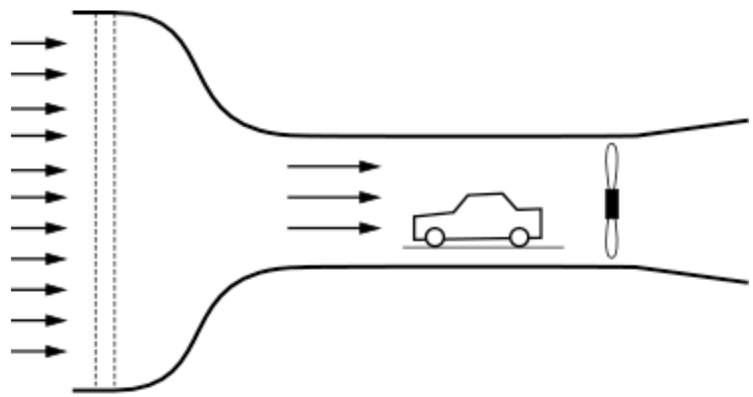
Design of the Inlet for an Open Circuit Wind Tunnel for Testing Full Scale Class Eight Trucks

Bhaskar Bhatnagar, Freightliner LLC
Gerald Recktenwald, Portland State University
gerry@me.pdx.edu

Overview

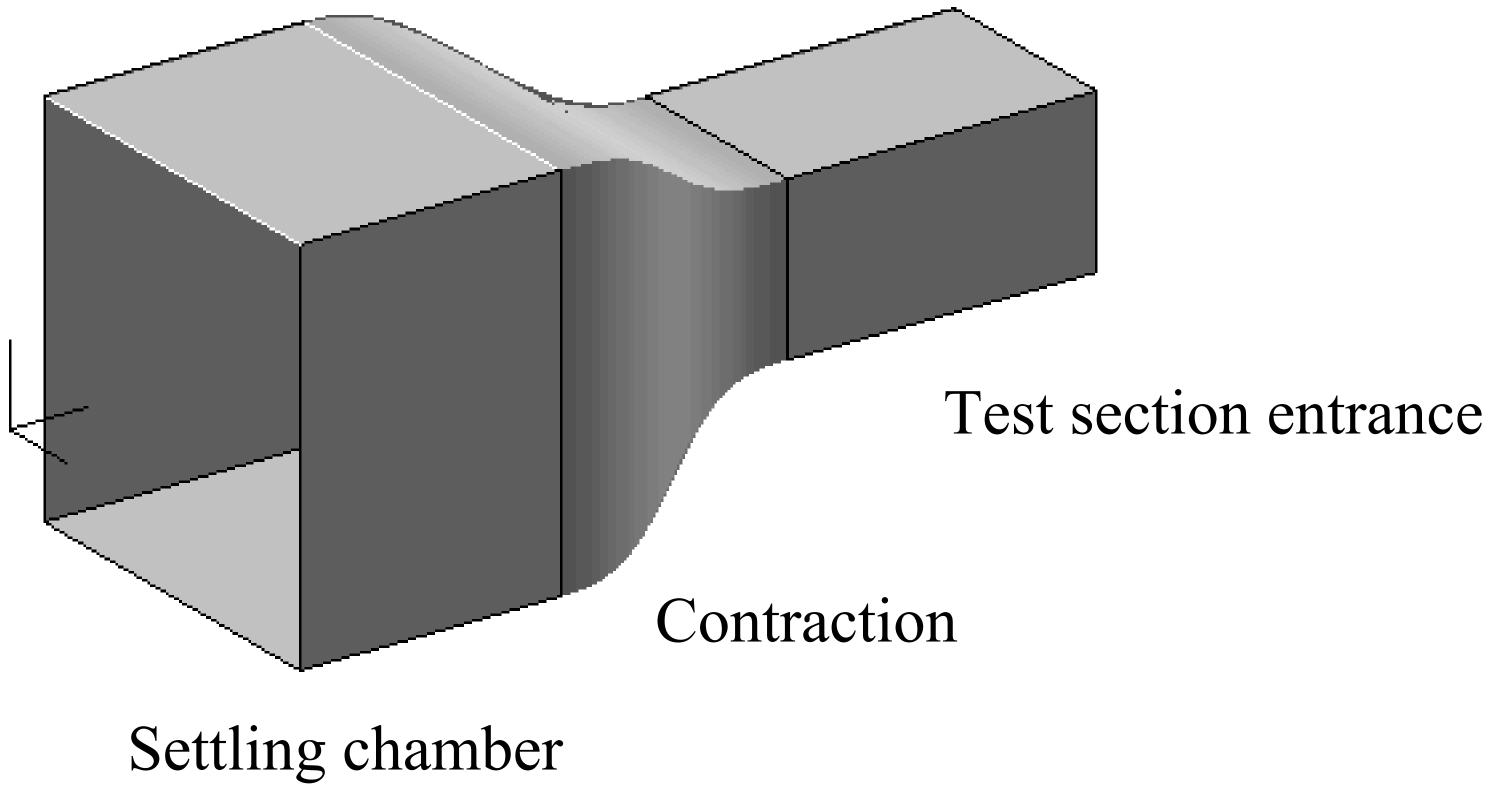
- Open circuit design
- Boundary layer analysis
- CFD analysis
- Conclusions



