A COMPUTATIONAL FLUID DYNAMICS STUDY OF SWIRLING FLOW REDUCTION BY USING ANTI-VORTEX BAFFLE

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Sloshing of Propellant Tanks

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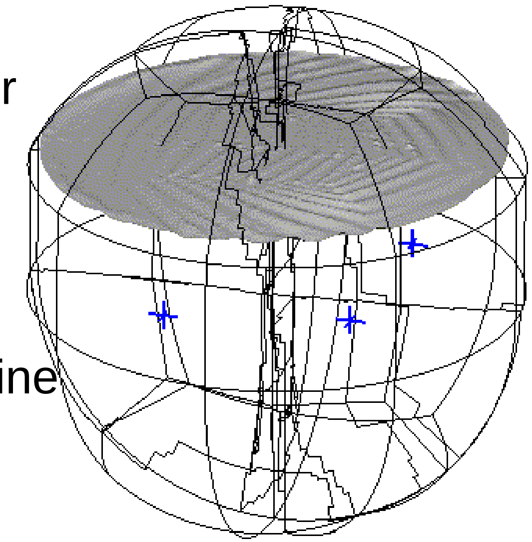
Phenomena

- Oscillations of the free surface of a liquid in a partially filled tank

Significance

- Potential source of disturbance that may affect the stability and structural integrity of space vehicles.
- Can circulate sub-cooled propellant near the liquid vapor interface resulting in increased condensation and corresponding pressure collapse. Conversely: rapid vaporization and pressure rise near heated wall.
- Concern for propellant surface orientation during Upper Stage burn (to ensure sufficient liquid propellant for engine firing).



Driving Mechanisms

- The driving slosh forces: lateral disturbance, oscillatory thrust force (TO), angular rotation during maneuverings.
- It occurs during vehicle taxi, takeoff, engine shut off, and flight maneuvers.

OBJECTIVES AND APPROACH

OBJETIVES

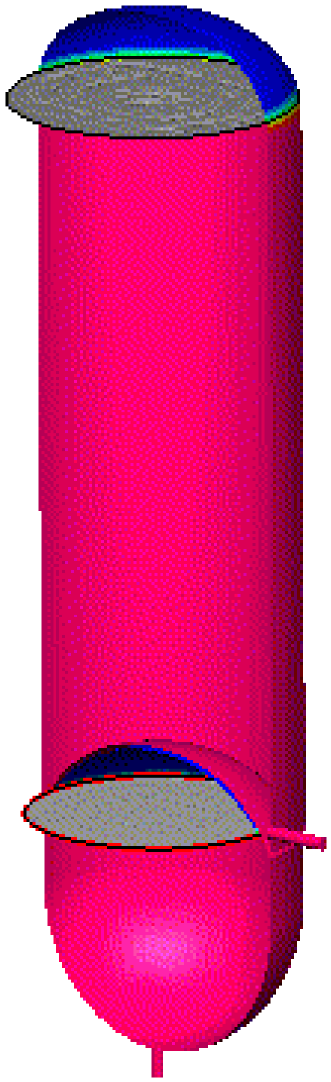
- To evaluate proposed anti-vortex design in suppressing swirling flow during US burn.

APPROACH

- Include two major body forces in the analysis
  - a) Vehicle acceleration (all three components);
  - b) Vehicle maneuvers (roll, pitch, and yaw)
- Perform two drainage analyses of Ares I LOX tank using 6 DOF body forces predicted by GN&C analysis (Guidance Navigation and Control) during vehicle ascent: one with baffle, one without baffle.

MODEL

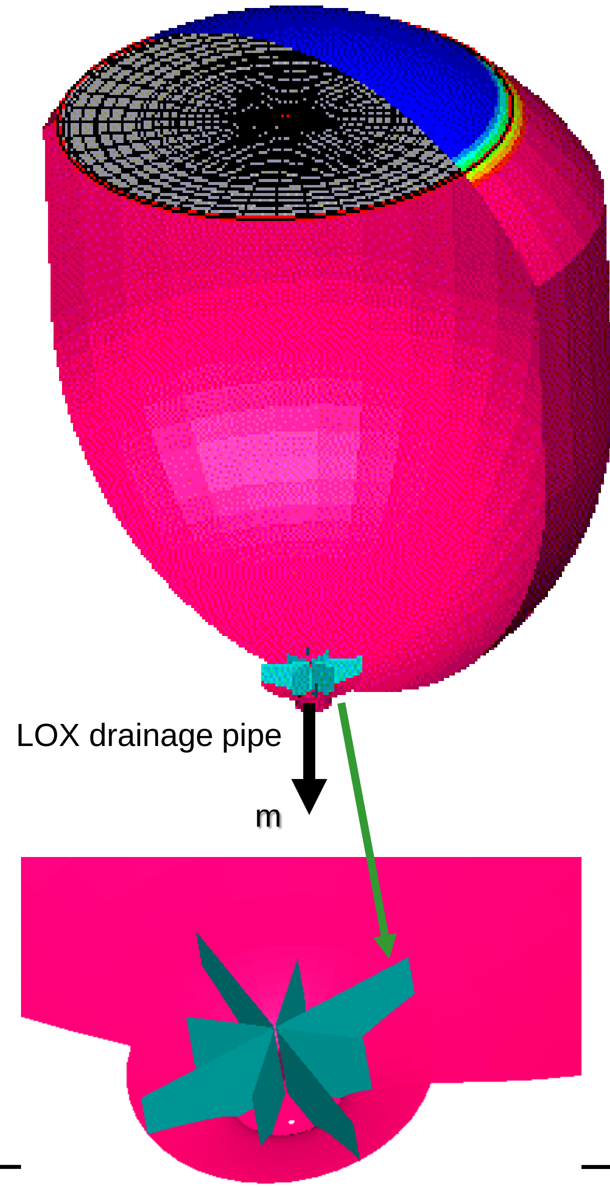
- Use Ares I defined geometry. O-Grid for easy fitting of baffle. In this preliminary analysis the holes are sealed.
- Use whole 360 deg. model with no assumption of symmetry or cyclic boundary conditions.
- Read in 6DOF data vs time from a file.



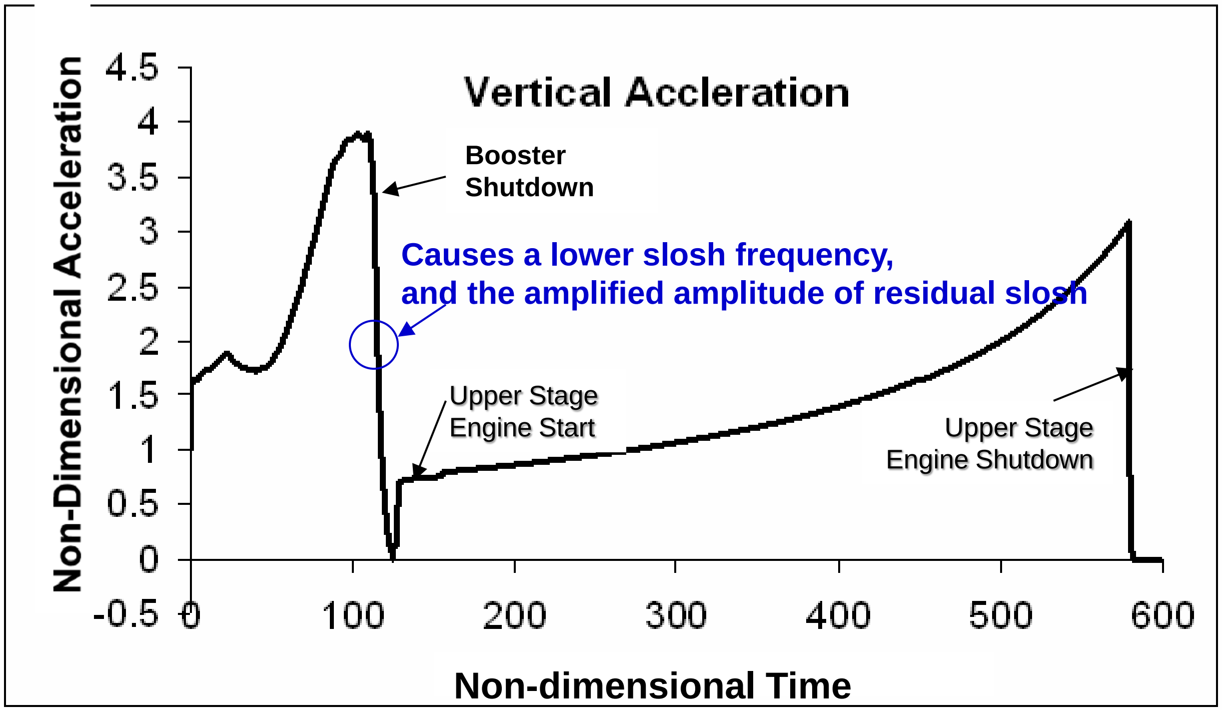
Simulation Model

Computational Model

- CFD software: CFD-ACE+ with VOF module.
- Isothermal incompressible fluids for gaseous phase and liquid phases. Thermodynamic, non-isothermal flow condition is under validation.
- 223,000 total cells for LOX tank with baffle and 50,212 total cells for LOX tank without baffle.
- Constant gas and liquid physical properties: density, viscosity, surface tension.
- Laminar flow assumption.
- Baffle is modeled as solid block with a thickness of 2^o in circumferential direction.
- When upper stage engine starts, the drainage pipe is prescribed as constant mass flow rate for LOX tank.



