Numerical Investigation of Slag Behavior for RSRM

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ABSTRACT

It is known that the flowfield of the SRM (Solid Rocket Motor) is very complicated due to the complex characteristics of turbulent multi-phase flow, chemical reaction, particle combustion, evaporation, breakup and agglomeration etc. It requires multi-phase calculations, chemical reaction simulation, and particle combustion, evaporation, and breakup models to obtain a better understanding of thermophysics for the SRM design using numerical methods. Also, the slag buildup due to the molten particles is another factor affecting the performance of the SRM. Thus, a more realistic simulation is needed to provide a better design guide to improve the performance of SRM. To achieve this goal, the VOF (Volume Of Fluid) method is used to capture the free surface motion so as to simulate the accumulation of the molten particles (slag) of SRM. A Finite-rate chemistry model is used to simulate the chemical reaction effects. For multi-phase calculations, Hermsen combustion model is used for the AL particle combustion analysis and Taylor Analogy Breakup (TAB) model is used for the particle breakup analysis. An interphase mass-exchange model introduced by Spalding is used for the evaporation calculation. The particle trajectories are calculated using a one-step implicit method for several groups of particle sizes by which the drag forces and heat fluxes are then coupled with the gas phase equations.

The preliminary results predicted a reasonable physical simulation of the particle effects using a simple 2-D solid rocket motor configuration. It shows that the AL/AL2O3 particle sizes are reduced due to the combustion, evaporation, and breakup. The flowfield is disturbed by the particles. Mach number distributions in the nozzle are deformed due to the effect of particle concentrations away from the center line.

The RSRM (Redesigned Solid Rocket Motor) geometry at 67 seconds is employed to investigate the slag behavior in the aft-end cavity with the combustion, evaporation, and breakup models. The particulate phase was assumed to be aluminum oxide (AL2O3) for the preliminary study. It is assumed that the propellant grain of the aft-end cavity has burned out completely at 67 seconds. The geometry and mass flow rate information were provided by the NASA Marshall Space Flight Center. The slag may flow out of the cavity and enter the nozzle due to the accelerations. The molten particles entering the aft-end cavity merge with the slag. The volume of the slag will grow and affect the performance of the RSRM. This shows that the effects of particles and slag on the flowfield are very significant. From the caculation, a flow vortex exists in the aft-end cavity of the RSRM. A stagnation point on the wall is captured. This flow impingement may cause the erosion of the wall. The shape of the vortex is changed due to the slag. The particles entering the cavity may become slag and either flow into or out of the cavity depending on the temperature and the surface tension of the molten particles. An axial gravity force of 2.4g is assumed to simulate the RSRM flowfield at 67 seconds.

The flowfield analysis using the FDNS code in the present research using the proposed models should provide a design guide for the solid rocket motors. The obtained results can give the designer a basic guide line for the use of materials and the nozzle geometry to improve the performance of SRMs.

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OBJECTIVE

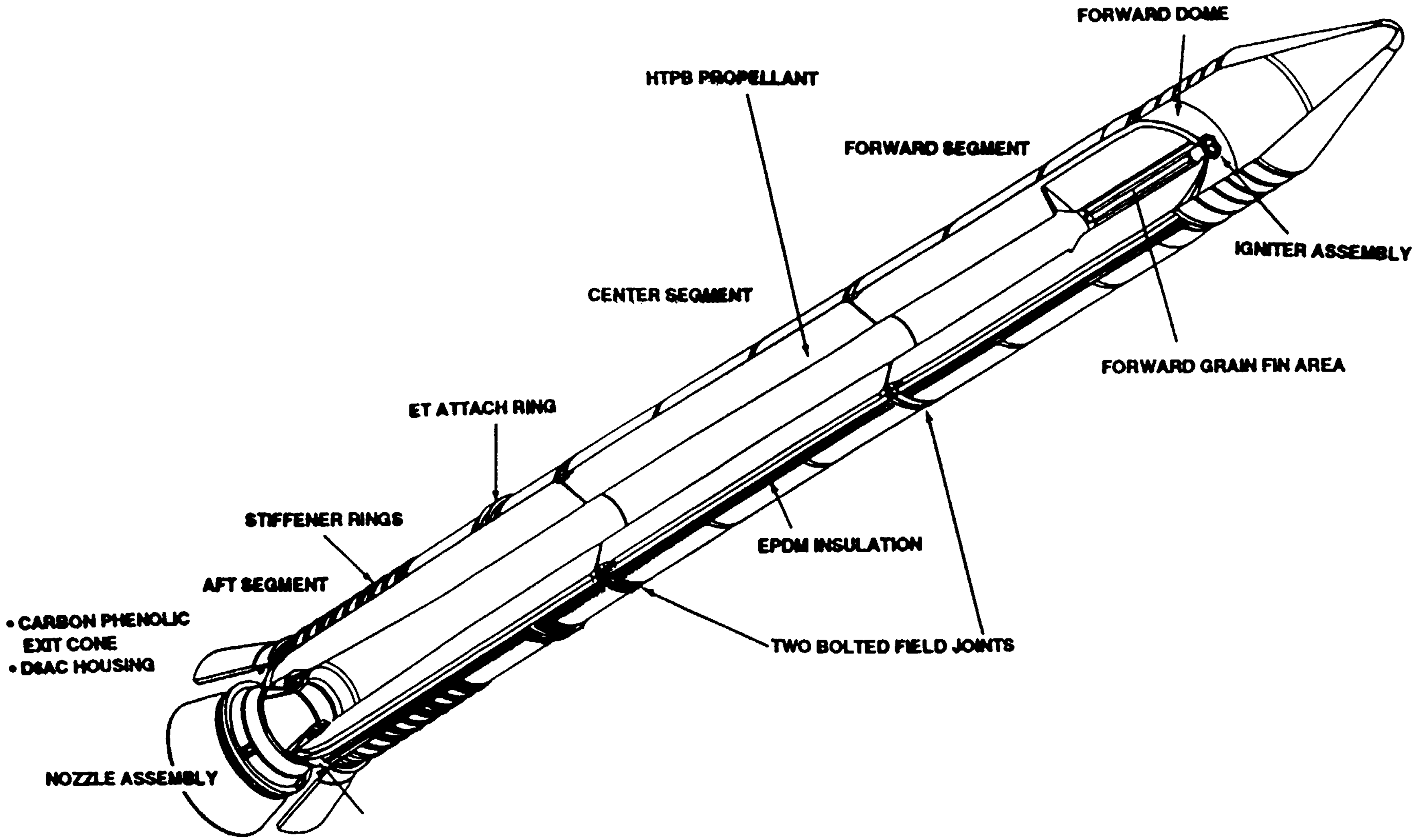
1. BACKGROUND AND GENERAL APPROACH
2. NUMERICAL METHOD
3. APPLICATION
4. CONCLUSIONS
5. FOLLOWING WORK

