Electrical Capacitance Volume Tomography (ECVT) imaging of gas-liquid multiphase flows

Aining Wang[1]

Qussai Marashdeh[2]

Prof. Liang-Shih Fan[1]

William G. Lowrie Department of Chemical and Biomolecular Engineering

1.The Ohio State University

2. Tech4Imaging, LLC

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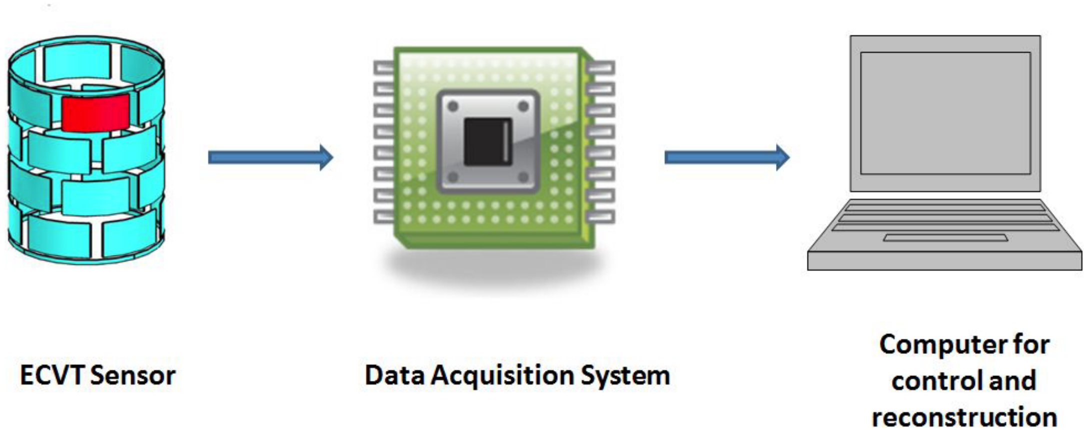
Outline

- Introduction of ECVT system
- ECVT applied to a trickle bed reactor
  - Liquid maildistribution in trickling regime
  - Pulse shape, frequency, velocity and liquid holdup in pulsating regime
  - Mathematical model to calculate the actual liquid velocity pulsating regime
- ECVT applied to a passive cyclonic gas-liquid separator
  - Liquid distribution and holdup
  - Mathematical model to describe the gas core behaviors

Electrical capacitance volume tomography

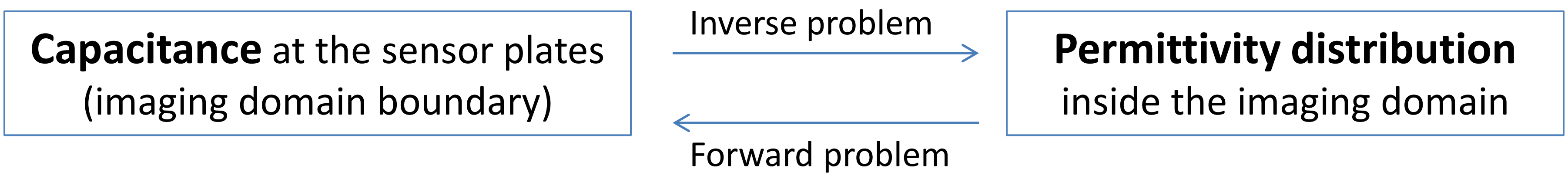
ECVT: a novel tool for multiphase flow imaging
(Phase distribution image)

▪Non-intrusive ▪3-D ▪High frame rate ▪Low cost ▪Safe



- Sensor (capacitance plates)
- Data acquisition device
- Computer with control/reconstruction software

Principle of ECVT



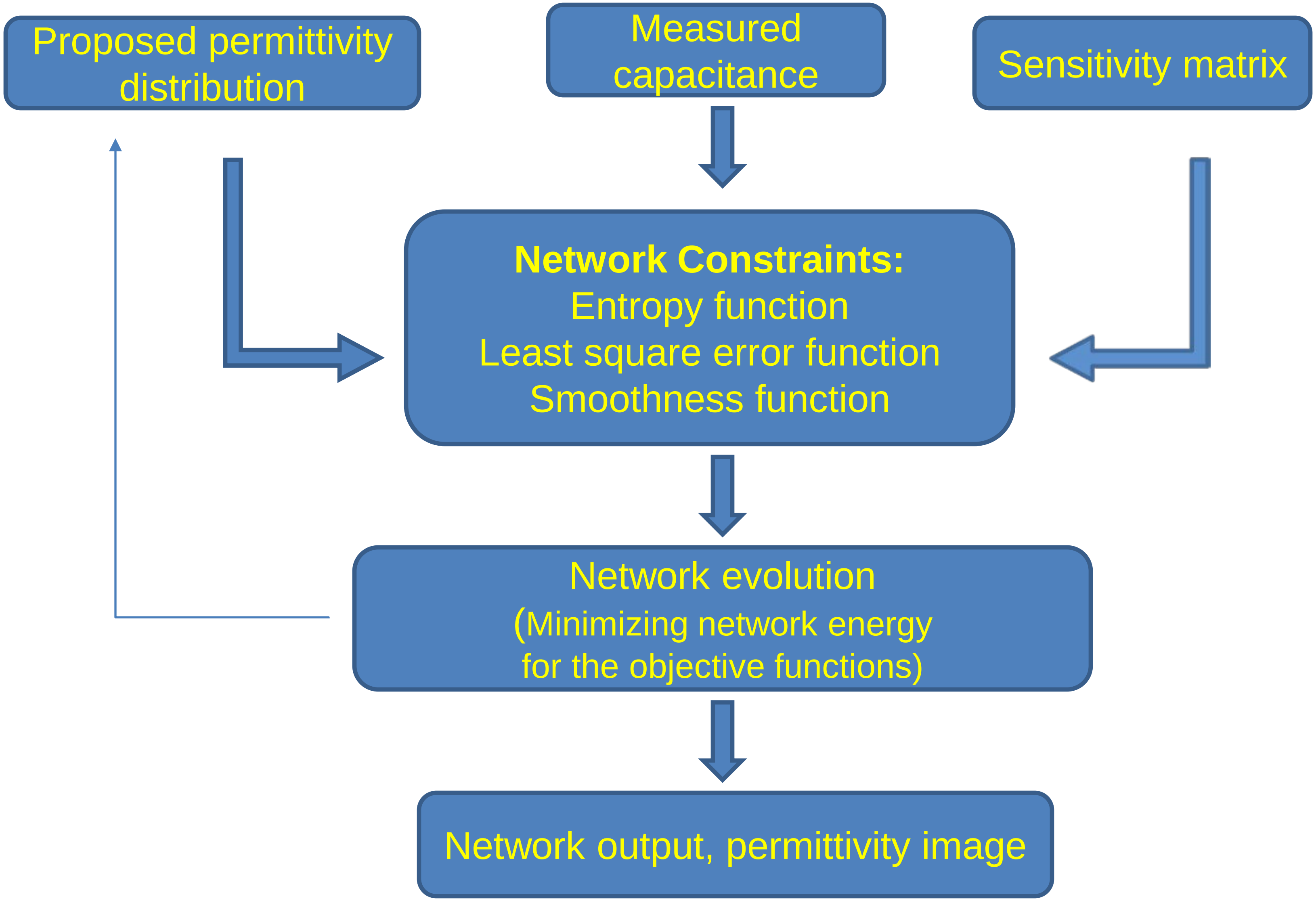
- Inverse problem: directly calculate the permittivity distribution based on capacitance, very difficult.

- Forward problem: calculate the boundary capacitance for a given permittivity distribution, can be done using linearization and ‘sensitivity model’.

- Practical method: Iteration optimization.
  1. Solve the forward problem, calculate the capacitance based on a ‘proposed’ permittivity distribution;
  2. Compare the calculated capacitance with measured capacitance with some criteria;
  3. If the proposed distribution is not ‘good’, modify it and go back to step 1; if the proposed distribution is ‘good’ enough, exit.