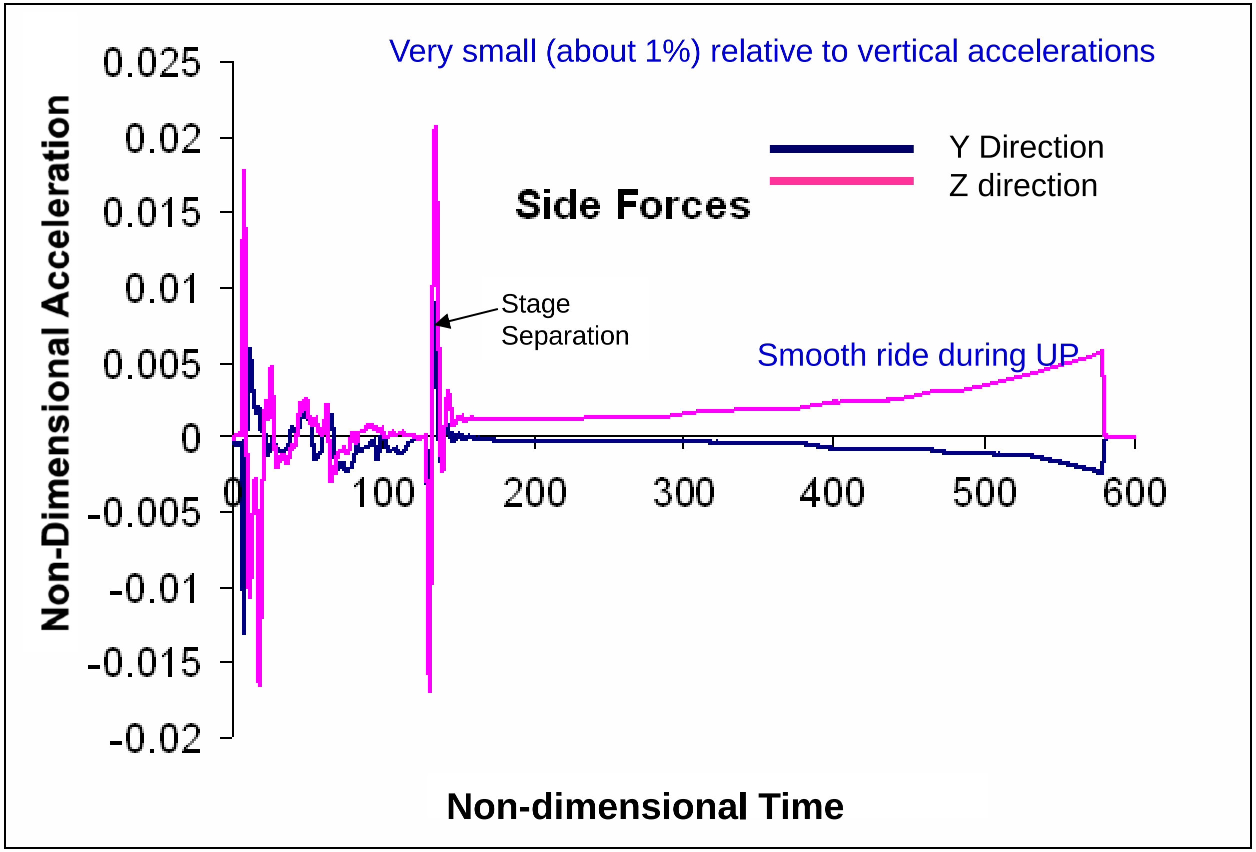
Vehicle Linear Acceleration from Guidance Navigation and Control Analyses



Vertical Acceleration at Center of Gravity $(a_{cg})_x$

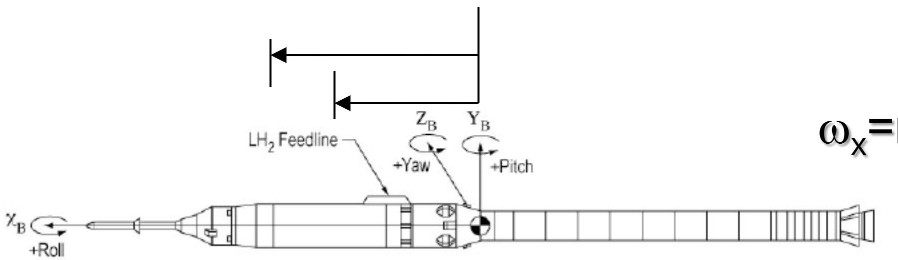
Input Data Analysis

<u>Vehicle Linear Acceleration</u> from Guidance Navigation and Control Analyses



Side Accelerations at Center of Gravity $(a_{cg})_y$, $(a_{cg})_z$,

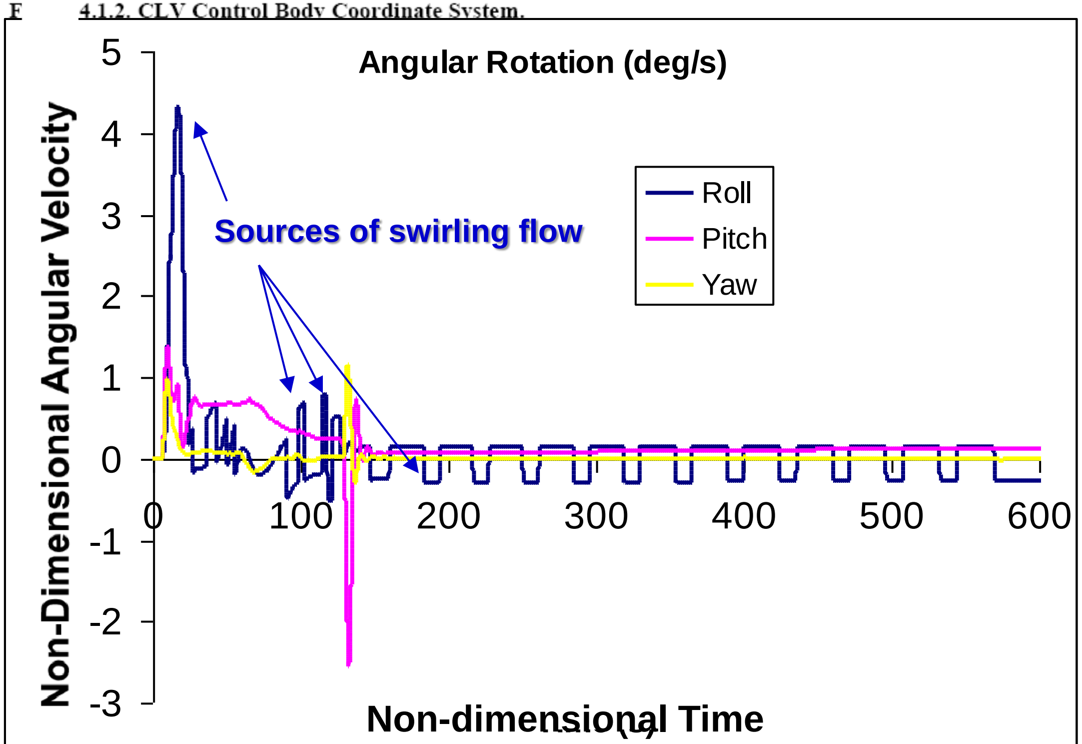
Maneuvering Data Analysis



F 4.1.2. CLV Control Body Coordinate System.

ω_x=roll; ω_y=pitch; and ω_z=yaw

Long moment arm



Side Loads due to Maneuvering:

Centrifugal forces: $\vec{\omega}\times(\vec{\omega}\times\vec{r})$

Angular acceleration forces: $\dot{\vec{\omega}}\times\vec{r}$

all, negligible !!

Significant, and in high frequency content

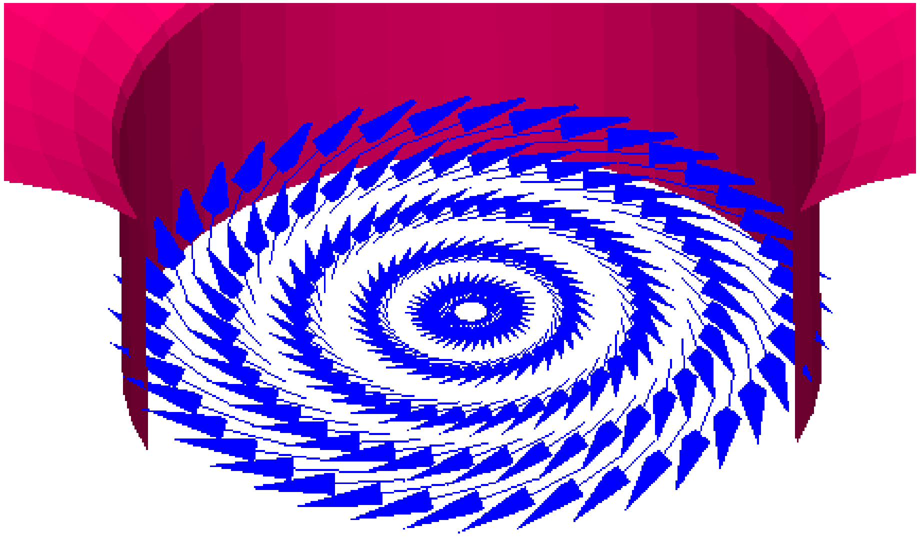
Swirling Flows in Drainage Pipe without Baffle

Three Major Contributing Factors to Swirling Flow in the Drainage Pipe:

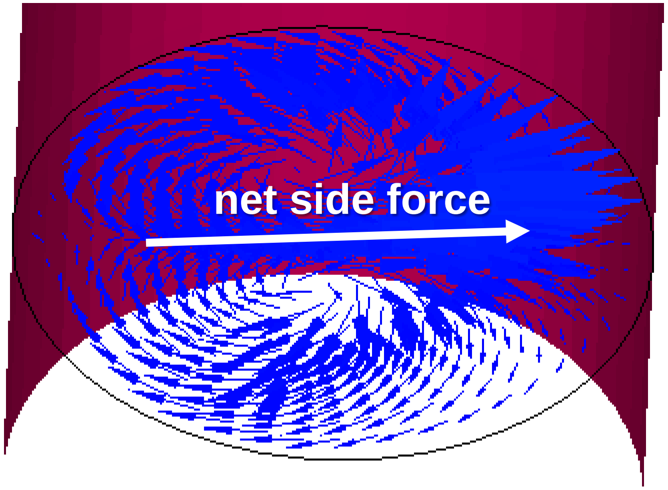
a) Rolling maneuvering:

b) Sloshing due to pitch and yaw maneuverings and side loads

c) Residual vortices transported from the tank during draining



Swirling flow due to rolling:
symmetrical to the center of the tank axis.



Swirling flow due to side forces:
two vortices side by side.

