CFD Analysis of Spacecraft Vehicle Fuel Tank to Reduce Sloshing by using ANSYS Fluent

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Abstract— In present work an attempt is made to analyze bullet headed spacecraft fuel tank by using Ansys Fluent 14.5 tank is partially filled with liquid oxygen (Lox). Two fuel tanks with and without baffles considered to study splatter behavior of fuel. The tanks were accelerated to 15 m/s2 in positive X direction for 1 second. From analysis it is found that intensity of sloshing is highly decreased in the fuel tank which is provided with baffles. The effects of baffles on fluid behavior are clearly seen in results drawn. Pressure distribution in both fuel tanks was determined and it is found pressure is less in fuel tank provided with baffles. Further work can be expandable to achieve more stability of fuel tank by varying number, shape and size of baffles.

Key words: Sloshing, CFD, Baffles, Lox

I. INTRODUCTION

Partially filled tanks with liquid fuels which are under acceleration are normally subjected to oscillation of fuel inside the tank [1].In the supercritical condition, perturbations created on the surface of the liquid cause waves to travel with the direction of the flow. On the other hand, surface waves can travel upstream and downstream in the subcritical condition [2]. However, the amplitude of slosh depends on the Amplitude and frequency of the tank motion, liquid-fill depth, liquid properties and tank geometry. The resonance in the case of horizontal excitation occurs when the external forcing frequency is close to the natural frequency of the liquid. Hence liquid sloshing is a practical problem with regard to the safety of transportation systems, such as oil tankers on highways, liquid tank cars on railroads, oceangoing vessels with liquid cargo, propellant tank used in satellites and other spacecraft vehicles, and several others [3]. Basic approaches to fluid- structure interaction can be given by four different methods Lagrangian approach; Euler approach; Euler and Lagrangian approach and SPH [4]. The VOF method is a very robust and flexible method than other methods for simulating complicated free surface. It is able to capture complex surface geometries having overturning waves and splashing.

It is a challenging task to study sloshing due to the presence of complex flow interactions with the container [5]. Depending on the type of disturbance and container shape, the free liquid surface may experience different types of motion including simple planar, non-planar, rotational, irregular beating, symmetric, asymmetric, quasi-periodic and chaotic. The effectiveness of baffles in suppressing fluid slosh, however, is dependent upon its geometry and layout. Furthermore, the slosh control analyses of baffles designs necessitate considerations of the transient fluid slosh behavior.

II. COMPUTATIONAL STUDY

The fuel tank was configured with baffles (fig.1) and without baffles (fig.2) is modeled and imported from CATIA V.5, comparison was made between the two using CFD analysis tools. The dimensions of the fuel tank are given in the table.1.The dimensions of the baffles are given in table.2.Both the configurations (with and without baffles) were set into same accelerated translation motion of -15 m/s^2 in the direction of +X axis, -9.8 m/s^2 in the direction of +Y axis, -0 m/s^2 in the direction of +Z axis. As the tank's motion actuates and bears acceleration for 1 second in the direction of +X axis, Liquid Oxygen experiences force in opposite direction of same magnitude according to the Newton's third law of motion.

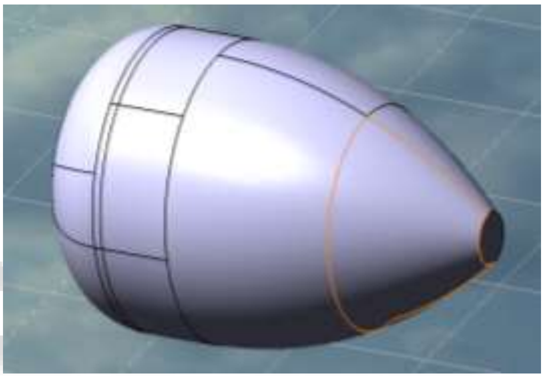

Fig. 1: Fuel tank without baffles.

