A New Unsteady Model for Dense Cloud Cavitation in Cryogenic Fluids

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BACKGROUND ON THERMAL EFFECTS IN CAVITATION

- When liquid temperature gets closer to its critical temperature (typical of cryogenic fluids) thermal effects become important
- In this operating regime
  - Vapor pressure and density are much higher. More liquid has to vaporize to sustain mass of vapor in cavity
  - Variation of vapor pressure and density with temperature is significant
- Vaporization results in evaporative cooling effect
  - Maximum Temperature/Pressure Depression at Leading Edge of Cavity
  - Lower Temperatures Result in Lower Cavity Pressures and Improve Mean Performance
- Cavitation zone in cryogenic fluids is visually described as "frothy" and distinct from the "sharp" cavity interfaces observed in water
  - Entrainment into the cavity is also significantly higher for cryogenic fluids
- Reynolds number for cryogenic fluids significantly higher than equivalent water tests
  - Kinematic viscosity smaller by factors of 10-20

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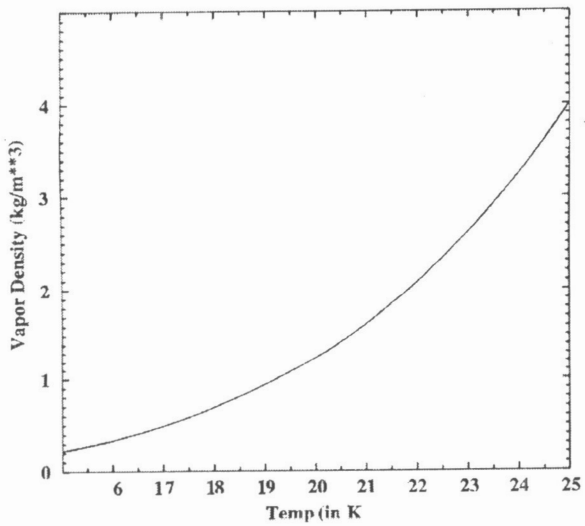
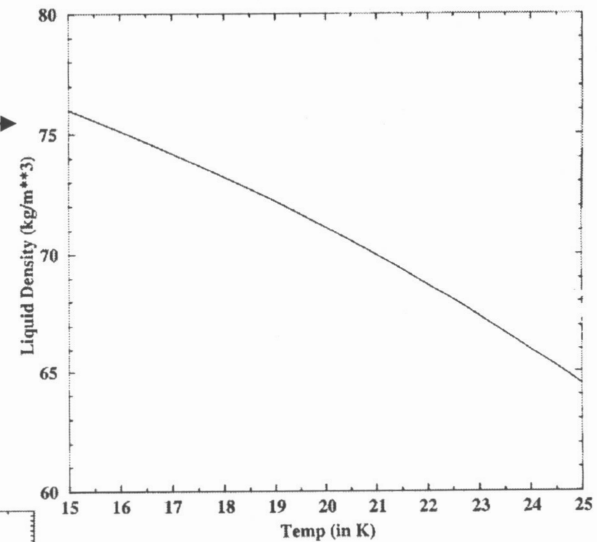
PHYSICAL PROPERTIES OF HYDROGEN
(Temperature Dependence)

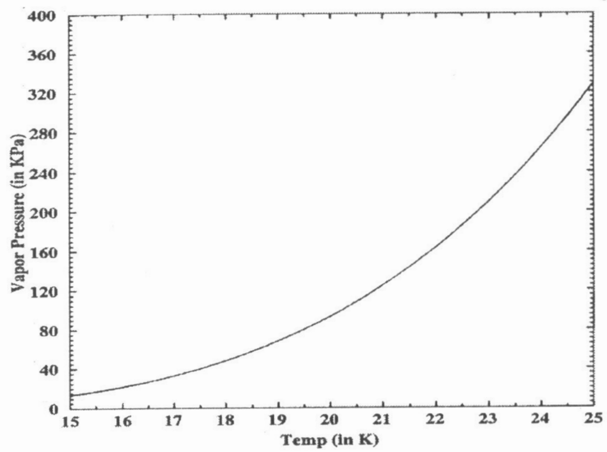
Density Variation with Temperature



Hydrogen Vapor



Liquid Hydrogen



Vapor Pressure

<u>Vapor Pressure Variation</u>

93.25 KPa at 20 K

100.5 KPa at 20.25 K

Slope= 29 KPa/K (Roughly Twice that of Liquid Nitrogen)

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MULTI-PHASE CAVITATION FORMULATION WITH THERMAL EFFECTS

- Start with compressible system $$\frac{\partial Q}{\partial t} + \frac{\partial E}{\partial x} = S \qquad (1)$$

$$Q = \begin{pmatrix} \rho_m \\ \rho_m u \\ \rho_g \phi_g \\ H_m \end{pmatrix} \quad E = \begin{pmatrix} \rho_m u \\ \rho_m u^2 + P \\ \rho_g \phi_g u \\ H_m u \end{pmatrix} \quad S = \begin{pmatrix} 0 \\ 0 \\ m_t \\ m_t \Delta h_{fg} \end{pmatrix}$$

$$\rho_g = f_g(P,T)$$
$$\rho_l = f_l(P,T)$$
$$\rho_m = \rho_g \phi_g + \rho_l \phi_l$$
$$H_m = \rho_g \phi_g h_g + \rho_l \phi_l h_l$$

  – Energy equation neglects pressure work ("low speed" approximation)

- Rewrite Eqn. (1) in pressure-temperature based form using EOS as

$$\Gamma \frac{\partial \mathrm{Q_V}}{\partial t} + \frac{\partial E}{\partial x} = S, \quad \left\{ Q_V = \begin{bmatrix} p \\ u \\ \phi_g \\ T \end{bmatrix} \right\}, \ \Gamma = \frac{\partial \mathrm{Q}}{\partial \mathrm{Q_V}}$$

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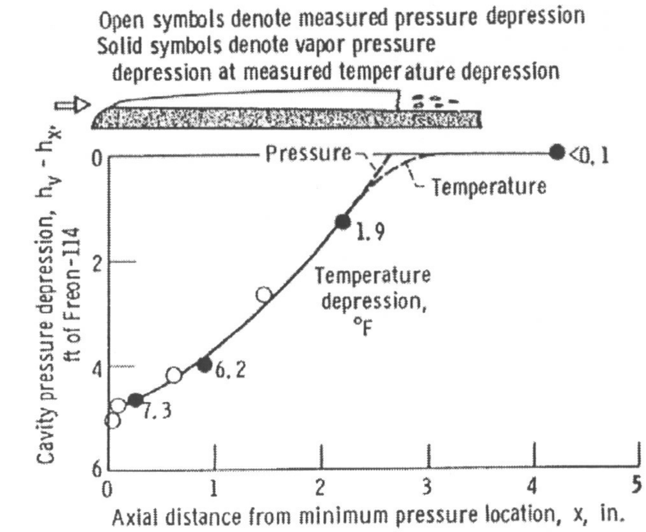
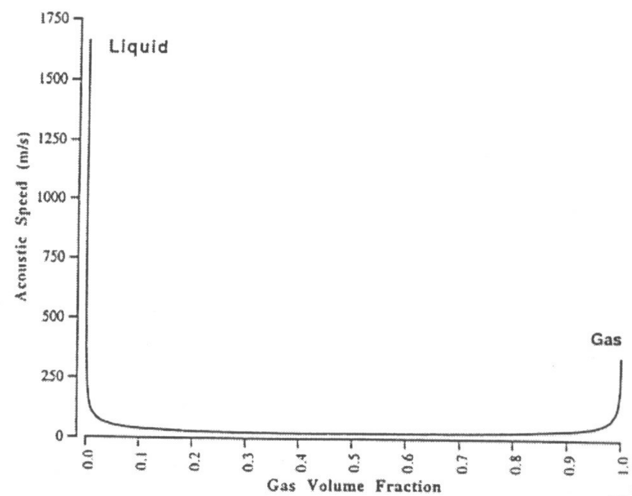
SOLUTION PROCEDURE

- Physical and thermodynamic properties for vapor and liquid specified as a function of saturation temperature
  - Tabular data generated from NIST database for various cryogenic fluids
- System is Stiff With Large Variations in Acoustic Speed
  - Preconditioning used to obtain an efficient integration procedure
- Cavitation Source Terms Specified Thru Finite Rate Phase Change
- More Rigorous Unsteady Bubbly Model For Dense Vapor Clouds Under Development





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CAVITATION MODEL OVERVIEW

- Cavitation models can broadly be classified into two categories:
  1) Using bubbly formulation with Rayleigh-Plesset Equation for cavitation growth (Kubota & Kato, Matsumoto and Coworkers, Colonius & Brennen)
     - Pro: Fundamental formulation for cavitation growth/decay
     - Con: Vapor density contribution neglected in defining mixture density; applicable to "dilute" volumetric fractions.
  2) Continuum formulations where the bubble dynamics are neglected and cavitation specified using ad-hoc finite-rate formulation
     - Pro: Can be applied to "dense" extensive cavitation applications
     - Con: Cavitation growth/decay decoupled from the net surface area associated with bubbles in the vapor cloud

CAVITATION SOURCE TERMS

- For Dense Cavitating Flows, CFD formulations Model the Phase Change as an Empirical Function of Local Pressure Variation relative to Vapor Pressure
  - Merkle, Kunz et al. (ARL), Hosangadi (CRAFT Tech)
  - Singhal et al. (CFDRC)
  - Senocak and Shyy (U. Florida)
  - Barotropic Model (Song. et al.) a subset of this with infinite rate assumption

$$\left(K = C * f(p - p_v)\right)$$

- Provides Good Agreement For Mean Cavity Pressures and Lengths
- Not Adequate For More Fundamental Modeling of Unsteady Dynamics
  - Relation of Mass transfer to Net Surface Area associated with Cavitation Cloud is ignored since Local Bubble Number Density and Radius are not accounted for
  - Integrating Bubbly Models within a Dense Cavitating framework essential for high fidelity Unsteady Simulations

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NEW CAVITATION MODEL

- Assume that a vapor cloud is comprised of bubbles whose Sauter mean radius is r_s
  - Mass of gas in cloud = $\rho_g \phi_g = \rho_g N 4 \pi r_s^3 / 3.0$
  - Surface area of bubbles in cloud = $S_g = N 4 \pi r_s^2$

$$r_s = \frac{3 \times \phi_g}{S_g}$$

- Solve conservation Equation for mass and surface area;

$$\frac{\partial S_g}{\partial t} + \frac{\partial S_g u}{\partial x} = s_t \qquad m_t = \rho_g S_g \frac{dr_s}{dt}$$

$$\frac{\partial \rho_g \phi_g}{\partial t} + \frac{\partial \rho_g \phi_g u}{\partial x} = m_t \qquad s_t = 2.0 * \frac{S_g}{r_s} \frac{dr_s}{dt}$$