Image Reconstruction

NNMOIRT: Neural Network Multi-criteria Optimization Image Reconstruction Technique



Case 1: Trickle bed reactors

Trickle bed reactors

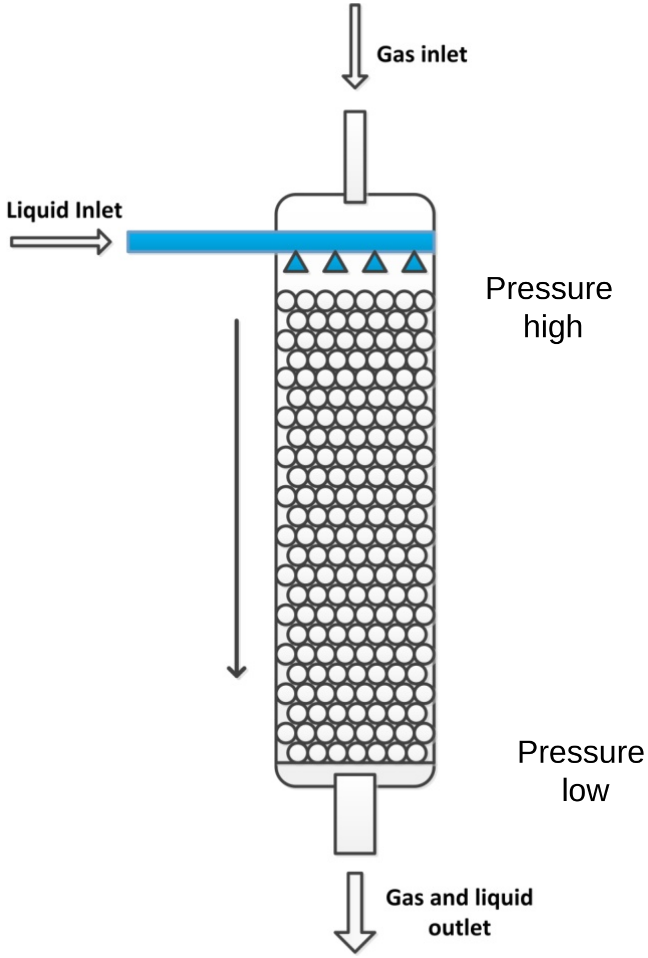
- Solids packed bed
- Gas-liquid concurrently down flow

Pros:

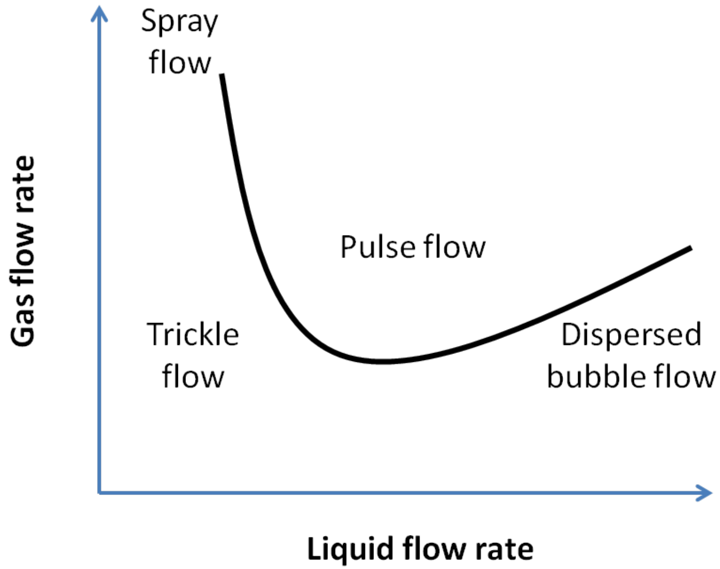
- Simple, no moving parts
- Near plug flow
- High catalysts loading
- Low catalysts attrition rate

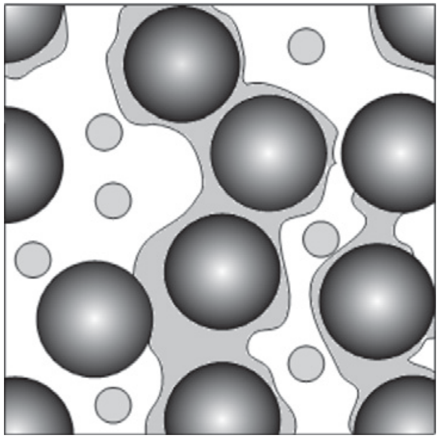
Cons:

- Incapable of rapidly deactivating catalysts
- Liquid maldistribution
- Temperature control

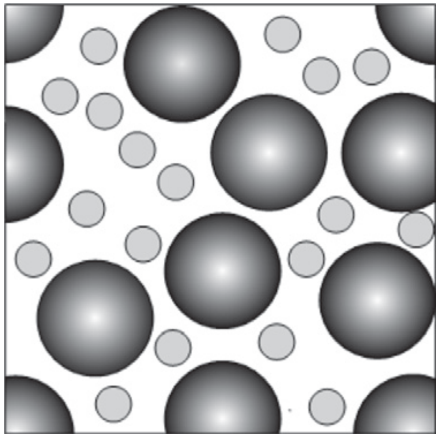


Flow regimes in a TBR

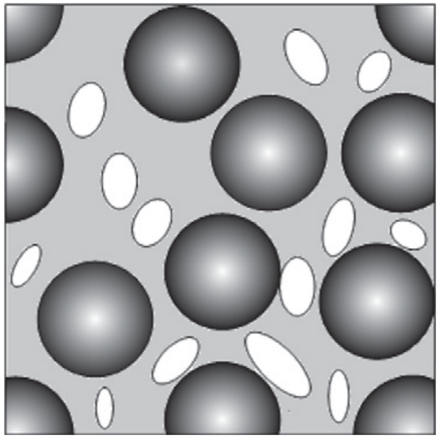




Trickle flow*



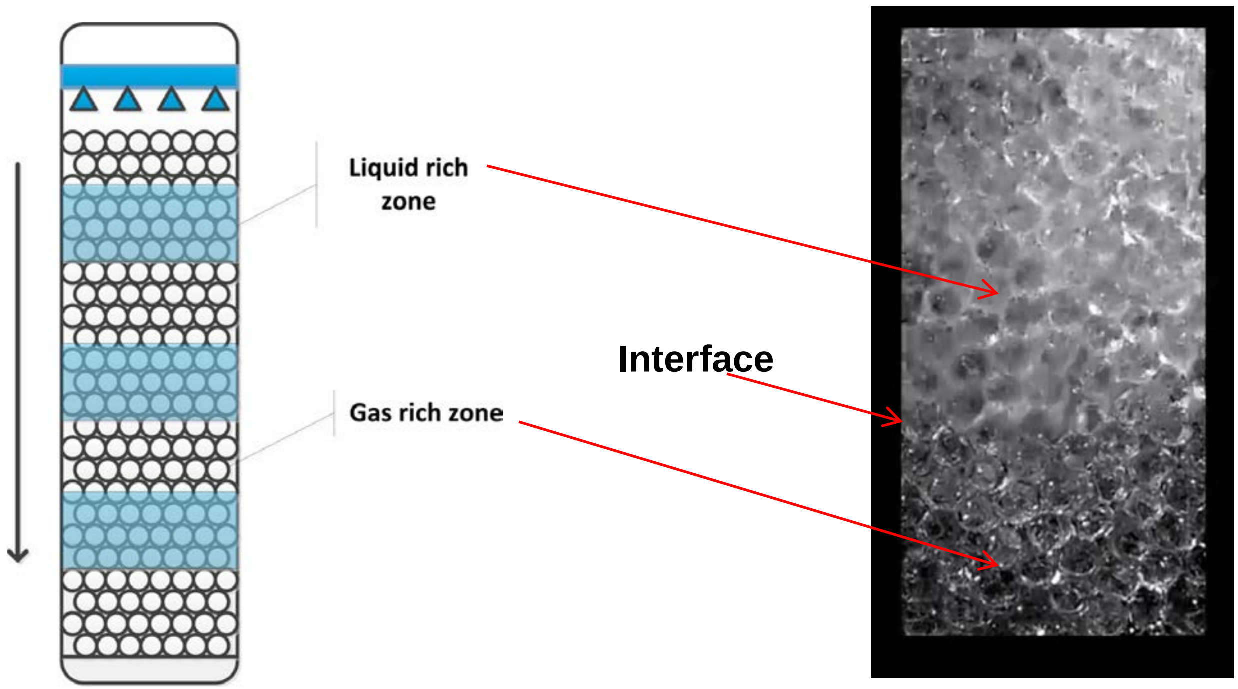
Spray flow*



Dispersed bubble flow*

*Ranade, Vivek V., Raghunath Chaudhari, and Prashant R. Gunjal. *Trickle Bed Reactors: Reactor Engineering & Applications*. Elsevier, pp28, 2011.