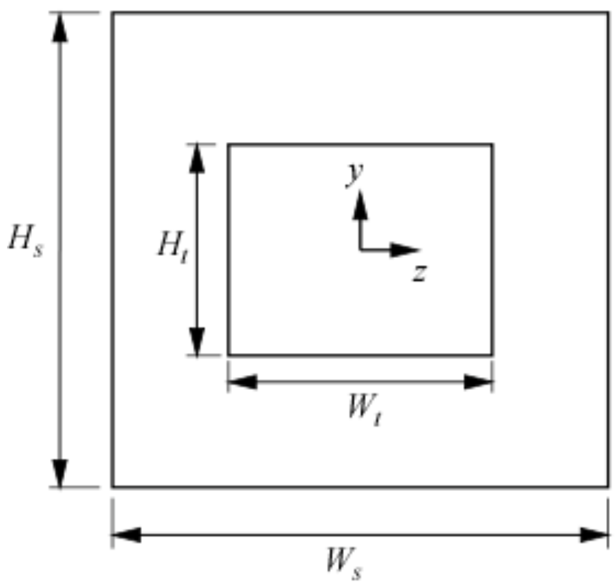
Design Strategy

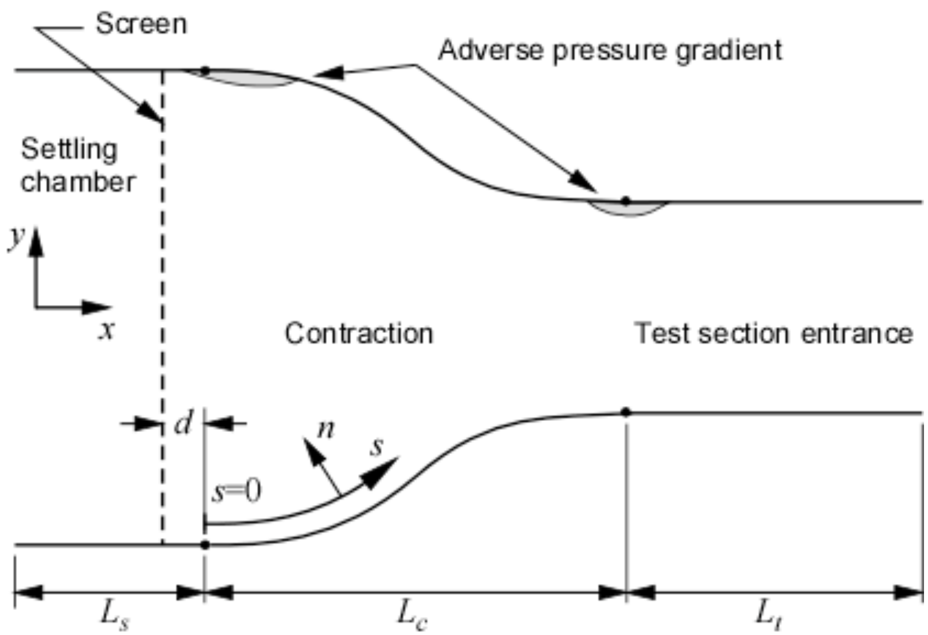
- Objectives
  - Guarantee no separation
  - Obtain uniform velocity profile upstream of vehicle under test
- Boundary layer analysis
  - Run CFD model with slip BC on walls
  - Use Thwaites' method to find $c_f(x)$ and $\theta(x)$
  - Goal: $c_f(x) > 0$ for all x
- CFD Analysis
  - Three dimensional, quarter model.
  - Goal: maximum velocity deviation < 1% outside the boundary layer
  - Look for secondary flow in corners

