Comparing different techniques to evaluate solids suspension flow in pipes and assessment through simulation

R. Silva (University of Coimbra), P. Faia (University of Coimbra), F. Garcia (University of Coimbra), F. Lundell (KTH Stockholm), M.G. Rasteiro (University of Coimbra)

Presenter: M.G. Rasteiro (University of Coimbra)

22-24th of October, 2014, Caen, France

Project supported by COST - European Cooperation in Science and Technology

COST FP1005 "Fibre Suspension Flow Modelling"

EUROPEAN COOPERATION IN SCIENCE AND TECHNOLOGY

Synopsis

The results presented here are a combination of experimental data acquired at KTH Mechanics during a two month period and numerical simulations using a Mixture Model with a standard k-ε Turbulence model.

- two sizes of glass beads (0.1-0.2mm and 0.4-0.6mm) were added with increasing volume fractions to a flow loop (Figure 1) where velocity profile measurements where done with both UPV and MRI apparatus (Figures 2 and 3).

- two different pipe diameters were studied, 34mm and 50mm. With the 50 mm pipe experiments, only the bigger particles (0.4-0.6 mm) were used In addition to the MRI and UVP data, EIT measurements (Figure 4) were also conducted to supply information about the solids distribution in the pipe.

Figure 1 – Flow Loop

Figure 2 – UPV Probes

Figure 3 – MRI apparatus

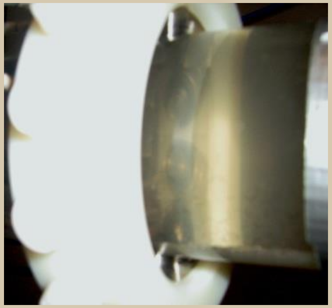

Figure 4 – EIT Electrodes Ring

Mixture Model

It is based on the following assumptions:

→ local equilibrium is established over a short spatial length scale;
→ the density of each phase is approximately constant;
→ both phases share the same pressure field;
→ the relative velocity between phases is determined considering equilibrium between pressure, gravity and viscous drag.

MOMENTUM EQUATION

$$\rho u_t + \rho(u \cdot \nabla)u = -\nabla p - \nabla \cdot \left((\rho c_d (1 - c_d)) u_{SLIP} u_{SLIP} \right) + \nabla \cdot \tau_{Gm} + \rho g + F$$

MIXTURE CONTINUITY EQUATION

$$\rho_c - \rho_d \left[\nabla \cdot (\phi_d (1 - c_d) u_{SLIP} - D_{md} \nabla \phi_d) + \frac{m_{dc}}{\rho_d} \right] + \rho_c (\nabla \cdot u) = 0$$

RELATIVE PHASES VELOCITY EQUATION

$$u_d - u_c = u_{cd} = u_{SLIP} - \frac{D_{md}}{(1 - c_d)} \nabla \phi_d$$

SCHILLER-NAUMANN DRAG CORRELATION

$$C_D = \begin{cases} \frac{24}{Re_p}(1 + 0.15 Re_p^{\,0.687}) & Re_p < 1000 \\ 0.44 & Re_p > 1000 \end{cases}$$

Standard k-ε Turbulence Model Closure

Turbulent Eddy Viscosity Equation

$$\mu_T = \rho\, C_\mu \frac{k^2}{\varepsilon}$$

Turbulent Kinetic Energy Equation

$$\rho \frac{\partial k}{\partial t} + \rho u \cdot \nabla k = \nabla \cdot \left(\left(\mu + \frac{\mu_T}{\sigma_k} \right) \nabla k \right) + \mu_T \left(\nabla u : \left(\nabla u + (\nabla u)^T \right) - \frac{2}{3} (\nabla \cdot u)^2 \right) - \frac{2}{3} \rho\, k\, \nabla \cdot u - \rho\, \varepsilon$$

Turbulent Dissipation Rate Equation

$$\rho \frac{\partial \varepsilon}{\partial t} + \rho u \cdot \nabla \varepsilon = \nabla \cdot \left(\left(\mu + \frac{\mu_T}{\sigma_\varepsilon} \right) \nabla \varepsilon \right) + C_{\varepsilon 1} \frac{\varepsilon}{k} \mu_T \left(\nabla u : \left(\nabla u + (\nabla u)^T \right) - \frac{2}{3} (\nabla \cdot u)^2 \right) - \frac{2}{3} \rho\, k\, \nabla \cdot u - C_{\varepsilon 2} \frac{\varepsilon^2}{k}$$

Turbulent Eddy Diffusion Coefficient Equation

$$D_{md} = \frac{\mu_T}{\rho\, \sigma_T}$$

Standard Closure Coefficents	
$C_{\varepsilon 1}$	1.44
$C_{\varepsilon 2}$	1.92
C_μ	0.09
σ_k	1.0
σ_ε	1.3

0.1-0.2 mm Particles

Normalized MRI , UPV & Numerical Velocity Profiles for a Pipe Diameter of 34mm

0.1-0.2 mm particles

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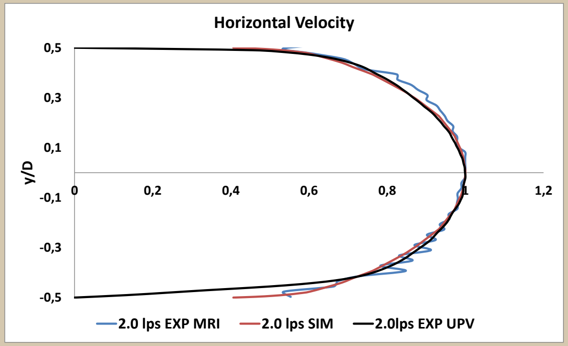
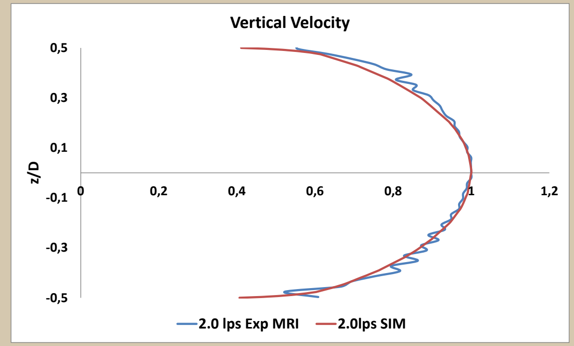
ϕ = 0.5 % (v/v)

Q = 2.0 l/s





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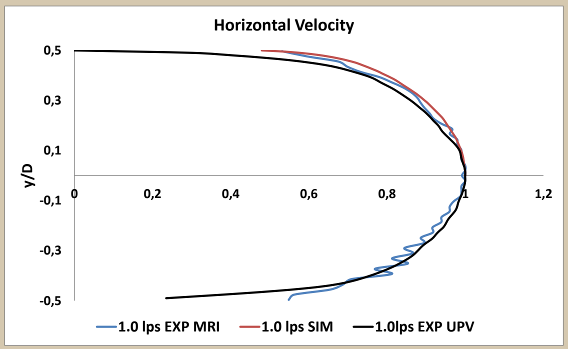
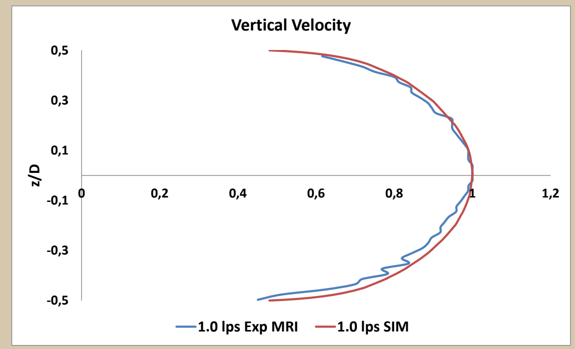
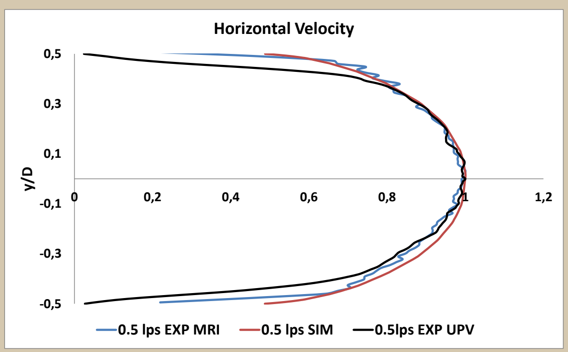
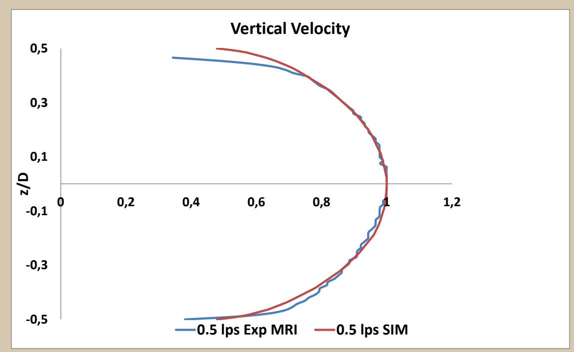