Transport Physics of A Vortex (from tank to pipe)

By applying $\nabla\times$ to N-S equations, and assuming incompressible flow, we have:

$$\frac{D\vec{\omega}}{Dt} = \nu\nabla^2\vec{\omega} + \vec{\omega}\bullet\nabla\vec{V}$$

Just as a scalar transport with convection and diffusion

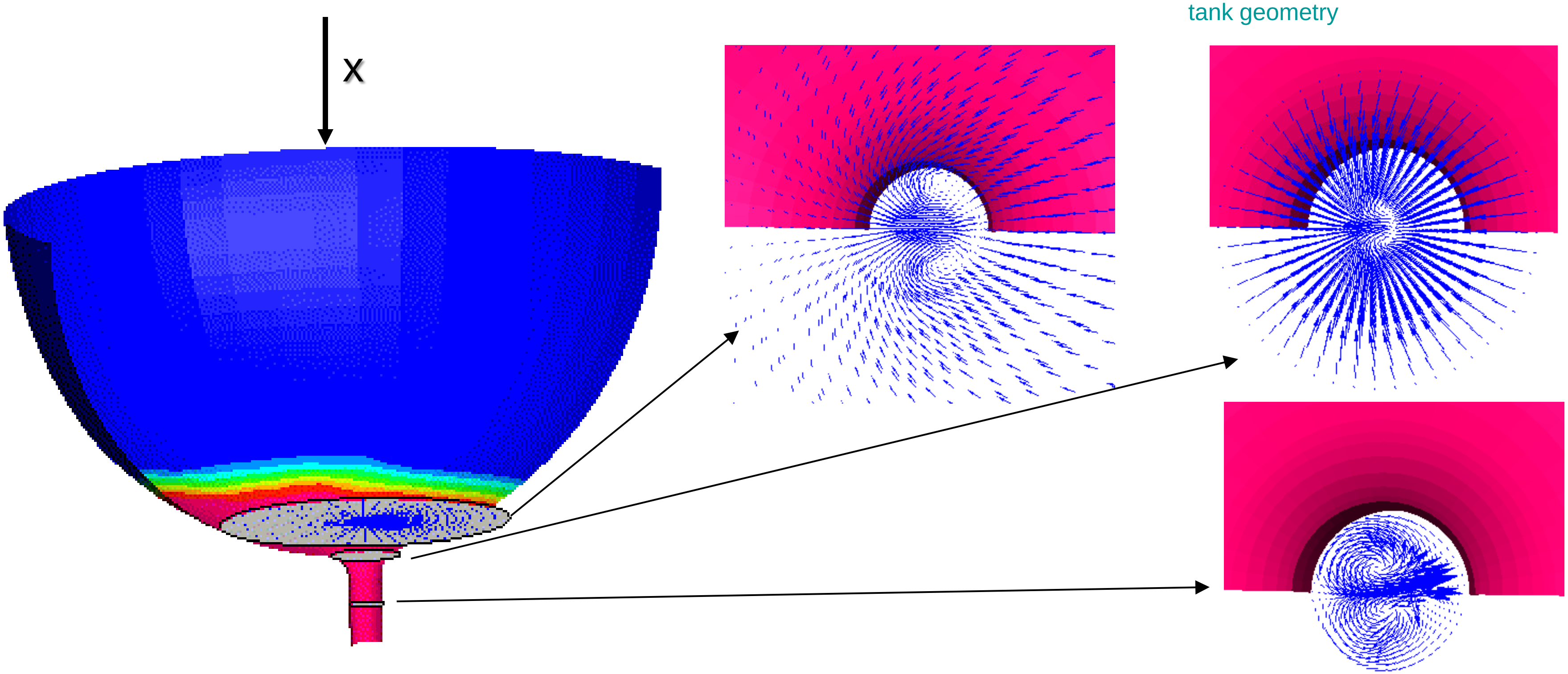
Stretching or titling of vorticity

consider ω_x →

$$\frac{D\omega_x}{Dt} = \nu\nabla^2\omega_x + \omega_x\frac{\partial v_x}{\partial x}$$

- **> 0, for the current tank during draining,**

→A positive source term for the convergent tank geometry



Vorticity strength increases as flow approaches the drainage pipe (conservation of angular momentum or stretching of vorticity)

Earth-to-Orbit Smooth LOX Tank Simulation

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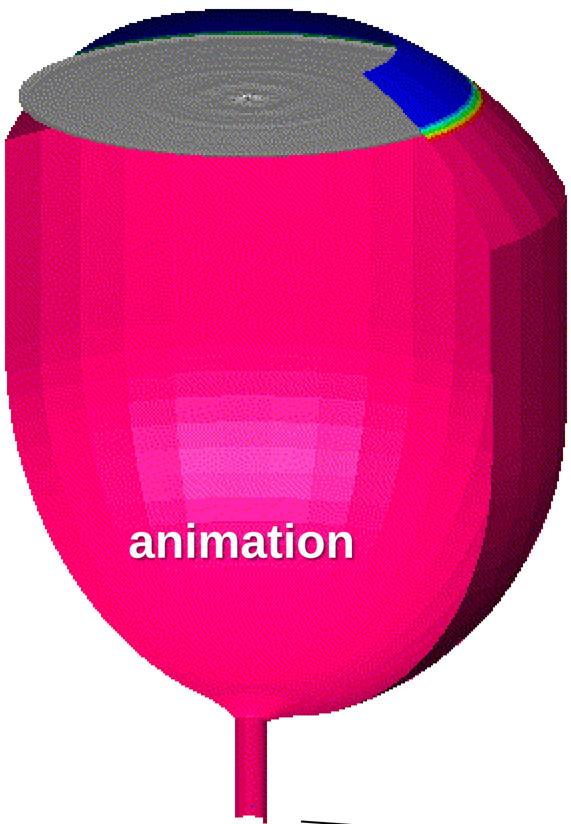
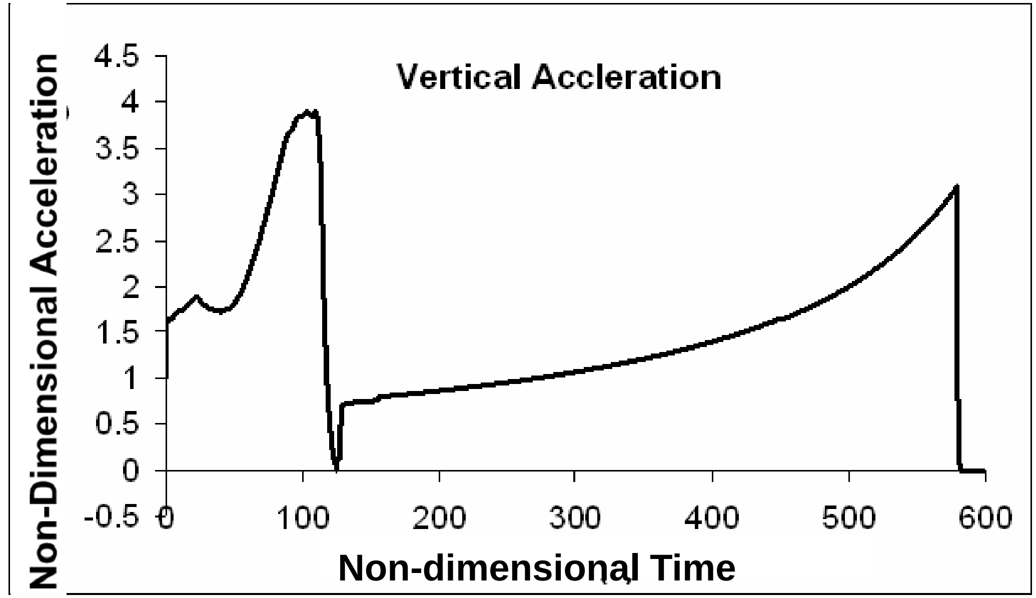
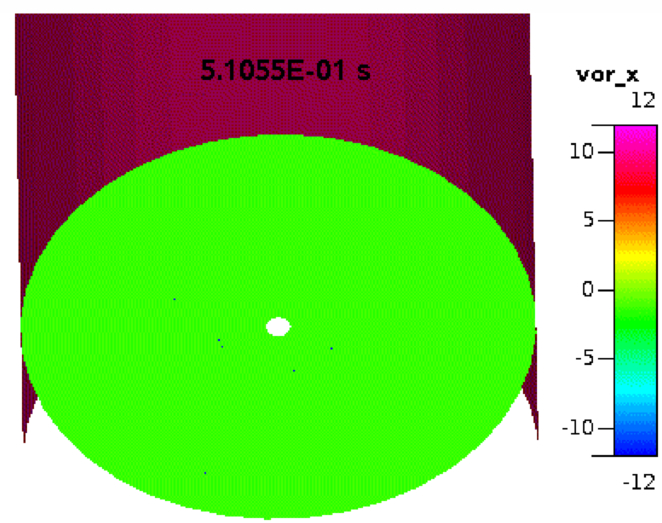
Non-dimensional Time







Cross-sectional velocity vector
at drainage pipe

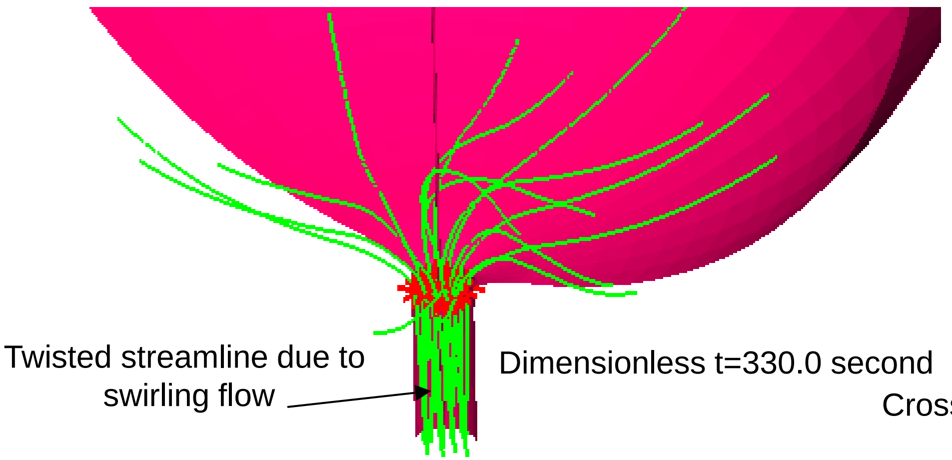
CFDRC
Delivering Breakthrough Solutions

Superposition of swirling flows
due to roll and slosh

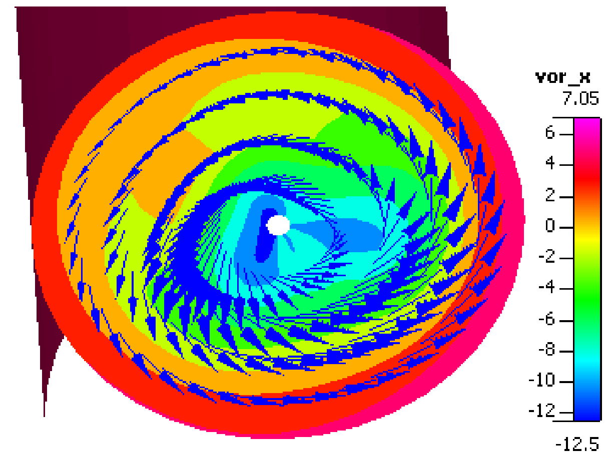
Effects of Vortical Flow in Drainage Pipe