Inlet Geometry



Inlet Geometry





$$\frac{y - y_1}{H_s - H_t} = -3\xi^5 + \frac{15}{2}\xi^4 - \xi^3$$

$$\xi = \frac{x - x_1}{L_c}$$

$$\frac{z - z_1}{W_s - W_t} = -3\xi^5 + \frac{15}{2}\xi^4 - \xi^3$$

Design Parameters

Fixed

Dimensions of cross section: H_s, W_s, H_t, W_t

Air speed in test section

Variable

Length of settling chamber, L_s

Length of contraction, L_c

Length of test section inlet, L_t

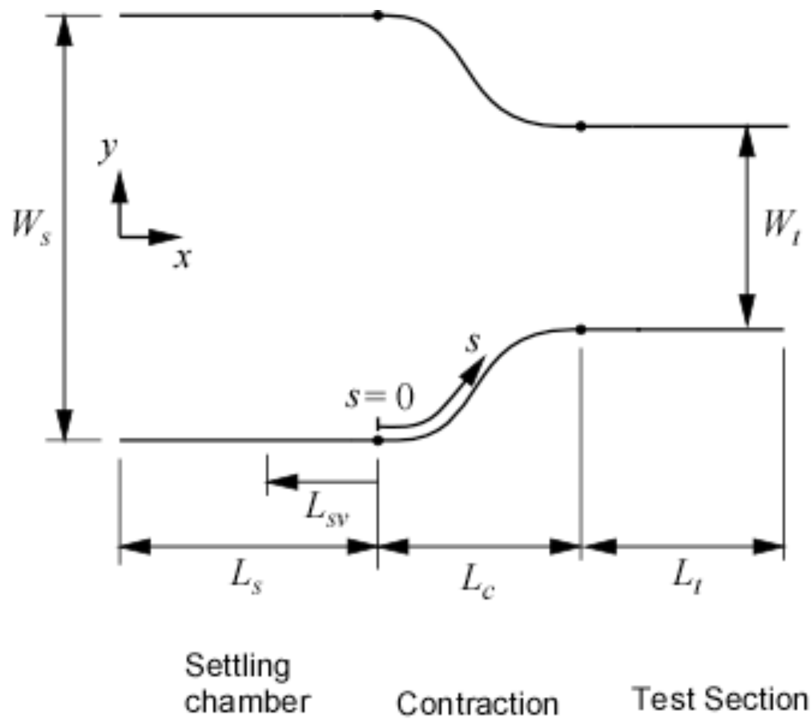
Number, location, and porosity of screens

Boundary Layer Analysis

- Preliminary CFD work found no separation
- Bell and Mehta showed that Thwaites' method predicted successful designs of low speed wind tunnels
- Run CFD model with slip BC on walls. Velocity along the wall from slip solution is external velocity for Thwaites' method.
- Thwaites' method used to check that boundary layer does not separate. Detailed CFD analysis is still useful.

