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NUMERICAL MODELLING OF CRYOGENIC PROPELLANT BEHAVIOR IN LOW-G

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A partial survey is presented of recent research, sponsored by the NASA Lewis Research Center, into the computational modelling of cryogenic propellant behavior in a low gravity environment. This presentation is intended to provide insight into some of the specific problems being studied and into how these studies are part of an integrated plan to develop predictive capabilities. A brief description of the computational models developed to analyze jet induced mixing in cryogenic propellant tankage is presented along with representative results. Similar information is presented for a recent examination of on-orbit self-pressurization. A study of propellant reorientation has recently been initiated and preliminary results are included. The presentation concludes with a list of ongoing efforts and projected goals.

For recent survey of general program in reduced gravity fluid management technology sponsored by NASA LeRC, see Reference 4.

SOLA is an acronym for SOLution Algorithm. This is a general technique for solution of the NAvier-Stokes Equations which has been developed by the Los Alamos National Laboratory.

1. COMPUTATIONAL TECHNOLOGY
   - SOLA FAMILY
   - UNIQUE FEATURES OF NASA-VOF2D
2. JET INDUCED MIXING
   - CODE DEVELOPMENT
   - COMPUTATIONAL RESULTS
3. SELF-PRESSURIZATION
   - CODE DEVELOPMENT
   - COMPUTATIONAL RESULTS
4. REORIENTATION
   - PROGRESS REPORT

Figure 1

For code details, see Reference 9.

This code is a member of a family of SOLA Codes developed at LASL. Most are available through NSIC at Argonne National Laboratory.

NASA–VOF2D

DEVELOPED FOR LeRC BY THE LOS ALAMOS SCIENTIFIC LABORATORY (LASL) AS PART OF AN ONGOING INTERAGENCY AGREEMENT.

GENERAL DESCRIPTION:

- TWO DIMENSIONAL (CARTESIAN OR CYLINDRICAL)
- EULERIAN MESH OF RECTANGULAR (ANNULAR) CELLS
- VARIABLE CELL SIZE (ROWS & COLUMNS)
- SOLUTION OF LAMINAR HYDRODYNAMIC PROBLEM
- STAGGERED GRID OF PRIMITIVE VARIABLES

Figure 2

A variable mesh is essential for resolving features of different scales (i.e. boundary layers, mixing jets, bulk flows).

Variables are evaluated at either the center of the computational cell or at the middle of a cell face.

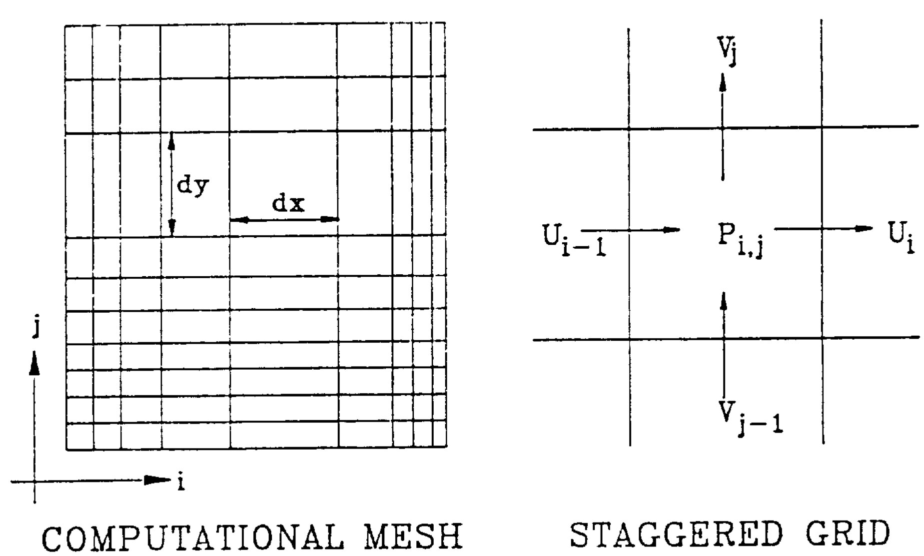


Figure 3

C-2

For details, see Reference 7.