Vortical flows are undesirable in the tank and drainage pipe:

a) Non-uniform flow into turbo pump



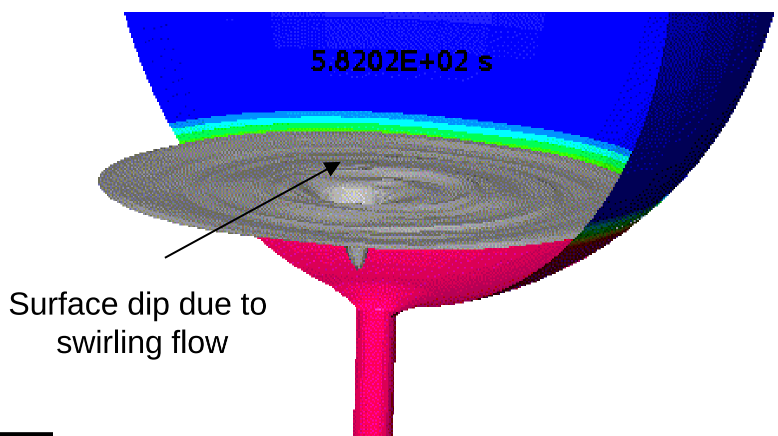
Dimensionless t=330.0 second



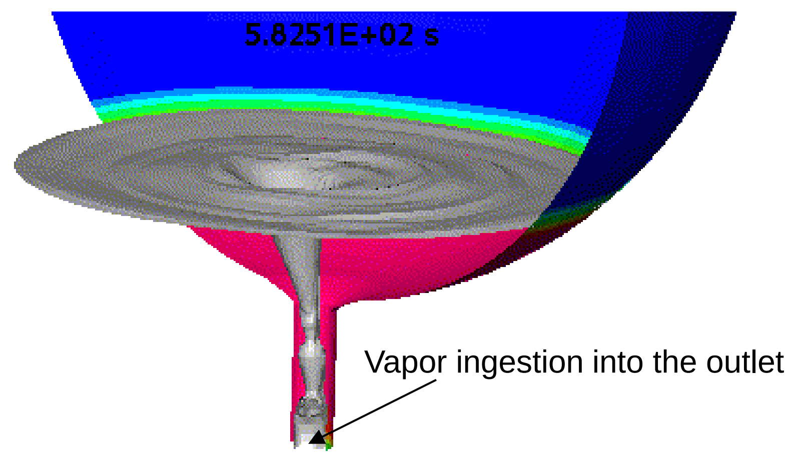
Cross-sectional velocity vector and vorticity

Dimensionless t=330.0 second

b) Formation of a dip and earlier vapor ingestion into the outlet, leading to higher residual mass.



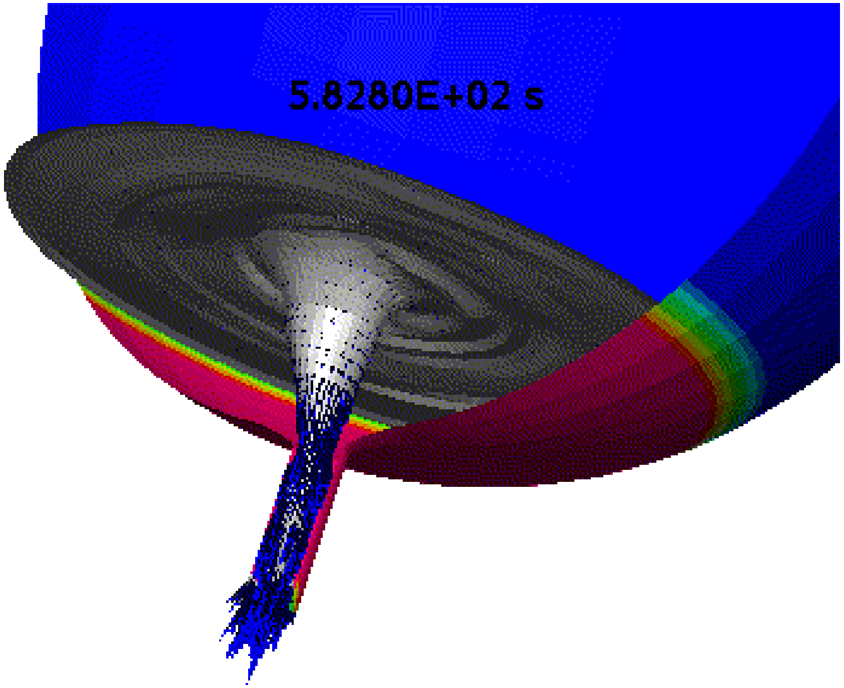
Dimensionless t=582.0 second



Dimensionless t=582.5 second

Effects of Vortical Flow in Drainage Pipe (cont.)

Nature's tornado



LOX tank gas-liquid interface without baffle

Small vortices in the tank are amplified while convecting into the pipe: the principle of vortex stretching, or conservation of angular moment

Surface Dip due to Swirling Flow:

1. Swirling flow induces a centrifugal body force in the tank, which is proportional to:

$$\rho r \omega^2$$

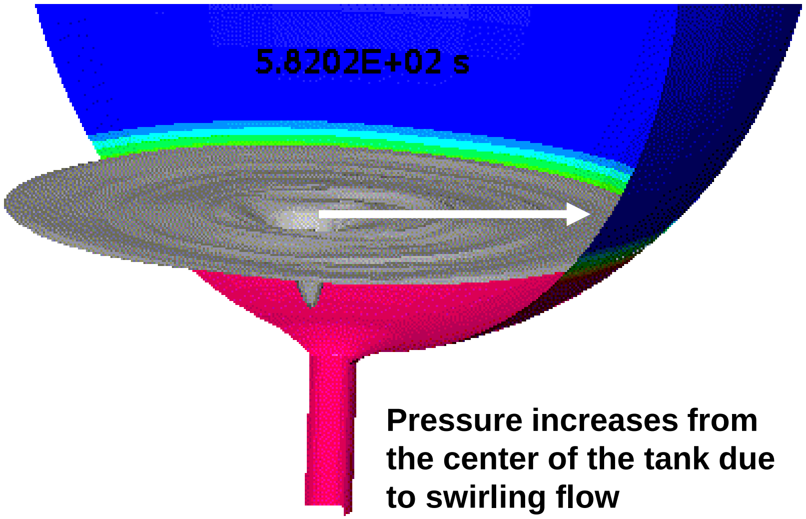
2. A pressure gradient is generated in the liquid to balance this body force:

$$\nabla p = \rho r \omega^2$$

3. Pressure increases with radius r. During the early stage of draining, this pressure gradient is relatively small. However, at the later stage, the pressure gradient amplifies due to conservation of angular moment.

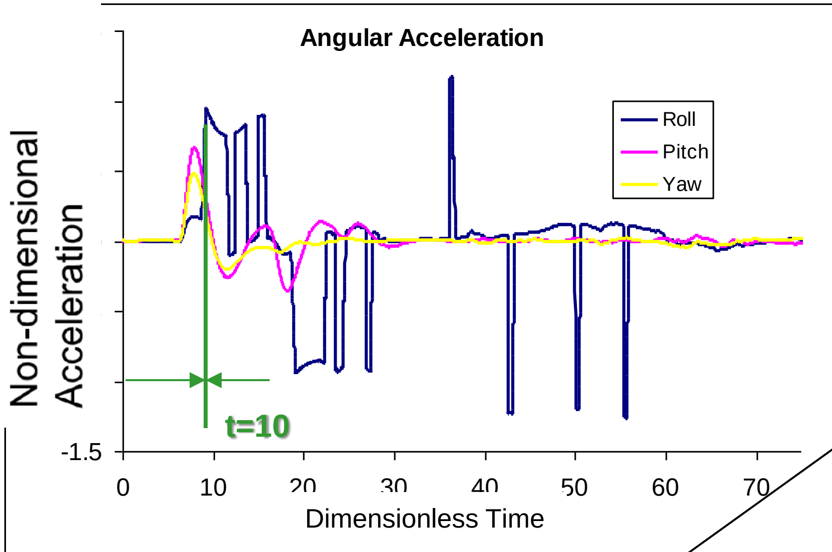
$$\nabla p = \rho r \omega^2 = \rho \frac{(r\omega)^2}{r} = \rho \frac{(Cont.)^2}{r}$$

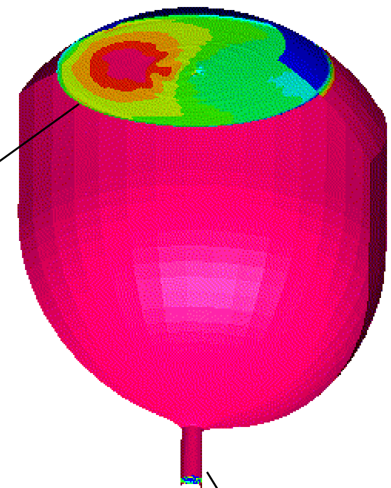
4. When r is small, there is a rapid pressure drop at the center of the interface causing the dip.

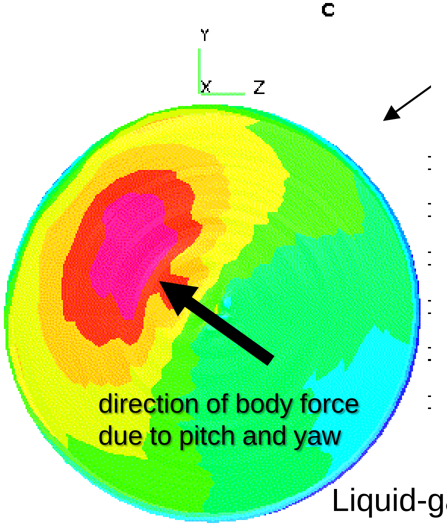


Pressure increases from the center of the tank due to swirling flow

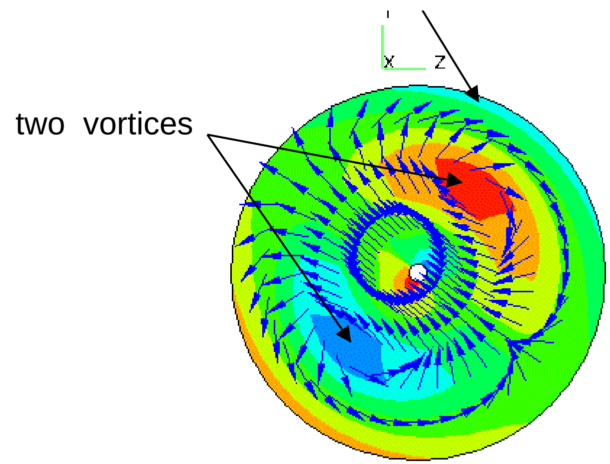
Maneuvering Induced Vortices: First Stage Burn