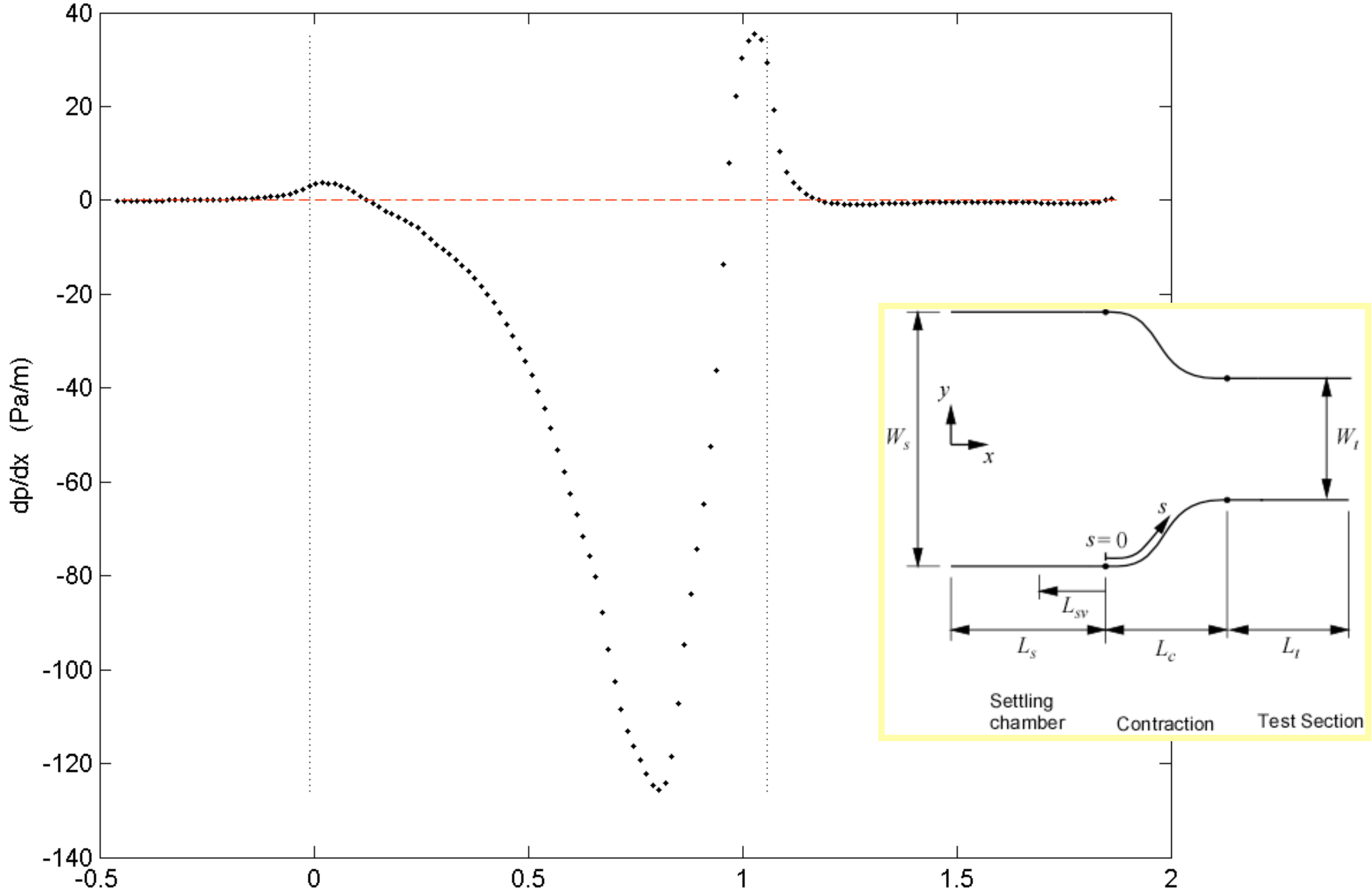
Thwaites Method

Given $u_e(s)$, the variation of free stream velocity outside the boundary layer, numerically integrate the momentum equation to get $\theta(s)$, $\delta(s)$, and $c_f(s)$



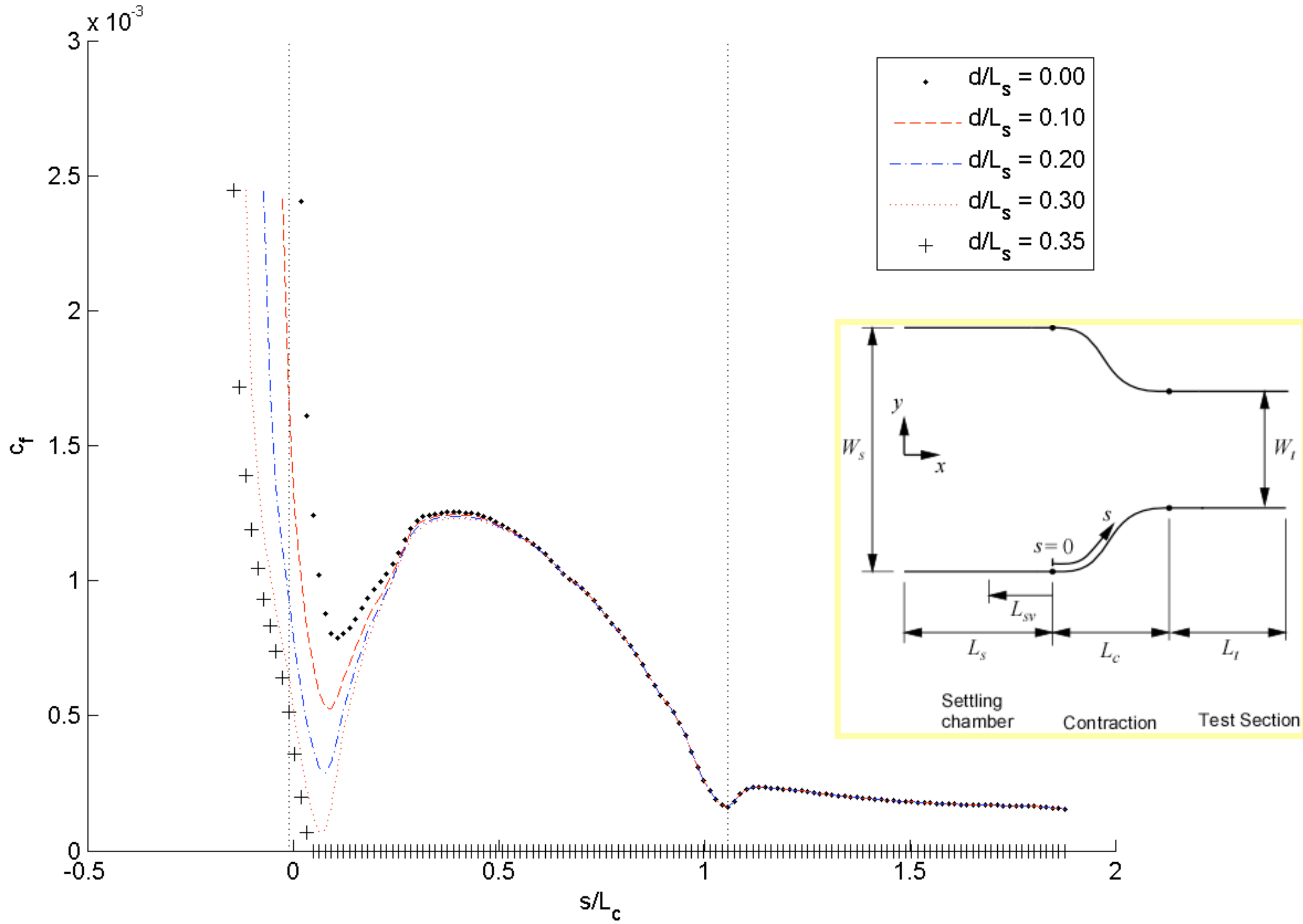
$$\theta^2 = \theta_0^2 + \frac{0.45\nu}{u_e^6}\int_{s_0}^{s} u_e^5(\zeta)\,d\zeta$$

