Predicting pressure drop in a pipe flow of concentrated pulp suspensions

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Outline

- Objectives
- Experimental data
- Previous studies
- Numerical model
- Bartosik damping function
- Numerical results
- Conclusions & Future work

Objectives

Modelling the flow of concentrated fiber suspensions in pipes using commercial CFD code

"Using CFD to model fibre suspensions flows - FIBERFLOW"

- **Characterization of the pulp suspension rheology**
- **Adaption of low-Reynolds (LRN) *k-ε* turbulence models** to take into account the presence of fibers – **source terms** and **rheological model**
- **Validation of the model**

Experimental data - Pressure drop

Eucalyptus pulp suspension

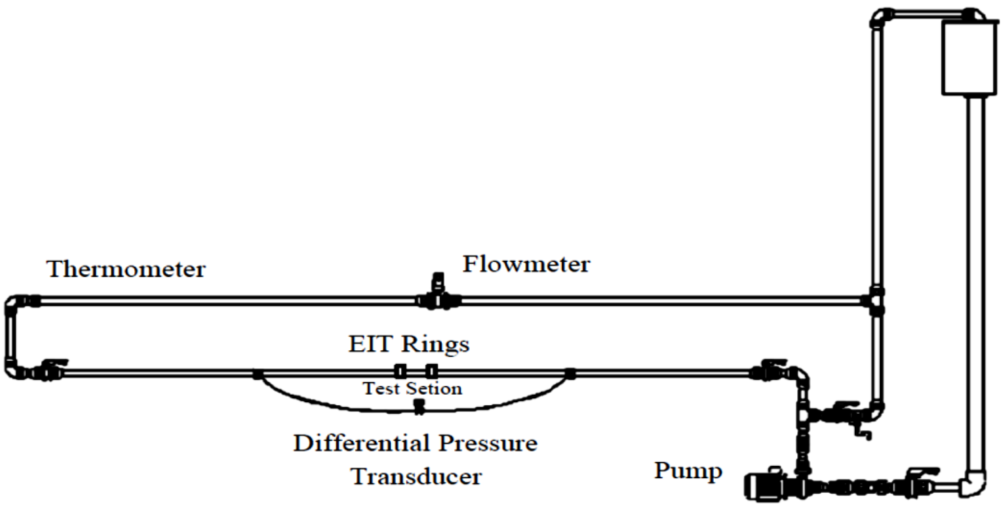
- **Fiber length = 0.706 mm**
- D_{fiber} = 16µm
- **ρ = 998.2 kg/m^3**

- **test section:** D=7.62cm L=4m
- **Main result**: pressure drop

c [% w/w]	N Crowding factor	Case	U_{bulk} [m·s^{-1}]	$\Delta P/L_{exp.}$ [Pa·m^{-1}]
1.50	1947	A	4.49	829
		B	6.21	1289
2.50	3245	C	4.90	2299
		D	5.55	2814

Crowding factor

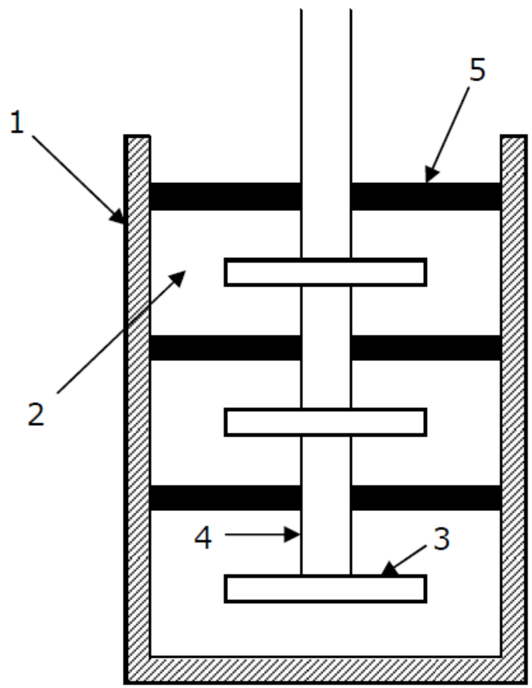
$$N = \frac{2}{3} c_V \left(\frac{L_{fiber}}{D_{fiber}} \right)^2$$



