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초공동 유동해석 기술

Numerical Analysis of Supercavitating Flow

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초공동 기술 토의,

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초공동 유동해석 기술

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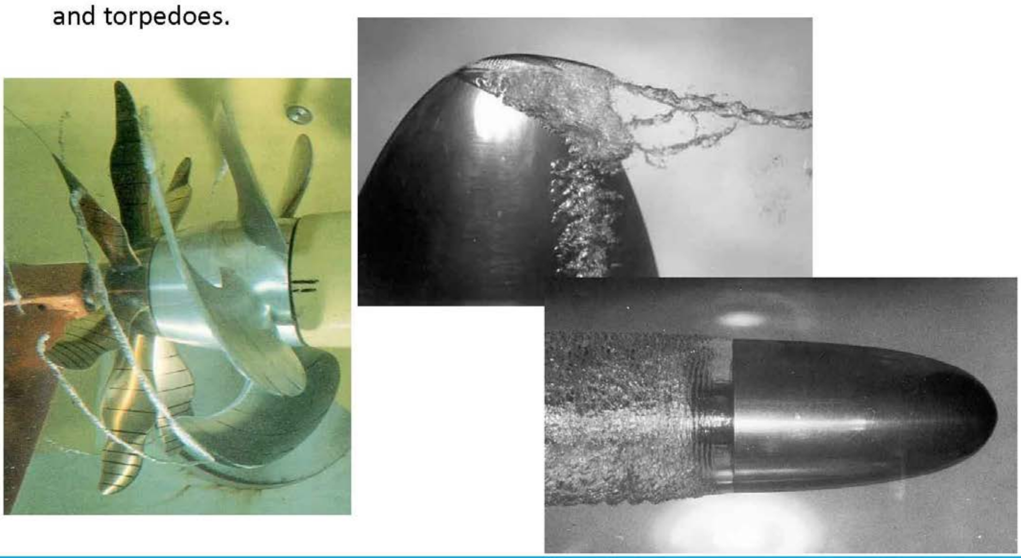
Cavitation

- Widely observed in various propulsion systems and high-speed underwater objects, such as marine propellers, impellers of turbomachinery, hydrofoils, nozzles, injectors and torpedoes.



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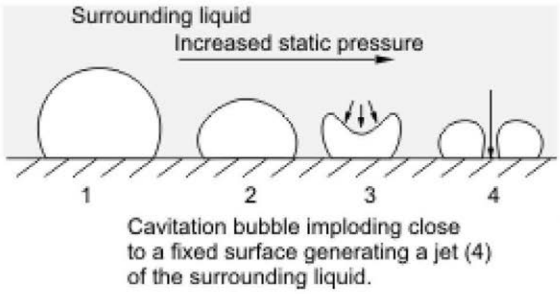
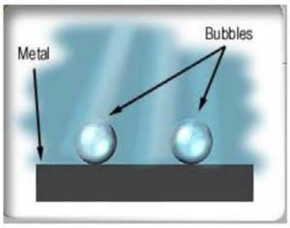
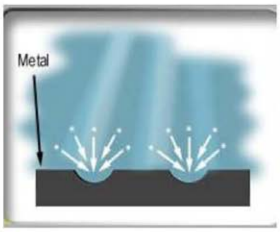
Erosion by Cavitation Bubble







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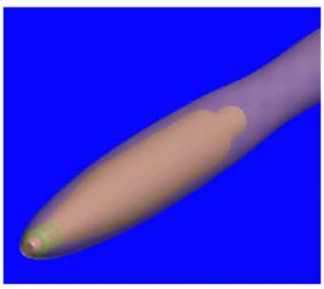
Drag Reduction

- Torpedo Speeds
  - Mk-46 Torpedo : 45 knots (80km/h)
  - Shkval I : > 250 knots (450km/h)
  - Shkval II : > 350 knots (rumored 720 knots)
  - Brracuda : > 360 knots (rumored 800 knots)
    1,440km/h

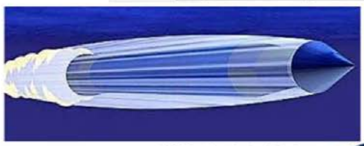
MK-46

- 초월공동어뢰



ONR/PSU ARL

Shkval(Squall)



Barracuda

2005 American Controls Conference Portland, OR June 10, 2005

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Drag Reduction

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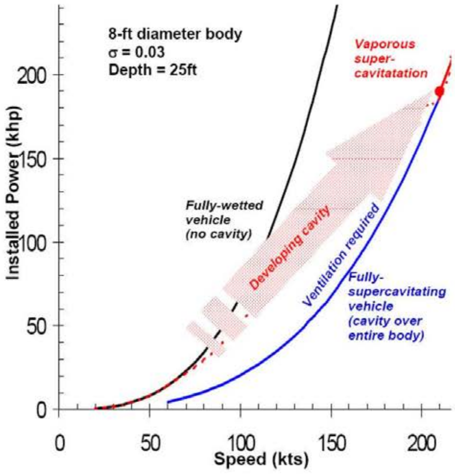

Drag Reduction Approaches	Speed +	Mechanism
Shaping	10%	Reduces form and wave drag
Polymers	20%	Reduces boundary layer frictional drag
Microbubbles	12%	Reduces boundary layer frictional drag
Coatings	4%	Modifies frictional drag of boundary layer
Supercavitation	**65%**	**Eliminates most frictional drag**

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Drag Reduction

초공동 기술 토의,
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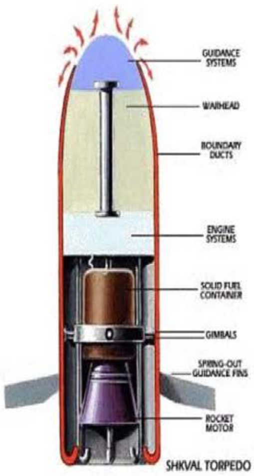
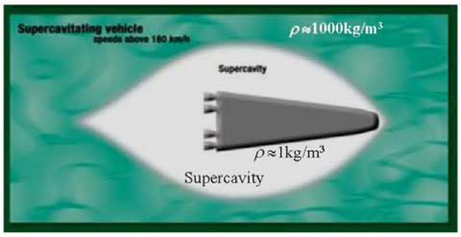
공동발생기법 → 자연공동
공동발생기법 → 환기공동(인위공동) → 비응축가스



< Shkval-I Torpedo >



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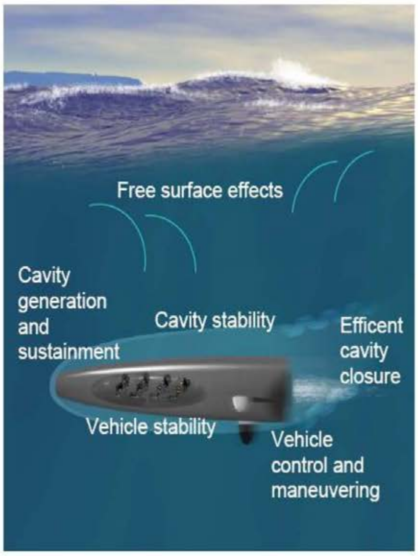
Drag Reduction

Underwater Express / SST (Super-fast Submerged Transport)

Speed ~100 knots
Size : 8 ft dia., 60 tones
- Comparable in size to current special purpose craft such as the MK V Special Operations Craft and the Advanced SEAL Delivery Vehicle
- Mark V: 82 feet long aluminum monohull surface craft, 40 knots

Demonstrate stable and controllable high-speed underwater transport through supercavitation for future littoral missions
Period : Nov. 2007 ~ 2010
Monitored by DARPA / ATO
Northrop Grumman Team selected
($45.8 million for 3 phases, ~4 years)



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Drag Reduction

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Supercavitating bullet

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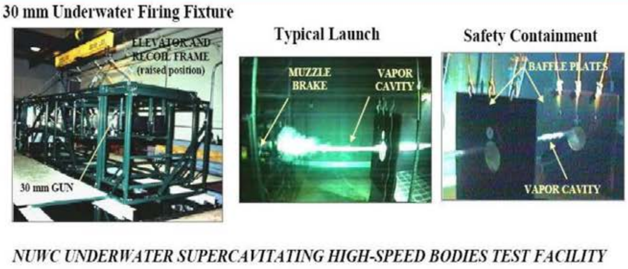

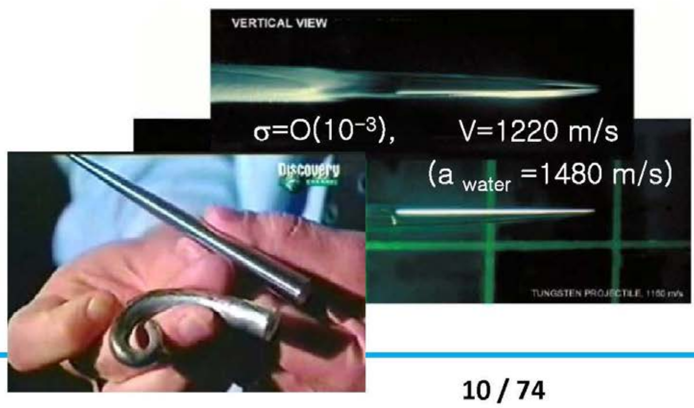

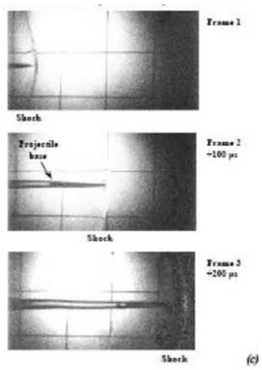

Supercavitating bullet

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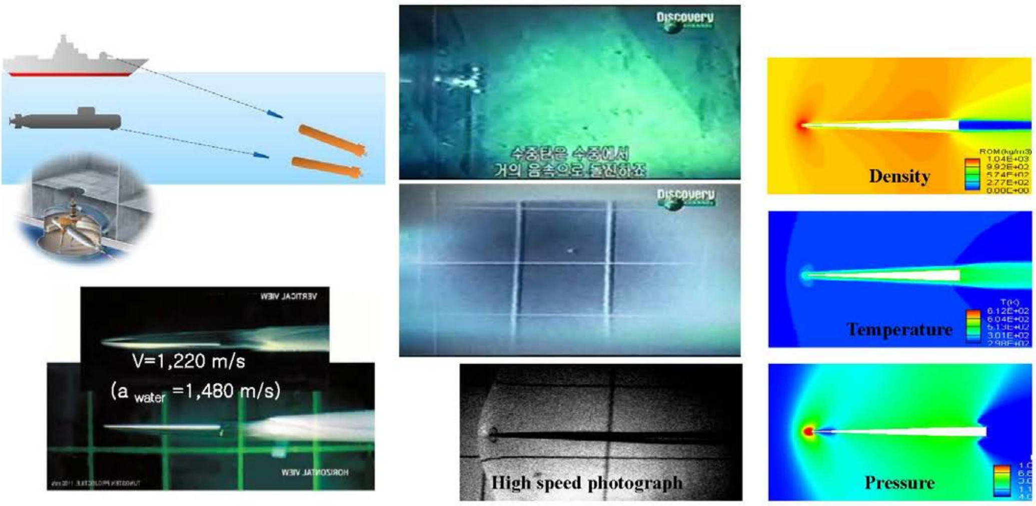
Supercavitating bullet

- High-Speed Underwater Bullet : U_∞=1,540 km/h (M_∞=1.03); P_∞=152.0 kPa (Depth : 4m); T_∞=27°C
  - AHSUM (Adaptable High-Speed Underwater Munitions)



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초공동 기술 토의, 2019.04.23

지배 방정식 (Governing Equation)

Phase change due to pressure : cavitation

Phase change due to temperature

□ Continuity Equation

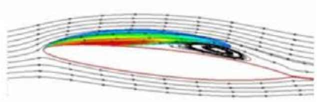
$$\frac{\partial}{\partial t}(Y_L\rho_m)+\frac{\partial}{\partial x}(Y_L\rho_m u)+\frac{\partial}{\partial y}(Y_L\rho_m v)+\frac{\partial}{\partial z}(Y_L\rho_m w)=\left[(\dot{m}_p^+ +\dot{m}_p^-)+(\dot{m}_T^+ +\dot{m}_T^-)\right]$$

$$\frac{\partial}{\partial t}(Y_v\rho_m)+\frac{\partial}{\partial x}(Y_v\rho_m u)+\frac{\partial}{\partial y}(Y_v\rho_m v)+\frac{\partial}{\partial z}(Y_v\rho_m w)=-\left[(\dot{m}_p^+ +\dot{m}_p^-)+(\dot{m}_T^+ +\dot{m}_T^-)\right]$$

$$\frac{\partial}{\partial t}(Y_g\rho_m)+\frac{\partial}{\partial x}(Y_g\rho_m u)+\frac{\partial}{\partial y}(Y_g\rho_m v)+\frac{\partial}{\partial z}(Y_g\rho_m w)=0$$

$$\dot{m}_T^+ = C_{rv}\rho_v\alpha_v \max\left(\frac{T_v-T}{T_v},0\right)$$

$$\dot{m}_T^- = C_{rL}\rho_L\alpha_L \min\left(\frac{T_v-T}{T_v},0\right)$$

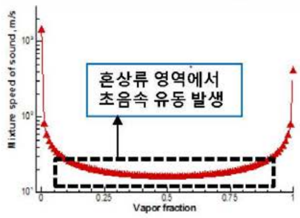


□ Momentum Equation

$$\frac{\partial}{\partial t}(\rho_m u)+\frac{\partial}{\partial x}(\rho_m u^2)+\frac{\partial}{\partial y}(\rho_m uv)+\frac{\partial}{\partial z}(\rho_m uw)=-\bar{\beta}_p\frac{\partial p}{\partial x}+\frac{\partial \tau_{xx}}{\partial x}+\frac{\partial \tau_{xy}}{\partial y}+\frac{\partial \tau_{xz}}{\partial z}+\rho_m g_x$$

$$\frac{\partial}{\partial t}(\rho_m v)+\frac{\partial}{\partial x}(\rho_m vu)+\frac{\partial}{\partial y}(\rho_m v^2)+\frac{\partial}{\partial z}(\rho_m vw)=-\bar{\beta}_p\frac{\partial p}{\partial y}+\frac{\partial \tau_{yx}}{\partial x}+\frac{\partial \tau_{yy}}{\partial y}+\frac{\partial \tau_{yz}}{\partial z}+\rho_m g_y$$

$$\frac{\partial}{\partial t}(\rho_m w)+\frac{\partial}{\partial x}(\rho_m wu)+\frac{\partial}{\partial y}(\rho_m wv)+\frac{\partial}{\partial z}(\rho_m w^2)=-\bar{\beta}_p\frac{\partial p}{\partial z}+\frac{\partial \tau_{zx}}{\partial x}+\frac{\partial \tau_{zy}}{\partial y}+\frac{\partial \tau_{zz}}{\partial z}+\rho_m g_z$$



