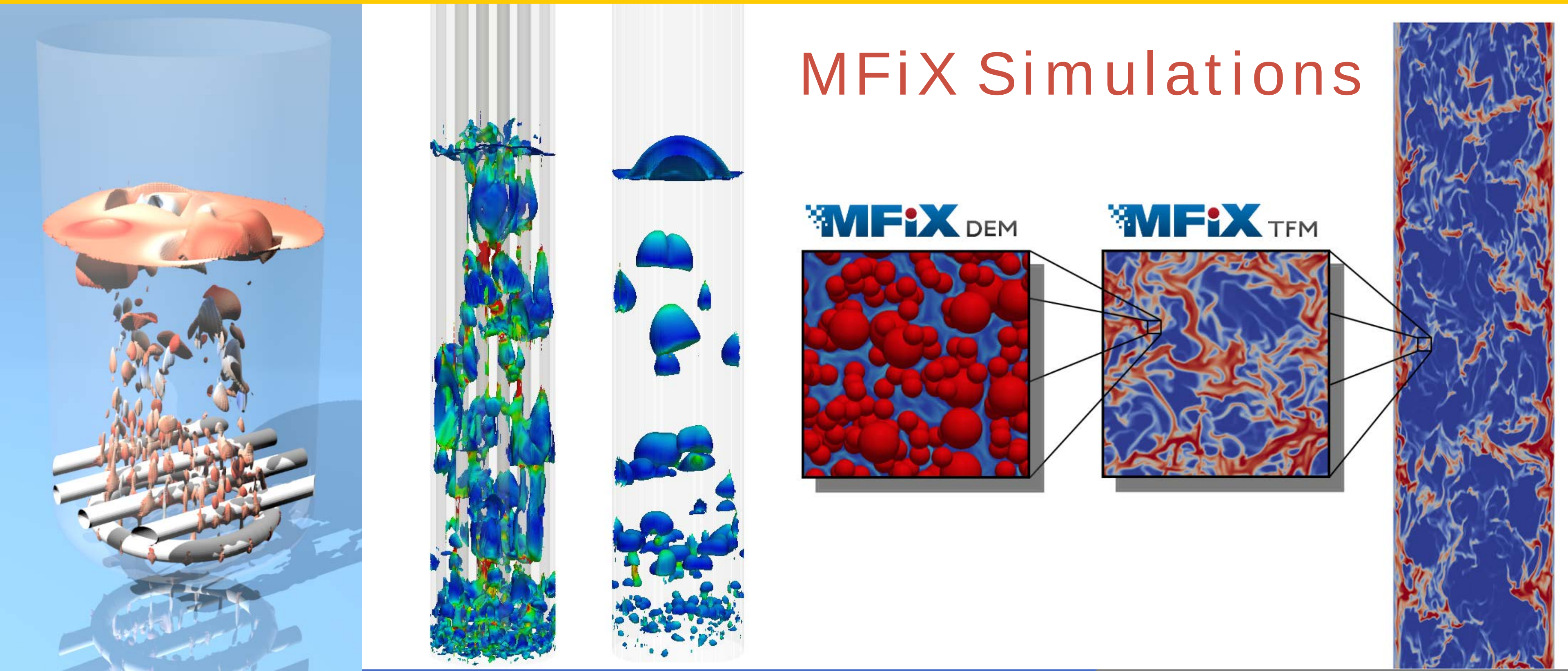
Driving Innovation ♦ Delivering Results



Hydrodynamics of gas-solids flow in a bubbling fluidized bed with immersed vertical U-tube banks

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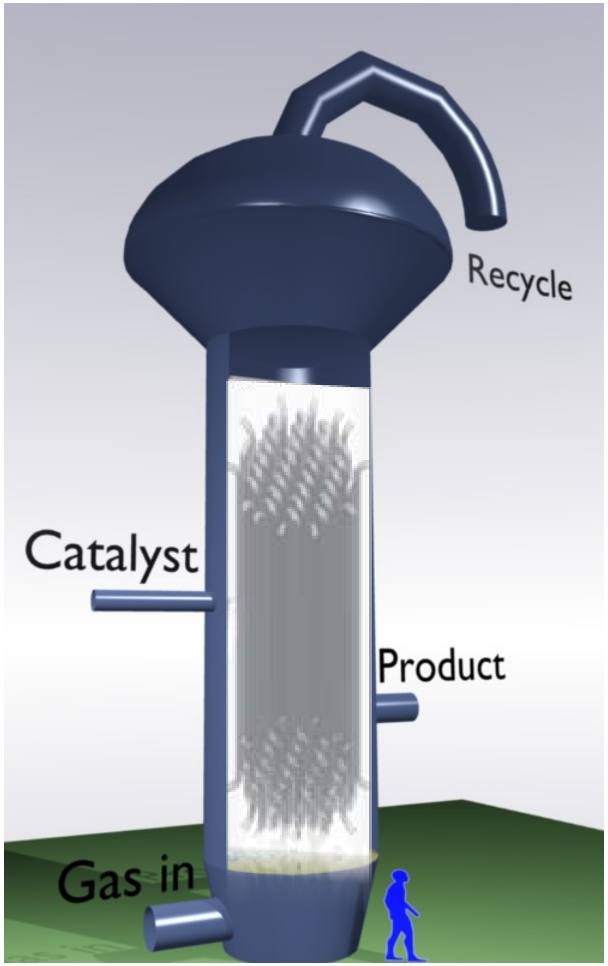
12th August, 2015

Outline

- **Fluidization**
- **Motivation**
- **Two fluid model**
- **Cut-cell method**
- **Geometry configuration**
- **Post processing**
- **Simulations results**
  - Bubble properties
  - Solids motion
- **Conclusions**

Fluidization



Gas-solid contacting in many different processes:

- polymerization
- fluid-catalytic cracking
- dry roasting
- Combustion and gasification
- …

Reactors:

Fluidized bed (fluidization: drag equals weight)

Key characteristics: intrinsically multiscale

- p-p & p-g interactions at 1-5 d_p
- flow structures (10-100 d_p)
- gas-solid behavior (industrial size: many other factor)

Motivation

- In industrial fluidized-bed applications, internals such as heat exchanger tubes and baffles are regularly employed
- Immersed internals modify the gas−solid flow structure and thus may have significant effects on the fluidization
- Complex hydrodynamics in bubbling fluidized beds with immersed internals are still difficult to describe.
- The effectiveness of internals is greatly dependent on their design (horizontal/vertical tubes, packing, baffles…)
- Experimental study of FBs with internals is challenging
- CFD has an advantage to investigate this complex hydrodynamics
- **Supporting CFD study of 1 MW pilot plant at ADA-Inc under CCSI, where internal vertical tubes in the FB acts as a heat exchangers.**

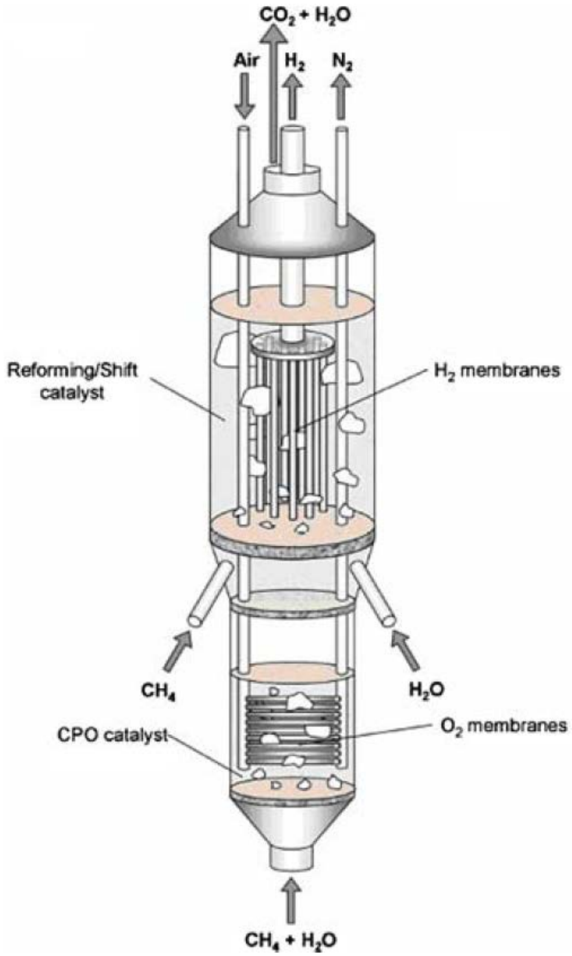


Image reference : J.F. de Jong, PhD Thesis, Eindhoven University of Technology

Two-fluid model

- **Generalized Navier-Stokes equations for interacting continua**

Mass conservation equations

$$\frac{\partial(\varepsilon_g \rho_g)}{\partial t} + \nabla \cdot \left(\varepsilon_g \rho_g \bar{u}_g \right) = 0 \qquad \frac{\partial(\varepsilon_s \rho_s)}{\partial t} + \nabla \cdot \left(\varepsilon_s \rho_s \bar{u}_s \right) = 0$$