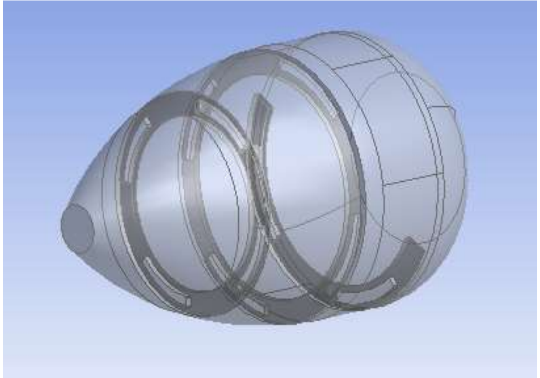

Fig. 2: Fuel tank with baffles

Name of parameter	Dimension in (mm)
Inlet diameter	150
Height(Y Axis)	850
Length(X Axis)	1550

Table 1: Dimensions of fuel tank

Name of parameter	Dimension(mm)
Thickness	25
Depth	75
Number of baffles	2 full circular 1 semi circular

Table 2: Dimensions of baffles

Baffle no	Baffle shape	Position from inlet(mm)
1	Full circular	500
2	Full circular	850
3	Semi circular	1200

Table.3: Position of baffles from inlet.

ANSYS 14.5 software was used to mesh the computational domain of the fuel tank under consideration. The volume of fuel tank as the control volume was the domain taken in consideration for the subsequent analysis. ANSYS FLUENT 14.5 commercial package was used to perform the CFD simulations. Fig.3 and fig.4 shows the meshed geometry of fuel tank.

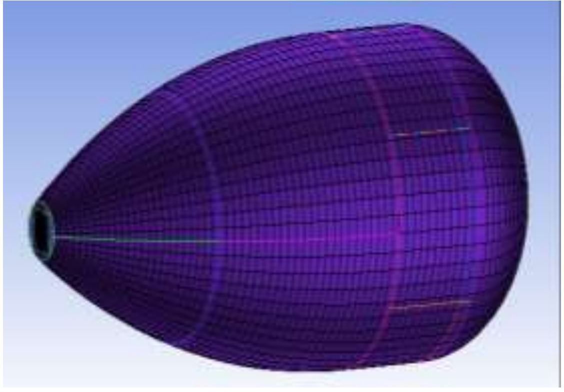

Fig. 3: Meshed geometry without baffles.

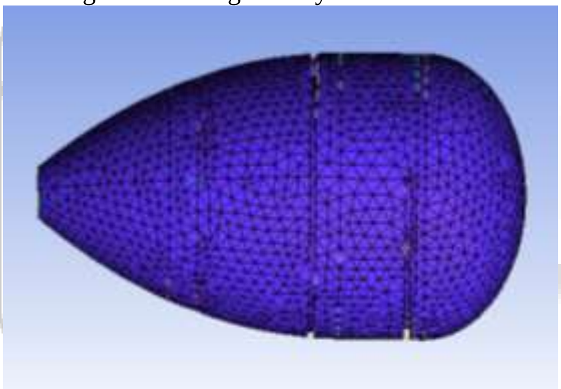

Fig. 4: Meshed geometry with baffles,

Table 4 and table 5 gives mesh information of fuel tank without and with baffles respectively.

Number of Elements	23268
Number of Nodes	20794

Table 4: Mesh information of fuel tank without baffles

Number of Elements	79841
Number of Nodes	18582

Table 5: Mesh information of fuel tank without baffles

III. COMPUTATIONAL MODELING

A. Computational Model

As the tank consist two immiscible fluids (Lox & Helium) it is important to select appropriate model. Volume of fluid multiphase model is considered to predict the splatter behavior of fuel under acceleration.VOF model helps to capture the position of interface between two or more immiscible fluids (Lox & He).It is assumed that 50% of tank volume is occupied by liquid oxygen fuel. Tank is accelerated to 15 m/s^2 in X direction for one second. Table 6 gives properties of Lox and helium.

