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Influence of Channel Orientation on the Subchannel Analysis of Two-Phase Flow

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Introduction

Background

- Water-cooled SMR for ship application
  - Inclined channels in reactor core
  - Need subchannel analysis for evaluation of thermal margin
- Key features of subchannel codes for interchannel-exchange
  - Diversion crossflow due to lateral pressure gradient
  - Turbulent mixing and void diffusion due to fluctuation
  - Turbulent void drift toward equilibrium state
  - Buoyancy drift due to gravity

Objectives

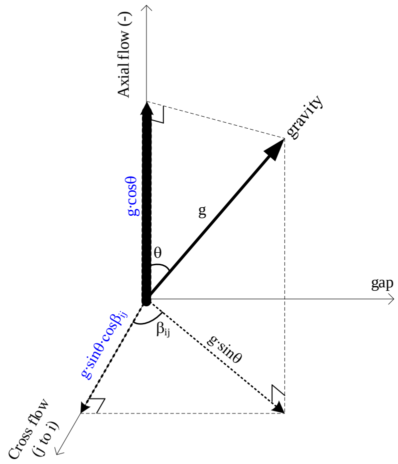
- Modify MATRA code by considering buoyancy drift effects
- Examine subchannel flow and void distributions for various bundle orientation conditions

Gravitational force in lateral momentum

✓ Mixture momentum equations (MATRA)

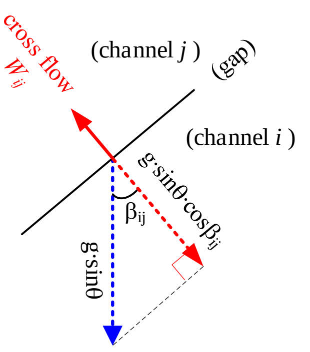
- Axial momentum

$$\frac{\partial \dot{m}_i}{\partial t} + \frac{\partial}{\partial z}\left(\frac{\dot{m}_i^2 v'}{A_i}\right) + \sum_j w_{ij} u^* + f_T \sum_j w'_{ij}\left(u_i - u_j\right) = -\bar{A}\frac{\partial P}{\partial z} - F_z - A_i \rho_i g \cos\theta$$



- Lateral momentum

$$\frac{\partial}{\partial t} W_{ij} + \frac{\partial}{\partial x} W_{ij} U'_{ij} = \frac{s_{ij}}{l}\left(P_i - P_j\right) - \underbrace{F_{ij}}_{\text{friction/form loss}} - \underbrace{s_{ij}\rho_i g \sin\theta \cos\beta_{ij}}_{\text{gravitational loss (added)}}$$



Gap orientation

Modeling of inter-channel mass transfer

- Vapor velocity

$$\underbrace{V_g}_{\text{lateral vapor velocity}} = \underbrace{C_0 j}_{\text{cross-sectional averaging effect}} + \underbrace{V_{gj}^*}_{\text{buoyancy drift}} - \underbrace{\frac{\varepsilon}{\alpha}\nabla\left(\alpha-\alpha_{eq}\right)}_{\text{turbulent diffusion and void drift}}$$

- Inter-channel mass transfer due to turbulent mixing and void drift
  - Liquid: $\left(w'_{ij}\right)_l = s\left(\varepsilon/l_t\right)\cdot\rho_l\left(1-\alpha_i\right)$
  - Vapor: $\left(w'_{ij}\right)_g = s\left(\varepsilon/l_t\right)\cdot\rho_g\left(\alpha_i-\alpha_{i,eq}\right)$
  - Mixture: $w'_{ij} = \left(w'_{ij}\right)_l + \left(w'_{ij}\right)_g = s\left(\varepsilon/l_t\right)\cdot\left[\rho_{m,i}-\rho_g\alpha_{i,eq}\right]$

- Inter-channel mass transfer due to buoyancy drift
  - Outward vapor flow due to buoyancy: $\left(\dot{m}_{ij}\right)_g = \alpha_i^*\cdot\rho_g^*\cdot V_{rise}\cdot\left(s\cdot dz\right)$
  - Inward compensating liquid flow: $\left(\dot{m}_{ij}\right)_l = \left(\dot{m}_{ij}\right)_g$

Energy transfer due to buoyancy drift

- Assumptions
  - Equal-mass-exchange due to buoyancy drift (vapor-out & liquid-in)
  - Outward vapor-phase from channel-i with saturated gas enthalpy
  - Inward liquid-phase from channel-j with saturated liquid enthalpy

- Subchannel energy balance equation (MATRA)

