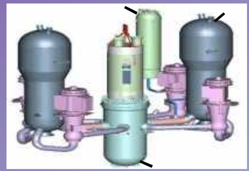

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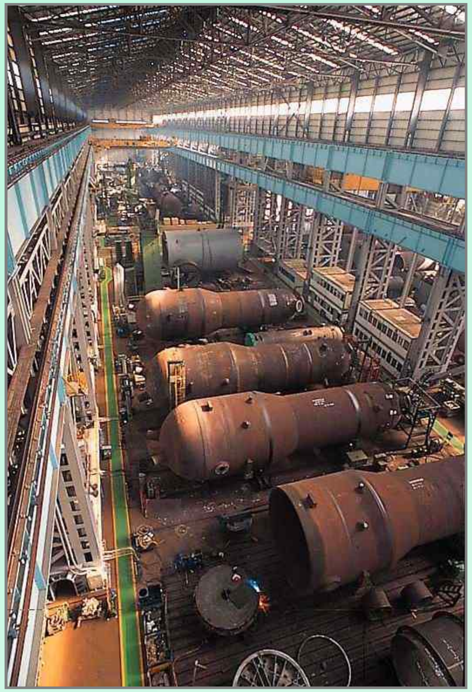
Fluid-elastic Instability of Normal Square Tube Bundles in Two-Phase Cross Flow

Woo Gun Sim Mi Yeon Park

ABSTRACT

Some knowledge on damping and fluid-elastic instability is necessary to avoid flow-induced vibration problems in shell and tube heat exchanger such as steam generator. Fluid-elastic instability is the most important vibration excitation mechanism for heat exchanger tube bundles subjected to the cross flow. Experiments have been performed to investigate fluid-elastic instability of normal square tube bundles, subjected to two-phase cross flow. The test section consists of cantilevered flexible cylinder(s) and rigid cylinders of normal square array. From a practical design point of view, fluid-elastic instability may be expressed simply in terms of dimensionless flow velocity and dimensionless mass-damping parameter. For dynamic instability of cylinder rows, added mass, damping and critical flow velocity are evaluated. The Fluid-elastic instability coefficient is calculated and then compared to existing results given for tube bundles in normal square.



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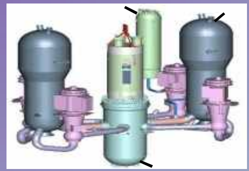
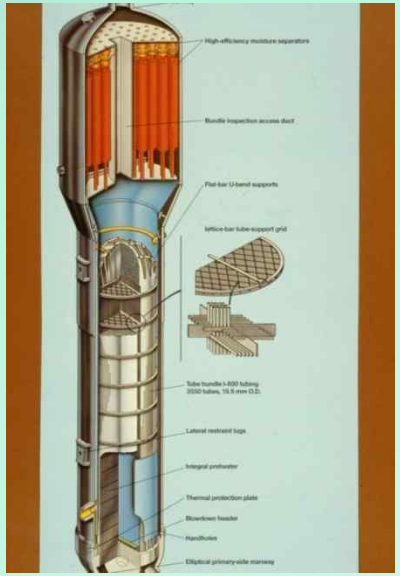
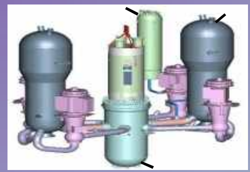


Content



- Introduction
- Fundamental Theory
  - Equation of motion for a cantilevered beam - Hydrodynamic mass
  - Flow parameter of two-phase flow - Damping ratio
  - An analytical two-phase damping model
- Experimental Study
  - Experimental set-up and test procedure - Experimental results and discussion
- Fluid-elastic Instability
  - Fluid-elastic instability coefficient - Critical flow-velocity
- Conclusions