Property	Liquid Oxygen	Helium
Density(Kg/m)	1142	0.1625
Specific heat(J/kg-k)	1699	5193
Thermal conductivity (W/m-k)	0.15	0.152
Viscosity(Kg/m-s)	0.0001958	1.55X10^{-5}
Molecular weight(Kg/kg mol)	31.99	4.002

Table 6: Properties of Lox and Helium.

B. Governing Equations

Volume fraction equation is given by

$$\frac{1}{\rho_q}\left[\frac{\partial}{\partial t}\left(\alpha_q\rho_q\right) + \nabla\cdot\left(\alpha_q\rho_q\vec{v}_q\right) = S_{\alpha_q} + \sum_{p=1}^{n}\left(\dot{m}_{pq} - \dot{m}_{qp}\right)\right]$$

Where, $\dot{m}_{qp}$ is mass transfer from phase q to phase p and $\dot{m}_{pq}$ is mass transfer from phase p to phase q.

The volume fraction equation was solved using explicit time discretization. In the explicit approach, standard finite interpolation schemes were applied to the volume fraction values computed at the previous time step.

$$\frac{\alpha_q^{n+1}\rho_q^{n+1} - \alpha_q^{n}\rho_q^{n}}{\Delta t}V + \sum_f\left(\rho_q U_f^{n}\alpha_q^{n}, f\right) = \sum_{p=1}^{n}\left(\dot{m}_{pq} - \dot{m}_{qp}\right) + S_{\alpha_q}]V$$

Where,
n+1 = index for new (current) time step
n = index for previous time step

Face value of the qth volume fraction, computed from the first- or second- order

Upwind, QUICK, modified HRIC, compressive, or CICSAM scheme.

V = volume of cell

Uf = volume flux through the face, based on normal velocity.

Momentum equation is given by

$$\frac{\partial}{\partial t}(\rho\vec{v}) + \nabla\cdot(\rho\vec{v}\vec{v}) = -\nabla p + \nabla\cdot\left[\mu\left(\nabla\vec{v} + \nabla\vec{v}^{T}\right)\right] + \rho\vec{g} + \vec{F}$$

Energy equation is given by

$$\frac{\partial}{\partial t}(\rho E) + \nabla\cdot\left(\vec{v}(\rho E + p)\right) = \nabla\cdot\left[\left(k_{eff}\nabla T\right)\right] + S_h$$

C. Boundary conditions and Solution Method

For computational purpose domain is defined with boundary conditions which were defined as inlet, int_fluid and walls. General solution setup is taken as pressure based solver with absolute velocity in transient condition. Table 7 gives brief inputs given to solver stage.

General setup	Pressure based solver with absolute velocity in transient condition.
Models	Multiphase-Volume of fluid
materials	Fluid-Helium, Lox Solid-Aluminum
Phases	Helium-Primary phase Lox- Secondary phase
Boundary conditions	Inlet.1 Int_fluid Walls
Solution methods	Scheme-Simple Gradient- Green Gauss node based Momentum-Second order upwind

	Volume fraction-Geo-Reconstruct
Solution controls	Relaxation factor Pressure-0.1 Density-1 Momentum-0.1 Body forces-1 Energy-1
Solution initialization	Standard initialization with relative to cell zone reference frame at room temperature(300K)
Run calculation	Time step size-0.001 second Number of time steps-1000

Table 7: Solver inputs

IV. RESULTS AND DISCUSSION

A. Lox Volume Fraction

Results of analysis are clearly observed and it is found that initially there were no disturbances on free surface of fuel at t=0 second for the both tanks (with and without baffles).Fig 5 shows the fluid position in the tank without baffles when there is no acceleration.

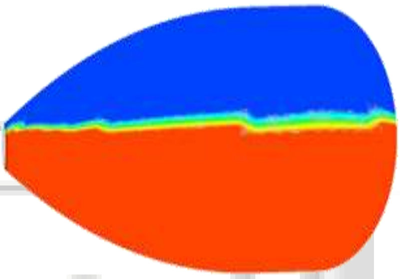

Fig. 5: Fuel position in the fuel tank without baffles at t=0 second.