BACKGROUND & GENERAL APPROACH

- ACCUMULATED SLAG WAS FOUND IN THE AFT-END CAVITY AND NOZZLE.
  ==> WILL THIS AFFECT THE MOTOR PERFORMANCE DUE TO ITS EFFECT ON THE PRESSURE?

- WILL VOF METHOD WORK FOR THE ANALYSIS OF SLAG BEHAVIOR?

THE ASRM



ESI Engineering Sciences, Inc.

VOF Model

The VOF transport equation is given below:

$$\frac{\partial \alpha}{\partial t} + \left(u - u_g\right)_i \frac{\partial \alpha}{\partial x_i} = S_\alpha$$

where α = 1 stands for liquid and α = 0 is for gas. The interface is located at 1 > α > 0. For a given solution of α field, equation (6) can be recast as:

for compressible gas:

$$\frac{\partial \rho_m \phi}{\partial t} + \frac{\partial \rho_m \left(u - u_g\right)_i \phi}{\partial x_i} = S_\phi \, , \alpha < 0.01$$

for incompressible gas:

$$\rho_m \frac{\partial \phi}{\partial t} + \rho_m \left(u - u_g\right)_i \frac{\partial \phi}{\partial x_i} = S_\phi \, , \alpha \geq 0.0$$

and

$$\rho_m = Max\left\{\rho_g , \alpha \rho_\ell\right\}$$

The interface α solution compression procedure is expressed as:

$${}_{new} = Max\left\{0, Min\left[1 , 0.5 + f\left(\alpha_{old} - 0.5\right)\right]\right\}$$

and

$$f = \frac{(Interface\ volume)_{new}}{(Interface\ volume)_{initial}}$$

The surface tension forces in the continuum surface force model is formulated as continuous body forces across the interface. These forces can be written as:

$$F_x = -\sigma\left(\nabla \hat{n}\right)\alpha_x$$

$$F_y = -\sigma\left(\nabla \hat{n}\right)\alpha_y + \left(\frac{|\alpha_y|}{y}\right), for\ 2D, axisymmetric\ case\ only$$

$$F_z = -\sigma\left(\nabla \hat{n}\right)\alpha_z,\quad for\ 3D\ case\ only$$

where

= surface tension constant

$$\nabla \hat{n} = \hat{\alpha}_{xx} + \hat{\alpha}_{yy} + \hat{\alpha}_{zz}$$

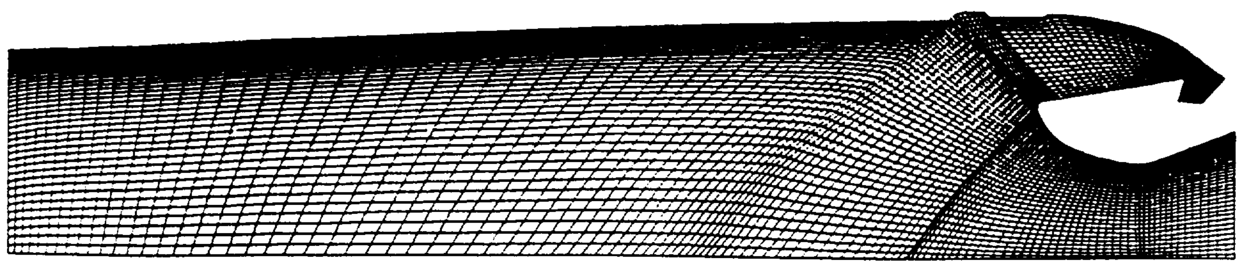
α is 0.5 for the free surface. The VOF method is used to represent the tracking of the free surface between the liquid and gas phase.