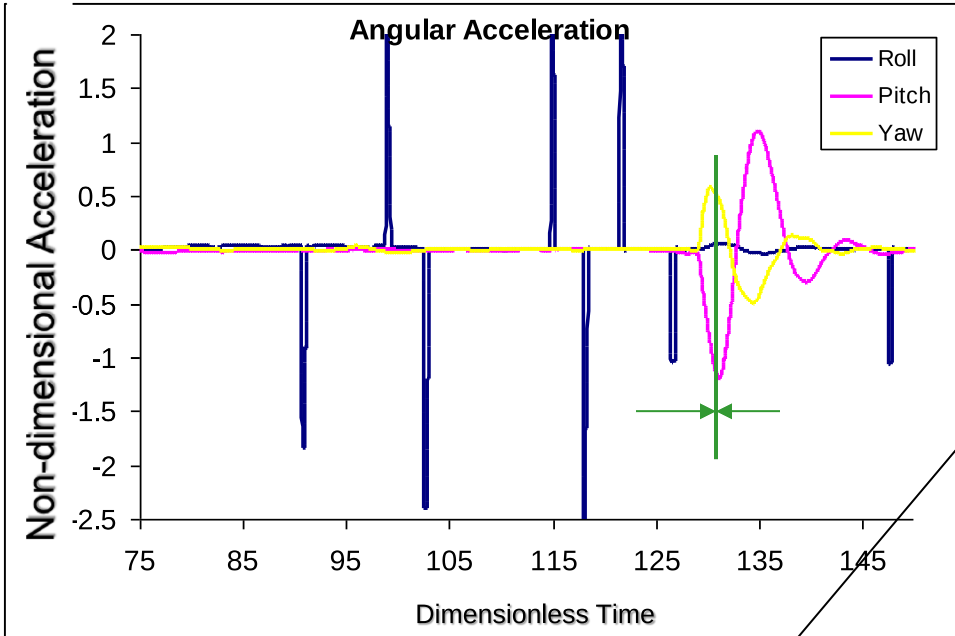


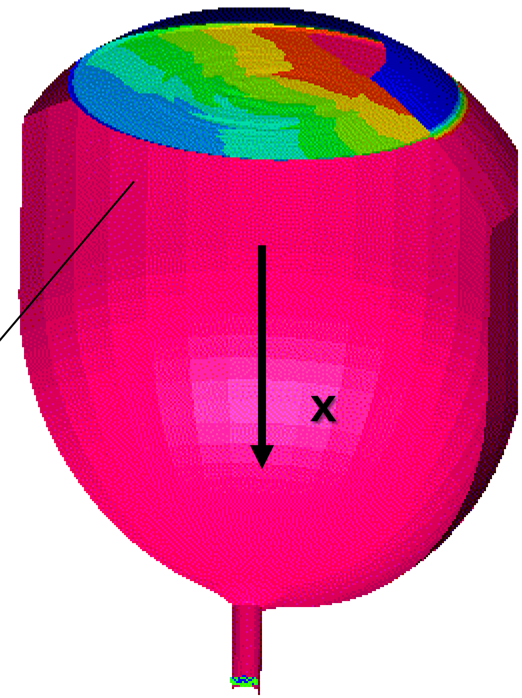
Liquid-gas Interface elevation

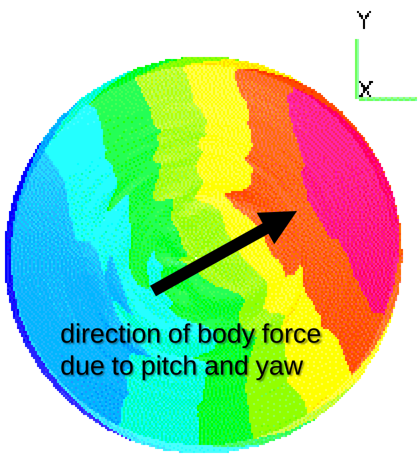


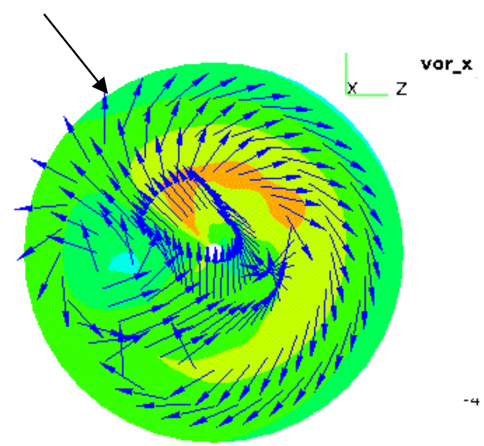
velocity vector and vortices in the drainage pipe due to the side force

Maneuvering Induced Vortices: Stage Separation



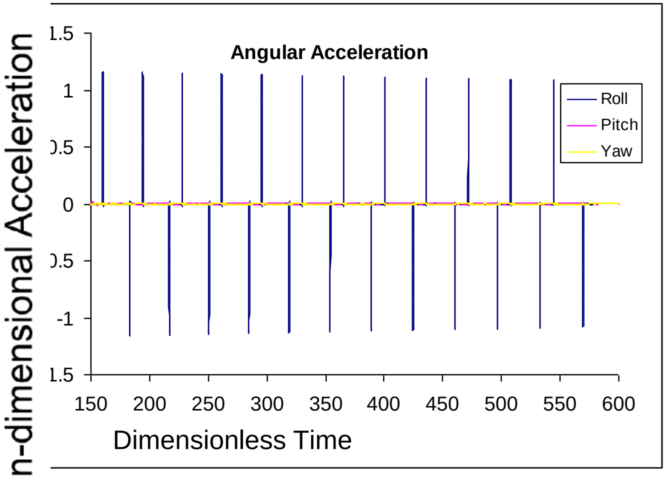




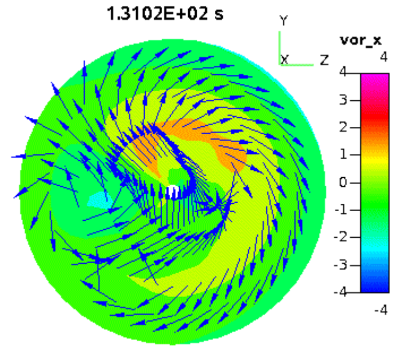


velocity vector and vortices in the drainage pipe:
vorticity due to roll and side force

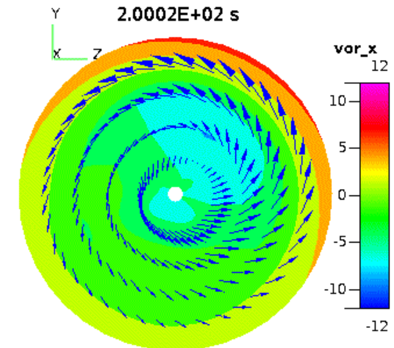
Maneuvering Induced Vortices: Upper Stage Engine Burn



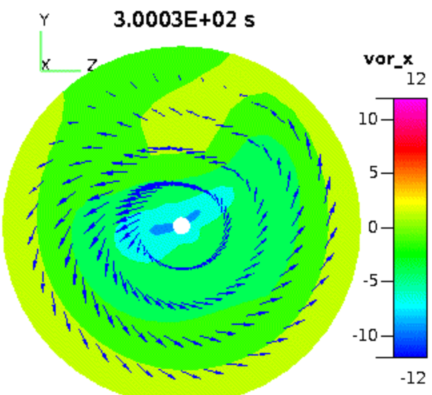
Less pitch and yaw, more roll spikes



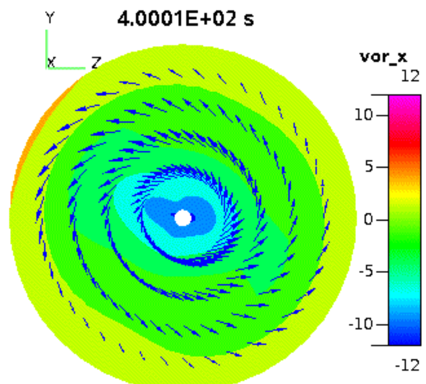
Dimensionless t=131



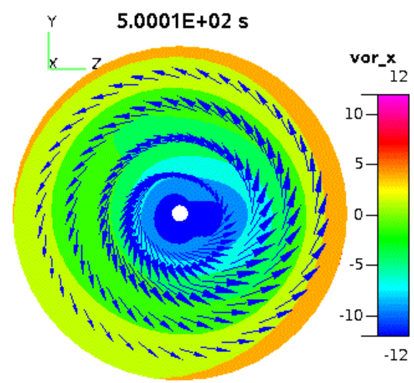
Dimensionless t=200



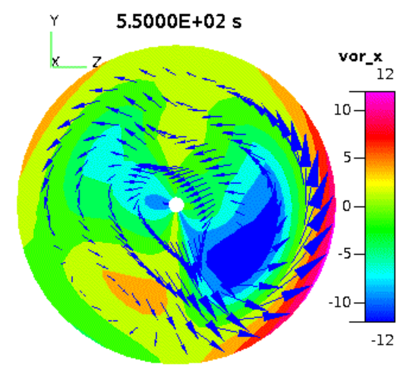
Dimensionless t=300



Dimensionless t=400



Dimensionless t=500

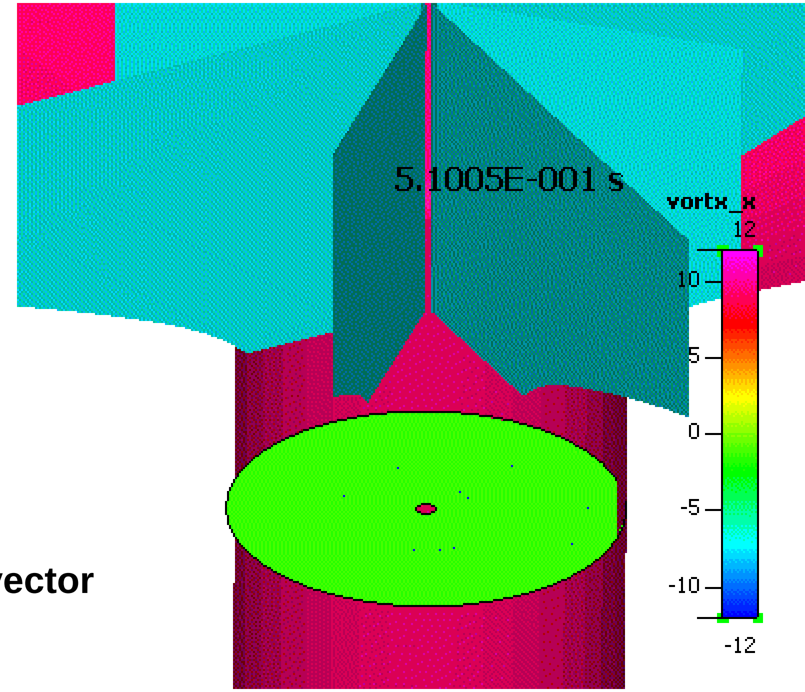


Dimensionless t=550

Unlike the roll profile with time, which has multiple positive and negative spikes, the circulation in the pipe keeps the same sense of rotation. It implies that the vortices in the drainage pipe during the UPE burn come from the residual vortices in the tank. The original vortices may be small but they are amplified while going through the convergent bottom section of the tank (conservation of angular momentum).