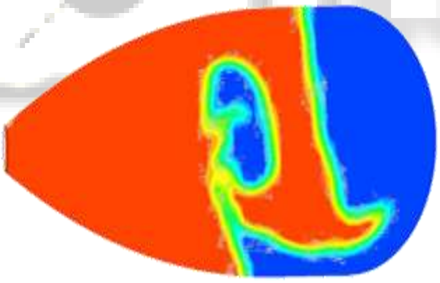

Fig. 6: Fuel position in the fuel tank without baffles at t=1 second

Fig.6 shows the fuel position in the fuel tank without baffles which is accelerated to 15 m/s2 for one second. By observing figure 6 it is found that when tank was at initial position there were no disturbances on free surface of Lox, but when the tank reaches final position there were an abrupt disturbance of Lox volume which overlaps on own surface and turbulence environment created (in figure saffron color indicates 100% volume fraction intensity of Lox and blue color indicates 0% volume fraction intensity of Lox)

Fig 7 shows the initial position of fuel in the fuel tank provided with baffles

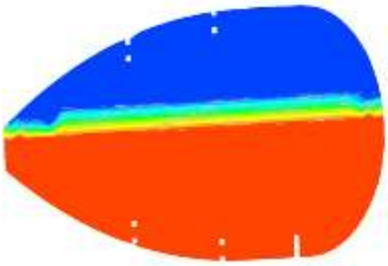

Fig. 7: Fuel position in the fuel tank with baffles at t=0 second.

Figure.8 shows the fuel position in the fuel tank with baffles which is accelerated to 15 m/s^2 for one second

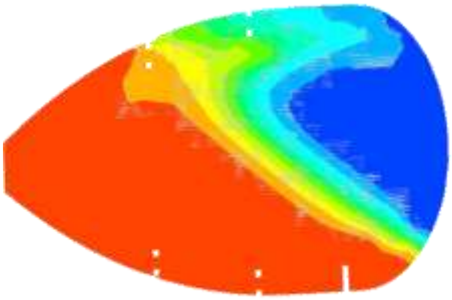

Fig. 8: Fuel position in fuel the fuel tank provided with baffles at t=1 second.

From fig.7 and fig.8 it is found that there were no disturbances at initial position but in final (at t=1 second) position there were free surface disturbances of Lox, from fig.6 and fig.8 one can say that sloshing is significantly reduced in fuel tank designed with baffles. There is no overlapping of fluid is clearly identified as in the fuel tank without baffles.

B. Pressure Contours

Fig.9 shows pressure distribution in fuel tank without baffles, due to high intensity of sloshing the maximum value of pressure is 9.6X102 Pa and minimum pressure is -1.4X104 Pa.

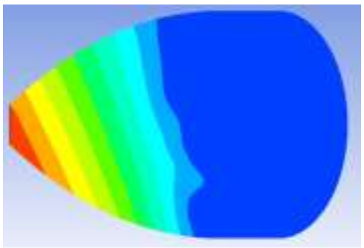

Fig. 9: Pressure distribution in the fuel tank without baffles at t=1 second.

Fig.10 indicates pressure distribution in fuel tank with baffles, the maximum value of pressure is 6.4X10^2 Pa and minimum value is -3.17X10^4 Pa.

From fig.9 and fig.10 we can say that pressure in fuel tank without baffle is more due to high intense sloshing where as pressure in fuel tank with baffles is less as there is significant reduction in sloshing. Table no 8 gives pressure values for both tanks.

As bullet headed tank is provided with 2 full circular baffles situated on entire inner circumferential of the tank so contact between liquid fuel and baffle surface restrict the free oscillation where as fuel tank without baffles there is no restriction for free oscillation of fuel.