Schematic view of the pilot rig (adapted from Ventura *et al* 2008)

Ventura, C.; Garcia, F.; Ferreira, P.; Rasteiro, M. (2008) – *"Flow Dynamics of Pulp Fiber suspensions"* – TAPPI Journal, 7(8): 20-26

Searle-type Plate viscometer
Blanco *et al* (2007)

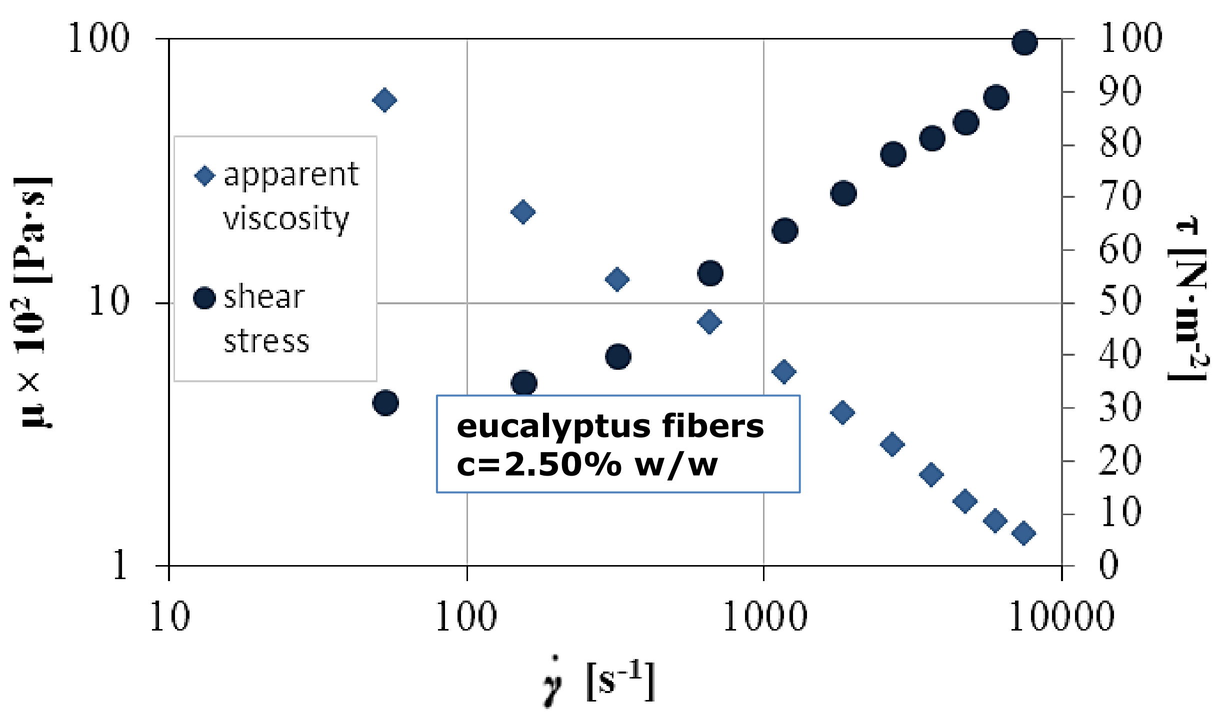


1 – Vessel
2 – Sample
3 – Moving plates
4 – Rotor
5 – Fixed plates

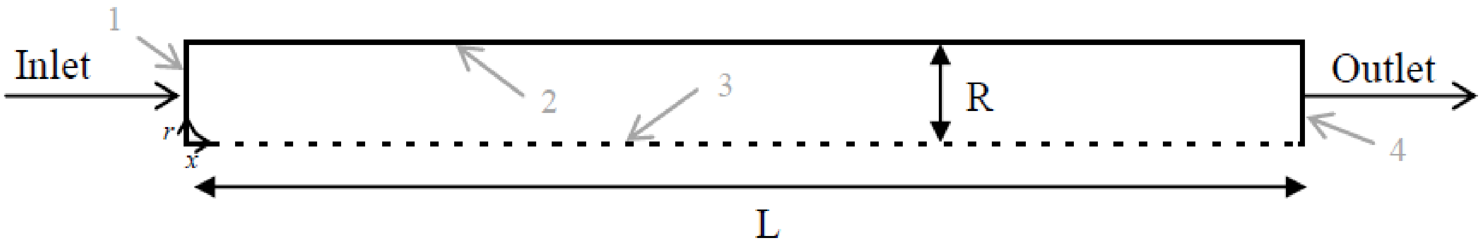
Output data:

τ - shear stress (torque)

$\dot{\gamma}$ - shear rate (rotational speed)



Numerical model



R = 0.0381 m

L = 1 m

Location	Left Side **1**	Right Side **4**	Bottom **3**	Top **2**
Boundary Condition	Periodic boundaries		Axis	Wall

- *single-phase (continuum)*
- *steady state (fully developed flow)*
- *isothermal*
- *incompressible*
- *2D axisymmetrical flow*
- *non-Newtonian fluid viscosity*
- *water annulus - water viscosity*

Numerical model

General transport equation

$$\frac{1}{r}\left[\frac{\partial}{\partial x}(r\rho u\phi)+\frac{\partial}{\partial r}(r\rho v\phi)\right]=\frac{1}{r}\left[\frac{\partial}{\partial x}\left(r\Gamma_\phi\frac{\partial\phi}{\partial x}\right)+\frac{\partial}{\partial r}\left(r\Gamma_\phi\frac{\partial\phi}{\partial r}\right)\right]+S_\phi$$