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NEW CAVITATION MODEL

- Two independent parameters control the cavitation growth and decay
  - Net surface area of cloud: S_g
  - Growth/decay rate of each individual bubble: $\frac{dr_s}{dt}$
- Growth rate $\frac{dr_s}{dt}$ can be specified using a fundamental bubble cavitation model
- Surface area S_g is obtained from the solution

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SOURCE TERM FOR BUBBLE GROWTH

- Take reduced form of Rayleigh-Plesset Equation

$$\underset{\text{I}}{r_s \frac{d^2 r_s}{dt^2}} + \underset{\text{II}}{\frac{3}{2}\left(\frac{dr_s}{dt}\right)^2} = \underset{\text{III}}{\frac{Pv - P}{\rho_L}} - \underset{\text{IV}}{\frac{4v_e}{r}\left(\frac{dr_s}{dt}\right)} - \underset{\text{V}}{\frac{2s}{\rho_L r_s}}$$

(Drop I, IV, V)

$$\frac{dr_s}{dt} = \left(\frac{2}{3}\right)^{1/2}\left(\frac{Pv - P}{\rho_L}\right)^{1/2}, \quad \frac{dr_s}{dt} = -\left(\frac{2}{3}\right)^{1/2}\left(\frac{P - P_v}{\rho_L}\right)^{1/2}$$

(growth) (decay)

C_ν

ONE EQUATION LES MODEL

- Equation for subgrid kinetic energy solved for to resolve turbulent length scales smaller than grid size

$$\frac{\partial \bar{\rho}\tilde{k}}{\partial t} + \frac{\partial}{\partial x_i}\left(\bar{\rho}\tilde{u}_i\tilde{k} - \bar{\rho}\nu_T \frac{\partial \tilde{k}}{\partial x_i} \right) = \tau_{ij}^{sgs} \frac{\partial \tilde{u}_i}{\partial x_j} - D_k$$

$$\tau_{ij}^{sgs} = \bar{\rho}(u_i u_j - \widetilde{u}_i \widetilde{u}_j)$$

$$\tau_{ij}^{sgs} = -2\bar{\rho}\nu_T(\tilde{S}_{ij} - \frac{1}{3}\delta_{ij}\tilde{S}_{kk}) + \frac{2}{3}\bar{\rho}\tilde{k}\delta_{ij}$$

$$\nu_T = C_\nu \widetilde{k}^{1/2} \Delta$$

- C_ν is the modeling constant and has been computed to be equal to 0.0667

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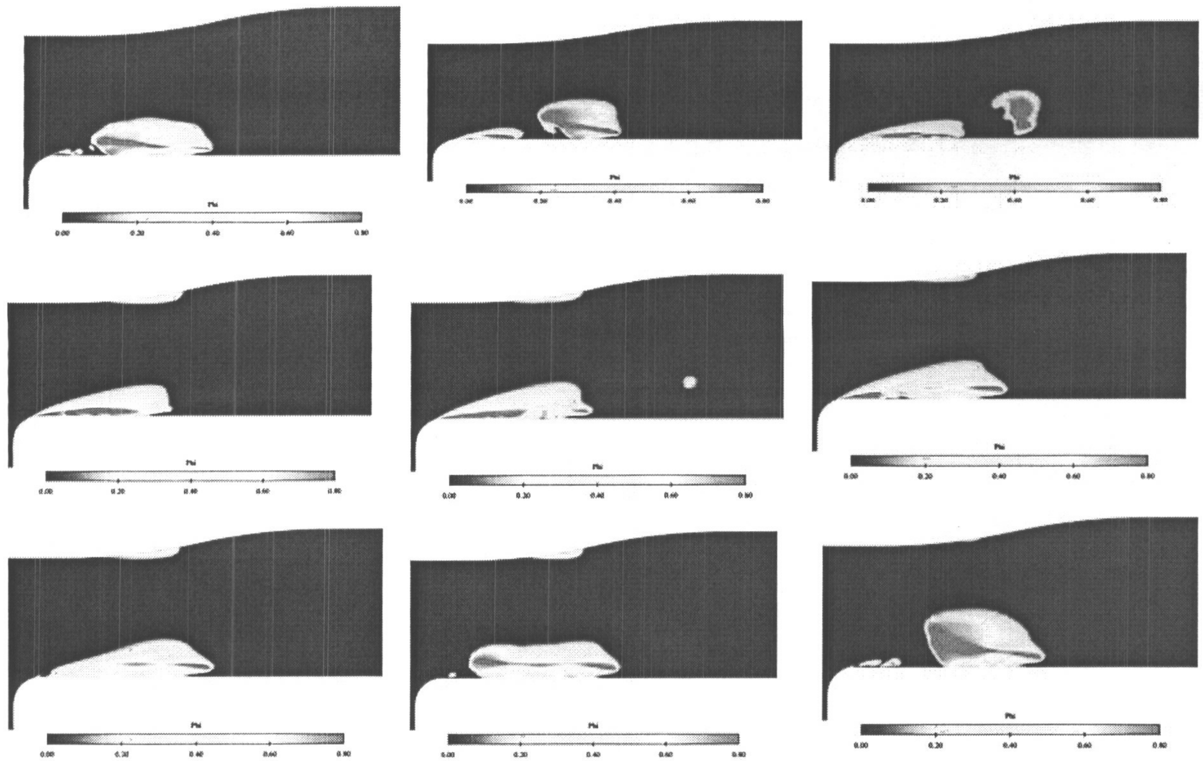
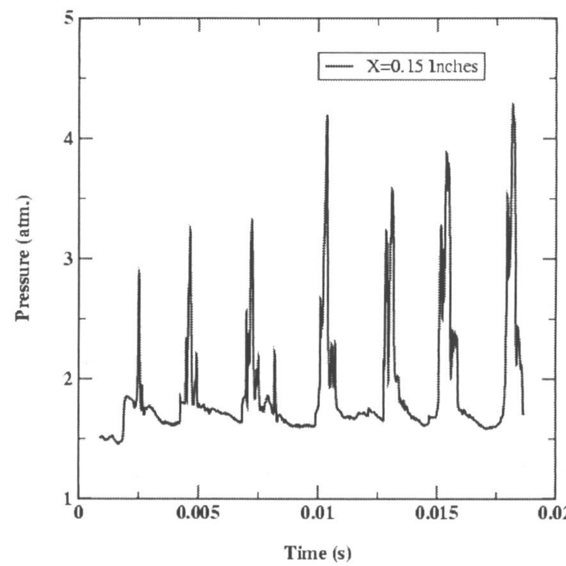
UNSTEADY OGIVE SIMULATIONS: LIQUID NITROGEN



Instantaneous Vapor Volume Fraction Contours for Unsteady LES Calculations Shown at Intervals of 0.29ms

Pressure Time Traces of Flow Variables Close to the Leadings Edge of Cavity on Ogive



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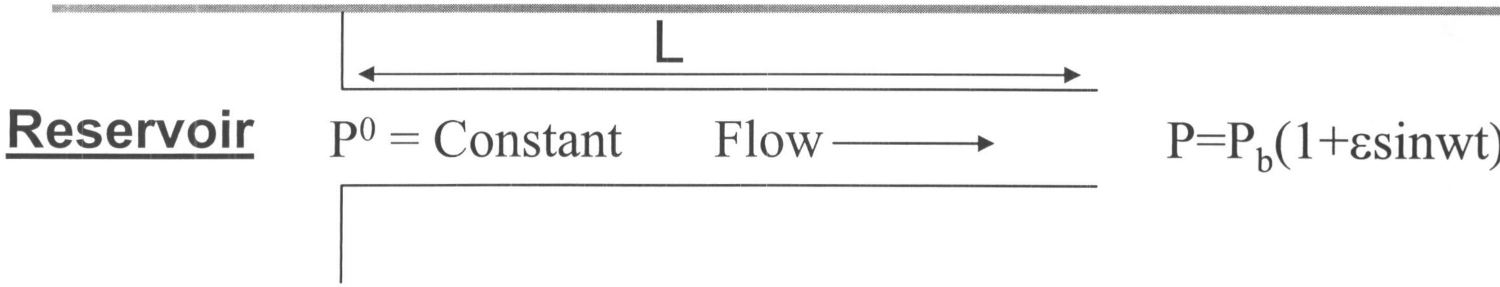
UNSTEADY IMCOMPRESSIBLE FLOW IN A PIPE



Continuity; $\dfrac{du}{dx} = 0,\ \ u = u(t)$

Momentum; $\rho\dfrac{du}{dt} = -\dfrac{\partial P}{\partial x};\ \dfrac{\partial P}{\partial x}$ function of time only $\therefore$ pressure is linear in x

Boundary Conditions;

$$P_{x=L} = P_b(1+\varepsilon \sin wt)$$

$$P^o_{x=0} = \text{constant}$$

$$u'(t) = -\left(\frac{\varepsilon}{\rho_L u_0^2}\right)\left(\frac{u_0}{1+\Omega^2}\right)\left[\sin wt - \Omega\cos wt + \Omega e^{\frac{-u_o t}{L}}\right],$$

$$P'(x,t) = \left[\varepsilon \sin wt + \rho u_0 u'\right]\frac{x}{L} - \rho u_0 u',$$