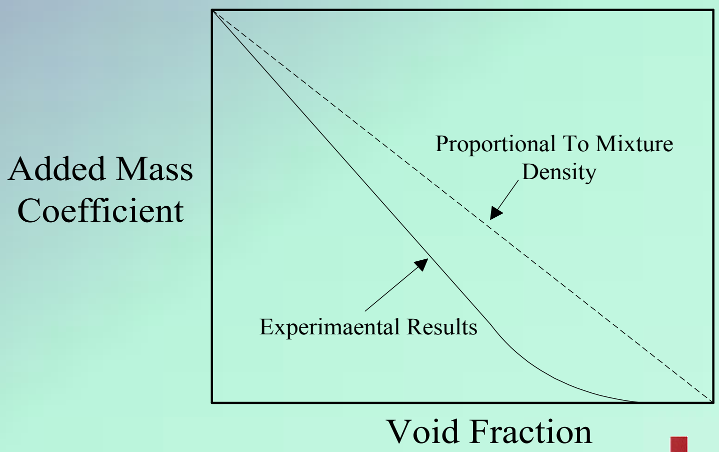


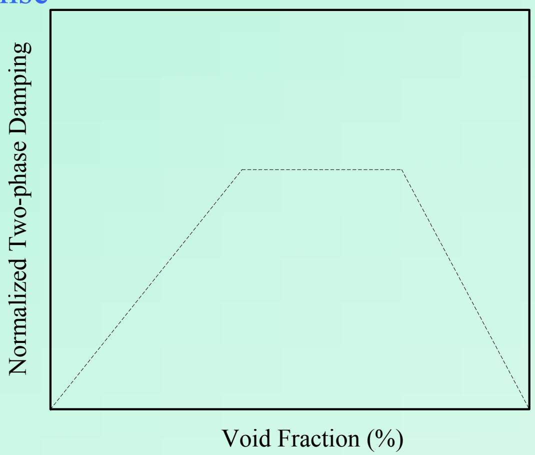
Introduction

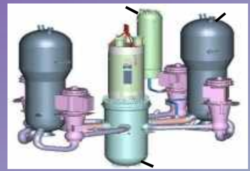
- **Initial Motivation**
  - **Slender Structural Elements - Fretting Wear Damage**
  - **Flow Mechanism of Two-phase Flow**

    Homogeneous Model-Only for Bubbly Flow
  - **Analytical Approach for Hydrodynamic Forces**

    Experimental Study, Reliable Prediction of Dynamic Response







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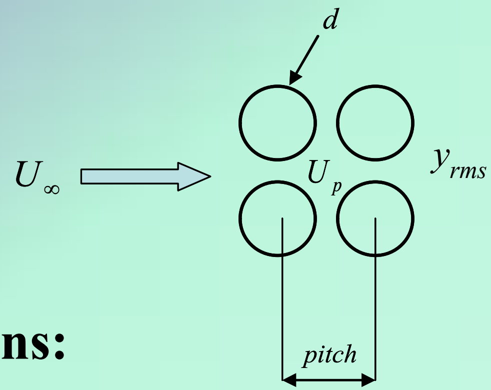
- **Hydrodynamic Forces**

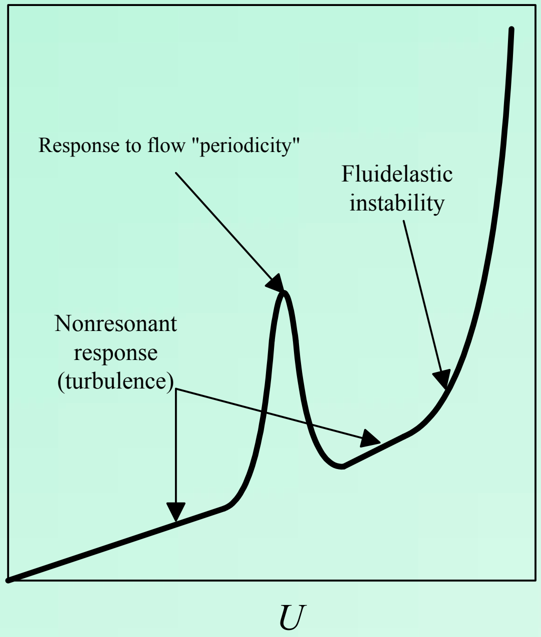
$$EI\frac{\partial^4 y}{\partial x^4}+\rho_s A_s\frac{\partial^2 y}{\partial t^2}=F_p+F_t+F_{vs}+etc.$$

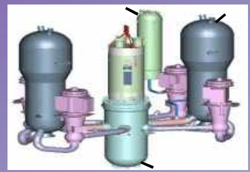
  - **Added Mass**
  - **Fluid Damping**
  - **Fluid Elastic Stiffness**



- **Engineering Applications:**
  - **Critical Flow Velocity**
  - **Design Criteria**
  - **Stability Analysis**

$$\frac{U_{PC}}{fd}=C\left(\frac{m(2\pi\zeta)}{\rho d^2}\right)^{1/2}$$





Fluid-elastic Instability for Normal Square Array

- Dimensionless critical flow velocity

$$\frac{U_{pc}}{fd} = K\left(\frac{2\pi\zeta m}{\rho d^2}\right)^n \qquad m = m_{tube} + m_h$$