□ Energy Equation

$$\frac{\partial}{\partial t}(\rho_m h_t-\bar{\beta}_p p)+\frac{\partial}{\partial x}(\rho_m h_t u)+\frac{\partial}{\partial y}(\rho_m h_t v)+\frac{\partial}{\partial z}(\rho_m h_t w)=\frac{\partial(u\tau_{xx}+v\tau_{xy}+w\tau_{xz}-q_x)}{\partial x}+\frac{\partial(u\tau_{yx}+v\tau_{yy}+w\tau_{yz}-q_y)}{\partial y}+\frac{\partial(u\tau_{zx}+v\tau_{zy}+w\tau_{zz}-q_z)}{\partial z}-h(\dot{m}_T^+ +\dot{m}_T^-)$$

Phase change induced energy transfer (latent heat)

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지배 방정식 (Governing Equation)

$$\Gamma_e\frac{\partial\hat{Q}}{\partial t}+\Gamma\frac{\partial\hat{Q}}{\partial\tau}+\frac{\partial(\hat{E}-\hat{E}_v)}{\partial\xi}+\frac{\partial(\hat{F}-\hat{F}_v)}{\partial\eta}+\frac{\partial(\hat{G}-\hat{G}_v)}{\partial\zeta}=\hat{S}$$

Isothermal

$$\Gamma_e=\begin{pmatrix}0&0&0&0&0\\0&\rho_m&0&0&u\Delta\rho_l\\0&0&\rho_m&0&v\Delta\rho_l\\0&0&0&\rho_m&w\Delta\rho_l\\0&0&0&0&1\end{pmatrix}$$

$$\Gamma=\begin{pmatrix}1/\beta^2&0&0&0&0\\0&\rho_m&0&0&u\Delta\rho_l\\0&0&\rho_m&0&v\Delta\rho_l\\0&0&0&\rho_m&w\Delta\rho_l\\\alpha_l/\beta^2&0&0&0&1\end{pmatrix}$$

Fully Compressible

$$\Gamma_e=\begin{bmatrix}Y_l\partial_p\rho_m&0&0&0&Y_l\partial_T\rho_m&-\rho_m+Y_l\partial_{Yv}\rho_m\\u\partial_p\rho_m&\rho_m&0&0&u\partial_T\rho_m&u\partial_{Yv}\rho_m\\v\partial_p\rho_m&0&\rho_m&0&v\partial_T\rho_m&v\partial_{Yv}\rho_m\\w\partial_p\rho_m&0&0&\rho_m&w\partial_T\rho_m&w\partial_{Yv}\rho_m\\ht\partial_p\rho_m+\rho_m\partial_p h-1&\rho_m u&\rho_m v&\rho_m w&ht\partial_T\rho_m+\rho_m\partial_T h&ht\partial_{Yv}\rho_m+\rho_m\partial_{Yv}h\\Y_v\partial_p\rho_m&0&0&0&Y_v\partial_T\rho_m&\rho_m+Y_v\partial_{Yv}\rho_m\end{bmatrix}$$

$$\Gamma=\begin{bmatrix}Y_l\partial_p\rho_m'&0&0&0&Y_l\partial_T\rho_m&-\rho_m+Y_l\partial_{Yv}\rho_m\\u\partial_p\rho_m'&\rho_m&0&0&u\partial_T\rho_m&u\partial_{Yv}\rho_m\\v\partial_p\rho_m'&0&\rho_m&0&v\partial_T\rho_m&v\partial_{Yv}\rho_m\\w\partial_p\rho_m'&0&0&\rho_m&w\partial_T\rho_m&w\partial_{Yv}\rho_m\\ht\partial_p\rho_m'+\rho_m\partial_p h-1&\rho_m u&\rho_m v&\rho_m w&ht\partial_T\rho_m+\rho_m\partial_T h&ht\partial_{Yv}\rho_m+\rho_m\partial_{Yv}h\\Y_v\partial_p\rho_m'&0&0&0&Y_v\partial_T\rho_m&\rho_m+Y_v\partial_{Yv}\rho_m\end{bmatrix}$$

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지배 방정식 (Governing Equation)

$$\left[I + \Delta\tau\Gamma^{-1}\left(\frac{\partial A}{\partial \xi} + \frac{\partial B}{\partial \eta} + 1.5\frac{\Gamma_e}{\Delta t} - S\right)\right]\Delta\hat{Q}^{n+1,k} = -\Delta\tau\Gamma^{-1}\hat{R}^{n+1,k}$$

$$\Delta\hat{Q}^{n+1,k} = \hat{Q}^{n+1,k+1} - \hat{Q}^{n+1,k} \quad \hat{R}^{n+1,k} = \Gamma_e \frac{3\hat{Q}^{n+1,k} - 4\hat{Q}^{n} + \hat{Q}^{n-1}_{i,j}}{2\Delta t} + \left[\left(\frac{\partial \hat{E}}{\partial \xi} + \frac{\partial \hat{F}}{\partial \eta}\right) - \left(\frac{\partial \hat{E}_v}{\partial \xi} + \frac{\partial \hat{F}_v}{\partial \eta}\right) + \hat{S}\right]^{n+1,k}$$

- Second-order accurate backward difference for the physical time derivative
- First order upwind for the convective flux terms (implicit part)
- First-order backward difference for the pseudo time derivative
- Upwind Non-MUSCL Total Variation Diminishing (TVD) approach for the convective flux terms (Residual part)
- A second-order central for the viscous flux terms (Residual part)

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Cavitation & Boiling Models

Cavitation Models

Option #1 : Merkle et al. 1998

$$\dot{m}^- = \frac{C_{dest}\rho_l\alpha_l \min[0, p - p_v]}{(\rho_l U_\infty^2/2)t_\infty}$$

$$\dot{m}^+ = \frac{C_{prod}\rho_v(1-\alpha_l)\max[0, p - p_v]}{(\rho_l U_\infty^2/2)t_\infty}$$

Option #2 : Lindau et al. 2002

$$\dot{m}^- = \frac{C_{dest}\rho_v\alpha_l \min[0, p - p_v]}{(\rho_l U_\infty^2/2)t_\infty}$$

$$\dot{m}^+ = \frac{C_{prod}\rho_v \alpha_l^2(1-\alpha_l)}{t_\infty}$$

Option #3 : Singhal et al. 2002

$$m^- = c_{dest}\frac{\sqrt{k}}{T}\rho_L\rho_v Y_L \frac{dR}{dt}$$

$$m^+ = c_{prod}\frac{\sqrt{k}}{T}\rho_L\rho_v Y_V \frac{dR}{dt}$$

Option #5 : Merkle et al. 2006

$$\dot{m}^- = -k_v \frac{\rho_v\alpha_l}{t_\infty} min\left\{1, max\left(\frac{(p_v - p)}{k_p p_v}, 0\right)\right\}$$

$$\dot{m}^+ = k_l \frac{\rho_v\alpha_v}{t_\infty} min\left\{1, max\left(\frac{(p - p_v)}{k_p p_v}, 0\right)\right\}$$

Option #4 : Yuan et al. 2003

$$\dot{m}^- = \begin{cases} -\rho_v L(4\pi N)^{1/3}(3\alpha_v)^{2/3}\sqrt{\frac{2}{3}\frac{|p_v - p|}{\rho_l}} & \text{if } p \le p_v \text{ and } \alpha_v < 1 \\ 0 & \text{if } p > p_v \text{ or } \alpha_v = 1 \end{cases}$$

$$\dot{m}^+ = \begin{cases} \rho_v L(4\pi N)^{1/3}(3\alpha_v)^{2/3}\sqrt{\frac{2}{3}\frac{|p_v - p|}{\rho_l}} & \text{if } p \ge p_v \\ 0 & \text{if } p < p_v \end{cases}$$

Boiling Model

Lee's boiling model

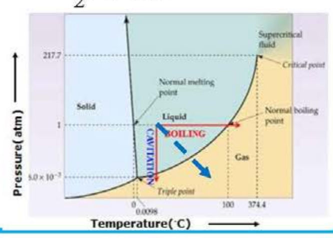
$$\dot{m}_T^+ = C_{rv}\rho_v\alpha_v \max\left(\frac{T_v - T}{T_v}, 0\right)$$

$$\dot{m}_T^- = C_{rL}\rho_L\alpha_L \min\left(\frac{T_v - T}{T_v}, 0\right)$$

PNU boiling model(based Merkle model), 2014

$$\dot{m}_T^- = \frac{C_{Tdest}\rho_L\alpha_L}{\frac{1}{2}\rho_\infty U_\infty t_\infty}\min(T_{sat} - T, 0)$$

$$\dot{m}_T^+ = \frac{C_{Tprod}\rho_v\alpha_v}{\frac{1}{2}\rho_\infty U_\infty t_\infty}\max(T_{sat} - T, 0)$$



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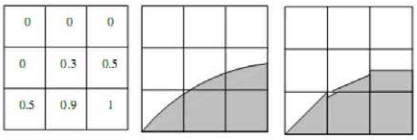
Numerical Methods

VOF MODEL + Multi phase Code

$$\frac{\partial \alpha}{\partial t}+\frac{\partial}{\partial x}(u\alpha)+\frac{\partial}{\partial y}(v\alpha)=0$$

$$\frac{1}{J}\frac{\partial \alpha}{\partial t}+\frac{\partial}{\partial \xi}\left(\frac{1}{J}U\alpha\right)+\frac{\partial}{\partial \eta}\left(\frac{1}{J}V\alpha\right)=0$$



(a) Volume Fractions (b) True Interface (c) Piecewise Linear Approximation

AHEM Mixture MODEL + Multi phase Code

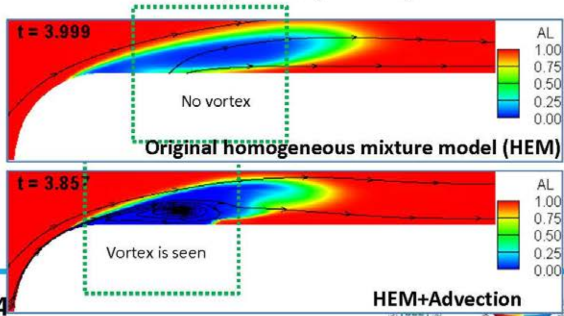
Adding the solution of volume fraction advection equations for both vapor and gaseous mixture to the solution of HEM

+ For vapor phase

$$\frac{\partial \alpha_v}{\partial t}+U\frac{\partial \alpha_v}{\partial \xi}+V\frac{\partial \alpha_v}{\partial \eta}+W\frac{\partial \alpha_v}{\partial \zeta}=-\frac{\left(\dot{m}^{+}+\dot{m}^{-}\right)}{\rho_v}$$

+ For non-condensable gaseuos mixture

$$\frac{\partial \alpha_g}{\partial t}+U\frac{\partial \alpha_g}{\partial \xi}+V\frac{\partial \alpha_g}{\partial \eta}+W\frac{\partial \alpha_g}{\partial \zeta}=0$$



* AHEM : Advanced Homogeneous Mixture

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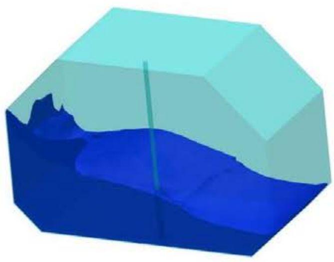
Numerical Methods

VOF equation in Cartesian coordinates

$$\frac{\partial \alpha}{\partial t}+\frac{\partial}{\partial x}(u\alpha)+\frac{\partial}{\partial y}(v\alpha)=0$$

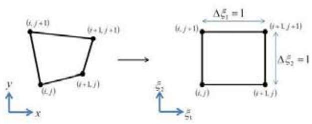
Transformation to curvilinear coordinates

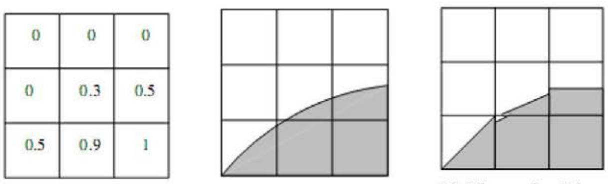
$$\frac{1}{J}\frac{\partial \alpha}{\partial t}+\frac{\partial}{\partial \xi}\left(\frac{1}{J}U\alpha\right)+\frac{\partial}{\partial \eta}\left(\frac{1}{J}V\alpha\right)=0$$



The contravariant velocities:

$$U=\xi_x u+\xi_y v\ ;\quad V=\eta_x u+\eta_y v$$





(a) Volume Fractions (b) True Interface (c) Piecewise Linear Approximation

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Results and Discussion

- Natural & Ventilated(Artificial) Caviattion

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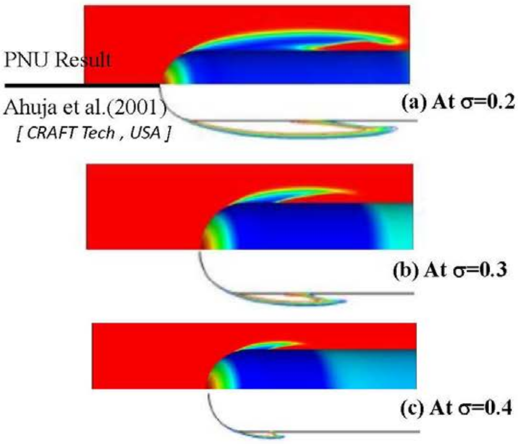
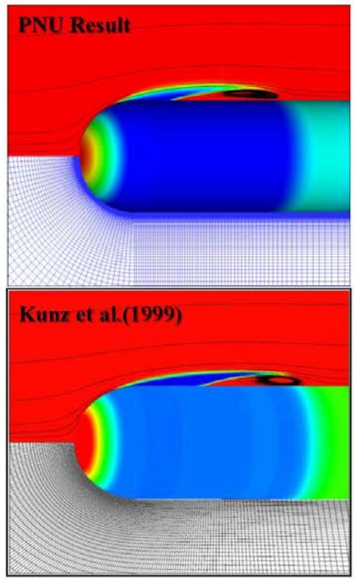
Natural Cavitation

Comparison with Ahuja's Result



Comparison with Kunz's Result(ONR/ARL)