$$\Omega = \frac{wL}{u_0}, Phase\ lag\,\phi = \tan^{-1}(\Omega)$$

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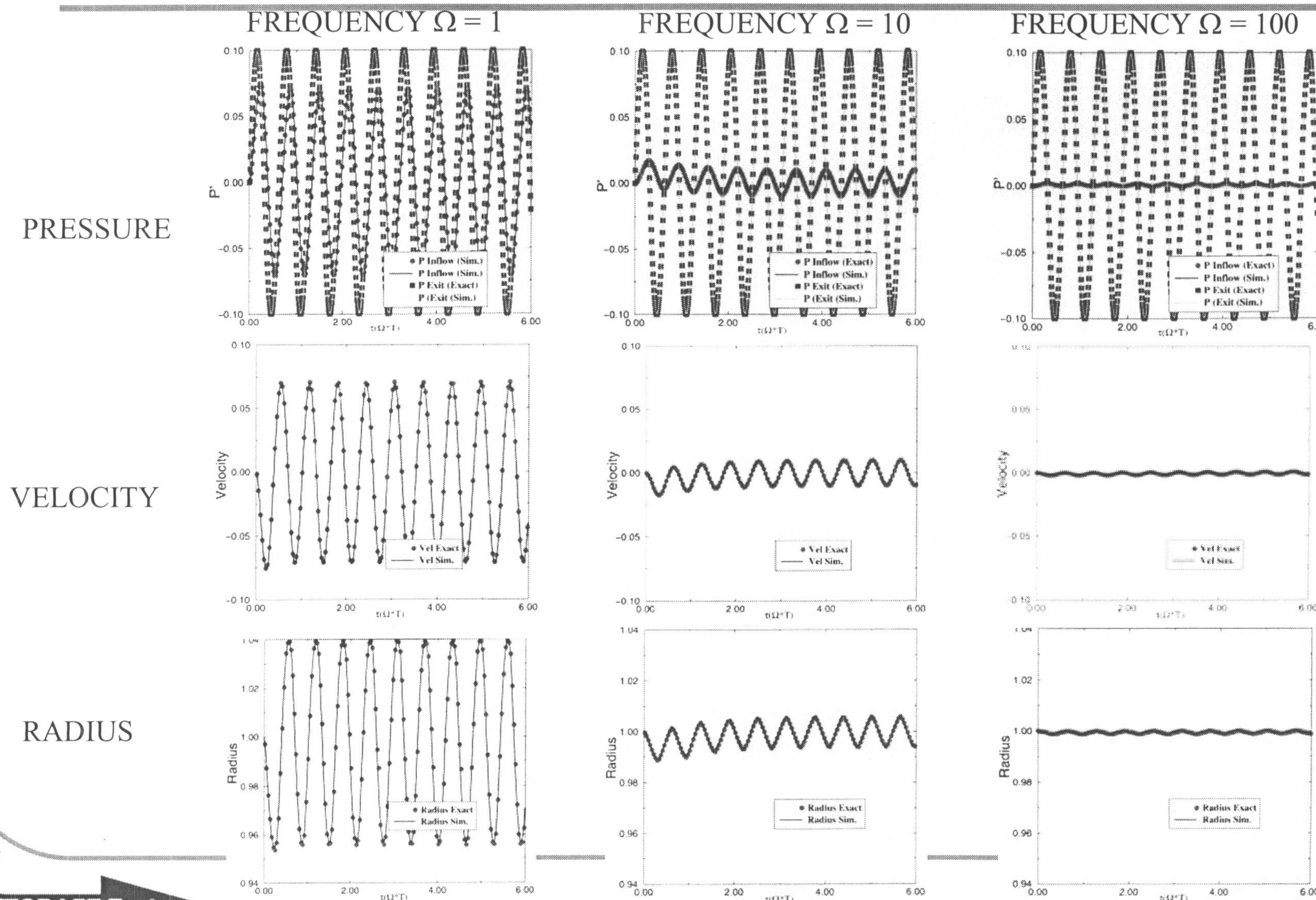
FREQUENCY RESPONSE OF BUBBLY FLOW IN A 1D PIPE



UNSTEADY CLOUD CAVITATION ON NACA15 HYDROFOIL

- **Detailed experiments characterizing cloud cavitation on NACA15 hydrofoil have been conducted by Prof. Arndt and coworkers**
  - Physics characterized over a wide parametric range of cavitation numbers (σ) and angles-of-attack (α)
  - Three regimes of cavitation observed that scaled with $\sigma/2\alpha$
    - Regime I: $1 < \sigma/2\alpha < 4$ where the frequency of oscillations are independent of cavitation number and cavity length greater than chord length
    - Regime II: $4 < \sigma/2\alpha < 6$ where the frequency of oscillations scaled with the length of cavity which was smaller than the chord length
    - Regime III: $6 < \sigma/2\alpha < 8.5$ spotty bubble/patch cavitation regime
- **Numerical simulations were performed for a case in Regime II with $\alpha = 5^\circ$, $\sigma = 0.79$, $\sigma/2\alpha = 4.52$**
  - Detailed comparisons with available experimental data were made:
    - Spectral content of oscillations and its comparison with high-speed video data
    - Time-averaged cavity length comparison with experimental measurements
    - Unsteady evolution of flow parameters to better understand the liquid-vapor interactions

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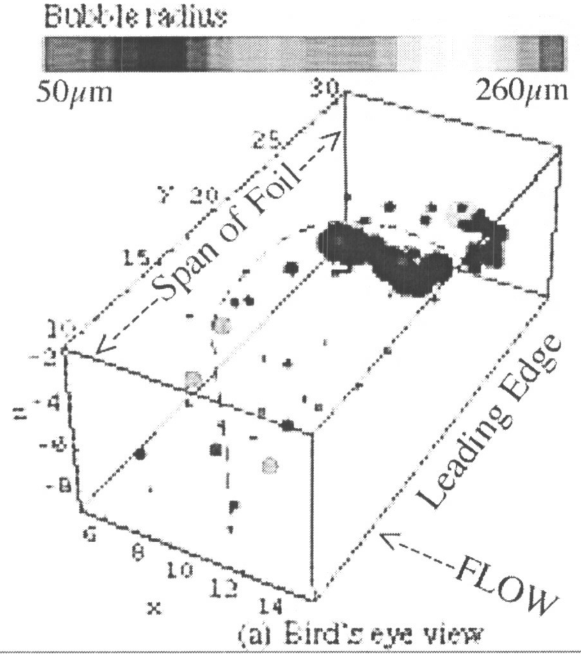
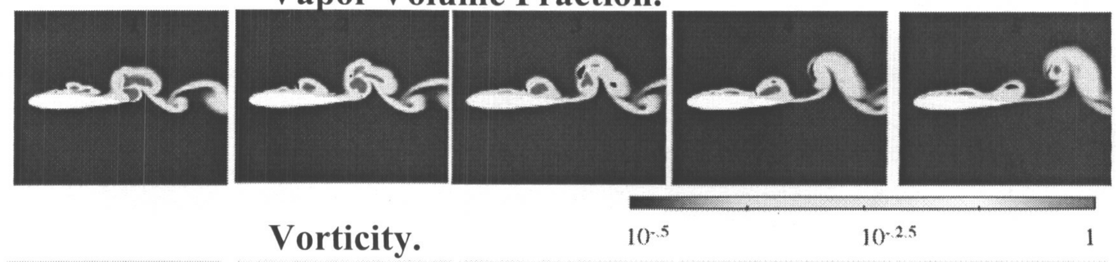
INSTANTANEOUS VISUALIZATIONS

Contours shown at intervals of T / 8 where T is time period of a 41Hz mode
Observe Counter Rotating Vortices Being Shed in the Wake

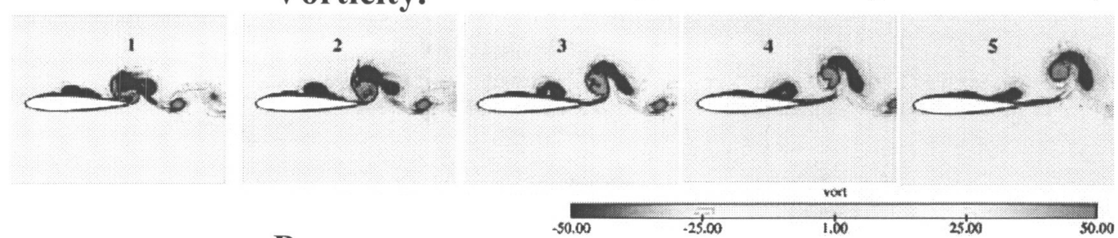


Bubble distribution in a cloud cavity σ = 1.86; α = 8.36°; (From Kawanami, et al., 2001)

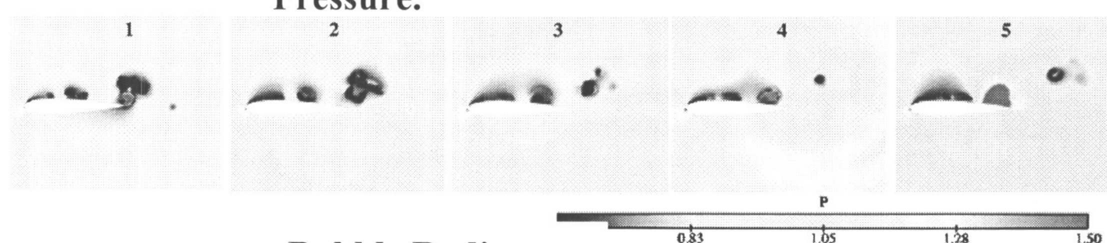
Vapor Volume Fraction.



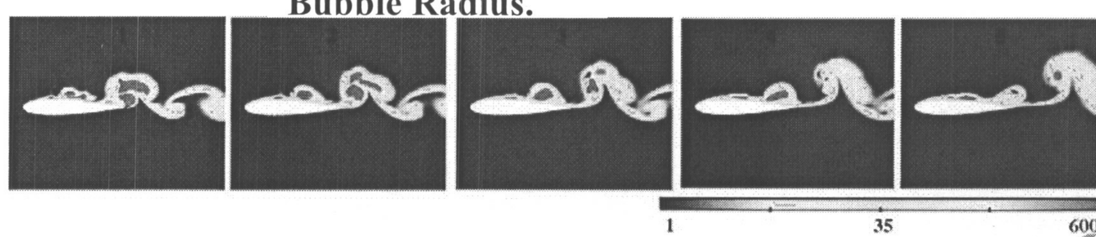
Vorticity.



Pressure.

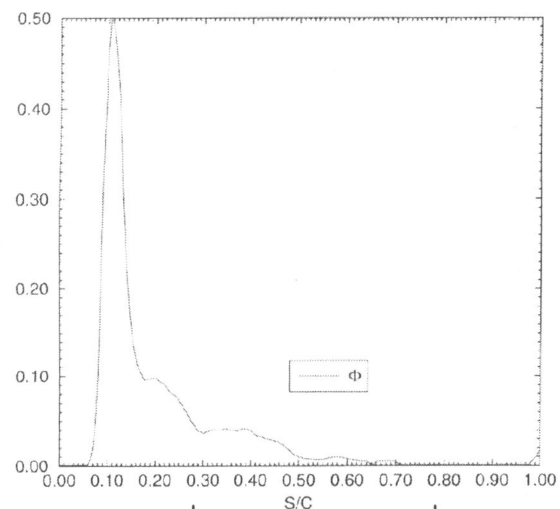


Bubble Radius.