Q = 0.5 l/s



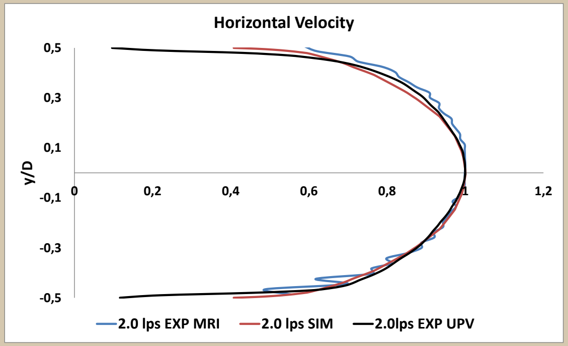


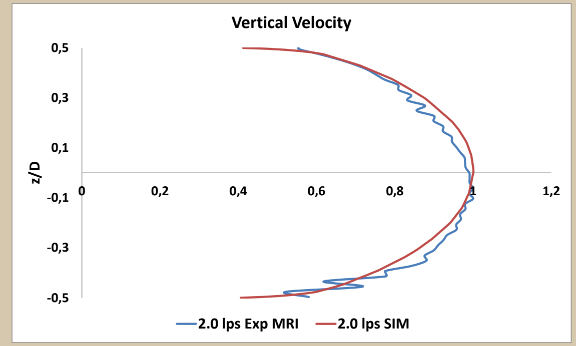
Normalized MRIUPV & Numerical Velocity Profiles for a Pipe Diameter of 34mm

0.1-0.2 mm particles

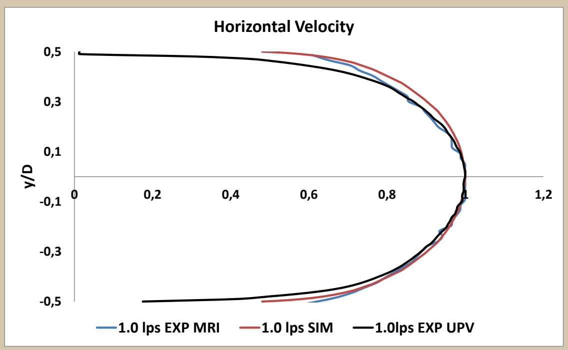
ϕ = 3.0 % (v/v)

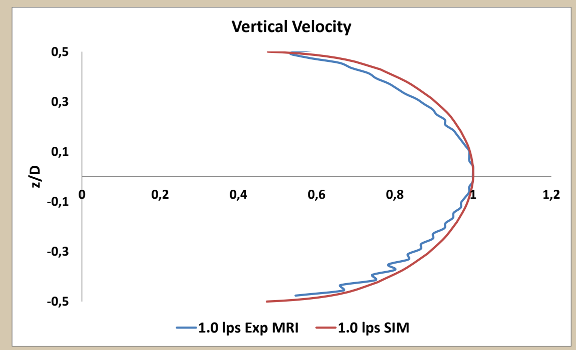
Q = 2.0 l/s



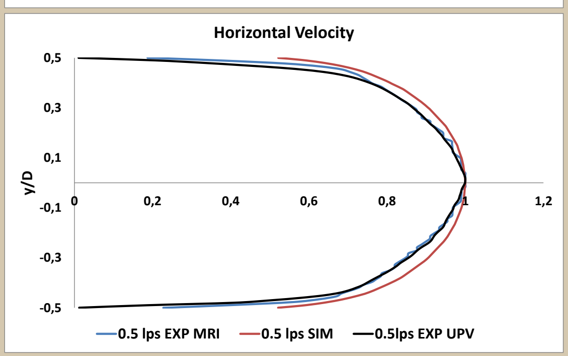


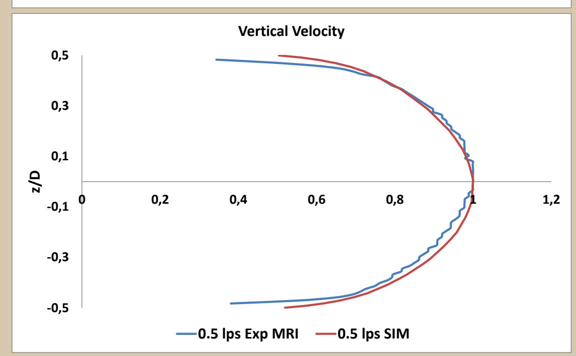
Q = 1.0 l/s





Q = 0.5 l/s

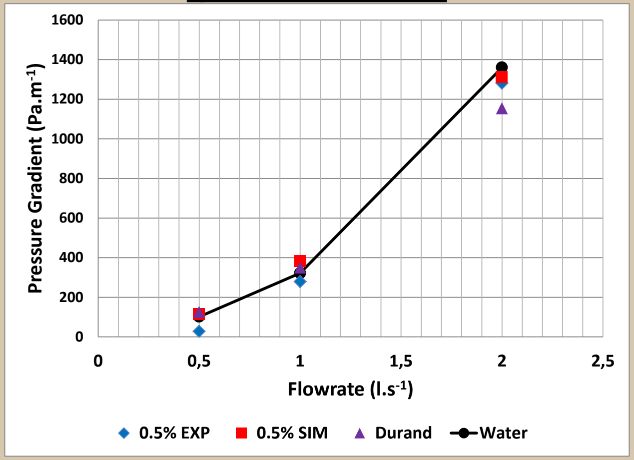




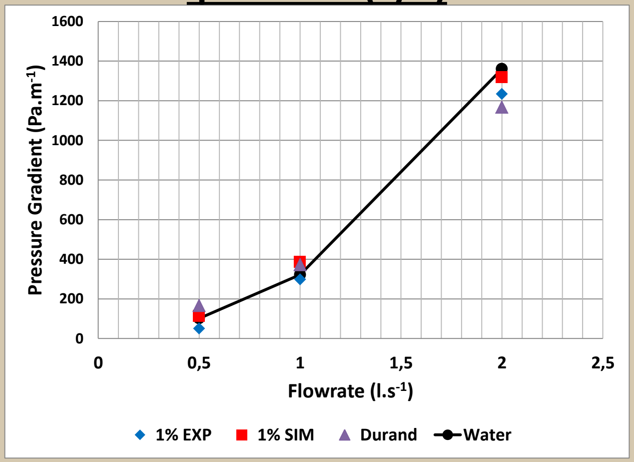
Numerical vs. Experimental Pressure Drop Profiles for a Pipe Diameter of 34mm

0.1-0.2 mm particles

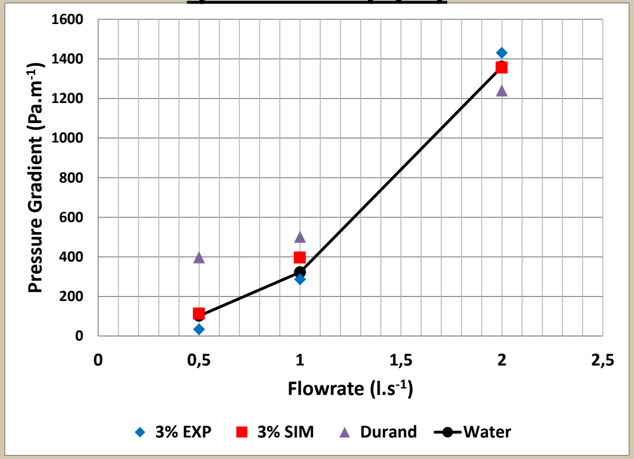
ϕ = 0.5 % (v/v)