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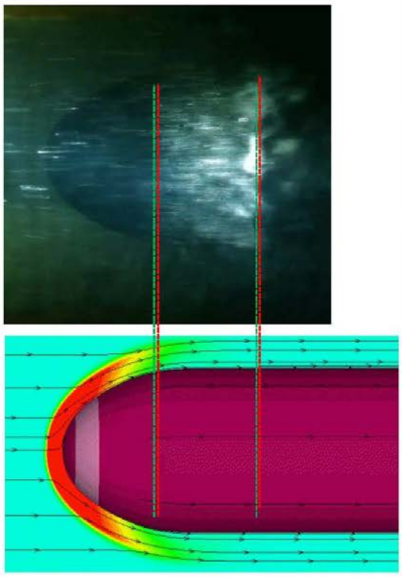
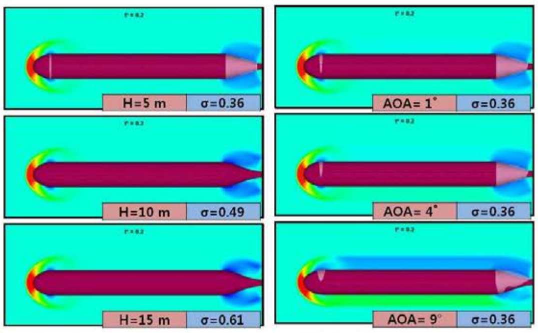
Natural Cavitation

Comparison with Experiment (ADD, Korea)





- Depth : 5 , 10 , 15 m
  (Fixed AOA=0°, V=55knot)
- AOA : 0°~ 9°
  (Fixed H=5m , V=55knot)

---Analysis
---Experiment

	Start of L/D (mean)	End of L/D(mean)	Length(mean)
Analysis	0.561	1.153	0.592
Experiment	0.613 ± 0.05	1.276±0.01	0.663

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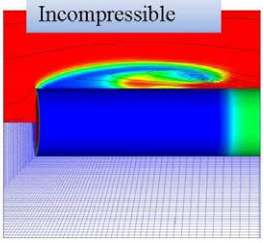
초공동 기술 토의,
2019.04.23

Compressible Effects

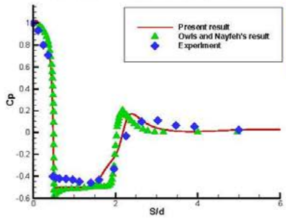
Caviatating Flows over a 0 Caliber(blunt) Cylinder

PNU CFD LAB.

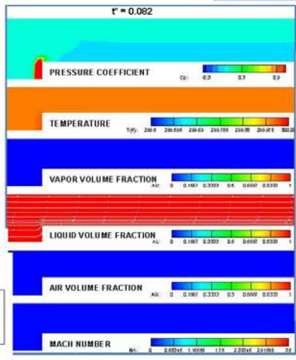
Incompressible

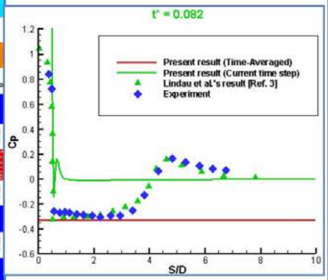


vapor volume fraction and streamlines at σ =0.3



Compressible





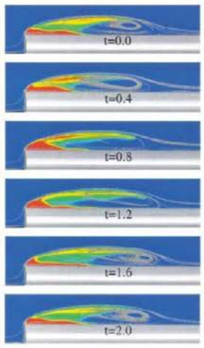
U_∞= 15.28 m/s, p_∞=38.5 kPa, T_∞=300K (σ=0.3), air content α_g=0.0,

preconditioning parameter β=1,

entropy correction parameters δ_1=0.015, δ_2=0.02

Kunz's Result

Isothermal Compressible



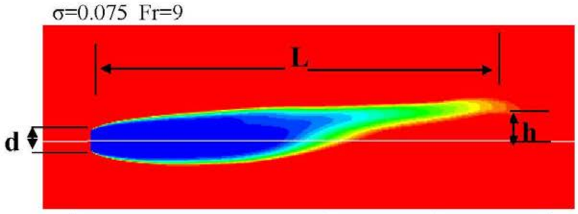
Sankaran Venkateswaran, Jules W. Lindau, Robert F. Kunz, and Charles L. Merkl: (2002)

초공동 기술 토의,
2019.04.23

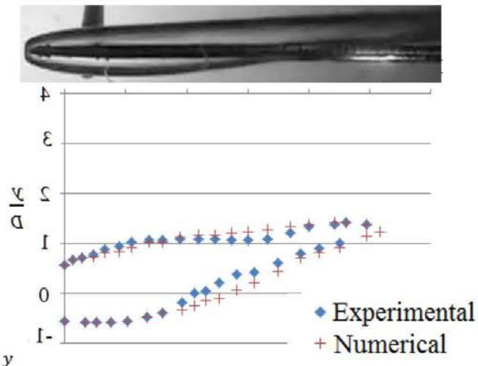
Buoyancy (Gravity) Effect

Disk with Gravity Effect : Ventilated Cavitation

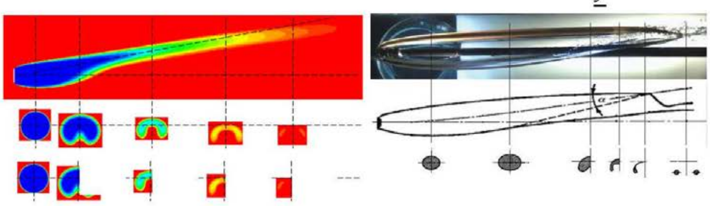
σ=0.075 Fr=9



	L/d	h/d
Numerical results	24	1.9
Experimental data <Epshtein – 1970>	23	1.8



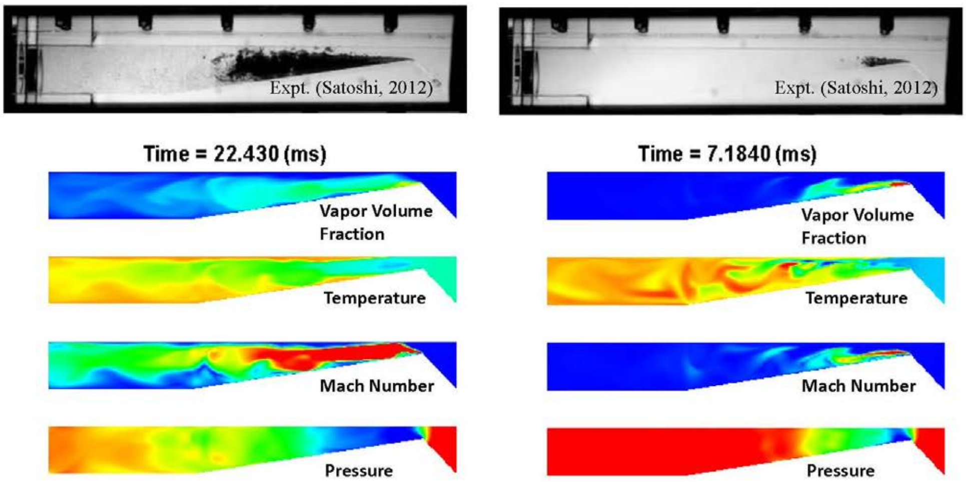
<Gravity effect on the shape of ventilated supercavitation, *ZHANG, 2007* >



초공동 기술 토의,
2019.04.23

Nozzle Cavitation

Cavitating Flows in a Nozzle



Flow conditions:	Flow conditions:
U_{inlet}=3.5 m/s; T_{inlet}= 27°C ; **p_{outlet}=94.5 kPa**	U_{inlet}= 3.5 m/s; T_{inlet}= 27°C ; **p_{outlet}=124 kPa**
($\sigma_{outlet} \approx$14.9)	($\sigma_{outlet} \approx$19.8)

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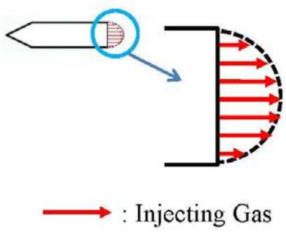
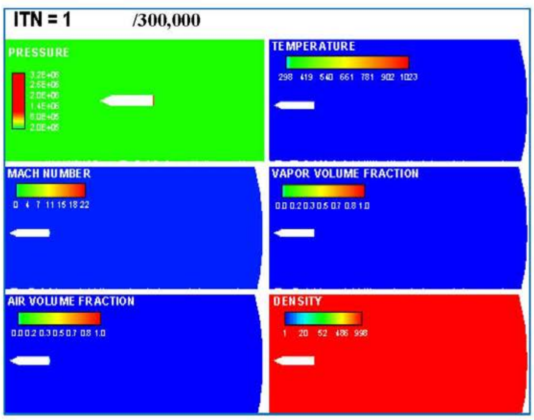
초공동 기술 토의,
2019.04.23

Compressible Effects

Ventilated Cavitation with Temperarure Difference

- Free stream conditions: U_∞=112 m/s
  p_∞=101.325, Pa; T_∞=25°C (298.15K) (M_∞=0.075)
- Conditions at the blowhole: U_{ven}=392 m/s ,
  p_{ven}=1.2x10^6 Pa; T_{ven}=750°C (1023.15K)





Steady equations were solved

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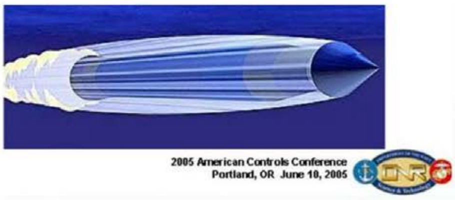
초공동 기술 토의,
2019.04.23

Supercavitating Torpedo

Barracuda



Without ventilated Cavitation

With ventilated Cavitation

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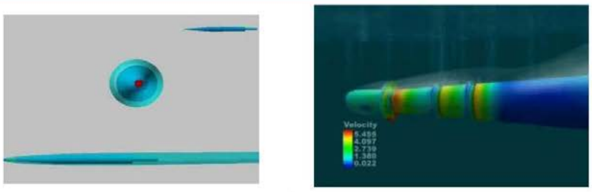
초공동 기술 토의,
2019.04.23

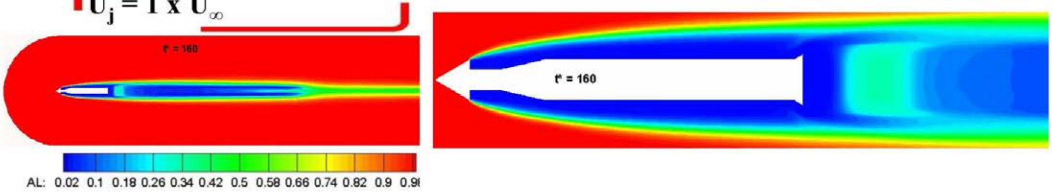
Ventilated Cavitation

Cavity Instability

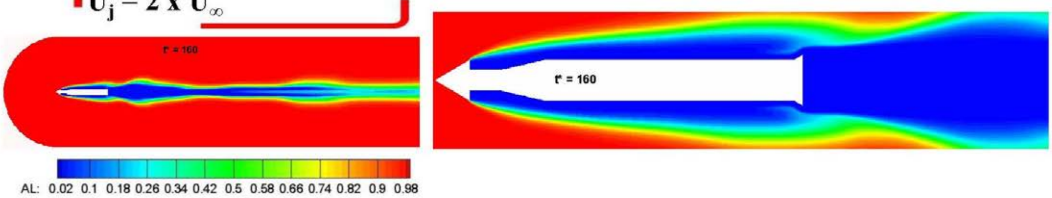


< ONR /ARL >

$U_j = 1 \times U_\infty$



$U_j = 2 \times U_\infty$



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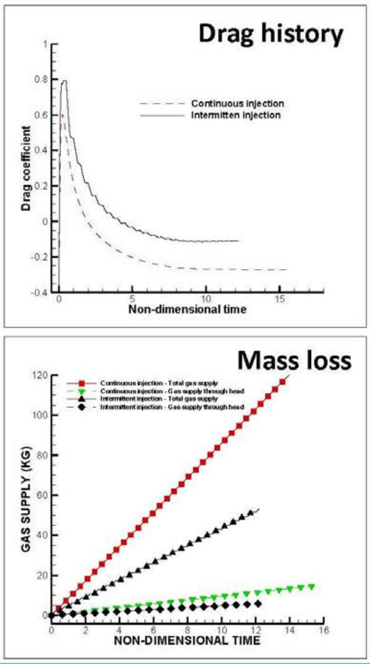
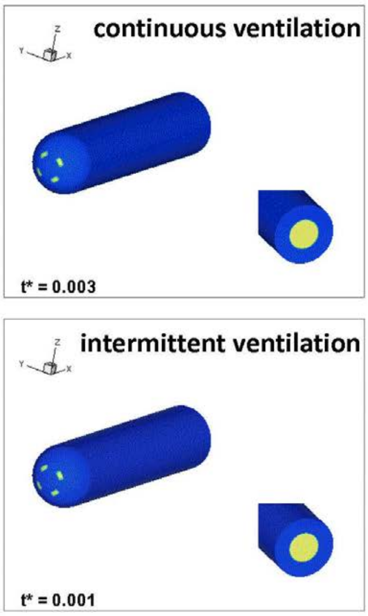
초공동 기술 토의,
2019.04.23

Ventilated Cavitation - continuous & intermittent ventilation





< Surface pressure and gas contour >

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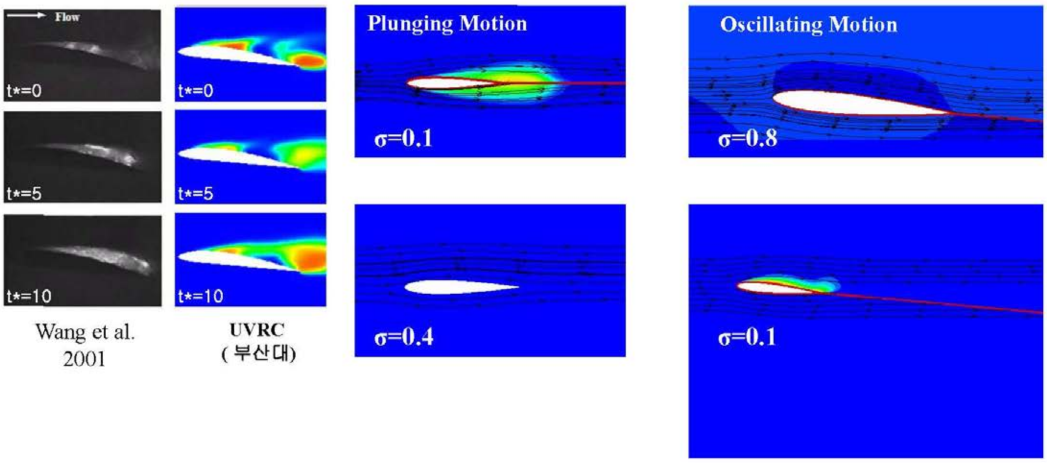
초공동 기술 토의,
2019.04.23

