Numerical Investigations on Unstable Direct Contact Condensation of Cryogenic Fluids

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Abstract

A typical problem of Direct Contact Condensation (DCC) occurs at the LOX booster turbopump exit of oxidiser rich staged combustion cycle based semi-cryogenic rocket engines, where the hot gas mixture (predominantly oxygen and small amounts of combustion products) runs that the turbine mixers with LOX from the pump exit. This complex multiphase phenomena leads to the formation of solid CO₂ & H₂O, which is undesirable for the functioning of the main LOX turbopump. As a starting point for solving this complex problem, in this study, the hot gas mixture is taken as pure oxygen and hence, DCC of pure gaseous oxygen jets in subcooled liquid oxygen is simulated using the commercial CFD package ANSYS CFX®. A two fluid model along with the thermal phase change model is employed for capturing the heat and mass transfer effects. The study mainly focuses on the subsonic DCC bubbling regime, which is reported as unstable with bubble formation, elongation, necking and collapsing effects. The heat transfer coefficients over a period of time will be computed and the various stages of bubbling have been analysed with the help of gas volume fraction and numerical simulations. The results obtained for DCC of GOX-LOX mixtures is in qualitative agreement with the experimental results on DCC of steam-water mixtures.

Objective

• In a typical semi-cryogenic rocket engine working on staged combustion cycle, the booster turbine is run by the oxidiser rich combustion products from the pre-burner, which then mix with LOX at the booster pump outlet.
• This leads to a complex direct contact condensation problem with heat transfer and phase change, including solidification of the combustion products CO₂ & H₂O.
• The design of this direct contact condenser is an optimisation problem where the heat and mass transfer characteristics should not be so imenso the size of solid contaminants which are outside the safety operational limits and at the same time, it should be high enough to convert the entire gas into liquid.
• The goal of this paper is to is to obtain the overall heat and mass transfer characteristics when pure oxygen gas jet/plumes condense in a pool of subcooled liquid oxygen, which provides an initial understanding to solve the complex heat and mass transfer direct contact condensation problem.

Literature Review

• In the open literature, there is no works reported on DCC of oxygen gas jets in liquid oxygen and hence, literature review focuses mainly on the DCC of steam jets in subcooled water.
• Chan et al. (1982) studied unstable DCC of steam jets at relatively higher subsonic speeds giving rise to bubble oscillation regimes consisting of the bubble formation, elongation, necking and collapsing stages.
• Some of the pioneering numerical works were done by Gulwani et al. (2006 & 2009) and Dahikar et al. (2010) on DCC of sonic steam jets in subcooled water using the two fluid multiphase formulation in the commercial CFD package ANSYS CFX®.

Geometry and boundary conditions

Table 1 Boundary conditions

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nozzle inlet mass flow rate (kg/s)</td>
<td>0.081</td>
</tr>
<tr>
<td>Nozzle inlet temperature (K)</td>
<td>90.15</td>
</tr>
<tr>
<td>Liquid temperature (K)</td>
<td>65.15</td>
</tr>
<tr>
<td>Tank pressure (MPa)</td>
<td>0.1</td>
</tr>
</tbody>
</table>

• The mass flux at the boundary condition is computed to ensure a DCC bubbling regime
• Gaseous oxygen at saturated condition enters through the nozzle and the initial conditions inside the tank is kept as subcooled liquid oxygen at atmospheric conditions.

Governing equations

\[
\rho \frac{\partial U}{\partial t} + \nabla \cdot (\rho U U) = -\nabla \cdot \Gamma \nabla T + \Gamma \frac{\partial T}{\partial t} + \nabla \cdot (\nabla T \cdot \Gamma) + S \frac{\partial U}{\partial t} + \Gamma \frac{\partial T}{\partial t} \]

Volume constraint:

\[
\sum_{i=1}^{n} \rho_{i} = \text{constant} \]

Pressure constraint:

\[
\rho_{i} P_{i} = \text{constant} \quad \text{for} \quad i = 1, 2 \]

Thermal phase change model:

\[
p_{j} = \rho_{j} (T_{j} - T_{f})
\]

A zero equation model is used to model the heat transfer effects on the gas side so that the gas is brought to the saturation conditions at the interface.

• The heat transfer on the liquid side is modelled using the commonly adopted Ranz-Marshall model as,

\[
\rho_{l} c_{p, l} \frac{\partial T_{l}}{\partial t} = \rho_{l} c_{p, l} \nabla \cdot (\nabla T_{l} \cdot \nabla) + \rho_{l} c_{p, l} (T_{l} - T_{f})
\]

Turbulence model: Standard k-ε turbulence model has been used to model turbulence characteristics in the liquid phase whereas dispersed phase zero equation model has been used on the gas side.

Results and discussion

(a) Grid independence study

(b) Heat transfer characteristics

(c) Bubbling characteristics

(d) Pressure oscillation studies

Figure 1 Geometry with dimensions (all dimensions are in cm)

Figure 2 Variation of heat transfer coefficient with grid size

Figure 3 Variation of heat transfer coefficient with time

Figure 4 Plume shapes for a typical cycle of 30ms - 37ms

Figure 5 Pressure values at an arbitrary point for a typical cycle of 30ms - 37ms

Conclusion

• A two-fluid multiphase formulation with thermal phase change model has been employed to capture the DCC bubbling phenomena in GOX-LOX mixtures.
• It has been observed that DCC condensation provides a heat transfer coefficient of approximately 10 times higher than the typical film condensation heat transfer coefficient for oxygen.
• It has been found that the heat transfer coefficient is maximum during the necking stage for GOX-LOX mixture which is also the case for reported works on steam-water mixtures.
• Pressure oscillations induced by bubbling was studied and it has been identified that peak to peak pressure oscillation amplitude is maximum at the necking stage.
• But, these peak to peak amplitudes are much lower compared to the DCC chugging regimes and hence can be considered comparatively safe from a structural design point of view.

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References