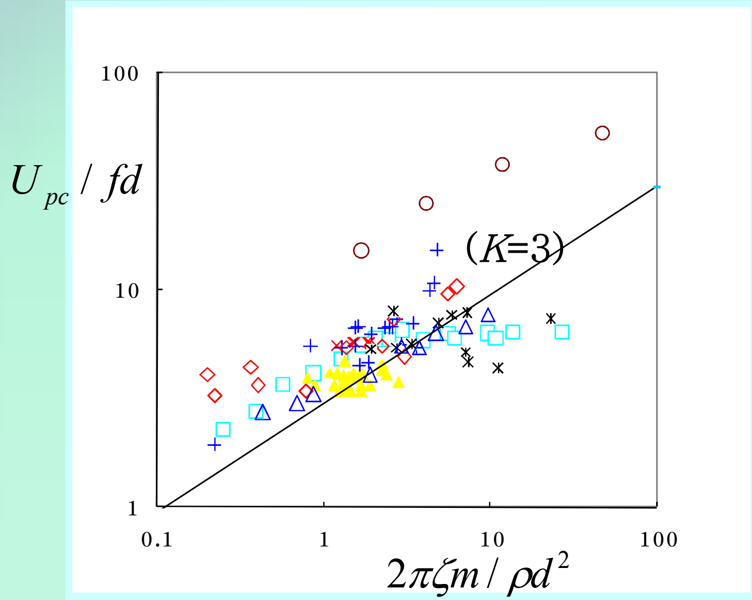
$$U_p = U_\infty p/(p-d)$$

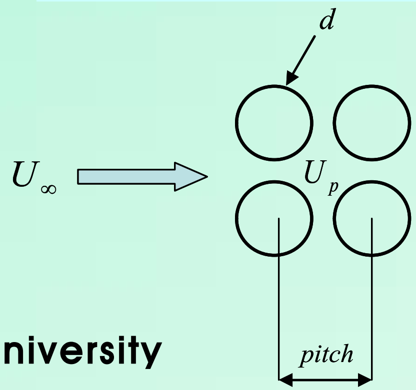
$$\rho = \rho_l(1-\alpha) + \rho_g \alpha$$

Hydrodynamic mass

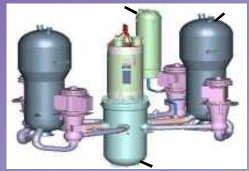
$$m_h = \frac{\pi\rho d^2}{4}\left(\frac{(De/d)^2+1}{(De/d)^2-1}\right) = m_t\left[\left(\frac{f_a}{f_{tp}}\right)^2 - 1\right]$$

$$De/d = (1.07 + 0.56\,p/d)\,p/d$$





$Y(x) = C_1 \cos \lambda x + C_2 \sin \lambda x + C_3 \cosh \lambda x + C_4 \sinh \lambda x$

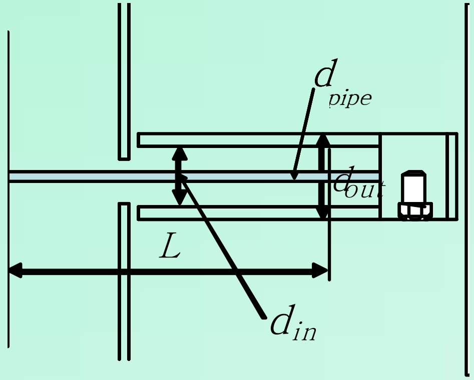


Fundamental Theory

- Equation of motion for a cantilevered beam

$$EI \frac{\partial^4 y}{\partial x^4} + [m + M\delta(x-L)] \frac{\partial^2 y}{\partial t^2} = 0, \quad y(x,t) = Y(x)T(t).$$

$$Y(x) = C_1 \cos \lambda x + C_2 \sin \lambda x + C_3 \cosh \lambda x + C_4 \sinh \lambda x$$



- Boundary conditions

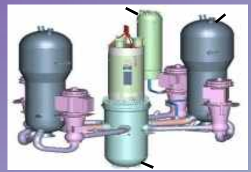
$$Y(x)\Big|_{x=0} = C_1 + C_3 = 0, \qquad \frac{dY(x)}{dx}\Bigg|_{x=0} = \lambda C_2 + \lambda C_4 = 0$$

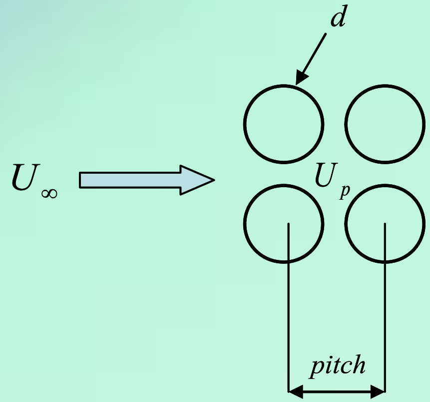
$$\frac{d^2Y(x)}{dx^2}\Bigg|_{x=L} = 0, \qquad \frac{d^3Y(x)}{dx^3}\Bigg|_{x=L} = -\frac{m_a \cdot \omega^2}{EI} Y(L)$$