APPLICATIONS

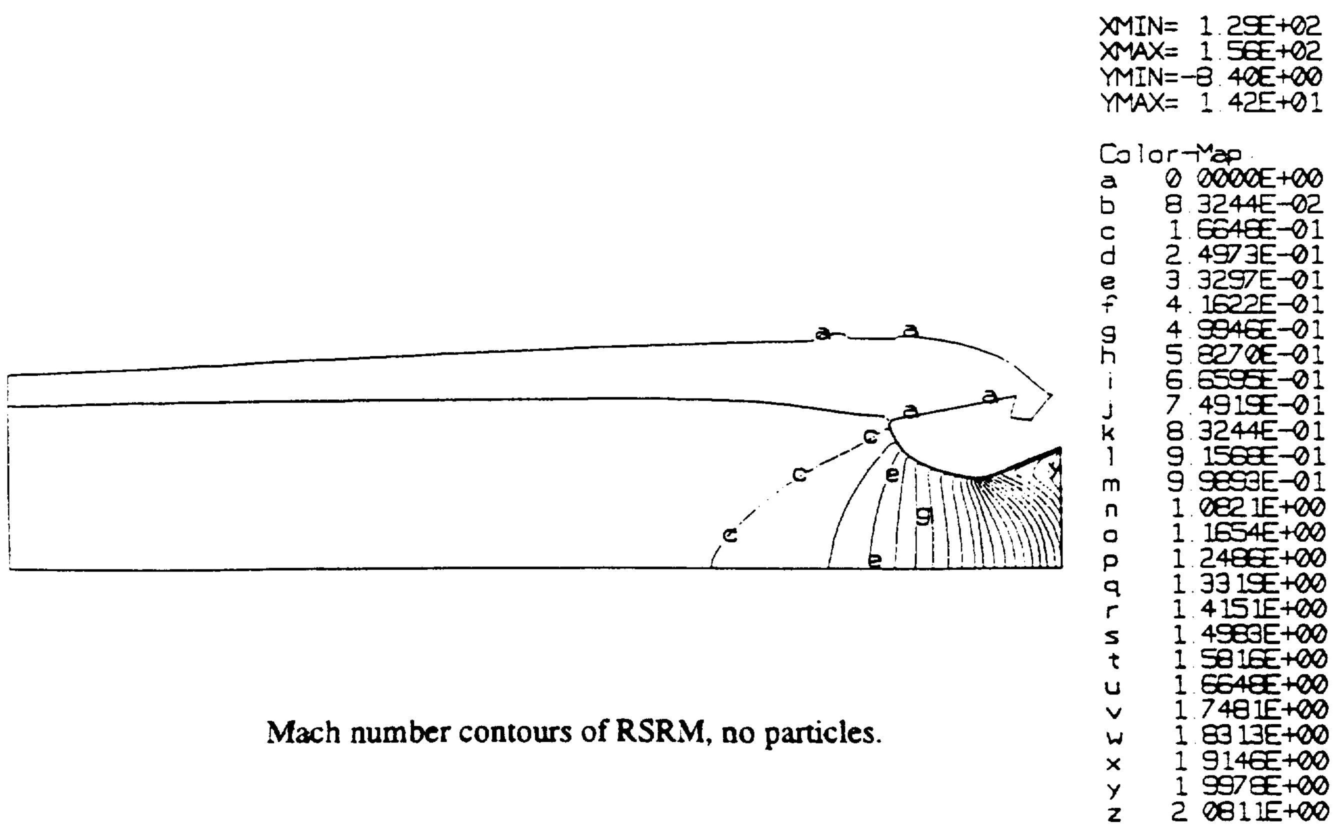
SLAG BEHAVIOR ANALYSIS FOR RSRM CONFIGURATION AT 67 SECONDS

(1) NO PRE-ACCUMULATED SLAG IN THE AFT-END CAVITY
--- 2D AND 3D

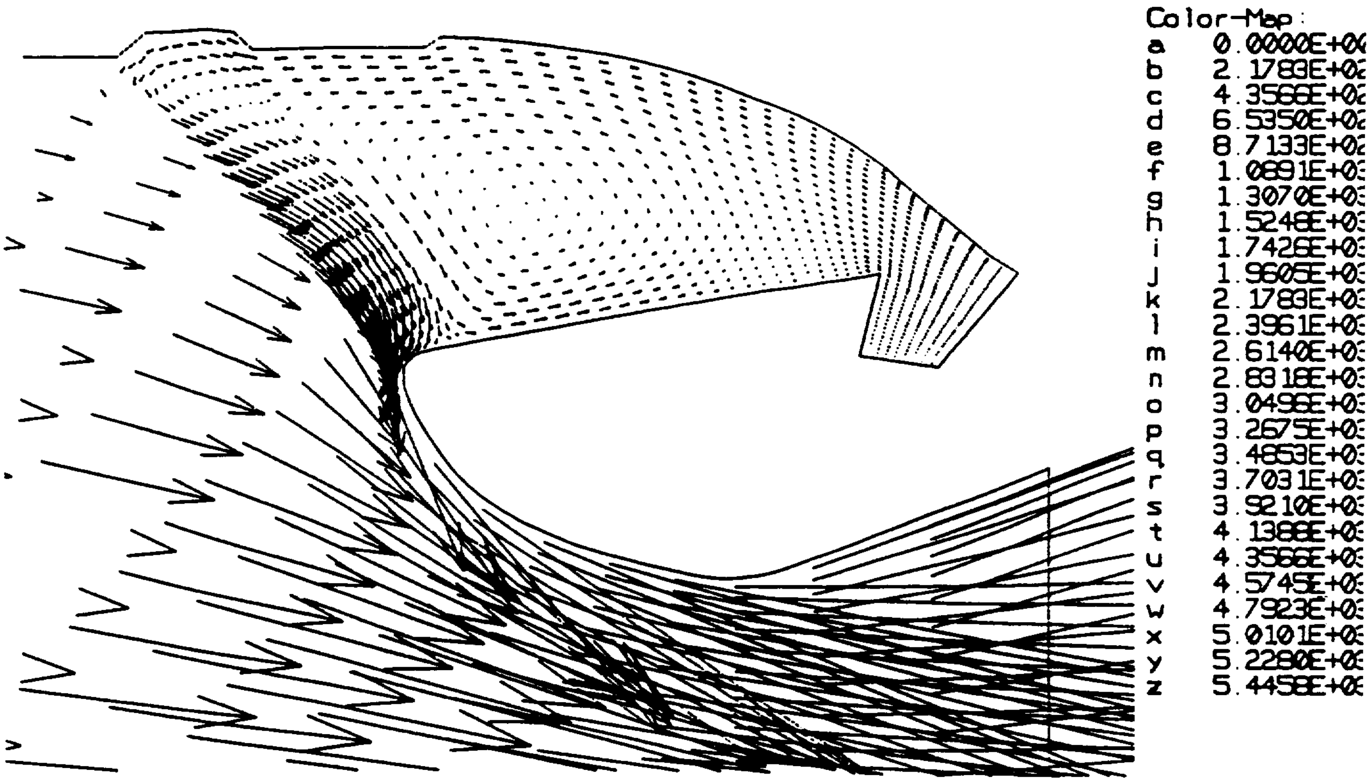
(2) ASSUMED PRE-ACCUMULATED SLAG IN THE AFT-END CAVITY
--- 2D