Cavitation over Hydrofoil

Cavitating Flows over Hydrofoil



Wang et al.
2001

UVRC
(부산대)

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초공동 기술 토의,
2019.04.23

Results and Discussion

- *Free Surface Simulations*

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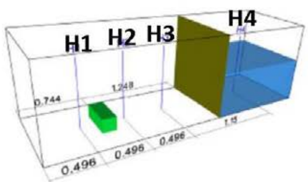
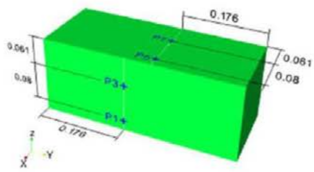
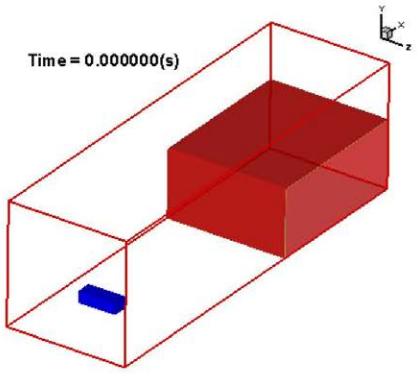
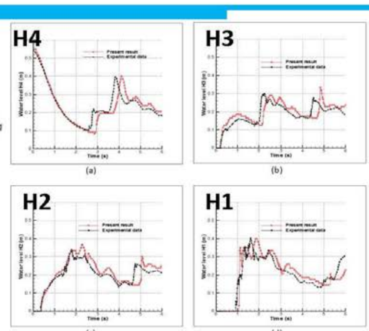
초공동 기술 토의,
2019.04.23

Dam-break problem with an object

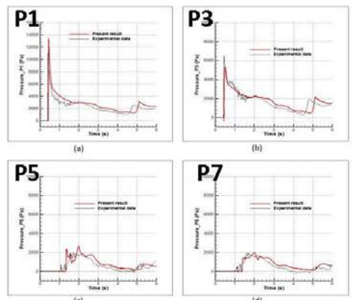








Water level at four positions



Pressures at four gauges

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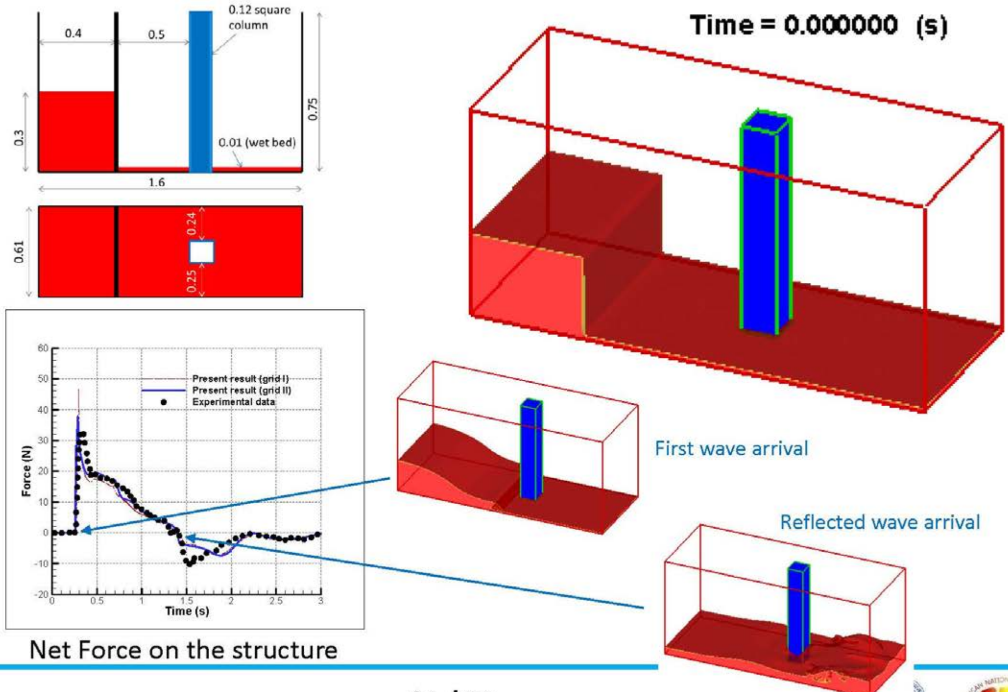
초공동 기술 토의,
2019.04.23

Dam-break problem with an object



Net Force on the structure

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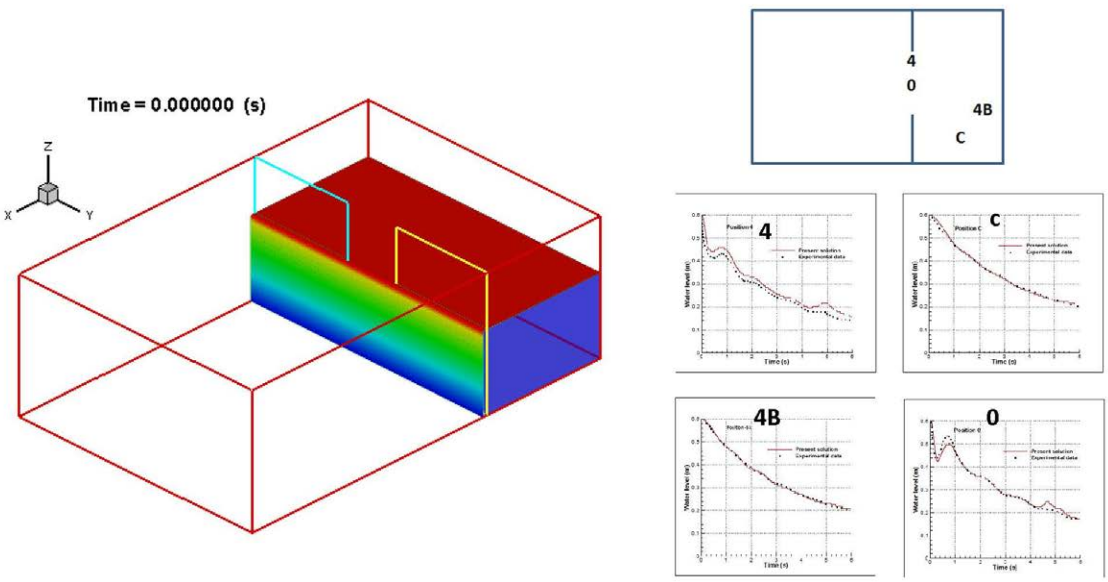
초공동 기술 토의,
2019.04.23

Dam-break problem



Velocities at four gauges

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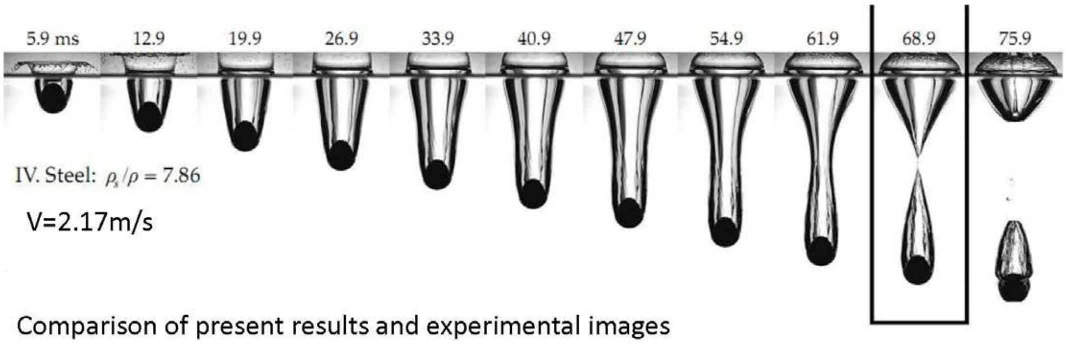
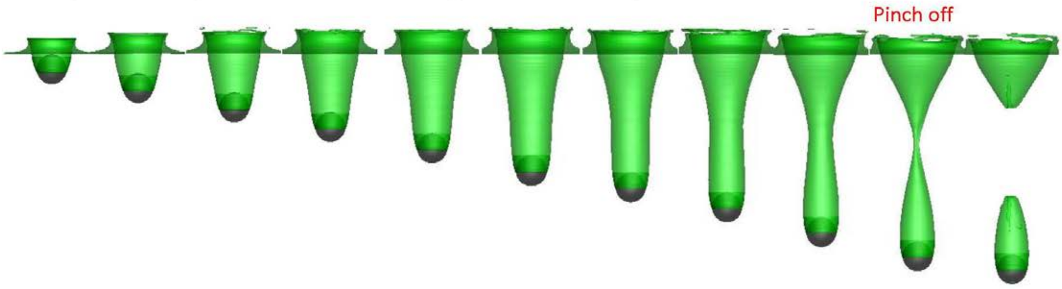
초공동 기술 토의,
2019.04.23

Simulation of a sphere entering into water using Chimera technique



Comparison of present results and experimental images



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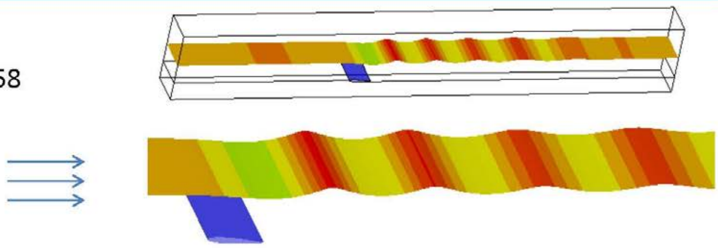
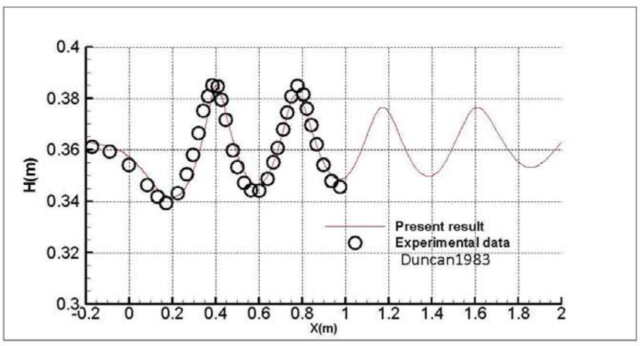
초공동 기술 토의,
2019.04.23

Steady Free Surface Flows about hydrofoil NACA0012

Fr=0.58

U=0.8 m/s





Comparison of wave profile between numerical and experimental results

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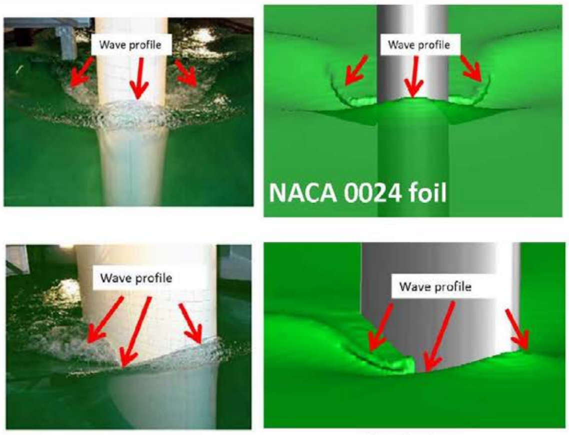
초공동 기술 토의, 2019.04.23

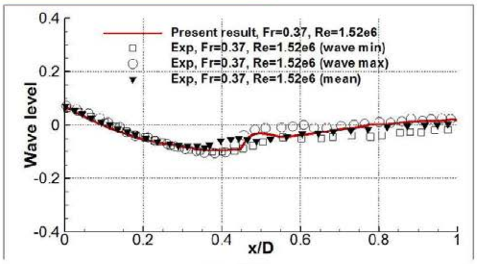
Free-surface Wave



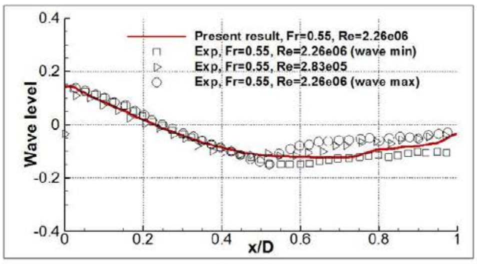
Experiment
Metcalf et al. 2006

Simulation

Visual comparison of wave profiles between CFD and experimental images



Fr=0.37



Fr=0.55

Wave profiles and near-field elevations close to the foil surface

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초공동 기술 토의, 2019.04.23

Results and Discussion

- *Water Entry Problems*

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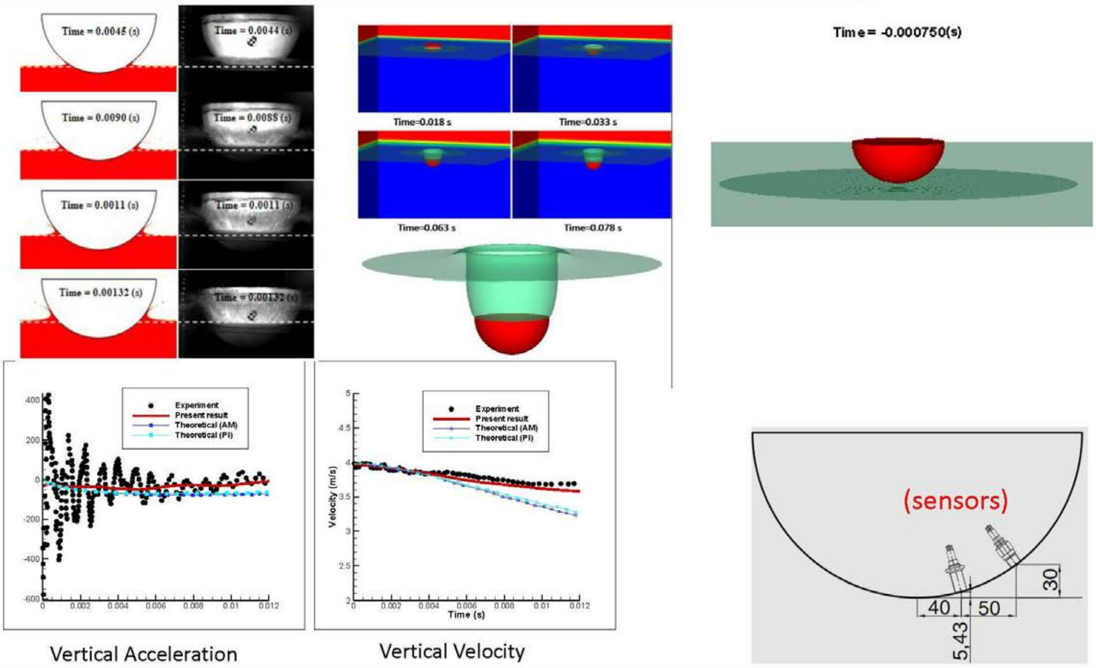
초공동 기술 토의, 2019.04.23