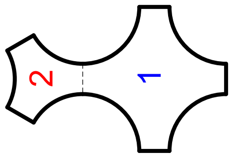
$$\frac{\partial(A\rho h)_i}{\partial t}+\frac{\partial(AGh)_i}{\partial x}+\sum_j W_{ij}\left(h^*-h_i\right)=Q-\underbrace{\sum_j\left(w'_{ij}h_i-w'_{ji}h_j\right)}_{\text{turbulent mixing \& void drift}}-\underbrace{\sum_j w'_{ij,g}\left(h_g-h_l\right)}_{\text{energy transfer by buoyancy drift (added)}}$$

$$w'_{ij}h_i-w'_{ji}h_j=\left(w'_{ij}\right)_{TP}\cdot\left[\left(\alpha_j-\alpha_i\right)-K_{VD}\frac{\left(G_j-G_i\right)}{G_{avg}}\right]\cdot\left(\frac{\rho_f h_f-\rho_g h_g}{\Delta\rho}\right)\quad ;\text{ EVVD}$$

$$w'_{ij,g}=s\cdot\alpha^*\cdot\rho_g^*\cdot\underbrace{\left[1.5\times F\times\alpha^{0.1}\times\left(\frac{\Delta\rho\cdot g\cdot\sigma}{\rho_l^2}\right)^{0.25}\times\cos\beta_{ij}\times\left|\sin\theta\right|\right]}_{\text{vapor rise velocity}}$$

2-channel analysis

- 2-channel geometry

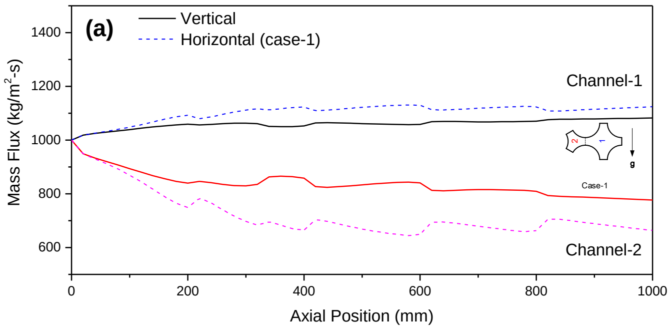


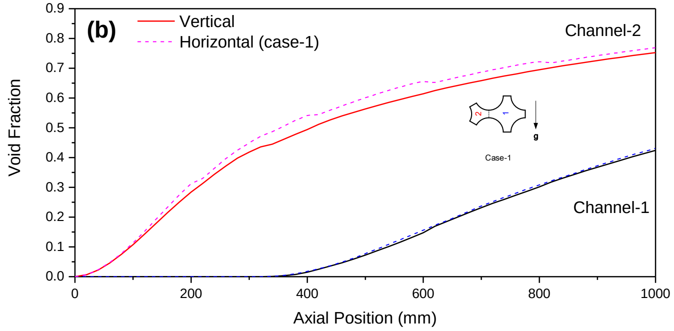
	Ch-1	Ch-2
shape	square	triangular
Hydrauilic diameter (mm)	15.6	11.5
Power factor	0.5	1.0

- Test cases

	θ	β_{ij}	Lateral ΔP_g	Buoyancy drift
Vertical	0	NA	NA	NA
Case-1	90	90	0	0
Case-2	90	180	Yes	No
Case-3	90	180	Yes	Yes

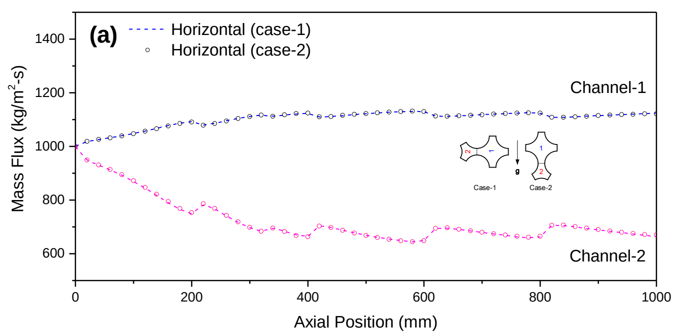
- Vertical vs. Horizontal
  - Friction loss dominant in axial momentum eq.