Momentum conservation equations

$$\frac{\partial(\varepsilon_g \rho_g \bar{u}_g)}{\partial t} + \nabla \cdot \left(\varepsilon_g \rho_g \bar{u}_g \bar{u}_g \right) = -\varepsilon_g \nabla p_g - \nabla \cdot \left(\varepsilon_g \bar{\bar{\tau}}_g \right) - \beta \left(\bar{u}_g - \bar{u}_s \right) + \varepsilon_g \rho_g \bar{g}$$

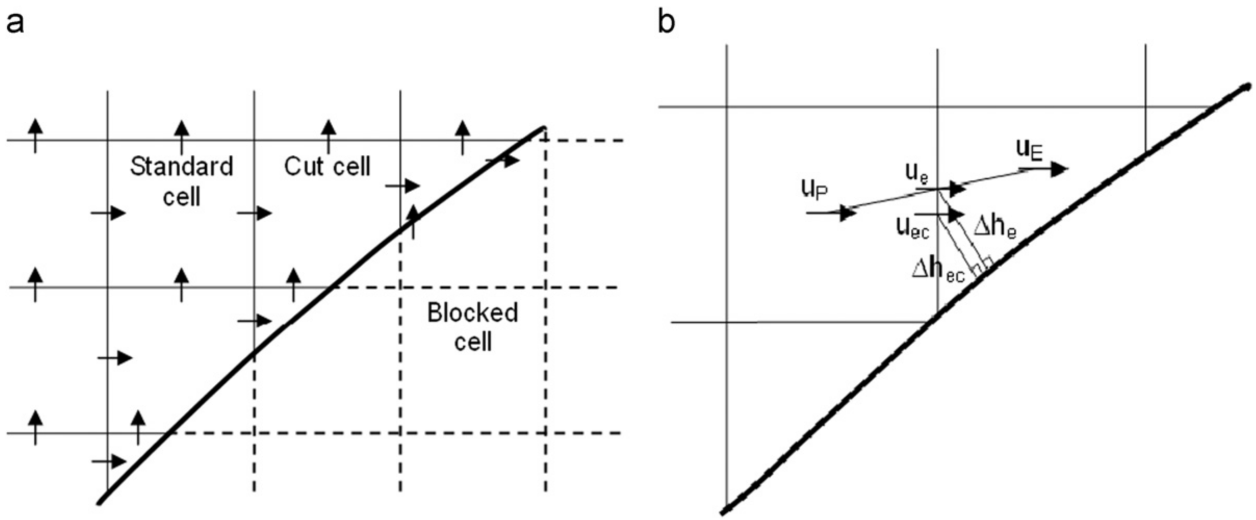
$$\frac{\partial(\varepsilon_s \rho_s \bar{u}_s)}{\partial t} + \nabla \cdot \left(\varepsilon_s \rho_s \bar{u}_s \bar{u}_s \right) = -\varepsilon_s \nabla p_g - \nabla p_s - \nabla \cdot \left(\varepsilon_s \bar{\bar{\tau}}_s \right) + \beta \left(\bar{u}_g - \bar{u}_s \right) + \varepsilon_s \rho_s \bar{g}$$

Granular temperature balances

$$\frac{3}{2}\left[\frac{\partial}{\partial t}(\varepsilon_s \rho_s \Theta) + \nabla \cdot \left(\varepsilon_s \rho_s \Theta \bar{u}_s \right) \right] = -\left(p_s \bar{\bar{I}} + \varepsilon_s \bar{\bar{\tau}}_s \right) : \nabla \bar{u}_s - \nabla \cdot \left(\varepsilon_s q_s \right) - 3\beta\Theta - \gamma$$

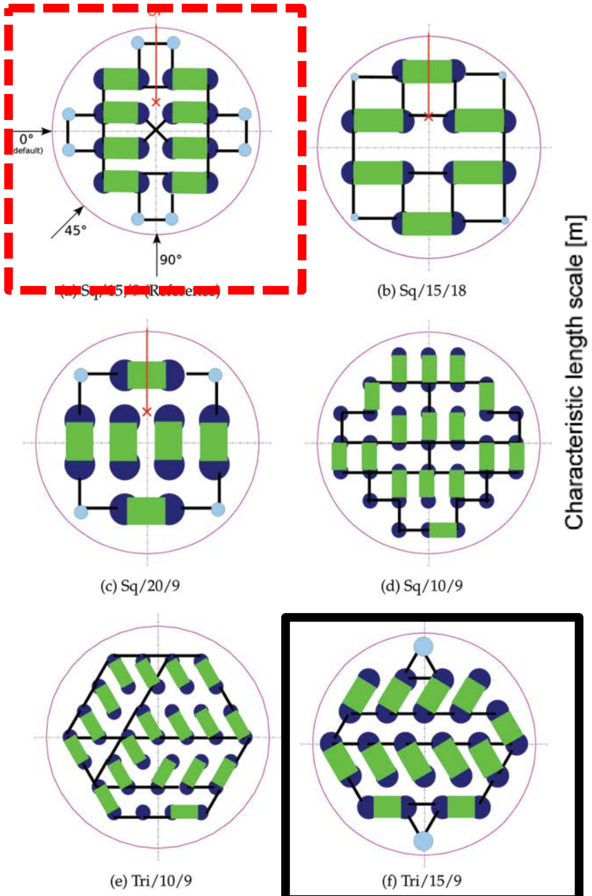
Cut cell method for internal surface

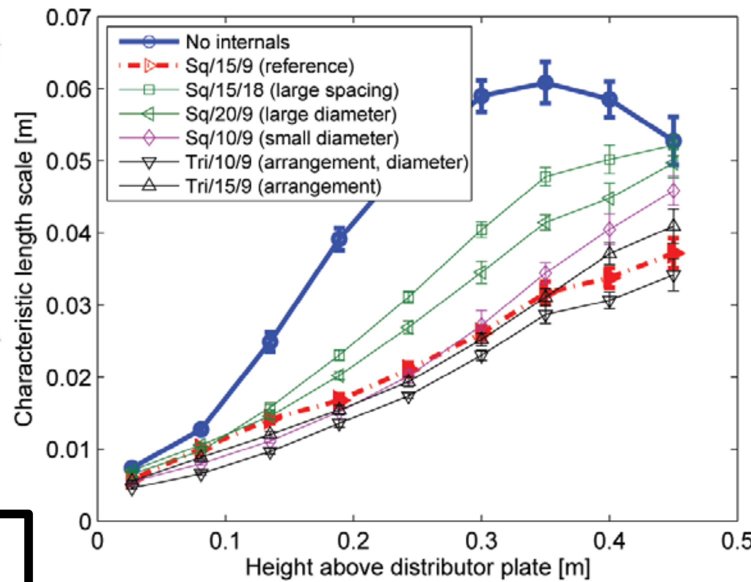
The internal surface (thick solid line) partition computational domain into three types of cells :
(1) standard (uncut) cells;
(2) cut-cells that require special treatment to incorporate the presence of the solid wall/surface (velocity nodes are adjusted to the center of the cut cell)
(3) blocked cells that are excluded from computations since they are located outside the active computational domain.
A no-slip or free-slip velocity boundary condition can be applied for each phase at the wall.



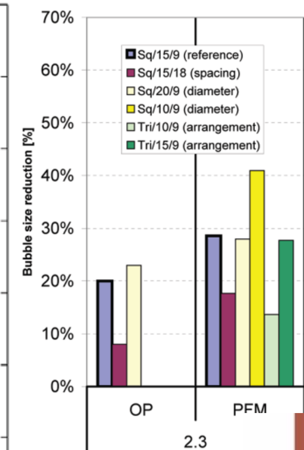
Reference: Dietiker et al., 2009, AIChE Annual Meeting