Earth-to-Orbit Baffled LOX Tank Simulation

Cross-sectional velocity vector at drainage pipe

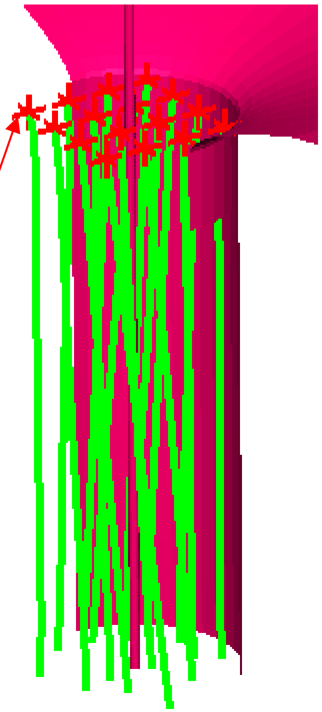


1. During the first stage (dimensionless t < 128) , behaves the same as without baffle
2. Much reduced swirling flow during drainage
3. Cross-sectional flows are almost constant and confined to 8 segments

Effect of Baffles in Reducing Swirling Flow

Without Baffle

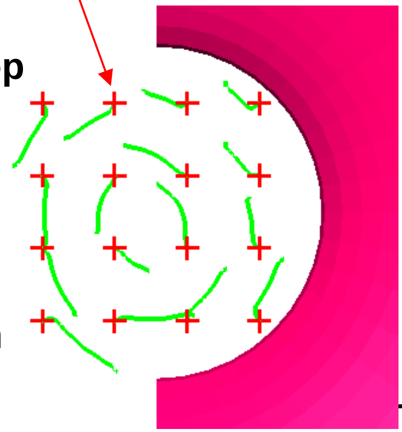
3D Particle Trace
3d particle traces from the pip inlet show twist due to cross swirling.



+ : particle releasing point

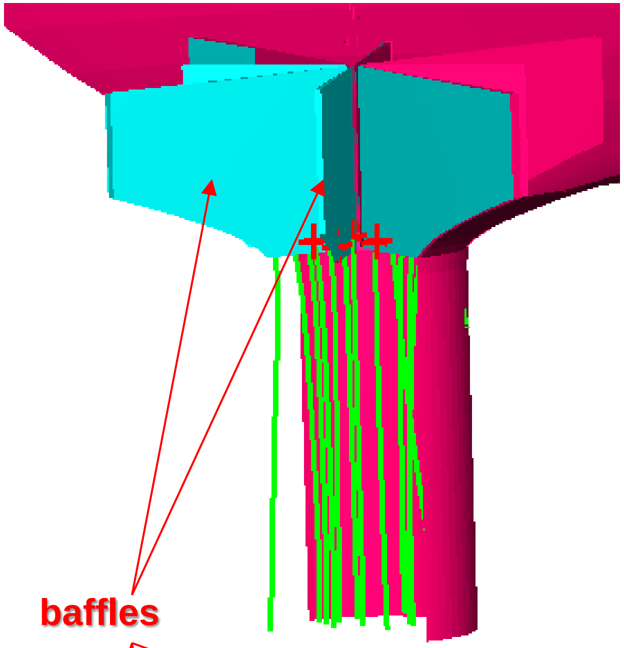
2D View from the Top

Top view of the 3D particle trace shows the direction and strength of the cross flow: 10% of the main flow.



With Baffle

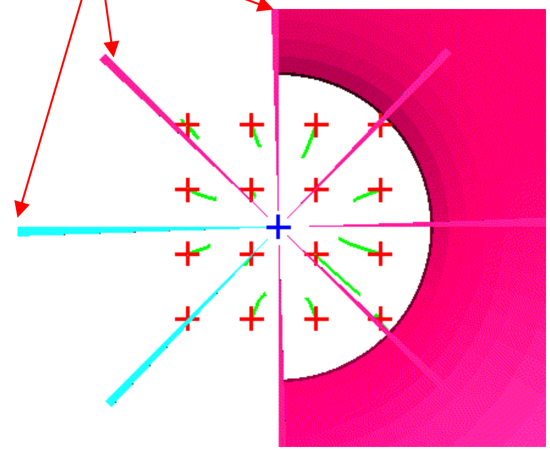
3D Particle Trace
3d particle traces from the pip inlet are all straight: minimum cross swirling effect



baffles

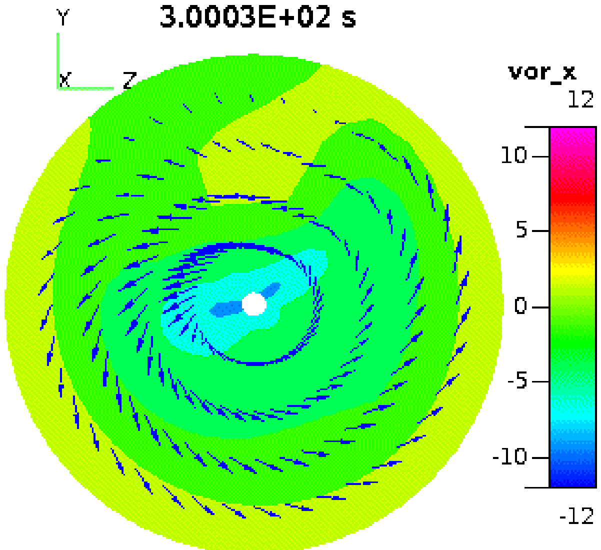
2D View from the Top

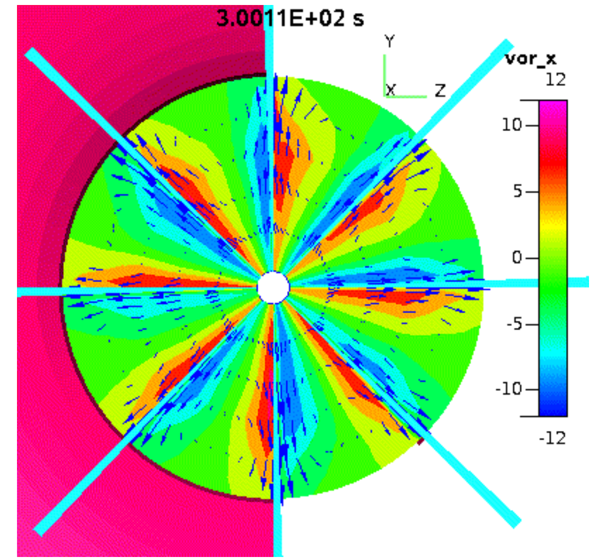
Top view of the 3D particle trace shows that the cross-sectional flow are mainly in radial direction, no circumferential flow.



Effect of Baffles in Reducing Swirling Flow

Secondary flows in the drainage pipe with and without baffles



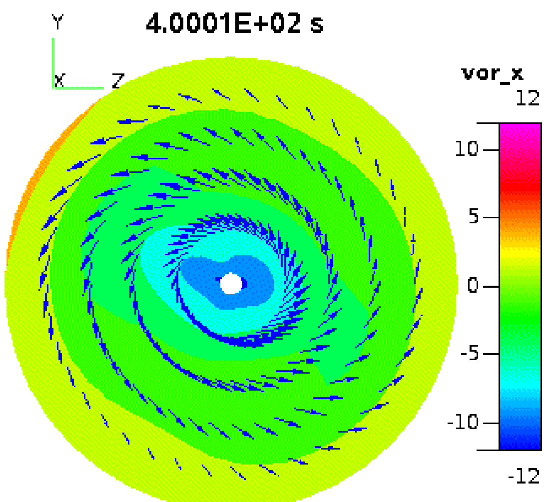


← **Without Baffle**

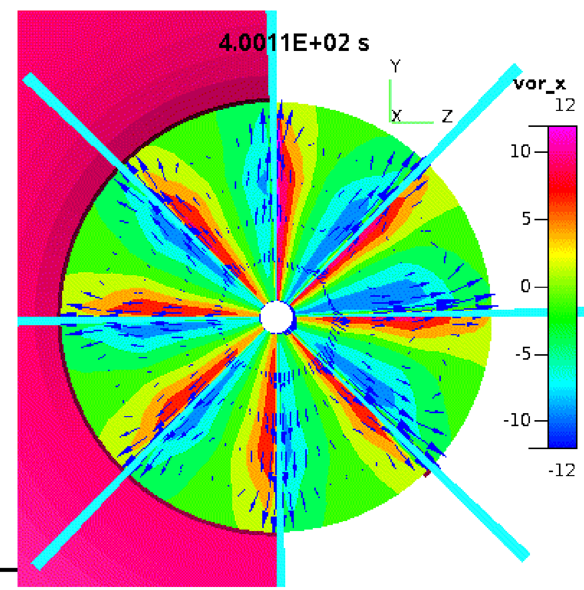
The cross-sectional flows are circumferential.

With Baffles →

The cross-sectional flows are radial, and are restricted inside each partition.



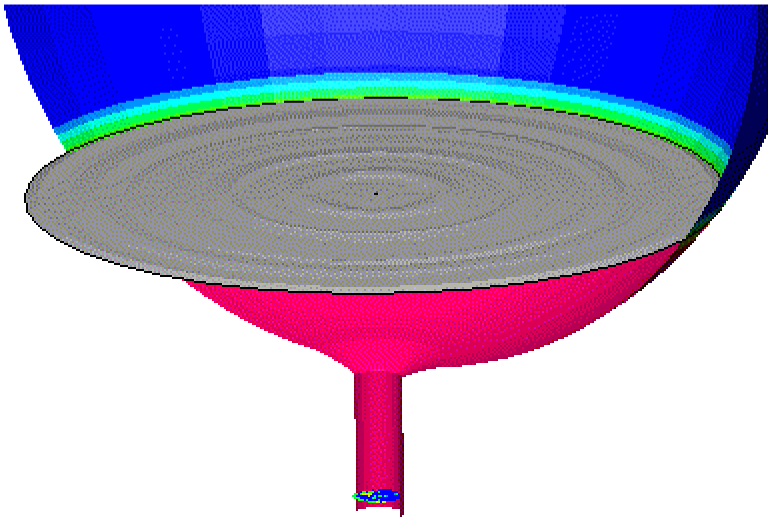
Baffles prevent residual swirling flows in the tank from flowing into the drainage pipe. They are very effective. The width of baffle seems to have less effect.