ϕ = 1.0 % (v/v)



ϕ = 3.0 % (v/v)



- The normalized velocity profiles seem to match quite well for both UPV and MRI. The numerical results reproduce well the experimental data, thus validating the Mixture Model with a standard k-ε turbulence closure as adequate choice for modelling solid-liquid flows for particle sizes of 0.1-0.2 mm, for the concentrations tested;

- The pressure drop profiles seem to agree quite well with the experimental ones. There are some deviations but nothing significant;

0.4-0.6 mm Particles

(34 mm pipe)

Normalized MRI, UPV & Numerical Velocity Profiles for a Pipe Diameter of 34mm

0.4-0.6 mm particles

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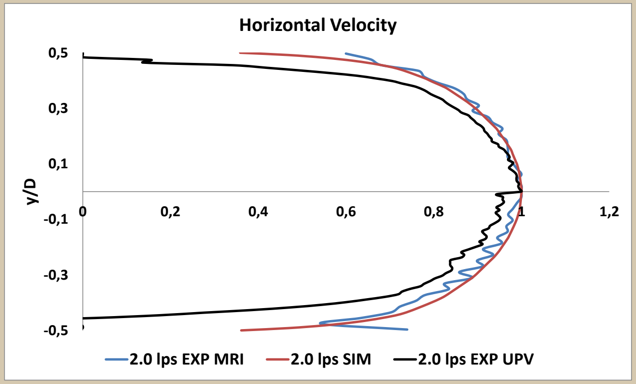
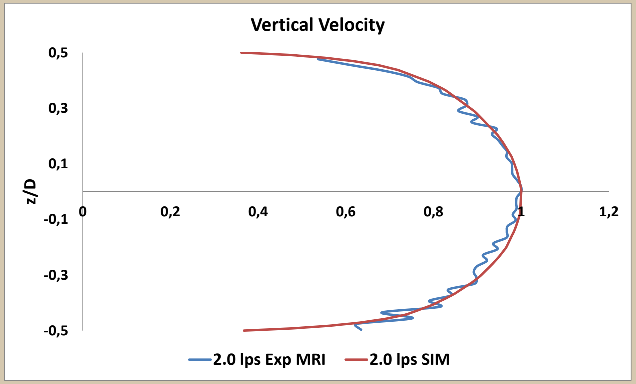
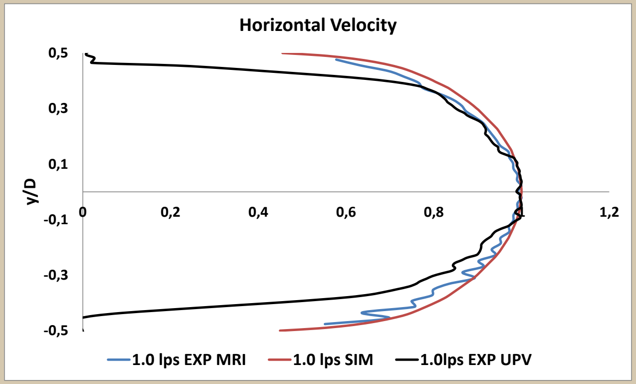
ϕ = 0.5 % (v/v)

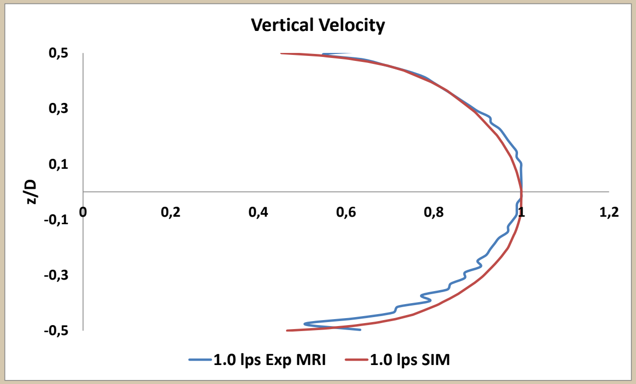
Q = 2.0 l/s





Q = 1.0 l/s





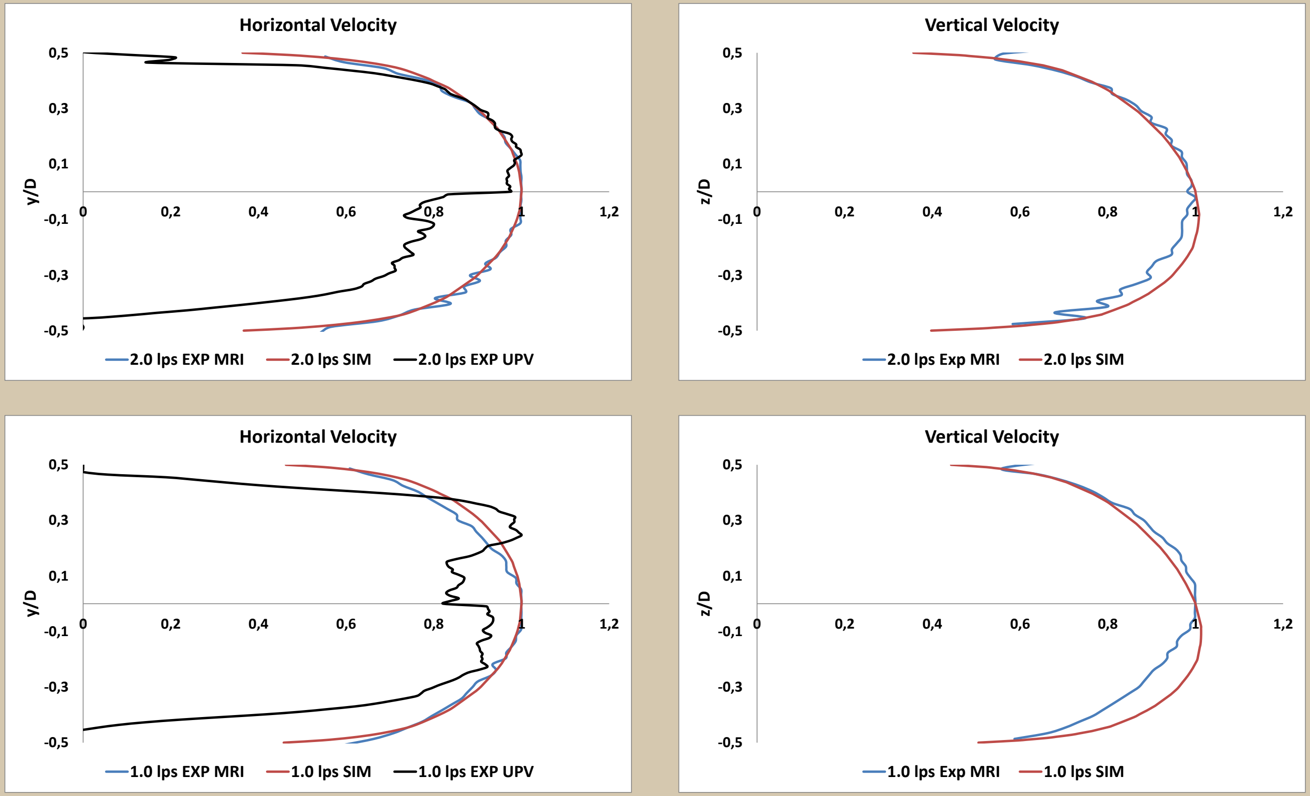
Normalized MRI, UPV & Numerical Velocity Profiles for a Pipe Diameter of 34mm

0.4-0.6 mm particles

ϕ = 3.0 % (v/v)

