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ADAPTATION OF THE ADVANCED SPRAY COMBUSTION CODE TO CAVITATING FLOW PROBLEMS

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ABSTRACT

A very important consideration in turbopump design is the prediction and prevention of cavitation. Thus far conventional CFD codes have not been generally applicable to the treatment of cavitating flows. Taking advantage of its two-phase capability, the Advanced Spray Combustion Code is being modified to handle flows with transient as well as steady-state cavitation bubbles. The volume-of-fluid approach incorporated into the code is extended and augmented with a liquid phase energy equation and a simple evaporation model. The strategy adopted also successfully deals with the cavity closure issue. Simple test cases will be presented and remaining technical challenges will be discussed.

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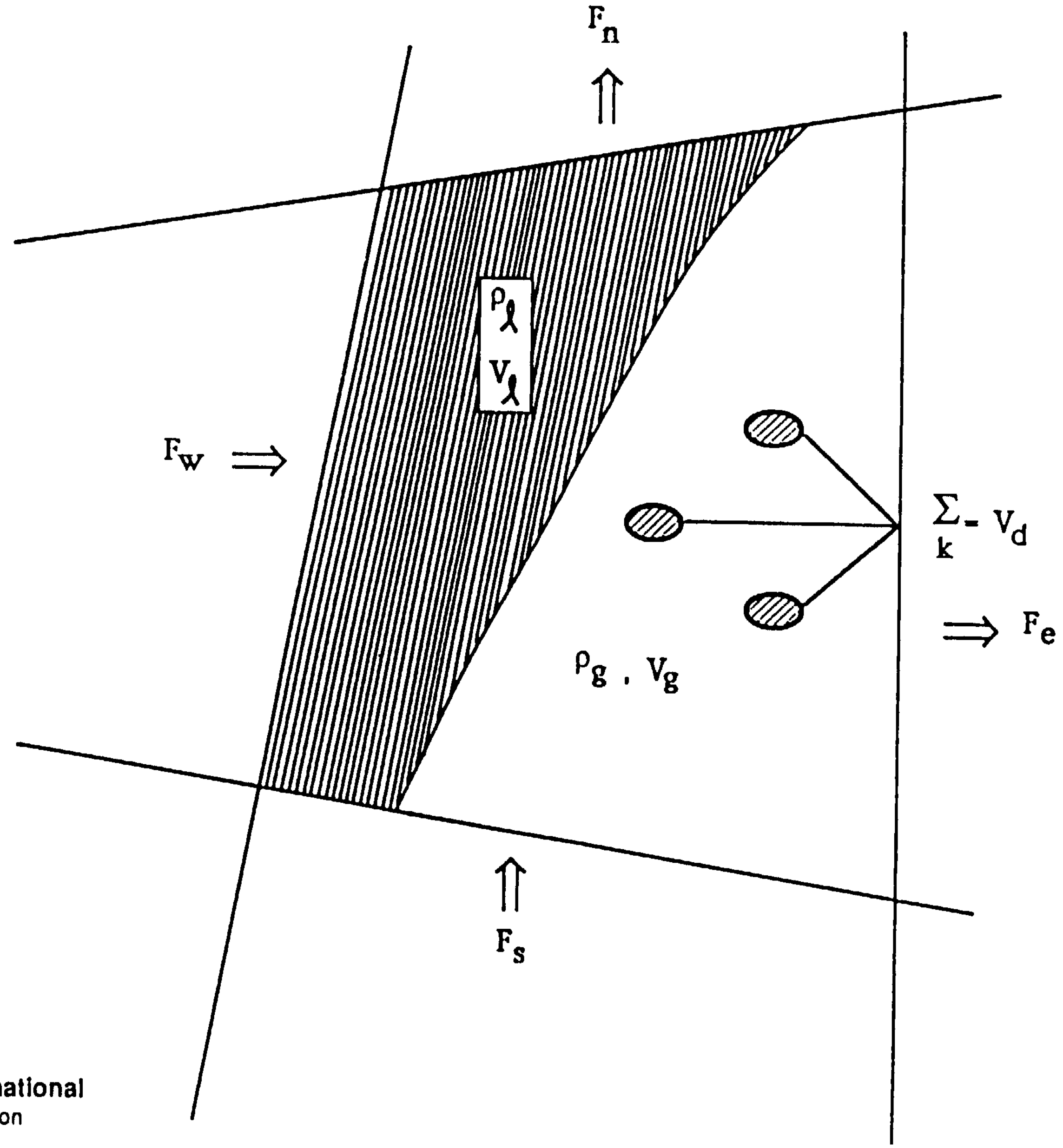
VOLUME-OF-FLUID TWO-PHASE TRACKING SCHEME IMPLEMENTED IN BOTH ARICC AND GALACSY-2D:

GENERAL ALGORITHM FOR ANALYSIS OF COMBUSTION SYSTEMS

VOF–BASED CELL PARTITIONING IN ASCOMB



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SUMMARY OF GOVERNING EQUATIONS

mass: $$\frac{\partial\bar{\rho}}{\partial t} + \nabla\cdot(\bar{\rho}\,\mathbf{u}) = \dot{\bar{\rho}}_d \quad \text{where} \quad \bar{\rho} = \mathcal{F}\rho_g + (1-\mathcal{F})\rho_\ell$$

momentum: $$\frac{\partial\bar{\rho}\mathbf{u}}{\partial t} + \nabla\cdot(\bar{\rho}\mathbf{u}\mathbf{u}) = -\nabla p - \nabla(\tfrac{2}{3}\bar{\rho}\bar{k}) + \nabla\cdot\underset{\approx}{\sigma} + \mathbf{S} + \bar{\rho}\mathbf{G}$$

internal energy: $$\frac{\partial\bar{\rho}\bar{I}}{\partial t} + \nabla\cdot(\bar{\rho}\bar{I}\mathbf{u}) = -p\nabla\cdot\mathbf{u} - \nabla\mathbf{J} + \bar{\rho}\bar{\varepsilon} + \underset{\text{chemistry}}{\dot{\mathbf{Q}}^c} + \underset{\text{spray}}{\dot{\mathbf{Q}}^s}$$

species m: $$\frac{\partial\bar{\rho}_m}{\partial t} + \nabla\cdot(\rho_m\mathbf{u}\mathcal{F}) = \mathcal{F}\nabla\cdot[\rho_g\mathcal{D}\nabla\left(\frac{\rho_m}{\rho_g}\right)] + \underset{\text{chemistry}}{\dot{\bar{\rho}}_m^c} + \underset{\text{evaporation}}{\dot{\bar{\rho}}_s\delta_{m,s}}$$

volume fraction: $$\frac{\partial\mathcal{F}}{\partial t} + \nabla\cdot\mathbf{u}\mathcal{F} = \dot{\mathcal{F}}_s = \frac{\text{net gas vol. outflux}}{\text{per unit total vol.}} = \frac{\dot{\bar{\rho}}_s}{\rho_g}$$