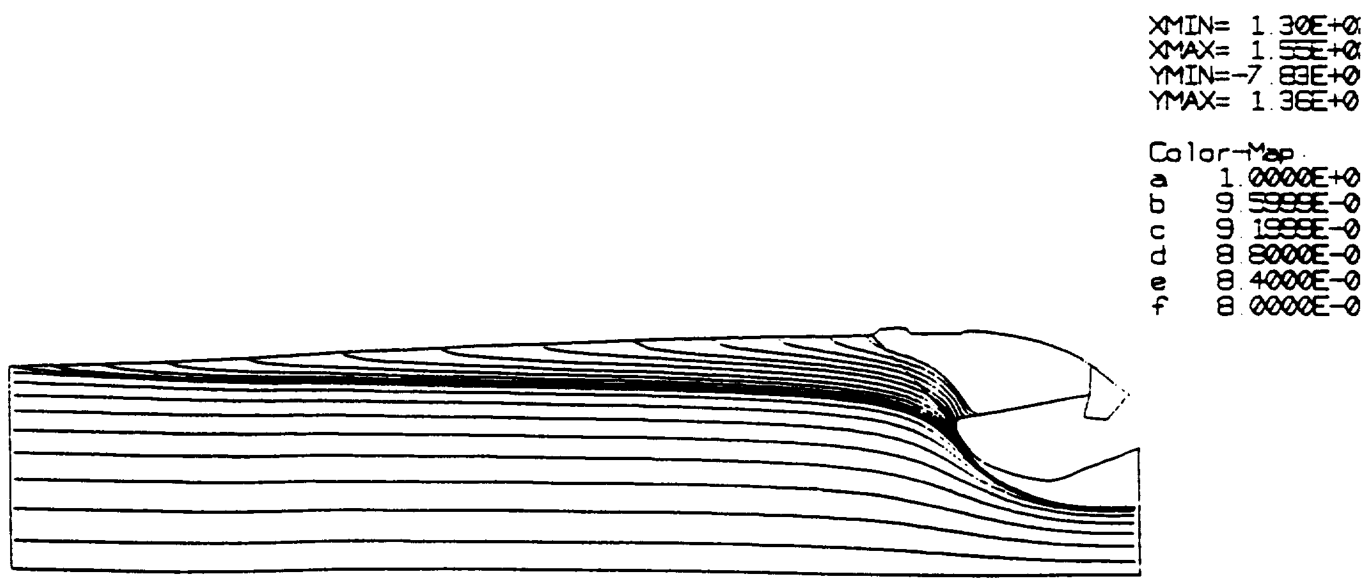
2D Grid system of RSRM configuration.



Mach number contours of RSRM, no particles.