Experimental work: Rudisuli et al. 2012



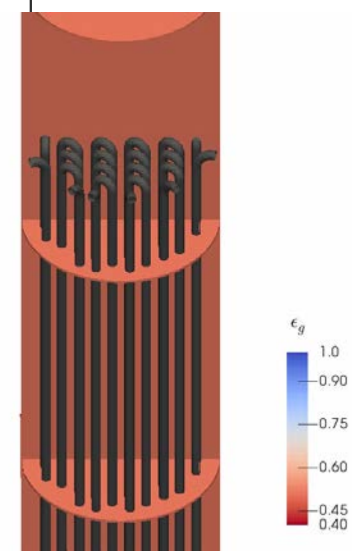


(c) $u_0/u_{mf} = 6.8$

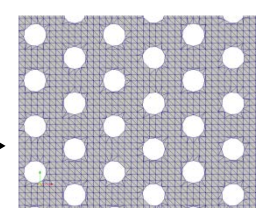


OP: optical probe measur

PFM: Pressure fluctuation



Conf. similar to ADA.inc 1MW pilot plant study



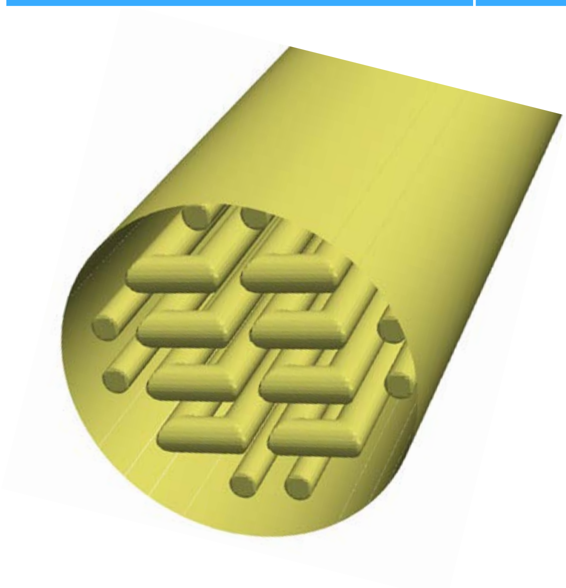
Computational geometry

Fluidized bed configurations

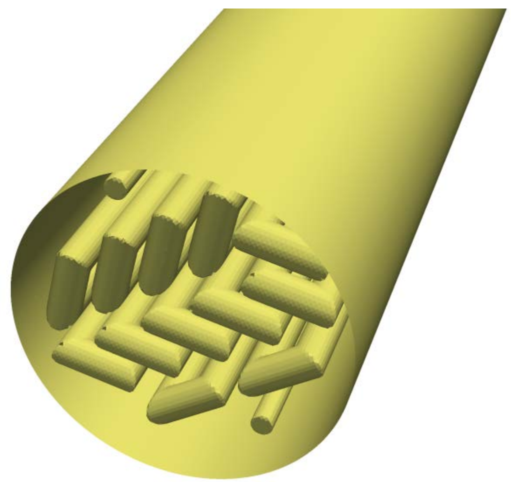
Properties	Without tubes	Sq. arrangement	Tri. arrangement
Column width (number of grids)	0.15 m (100)	0.15 m (100)	0.15 m (100)
Column depth (number of grids)	0.15 m (100)	0.15 m (100)	0.15 m (100)
Column height (number of grids)	0.96 m (640)	0.96 m (640)	0.96 m (640)
Bed diameter from cut-cells	0.145 m	0.145 m	0.145
Number of principal tubes (diameter)	-	16 (15 mm)	24 (15 mm)
Number of auxiliary tubes (diameter)	-	8 (12 mm)	2 (10 mm)

Particle properties

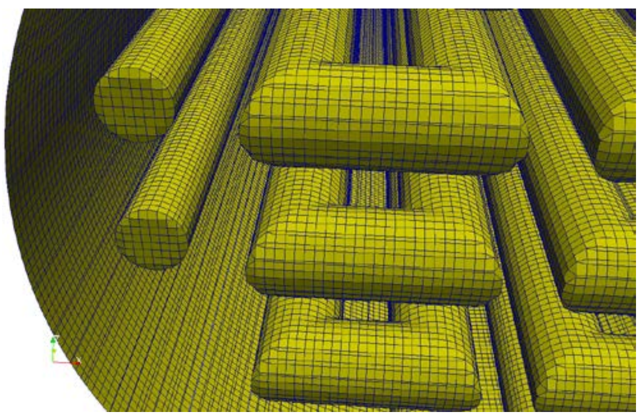
Properties	Values
Particle type	Aluminum oxide
Particle density	1350 kg/m^3
Particle diameter	289μm
Coefficient of restitution	0.90
Minimum fluidizing velocity (U_{mf})	0.041 m/s
Superficial velocity at inlet (U_0)	2.3U_{mf}, 4.5U_{mf}, 6.8U_{mf}



Square arrangement



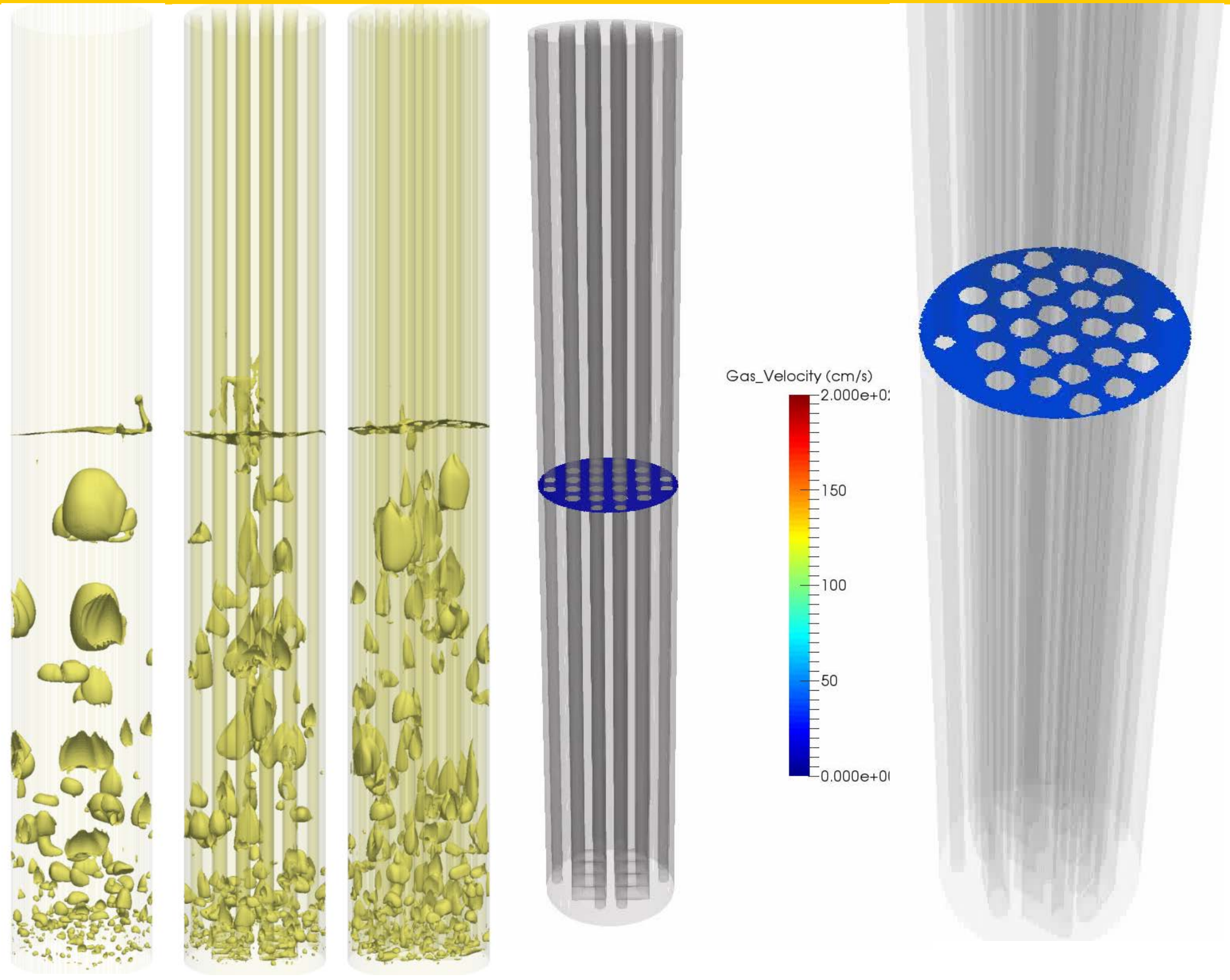
Triangular arrangement



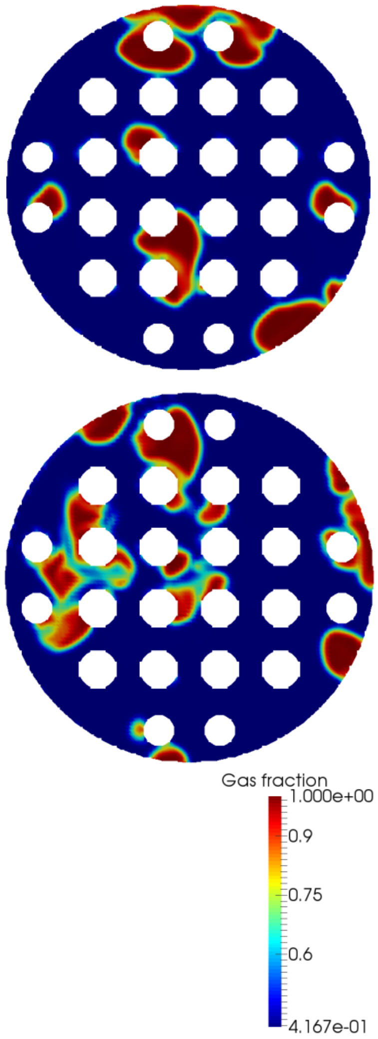
Computational grids

Computational time: Real time of 1 s per day using 128 processors on NETL supercomputers for 6.4 million computational cells
Simulations were performed for 25 s of real time