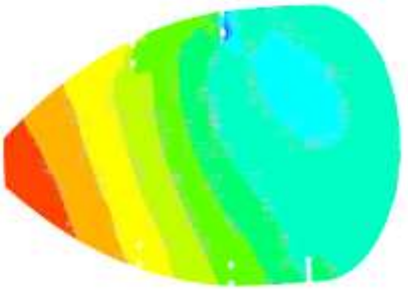

Fig. 10: Pressure distribution in the fuel tank with baffles at t=1 second.

Tank geometry	**Maximum pressure(Pa)**	**Minimum pressure(Pa)**
Tank without baffles	$9.6X10^2$	$-1.4X10^4$
Tank with baffles	$6.4X10^2$	$-3.17X10^4$

Table.8: Pressure contour values

As bullet headed tank is provided with 2 full circular baffles situated on entire inner circumferential of the tank so contact between liquid fuel and baffle surface restrict the free oscillation where as fuel tank without baffles there is no restriction for free oscillation of fuel.

Fig.11.A to fig.11C shows fuel position in the fuel tank without baffles which is accelerated to 15 m/s^2 for 1 second.

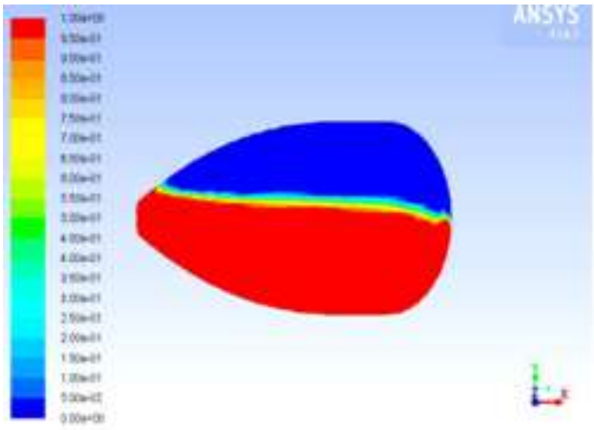

Fig.11A: fuel position in the fuel tank without baffles at t=0

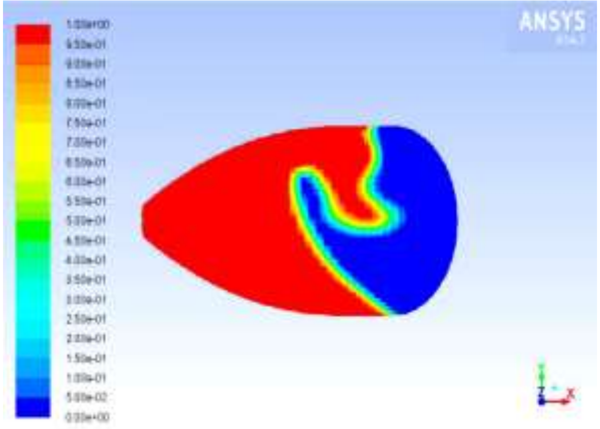

Fig. 11B: fuel position in the fuel tank without baffles at 0 < t < 1 sec

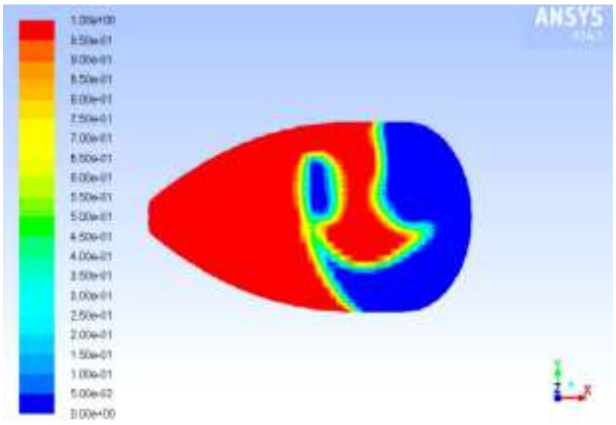

Fig. 11C: fuel position in the fuel tank without baffles at t=1 sec

Fig.12A to fih.12C shows fuel position in the fuel tank with baffles which is accelerated to 15 m/s2 for 1 second.