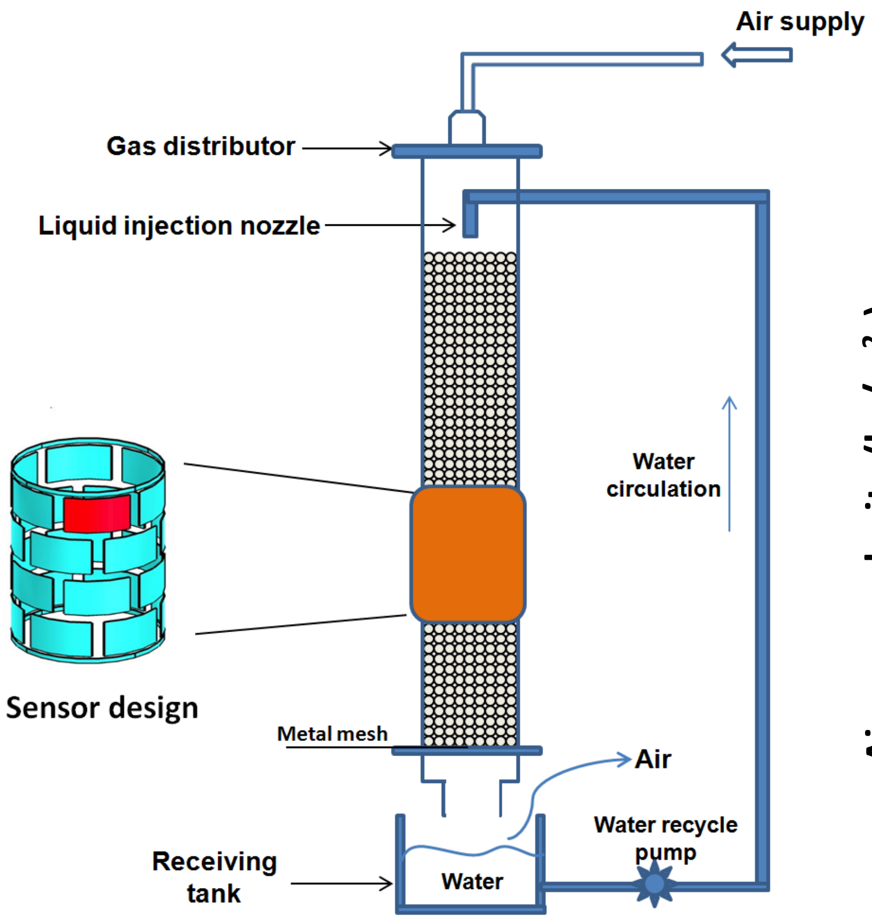
Pulsating flow

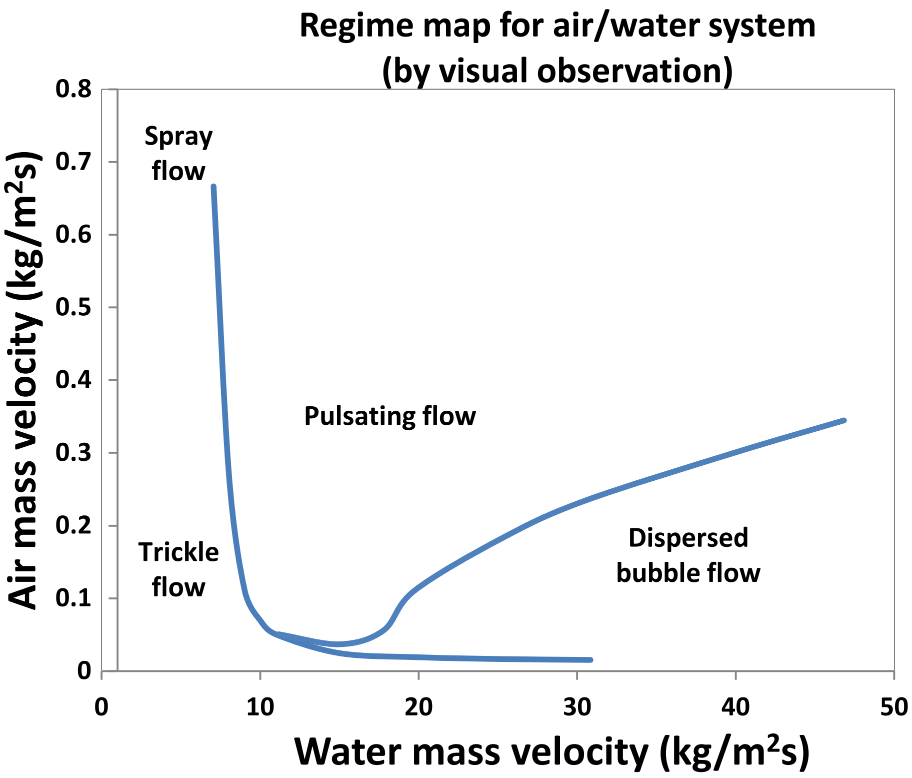


Picture Source:
https://www.youtube.com/watch?v=x6U7OeBV2cs

Potential Benefits:
Intense interactions increase the mass/heat transfer between phases.

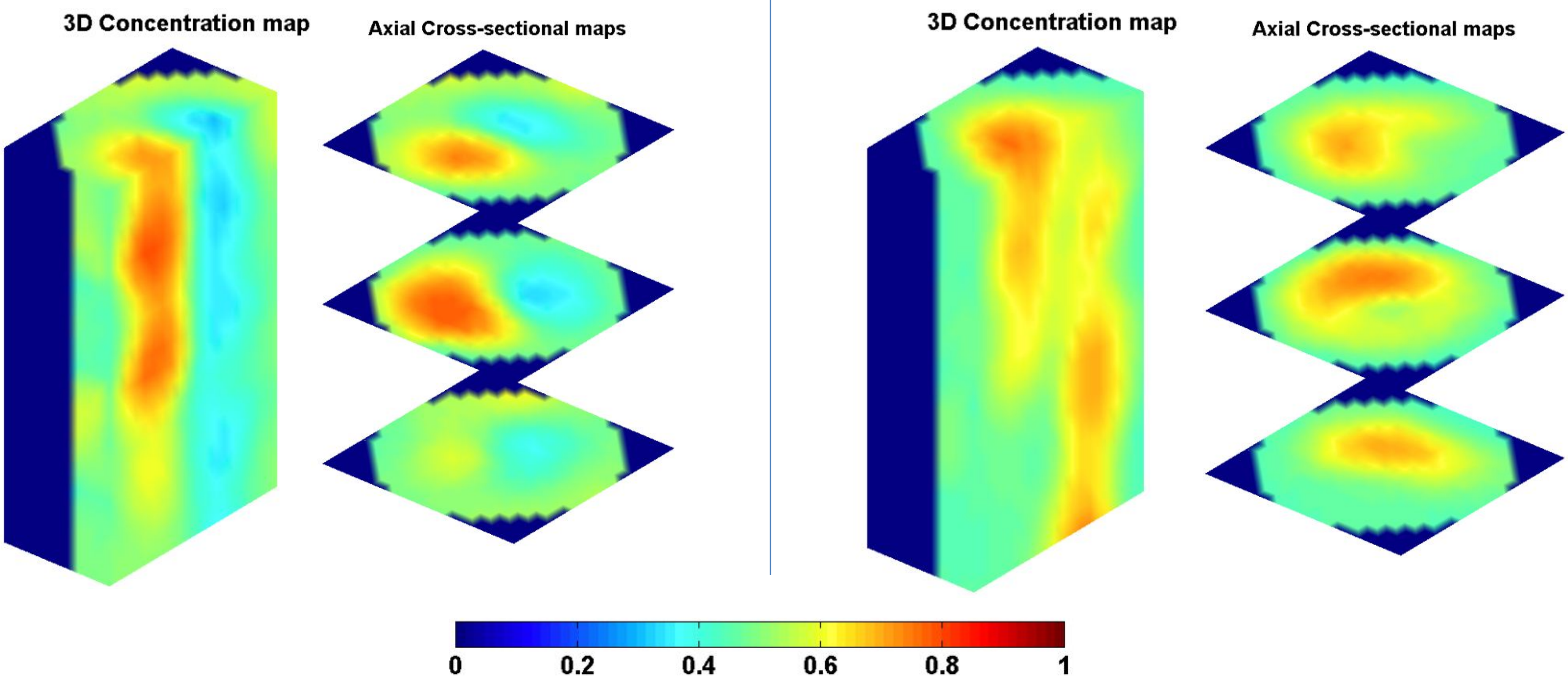
Air-water trickle bed





Particles: 3 mm glass beads.