Q = 2.0 l/s

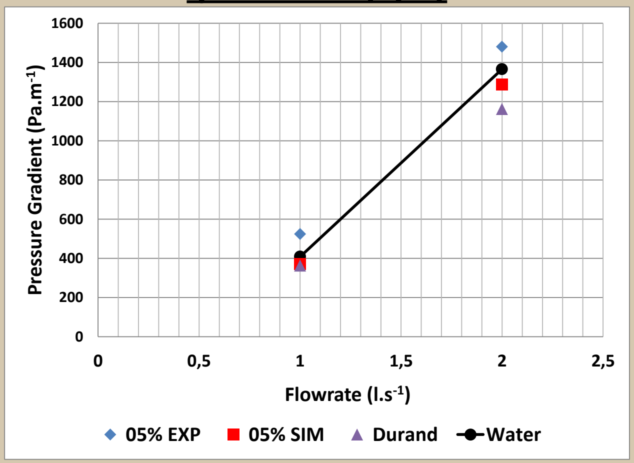
Q = 1.0 l/s



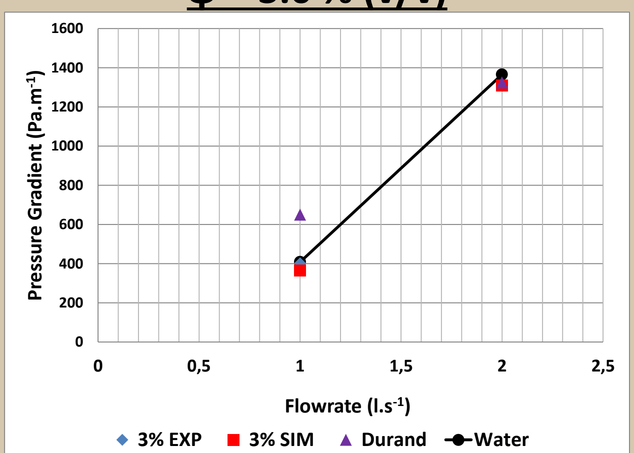
Numerical vs. Experimental Pressure Drop Profiles for a Pipe Diameter of 34mm

0.4-0.6 mm particles

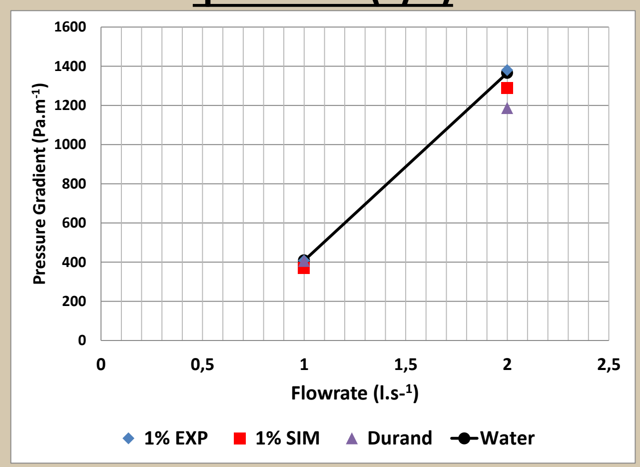
ϕ = 0.5 % (v/v)



ϕ = 3.0 % (v/v)



ϕ = 1.0 % (v/v)



Numerical vs. Experimental Profiles for a Pipe Diameter of 34mm

0.1-0.2 mm particles

- **The UPV profiles seem to deteriorate with increasing particle concentration, becoming reliable mostly near the pipe wall. This can be attributed to the offset in the angle of one of the probes but also to attenuation of the probes signal due to the increasing amount of particles;**

- **The normalized velocity profiles match quite well when MRI and numerical results are compared;**

- **The vertical asymmetry resulting from particle settling is also well matched between the experimental and numerical profiles, which was more notorious for higher particle concentrations as expected;**

- **The pressure drop profiles calculated also agree quite well with the experimental ones. There are some deviations but nothing significant;**

0.4-0.6 mm Particles

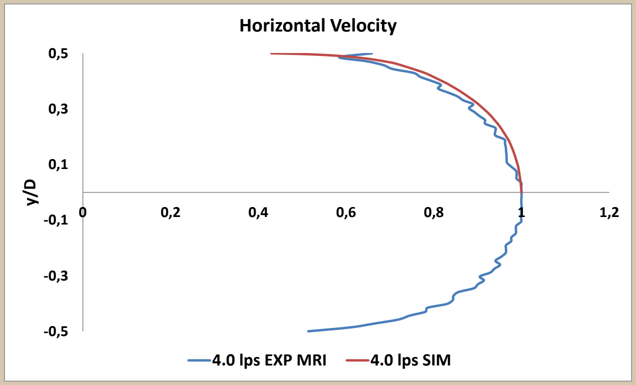
(50 mm pipe)

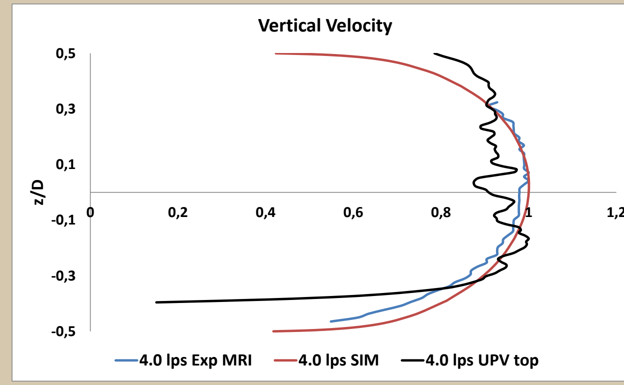
Normalized MRI, UPV & Numerical Velocity Profiles for a Pipe Diameter of 50mm

0.4-0.6 mm particles

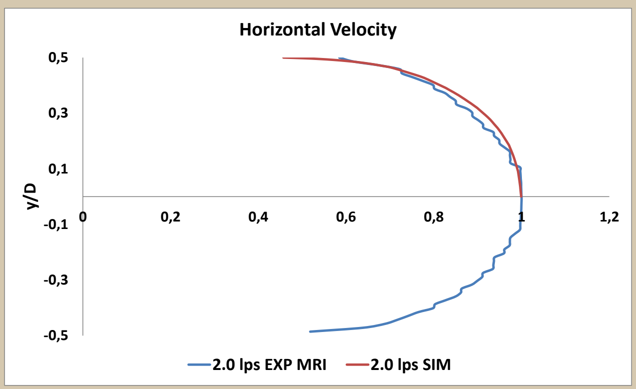
ϕ = 1.0 % (v/v)

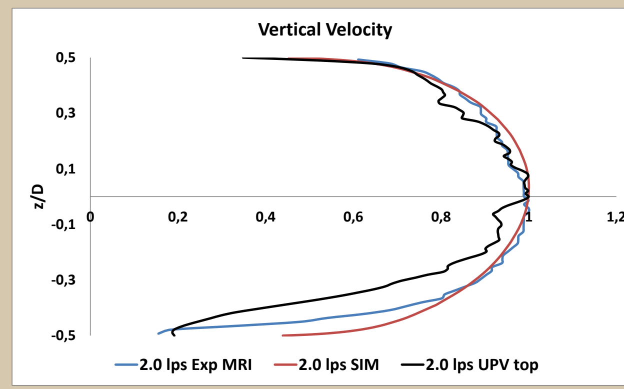
Q = 4.0 l/s





Q = 2.0 l/s



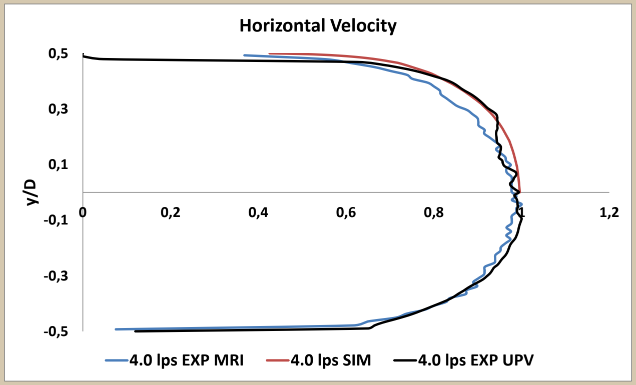


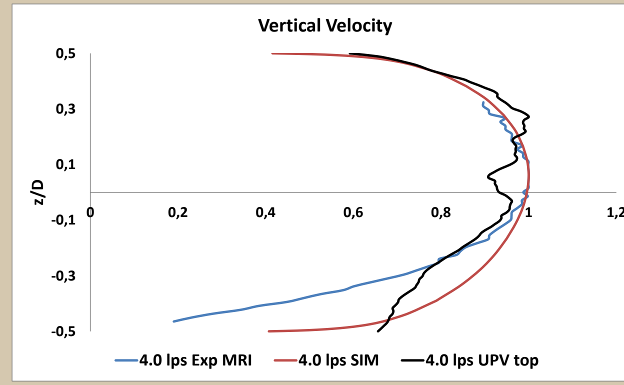
Normalized MRI, UPV & Numerical Velocity Profiles for a Pipe Diameter of 50mm