Snapshots



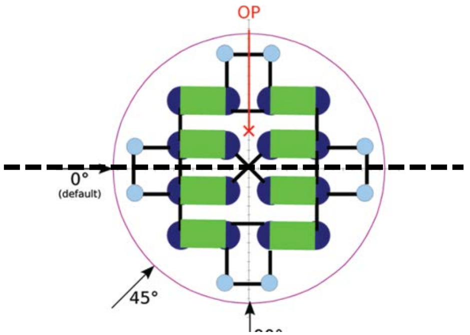
Gas_Velocity (cm/s)
2.000e+02
150
100
50
0.000e+00



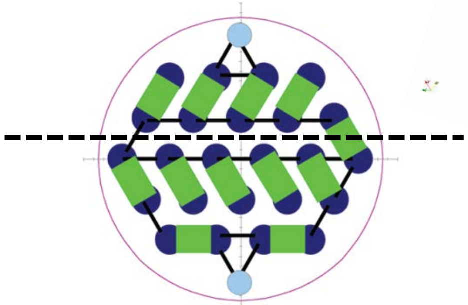
Gas fraction
1.000e+00
0.9
0.75
0.6
4.167e-01

Post processing

Plane of measurements

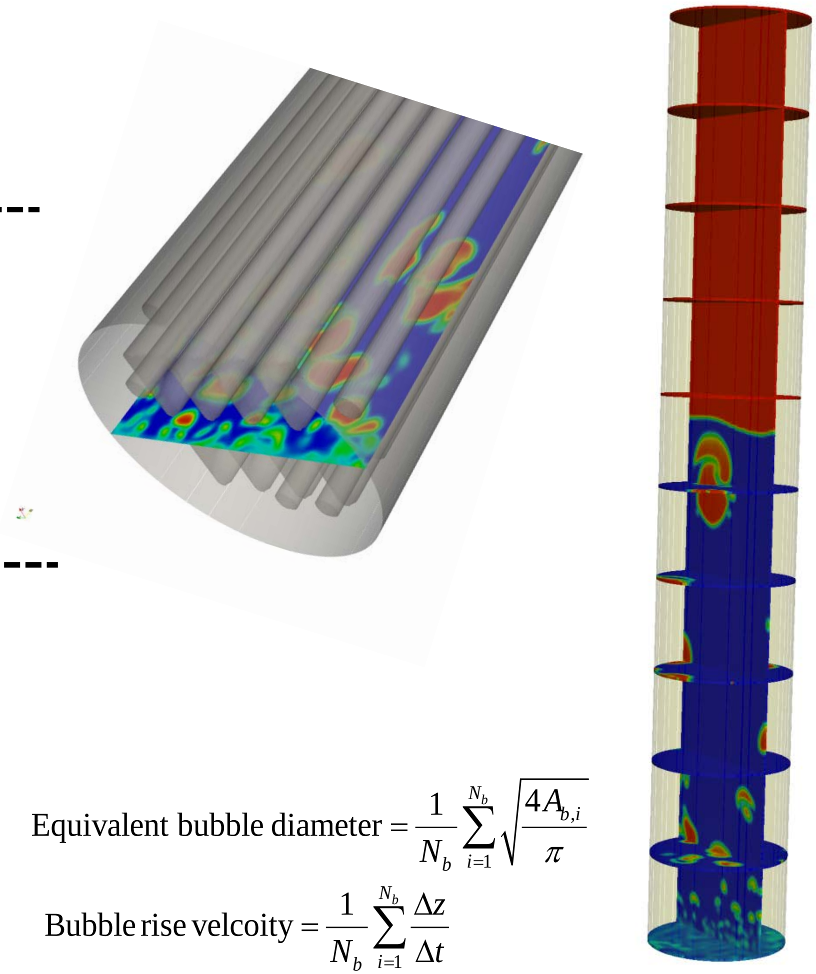


Sq. arrangement



Tri. arrangement

Data storage 3D domain

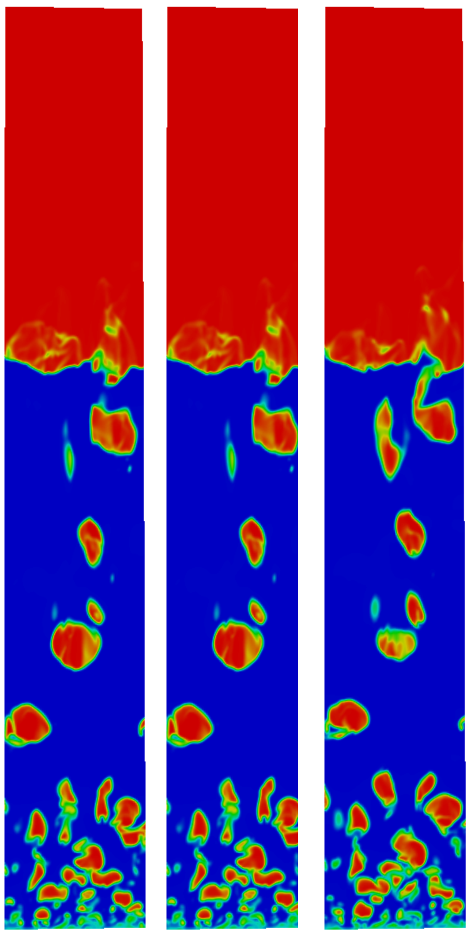


$$\text{Equivalent bubble diameter} = \frac{1}{N_b}\sum_{i=1}^{N_b}\sqrt{\frac{4A_{b,i}}{\pi}}$$

$$\text{Bubble rise velcoity} = \frac{1}{N_b}\sum_{i=1}^{N_b}\frac{\Delta z}{\Delta t}$$