Water Impact Force Analysis



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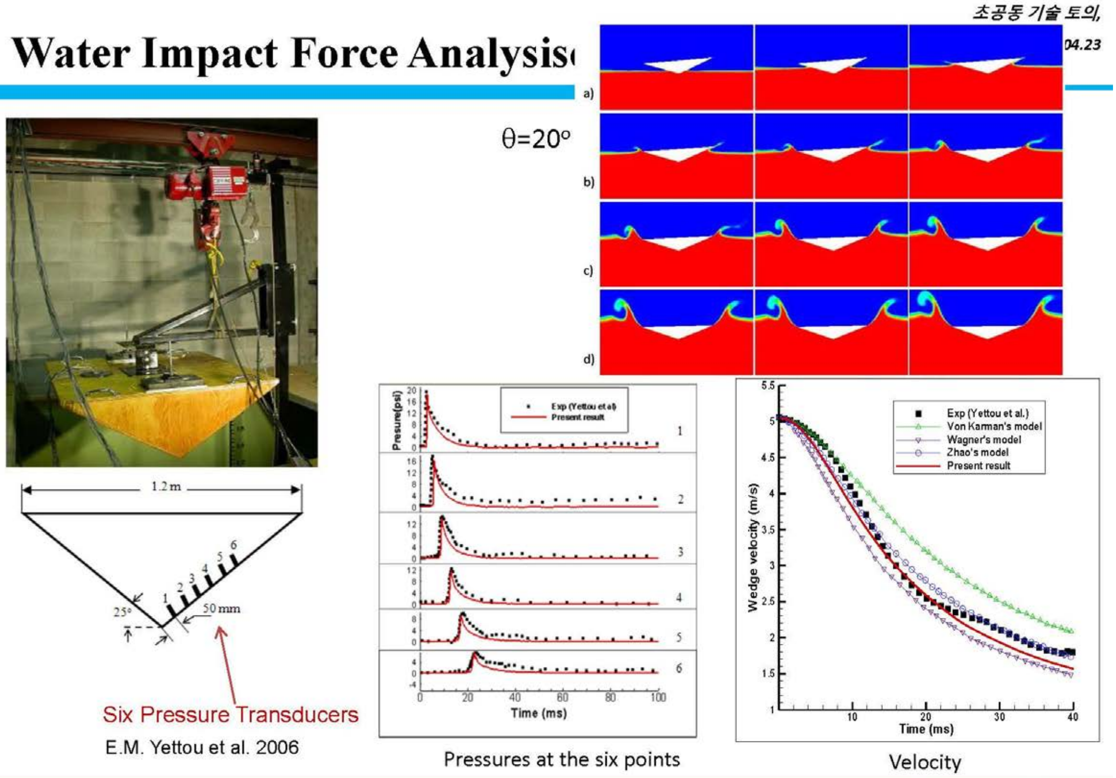
초공동 기술 토의, 2019.04.23

Water Impact Force Analysis



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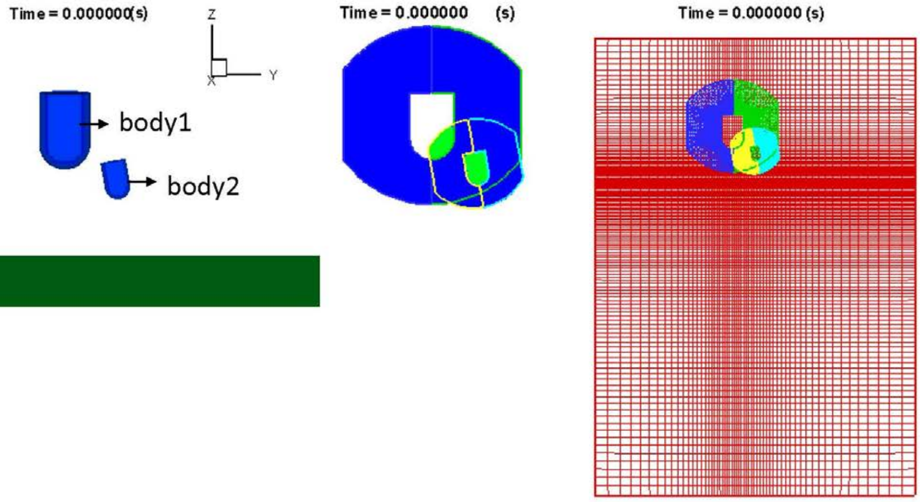
초공동 기술 토의,
2019.04.23

6 DOF Motion Analysis and Chimera Grid

Multi-body entering to the water with multiple Chimera grid

V_{body1} =3m/s
V_{body2} =5m/s
α_1 =0°
α_2=10°



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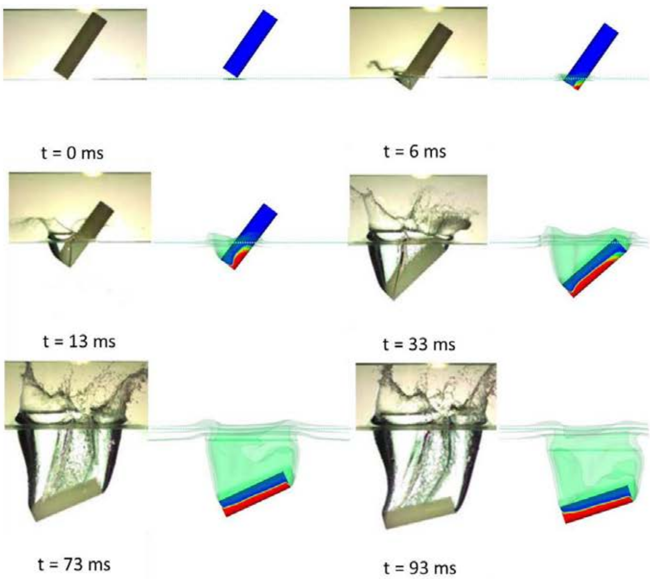
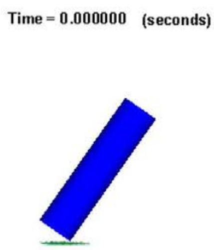
초공동 기술 토의,
2019.04.23

Simulation of a water entry cylinder with inclined angle





- U_{entry}=6.1m/s
- Inclined angle=60°

**'Evolution of three-dimensional cavitation following water entry of an inclined cylinder', Zhaoyu Wei,et.al(2012)

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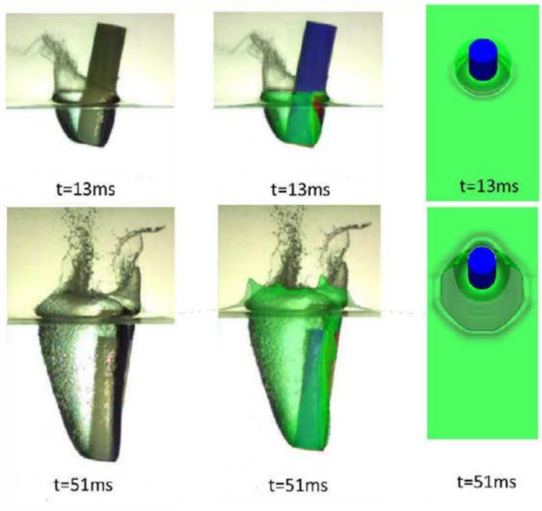
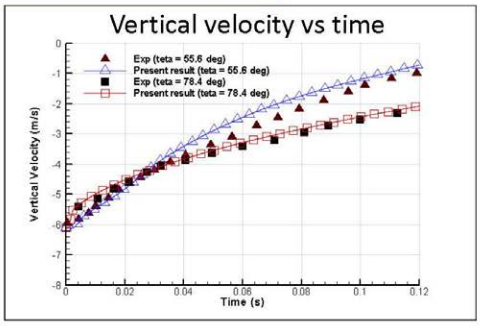
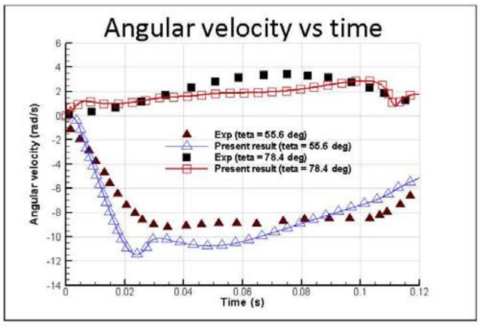
초공동 기술 토의,
2019.04.23

Simulation of a water entry cylinder with inclined angle



Snapshots of water entry cylinder at inclined angle of 78.4 degrees





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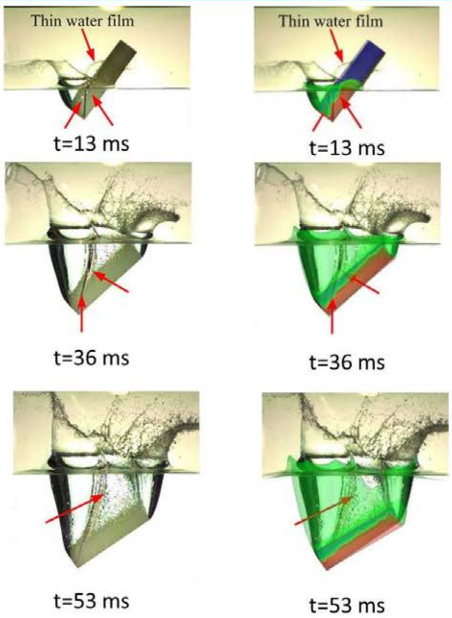
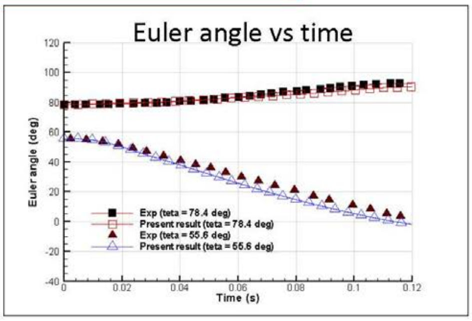
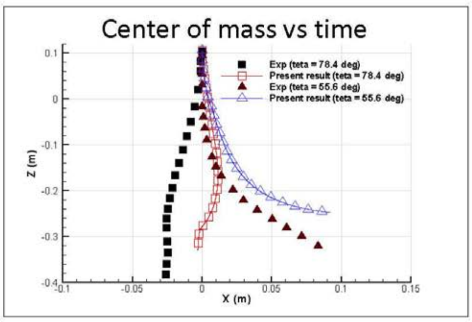
초공동 기술 토의,
2019.04.23

Simulation of a water entry cylinder with inclined angle



Snapshots of water entry cylinder at inclined angle of 53 degrees





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6DOF water entry behavior of hollow cylinder

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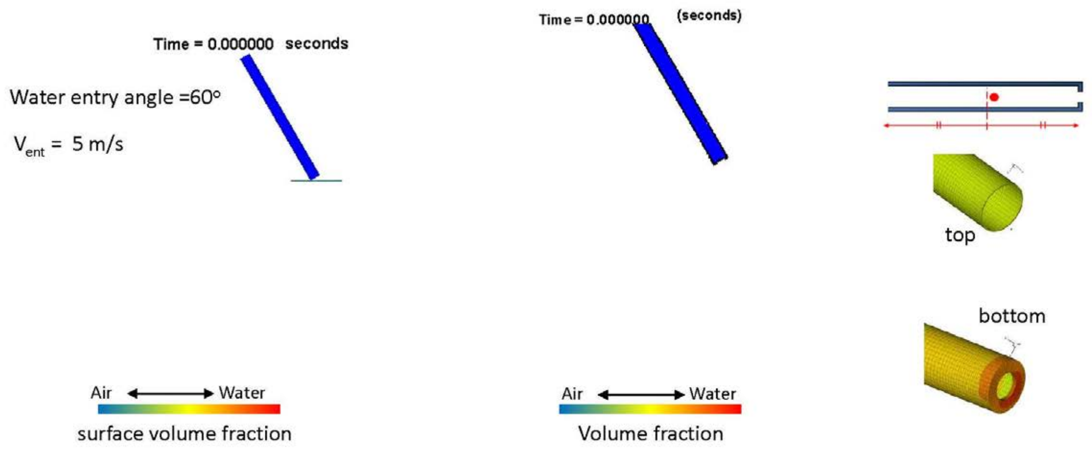
2019.04.23



3D flow of hollow cylinder entry **Internal flow of cylinder**

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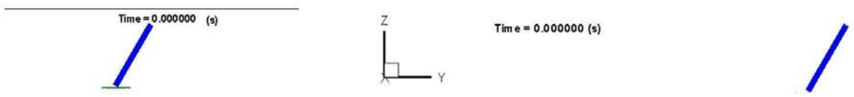
6DOF water entry behavior of solid/hollow cylinder

초공동 기술 토의,
2019.04.23

- Inclined angles: 60°
- initial entry velocities: 10 m/s



Solid cylinder **Hollow cylinder**

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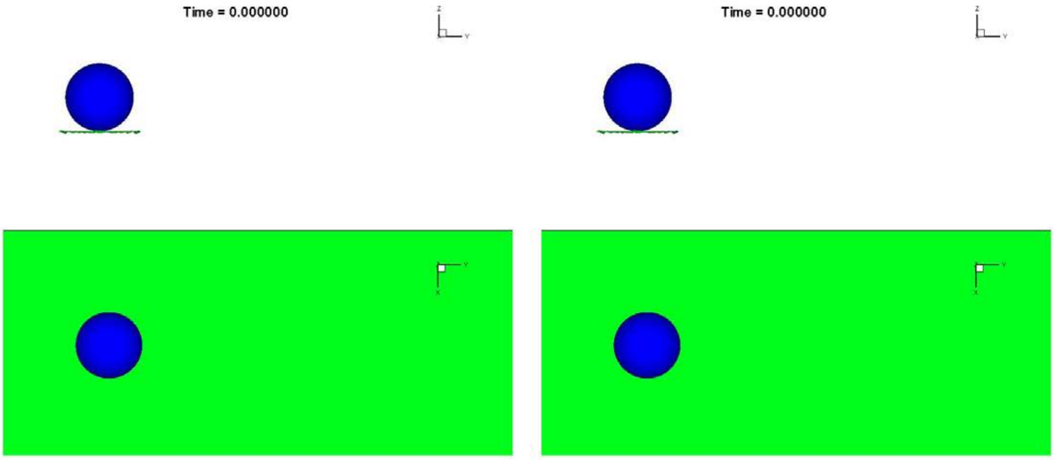
초공동 기술 토의, 2019.04.23