Liquid maldistribution of trickling flow

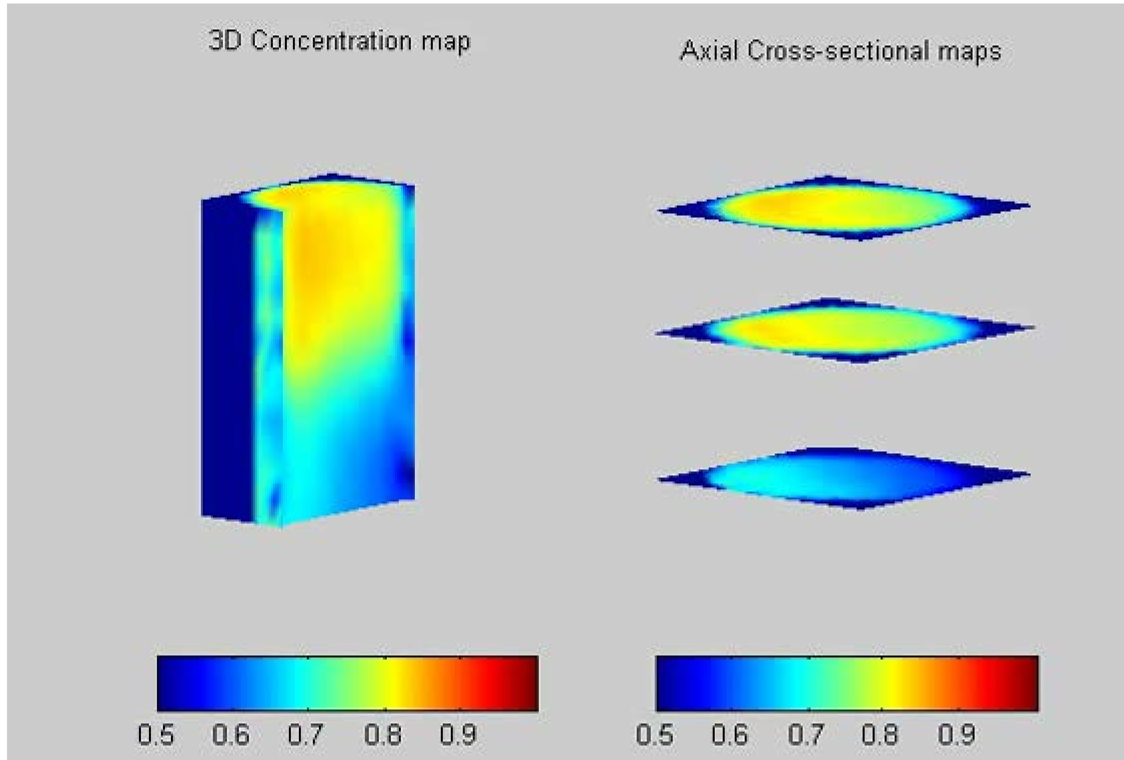


Condition 1: Without any pre-wetting

Condition 2: After several draining-filling cycles

Air: 0 kg/m^{2}s, Water:4.1 kg/m^{2}s

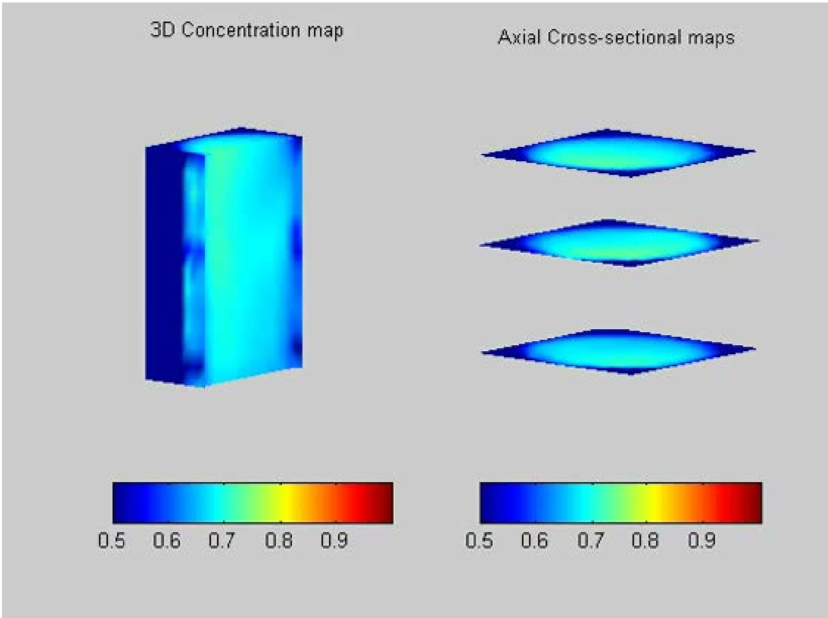
Videos of pulsating flow



(Color bar represents particle-free holdup)

Air: 0.454 kg/m^2s, Water:21.7 kg/m^2s

Pulsating flow properties



Slow motion (0.1X of original speed, 5fps)
(Air: 0.454 kg/m^{2}s, Water:21.7 kg/m^{2}s)

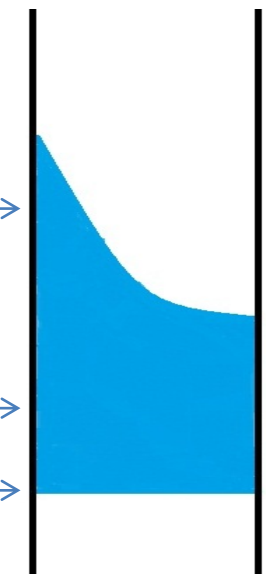
Observations:
The length and shape of the pulses are not the same, unsteady state.

Liquid pulse shape:

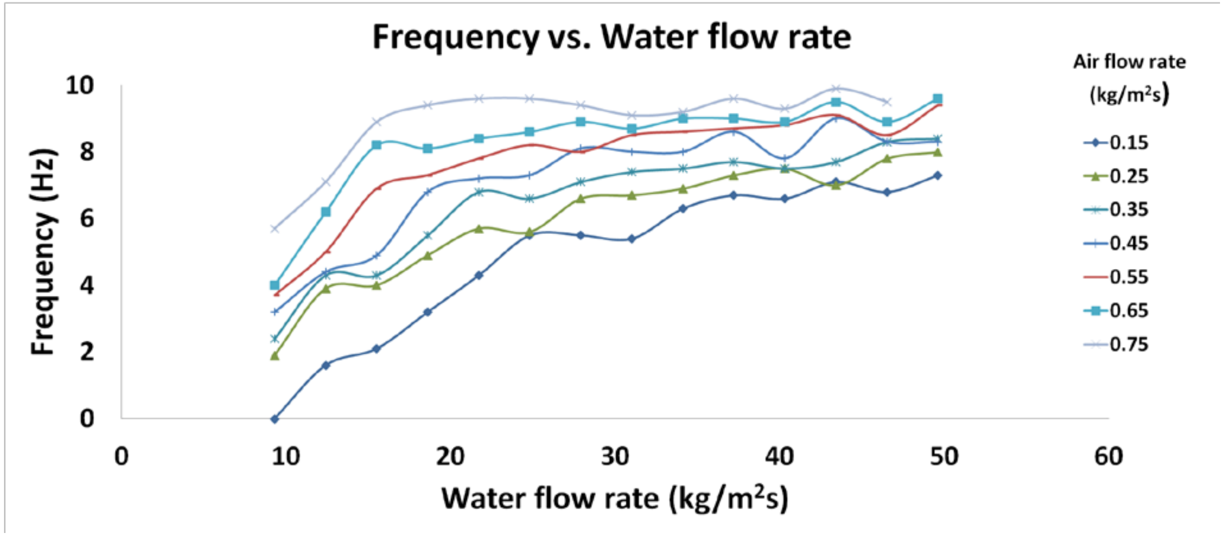
A tail, normally off-center
(Sometimes no tail at all)

A relatively uniform main body

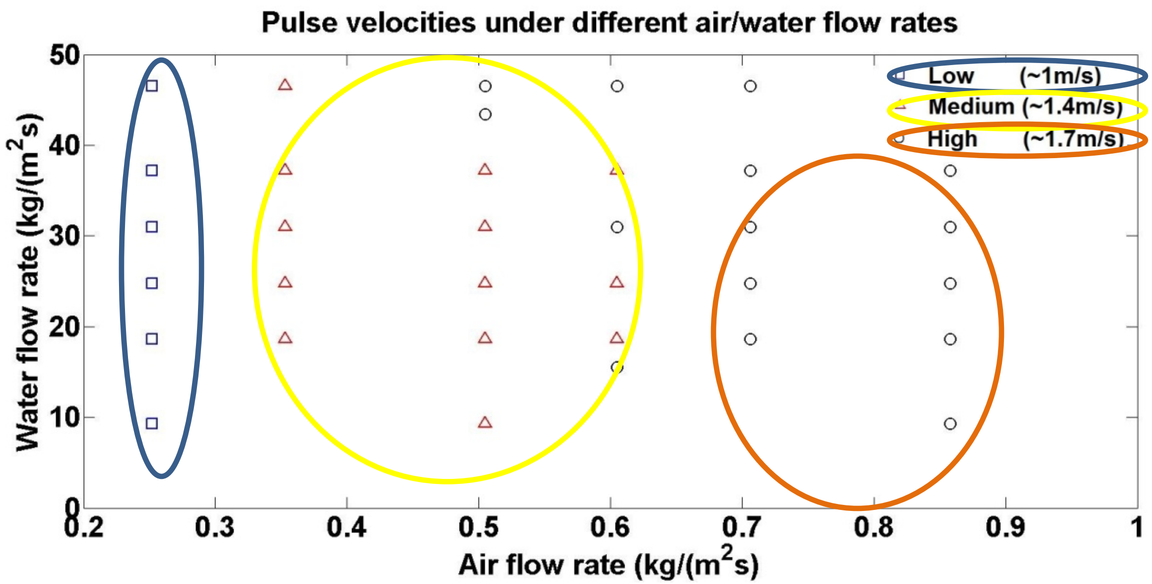
A flat, sharp leading front



Pulse frequency and velocity

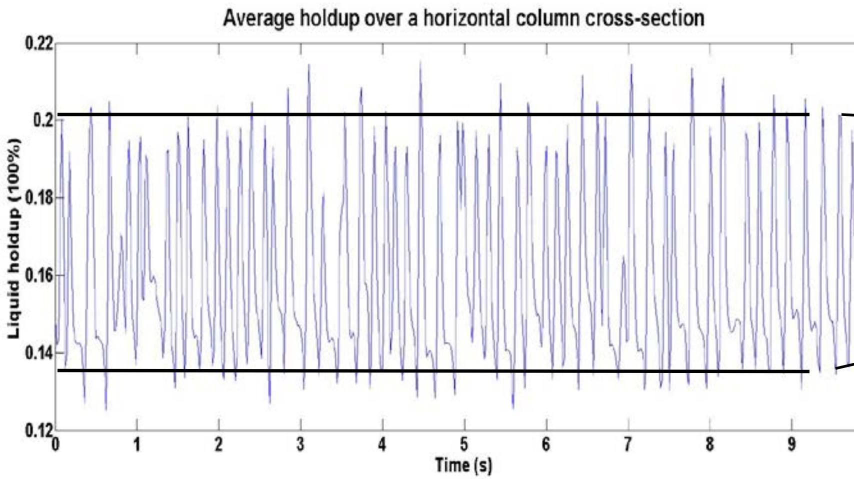


- ❖Increasing the air flow rate will always increase the pulse frequency.
- ❖Water flow rate only affects the frequency when water flow rate is low.