N_b ~ Number of bubble detected

Bubble tracking



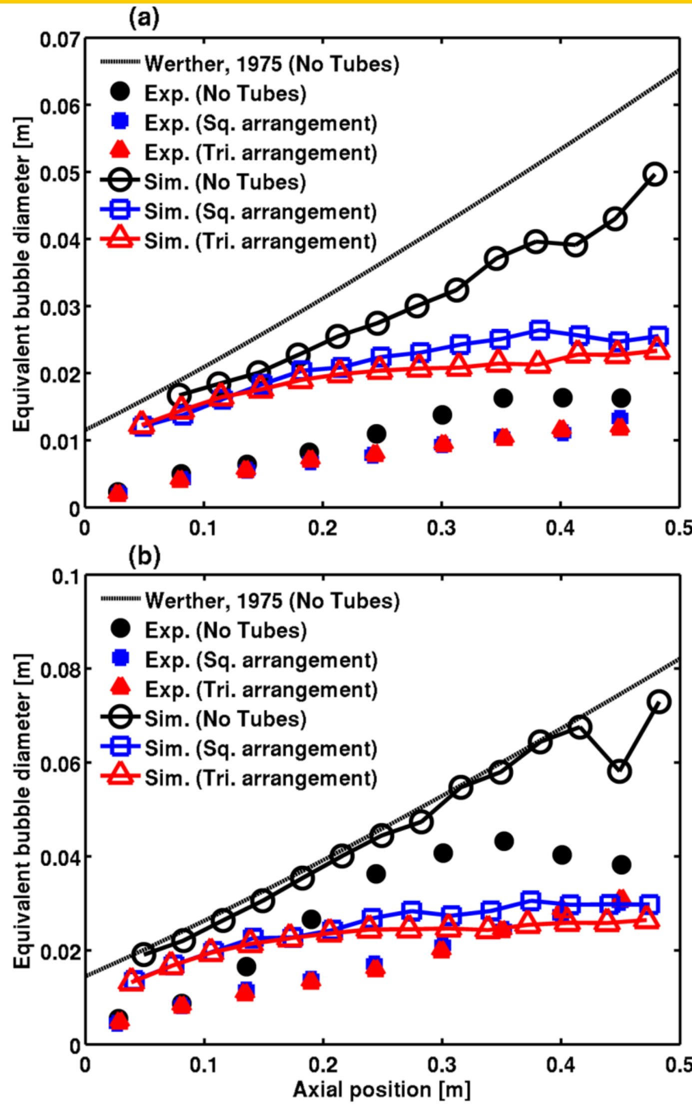
t t+Δt t+2Δt
Where Δt=0.01s

Simulation Results

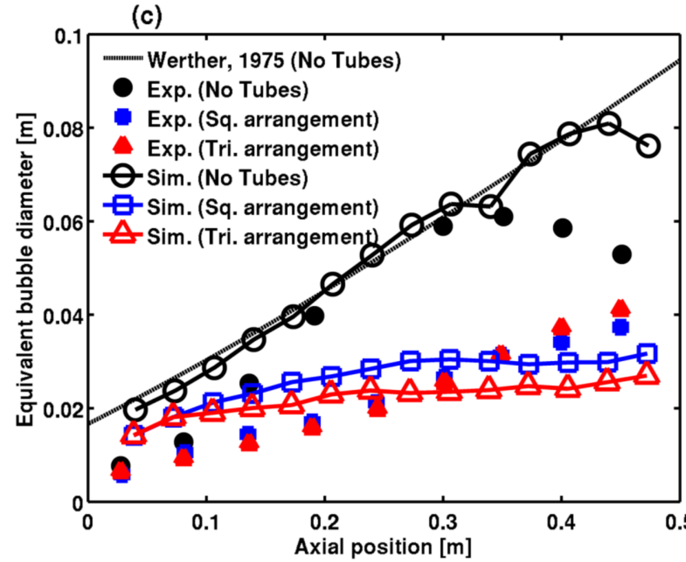
Equivalent bubble diameter

U/U_{mf}=2.3

U/U_{mf}=4.5



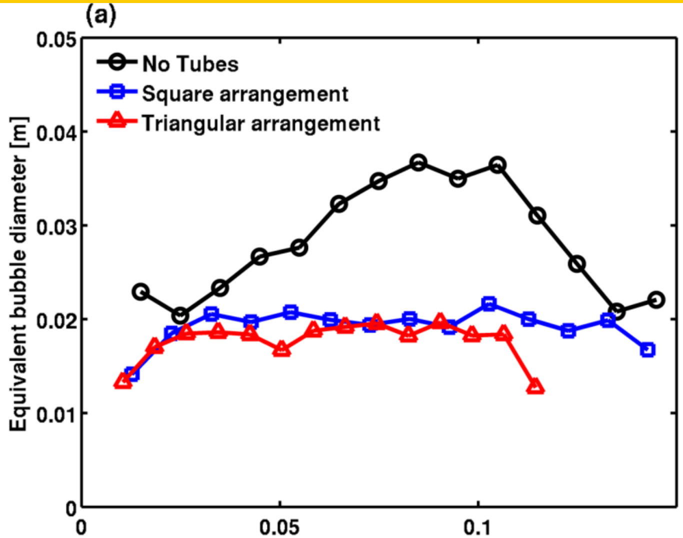
U/U_{mf}=6.8



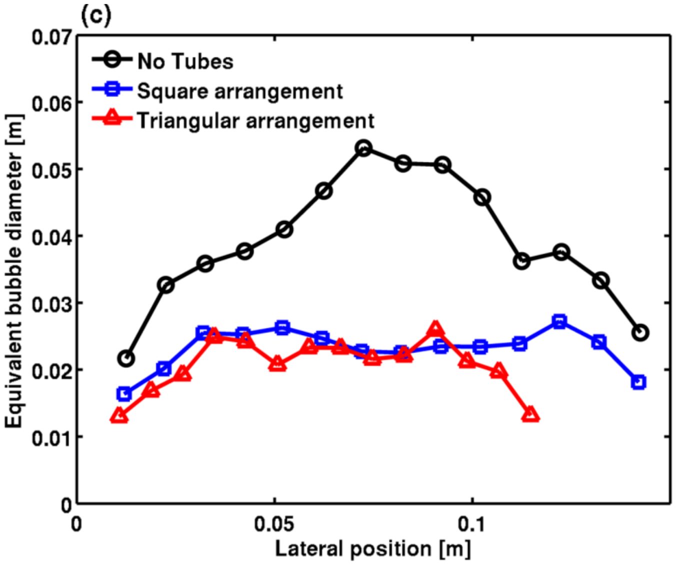
- ✓ Predicted bubble size for no tube is in good agreement with literature correlation of Werther
- ✓ Bubble size decreases with the effect of vertical tubes
- ✓ Sim. and Exp. results are in good agreement for the higher inlet gas velocities of U/Umf = 4.8 and 6.8
- ✓ At U/Umf = 2.3 Exp. results are under predicted, considering Sim. result in a close agreement with bubble size correlation of Werther

Equivalent bubble diameter

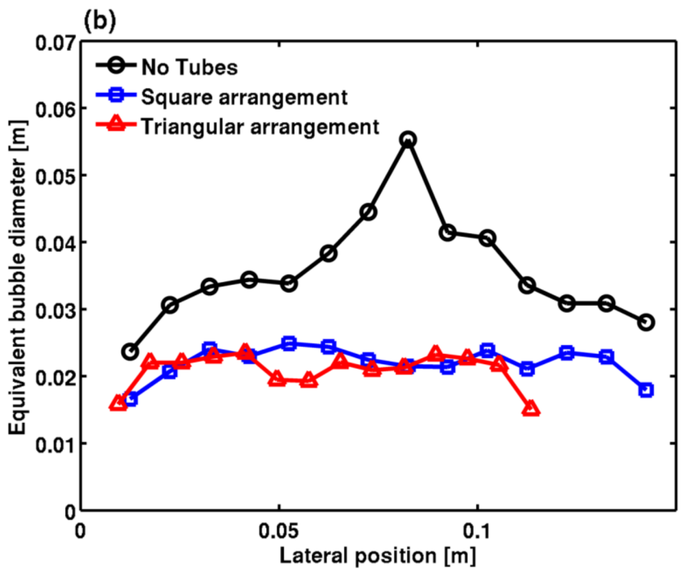
U/U_{mf}=2.3



U/U_{mf}=6.8



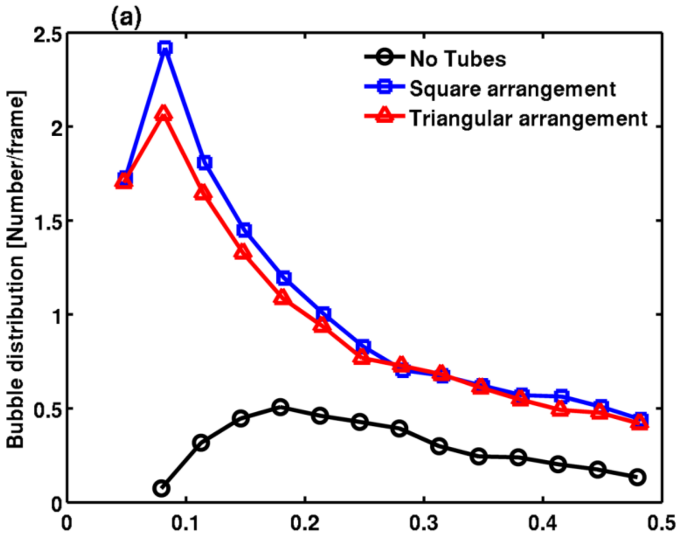
U/U_{mf}=4.5



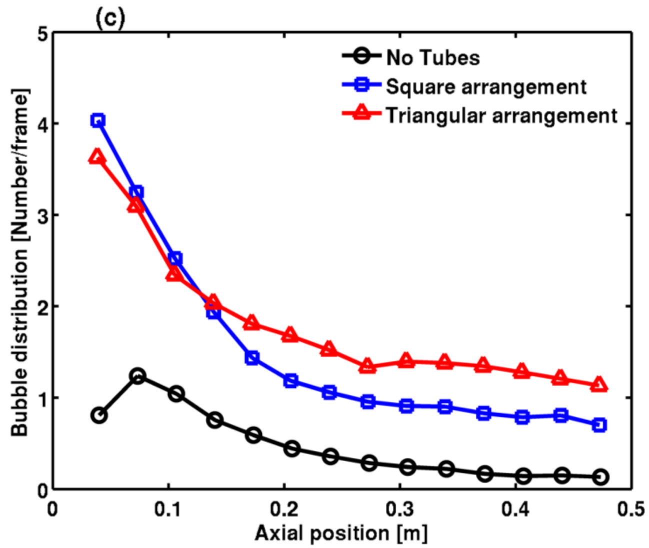
- ✓ Bubble size is larger in the center for No tubes
- ✓ Uniform bubble size predicted across the bed diameter when there are vertical tubes in the bed
- ✓ Vertical tubes prevent coalescence and also promote larger bubbles to split
- ✓ Slugging of bubbles can be prevented using vertical tubes, enhances quality fluidization