0.4-0.6 mm particles

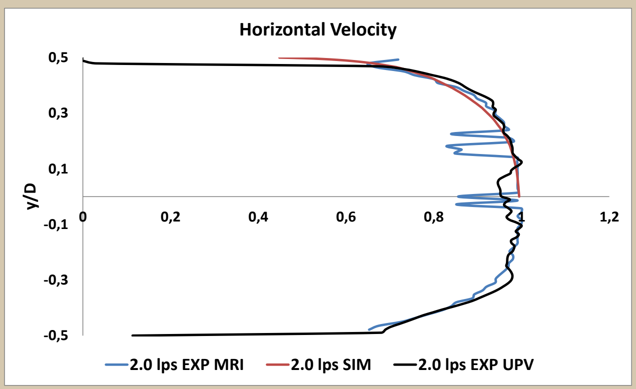
ϕ = 5.0 % (v/v)

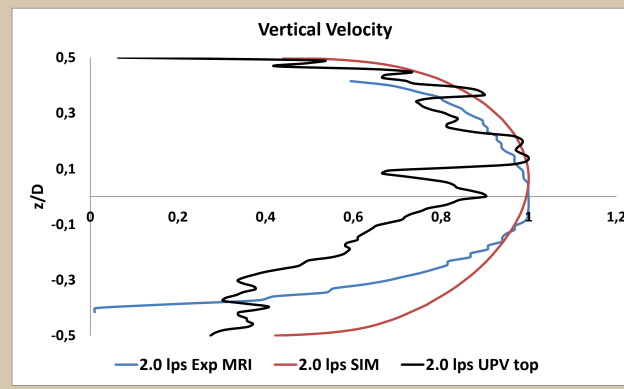
Q = 4.0 l/s





Q = 2.0 l/s

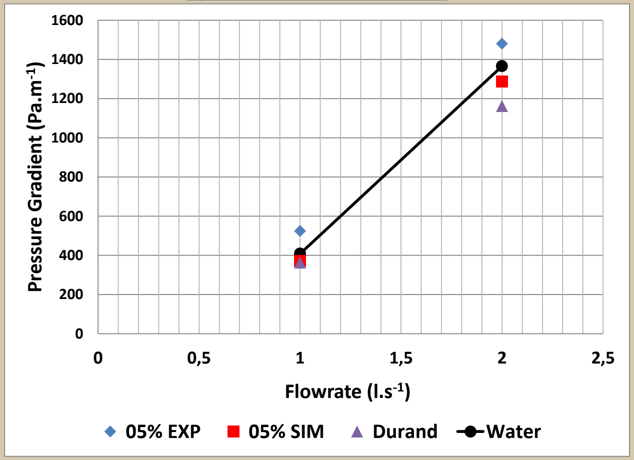




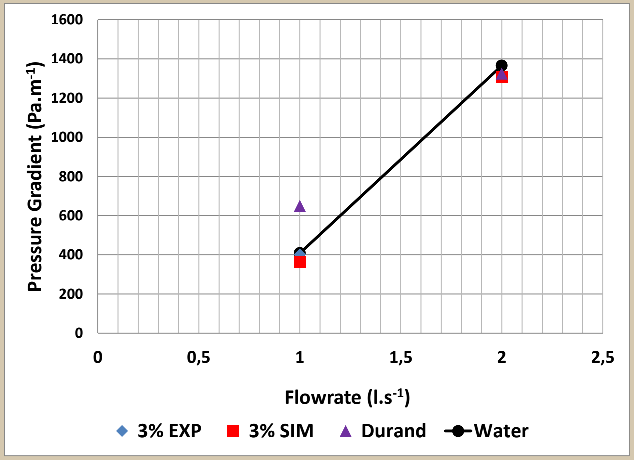
Numerical vs. Experimental Pressure Drop Profiles for a Pipe Diameter of 50mm

0.4-0.6 mm particles

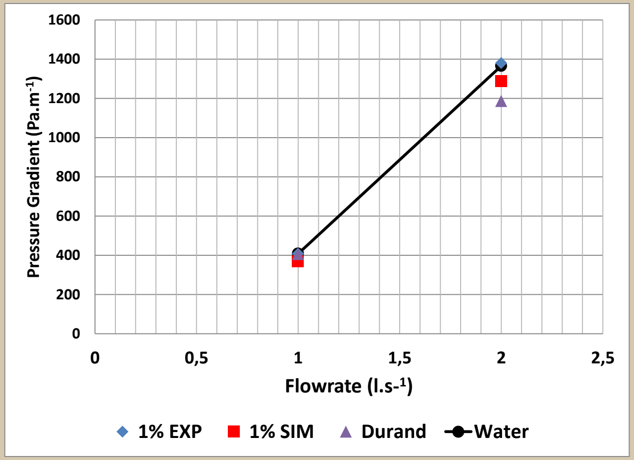
ϕ = 1.0 % (v/v)



ϕ = 5.0 % (v/v)



ϕ = 3.0 % (v/v)



Numerical vs. Experimental Profiles for a Pipe Diameter of 50mm

0.4-0.6 mm particles

- **The UPV probes were in a vertical position for most measurements and due to settling of particles over the bottom probe the profiles seem to become unreliable at the pipe centre. In this area a lot of noise is present in the profiles. The vertical positioning of the probes did provide an opportunity to use UPV to recognize the heterogeneous flows, as can be seen with the sharp variation of the vertical UPV profiles at the bottom;**

- **The noisy data is still present in the normalized velocity profiles, however with the normalization most of the profiles seem to match for both UPV, MRI and also with the numerical data;**

- **The vertical asymmetry resulting from particle settling is also well matched between the experimental and numerical profiles, after the normalization, being more notorious for the higher concentrations, although at the pipe bottom there are differences, which can be attributed to the loss of signal of the UPV probe.**

- **Since MRI measures the velocity of water, at the pipe bottom there will be a sharper variation when compared to the numerical profiles, since the settled particles will slow the water velocity.**

- **The pressure drop profiles also agree quite well with the experimental ones. There are some deviations but nothing significant.**