Ricochet problem

Case1: 10m/s

Case2: 5m/s



Diameter of sphere = 0.025 m
Density of sphere = water density

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초공동 기술 토의, 2019.04.23

Results and Discussion

- Full Fluids Equation Solver for Multiphase Flow Analysis

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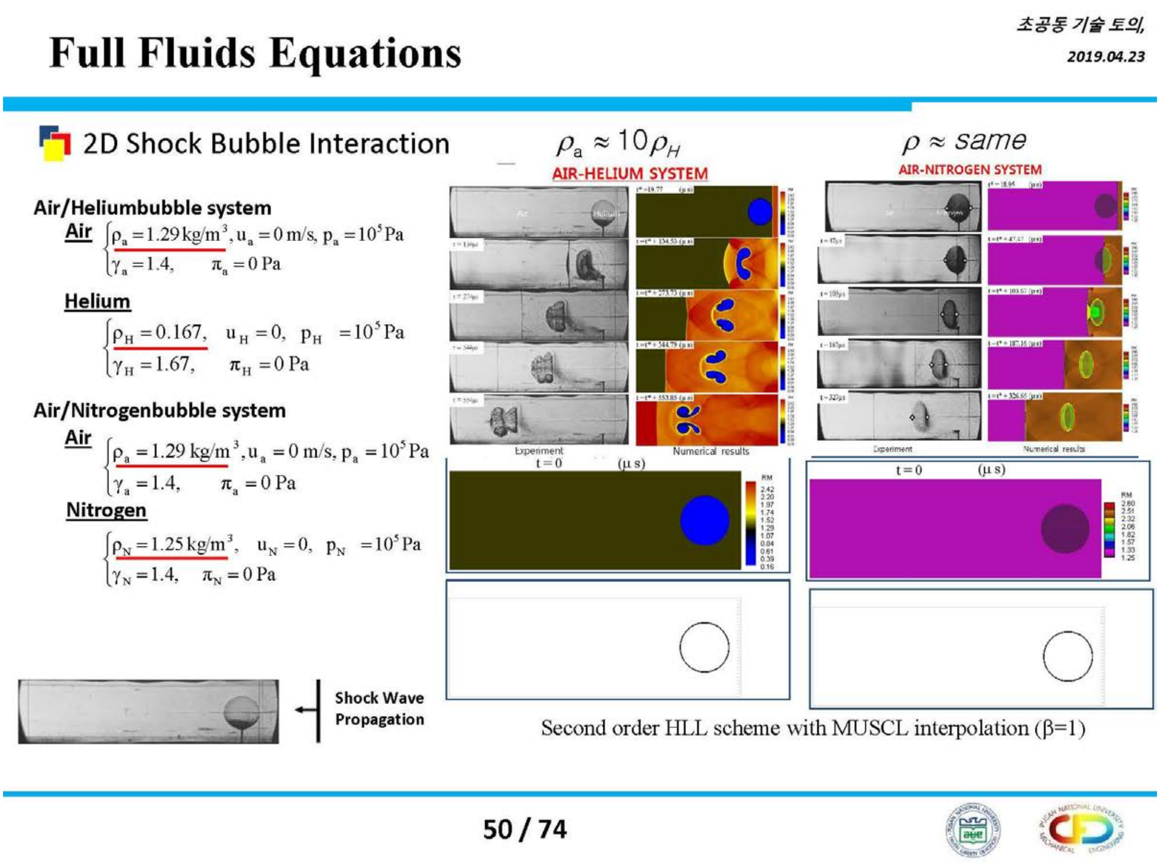
Full Fluids Equations
초공동 기술 토의,
2019.04.23
2D Shock Bubble Interaction
Air/Heliumbubble system
Air
ρa = 1.29 kg/m³, ua = 0 m/s, pa = 10⁵ Pa
γa = 1.4, πa = 0 Pa
Helium
ρH = 0.167, uH = 0, pH = 10⁵ Pa
γH = 1.67, πH = 0 Pa
Air/Nitrogenbubble system
Air
ρa = 1.29 kg/m³, ua = 0 m/s, pa = 10⁵ Pa
γa = 1.4, πa = 0 Pa
Nitrogen
ρN = 1.25 kg/m³, uN = 0, pN = 10⁵ Pa
γN = 1.4, πN = 0 Pa
Shock Wave Propagation
ρa ≈ 10ρH
AIR-HELIUM SYSTEM
ρ ≈ same
AIR-NITROGEN SYSTEM
Experiment
Numerical results
t = 0 (μs)
Second order HLL scheme with MUSCL interpolation (β=1)
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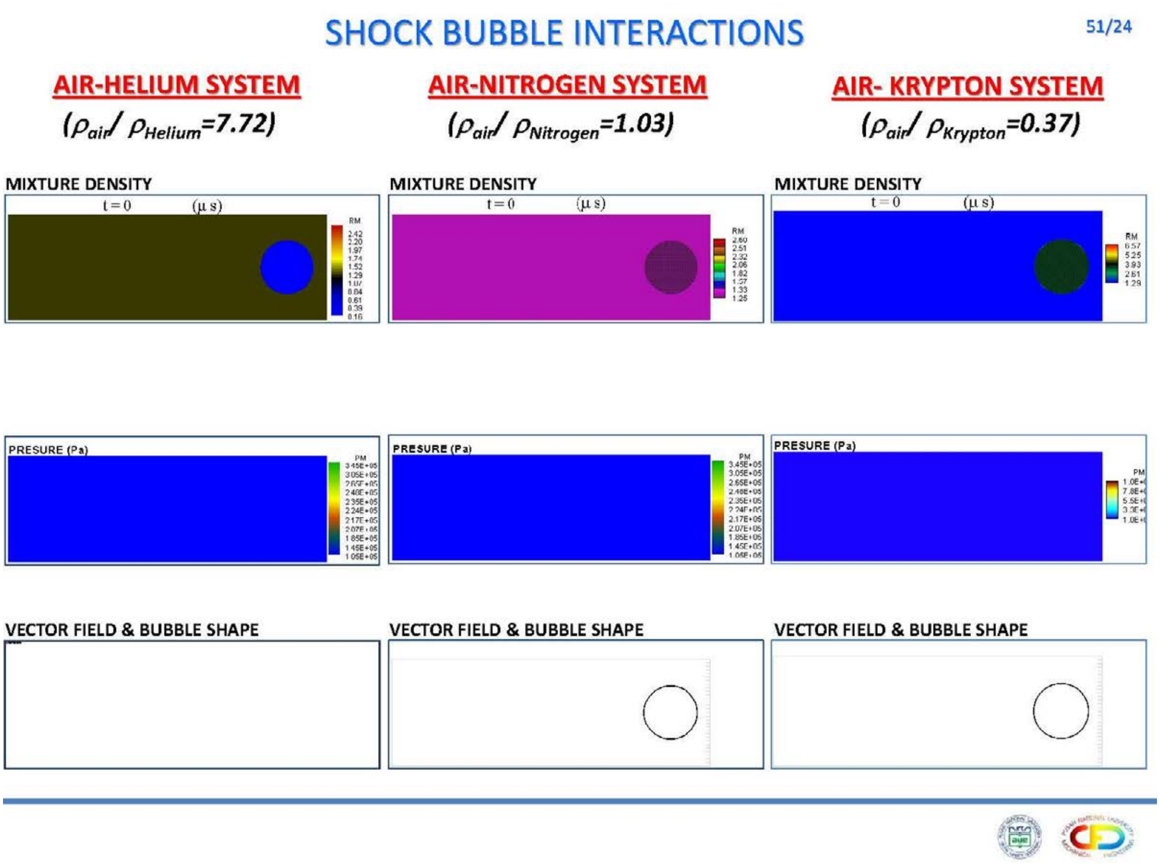
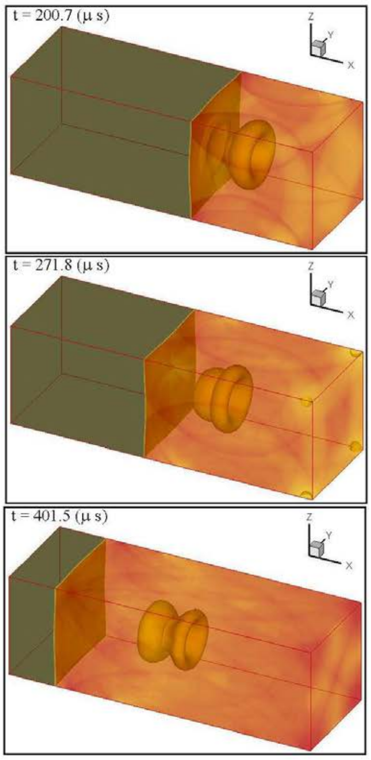
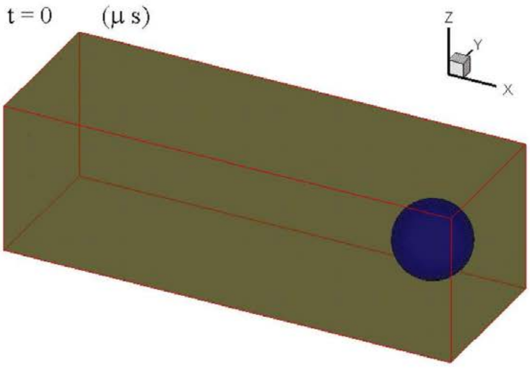

SHOCK BUBBLE INTERACTIONS
51/24
AIR-HELIUM SYSTEM
(ρair/ ρHelium=7.72)
AIR-NITROGEN SYSTEM
(ρair/ ρNitrogen=1.03)
AIR- KRYPTON SYSTEM
(ρair/ ρKrypton=0.37)
MIXTURE DENSITY
t = 0 (μs)
PRESURE (Pa)
VECTOR FIELD & BUBBLE SHAPE

THREE-DIMENSIONAL SHOCK BUBBLE INTERACTION



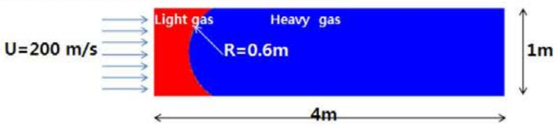
AIR-HELIUM SYSTEM



Full Fluids Equations

초공동 기술 토의,
2019.04.23

Richtmeyer-Meshkov Instability



Initial conditions :

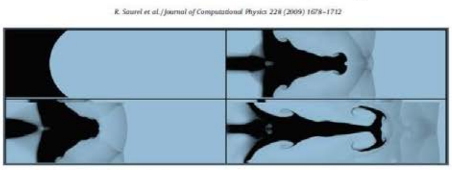
$$\begin{cases}\rho_{lightgas} = 1\text{kg/m}^3, & p_{lightgas} = 10^5, \\ u_{lightgas} = 0 \text{ m/s}, & v_{lightgas} = 0 \text{ m/s}\end{cases}$$

$$\begin{cases}\rho_{heavygas} = 50 \text{ kg/m}^3, & p_{heavygas} = 10^5 \text{ Pa}, \\ u_{heavygas} = 0 \text{ m/s}, & v_{heavygas} = 0 \text{ m/s},\end{cases}$$

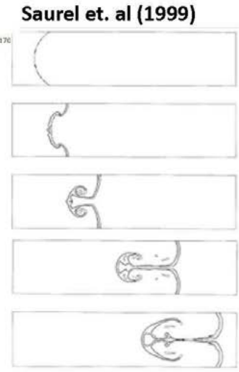
$$\gamma_{lightgas} = 1.4, \quad \pi_{lightgas,\infty} = 0\,(\text{Pa}),$$

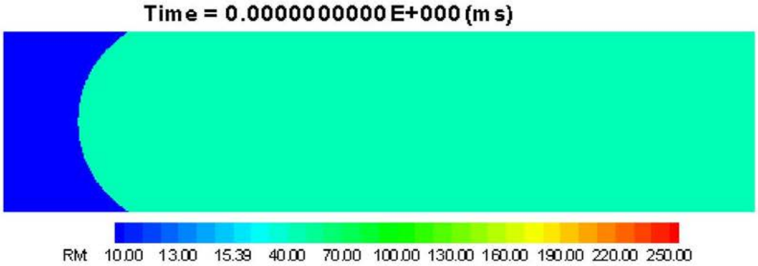
$$\gamma_{heavygas} = 1.6, \quad \pi_{heavygas,\infty} = 0\,(\text{Pa})$$

Saurel et. al (2009)



Saurel et. al (1999)





Second order HLL scheme with MUSCL interpolation (β=1)

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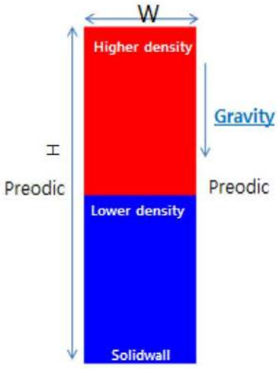
초공동 기술 토의,
2019.04.23

Full Fluids Equations

Rayleigh-Taylor Instability

Kelvin-Helmholtz instability may occur :
- If a fluid of high density resting on top of a low-density fluid
- And if a small disturbance, such as a wave, is introduced at the interface

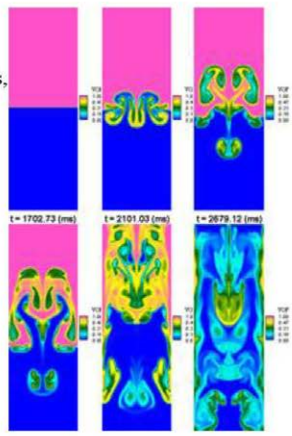


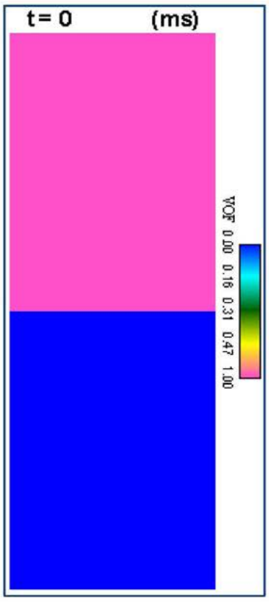
Initial conditions :

$$\begin{cases}\rho_1 = 2\text{kg/m}^3, & u_1 = 0 \ \text{m/s},\\ v_1 = 0 \ \text{m/s}\end{cases}$$

$$\begin{cases}\rho_2 = 1\,\text{kg/m}^3, & u_2 = 0 \ \text{m/s},\\ v_2 = 0 \ \text{m/s},\end{cases}$$