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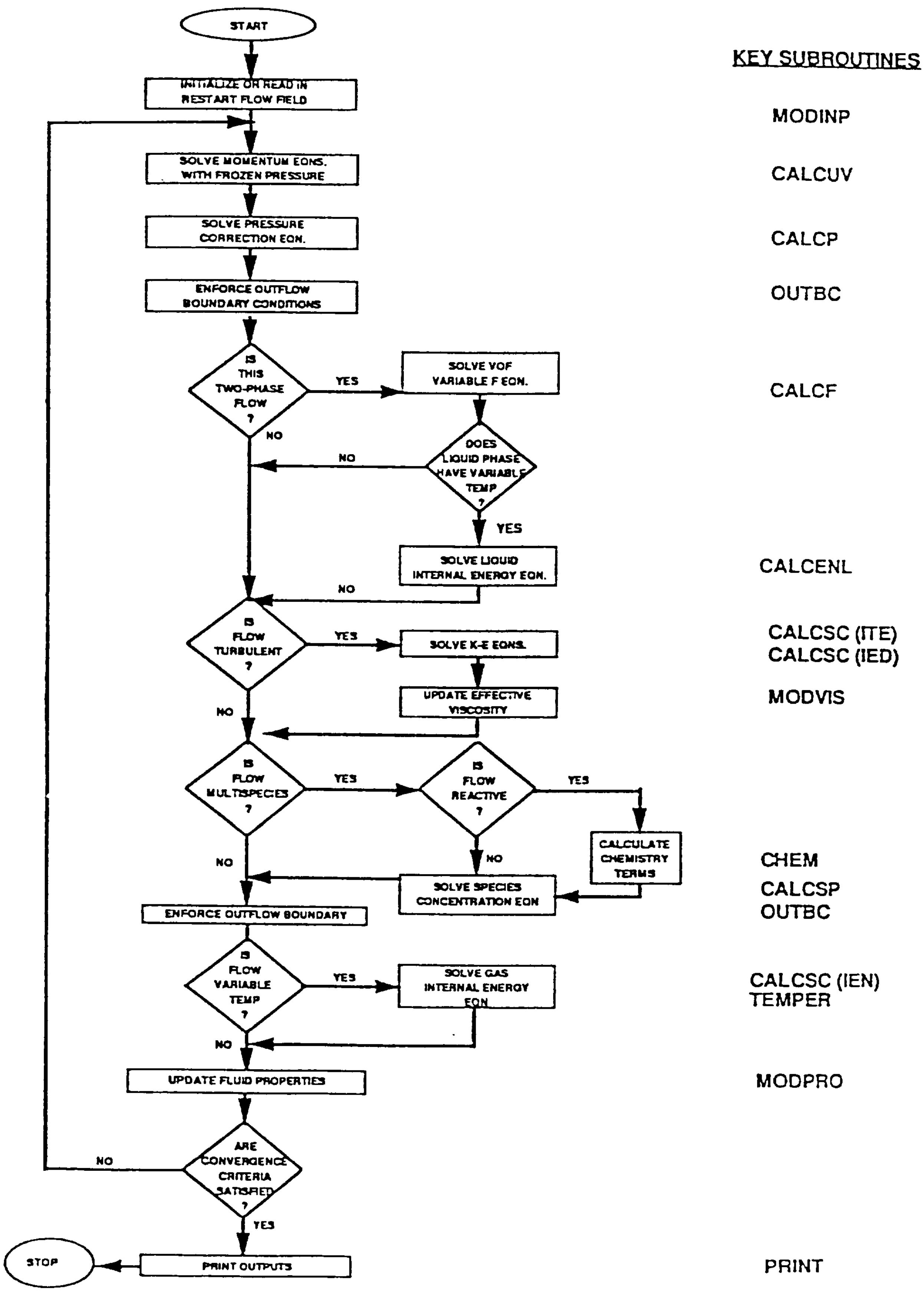
OVERALL FLOW CHART FOR ASCOMB



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SYNOPSIS OF SOLUTION APPROACH

- CAST ALL MATRIX EQUATIONS INTO GENERIC FORM

$$a_p \phi_p = \sum_m a_m \phi_m + C_p$$

WHERE

$$a_p = \sum_m a_m + \dot{\tilde{\rho}}_s V_c$$

EXCEPT FOR $\mathcal{F}$-EQUATION, WHERE

$$a_p = \sum_m a_m + \sum_m \dot{V}_m$$

- KEEP COEFFICIENT MATRIX TO 5-DIAGONAL FOR 2D AND 7-DIAGONAL FOR 3D FLOWS BY DOING IMPLICIT DIFFERENCING ONLY FOR CONVECTION AND NORMAL DIFFUSION TERMS.

- SOLVE WITH STONE'S STRONGLY IMPLICIT PROCEDURE

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OBSERVATIONS ON GENERAL FLOW CHARACTERISTICS THAT FORM THE BASIS OF SOLUTION STRATEGY

1. • VELOCITY COMPONENTS STRONGLY COUPLED TO EACH OTHER ONLY BY WAY OF PRESSURE; WEAKLY COUPLED TO TURBULENCE & TEMPERATURE FIELDS

   • HENCE, 2-STEP PRESSURE CORRECTION APPROACH OF "SIMPLE"