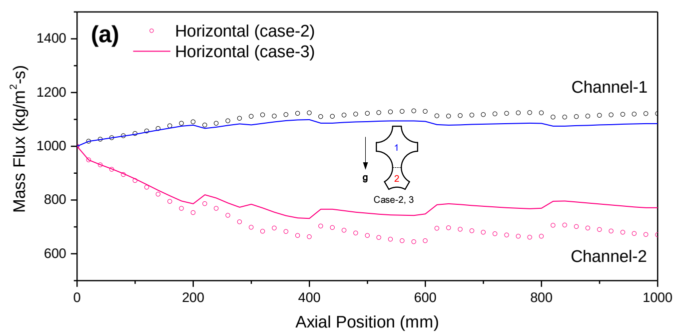


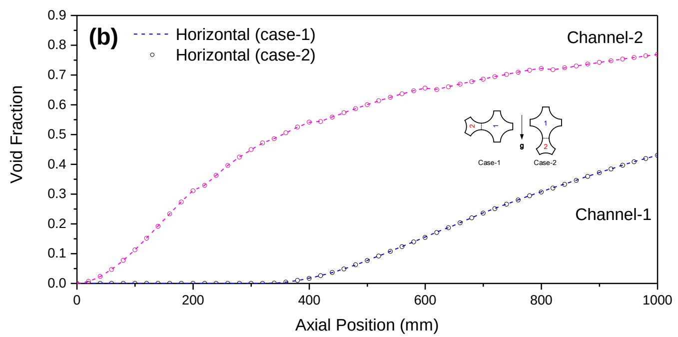


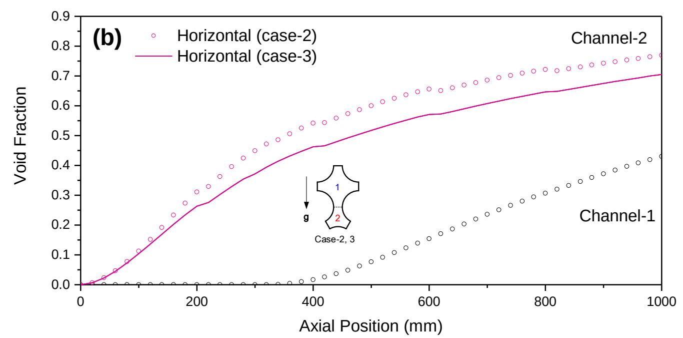
2-channel analysis

- **Influence of gravitational force**
  - Influence of gravitational loss in lateral momentum is not important
- **Influence of buoyancy drift**
  - Remarkable energy transfer by buoyancy drift



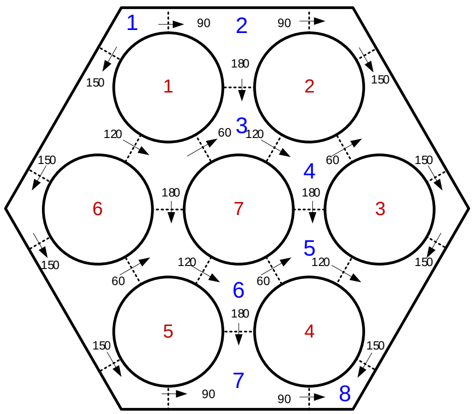






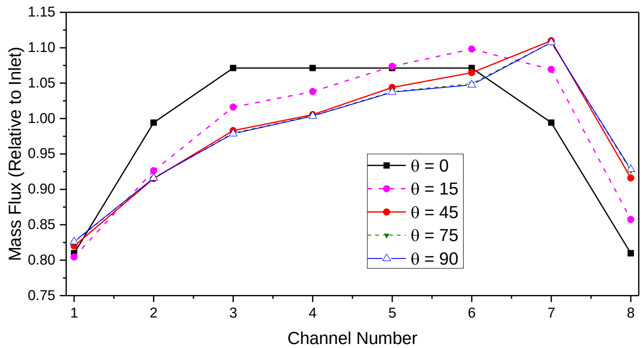
7-rod bundle analysis

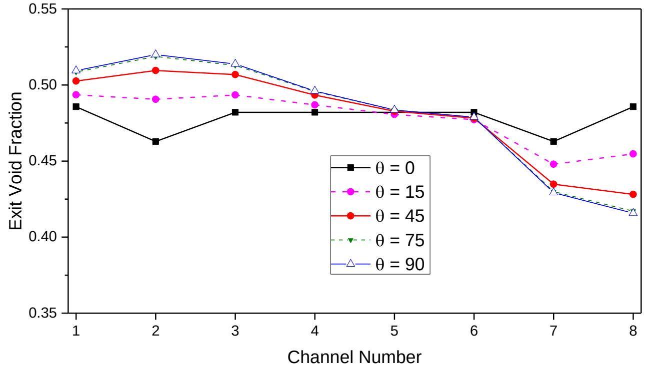
- 7-rod bundle geometry



Rod diameter (mm)	15
Rod pitch (mm)	19
Rod to wall gap (mm)	2
Hydraulic diameter (mm): - Bundle average - Ch-1 / Ch-2 / Ch-3	 8.6 4.8 / 8.7 / 11.5

- Mass flux & Void distributions
  - Upward migration of void
  - Increased void in upper channel reduces channel flow rate





Summary

- **Channel orientation effects on subchannel analysis**
  - ✓ Establish MATRA code model for inclined subchannels
    - Energy transfer by buoyancy drift
    - Gravitational force in lateral momentum equation
    - Consideration of gap orientation effect between adjacent subchannels
  - ✓ Examine MATRA for sample problems
    - 2-channel model & 7-rod bundle model
    - Effect of inclination angles on subchannel void & mass flux distributions

- **Further works**
  - ✓ Modeling of buoyancy drift (V_{rise}, equal-volume exchange, etc.)
  - ✓ Experimental data for model validation (inclined channels)