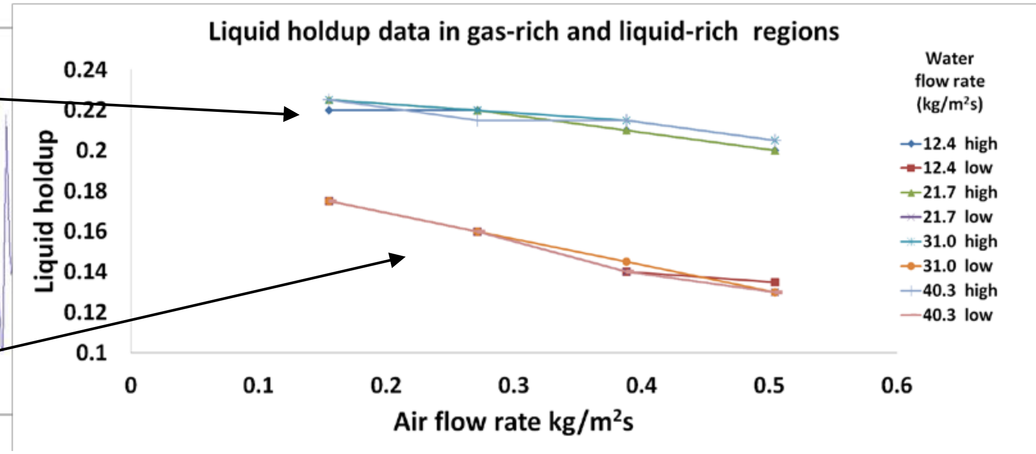


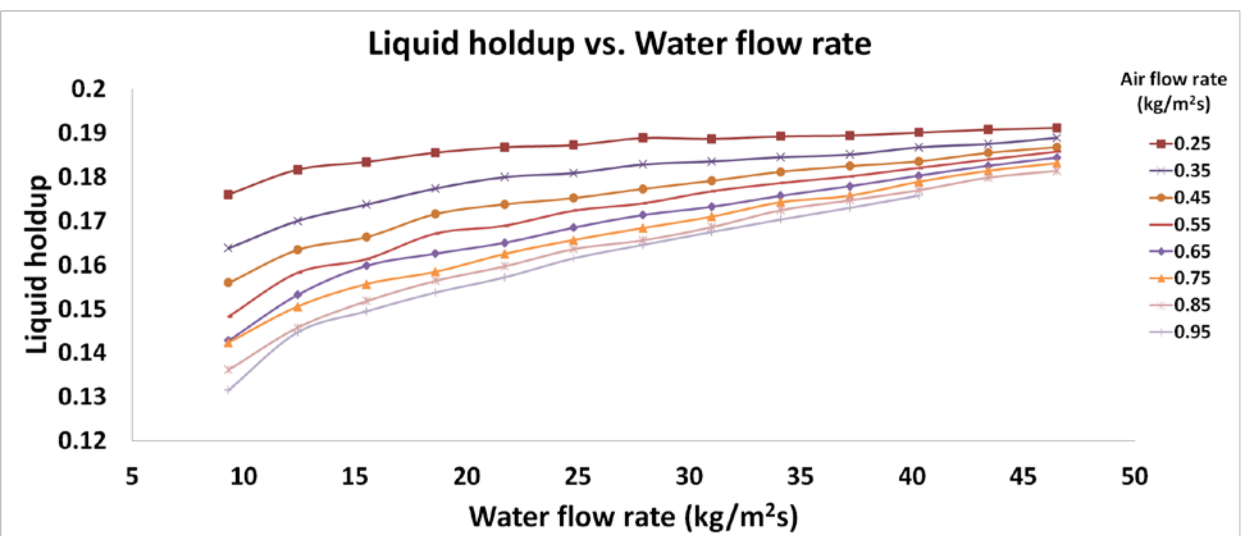
- ❖Pulse velocity is only decided by air flow rate, water flow rate has negligible effect.

Liquid holdup (particle-free holdup)



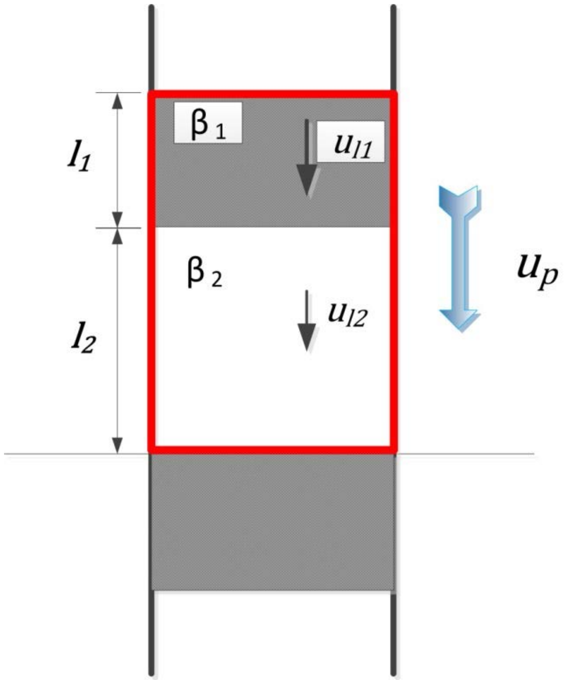
Air: 0.5 kg/m^{2}s, Water: 21.7 kg/m^{2}s





- ❖Holdup in individual pulse is only decided by gas flow rates.
- ❖ Overall holdup changes with both air and water flow rates.
- ❖Water flow rates only affacts the length ratio of gas/liquid rich regions.

Model for actual liquid velocity



Assumptions

At any given inlet air/water flow rates:

- Rectangular shape pulse
- Steady state
- All gas/liquid rich regions are identical
- Uniform liquid holdup/velocity in each region

u_{l1} and u_{l2}: linear liquid velocity in liquid and gas rich regions.
β_1 and β_2: liquid holdup in liquid and gas rich regions.
u_p: pulse velocity.
Q: total water inlet flow rate.
A: column cross-sectional area.
1: liquid rich region; 2: gas rich region.

$$\begin{cases} \Delta t_1 = l_1/u_p \\ \Delta t_2 = l_2/u_p \end{cases}$$

$$V_l = u_{l1}\Delta t_1 \beta_1 A + u_{l2}\Delta t_2 \beta_2 A$$

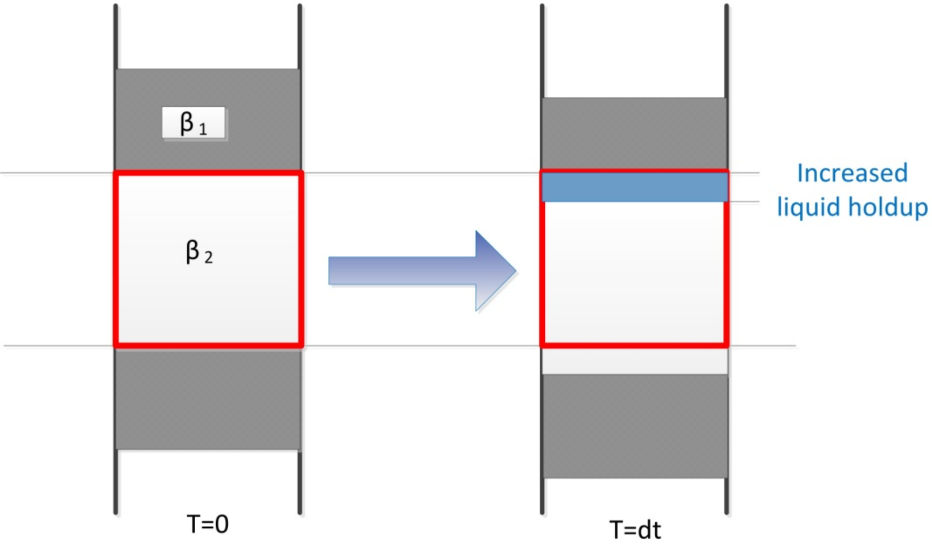
$$V_{add} = Q(\Delta t_1 + \Delta t_2)$$

$$V_l = V_{add}$$

$$Q/A = u_{l1}\beta_1 \frac{l_1}{l_1+l_2} + u_{l2}\beta_2 \frac{l_2}{l_1+l_2} \quad (1)$$

Ref: Dimenstein, D. M., & Ng, K. M. (1986). *Chemical Engineering Communications*, 41(1-6), 215-235.