- Characteristic equation

$$(1 + \cos \beta_k \cosh \beta_k) + \frac{\beta_k m_a}{Lm} (\cos \beta_k \sinh \beta_k - \sin \beta_k \cosh \beta_k) = 0,$$

- Natural Frequency $\qquad \omega_k = \beta_k{}^2 \left(\frac{EI}{mL^4} \right)^{0.5}$

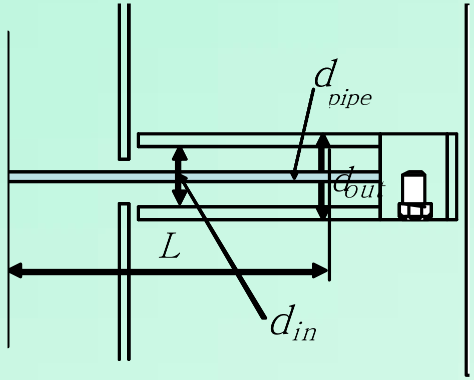




- Hydrodynamic mass within tube bundle

$$m_{h,tube} = \frac{\pi \rho d^2}{4}\left(\frac{(De/d)^2+1}{(De/d)^2-1}\right) = m_{OT}\left[\left(\frac{f_a}{f_{tp}}\right)^2 - 1\right]$$

$$De/d = (1.07 + 0.56\,p/d)\,p/d$$

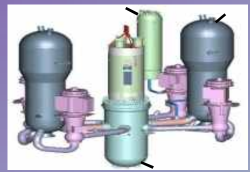


- Hydrodynamic mass due to the liquid in the annulus

$$m_{h,in} = \frac{\pi}{4} d_{in}{}^2 \rho_l \chi_{in}, \quad \chi_{in} = \frac{(d_{in}/d_{pipe})^2+1}{(d_{in}/d_{pipe})^2-1}$$

- Total mass acting on the flexible inner cylinder

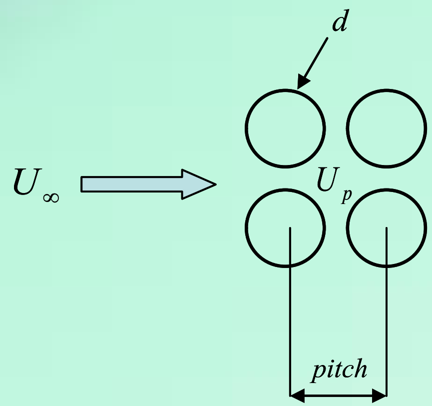
$$m = m_s + m_{h,in}.$$



- Flow parameters of two phase flow

Homogeneous void fraction

$$\varepsilon = \frac{\dot{Q}_g}{\dot{Q}_l + \dot{Q}_g}$$



Homogeneous density

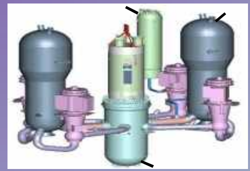
$$\rho_h = \rho_l (1-\varepsilon) + \rho_g \varepsilon$$

Free stream velocity

$$U_\infty = \frac{\dot{Q}_l + \dot{Q}_g}{\rho_h A_\infty}$$

Pitch velocity

$$U_p = U_\infty \frac{p}{p-d}$$



- Damping ratio $\zeta_t = \zeta_v + \zeta_s + \zeta_{tp}$

Viscous damping ratio for $\pi f d^2 / 2\nu > 3300$ & $d / De < 0.5$

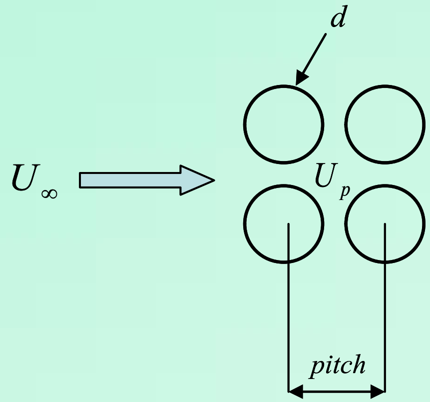
$$\zeta_v = \frac{\pi}{\sqrt{8}} \left(\frac{\rho_{tp} d^2}{m_t} \right) \left(\frac{2\nu_{tp}}{\pi f d^2} \right)^{0.5} \left\{ \frac{1 + (d / D_e)^3}{\left[1 - (d / D_e)^2\right]^2} \right\}$$