dependent variables ϕ, diffusibility term Γ_ϕ and source-term S_ϕ (Hsieh and Chang, 1996).

Equation	ϕ	Γ_ϕ	S_ϕ
Continuity	1	0	0
Momentum - axial	u	$\mu_{eff}=\mu+\mu_t$	$-\frac{\partial P}{\partial x}+\frac{\partial}{\partial x}\left(\mu_{eff}\frac{\partial u}{\partial x}\right)+\frac{1}{r}\frac{\partial}{\partial r}\left(r\mu_{eff}\frac{\partial v}{\partial x}\right)$
Momentum - radial	v	$\mu_{eff}=\mu+\mu_t$	$-\frac{\partial P}{\partial r}+\frac{\partial}{\partial x}\left(\mu_{eff}\frac{\partial u}{\partial r}\right)+\frac{1}{r}\frac{\partial}{\partial r}\left(r\mu_{eff}\frac{\partial v}{\partial r}\right)-2\mu_{eff}\frac{v}{r^2}$
Kinetic energy	k	$\mu+\mu_t/\sigma_k$	$G_k-\rho\varepsilon$
Dissipation rate	ε	$\mu+\mu_t/\sigma_\varepsilon$	$\left(C_{\varepsilon 1}f_1G_k-C_{\varepsilon 2}f_2\rho\varepsilon\right)\varepsilon/k$

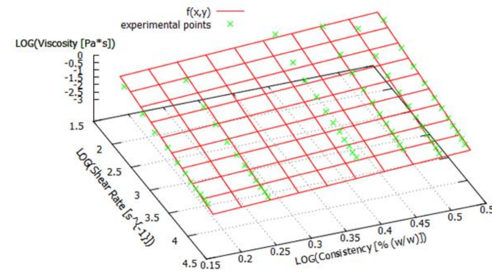
$$G_k=\mu_t\left\{2\left[(\partial u/\partial x)^2+(\partial v/\partial r)^2+(v/r)^2\right]+(\partial v/\partial x+\partial u/\partial r)^2\right\};\qquad \mu_t=\rho C_\mu f_\mu k^2/\varepsilon$$