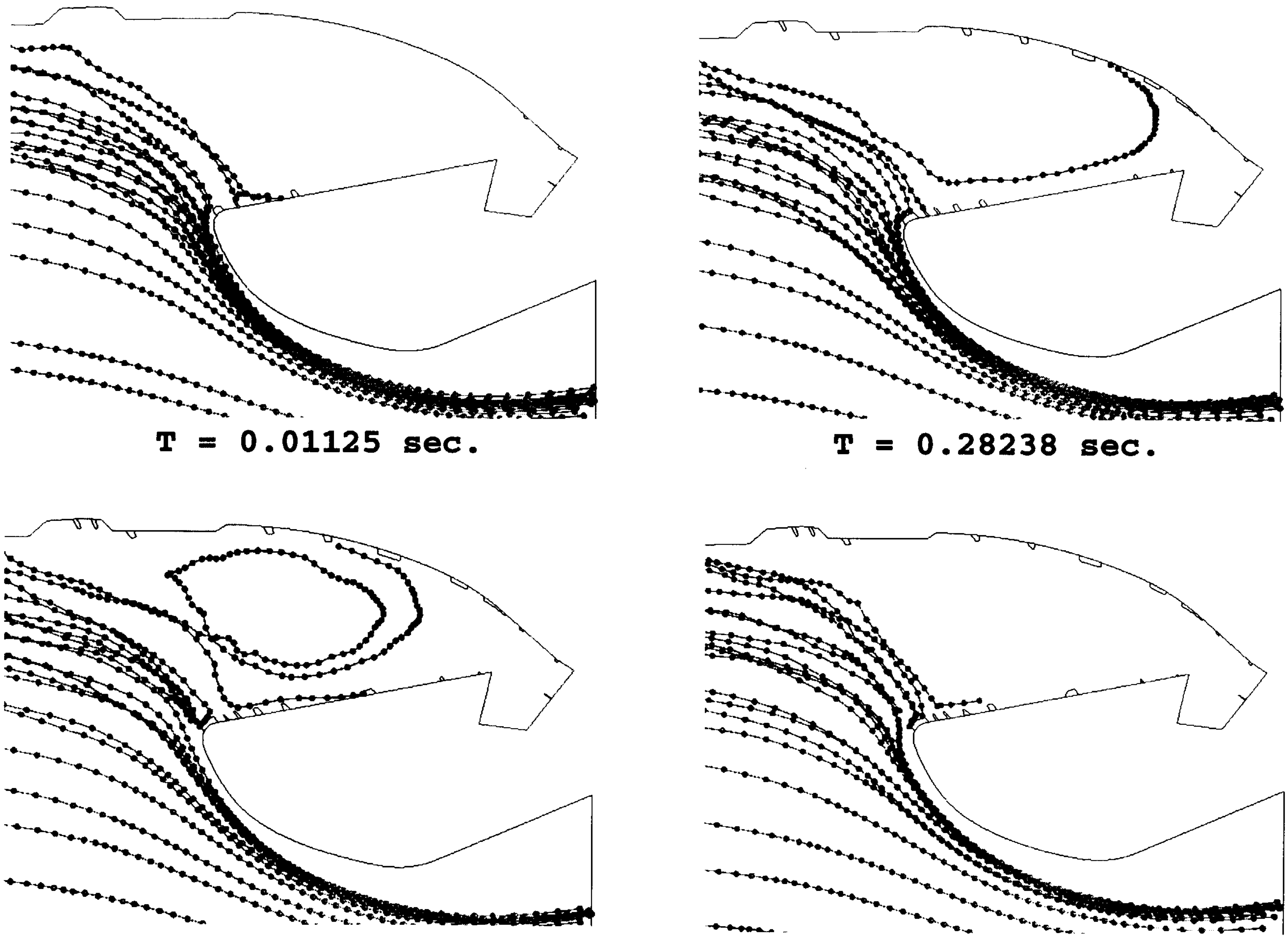


Velocity vectors near the aft-end cavity, no particles.



Particle trajectories.

Slag accunulation in the aft-end cavity



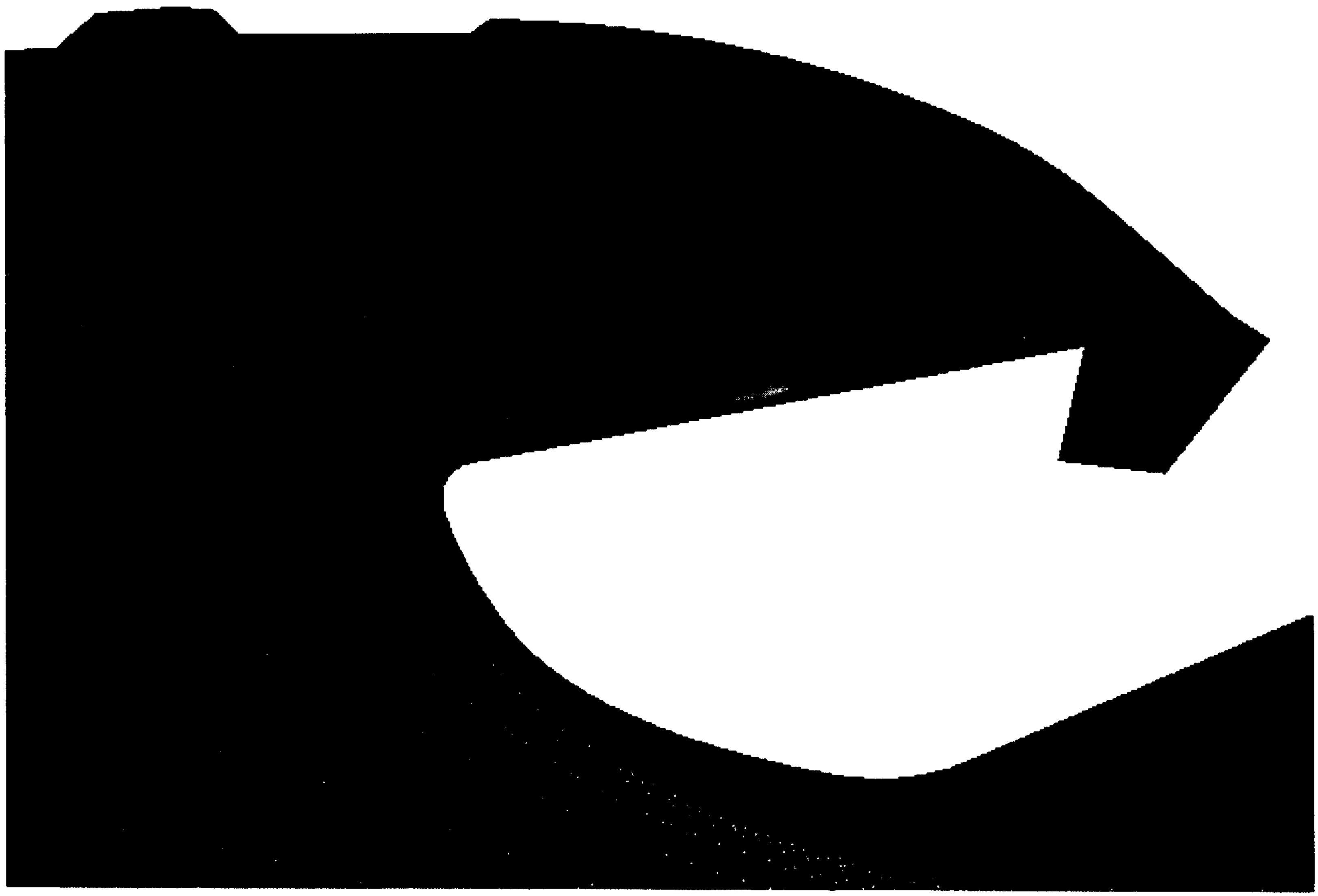
T = 0.01125 sec.