Bubble distribution

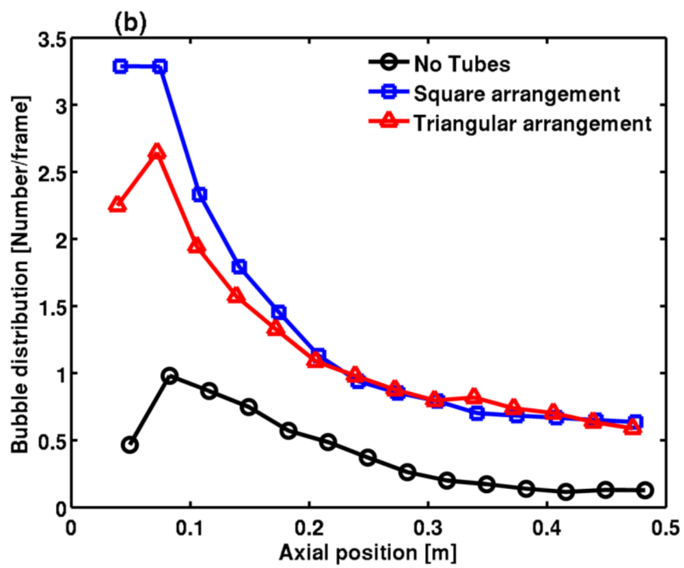
U/U_{mf}=2.3



U/U_{mf}=6.8



U/U_{mf}=4.5

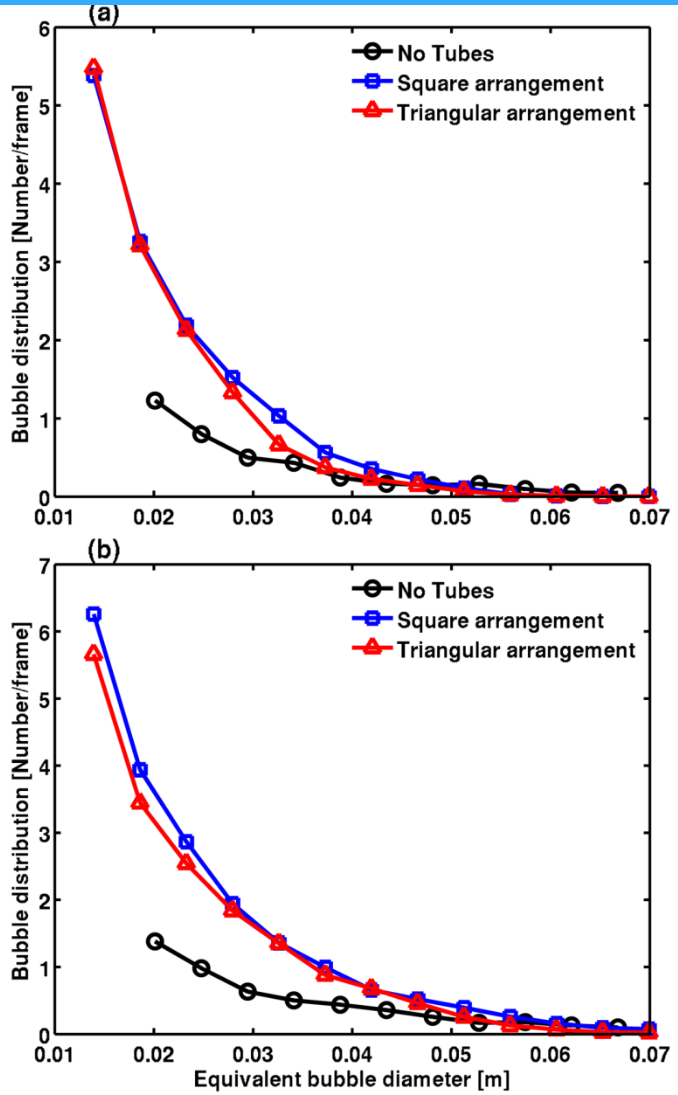


- ✓ For vertical tubes inside, large number of bubbles are predicted throughout the height
- ✓ Significantly more bubbles are predicted in the bottom section of the bed
- ✓ U-shape bank prevents bubble coalescence at the initial stage as the bubble grows
- ✓ Square tube arrangement create parallel chambers for the bubble to rise, hence efficient in preventing bubble coalescence
- ✓ Triangular tube forms staggered alignment of the tubes, promote splitting of larger bubbles

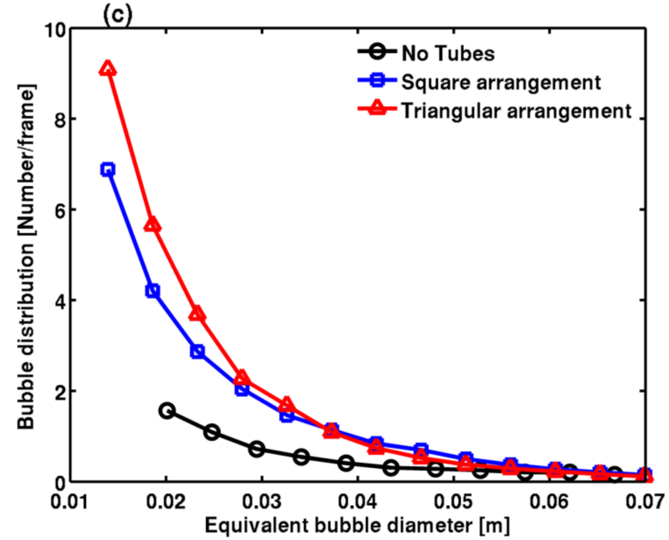
Bubble distribution

$U/U_{mf}=2.3$

$U/U_{mf}=4.5$



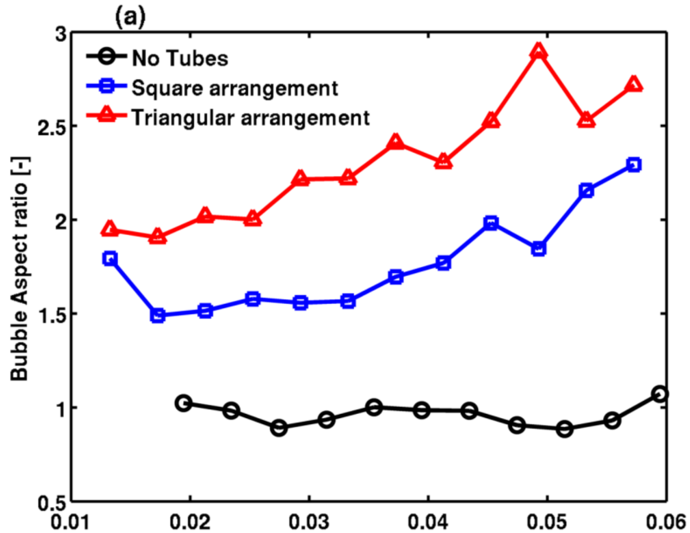
$U/U_{mf}=6.8$



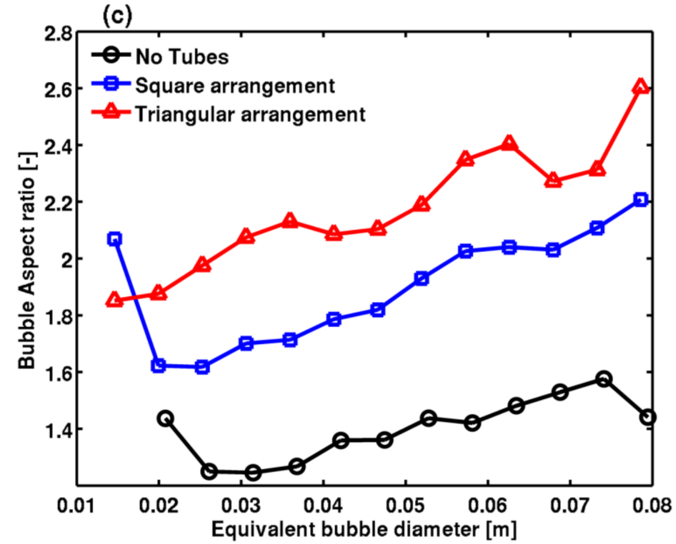
- ✓ Number of small bubbles in the bed is significantly greater for the beds with vertical tubes when compared to the bed with no tubes
- ✓ The number of larger bubbles is similar for both tube arrangements indicating that bubble size is unaffected if it is sufficiently large compared to the tube spacing