Model for actual liquid velocity



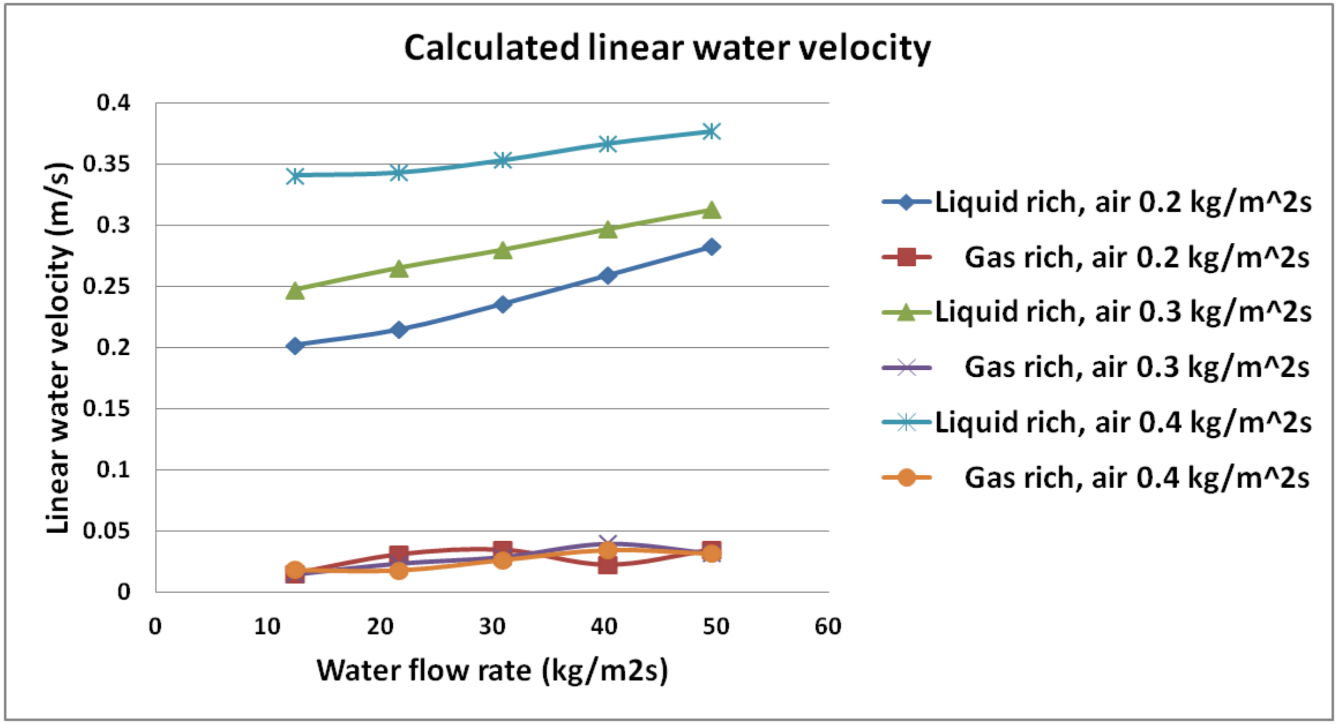
$$\left.\begin{aligned} H_{in} &= u_p A dt(\beta_1 - \beta_2) \\ H_{in} &= u_{l1} A dt \beta_1 - u_{l2} A dt \beta_2 \end{aligned}\right\}$$

$$\longrightarrow u_p = \frac{u_{l1}\beta_1 - u_{l2}\beta_2}{\beta_1 - \beta_2} \qquad (2)$$

Combining Eqs. (1) and (2):

$$\begin{cases} u_{l1} = \left(\frac{Q}{A} + (\beta_1 - \beta_2)\frac{l_2}{l_1 + l_2} u_p\right)/\beta_1 \\ u_{l2} = \left(\frac{Q}{A} - (\beta_1 - \beta_2)\frac{l_1}{l_1 + l_2} u_p\right)/\beta_2 \end{cases}$$

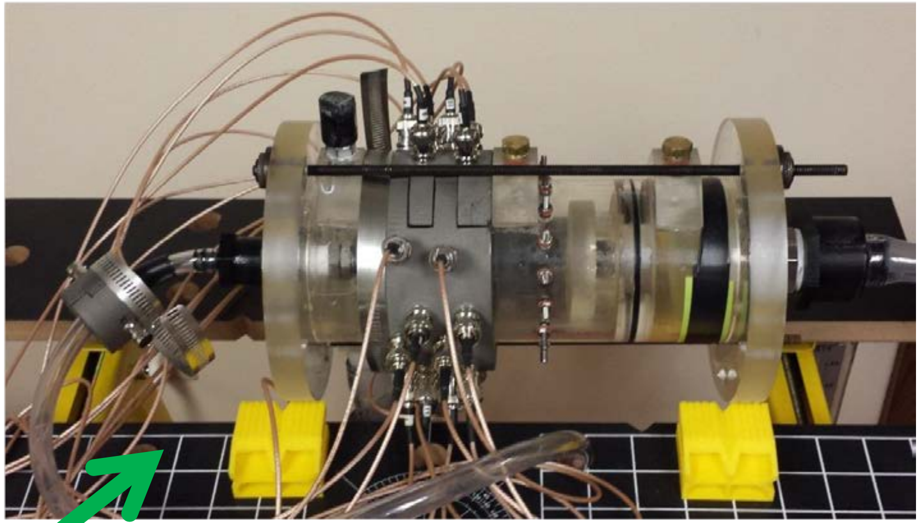
Calculated actual liquid velocity

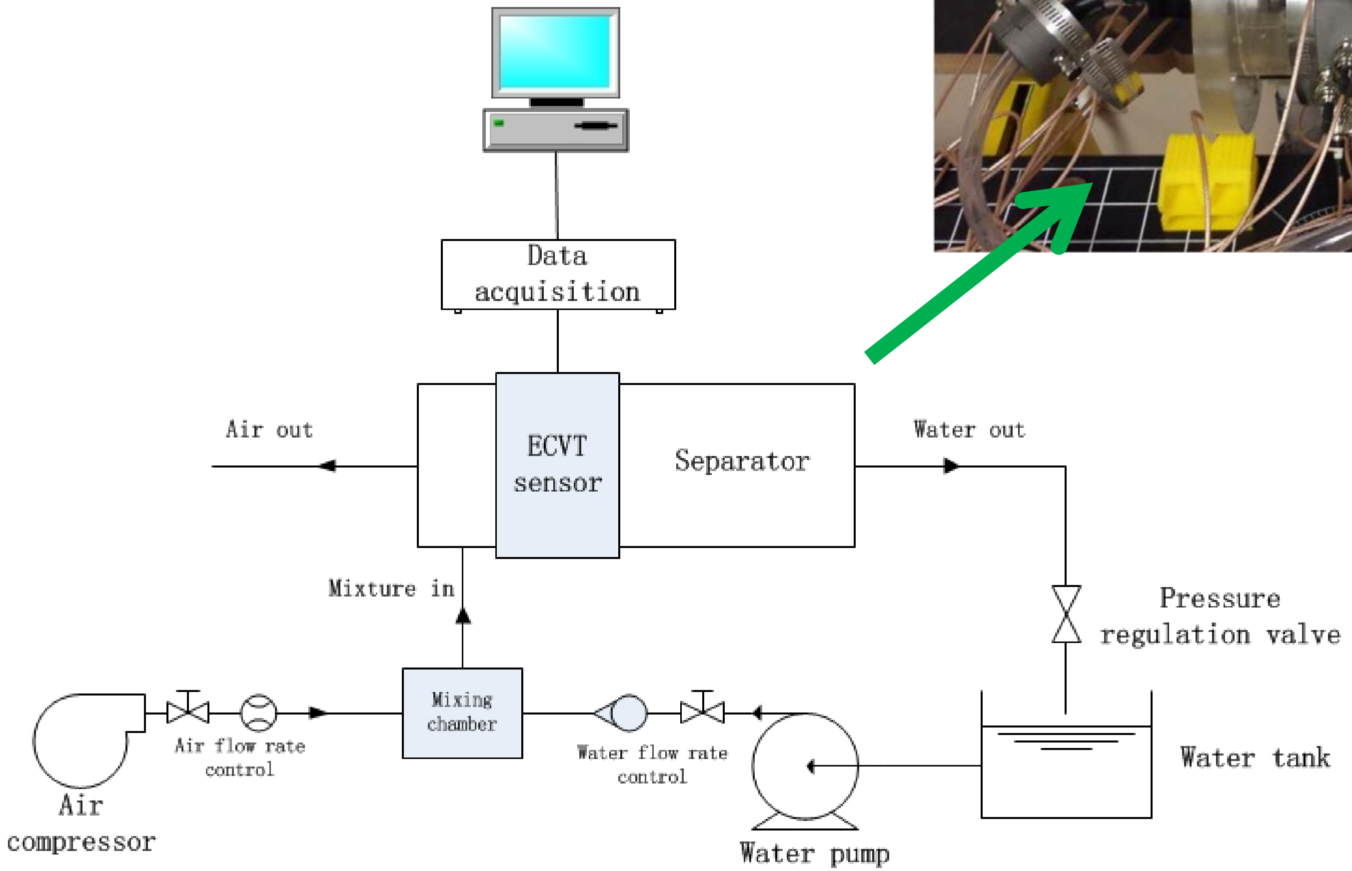


- ❖Linear liquid velocity in liquid rich region is higher than that in the gas rich region.
- ❖Increasing the air and water flow rates can increase the linear velocity in liquid rich region.
- ❖Linear liquid velocity is much slower than the pulse velocity (1-2 m/s): Pulsating is a wave.