Thwaites Method – External Pressure Gradient



Bhatnagar and Recktenwald
ASME FED/HT 2004

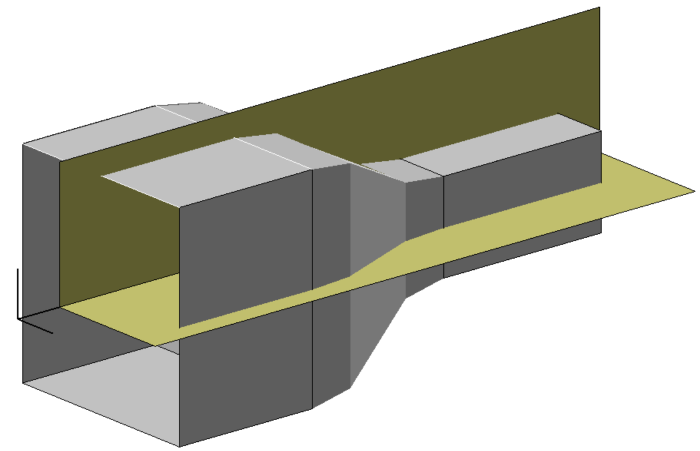
Thwaites Method – Wall shear vs. L_{sv}



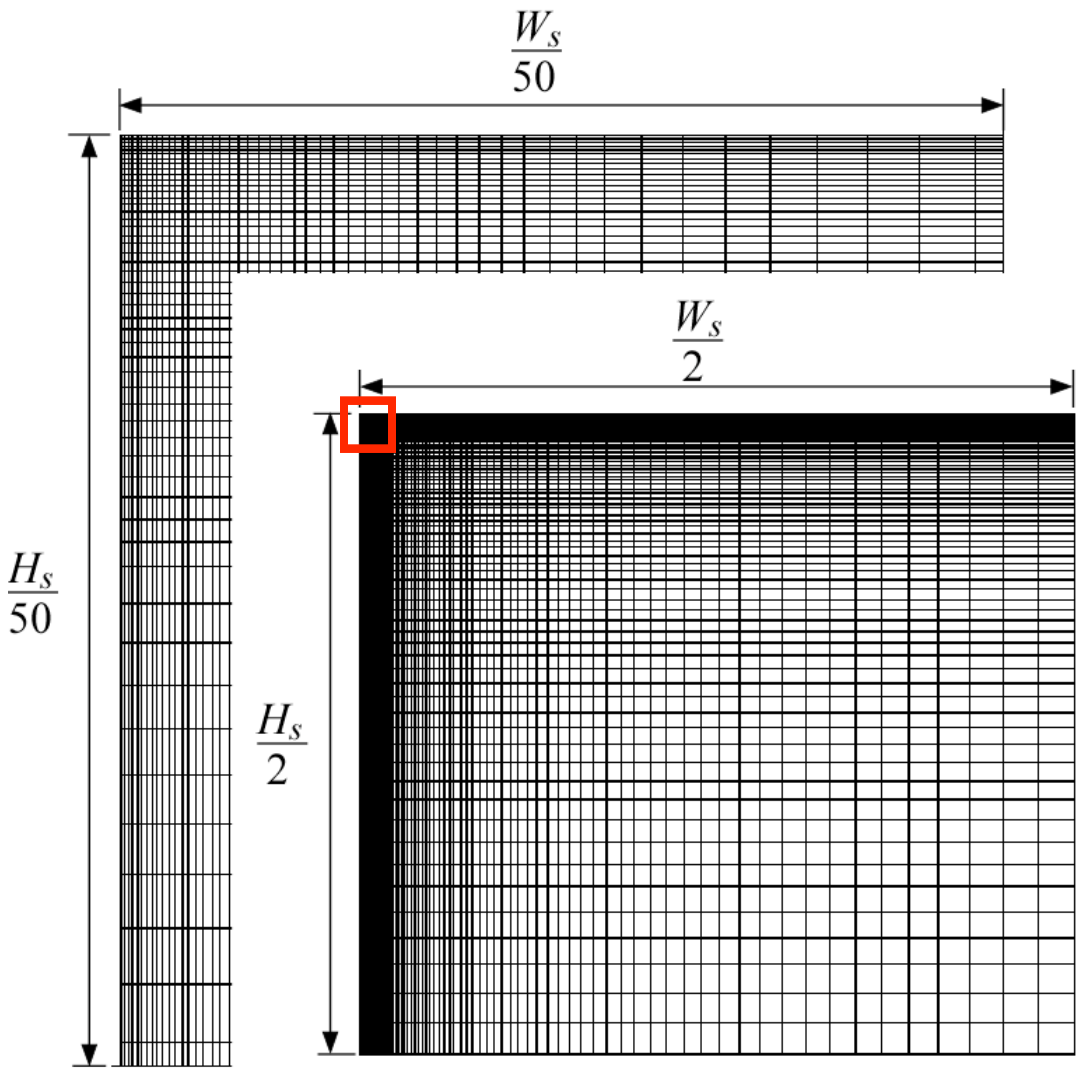
Bhatnagar and Recktenwald
ASME FED/HT 2004