EIT Normalized Electrical Conducivity Profiles for a Pipe Diameter of 50mm

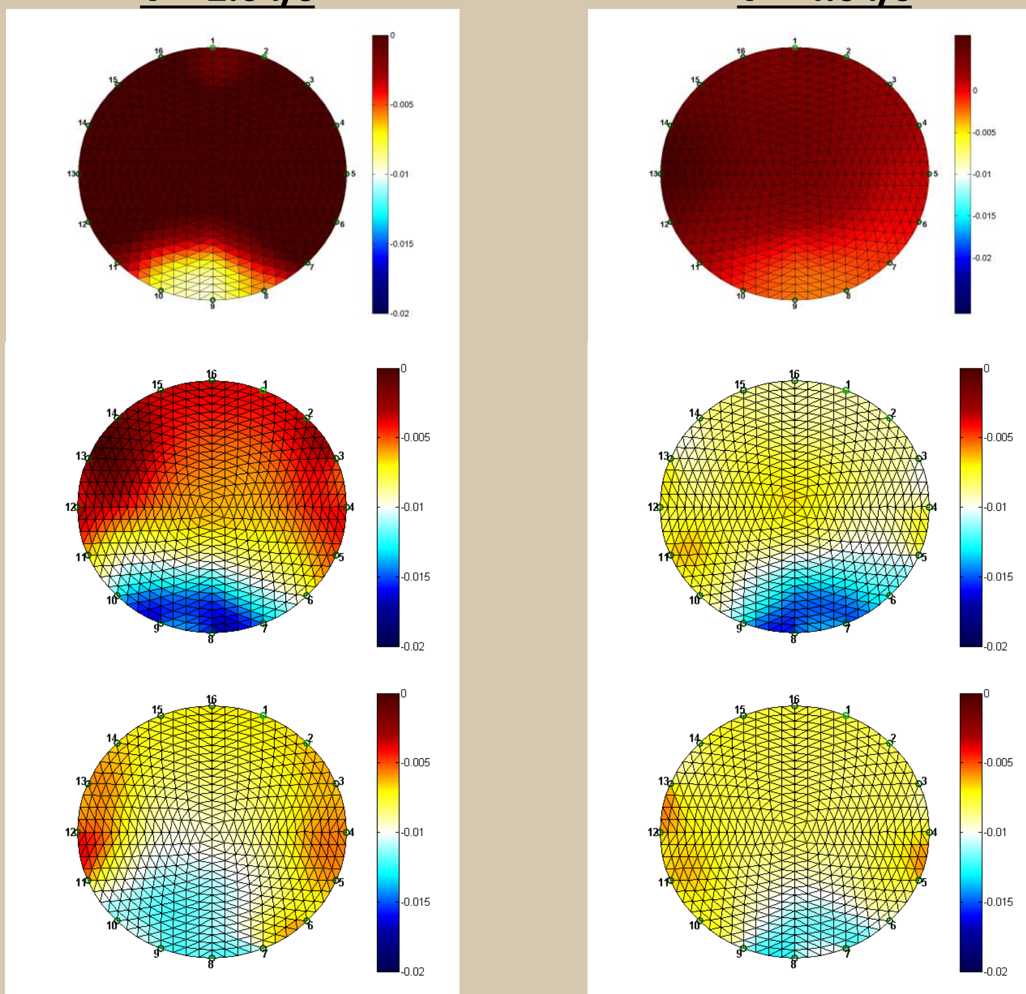
0.4-0.6 mm particles

	V = 2.0 l/s	V = 4.0 l/s

ϕ = 1.0 % (v/v)

ϕ = 3.0 % (v/v)

ϕ = 5.0 % (v/v)



Note: here the same limits were used on all images for the colorbar.

EIT vs Numerical Particle Concentration Profiles for a Pipe Diameter of 50mm

0.4-0.6 mm particles

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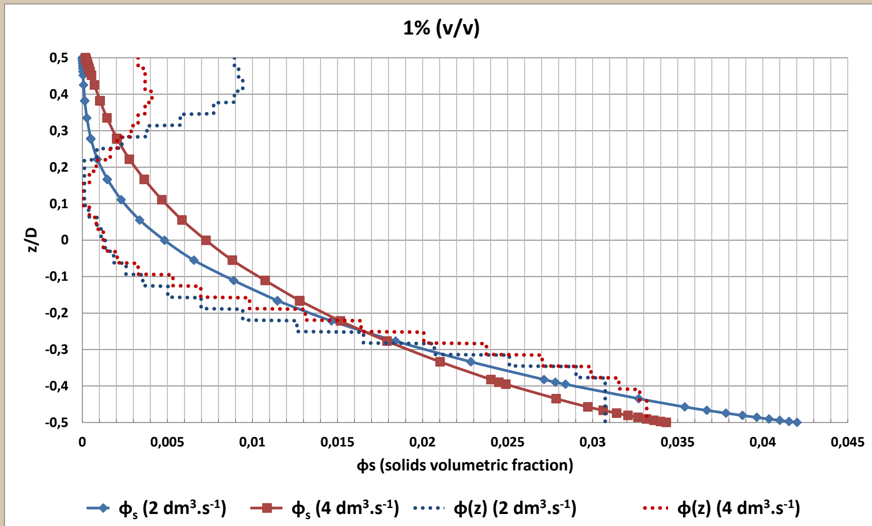
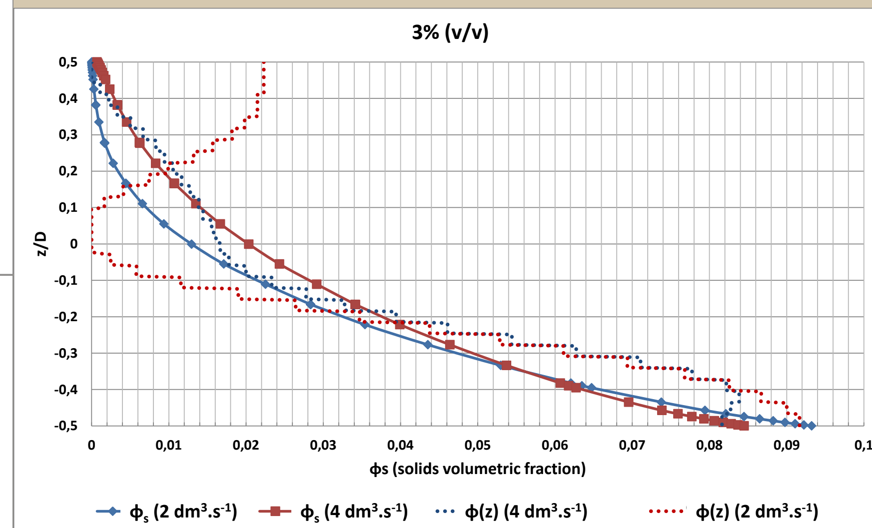
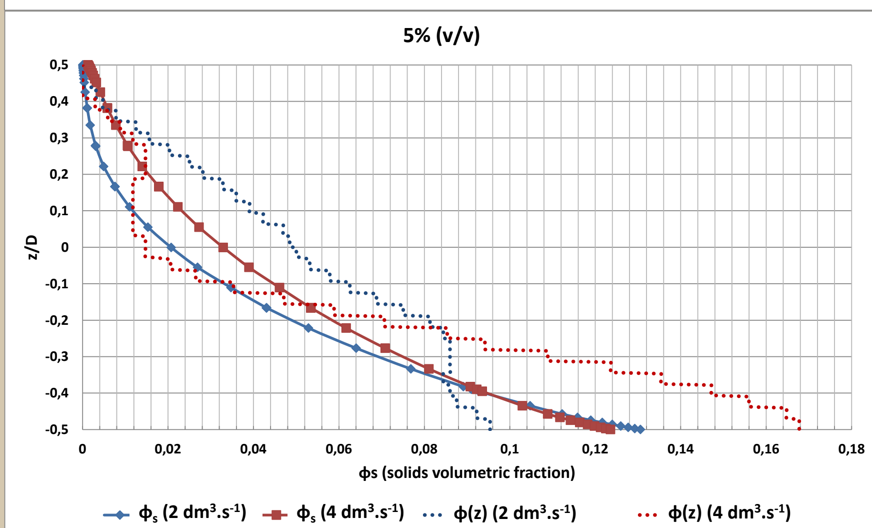
ϕ_s - numerical solids distribution from Mixture Model

$\phi(z)$ - solids distribution profiles normalizing the electrical conductivity results