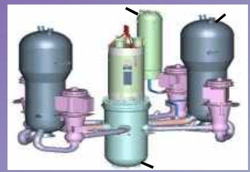
Two-phase kinematic viscosity

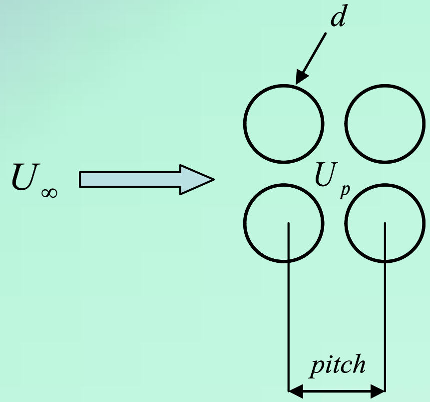
$$\nu_{tp} = \frac{\nu_l}{1 + \varepsilon(\nu_l / \nu_g - 1)}$$

Two-phase damping ratio

$$\zeta_{tp} = \zeta_t - \zeta_v$$







- An Analytical two-phase damping model

Euler number for single phase flow

$$Eu_{LO} = \frac{\Delta p / z}{\rho_{L0} u^2 / 2} = 0.307 \,\mathrm{Re}_{LO}^{-0.1} (p/d - 1)^{-0.36}$$

Two-phase friction multiplier

$$\phi_{LO}^2 \Big| = \left.\frac{dp}{dl}\right|_{tp} \Big/ \left.\frac{dp}{dl}\right|_{LO} = \left[\frac{(1-x)^2}{1-\alpha} + \frac{g(\rho_l - \rho_g)\rho_l d_e}{2 f_{LO} G^2} \alpha \right]$$

Two-phase damping ratio

$$\zeta_{tp} = \zeta_y - \zeta_v = K_{tp} \cdot Eu_{LO} \cdot \phi_{LO}^2 \cdot \frac{MF_{LO}}{u m_t} \frac{1}{8\pi f_n} - \zeta_v$$

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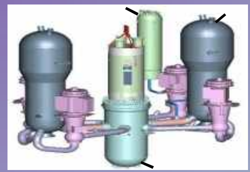
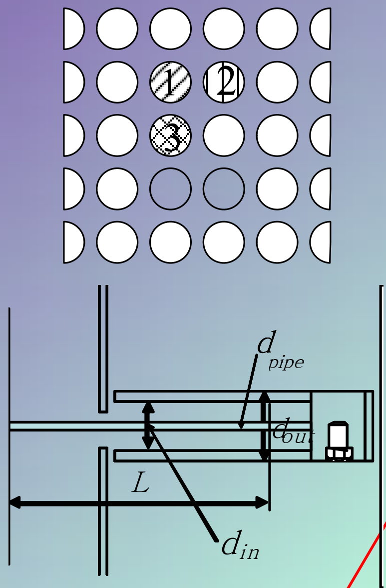


Experimental Study

- **Experimental set-up and test procedure**

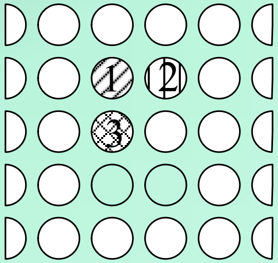


- Pressure perturbation, Acceleration
- Added mass, Frequency, Damping ratio,
- Critical flow velocity,
  Fluid-elastic instability coefficient

Modulus of Elasticity, E	0.12 GPa
Length of the flexible pipe, L	123 mm
Mass of inner pipe per unit length, m_s	0.017 kg/m
Outer diameter of inner pipe, d_{pipe}	5 mm
Outer tube mass per unit length, m_{OT}	0.289 kg/m
inner diameter of outer tube, d_{in}	8 mm
outer diameter of outer tube, d_{out}	20 mm

- **Typical Results and discussion**

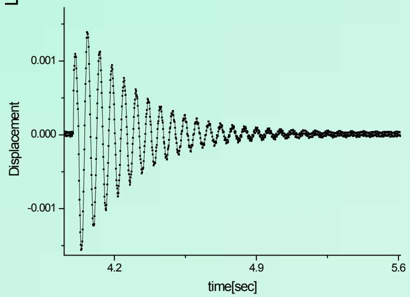
$$G_p = 459\ kg/(m^2 \cdot s), \dot{Q}_l = 6.42\ m^3/h$$



