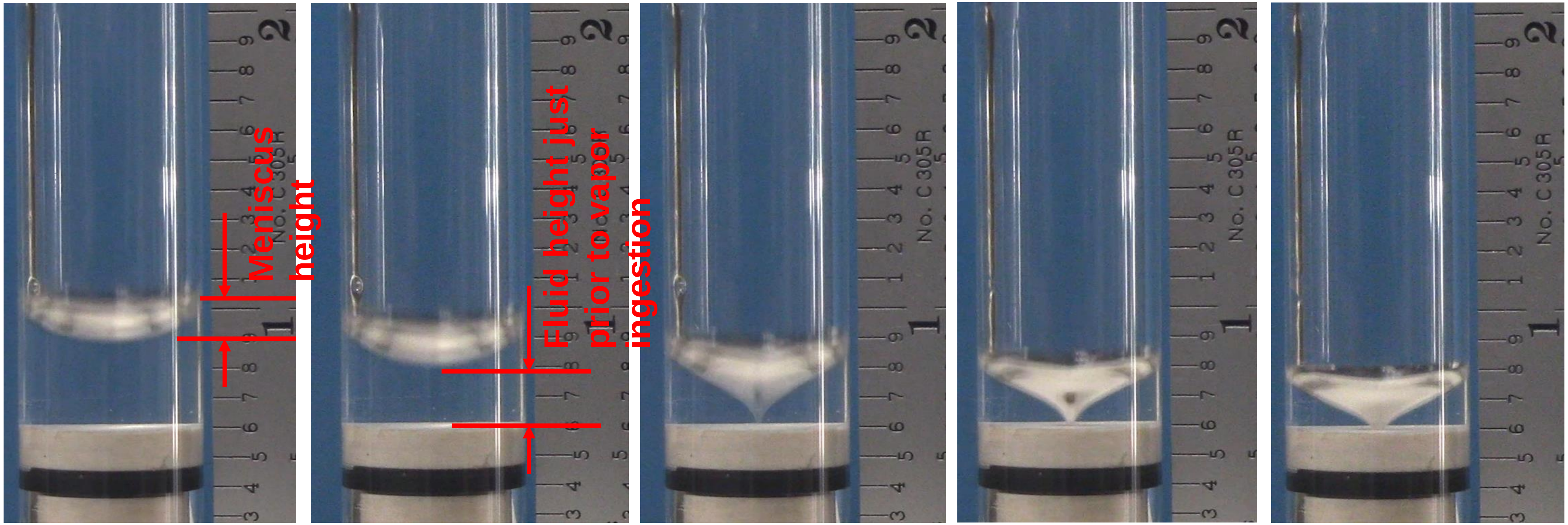
$$\dot{Q}_m = 5.2 \cdot 10^{-6}\, {}^{m^3}/_{s}$$

- **Conclude that a 0.5 inch dia model will simulate a 4.5 m LH2 tank at 2.9x10^{-6} g (very small but manageable size)**
- **Furthermore, model outlet velocity is achievable with moderate pressurization levels**

Subscale model test results

Water draining from 0.5 inch diameter tank
Outlet orifice 0.040 inch dia

Ullage pressure ~ 30 psig (45 psia)
Tank dumped to atmospheric pressure



Frame rate 59.94 f/s (16.67 ms between each image)

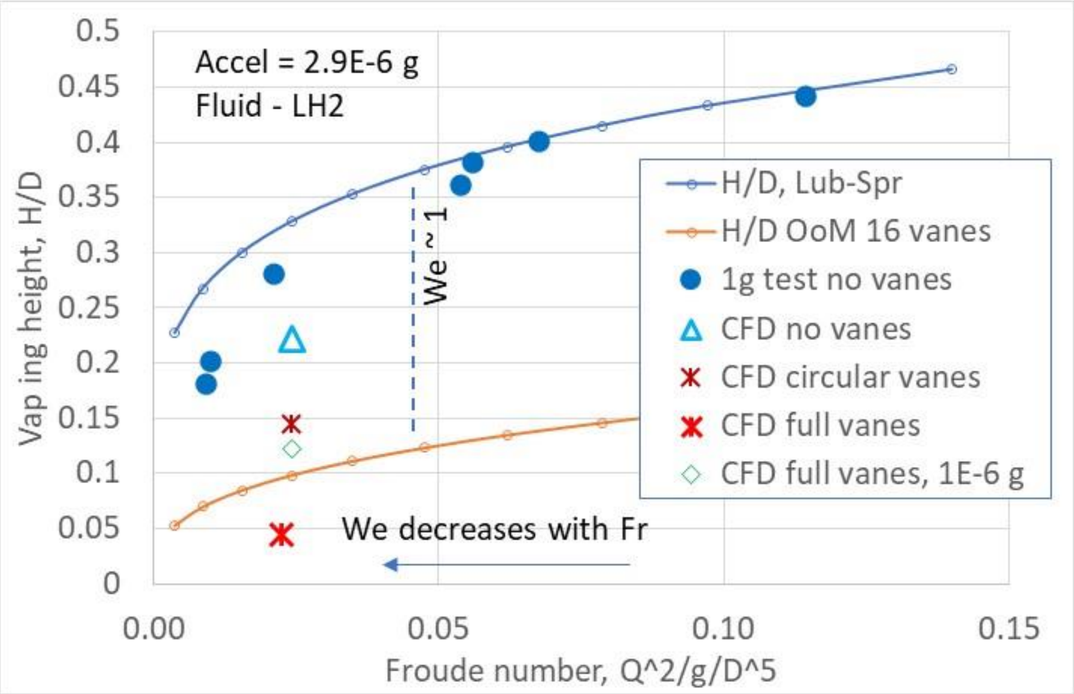
Comparison of theory, CFD, and model test results