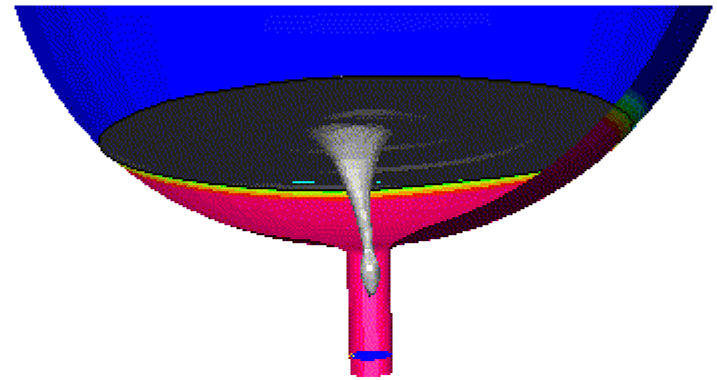
Effect of Baffles in Reducing Residual Mass

Without Baffle: Very high Residual Mass: 11,474 dimensionless mass

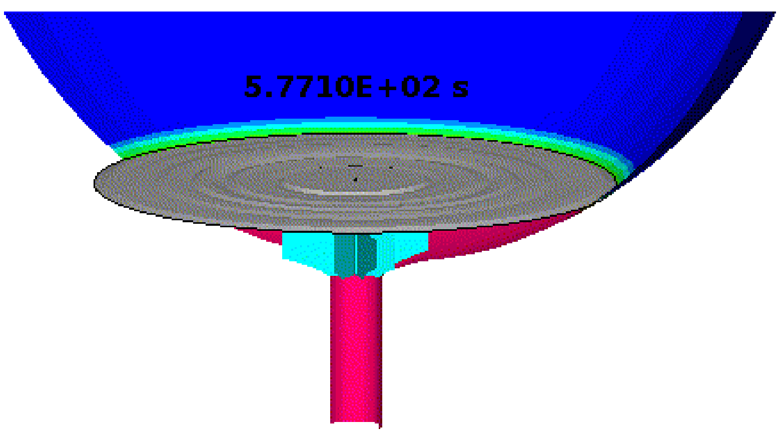
Animation of free surface at later stage



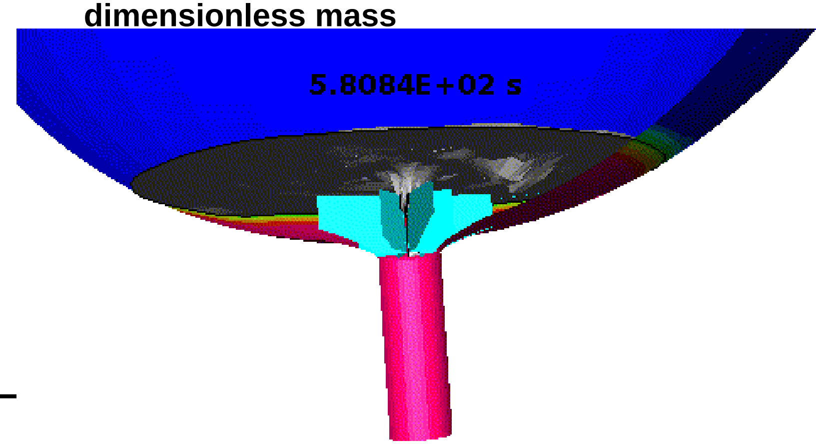
Vapor ingestion, residual mass: 11,474 dimensionless mass



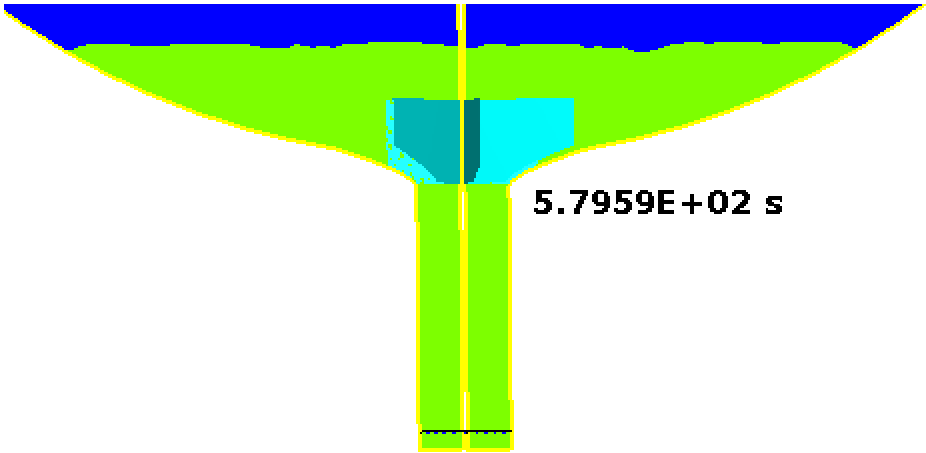
With Baffle: Residual Mass Reduced from 11,474 to 2,596.6 dimensionless mass



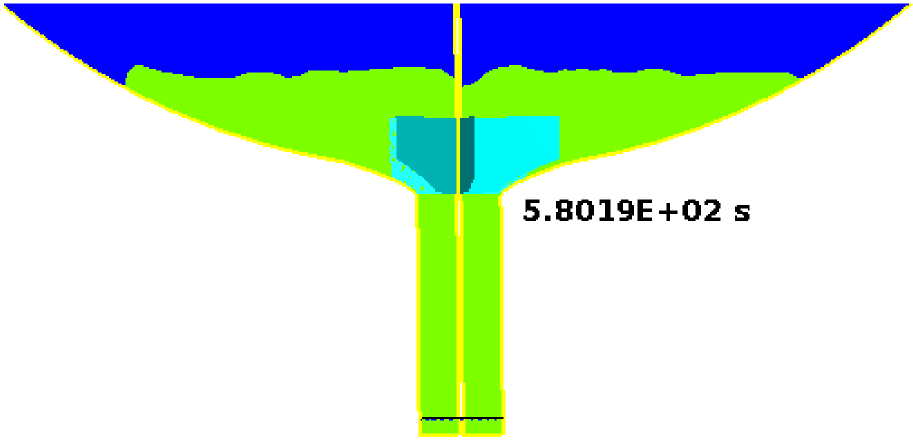
Vapor ingestion, residual mass: 2596.6 dimensionless mass



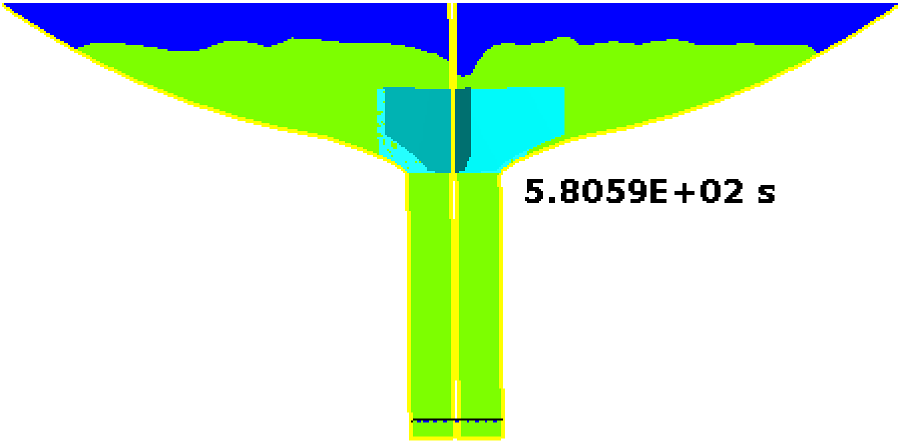
With Baffle and Sloshing



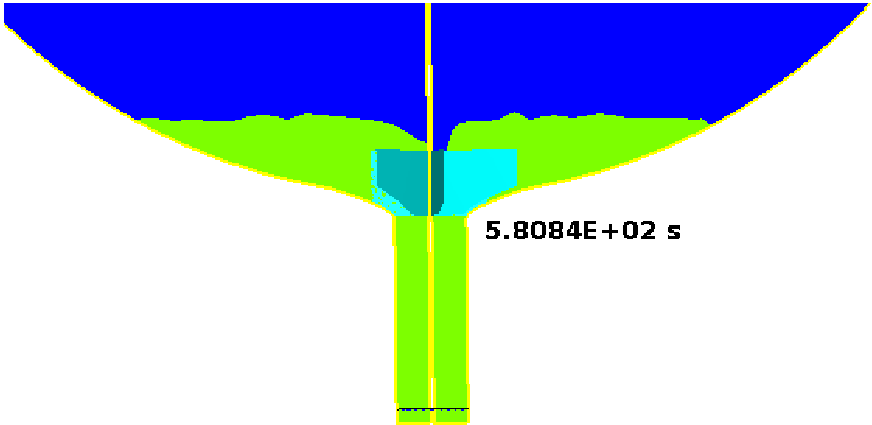
Residual mass: 3334.5 dimensionless mass



Residual mass: 2978.6 dimensionless mass



Residual mass: 2721.83 dimensionless mass



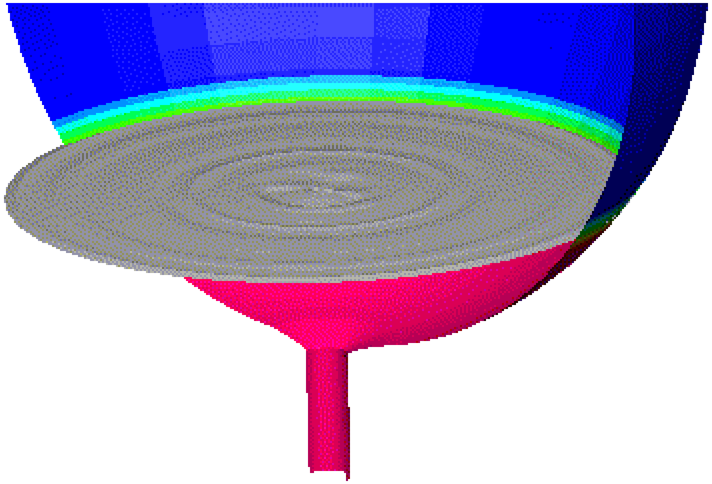
Residual mass: 2596.6 dimensionless mass