CFD Model

- Quarter model
- 1.6×10^6 cells
- Highly graded mesh
- MARS convection scheme
- Low Reynolds number k-ε turbulence model



100×100 Mesh in Cross Section



Screen Models

Local pressure drop

$$\Delta p = \frac{1}{2} K_m \rho \upsilon_n^2$$

Idelchik model

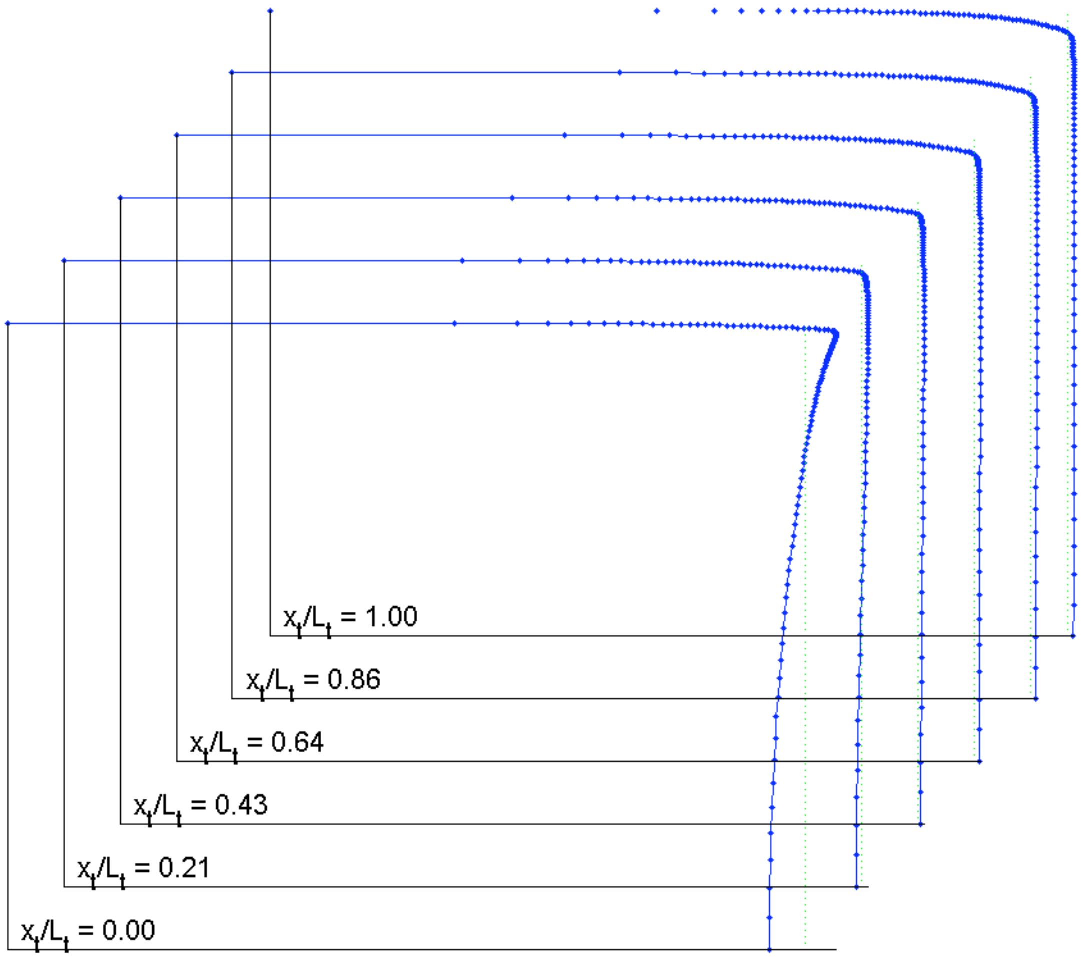
$$K_m = K_{\text{mesh}} K_{\text{Rn}} (1 - f) + \frac{(1 - f)^2}{f^2}$$