Previous studies

- **6 built-in LRN turbulence models were evaluated**
- **2 different rheological models were evaluated:**

$$\eta_{app} = K\left(\dot{\gamma}\right)^{n} \quad (n < 0)$$

$$\eta_{app} = \frac{c^{a1}}{\dot{\gamma}^{a0}} \cdot a2$$



- A ***drag reduction*** can be observed in **all cases** when using **LRN turbulence models**
- The models of **Abe-Kondoh-Nagano (AKN)** and **Chang-Hsieh-Chen (CHC)** showed the best fit to the experimental data
- The **damping function f_μ** can be **modified** taking into account the literature for **polymer solutions flows** (Malin damping function) and for **particle suspensions flow** (Bartosik damping function).
- The application of the **damping function of Malin was not able to improve** the numerical results.
- The numerical results **can be improved significantly** by applying an **"optimized"** Malin **damping function**.
- **Further improvement needed...**

Pulp rheology

pulp consistencies c [%]:
1.50, 1.80, 2.50
2.90, 3.20 , 3.50

The best fit of experimental rheological data

modified expression

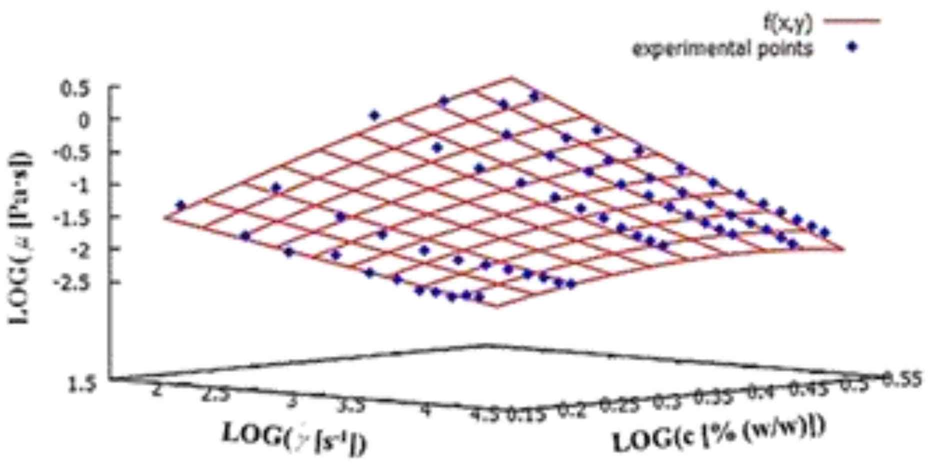
$$\eta_{app} = \frac{c^{a1}}{\dot{\gamma}^{a0}} \cdot 10^{a2}$$

a0=0.683566

a1=2.39972

a2=-0.225815

R^2=0.954



$$\eta_{app} = \frac{c^{a1}}{\dot{\gamma}^{a0 \cdot c}} \cdot 10^{a2}$$

a0=0.259433

a1=6.97456

a2=-2.07198

R^2=0.984

Bartosik Damping Function

- **Modification** of the **damping functions** f_μ of the **AKN** and **CHC** turbulence models (implemented in Ansys Fluent) according to **Bartosik (2011)** for **particle suspensions flow** (uniform particles distribution):

$$f_\mu = 0.09\exp\left[-\frac{-3.4\left[1 + {A_s}^3 d^2 (8 - 88 A_s d) {c_v}^{0.5}\right]}{\left(1 + \frac{Re_t}{50}\right)^2}\right]$$

A_s – empirical constant (=100)
c_v – averaged volume fraction of solids
d – averaged solid particles diameter