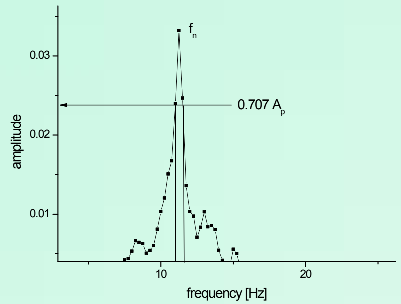
ε %	m_h [kg/m]	m_t [kg/m]	f [Hz]	ζ_t
3.0	0.3612	0.6462	12.45	0.1128
5.8	0.3725	0.6575	12.34	0.1245
8.5	0.4108	0.6958	12.00	0.1150
11.0	0.3556	0.6406	12.50	0.1264
13.4	0.3255	0.6105	12.81	0.1270
15.0	0.3117	0.5967	12.95	0.1284
17.8	0.3598	0.6448	12.46	0.1336
22.3	0.2874	0.5724	13.22	0.1241
26.5	0.2966	0.5816	13.12	0.1387
30.0	0.2336	0.5186	13.89	0.1254
34.0	0.2830	0.5680	13.28	0.1474
38.0	0.3253	0.6103	12.81	0.1154

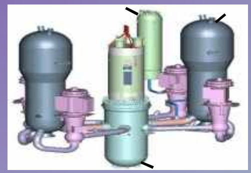
$$m_{h,tube} = m_{OT}\left[\left(\frac{f_a}{f_{tp}}\right)^2 - 1\right]$$

$$\zeta_s = \delta / \sqrt{4\pi^2 + \delta^2}$$

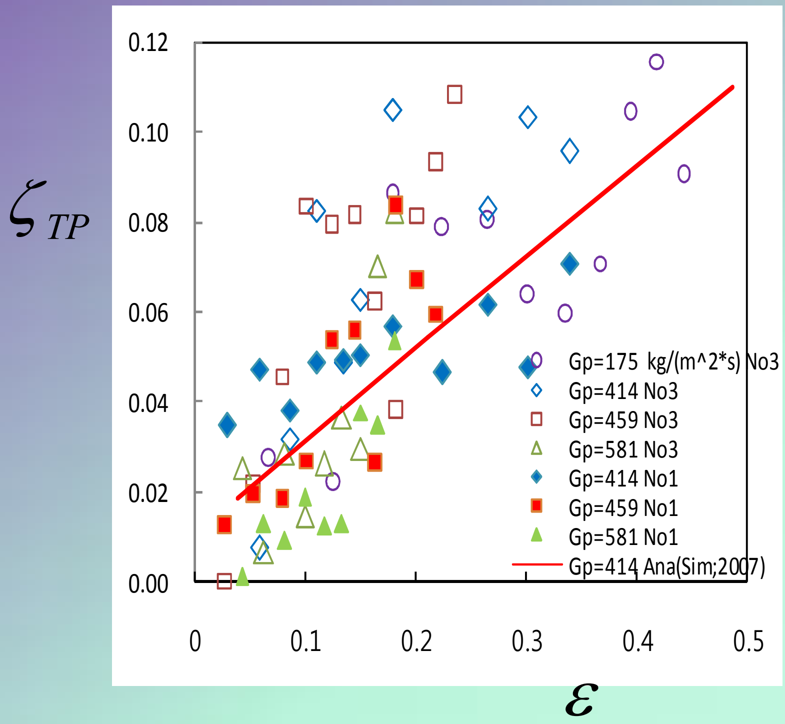


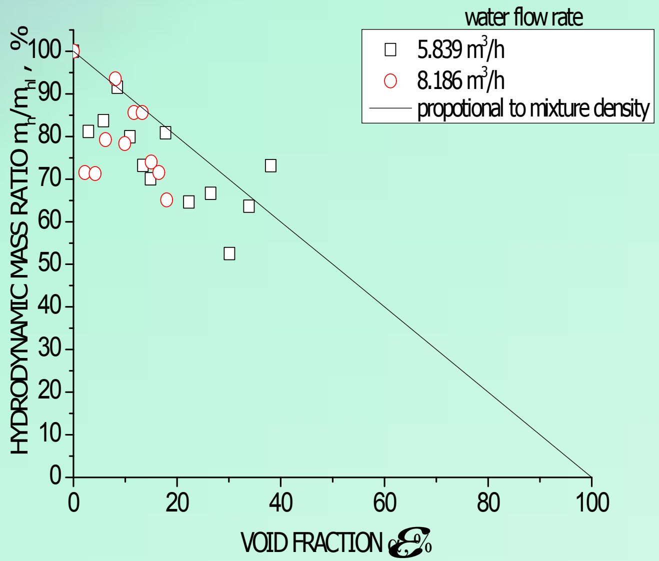
$$\zeta_t = (f_2 - f_1)/2f_n$$





- **Experimental results and discussion**





$$\zeta_{tp} = \zeta - \zeta_s - \zeta_v = K_{tp} \cdot Eu_{LO} \cdot \phi_{LO}{}^2 \cdot \frac{MF_{LO}}{um_t} \frac{1}{8\pi f_n} - \zeta_v$$

$$m_{h,tube} = \frac{\pi\rho d^2}{4}\left(\frac{(De/d)^2+1}{(De/d)^2-1}\right) = m_{OT}\left[\left(\frac{f_a}{f_{tp}}\right)^2 - 1\right]$$