   • FLUX UPDATE INCLUDES DENSITY CORRECTION TERM FOR COMPRESSIBLE FLOWS, I.E.,

$$F_{gi} = F^{*}_{gi} + F'_{gi} + \hat{F}_{gi}$$

WHERE

$$F^{*}_{gi} = \mathcal{F}_i \, \rho^{*}_i (u^{*}_1 b^i_1 + u^{*}_2 b^i_2 + u^{*}_3 b^i_3)_i = \mathcal{F}_i \, \rho^{*}_i \, \dot{V}^{*}_i$$

$$F'_{gi} = \mathcal{F}_i \, \rho^{*}_i (u'_1 b^i_1 + u'_2 b^i_2 + u'_3 b^i_3)_i = \mathcal{F}_i \, \rho^{*}_i \, \dot{V}'_i$$

$$\hat{F}_{gi} = \mathcal{F}_i \, \rho'_i (u^{*}_1 b^i_1 + u^{*}_2 b^i_2 + u^{*}_3 b^i_3)_i = \mathcal{F}_i \, \rho'_i \, \dot{V}^{*}_i$$

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OBSERVATIONS ON GENERAL FLOW CHARACTERISTICS THAT FORM THE BASIS OF SOLUTION STRATEGY

2.
- WITH SECOND, DENSE LIQUID PHASE, ALL VARIABLES BECOME STRONGLY COUPLED TO THE $\mathscr{F}$-FIELD THROUGH THE CONVECTIVE MASS FLUXES

- TOTAL MASS FLUX GIVEN BY

$$F_i = F_{\ell i} + F_{gi}$$

WHERE

$$F_{\ell i} = \rho_\ell (1 - \mathscr{F}_i)(\dot{V}_i^* + \dot{V}_i')$$

- $\mathscr{F}$-FIELD MUST BE ALLOWED TO EVOLVE MORE SLOWLY THAN VELOCITY AND OTHER GAS SCALAR FILEDS, EXCEPT FOR TOTAL MASS CONSERVATION (PRESSURE-CORRECTION) ESP. WHEN BOILING IS INVOLVED

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ADDITIONAL UPGRADES NEEDED TO TREAT CAVITATION PROBLEMS

1. VARIABLE TEMPERATURE/ADDITIONAL ENERGY EQUATION FOR THE LIQUID PHASE

   - EQUALIZATION OF TEMPERATURES IN PARTIALLY LIQUID CELLS ASSUMED

2. SIMPLE EVAPORATION (CAVITATION INCEPTION) MODEL REQUIRED

$$\dot{m} = E_p A_s (P_v - P)/\sqrt{2\pi RT}$$

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ADVANTAGES OF VOF-APPROACH OVER OTHER CAVITATION MODELS

- PHYSICALLY RIGOROUS DESCRIPTION FROM FIRST PRINCIPLES
- NO NEED FOR HEURISTIC CAVITY CLOSURE MODELS
- DESCRIBES FLOW FIELDS BOTH INSIDE AND OUTSIDE OF CAVITY
- NATURALLY HANDLES CLOUD CAVITATION, TRAVELING CAVITATION, VORTEX CAVITATION, AND VIBRATORY CAVITATION
- POTENTIALLY CAPABLE OF DESCRIBING CAVITATION BUBBLE COLLAPSE
- HIGHER ORDER EFFECTS (DIFFERENT ρ_ℓ/ρ_g RATIOS, FINITE EVAPORATION RATES, RECONDENSATION, ROUGHNESS EFFECTS ON CAVITATION INCEPTION ETC.) CAN BE ACCOMMODATED