Effect of Tank Sloshing on Residual Mass

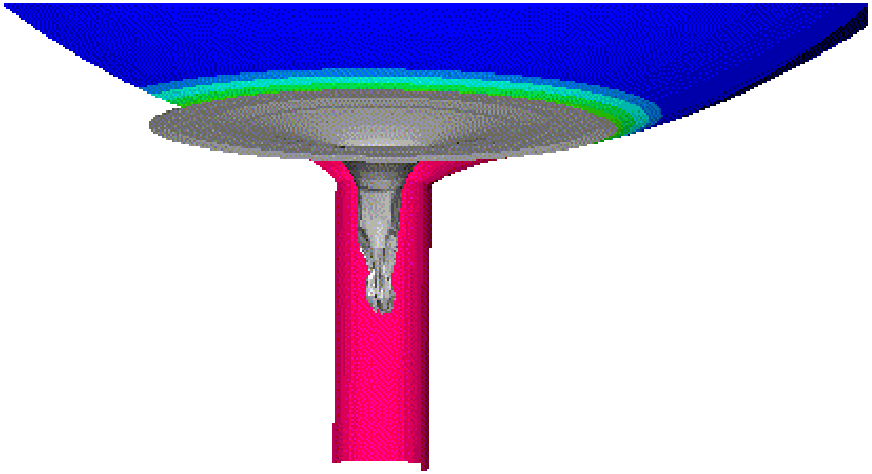
Simulations under ground draining, without slosh due to maneuverings.

Without Baffle: Low Residual Mass when there is no sloshing:

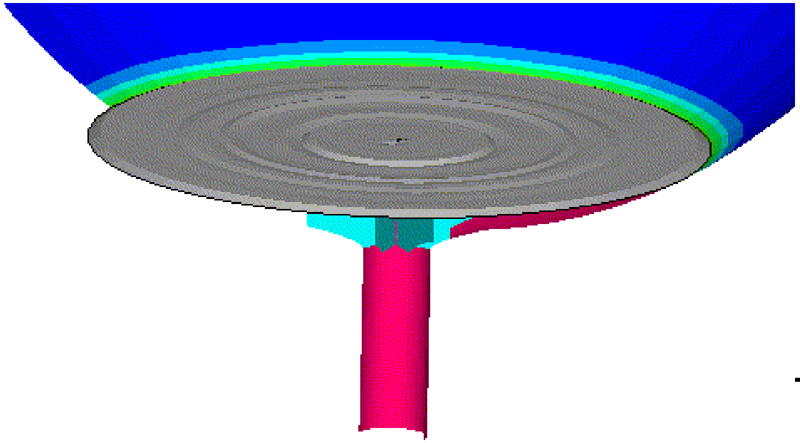
Animation of free surface at later stage



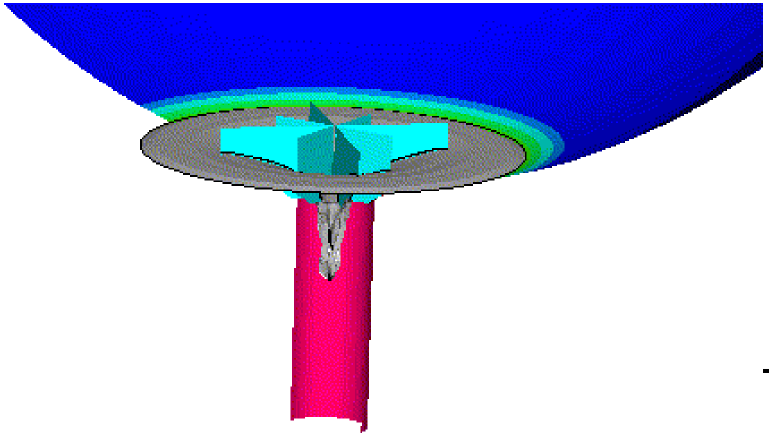
Vapor ingestion, residual mass: 406.6 dimensionless mass



With Baffle: Same Low Residual Mass when there is no sloshing.



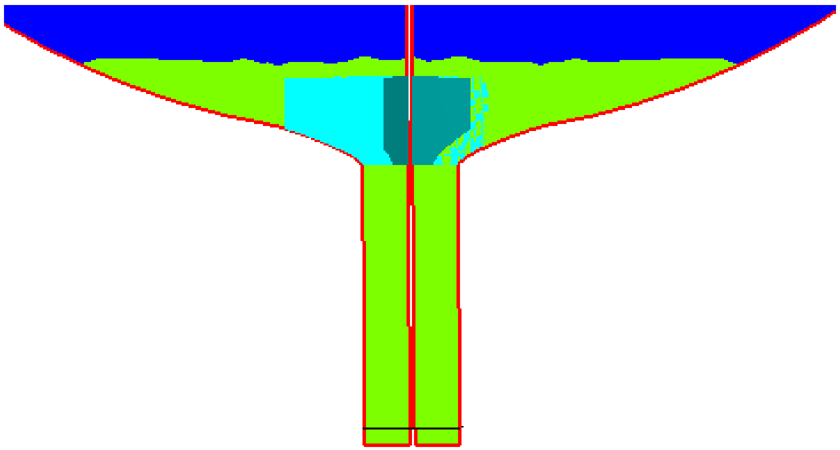
Vapor ingestion, dimensionless residual mass: 416.5



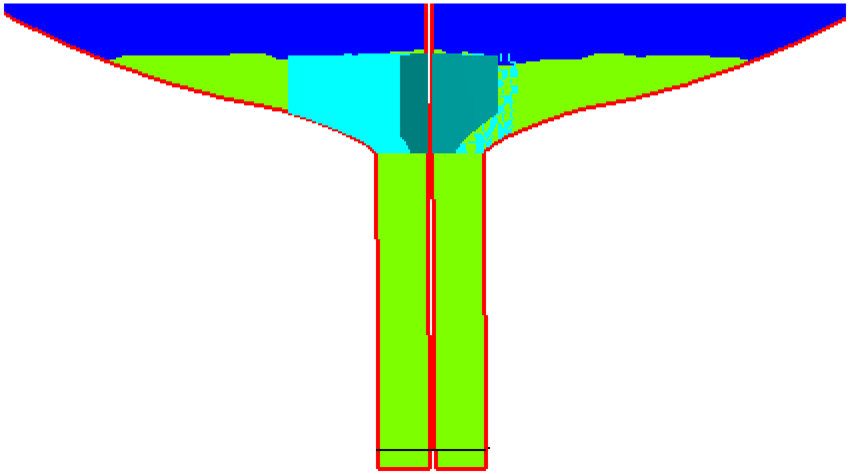
Delivering Break

Simulations under ground draining, without slosh due to maneuverings.

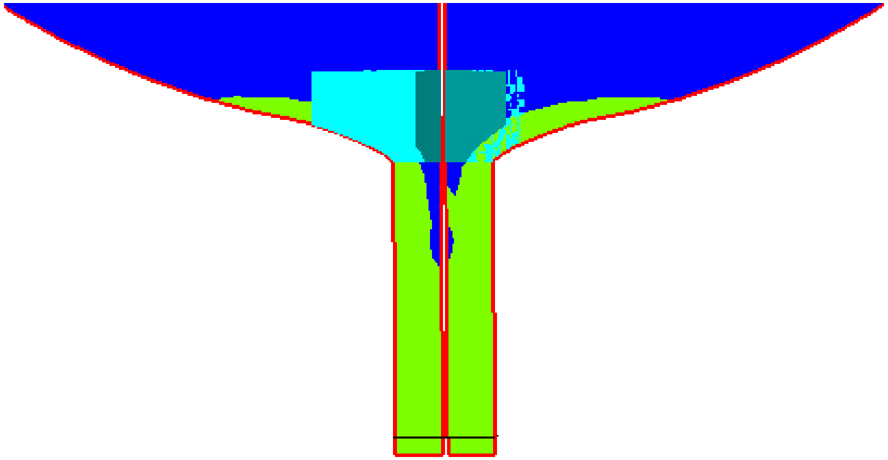
Non-dimensionless residual mass: 1515



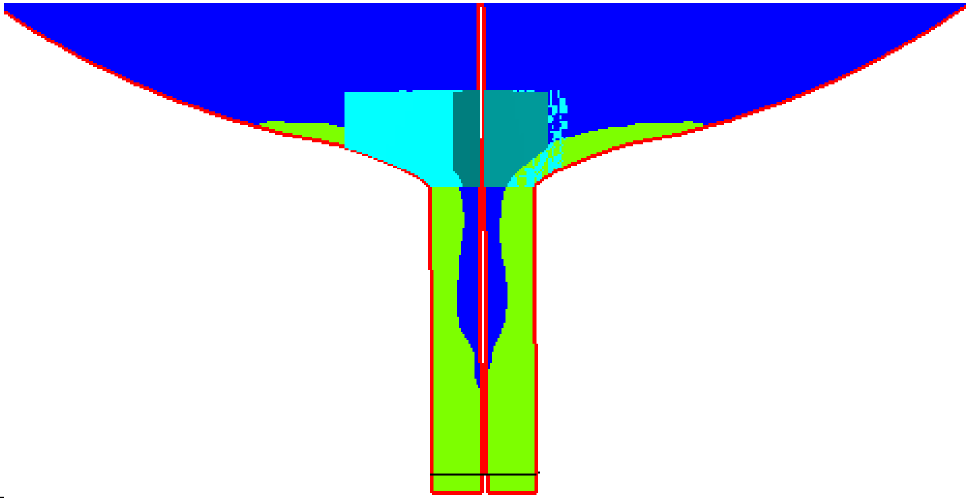
Non-dimensionless residual mass: 965.3



Non-dimensionless residual mass: 416.5



Non-dimensionless residual mass: 360



Summary

. Simulations were made for the LOX tank subjected to the simulated Ares I flight loads under the conditions with anti-vortex baffles and without the baffles.

. The results showed that roll maneuvering and side loads due to pitch and yaw can all lead to swirling flow inside the tank. The vortical flow due to roll is symmetrical with respect to the tank center line, while those induced by pitch and yaw maneuverings showed two vortices side by side.

. The swirling flows are undesirable. They cause surface dip during the late stage of drainage and non-uniform flow velocity in the drainage pipe. Secondary flow velocity component is as high as 10% of the draining velocity.

. The swirling flows in the drainage pipe during the Upper Stage Burn are mainly the results of the residual vortices inside the tank.

. Baffles are shown to be able to effectively suppress the swirling flows into the drainage pipe.