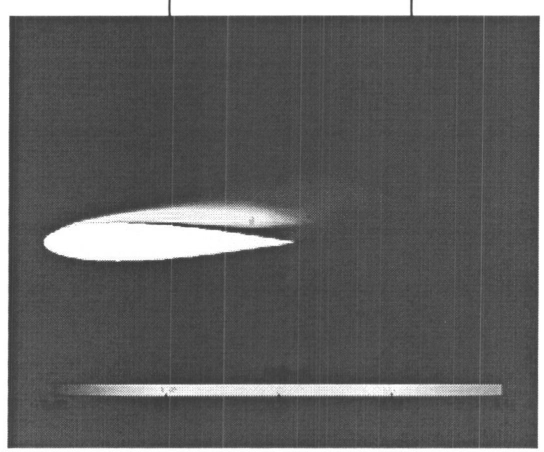


TIME AVERAGED CAVITY LENGTH FOR NACA15 FLOWFIELD

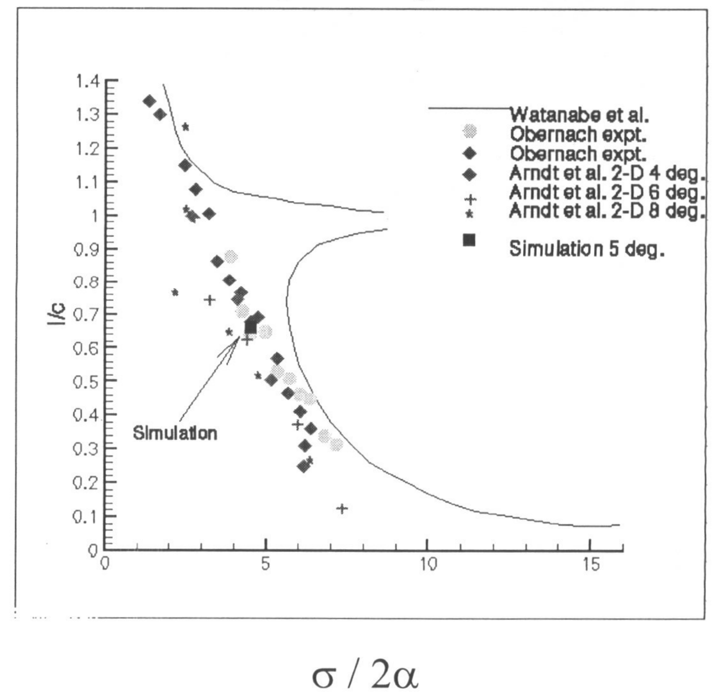
Vapor Volume Fraction on Hydrofoil Surface



Contours of Time-Averaged Vapor Volume Fraction



Mean Cavity Length Prediction

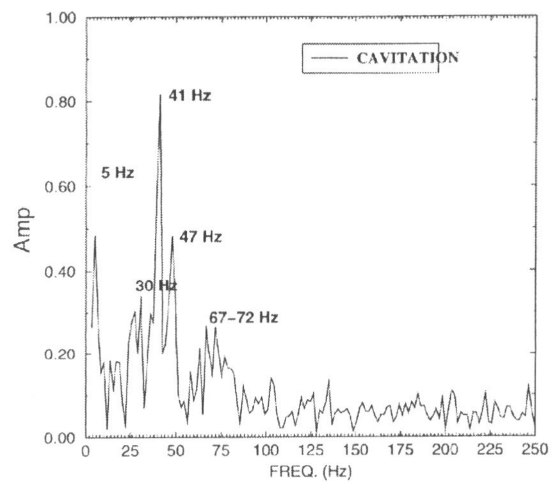


Chord Length 128mm

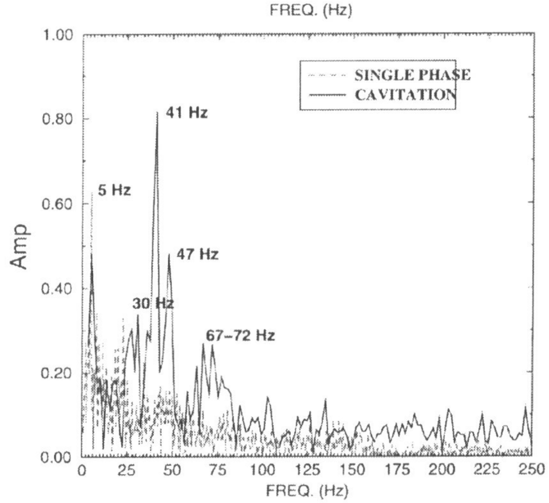
$\alpha = 5^{\circ}, \sigma = 0.79$

SPECTRAL CHARACTERISTICS OF CAVITATING NACA15 FLOWFIELD

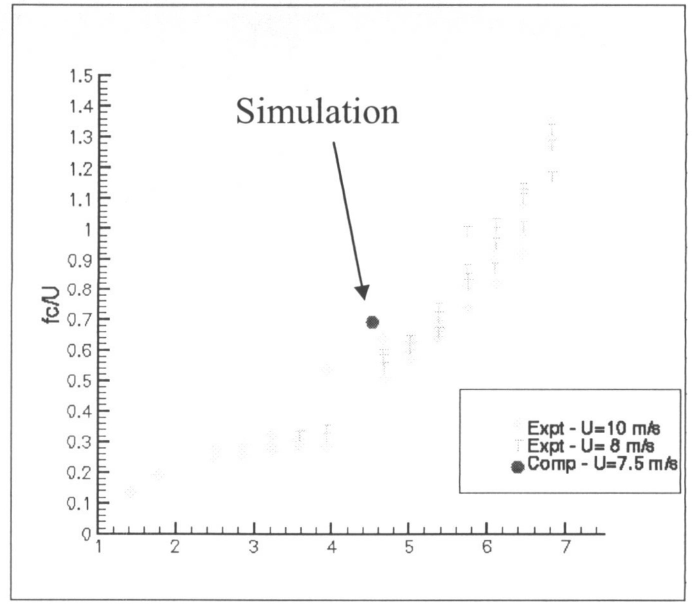
Lift Spectrum for Cavitating Case



Comparison of Single Phase and Cavitating Lift Spectra



Strouhal Number Prediction



Chord Length 128mm

$\alpha = 5^\circ, \sigma = 0.79$

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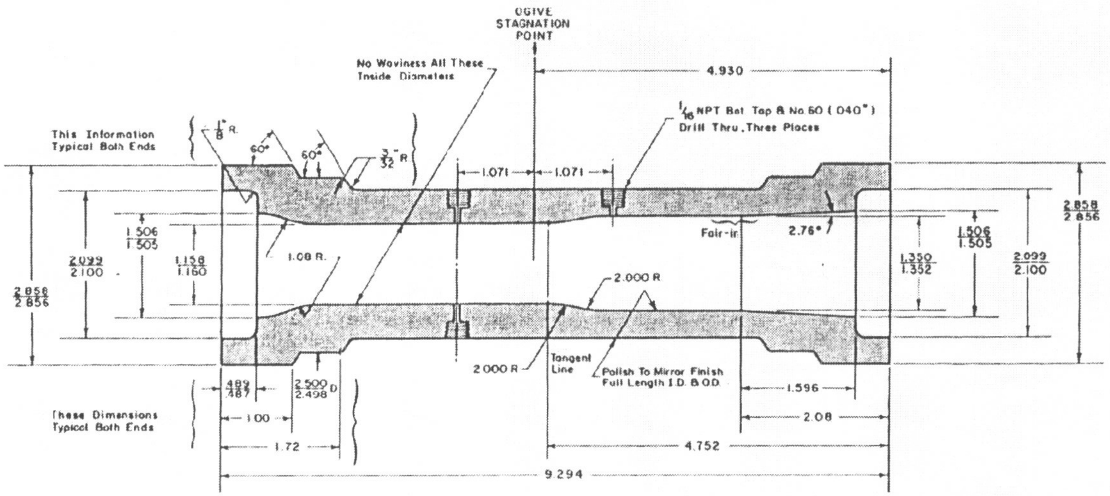
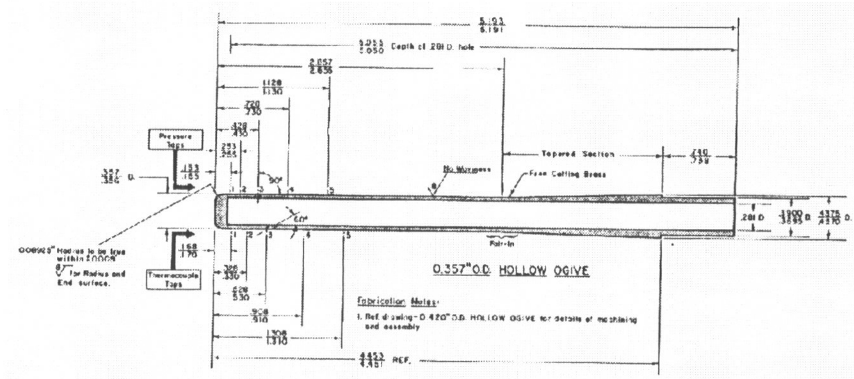
DETAILS OF SUBSCALE TUNNEL OGIVE TEST ARTICLE FROM HORD (1973)