SOLUTION ALGORITHM (SOLA)

- EVOLVED FROM LASL SIMPLIFIED MARKER & CELL
- LASL HAS DEVELOPED A FAMILY OF SOLA CODES
- BASIC STEPS IN SOLUTION OF N-S EQUATIONS:

1. SOLVE AN EXPLICIT FINITE DIFFERENCE APPROXIMATION TO THE MOMENTUM EQUATIONS TO OBTAIN A FIRST GUESS FOR NEW-TIME-LEVEL VELOCITIES.
2. ITERATIVELY ADJUST CELL PRESSURES AND VELOCITIES TO SATISFY CONTINUITY AT THE NEW-TIME-LEVEL.

REPEAT STEPS 1 AND 2 TO MARCH THROUGH TIME.

Figure 4

The VOF Algorithm has evolved and improved with recent members of the SOLA family of codes.

The surface tension model is still under development. Flows with sharp corners, such as a geyser piercing a surface, are difficult to compute.

UNIQUE FEATURES:

VOLUME-OF-FLUID (VOF) METHOD

- REPLACES MARKER PARTICLES OF EARLIER LASL CODES
- CAPABLE OF MODELLING COMPLEX FREE SURFACES
- SPECIAL ALGORITHM TO MAINTAIN SHARP FEATURES

SURFACE TENSION MODEL

- COMPUTES SURFACE TENSION FORCE BASED ON CURVATURE OF FREE SURFACE
- IMPOSES EQUIVALENT PRESSURE USING AN INTER-CELL INTERPOLATION SCHEME
- PERFORMS SPECIAL CALCULATIONS AT INTERSECTION OF FREE SURFACE WITH A SOLID BOUNDARY TO COMPUTE WALL ADHESION FORCES.

Figure 5

Partial cell blockage is required for reorientation problems.

Tools include: zero-g equilibrium interface calculation, appropriate dimensionless variables, and non-aligned solid boundary definition routine.

PARTIAL CELL BLOCKAGE

LIMITED-POROSITY TECHNIQUE PROVIDES SIGNIFICANTLY IMPROVED MODELLING OF CURVED BOUNDARIES

ASSORTED TOOLS TO AID IN SETUP AND ANALYSIS OF PROBLEMS IN A LOW-G ENVIRONMENT

Figure 6

For details, see References 2 and 3.

MOTIVATION

THERMODYNAMIC VENT SYSTEM (TVS)

- CONCEPT: EXTRACT SACRIFICIAL FLUID, EXPAND THROUGH VALVE, USE COOLED LIQUID TO HELP CONTROL TANK PRESSURE
- PROBLEM: HOW TO DISPERSE COOLING EFFECT THROUGHOUT PROPELLANT POOL
- PROPOSED SOLUTION: JET INDUCED MIXING
- NEED: A TOOL TO PREDICT EFFECTIVENESS OF JET INDUCED MIXING IN DISPERSING COOLING EFFECT OF TVS

Figure 7

For details, see Reference 5.

SOLA-ECLIPSE

ENERGY CALCULATIONS FOR LIQUID PROPELLANTS
IN A SPACE ENVIRONMENT

BASELINE CODE: NASA SOLA-VOF (PREDECSSOR OF NASA-VOF2D)

MAJOR ADDITIONS TO BASELINE CODE REQUIRED TO ANALYZE JET INDUCED MIXING PROBLEM:

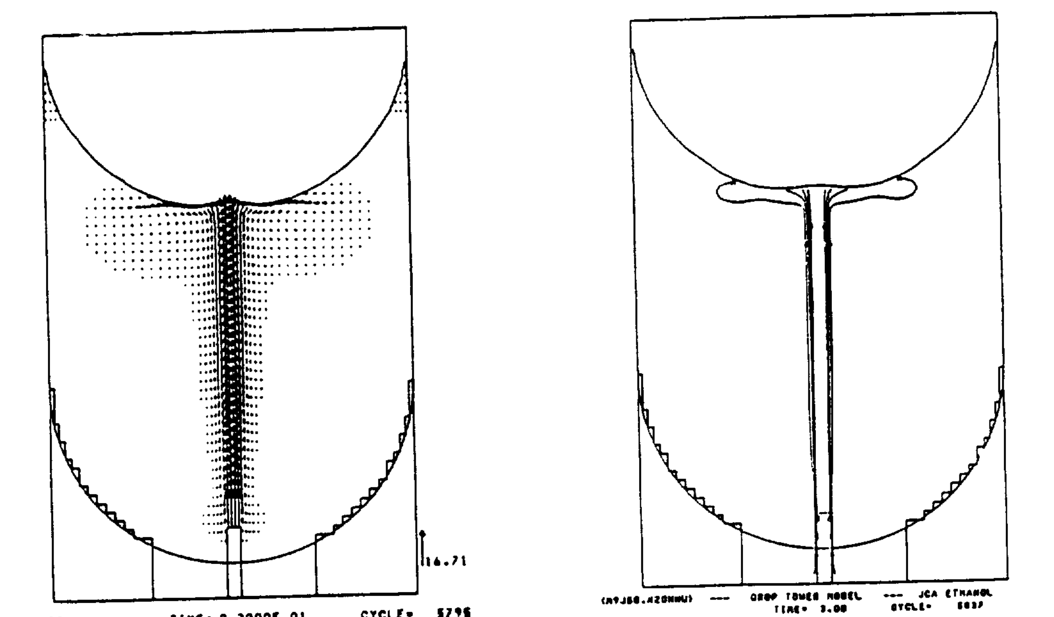
- ENERGY EQUATION
  CONDUCTION AND FORCED CONVECTION WITHIN THE LIQUID PHASE
- TURBULENCE MODEL
  TWO-EQUATION MODEL (k-e)
- NEW GRAPHICAL DISPLAY OPTIONS

Figure 8

Scale model experiments to investigate jet induced mixing were performed in the LeRC Zero-G Facility, (ZGF). Reference 2 reports the results of experiments which used ethanol in plexiglas tanks. Dyed ethanol was injected and high-speed photography was used to record the mixing. Approximately 3 seconds of mixing time is available in the ZGF.

As part of the code verification process, computationally predicted mixing was compared to the experimental results reported in Reference 2. Figure 9 shows computational predictions for a laminar jet in a 10 cm diameter tank.

There is a good match between computational predictions and experimental data.



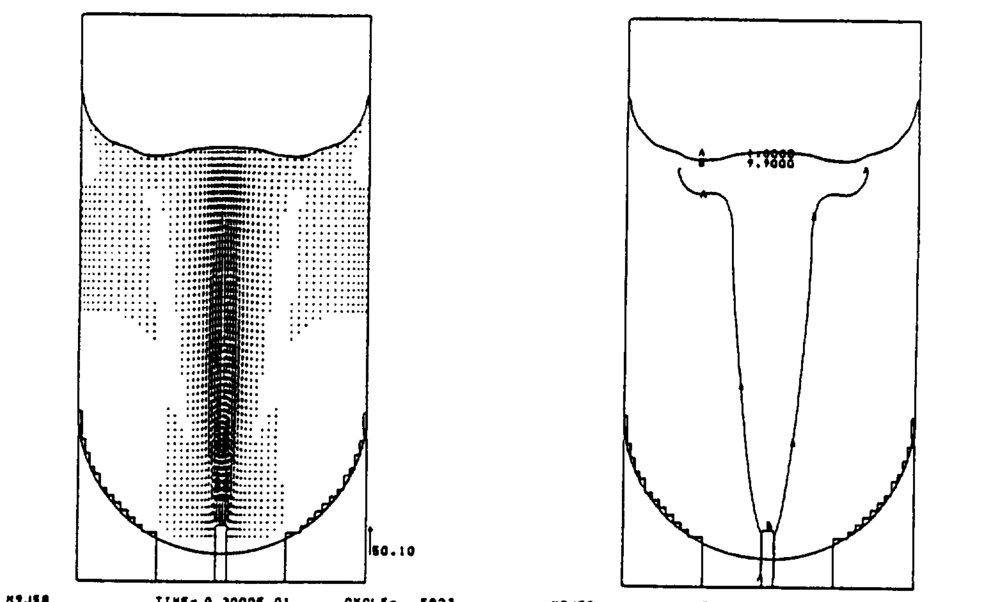
VECTOR FIELD CONCENTRATION CONTOURS

SCALE MODEL TANK, LAMINAR JET AT 3 SEC.