Bubble shape/Aspect ratio

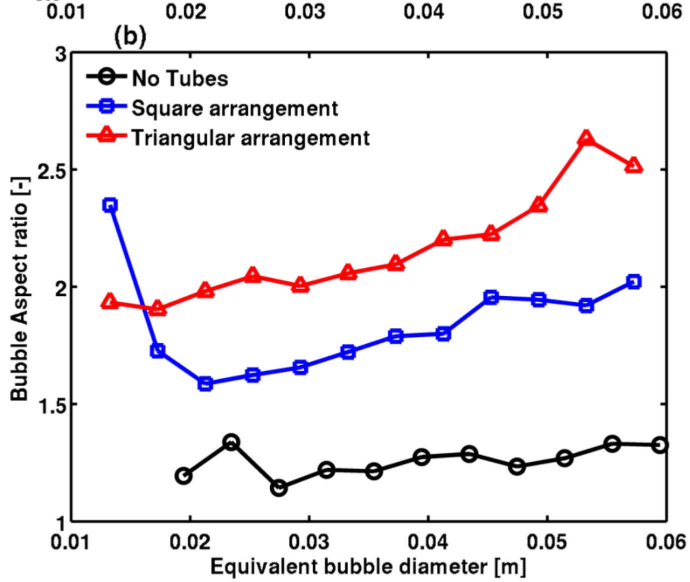
U/U_{mf}=2.3



U/U_{mf}=6.8



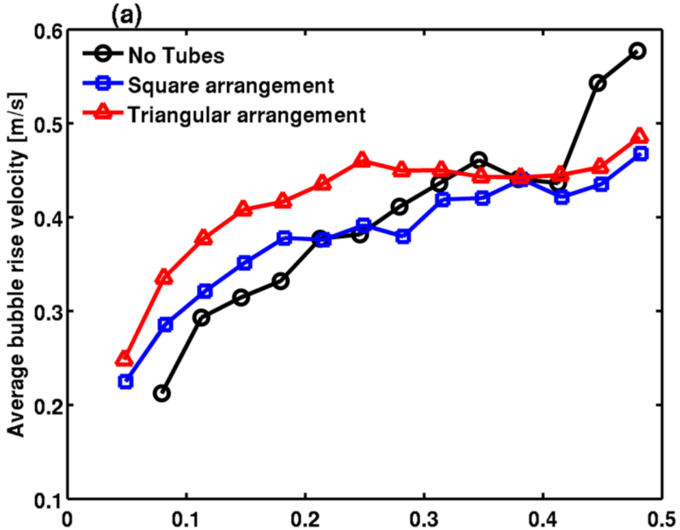
U/U_{mf}=4.5



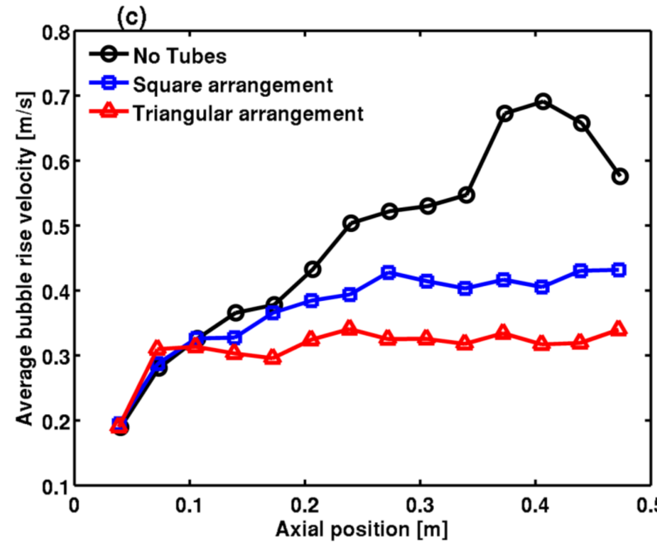
- ✓ The shape of the bubble is estimated from the bubble aspect ratio, i.e. ratio of vertical length to the horizontal length of the bubble
- ✓ For no tubes, bubbles are nearly spherical in shape.
- ✓ Bubbles elongate significantly under the influence of vertical tubes
- ✓ The initial effect of vertical tubes is to squeeze and deform bubbles to fit the space between the tubes
- ✓ Tri. tube arrangements shows considerable difference when compared with Sq. tube arrangement

Average bubble rise velocity

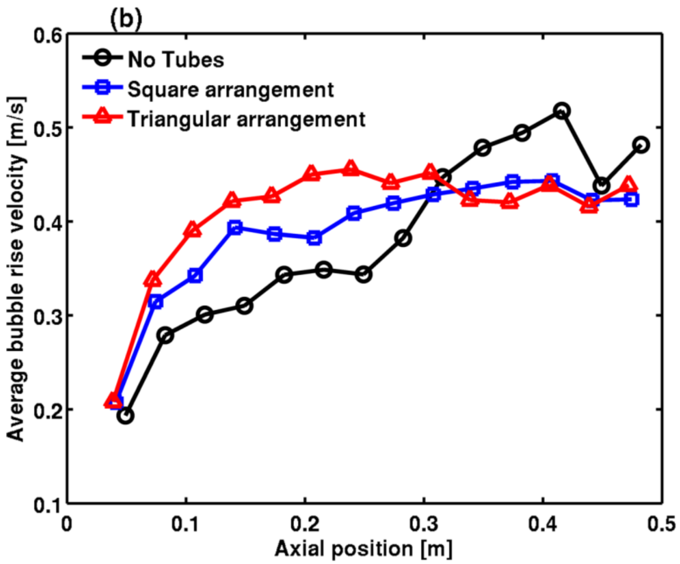
U/U_{mf}=2.3



U_{mf}=6.8



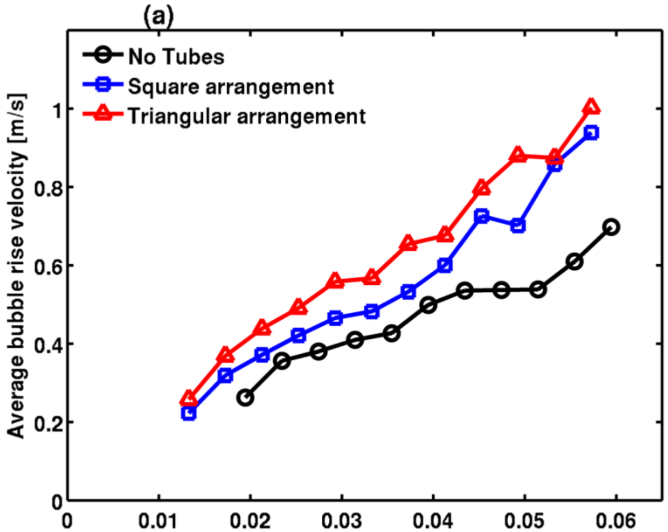
U/U_{mf}=4.5



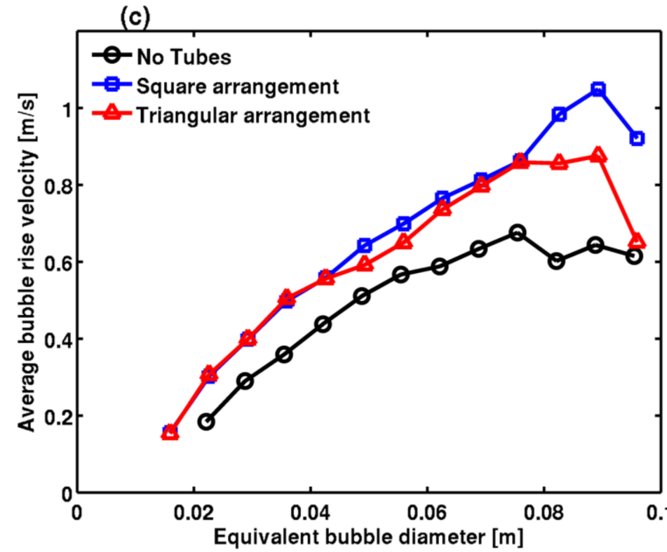
- ✓ Bubble rise velocity shows an increasing trend in the presence of tubes for lower inlet gas velocity
- ✓ At low inlet gas velocities bubble size is comparable to the tube spacing, therefore considerable squeeze occurs between the tubes and bubbles rise faster
- ✓ Squeezing of bubble between the tubes, the centroid of bubble moves a longer distance than uniform size bubble
- ✓ At higher gas velocities, bubble sizes are large enough that they enclose the tube and rise along the tube walls

