NUMERICAL SIMULATION OF THRUST-DRIVEN CLOSE CONTACT MELTING AT A FROZEN PROPELLANT INTERFACE

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INTRODUCTION

The phase change mechanism and its modelling is of practical interest, especially after the widespread applications of Phase-Change Materials (PCM). Close contact melting is a class of phase change problem, wherein, the melt is “squeezed” out of the interface, owing to an external force. When the external force is the weight of the material being melted, it results in transient behavior of the melt line position, governed by the flow, heat transfer and normal force balance characteristics of the problem. In the absence of convection, the one-dimensional phase change problem is called the “Stefan problem”, wherein Neumann analytical solution predicts the position of the interface, as a function of time. Subsequently, many analytical solutions have been developed to solve simplified two-dimensional problem, wherein the convective effects are neglected or limited to simplified Navier-Stokes equation. Since analytical techniques are typically restricted to simplified problems, solutions for practical industrial problems in more complex domains commonly require numerical solutions to allow insight. Phase change problems come under class of numerical problems called the “Moving Boundary Problem”. Two general techniques in solving phase change problem is “Variable domain technique” (strong technique) and “Fixed domain” (weak technique). The preferred fixed domain technique is the Enthalpy porosity technique. Front tracking methods comprises the “Variable domain technique”. In the present work, a variant of close contact melting process is modelled using the “Front fixing” or “Coordinate transformation” technique.

PROBLEM DESCRIPTION AND APPROACH:

As mentioned earlier, the close contact melting process being studied is as a subset to the novel concept of using frozen propellant for rocket propulsion. The frozen propellant, apart from being an energy source, would be used as a thrust-transmitting member. The propellant melting interface, in the form of a grill structure, melts the frozen propellant, which is squeezed out of the interface by the thrust produced by the engine, thereby giving sufficient pressure difference to enable liquid melt injection into the thrust chamber. This combination of “squeeze flow” and phase change is called “Close Contact Melting” (CCM). The propellant interface serves to melt the propellant and its injection into the thrust chamber. Three basic configurations are considered for the interface: Flat plate, wedge and circular. The basic figure explaining the idea is shown below in Figure 1:

![Figure 1. Melting configuration in application.](image)

The section shown in the above figure, for the melting interface (grill), is circular. The problem is restricted to a two dimensional domain. As only phase change of homogeneous material is being studied, the front fixing technique by coordinate transformation is chosen as the method to track the position of the melting interface, solving the pertinent governing equation. The general schematic of the problem being studied is shown below in Figure 2:
Figure 2. Simplified contact melt configuration.

The melt interface as function of time is marked as \( \delta(t) \). The ‘T’ in the above schematic represents the temperature of the corresponding regions. The varying mass in the above schematic is replaced by thrust of the launch vehicle. A typical melt rate profile can be classified into three zones: start transient, pseudo-steady state and end transient zone.

GOVERNING EQUATIONS AND SOLUTION PROCEDURE:

Momentum equation: (incompressible, laminar)

\[
\rho \frac{Du}{Dt} = -\nabla p + \rho g + \mu \nabla^2 u
\]

Energy equation:

\[
\rho c_p \left( \frac{DT_s}{Dt} \right) = k_s \nabla^2 T_s
\]

\[
\rho c_p l \left( \frac{DT_l}{Dt} \right) = k_l \nabla^2 T_l
\]

Melt Interface equation:

Stefan condition:

\[
\rho L V_n = (k_s \nabla T_s - k_l \nabla T_l) \cdot \vec{N}
\]

Force balance:

\[
m \frac{dV}{dt} = mg - P_f
\]

\( \rho \) - Density
\( C_p \) - Heat capacity of the phase.
\( t \) - time.
\( g \) - gravity
\( P_f \) - Pressure force.
\( N \) - normal vector to the melt interface
\( L \) - latent heat (solid-liquid)

Subscript:

\( l \) - Liquid region
\( s \) - solid region
\( n \) - normal component

The above equations are transformed to and solved on fixed curvilinear boundary fitted co-ordinate system \((\xi, \eta)\) [1, 4]. The governing equations are solved using the control volume discretization technique on a non-orthogonal grid system, generated by algebraic interpolation method. The momentum equation is solved on a staggered grid arrangement wherein the velocity points shifted to the control volume faces and also, on a collocated grid arrangement. The pressure velocity coupling is achieved through the continuity equation using the SIMPLER algorithm. The energy equations in liquid and solid regions are solved separately then are coupled through the Stefan condition at the interface. The above equations are solved using a “non-iterative” algorithm marching in time at each execution step [1, 2]. The grid generation and the above mentioned solution algorithm was coded in MATLAB.

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REFERENCES