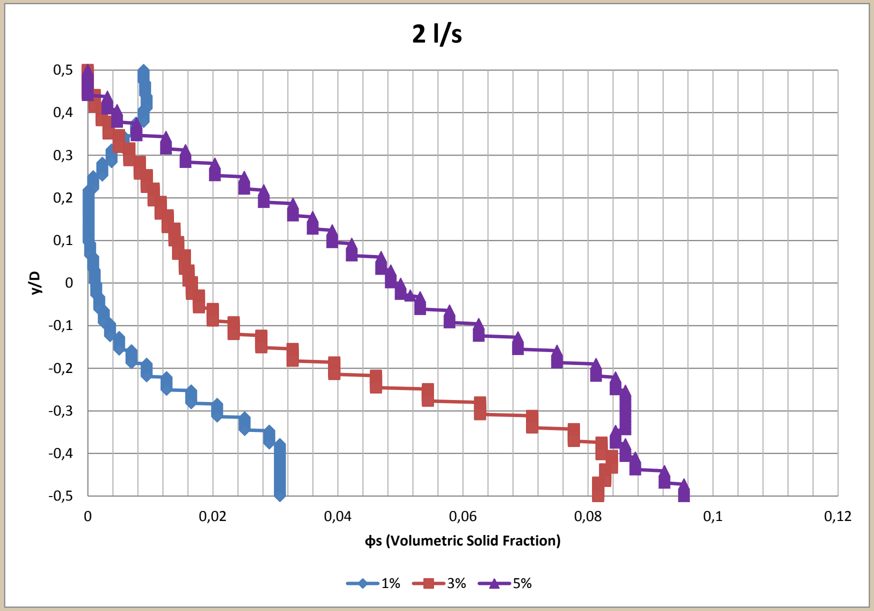


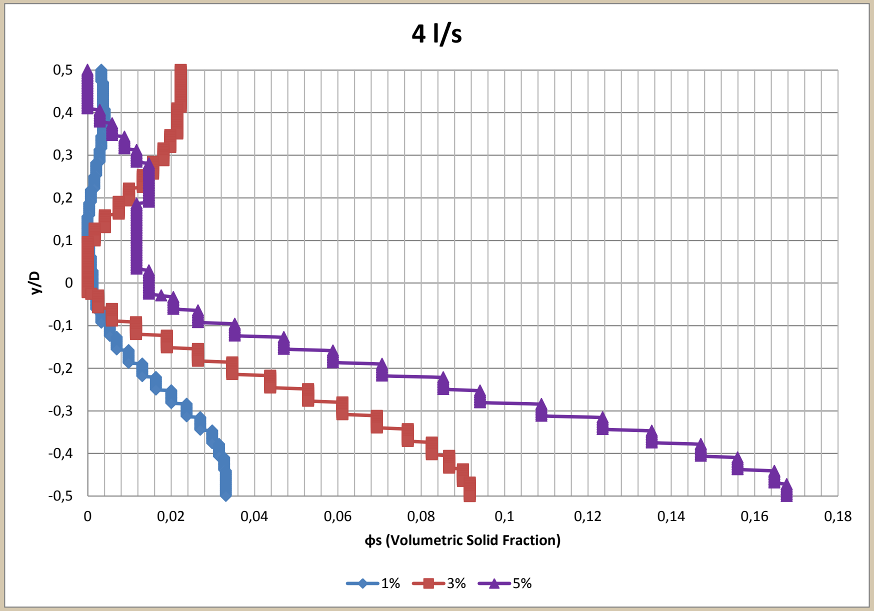


- increased values of the normalized electrical conductivity at the top is likely due to small air bubbles that were present in the region of the EIT data acquisition.

Comparison of EIT Concentration Profiles for a Pipe Diameter of 50mm

0.4-0.6 mm particles





- As concentration increases there is an increase on the concentration of particles settled in the pipe bottom;
- At the lowest flowrate the concentration of settled particles at the pipe bottom is larger;
- For the highest flowrate the concentration of particles settled in the pipe bottom diminished and more particles are fluidized.

Numerical vs. Experimental

- **From the numerical data, the Figures seem to show the presence of particle-particle interaction resulting from the increased flow velocity (larger particles). This can be inferred from the graphs by comparison for the same flow velocity and different particle concentrations, the fluidization of particles seeming to increase with particle concentration;**

- **In general experimental data (particle distribution, velocity profiles and pressure drop), MRI or EIT, agree well with the simulated results obtained using the mixture model.**

Acknowledgments

THIS WORK HAS BEEN FINANCIALLY SUPPORTED BY FUNDAÇÃO PARA A CIÊNCIA E TECNOLOGIA, PROJECT PTDC/EQU-EQU/66670/2006, INDIVIDUAL PHD SCHOLARSHIP SFRH/BD/79247/2011 AND STRATEGIC RESEARCH CENTER PROJECT PESTC/EQB/UI0102/2013 AS WELL AS BY COST ACTION FP1005

Rheology Conference – Coimbra, September 2015

IBEReo15
Coimbra 2015

Challenges in rheology and product development

Coimbra, Portugal, 7-9 September 2015

http://www.uc.pt/en/events/ibereo15

Abstracts submission deadline: February 2015

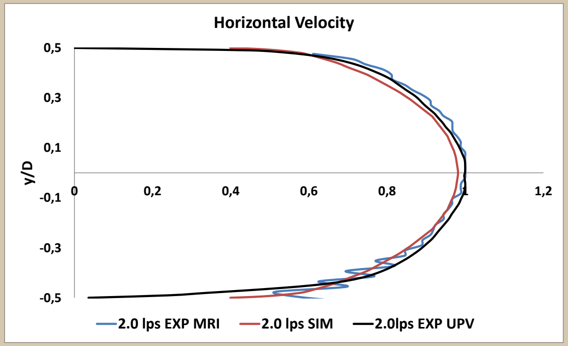
THANK YOU FOR YOUR ATTENTION.

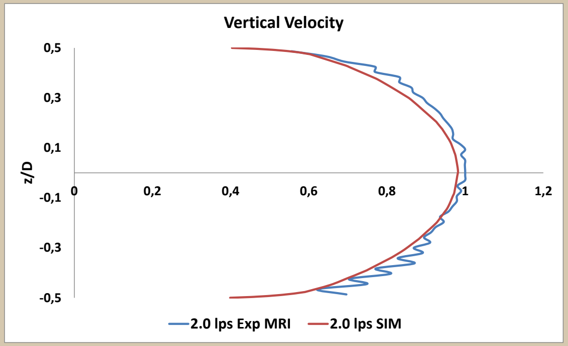
Normalized MRI, UPV & Numerical Velocity Profiles for a Pipe Diameter of 34mm

0.1-0.2 mm particles

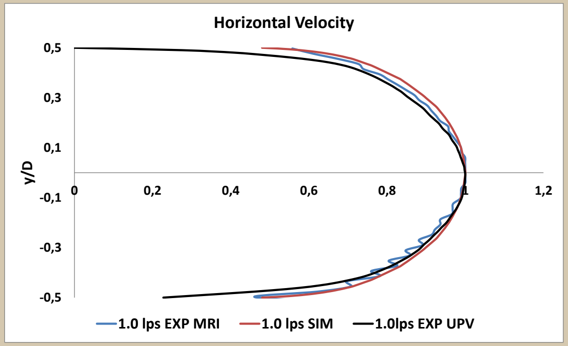
ϕ = 1.0 % (v/v)