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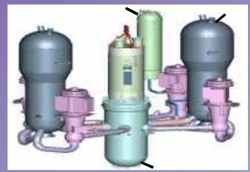
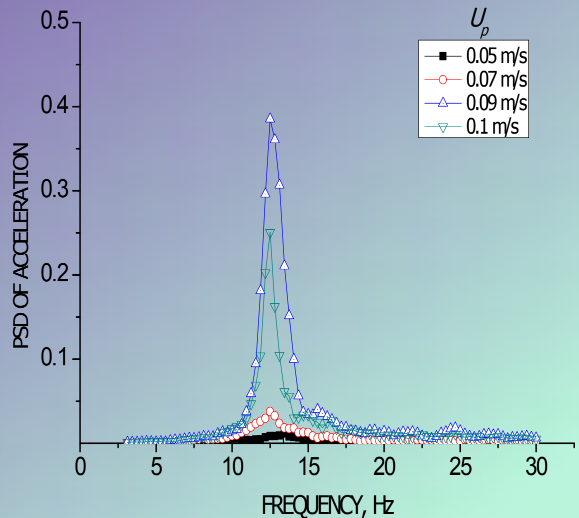
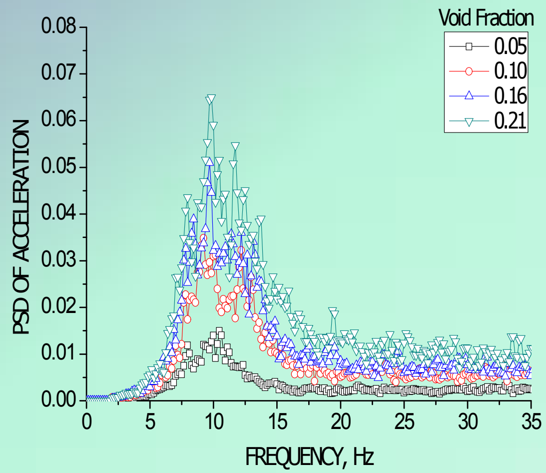
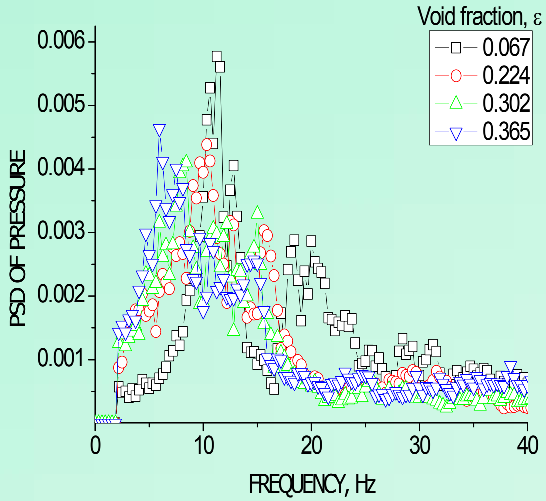
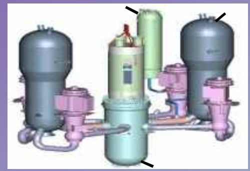