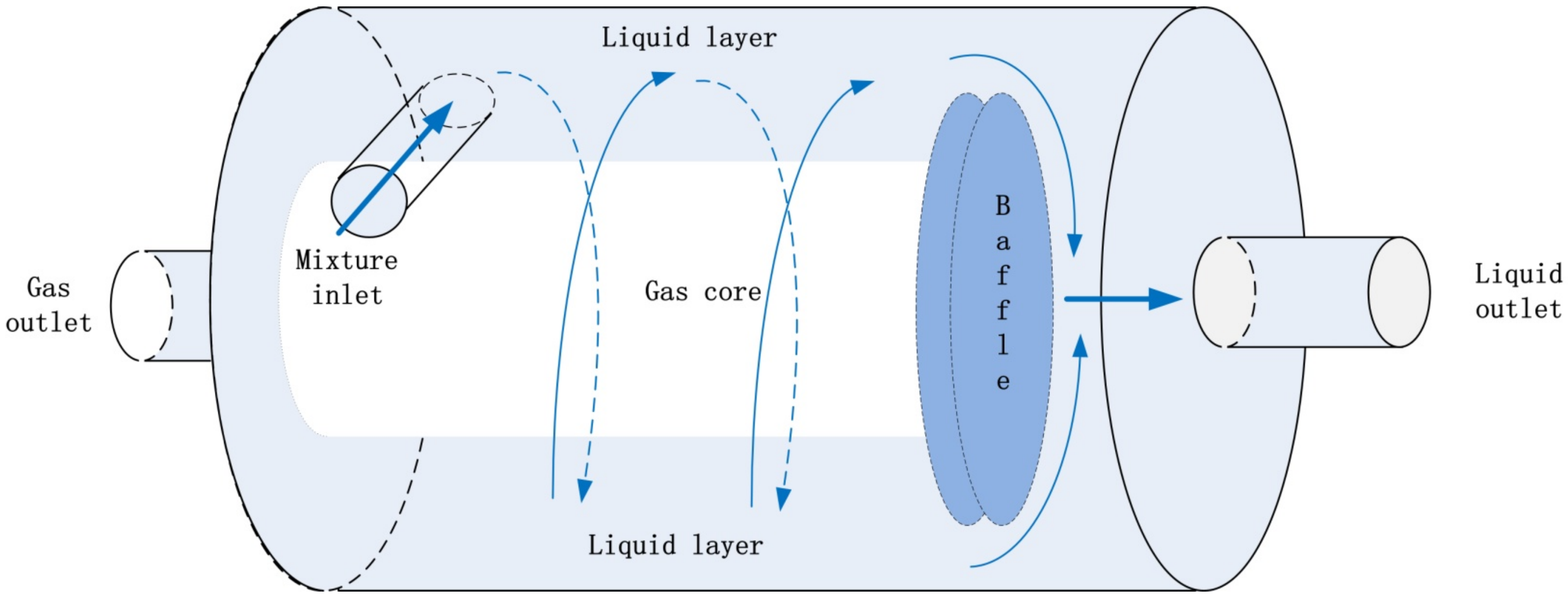
Case 2: Passive cyclonic gas-liquid separator