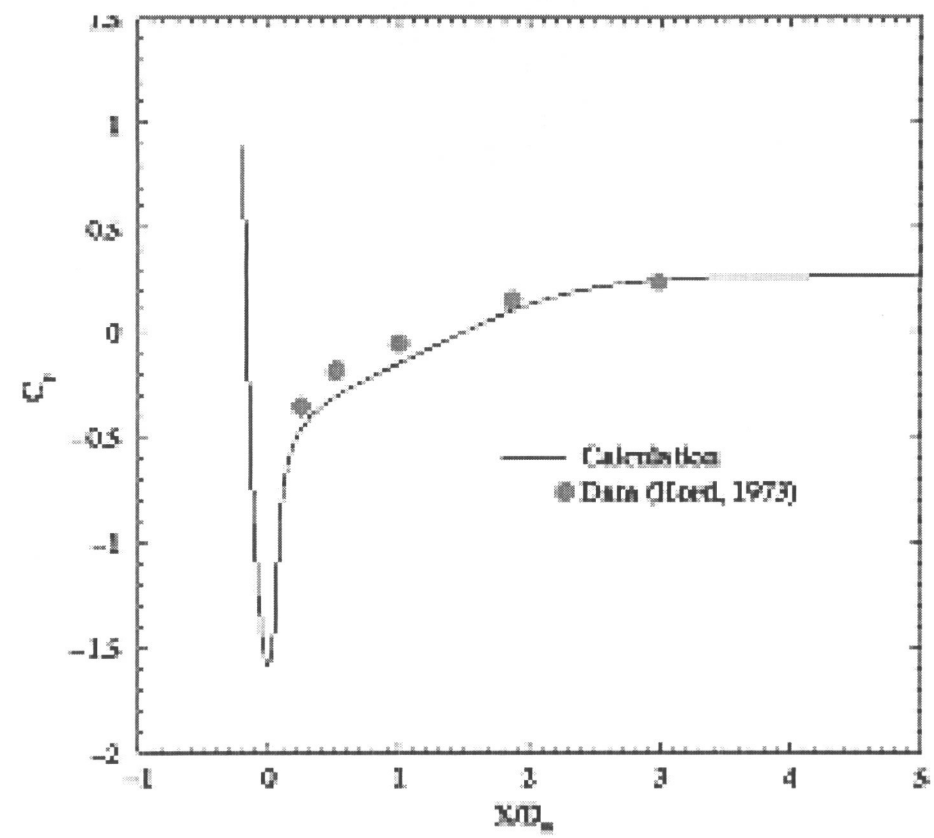


Tunnel Configuration



Ogive Test Article

PRESSURE COEFFICIENT FOR SINGLE PHASE FLOW IN SUB-SCALE TUNNEL



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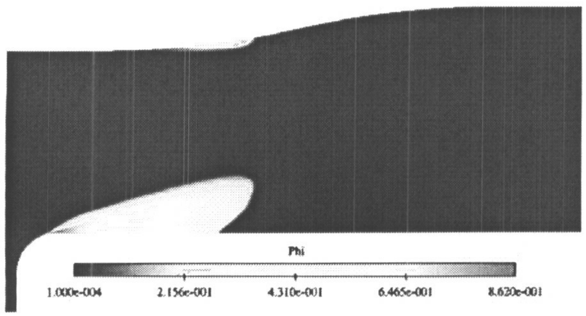
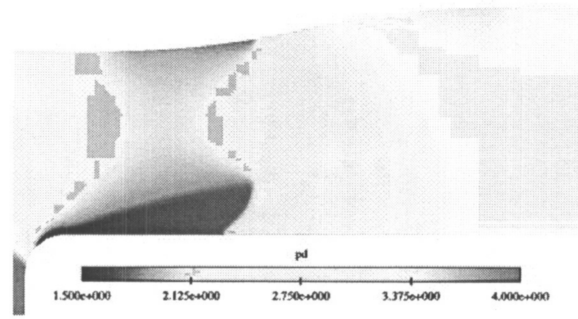
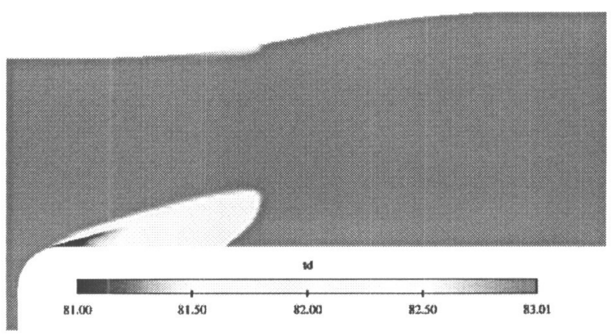
FLOWFIELD CONTOURS FOR CAVITATING OGIVE USING A RANS TURBULENCE MODEL



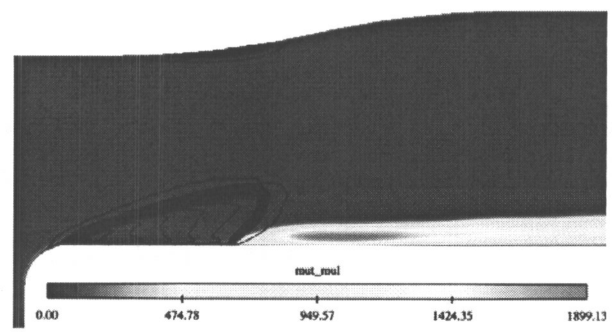
Vapor Volume Fraction



Pressure



Temperature



Turbulent Viscosity

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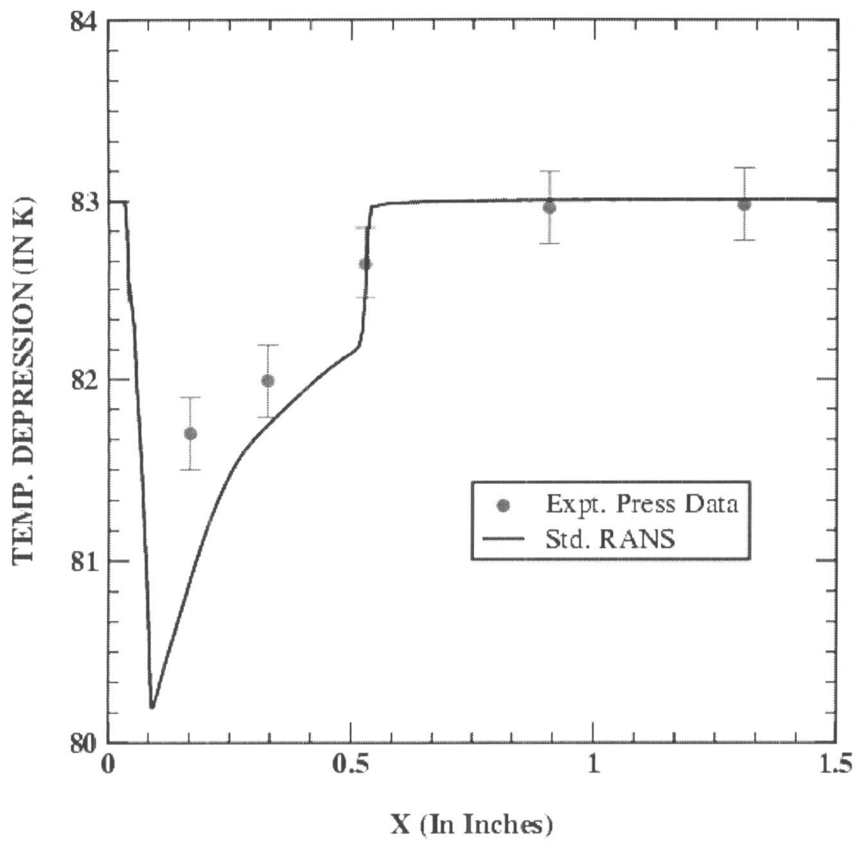
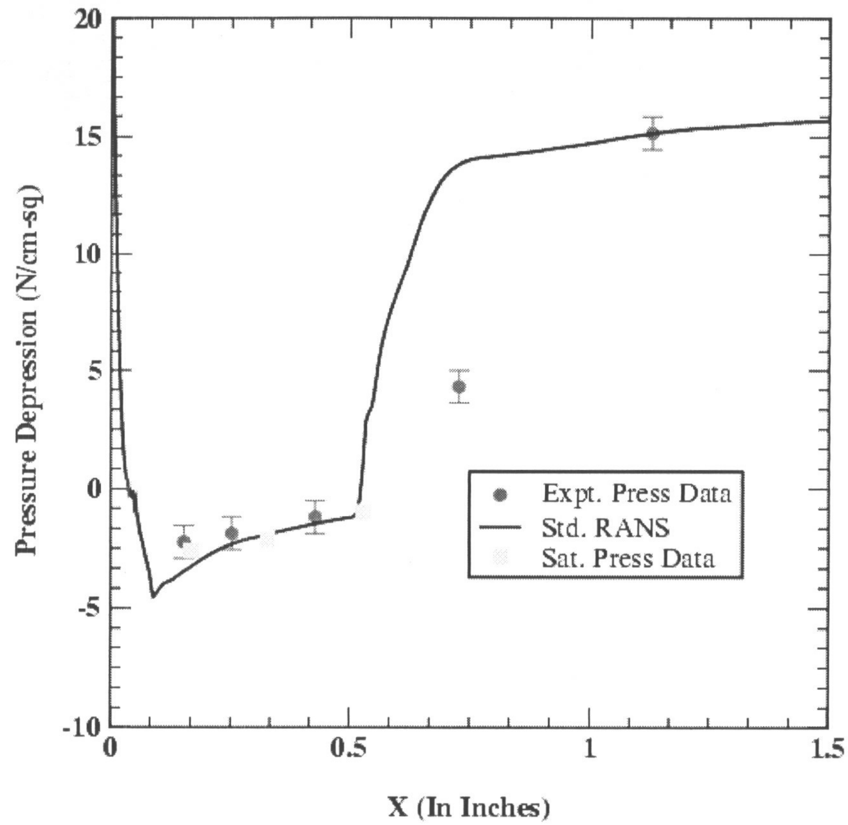
COMPARISON OF PRESSURE AND TEMPERATURE DEPRESSION COMPLETED WITH RANS TURBULENCE MODEL WITH DATA