Figure 9

Figure 10 shows computational predictions for a turbulent jet issuing into a a partially filled tank. This case was chosen from among the experimental results reported in Reference 2.

Again, there is a good match between computational predictions and experimental data.



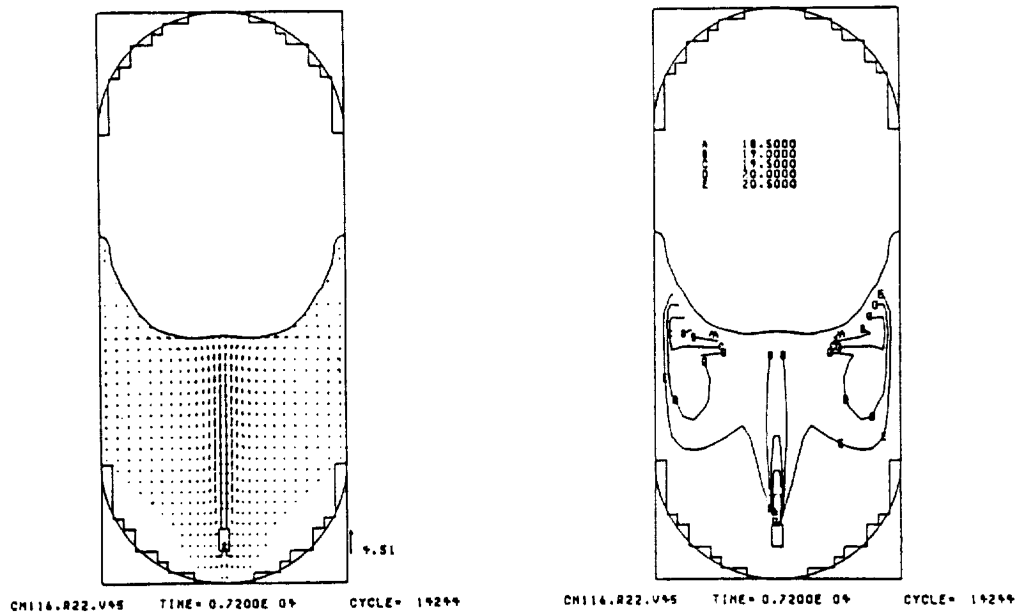
VECTOR FIELD CONCENTRATION CONTOURS

SCALE MODEL TANK, TURBULENT JET AT 3 SEC.

Figure 10

The axial jet appears to be capable of adequately mixing the propellant pool in a typical Orbit Transfer Vehicle, (OTV), tank.

Difficulties with the thermal model leave some questions as to accuracy of thermal results.



VECTOR FIELD TEMPERATURE CONTOURS

FULL SCALE TYPICAL OTV, TURBULENT JET AT 1 HOUR

Figure 11

For details, see Reference 5.

CONCLUSIONS

- VOF COMBINED WITH SURFACE TENSION MODEL IS CAPABLE OF MODELING THE JET MIXING PROBLEM PROVIDED THE JET GEYSER DOES NOT PIERCE THE FREE SURFACE.
- k-e TURBULENCE MODEL IS ADEQUATE FOR THE JET MIXING PROBLEM
- MORE WORK IS NEEDED ON LIQUID-LIQUID HEAT TRANSFER AT THE FREE SURFACE

- JET INDUCED MIXING APPEARS TO BE A VIABLE TECHNIQUE FOR DISPERSING THE COOLING EFFECT OF A TVS

Figure 12

For details, see Reference 6.

MOTIVATION

- THE NEED TO PREDICT THE SELF-PRESSURIZATION RATE OF CRYOGENIC PROPELLANT TANKAGE DURING PROLONGED EARTH ORBIT
- THE DESIRE TO MAXIMIZE PROPELLANT CONSERVATION DURING PROLONGED EARTH ORBIT

SPECIFIC QUESTION:

DOES INITIAL SUBCOOLING OF THE LIQUID PHASE SIGNIFICANTLY EFFECT THE SELF-PRESSURIZATION RATE OF A CRYOGENIC PROPELLANT TANK IN EARTH ORBIT?