Passive cyclonic gas-liquid separator



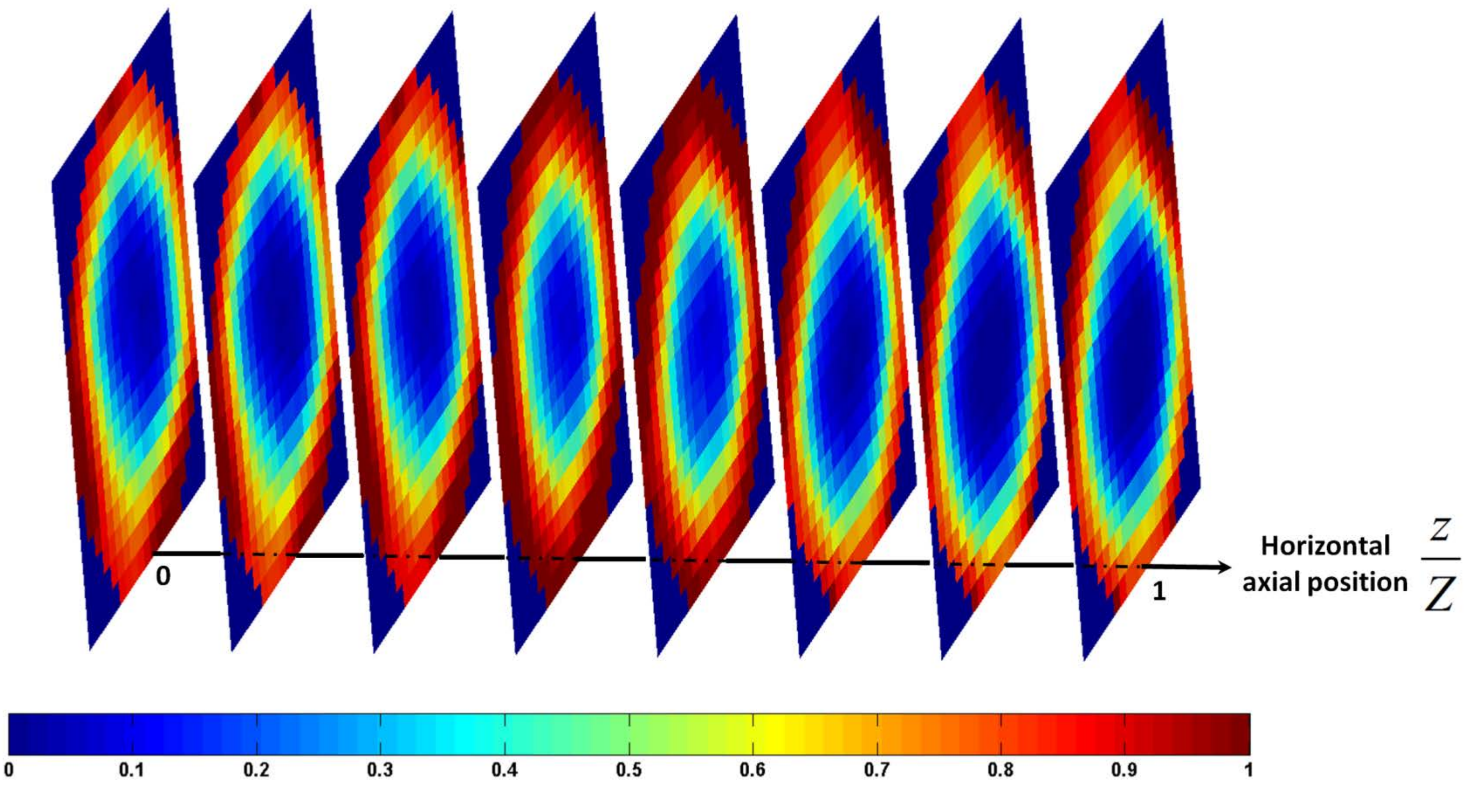


General flow pattern

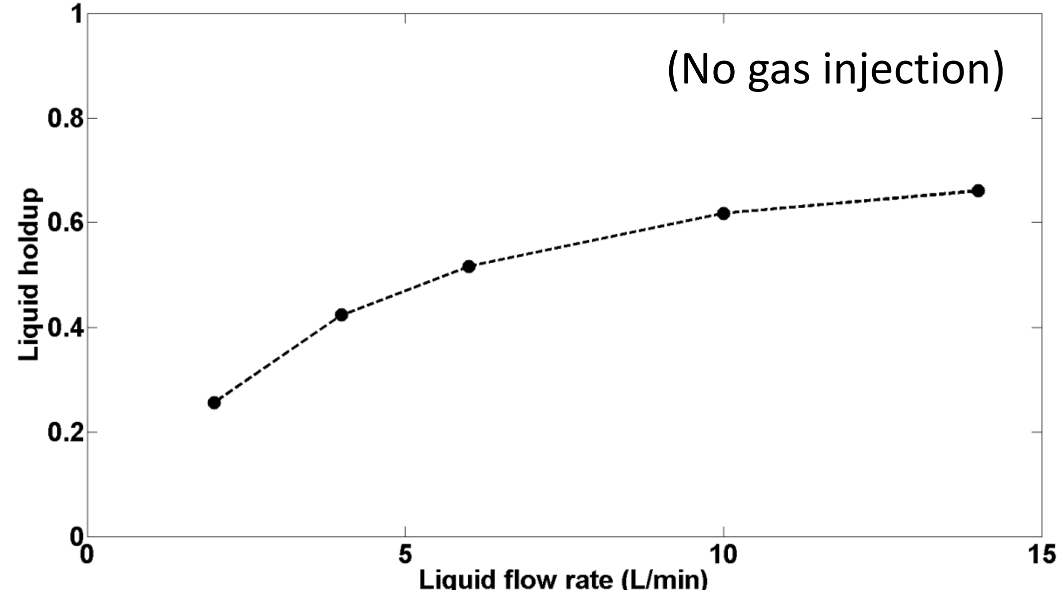


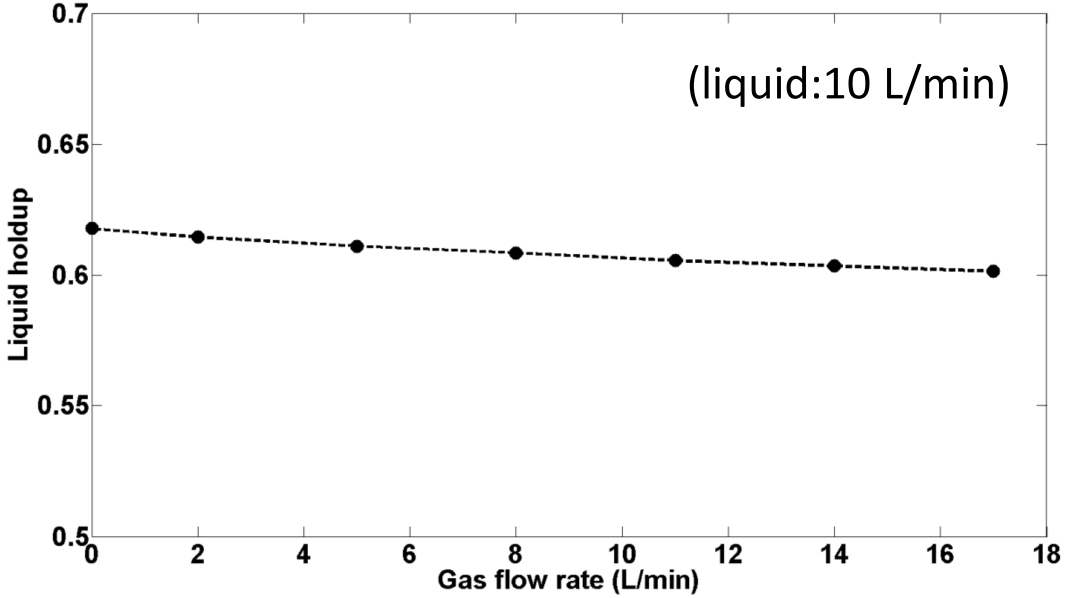
Liquid will rotate near the separator wall and exit from the liquid outset. Gas core will be pushed out through the gas outlet.

Typical ECVT results

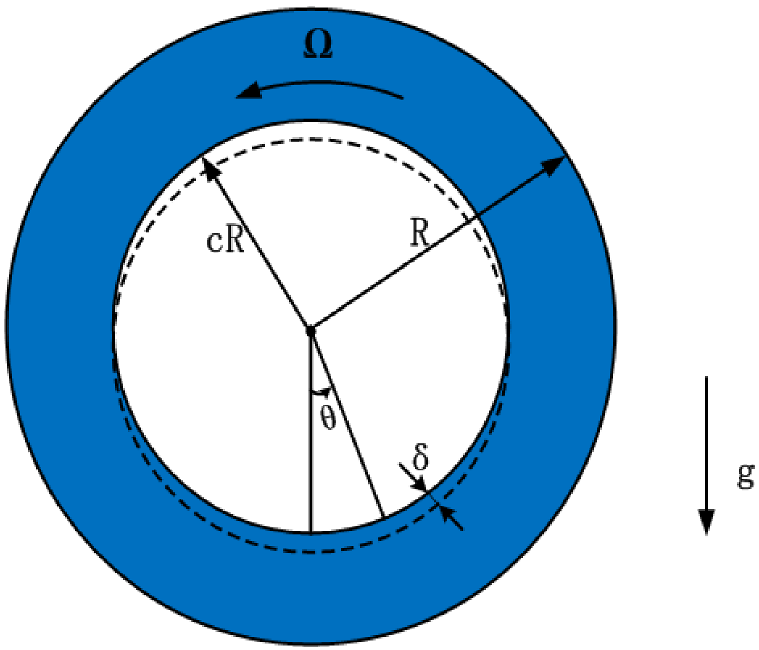


Liquid holdup results





Mathematical model



$$u_r\frac{\partial u_r}{\partial r}+\frac{u_\theta}{r}\frac{\partial u_r}{\partial \theta}-\frac{u_\theta^2}{r}=-\frac{1}{\rho}\frac{\partial p}{\partial r}+g_r$$

$$u_r\frac{\partial u_\theta}{\partial r}+\frac{u_\theta}{r}\frac{\partial u_\theta}{\partial \theta}+\frac{u_r u_\theta}{r}=-\frac{1}{\rho r}\frac{\partial p}{\partial \theta}+g_\theta$$

$$\frac{\partial (r u_r)}{\partial r}+\frac{\partial (u_\theta)}{\partial \theta}=0$$

If gravity is neglected, the solution is a centro-symmetric rigid-body motion around the gas core. By assuming that gravity is a small perturbation on this simple rigid-body motion, the above equations can be solved as:

$$u_r=\frac{gc^2}{2\Omega}\left(1-\frac{R^2}{r^2}\right)\sin\theta$$

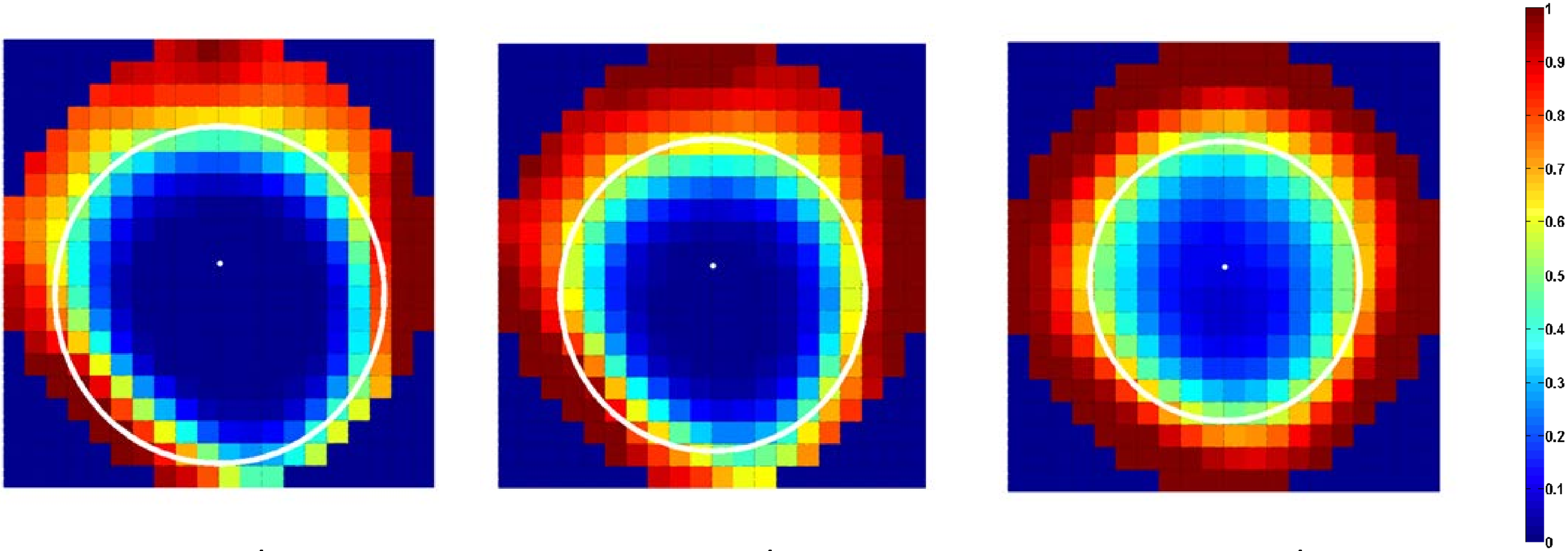
$$u_\theta=\Omega R\left[\frac{r}{R}+\frac{gc^2}{2\Omega^2 R}\left(1+\frac{R^2}{r^2}\right)\cos\theta\right]$$

$$p=\frac{1}{2}\rho\Omega^2R^2\left(\frac{r^2}{R^2}-c^2+\frac{2gr}{\Omega^2R^2}\left[1+\frac{c^2}{2}\left(1-\frac{3R^2}{r^2}\right)\right]\cos\theta\right)+p_0$$

$$\delta=\frac{g}{2\Omega^2 R}\left(1-c^2\right)\cos\theta$$

Comparison between ECVT and model

$$\delta = \frac{g}{2\Omega^2 R}(1 - c^2)\cos\theta$$



Liquid: 4 L/min   Liquid: 6 L/min   Liquid: 10 L/min

Gas core size will shrink with increasing flow rate.
Gas core's center is always below the center of the separator.
Gas core's center will move to the separator's center when liquid flow rate increases.

Acknowledgment

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Thank you!