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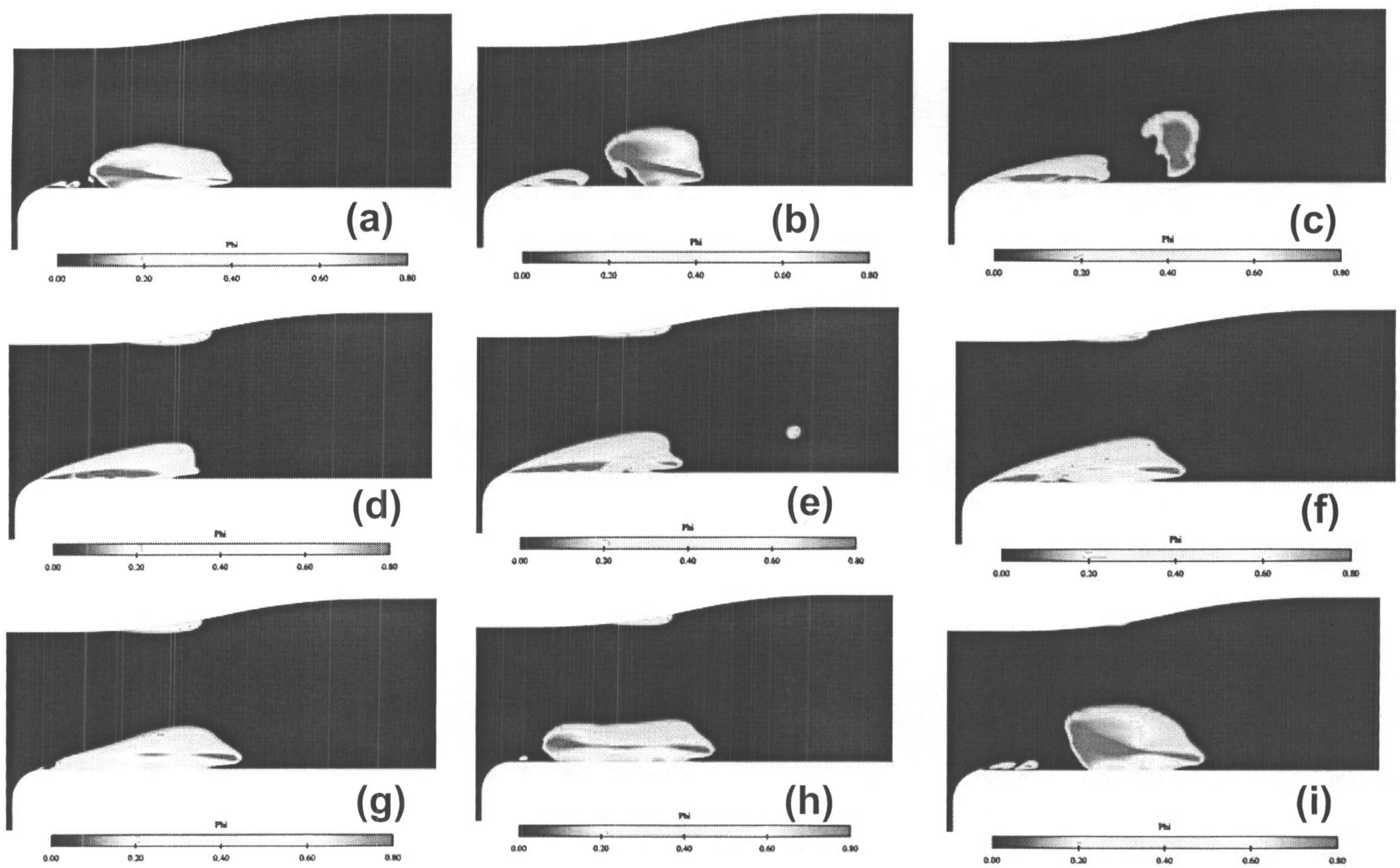
INSTANTANEOUS VAPOR VOLUME FRACTION CONTOURS FOR UNSTEADY LES CALCULATIONS SHOWN AT INTERVALS OF 0.29 MS



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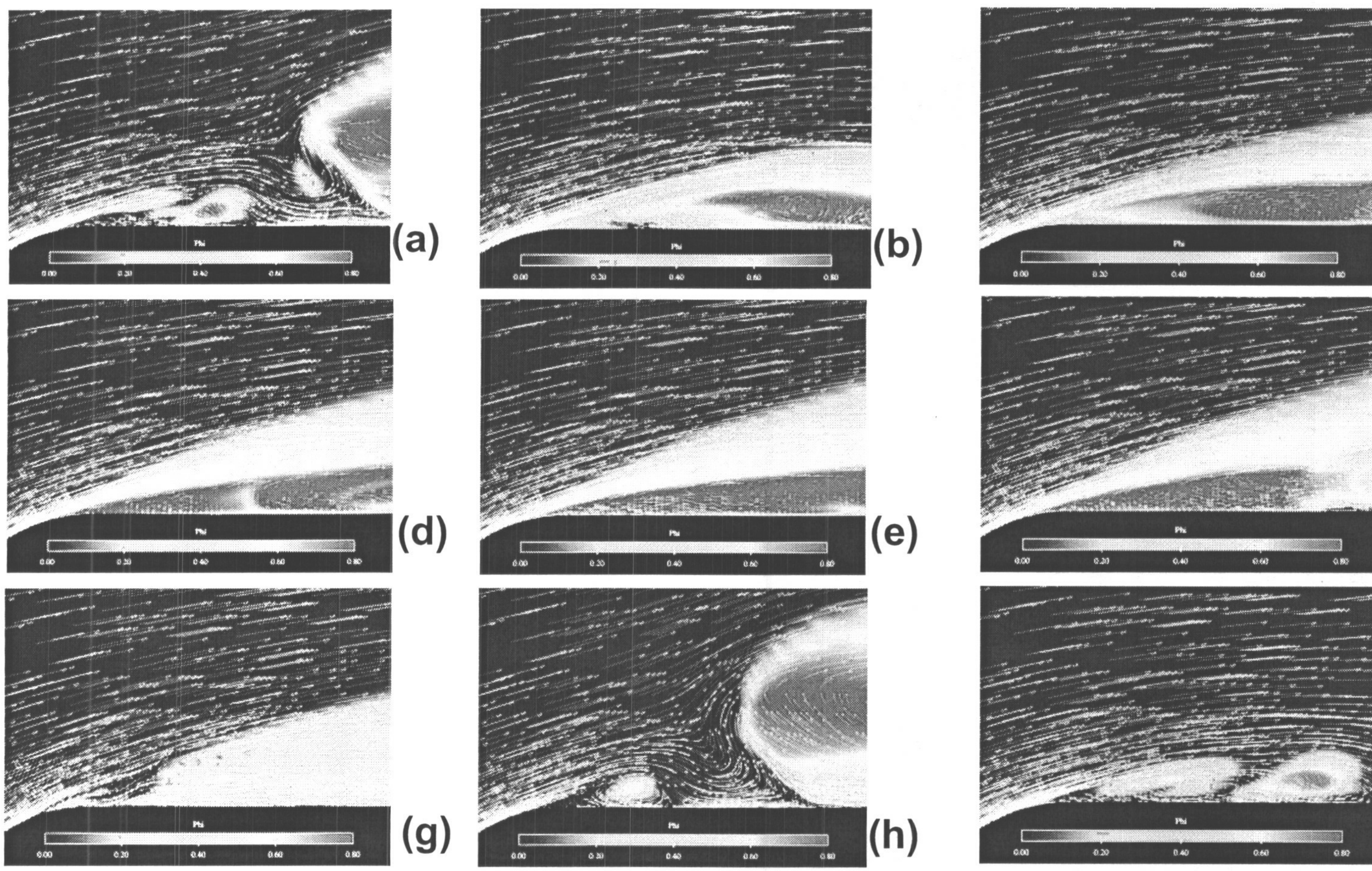
INSTANTANEOUS VELOCITY VECTORS CONTOURS FOR UNSTEADY LES CALCULATIONS SHOWN AT INTERVALS OF 0.29 MS



(a) (b) (c) (d) (e) (f) (g) (h) (i)

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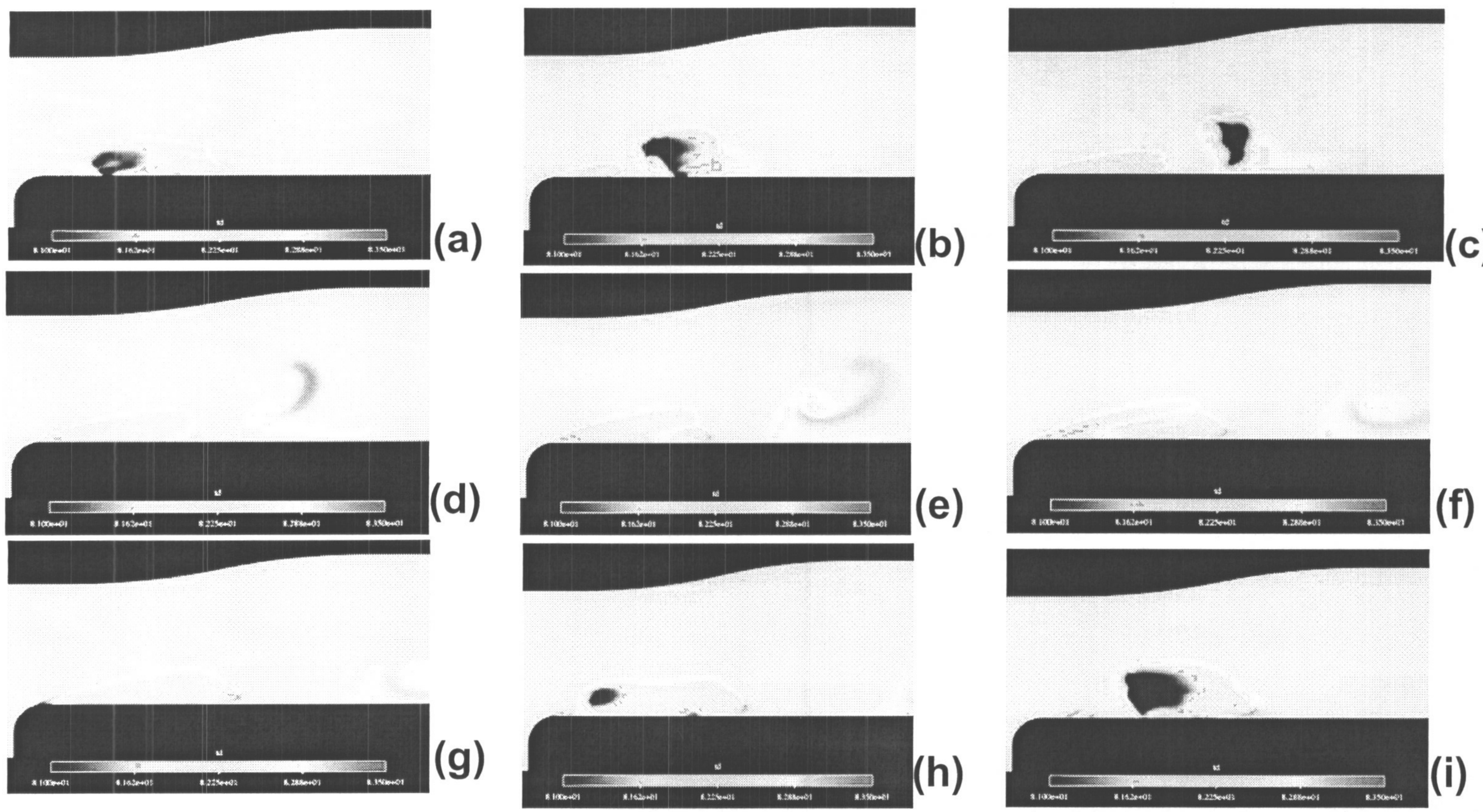
INSTANTANEOUS TEMPERATURE CONTOURS FOR UNSTEADY LES CALCULATIONS SHOWN AT INTERVALS OF 0.29 MS