- **Typical Results and discussion**









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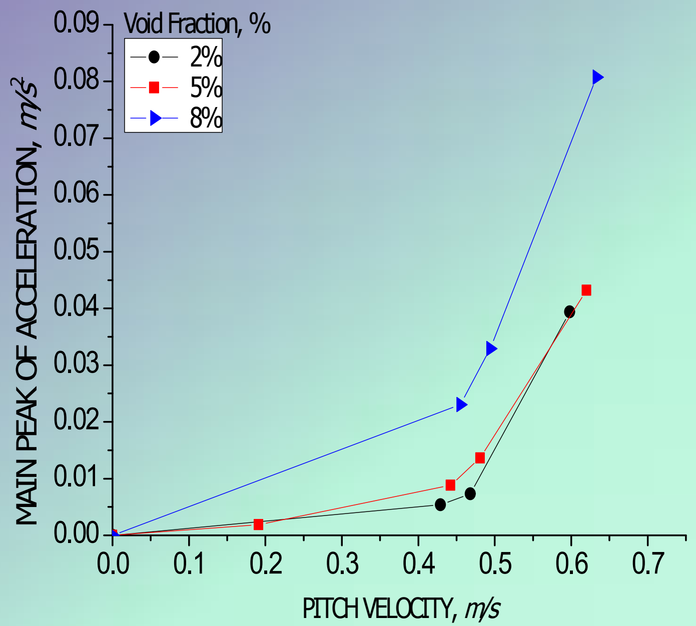
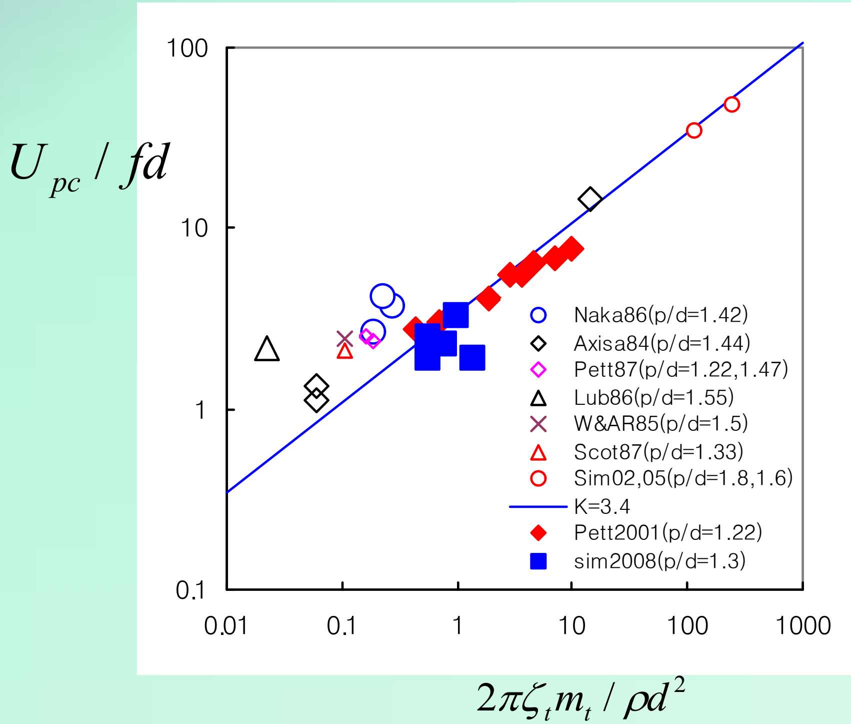
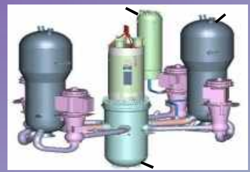
Fluid-elastic Instability

- Dimensionless critical flow velocity

$$\frac{U_{pc}}{fd_{out}} = K\left(\frac{2\pi\zeta_t m_t}{\rho d_{out}^2}\right)^{0.5}$$







- **Experimental data for fluid-elastic instability of tube bundles**

Tube No.	m_t kg/m	f Hz	ε %	$\nu_{tp} \cdot 10^6$ m^2/s	ρ kg/m^3	U_{pc} m/s	$\frac{2\pi\zeta_t m_t}{\rho d^2}$	$\frac{U_{pc}}{fd}$		Damping ratio [%]			
										ζ_t	ζ_s	ζ_v	ζ_{tp}
2	0.870	8.25	0	1.31	1000	0.096	0.547	2.521	3.410	4.00	2.70	1.30	0
3	0.870	11.25	0	1.31	1000	0.100	0.560	1.926	2.573	4.10	2.90	1.20	0
3	0.615	10.13	2	1.34	973.03	0.468	0.775	2.309	2.622	7.80	6.13	1.64	0.02
3	0.677	9.53	5	1.37	942.07	0.442	0.948	2.319	2.382	8.39	6.13	1.51	0.74
1	0.692	12.03	8	1.42	915.10	0.455	1.367	1.896	1.622	11.55	6.39	1.29	0.39

Conclusions

- An experimental program has been performed with normal square array of cylinders subjected to air/water flow, to investigate fluid-elastic instability of tube bundles.

  The pitch over diameter ratio was 1.3 and the diameter of cylinder is 20 *mm*.
- The dynamic instability of cylinder(s) is evaluated with added mass, damping and the threshold flow velocity.
- The two-phase damping was calculated, considering viscous damping, structure damping and the total damping, measured at two-phase flow.
- The measured two-phase damping ratios are compared to the semi-analytical results proposed by Sim (2007).
- However the two-phase damping data is scattered, average values of the data versus void fraction agree well with the analytical results.
- Two-phase damping is very dependent on void fraction
- The calculated fluid-elastic instability coefficients for p/d=1.3 is slightly less than K=3.4 recommended by the design guideline, ASME Code Section Ⅲ App. N-1300.