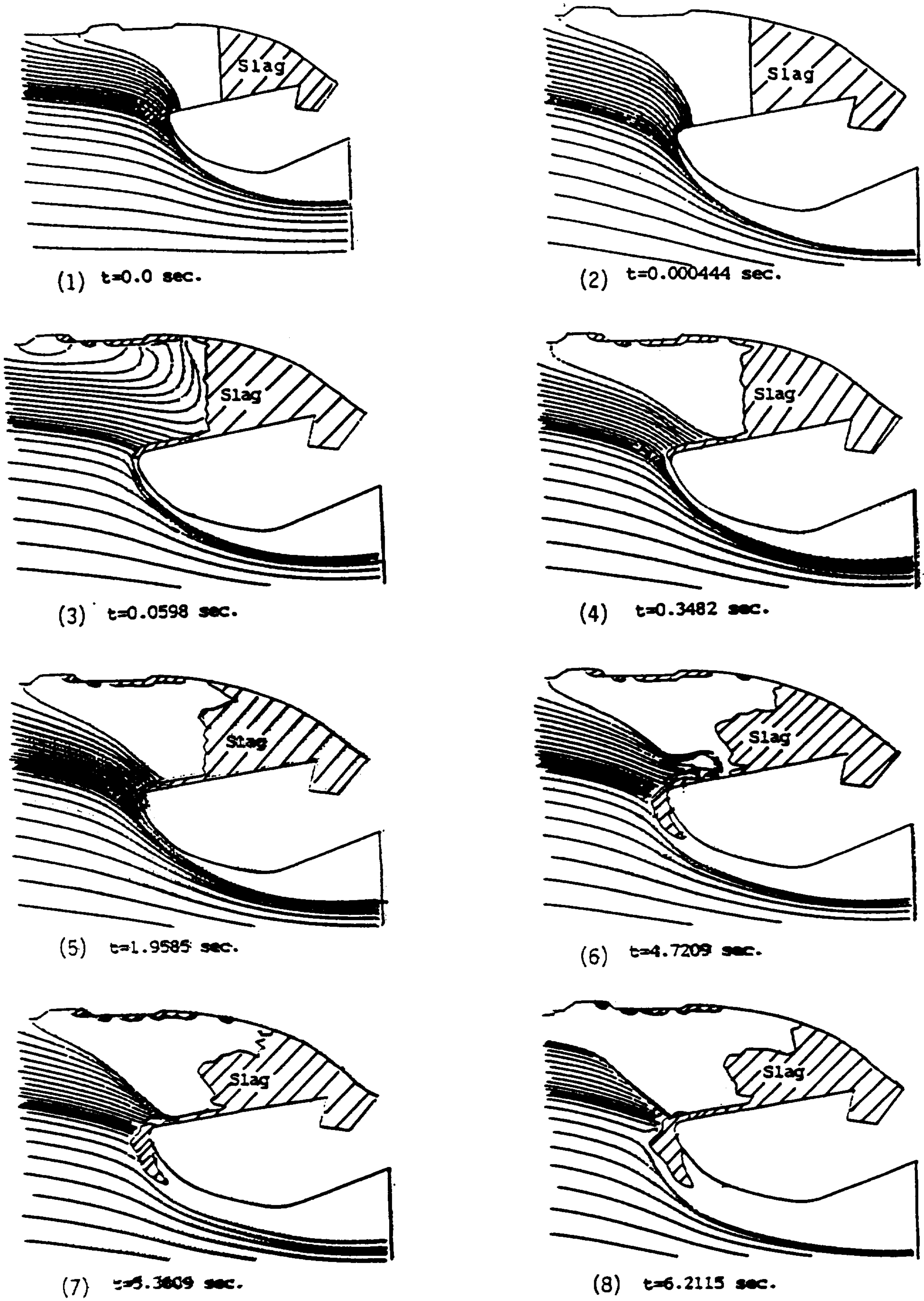
T = 0.28238 sec.

T = 0.91531 sec.

T = 2.31444 sec.