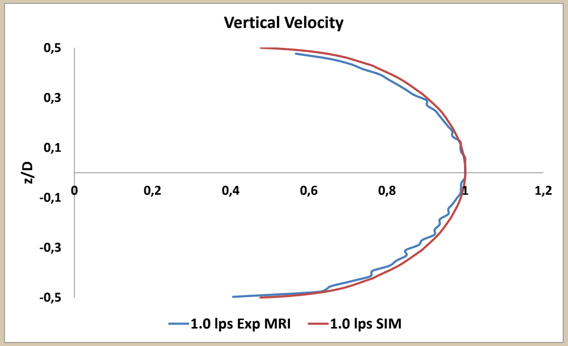
Q = 2.0 l/s



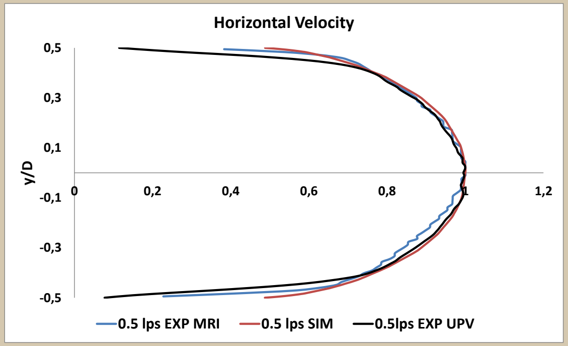


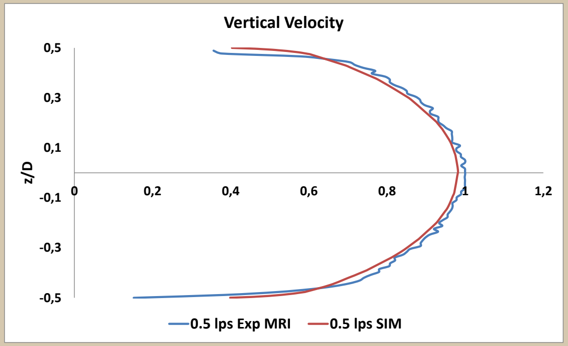
Q = 1.0 l/s





Q = 0.5 l/s



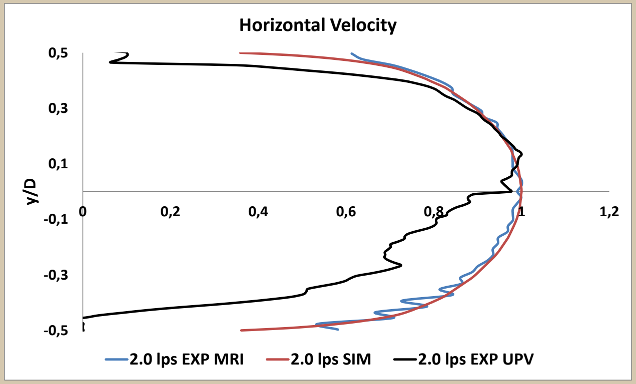


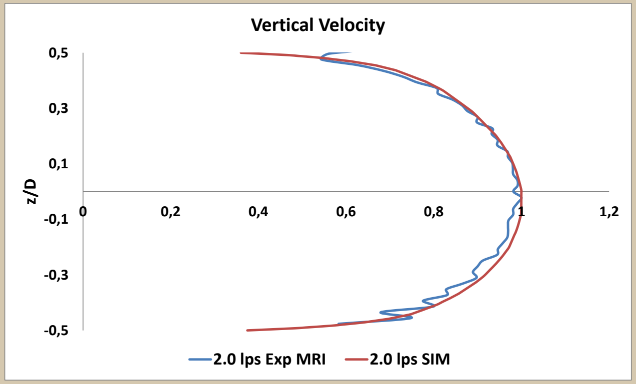
Normalized MRI, UPV & Numerical Velocity Profiles for a Pipe Diameter of 34mm

0.4-0.6 mm particles

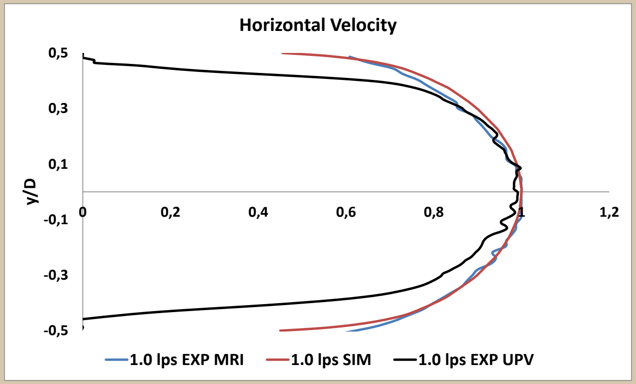
ϕ = 1.0 % (v/v)

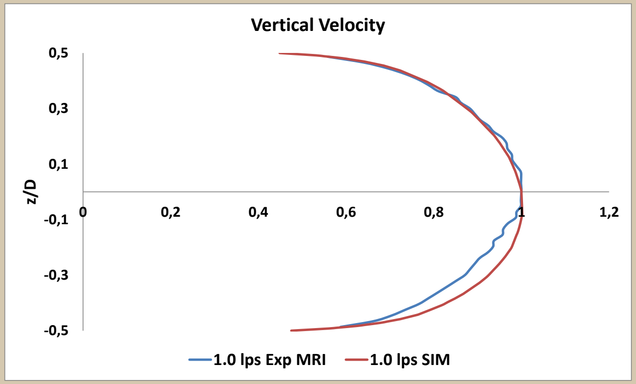
Q = 2.0 l/s





Q = 1.0 l/s



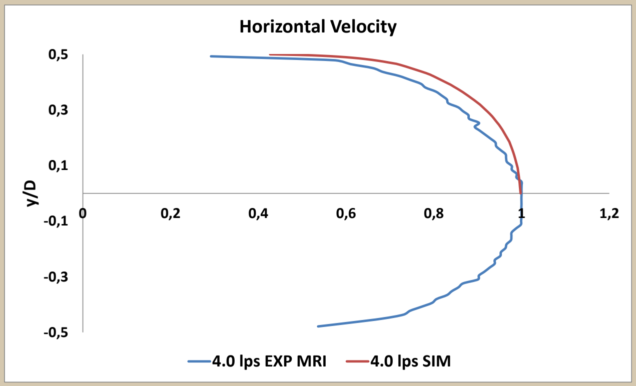


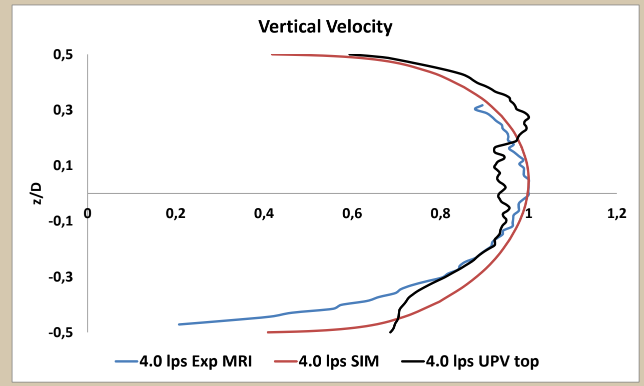
Normalized MRI, UPV & Numerical Velocity Profiles for a Pipe Diameter of 50mm

0.4-0.6 mm particles

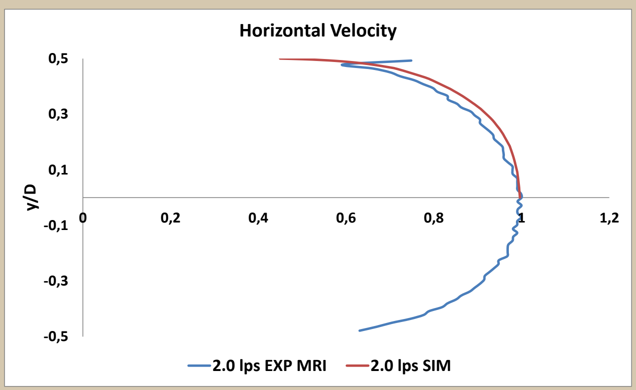
ϕ = 3.0 % (v/v)

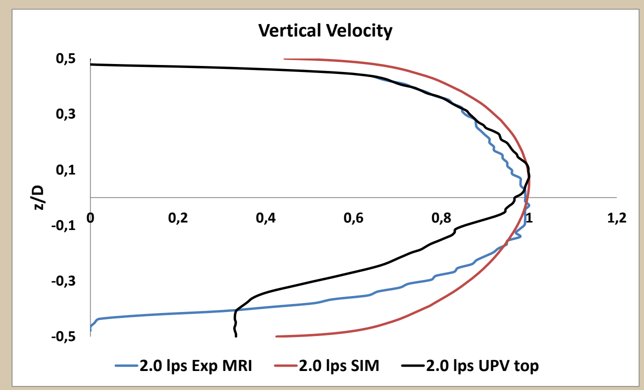
Q = 4.0 l/s





Q = 2.0 l/s





Comparison of EIT Concentration Profiles for a Pipe Diameter of 50mm

0.4-0.6 mm particles

Normalized Electrical Conductivity

$$\eta = \frac{\sigma_0 - \sigma_m}{\sigma_0}$$

Modified Maxwell Equation

$$\sigma_{s0} = \sigma_0 \left(\frac{2 - 2\,\eta\,\phi_0}{2 + \eta\,\phi_0} \right)$$

$$\phi_{ap} = \frac{2 - 2\big((1+\eta)(\sigma_w/\sigma_{s0})\big)}{2 - \big((1+\eta)(\sigma_w/\sigma_{s0})\big)}$$

Particle Concentration Equation using Area under Normalized Electrical Conductivity Profile

$$\phi(z) = \frac{\phi_0}{A_\sigma}\eta$$

σ_0 - electrical conductivity of reference
σ_m - electrical conductivity of the mixture
σ_{s0} - electrical conductivity of homogenous mixture for ϕ_0
ϕ_0 - initial solids concentration
ϕ_{ap} - apparent distribution of solids by Maxwell
A_σ - area under the mixture's electrical conductivity curve