- Modification the constants of the Bartosik damping function:

$$f_\mu = C \cdot \exp\left[-\frac{-3.4\left[1 + A^3 B^2 (8 - 88 \cdot A \cdot B) {c_v}^{0.5}\right]}{\left(1 + \frac{Re_t}{50}\right)^2}\right]$$

$$Re_T = \frac{k^2}{\varepsilon \nu}$$

Bartosik, A. – *"Mathematical modelling of slurry flow with medium solid particles"* – Mathematical Models and Methods in Modern Science, International Conference Mathematical Models and Methods in Modern Science, Spain, 10-12 December, 2011. ISBN 978-1-6-61804-055-8, pp.124-129.

Simulation results

Convergence criterion = 1 ×10^-5^

Water annulus and non-Newtonian fluid

$$\eta_{app} = \frac{c^{a1}}{\dot{\gamma}^{a0 \cdot c}} \cdot 10^{a2}$$

c [% w/w]	U_{in} [m·s^{-1}]	$\Delta P/L_{exp.}$ [Pa·m^{-1}]	$\Delta P/L_{num}$ [Pa·m^{-1}]	δ [%]	$\Delta P/L_{num}$ [Pa·m^{-1}]	δ [%]	$\Delta P/L_{num}$ [Pa·m^{-1}]	δ [%]	$\Delta P/L_{num}$ [Pa·m^{-1}]	δ [%]
1.50	4.49	829	1560	88	1032	24	1763	113	1022	**23**
	6.21	1289	387	70	1776	**38**	3164	146	2026	57
2.50	4.90	2299	1861	18	1624	**3**	1843	17	1632	**3**
	5.55	2814	2046	17	1800	**3**	2022	16	1811	**3**
			AKN		**AKN-Bartosik**		**CHC**		**CHC-Bartosik**	

Simulation results

- *A **drag reduction*** can be observed in **all cases** when ***AKN*** and ***CHC*** turbulence models are used.
- Results allow to conclude that the ***AKN*** and ***CHC*** models modified with the **damping function of Bartosik** show a **better fit** to the experimental data.
- To improve the numerical results, the constants of **Bartosik damping function** f_μ can be **modified** - A_s and d for the pulp flow can be different from those used by Bartosik to study the particle suspensions flow.

Simulation results

Bartosik damping function

$$f_\mu = C \cdot \exp\left[-\frac{-3.4\left[1 + A^3 B^2 (8 - 88 \cdot A \cdot B) {c_v}^{0.5}\right]}{\left(1 + \frac{Re_t}{50}\right)^2}\right]$$

	Case							
	1	***2***	***3***	***4***	***5***	***6***	***7***	***8***
A	100	**50**	**150**	100	100	100	100	100
B×10⁵	1.6	1.6	1.6	**70.6**	1.6	1.6	1.6	1.6
C×10²	9	9	9	9	**6.75**	**4.75**	**3.75**	**2.45**

- Change of ***A*** does not have a significant effect on the numerical pressure drop
- Change of ***B*** (regarded as fiber length instead of the fiber diameter) does not influence significantly the numerical pressure drop

Simulation results

New damping function tested – Bartosik (*AKN model modified*)

Case	*Modification*	*c* [% w/w]	U_b [m·s^{-1}]	Re_w	$\Delta P/L_{exp.}$ [Pa·m^{-1}]	$\Delta P/L_{num.}$ [Pa·m^{-1}]	δ [%]
A1	AKN-Bartosik	1.50	4.49	62830	829	1032	24
B1		1.50	6.21	95822	1289	1776	38
C1		2.50	4.90	15904	1579	1624	3
D1		2.50	5.55	19479	1754	1800	3
A6	**C=0.0475**	1.50	4.49	63071	829	**808**	**3**
B7	**C=0.0375**	1.50	6.21	96694	1289	**1298**	**1**
C5	**C=0.0675**	2.50	4.90	15868	1579	**1577**	**0.1**
D5	**C=0.0675**	2.50	5.55	19467	1754	**1750**	**0.2**

Simulation results

***New damping function tested* – Bartosik (*AKN model modified*)**

- The **AKN** LRN turbulence model considering the **Bartosik damping function f_{μ}** with ***C* modified** improves the numerical results.