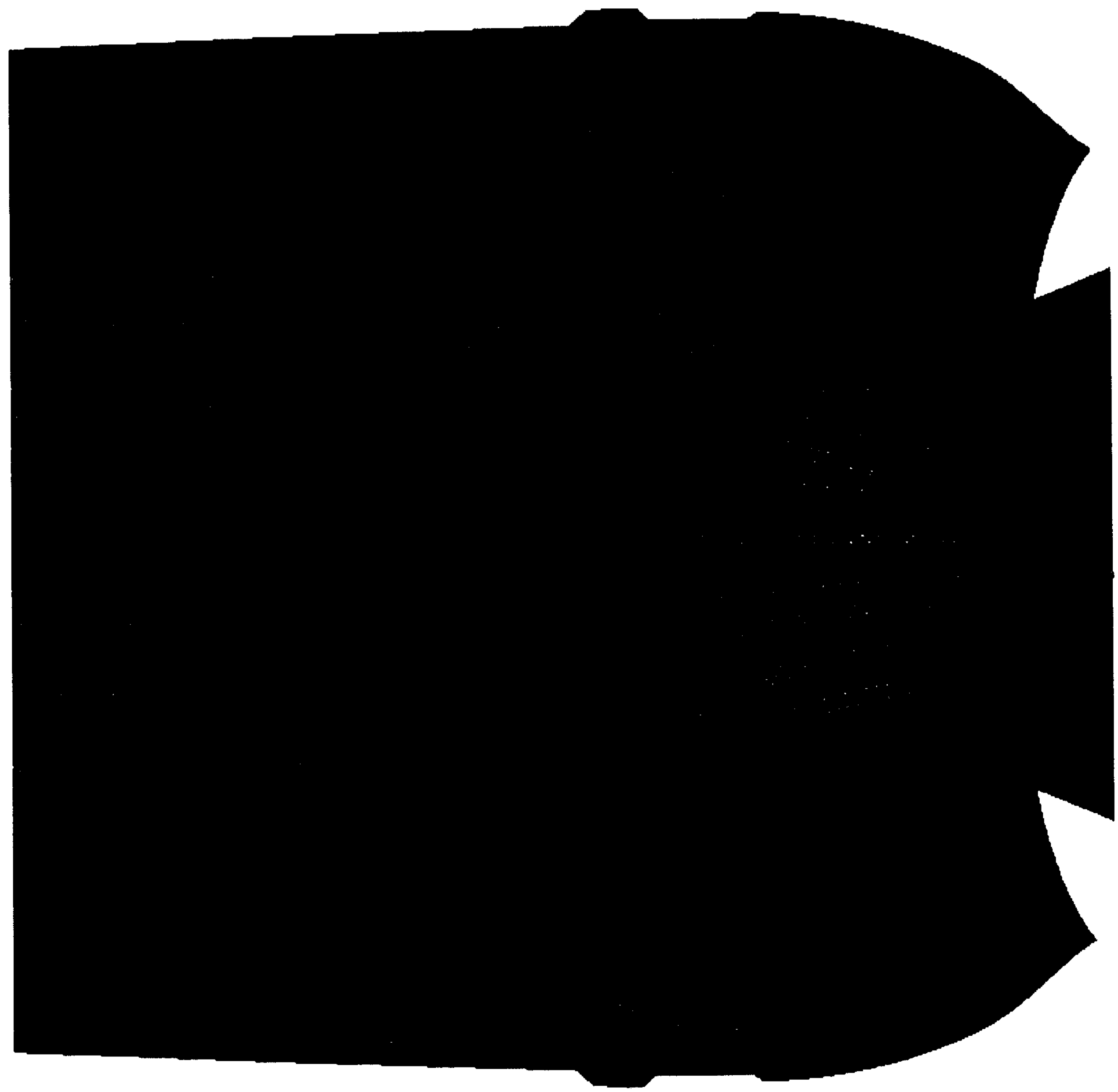
Slag accumulation at T = 2.3144 sec.



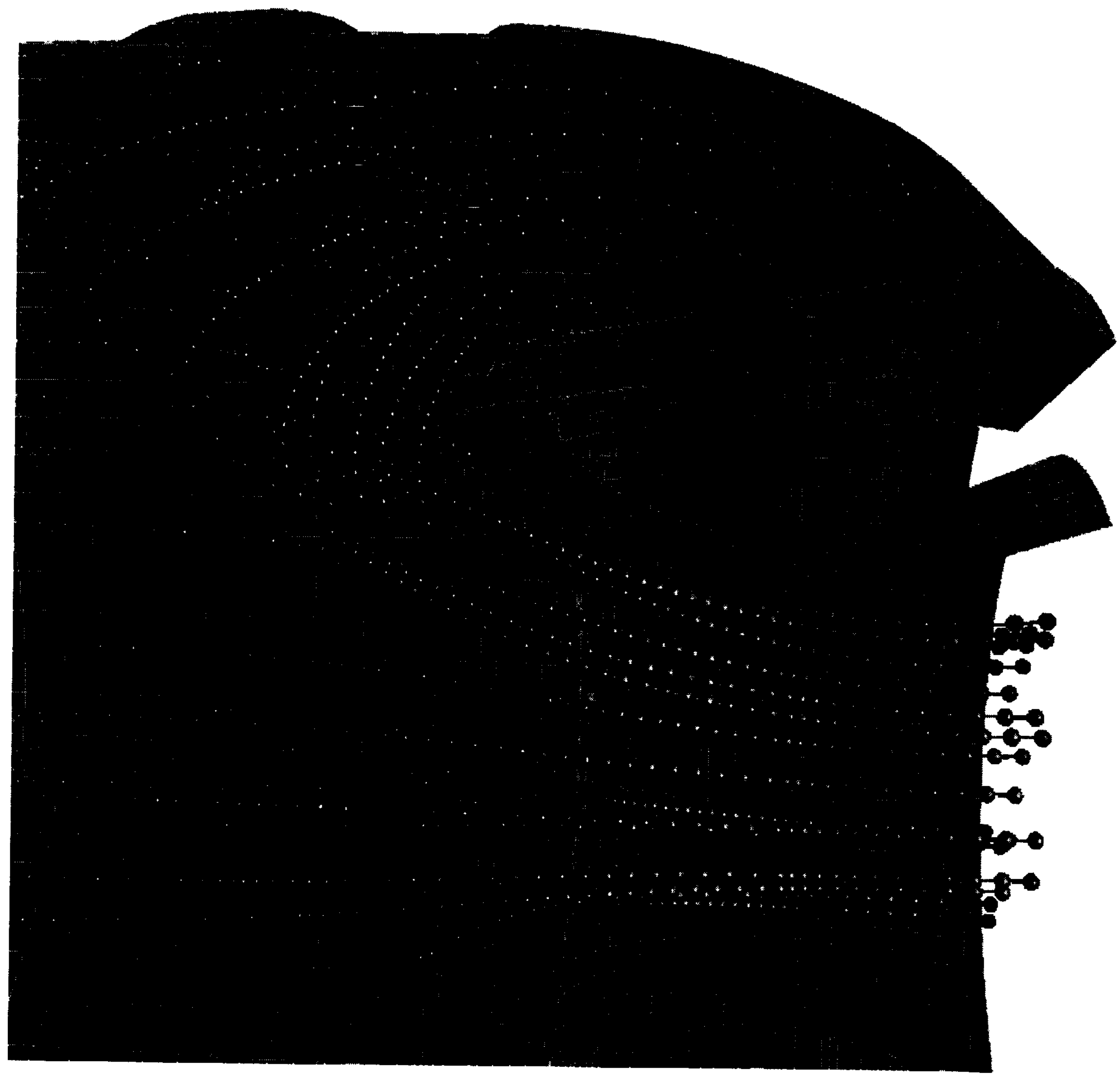


Slag buildup history in the aft-end cavity.