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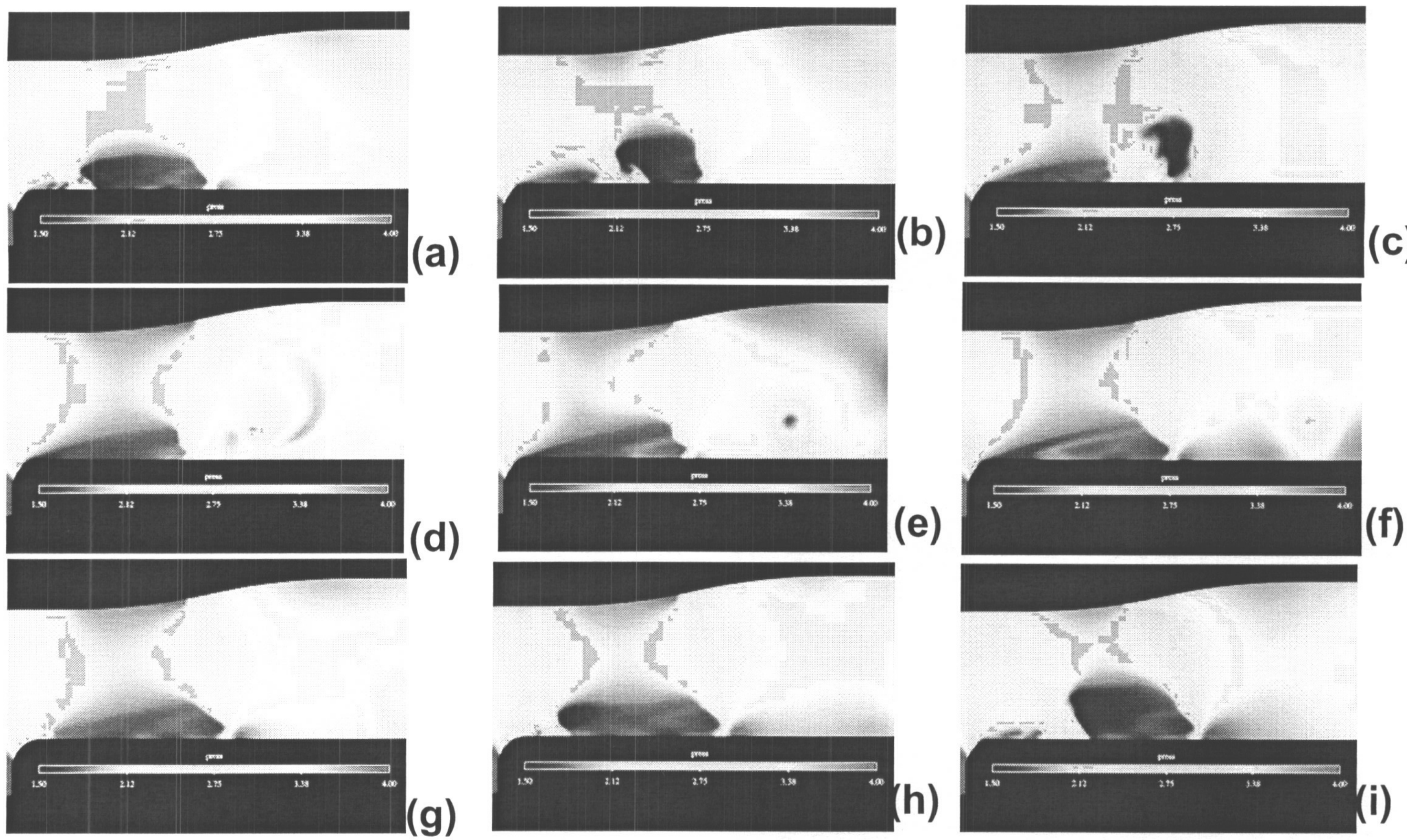
INSTANTANEOUS PRESSURE CONTOURS FOR UNSTEADY LES CALCULATIONS SHOWN AT INTERVALS OF 0.29 MS



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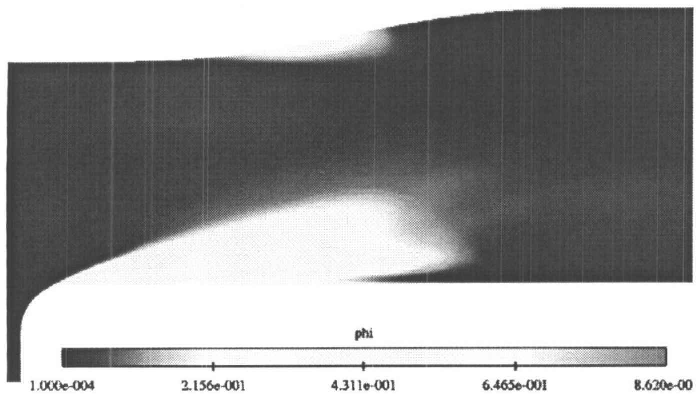
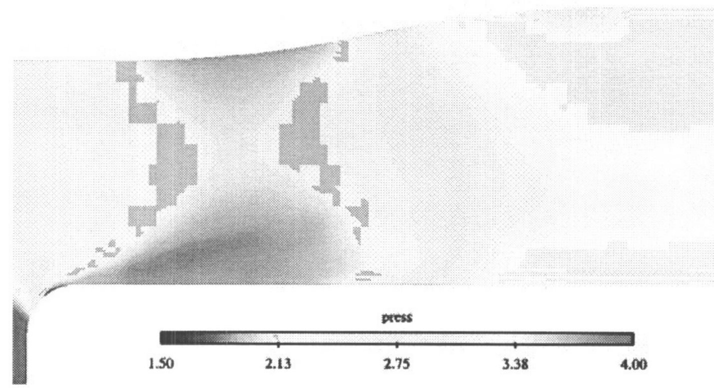
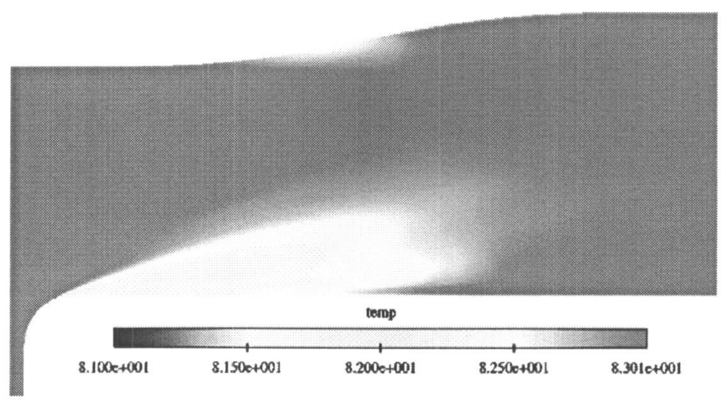
TIME-AVERAGED MEAN FLOWFIELD CONTOURS FROM UNSTEADY LES CALCULATION



(a) Vapor Volume Fraction



(b) Pressure



(c) Temperature

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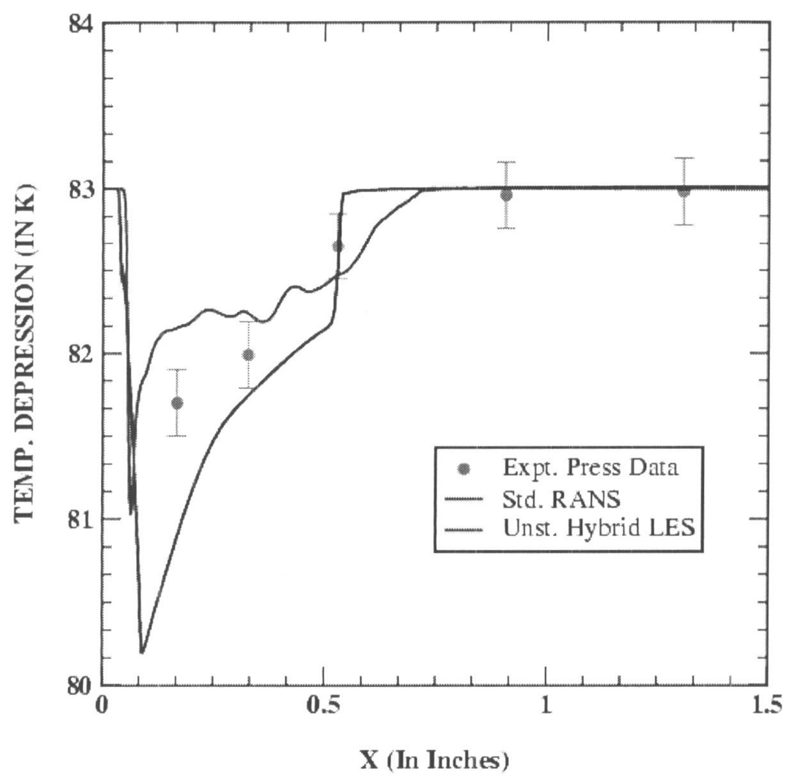
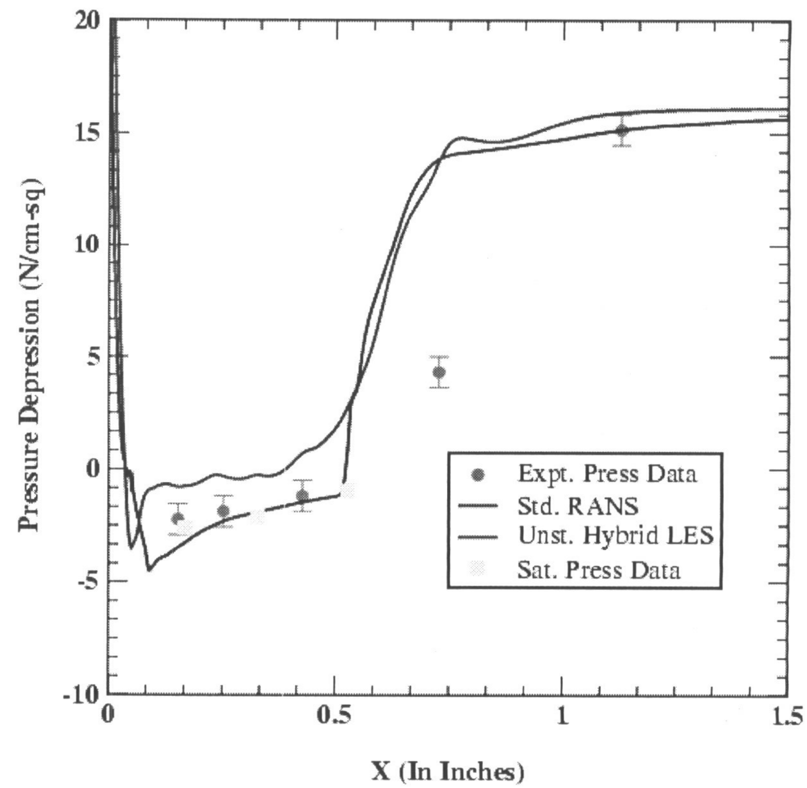
COMPARISON OF MEAN PRESSURE AND TEMPERATURE DEPRESS FROM UNSTEADY LES CALCULATIONS WITH RANS SOLUTION AND EXPERIMENTAL DATA