Average bubble rise velocity

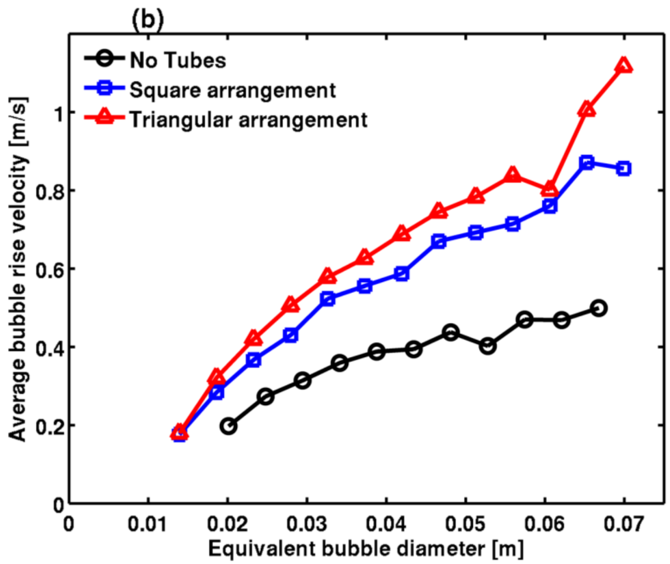
U/U_{mf}=2.3



U/U_{mf}=6.8

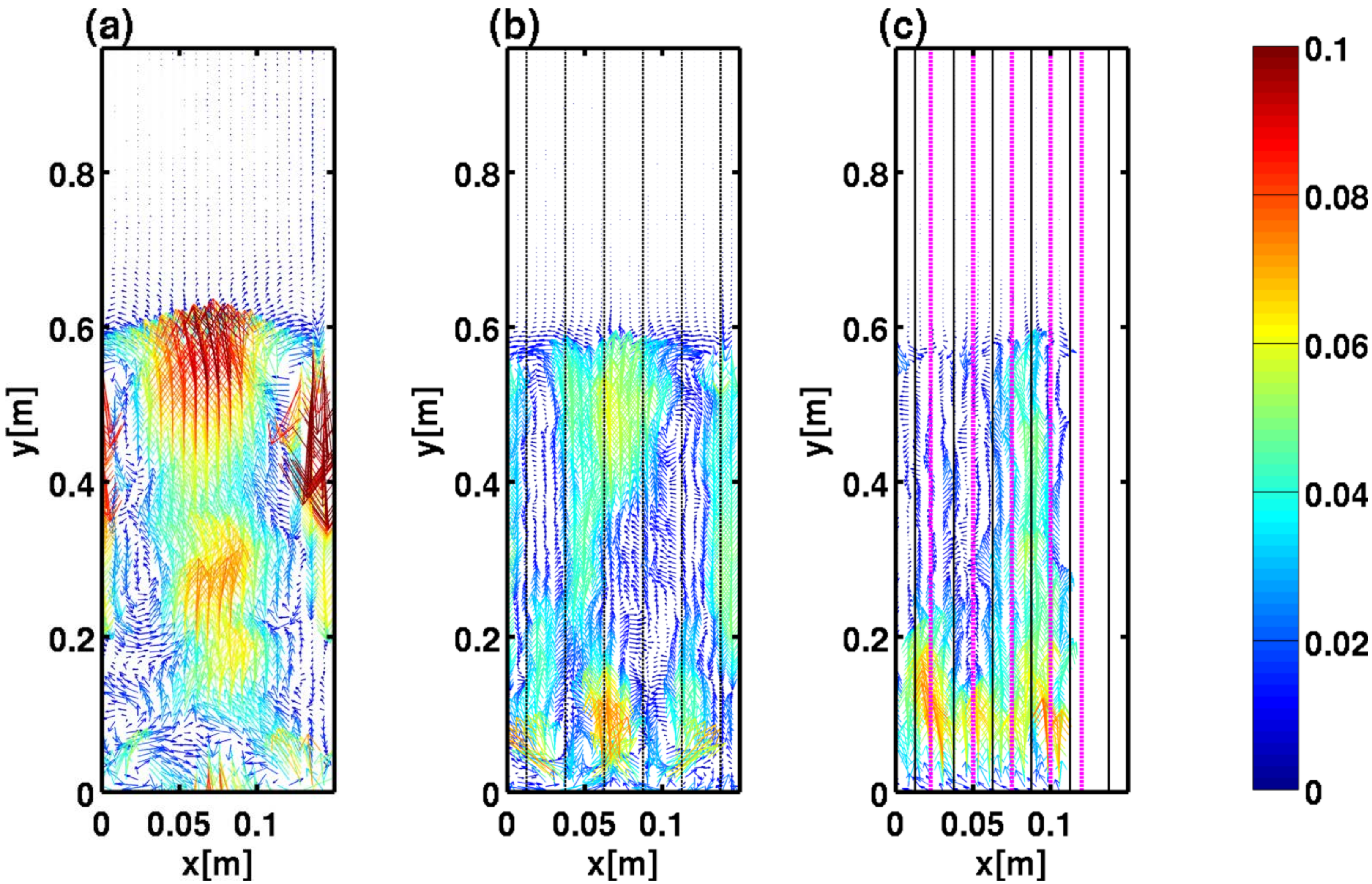


U/U_{mf}=4.5



- ✓ Bubbles of the same size rise with different velocities, where bubbles travel faster in the bed with tubes
- ✓ Because the bubble is elongated and follows preferential path along the vertical tubes
- ✓ Bubble rise velocity in the bed with tubes depends upon fluidizing gas velocity and tube arrangements

Solids circulations

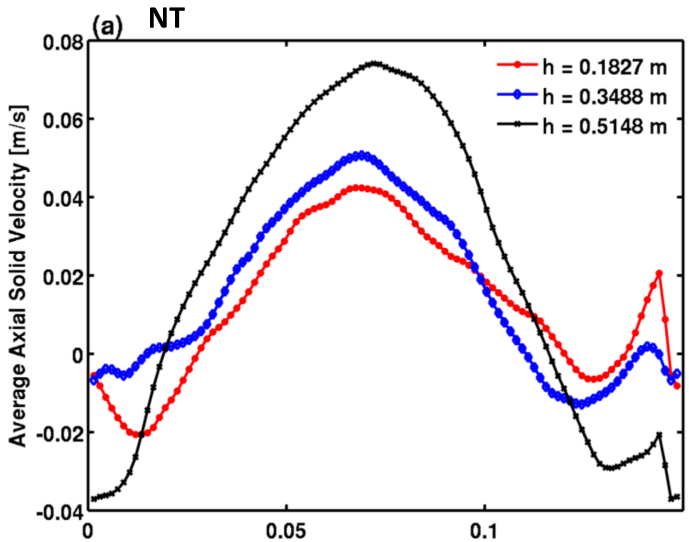


NT

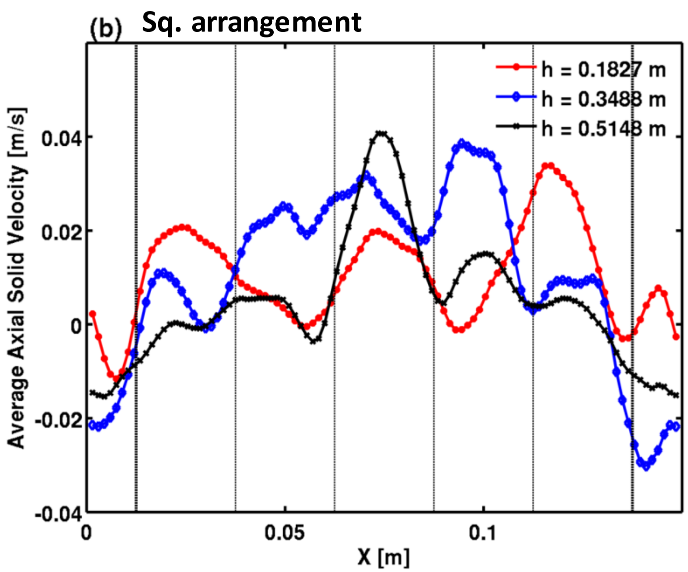
Sq. arrangement

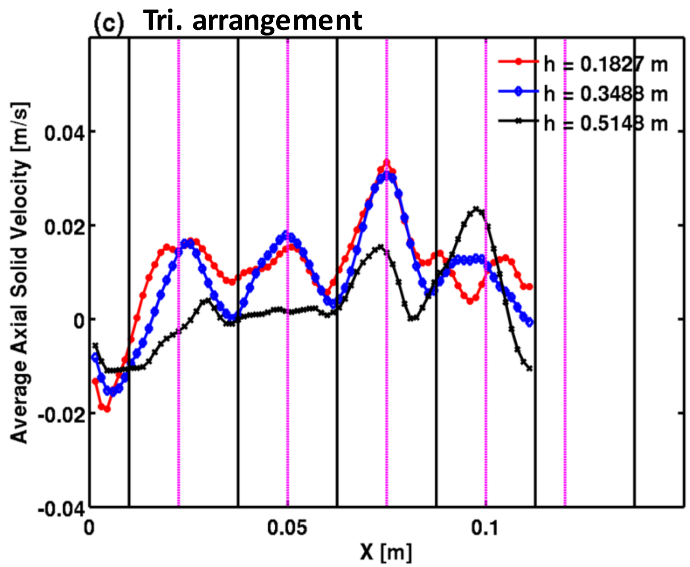
Tri. arrangement

Solids velocity profile



- ✓ Upward motion of solids in the center and downward motion near to the walls for no tubes.
- ✓ For tubes higher solids velocities lie in the region between the tubes.
- ✓ The magnitude of solids velocities is nearly the same at these three heights for vertical tubes.





Conclusions

- ✓ The influence of vertical tubes on bubble characteristics and solids motion in a fluidized bed has been investigated using the MFIX two-fluid model
- ✓ A comparison of simulation results with experimental data shows good agreement
- ✓ Square and triangular tube arrangements have been compared to the bed without tubes
- ✓ A decrease in equivalent bubble diameter and a uniform distribution of bubble are seen for the bed with vertical tubes
- ✓ Simulation results show that the square tube arrangement forms longitudinal, parallel chambers that prevent bubble coalescence
- ✓ Triangular tubes are in a staggered arrangement, they promote bubble splitting
- ✓ Splitting and squeezing of bubbles between the tubes their shapes change significantly, becoming more elongated and travel faster
- ✓ Differences in solids circulation patterns are very distinct for the three bed configurations
- ✓ Solids motion is rarely seen in the radial direction because the vertical tubes prevent lateral solids motion

Acknowledgements

CCSI

Carbon Capture Simulation Initiative

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Thank you

Questions ?

Disclaimer