Star-CD model

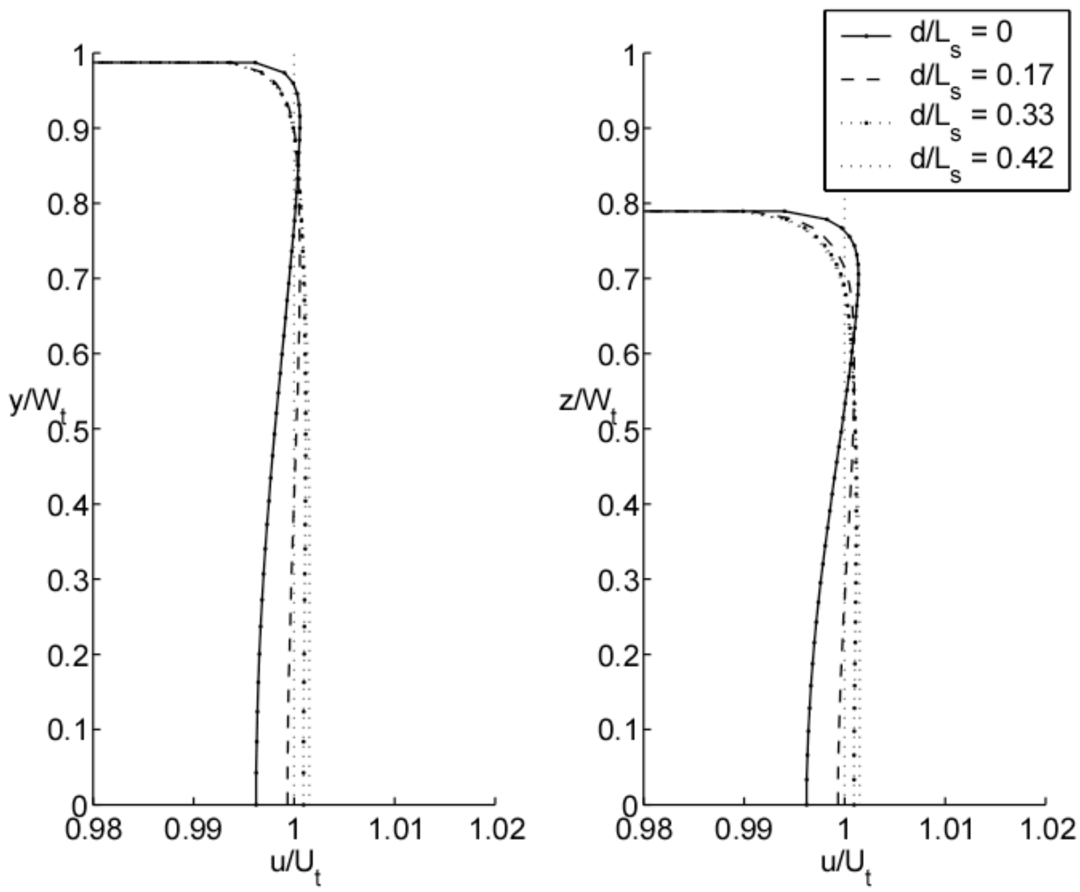
$$\Delta p = \rho \left(\alpha |\upsilon_n| + \beta \right) \upsilon_n$$

$$\alpha = \frac{K_m}{2} - \frac{\beta}{\upsilon_n} \qquad \beta = 0.01$$

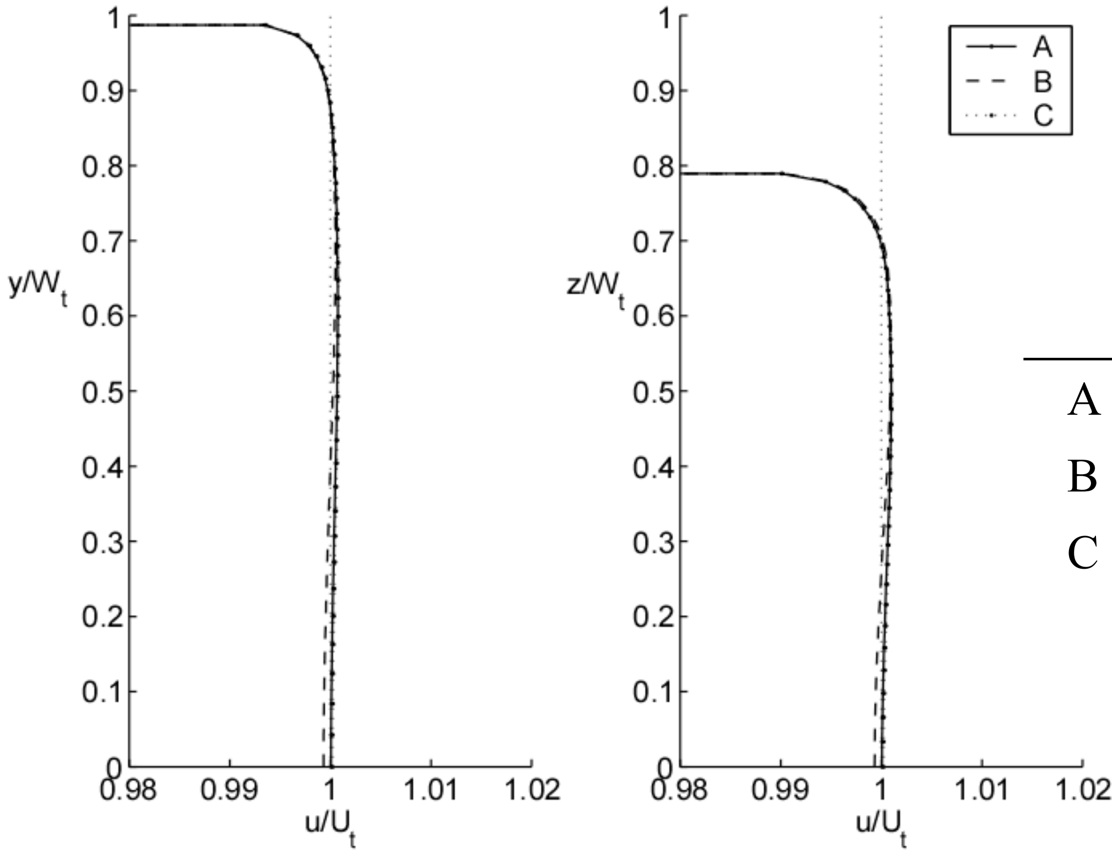
Velocity Profiles development in test section