- The parameter ***C*** should be **lower** than the value used by Bartosik for particle suspensions flow.

0.09 -> 0.04-0.07

Simulation results

New damping function tested – Bartosik (*CHC model modified*)

Case	*Modification*	*c* [% w/w]	U_b [m·s^{-1}]	Re_w	$\Delta P/L_{exp.}$ [Pa·m^{-1}]	$\Delta P/L_{num.}$ [Pa·m^{-1}]	δ [%]
A1	CHC-Bartosik	1.50	4.49	62531	829	1022	23
B1		1.50	6.21	94868	1289	2026	57
C1		2.50	4.90	16357	1579	1632	3
D1		2.50	5.55	20040	1754	1811	3
A6	**C=0.0475**	1.50	4.49	62403	829	**832**	**0.3**
B8	**C=0.0245**	1.50	6.21	95583	1289	**1302**	**1**
C5	**C=0.0675**	2.50	4.90	16270	1579	**1587**	**0.5**
D5	**C=0.0675**	2.50	5.55	20009	1754	**1761**	**0.4**

Simulation results

New damping function tested* – Bartosik *(CHC model modified)

- The numerical pressure drop, U^+ and k profiles are very similar to that obtained with the AKN-Bartosik model modified (c=2.50% (w/w))
- The **CHC** LRN turbulence model considering the **Bartosik damping function** f_μ with ***C* modified** improves significantly the numerical results
- The parameter ***C*** should be **lower** than the value used by Bartosik for particle suspensions flow, mainly, for c=1.50% (w/w)

0.09 -> 0.025-0.07

Conclusions

- The **non-Newtonian behaviour of pulp** can be expressed as a function of **shear rate** and **pulp consistency** - a **power-law** considering the **consistency index** and the **flow behaviour** index as a function of **pulp consistency**
- The **damping function** f_μ on these models **can be modified taking into account** the cases from literature for the simulation of **particles turbulent flow**
- **Modifications of** the AKN and CHC LRN turbulence models with the damping function according to **Bartosik** lead to **better fit** to the experimental data
- **Noticeable improvement** of the numerical results can be obtained by **modifying the Bartosik damping function**
- **Model should be used with care - limited applicability**
- **Prediction of pressure drop in a pipe flow of pulp suspensions is a challanging task -> need of further studies...**

Future work

- Simulation of wider range of fibre consistencies - to generalize the model

- Study the modification of the damping function f_μ according to Bartosik (2010):

$$f_\mu = 0.09 \exp\left[\frac{-3.4\left(1 + \frac{\tau_0}{\tau_w}\right)}{\left(1 + \frac{Re_t}{50}\right)^2}\right]$$