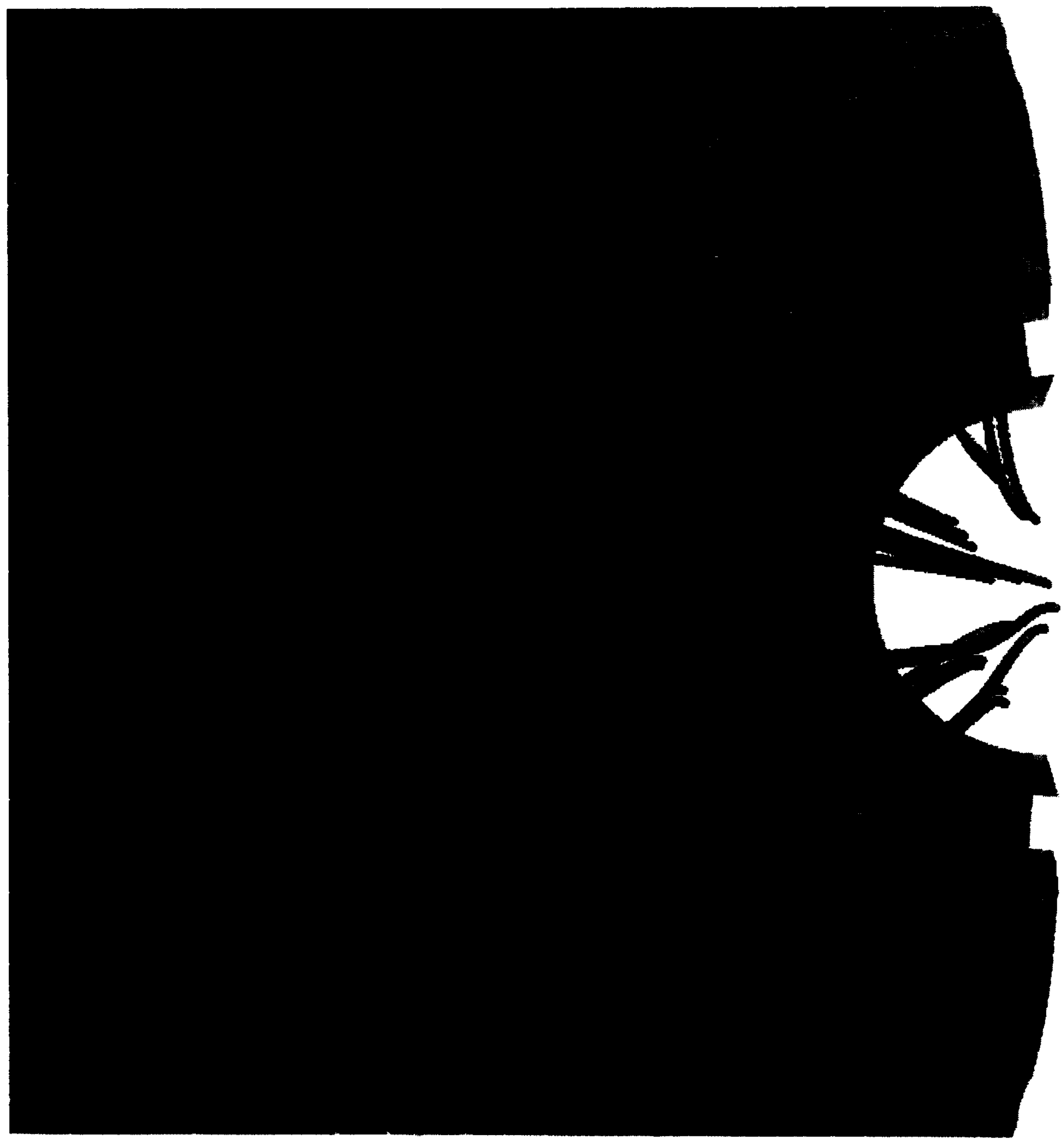
Slag Accumulation for 3D RSRM at T = 0.031687



Slag Accumulation for 3D RSRM at T = 0.031687



Slag Accumulation for 3D RSRM at T = 0.031687



Slag Accumulation for 3D RSRM at T = 0.031687

Slag Accumulation for 3D RSRM at T = 0.031687

CONCLUSIONS AND RECOMMENDATIONS

- THE OBTAINED PRELIMINARY NUMERICAL RESULTS USING FDNS CODE SHOW THAT THE SLAG BEHAVIOR CAN BE PREDICTED NUMERICALLY. THE PREDICTED FLOW FIELD IS REASONABLE BASED ON THE PHYSICAL POINT OF VIEW.

- A DIRECT SIMULATION USING CHEMICAL REACTION, COMBUSTION/EVAPORATION/BREAKUP/AGGLOMERATION MODELS IS NECESSARY FOR A MORE ACCURATE NUMERICAL ANALYSIS OF SLAG BEHAVIOR.