SG - EOS
$\gamma_1 = 1.4, \quad p_{1,\infty} = 0\,(\text{Pa}),$
$\gamma_2 = 1.4, \quad p_{2,\infty} = 0\,(\text{Pa})$





The interface is initially perturbed with

$$v_{dis} = 0.05\left[1+\cos\left(\frac{2\pi x}{W}\right)\right]\left[1+\cos\left(\frac{2\pi z}{H}\right)\right]$$

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초공동 기술 토의,
2019.04.23

Full Fluids Equations

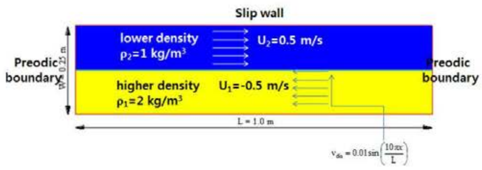
Kelvin-Helmholtz Instability

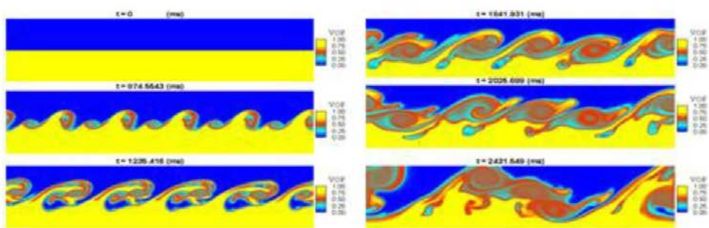
Initial conditions :

$$\begin{cases}\rho_1 = 2\text{kg/m}^3, & u_1 = 0 \ \text{m/s},\\ v_1 = 0 \ \text{m/s}\end{cases}$$

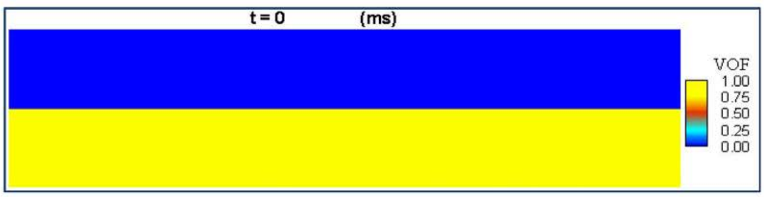
$$\begin{cases}\rho_2 = 1\,\text{kg/m}^3, & u_2 = 0 \ \text{m/s},\\ v_2 = 0 \ \text{m/s},\end{cases}$$

SG - EOS
$\gamma_1 = 1.4, \quad p_{1,\infty} = 0\,(\text{Pa}),$
$\gamma_2 = 1.4, \quad p_{2,\infty} = 0\,(\text{Pa})$





VOID FRACTION



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Expansion of Spherical Shock

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Initial conditions :

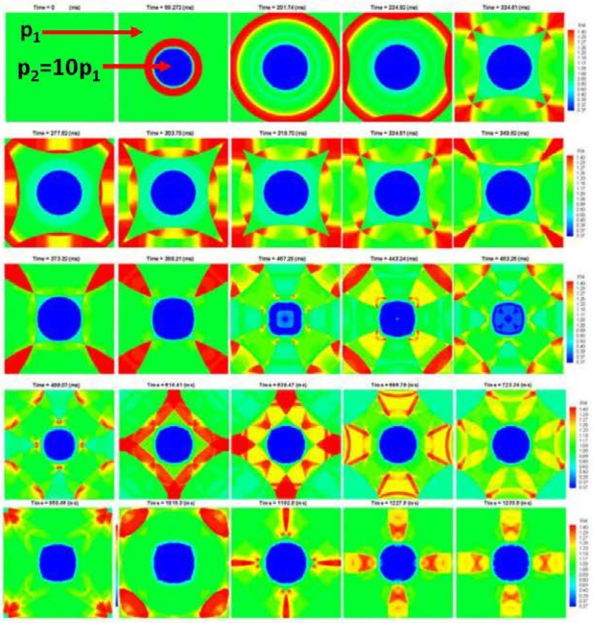
$$\begin{cases}\rho_1 = 1.0\,\mathrm{kg/m^3}, & p_1 = 1\,\mathrm{Pa}, \quad u_1 = 0\ \mathrm{m/s}, \\ v_1 = 0\ \mathrm{m/s}\end{cases}$$

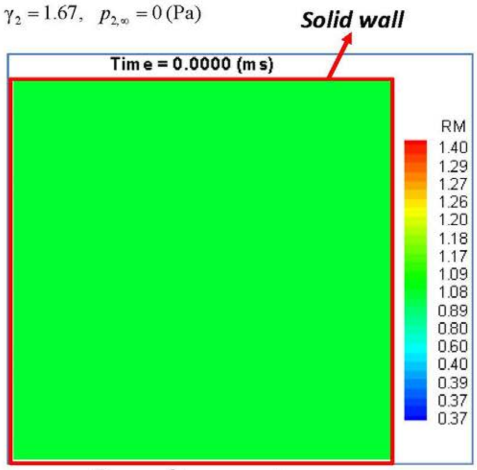
$$\begin{cases}\rho_2 = 1.0\,\mathrm{kg/m^3}, & p_2 = 10\,\mathrm{Pa}, \quad u_2 = 0\ \mathrm{m/s}, \\ v_2 = 0\ \mathrm{m/s},\end{cases}$$

SG - EOS

$\gamma_1 = 1.67, \quad p_{1,\infty} = 0\,(\mathrm{Pa}),$

$\gamma_2 = 1.67, \quad p_{2,\infty} = 0\,(\mathrm{Pa})$





Density contours

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Underwater Explosion

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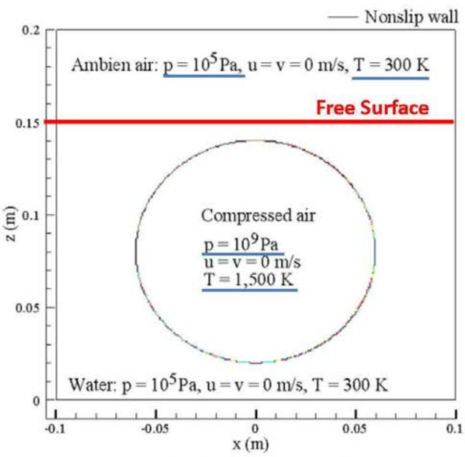
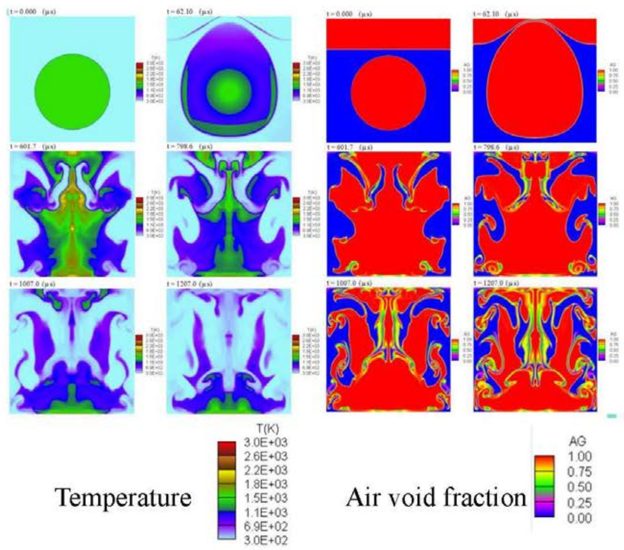
2019.04.23

To examine the capability for capturing the interface with large jump in pressure, temperature, and density.



$\Delta x/D = \Delta y/D = 1/180$
(300×300 cells)



Temperature   Air void fraction

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Underwater Explosion

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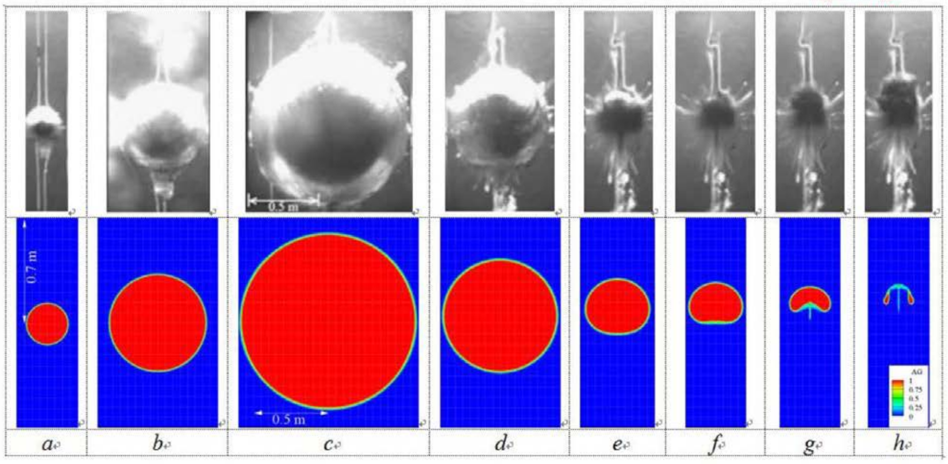
g= 55 (g)



The evolution of bubble shape for case 55g; from the left to right the bubble shape at time, t= 1, 7, 50, 85, 93, 94, 95, and 96 ms.

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Underwater Explosion

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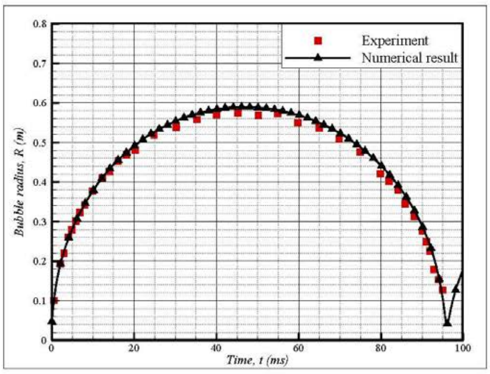
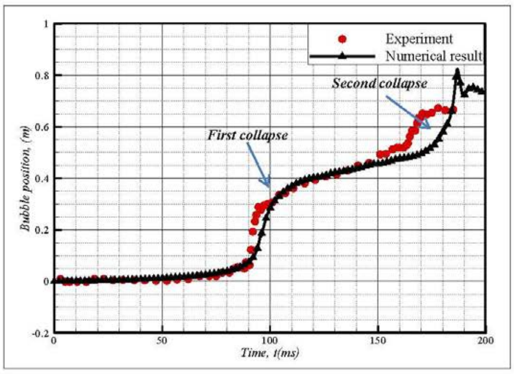
g= 55 (g)



The comparison of bubble radius with experiment result for the 55 g case.



The position of the center mass of bubble as function of time

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Results and Discussion

- *SuperCavitation*

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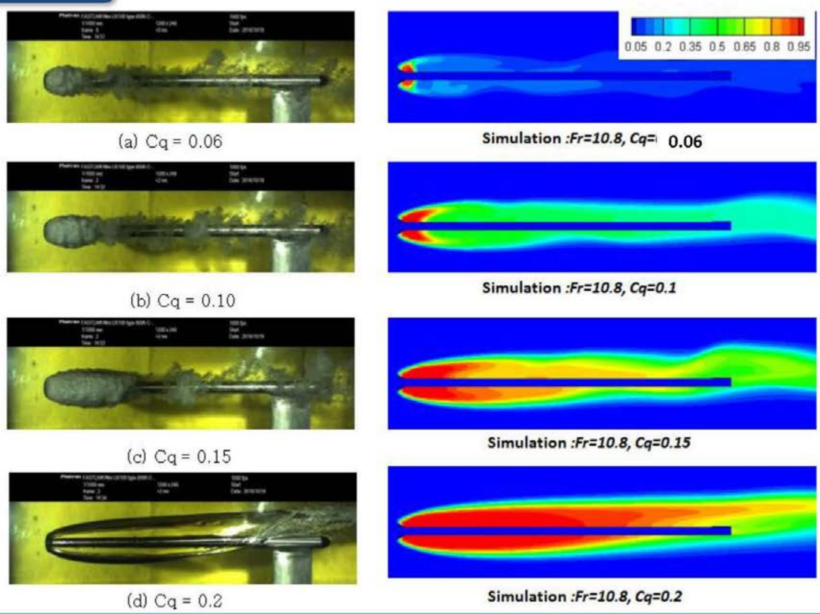
2019.04.23

Super Cavitation

Ventilated flow

Fr=10.8

$$\frac{D_{H.KRISO}}{d_{C.KRISO}} = \frac{D_{H.PNU}}{d_{C.PNU}} = 9.49$$



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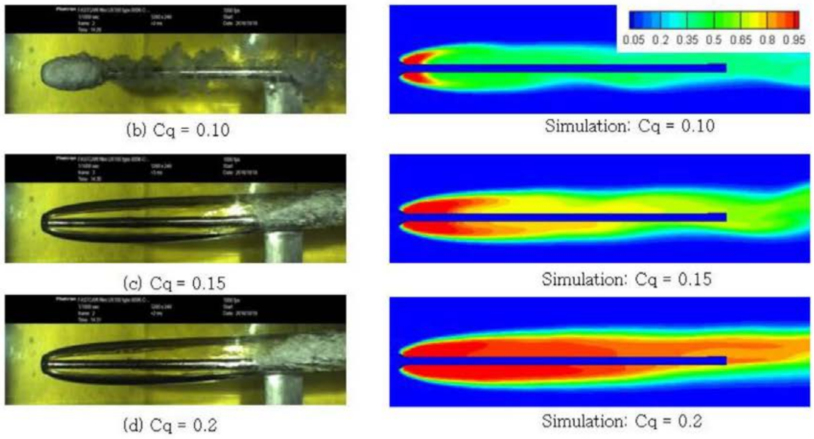
Super Cavitation