Figure 13

For details of baseline code, see Reference 7.

For details of heat transfer and thermodynamic models, see Reference 6.

SOLA-ECLIPSE

BASELINE CODE: NASA-VOF2D

MAJOR ADDITIONS TO BASELINE CODE REQUIRED TO ANALYZE THE SELF-PRESSURIZATION PROBLEM:

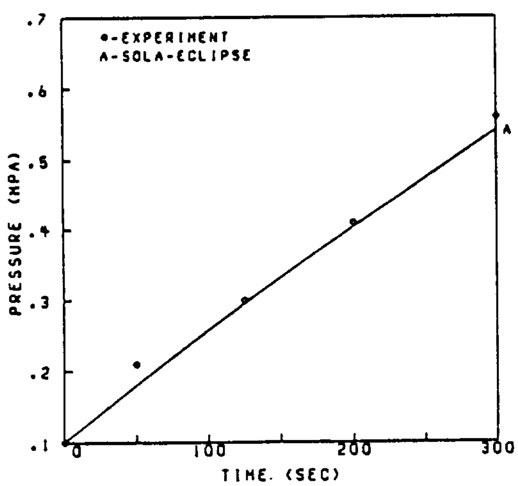
1. THERMODYNAMIC MODEL FOR THE VAPOR PHASE
2. THERMAL ENERGY EQUATION
   - SOLID-TO-LIQUID
   - LIQUID-TO-LIQUID
   - LIQUID-TO-VAPOR
   - SOLID-TO-VAPOR
3. PHASE CHANGE MODEL

Figure 14

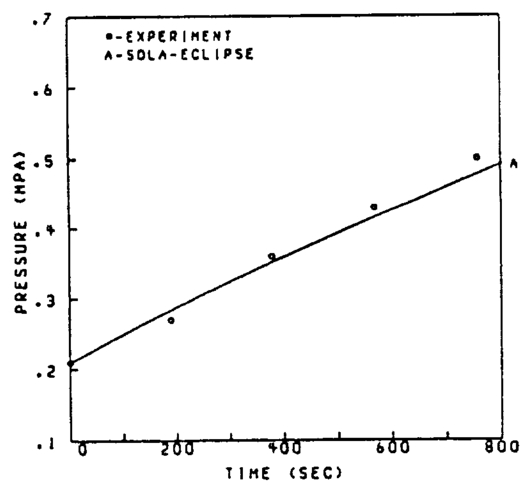
Reference 1 reports the experimental results used for evaluation of code performance.

There is good agreement between computational predictions and experimental data.

The accuracy of computational predictions breaks down for high heat flux rates that induce pool boiling.



Self-Press. (Unif.) (Dia=23cm) (1g)



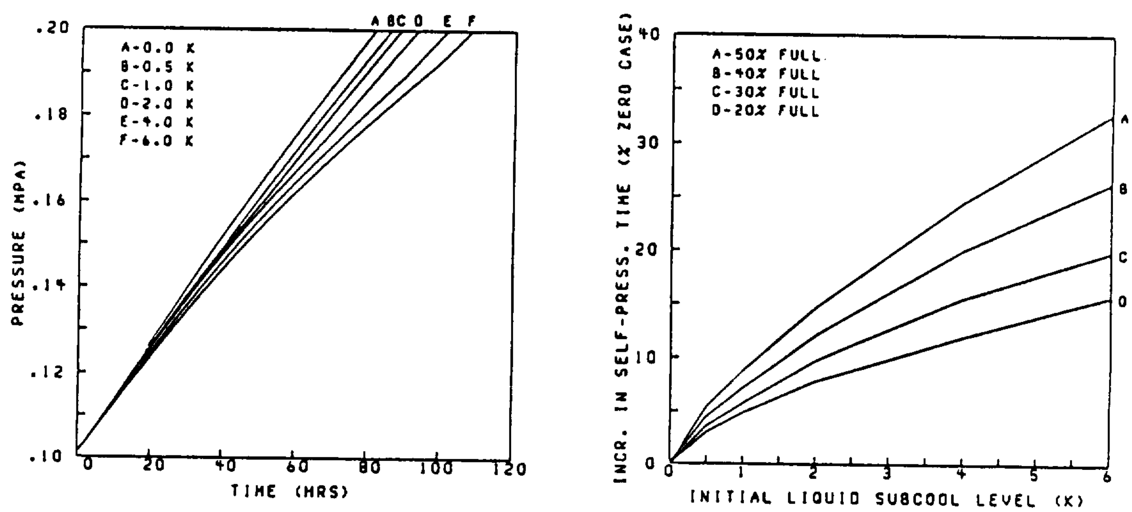
Self-Press. (Unif.) (Dia=23cm) (low-g)