τ_0 - yield stress

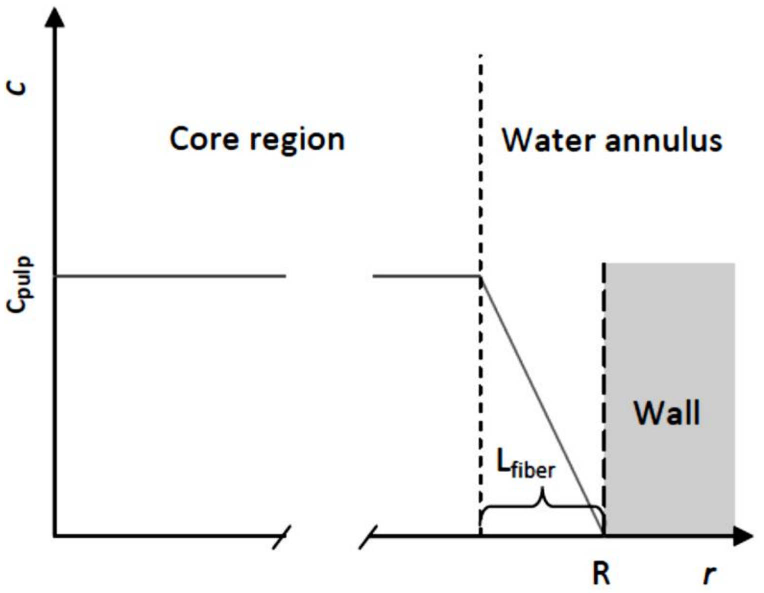
τ_w - stress at the wall

- **Rheological tests** to try obtain information for **low shear rates**.

Bartosik, A. (2010) – *"Application of Rheological Models in Prediction of Turbulent Slurry Flow"* - Flow Turbulence Combust, 84(2):277-293.

Future work

- Development of the "water annulus" model:
  - "water annulus" thickness
  - variation of fibre consistency across -> viscosity



$$c(r) = -c_{pulp}\left[r - \left(R - L_{fiber}\right)\right] / L_{fiber} + c_{pulp}$$

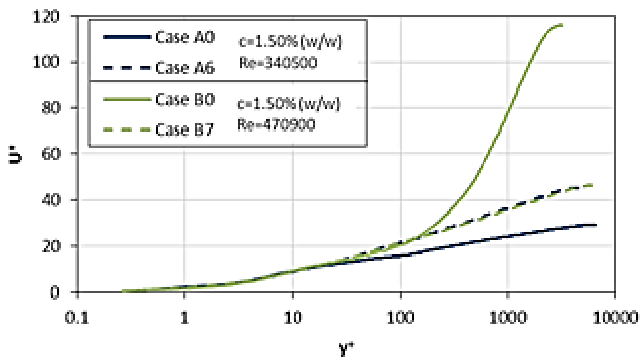
- Apply the CFD model to study the flow of **pine** suspensions.

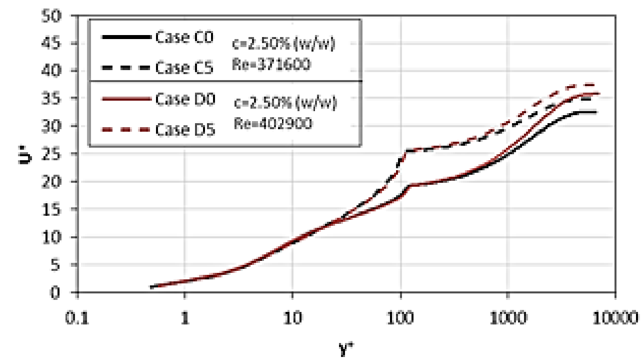
Thank you for your attention...

Simulation results

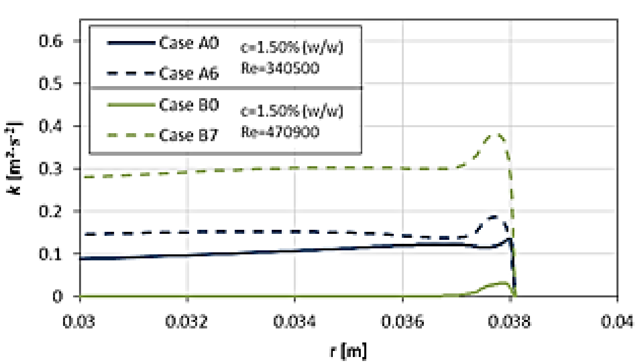
***New damping function tested* – Bartosik (*AKN model modified*)**