초공동 기술 토의,
2019.04.23

Ventilated flow

Fr=14.4

$$\frac{D_{H.KRISO}}{d_{C.KRISO}} = \frac{D_{H.PNU}}{d_{C.PNU}} = 9.49$$



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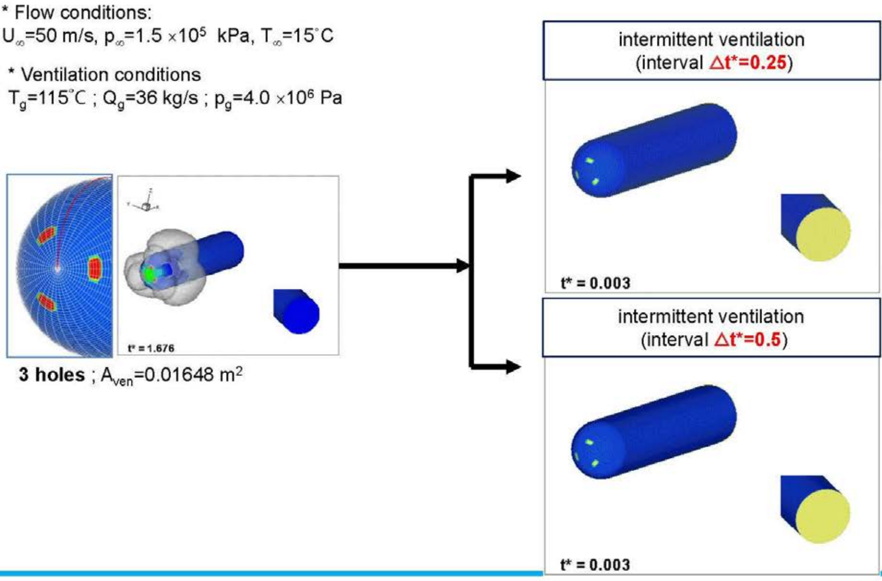
Super Cavitation

초공동 기술 토의,
2019.04.23

분사 간격 변화

* Flow conditions:
U_∞=50 m/s, p_∞=1.5 ×10^5 kPa, T_∞=15˚C

* Ventilation conditions
T_g=115˚C ; Q_g=36 kg/s ; p_g=4.0 ×10^6 Pa



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Super Cavitation

초공동 기술 토의,
2019.04.23

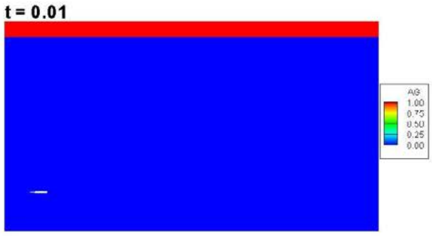
수면 변화

Inlet velocity = 5m/s;   Inlet P= 1.00506kPa;   Injection velocity = 2m/s;
Injection P = 4.0kPa;   Re = 408,482.89;   Fr = 17.06;

t = 0.01

10m below the free surface

t = 0.01



20m below the free surface

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Super Cavitation

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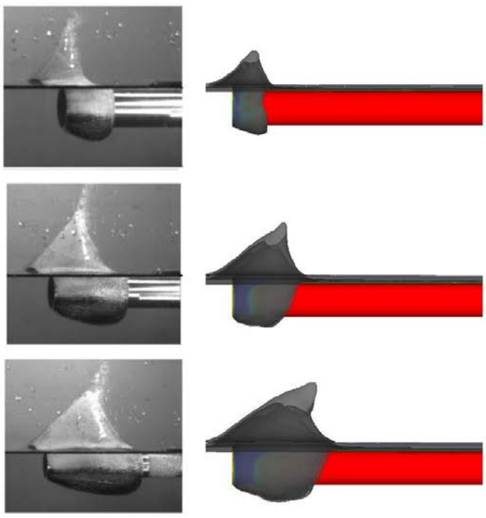
수면 변화

Velocity: U=19.1 m/s
Diameter: D=37mm
Cav number: 0.54



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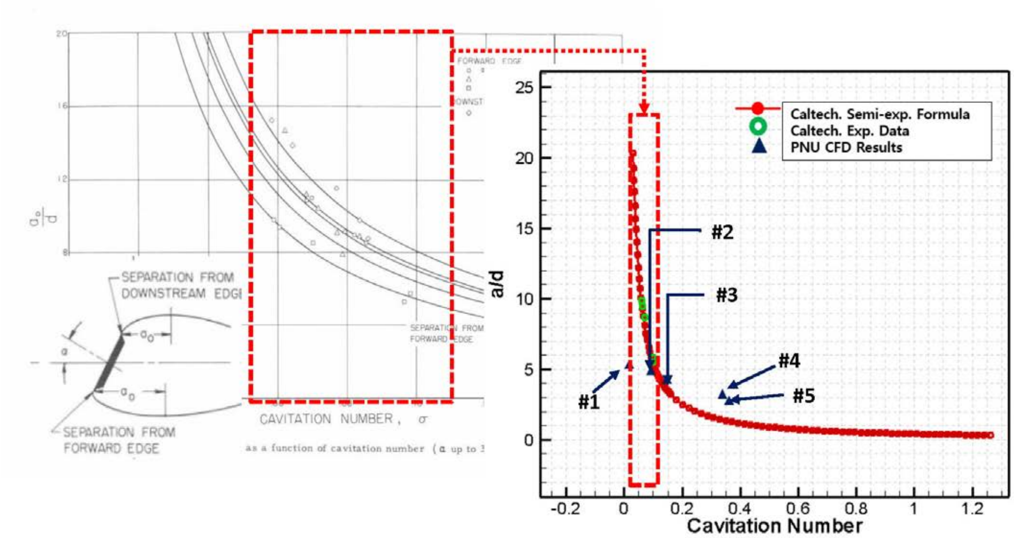
Super Cavitation

초공동 기술 토의, 2019.04.23

Cavitation Flow in Disk Cavitator with AoA



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Super Cavitation

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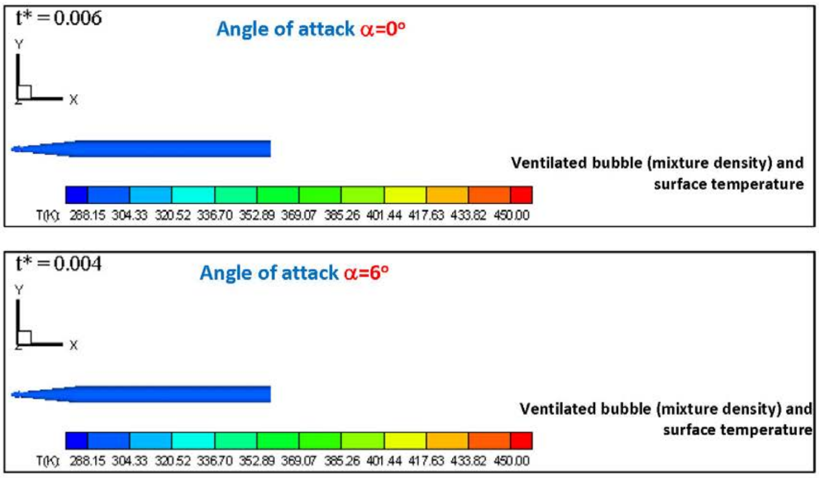
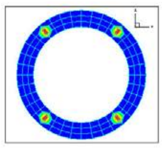
Cavitation Flow in Torpedo with AoA

Flow conditions U_∞=50 m/s , p_∞ = 101,325 Pa, T_∞ = 288.15 K

Ventilation conditions P_{ven} = 2.5 MPa, T_{ven} = 375 K, U_{ven}=390 m/s





Four holes

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Super Cavitation

초공동 기술 토의,
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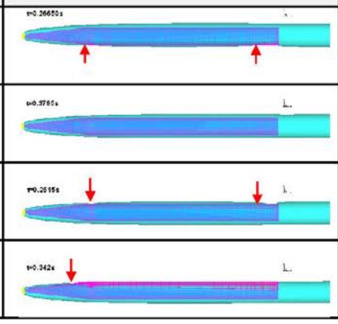
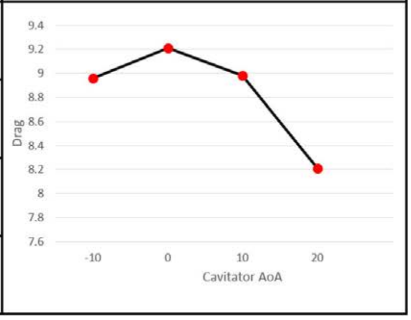
Cavitation Flow in Cavitator with AoA

Cavitator AoA	Cavity shape (volume fraction)	Point of collapse	Wetted Surface ratio	Drag (cavitator only)
-10°		$14d_c$, $48d_c$ (Underside)	~5%	
0°		-	0.0	
+10°		$14d_c$, $52d_c$ (Upperside)	~5%	
+20°		$11d_c$ (Upperside)	~20%	

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Super Cavitation

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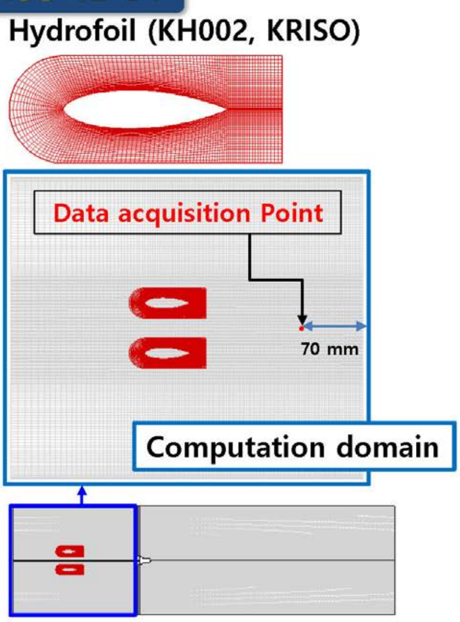
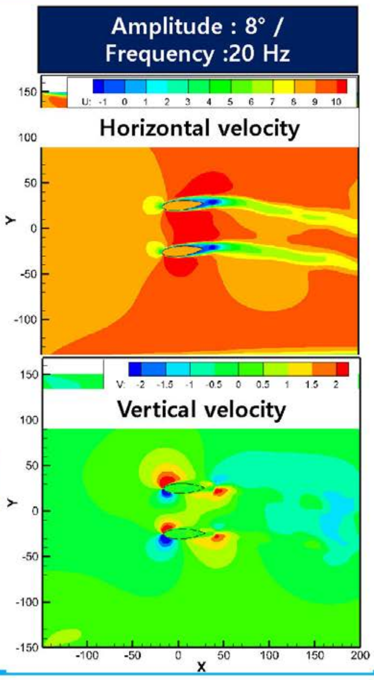
비정상 외란 해석





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Super Cavitation

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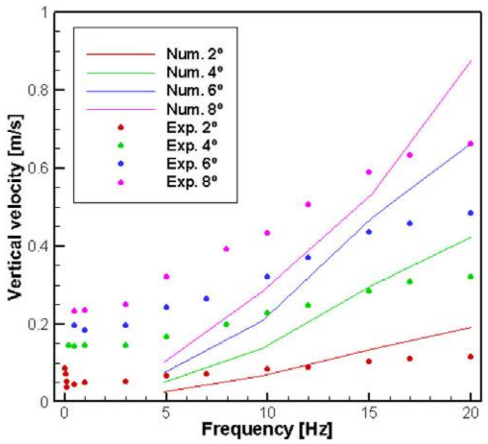
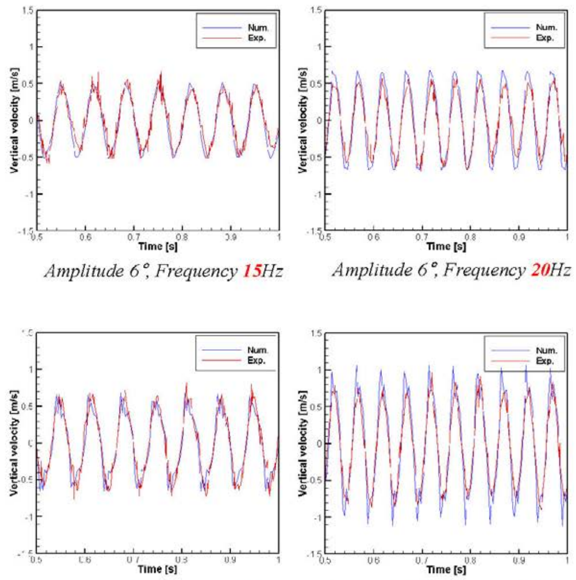
비정상 외란 해석



The maximum velocity in vertical direction according to amplitude and frequency



Amplitude 6°, Frequency ***15****Hz*　*Amplitude 6°, Frequency* ***20****Hz*

Amplitude ***8****°, Frequency* ***15****Hz*　*Amplitude* ***8****°, Frequency* ***20****Hz*

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Super Cavitation

초공동 기술 토의,
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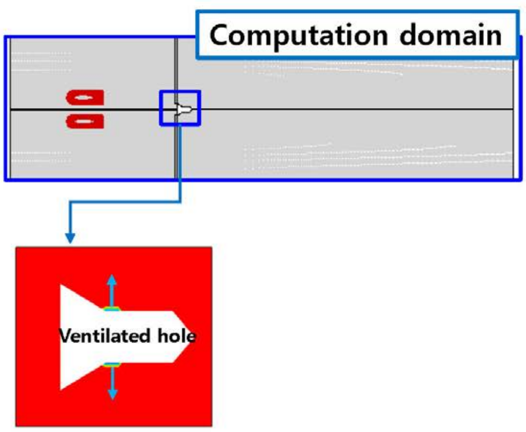
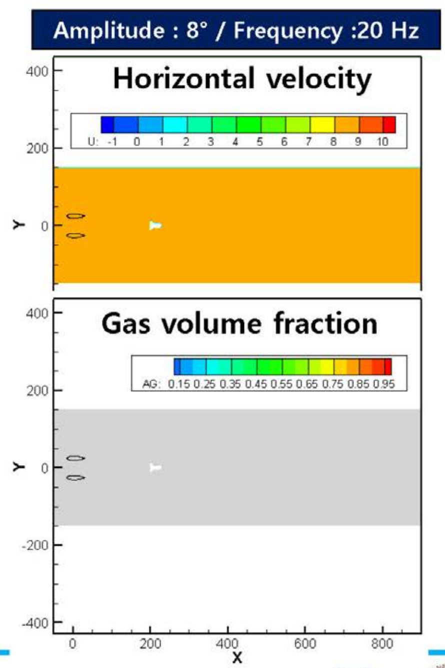
비정상 외란 해석



Cavitator with ventilated hole



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초공동 기술 토의,
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Conclusions

- N-S equations based on homogeneous mixture model could be effective method to analyze cavitation
- The in-house code has been successfully developed to capture cavitation phenomena including full compressible effects, non-condensable gas, buoyancy force, temperature difference effects, and ventilated cavitation.
- Free surface was effectively handled by VOF method
- The 6 DOF motion analysis has been done by using chimera grid.
- Also, the in-house code using full fluid equations, not using homogeneous mixture model, has been also successfully developed.

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Thank you so much!

Q&A

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