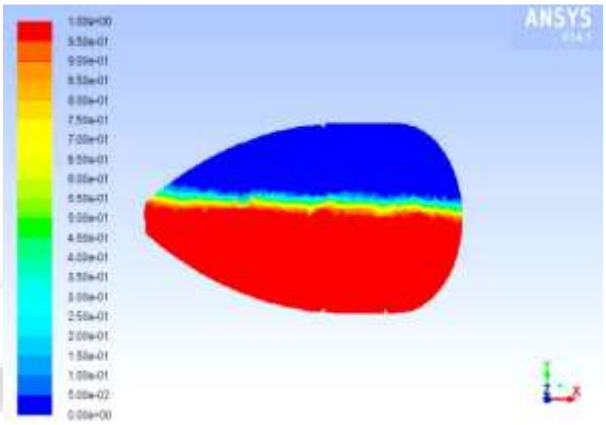

Fig.12A: fuel position in the fuel tank with baffles at t=0

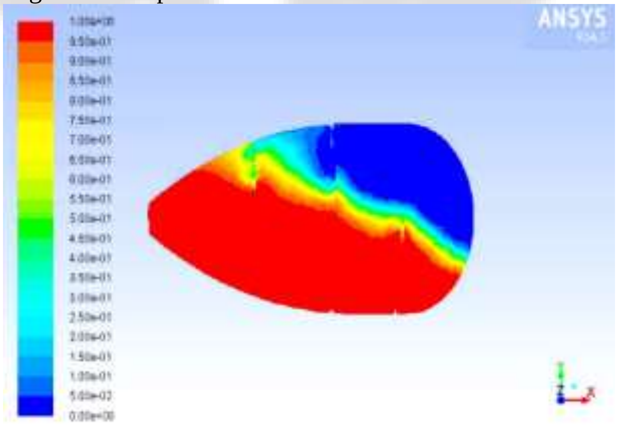

Fig. 12B: fuel position in the fuel tank with baffles at 0 < t < 1 sec

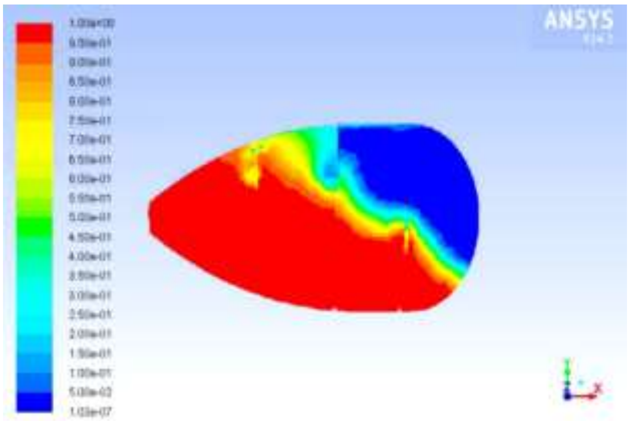

Fig. 12C: fuel position in the fuel tank with baffles at t=1 sec

V. CONCLUSIONS

Tremendous work has been done to minimize sloshing in fuel tank, however it’s impossible to nullify the sloshing but we can minimize its effect significantly which reduces the chances of auto flammability, noise and vibration in order to maintain stability of fuel tank under acceleration and deceleration.

With regards to the computational simulation in the present study the following conclusions can be drawn

- Sloshing is significantly reduced in the fuel tank which is provided with baffles.
- Tendency of slosh is highly influenced by shape, size and numbers of baffles.
- From pressure contours it is clear that pressure value in the fuel tank with baffles is less than the value of pressure in the fuel tank without baffles.
- Design optimization can be forecasted in the development of an anti-slosh fuel tank geometry.

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