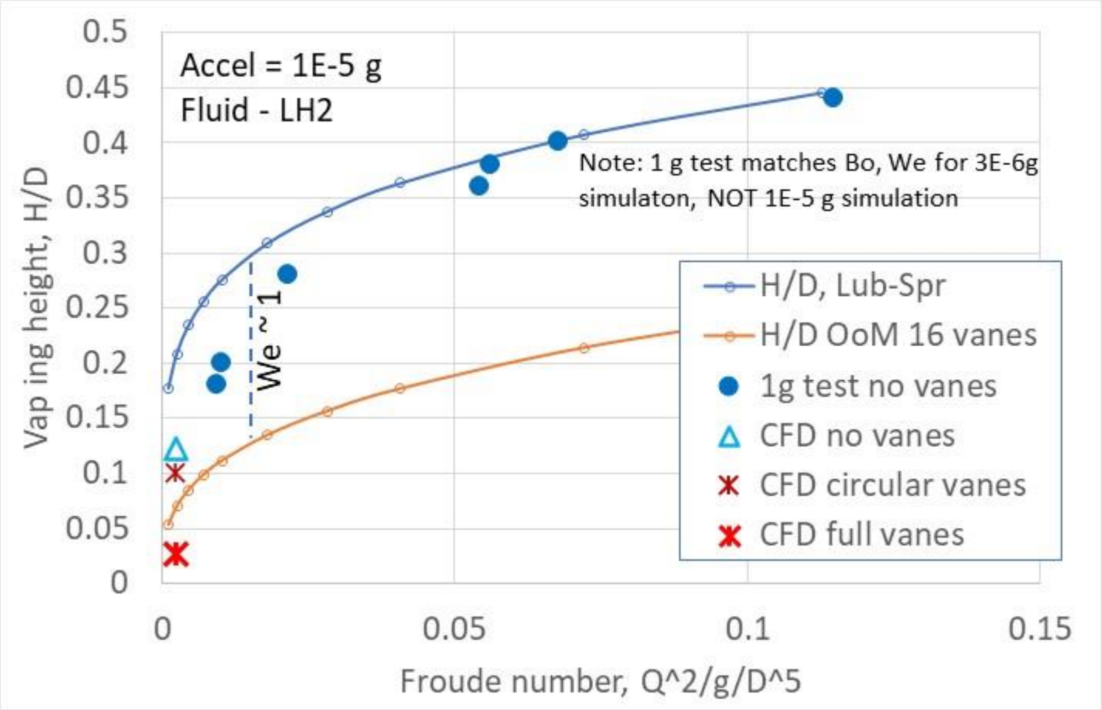
Stagnant wall wicking height predicted for LH2 at 10^{-5} g :

Method	Wicking height
OoM analysis	0.5 m
CFD (STAR-CCM+)	0.65 m
Subscale test	0.4 – 0.5 m

- Generally very good agreement between various methods

Normalized vapor ingestion height versus Froude number





Summary and Conclusions

- Simple, Order-of-Magnitude (OoM) force balance analysis can greatly assist in:
  - Understanding of fluid physics
  - Estimating performance and flow characteristics for normal vapor ingestion, even when surface tension is a dominant force
  - Proposing reasonable preliminary design and vane spacing for vane devices
- CFD (STAR-CCM+) analysis:
  - Accurately captures surface tension characteristics at liquid-vapor interface
  - Identified additional design consideration for vane device
- Simple, very small scale water flow test provides further confirmation of OoM and CFD results
- Thermal gradients in tank and vanes will impact surface tension behavior (driving liquid away from warm areas). Outlet and vane region must be maintained at or below bulk liquid temperature for cryogenic applications
- This study ignores vortexing, another important design consideration for tank outlets
- Viscous (Reynold's number) effects were not considered
  - Generally minor impact on tank outflow for many fluids and configurations of interest
  - Confirmed by agreement between full scale (proper Re) CFD and model (low Re) test results

Supplementary comments

Some backup details and comments:

- Lubin and Springer analysis ignores surface tension and viscous forces
- Lubin and Springer analysis assumes (and is valid for):
  - Flat bottomed cylindrical tank
  - Tank diameter large compared to dip formation (pullthrough) height (h)
  - Outlet diameter small compared to dip formation (pullthrough) height (h)
  - Experience has shown that it is reasonably accurate for many tank shapes (e.g. concave aft bulkhead shapes, moderately off-centerline outlets, etc.

- Time scaling for model tests: $t \approx \frac{l}{V}$
- Time interval ratio, if $\frac{Fr_m}{Fr_{fs}} \equiv 1$: $\frac{t_m}{t_{fs}} = \left(\frac{l_m}{l_{fs}}\right)\left(\frac{V_{fs}}{V_m}\right) = \left(\frac{l_m}{l_{fs}}\right)\sqrt{\left(\frac{g_{fs}}{g_m}\right)\left(\frac{l_{fs}}{l_m}\right)} = \sqrt{\left(\frac{g_{fs}}{g_m}\right)\left(\frac{l_m}{l_{fs}}\right)}$

- Time interval in small 1 g model test corresponds to a much longer full scale time interval at low g