SCALE MODEL TANKS, PREDICTIONS & EXPERIMENTAL DATA

Figure 15

Figure 16 shows predicted self-pressurization rates for a typical OTV in earth orbit.

From the curves displayed in Figure 16, it is concluded that the effectiveness of subcooling in suppression of self-pressurization rate decreases with increased subcooling.



Pressure Rise in OTV Tank (50% Full)

Effectiveness of Subcooling

COMPUTATIONAL PREDICTIONS FOR OTV TANKS

Figure 16

CONCLUSIONS

- THE THERMODYNAMIC AND HEAT TRANSFER MODELS ARE ADEQUATE FOR PREDICTING SELF-PRESSURIZATION RATES FOR ON-ORBIT CRYOGENIC TANKAGE

- THE SELF-PRESSURIZATION RATE CAN BE SIGNIFICANTLY DECREASED THROUGH INITIAL SUBCOOLING OF THE LIQUID PHASE

- THE EFFECTIVENESS OF INCREMENTAL INCREASES IN INITIAL SUBCOOL LEVEL DIMINISHES WITH INCREASING LEVELS OF SUBCOOLING

Figure 17

MOTIVATION

THE DESIRE TO PREDICT BULK PROPELLANT MOTION DUE TO IMPOSED ACCELERATIONS WHICH ARE INTENDED TO POSITION THE LIQUID OVER THE TANK OUTLET PRIOR TO FIRING OF THE MAIN ROCKET ENGINES.

APPLICATIONS:

- OPTIMIZE NEW DESIGNS WITH RESPECT TO CONSERVATION OF PROPELLANT
- EVALUATE THE SUITABILITY OF EXISTING EQUIPMENT FOR NEW APPLICATIONS
- INVESTIGATE NOVEL APPROACHES AIMED AT MINIMIZING PROPELLANT EXPENDITURE

Figure 18

For details of NASA-VOF2D, see Reference 9.

NASA-VOF2D is the newest member of the SOLA family of codes.

Work on this problem is just beginning.

NASA-VOF2D

HOPEFULLY, ONLY MINOR CHANGES WILL BE REQUIRED IN ORDER TO RUN THE PROBLEMS OF INTEREST:

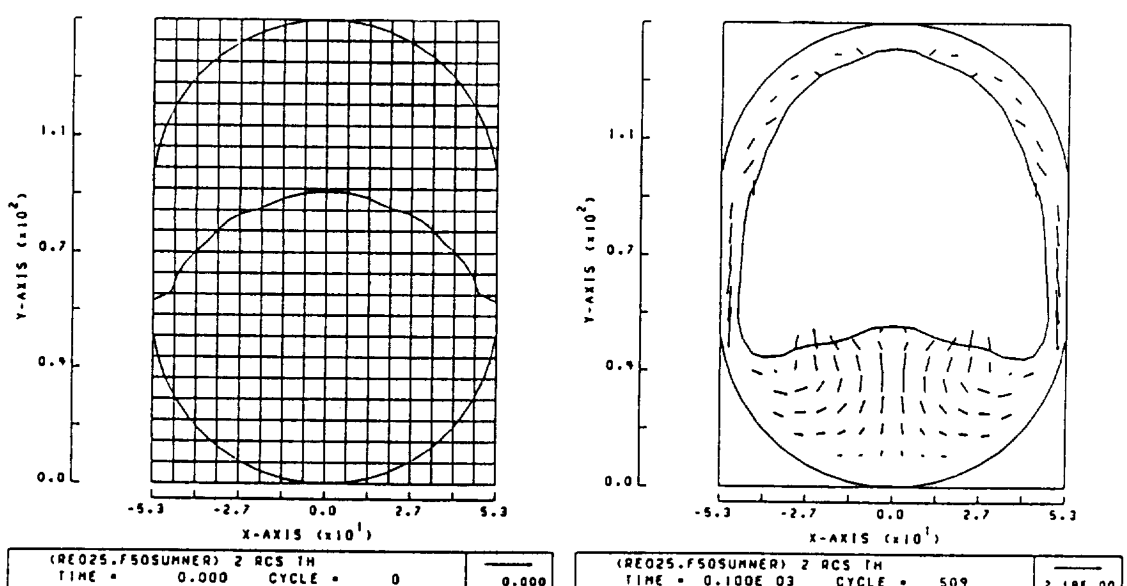
- TIME-DEPENDENT BOUNDARY CONDITIONS
- UNKNOWN AT THIS TIME BUT SURELY EXIST

Figure 19

The tank is a 1/4 scale model of typical OTV tank that has been proposed for the CFMFE.

This is the optimal acceleration level predicted for this configuration using the correlations presented in Reference 8.

There is reasonable agreement between computational predictions and correlations.



INITIAL CONDITION

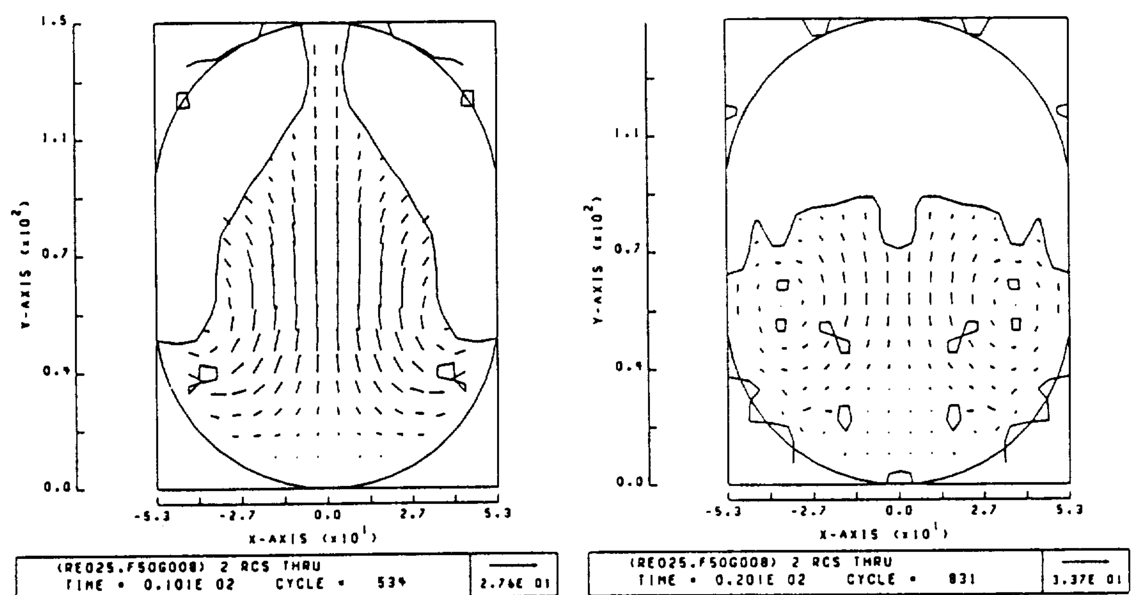
a=0.000037g's, 100 sec
STEADY ACCELERATION

COMPUTATIONAL PREDICTIONS FOR 1/4 SCALE CFMFE TANK

Figure 20

This acceleration level corresponds to the firing of 2 Shuttle RCS thrusters.