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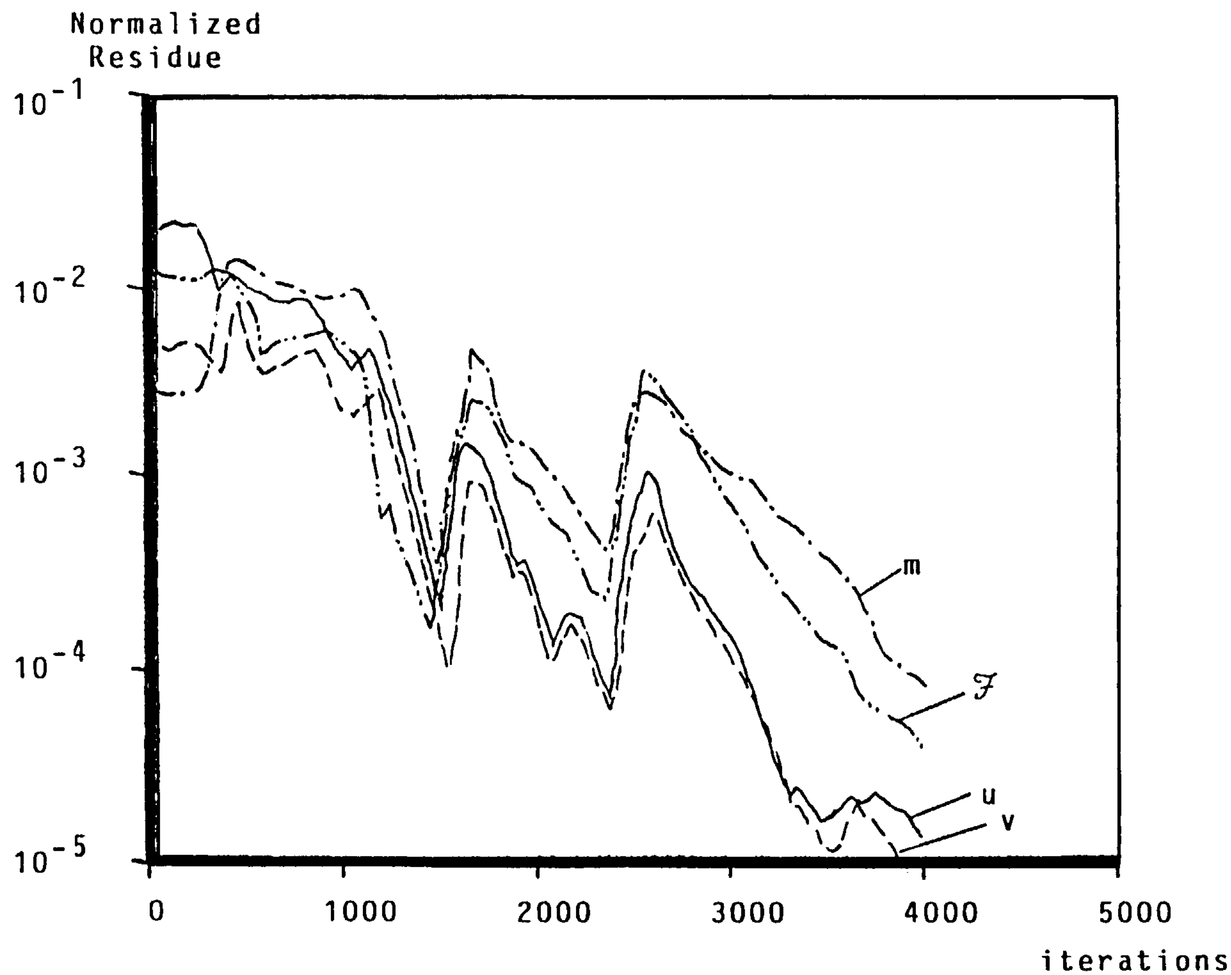
TYPICAL CONVERGENCE CHARACTERISTICS FOR NONREACTING CAVITATING FLOW



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STATUS OF THE CAVITATION UPGRADE SUBTASK

- **QUALITATIVELY AT LEAST, THE CAVITATION SCHEME NOW SEEMS TO FUNCTION PROPERLY**
  - STRAIGHT CHANNEL LIQUID FLOW WITH INCOMING GASEOUS "LAYER"
    - OVERALL CHANNEL PRESSURE RESPONDS CORRECTLY TO CHANGES IN VAPOR PRESSURE
    - NUMERICAL DIFFUSION OF VOF VARIABLE APPEARS TO BE ACCEPTABLE EVEN FOR FIRST ORDER UPWIND SCHEME
  - CURVED CHANNEL FLOW WITH CAVITATING BUBBLE ON CONVEX WALL
    - BUBBLE FORMATION AND TERMINATION PROPERLY CAPTURED
    - BUBBLE SIZE ADJUSTS TO CHANGES IN VELOCITY AND MAGNITUDE OF LIQUID EVAPORATION TERM

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CONCLUDING REMARKS

- NUMERICAL STIFFNESS ISSUES STILL NEED CLOSER EXAMINATION
- SPATIAL DIFFERENCING OF $\mathscr{F}$-VARIABLE MAY NEED SOMETHING LESS DIFFUSIVE
- NEXT TEST CASES SHOULD EXPLORE TRUE POTENTIAL OF VOF-APPROACH E.G., TRAILING EDGE CAVITATION PROBLEMS

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