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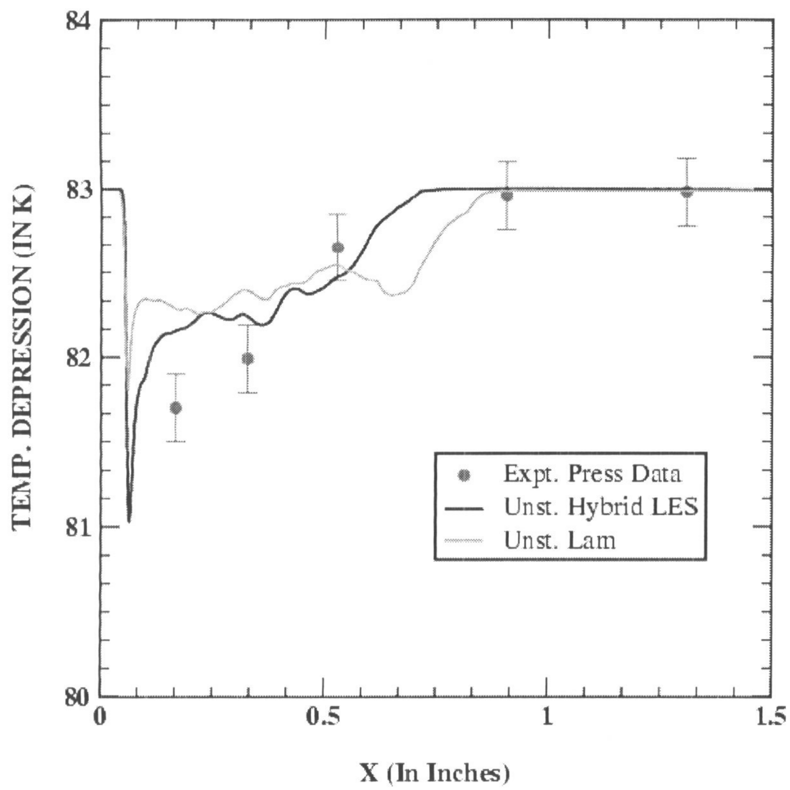
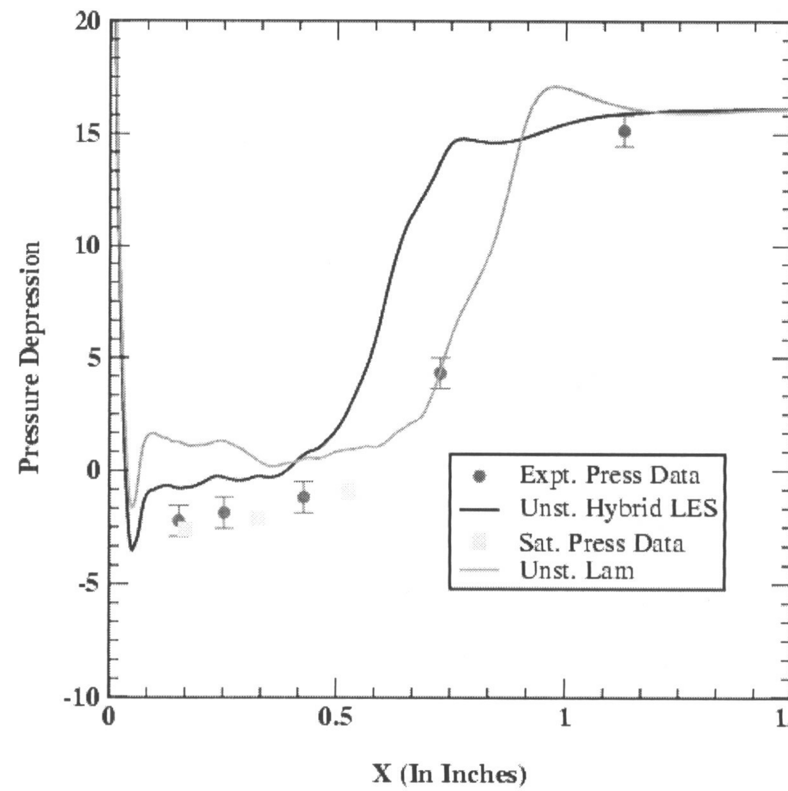
EFFECT OF SUBGRID VISCOSITY LEVELS ON PRESSURE AND TEMPERATURE DEPRESSION CAVITY





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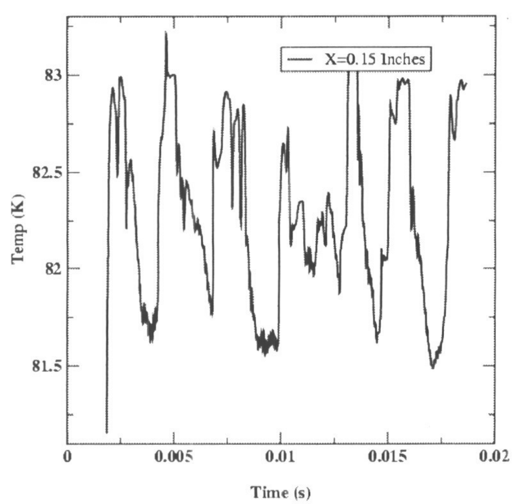
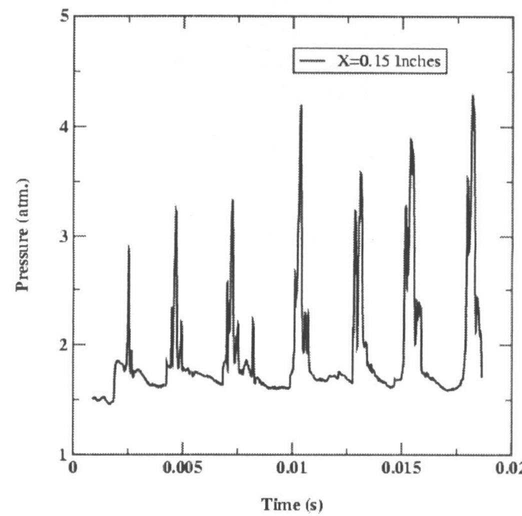
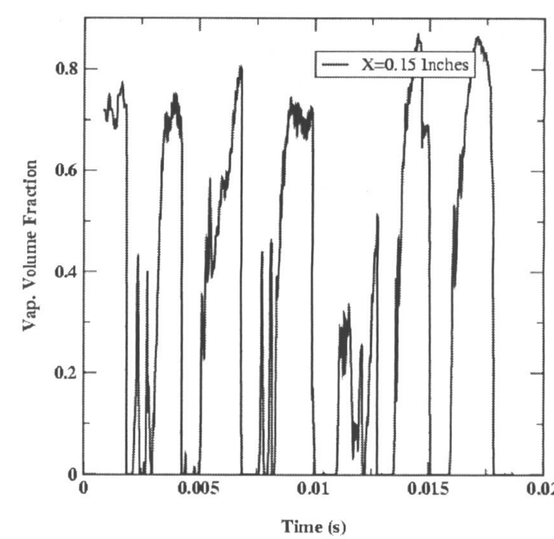
TIME TRACES OF FLOW VARIABLES CLOSE TO THE LEADING EDGE OF CAVITY ON OGIVE



(a) Temperature



(b) Pressure



(c) Volume Fraction

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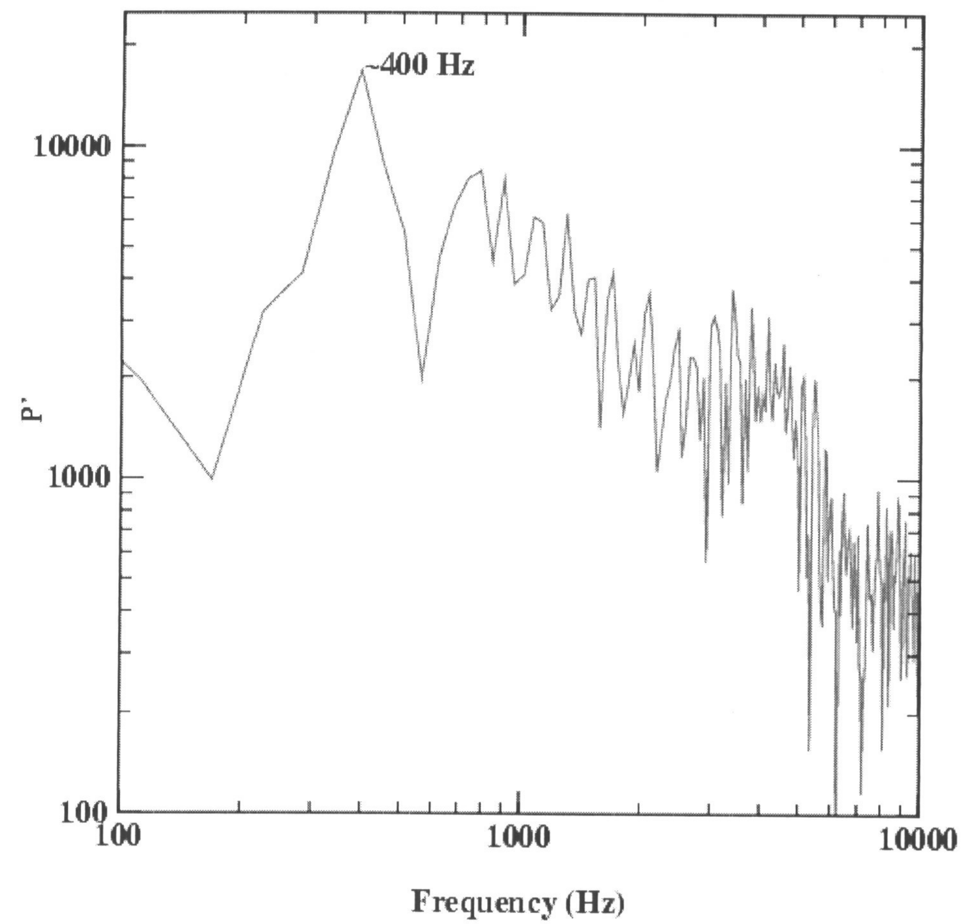
FREQUENCY SPECTRUM OF PRESSURE OSCILLATIONS NEAR THE LEADING EDGE OF CAVITY



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