Figure 21 presents computational predictions for the flow resulting from continuous thruster firing.



a=0.008g's, 10 sec
STEADY ACCELERATION

a=0.008g's, 20 sec
STEADY ACCELERATION

COMPUTATIONAL PREDICTIONS FOR 1/4 SCALE CFMFE TANK

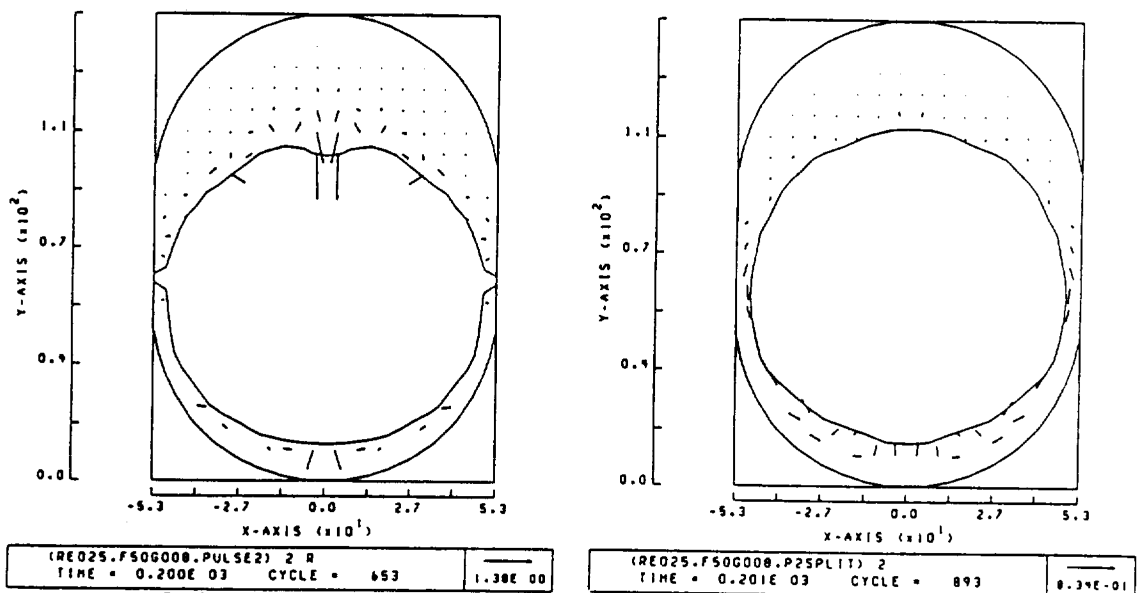
Figure 21

Figure 22 presents computational predictions for propellant motion due to intermittent thruster firing. The same total impulse is applied for both cases.

In the first case, the total impulse is applied through a single firing of the thrusters which occurs from t=0.0 until t=0.2 seconds.

In the second case, the total impulse is broken into two segments. The first thruster firing occurs at t=0.0 and has a duration of 0.1 seconds. The second firing occurs at t=0.1 seconds and also has a duration of 0.1 seconds.

Conclusion: there is a slight improvement with a split impulse.



a=0.008g's, 200 sec
dt=0.2 @ t=0.

a=0.008g's, 201 sec
dt=0.1 @ t=0., 100.

COMPUTATIONAL PREDICTIONS FOR 1/4 SCALE CFMFE TANK

Figure 22

THE FOLLOWING LIST PRESENTS SOME OF THE TASKS CURRENTLY BEING PERFORMED THROUGH THE SUPPORT OF NASA GRANT NAG3-578.

- ANALYSIS OF REORIENTATION PROCESS WITH PARTICULAR APPLICATION TO CFMFE.
- ADDITION OF CONVECTION AND TURBULENCE MODELS TO LATEST VERSION OF SOLA-ECLIPSE
- USER'S MANUAL FOR EXECUTION OF NASA-VOF2D IN THE LeRC COMPUTING ENVIRONMENT
- IMPROVED GRAPHICAL OUTPUT CAPABILITIES

A LONG RANGE GOAL OF THIS EFFORT IS TO MAKE THE SOLA-ECLIPSE CODE AVAILABLE THROUGH "COSMIC".

Figure 23

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