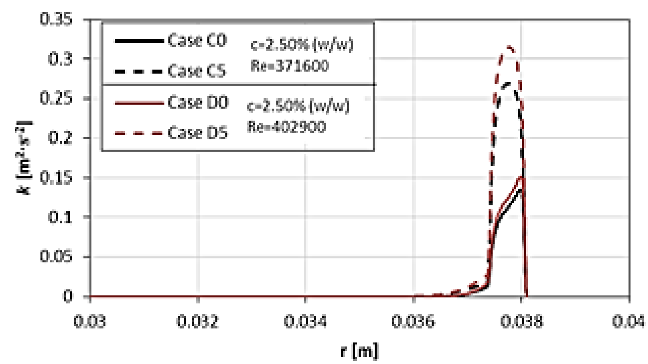
Dimensionless velocity





Turbulent kinetic energy



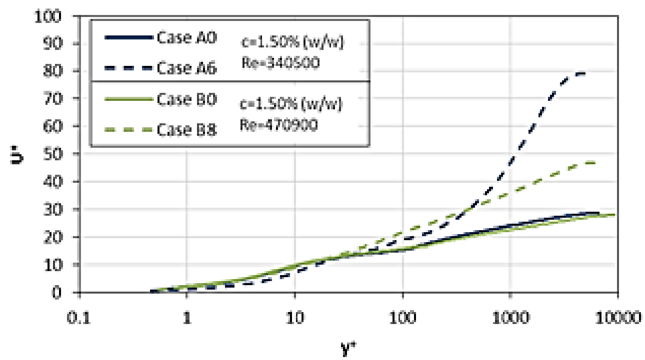


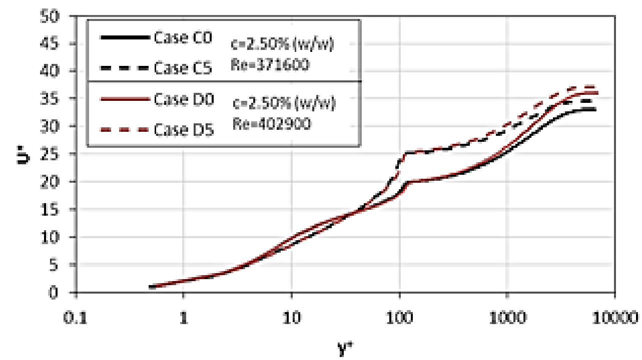
Cases 0 - AKN model without damping function modification

Simulation results

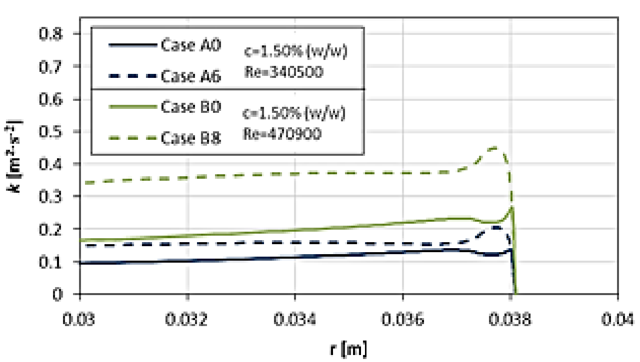
New damping function tested – **Bartosik** (***CHC model modified***)

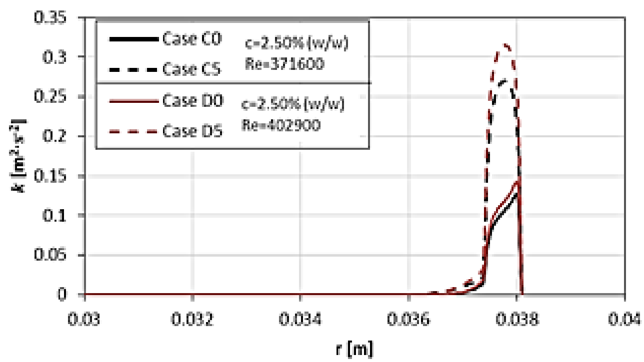
Dimensionless velocity





Turbulent kinetic energy





Cases 0 - CHC model without damping function modification