Single screen in settling chamber

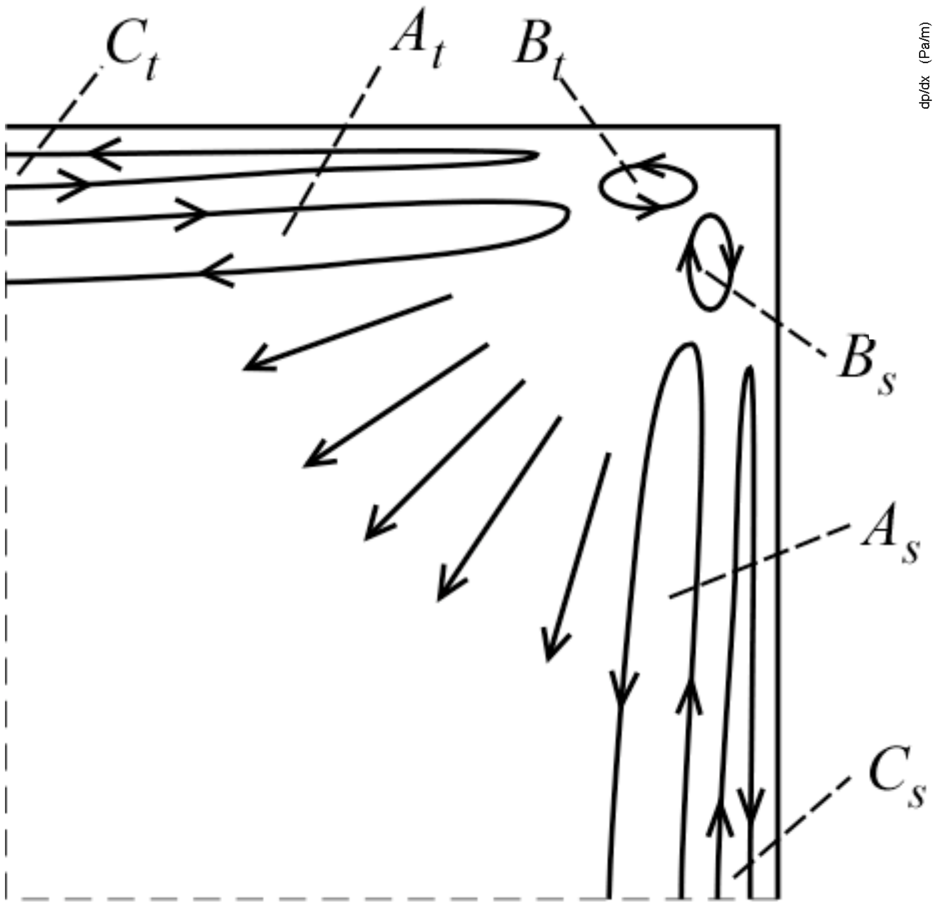


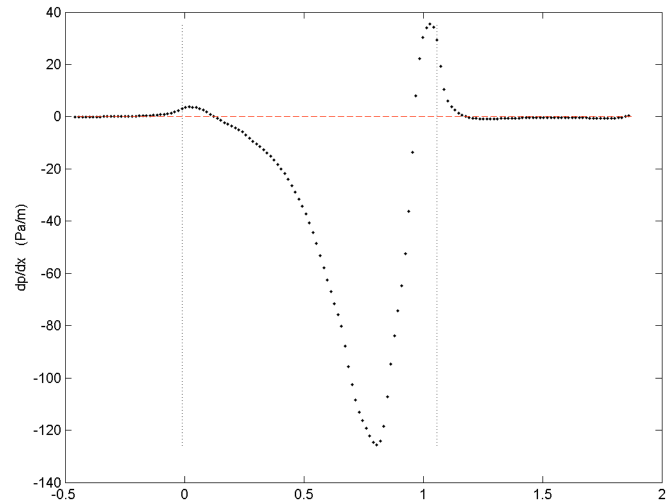
Two screens in settling chamber



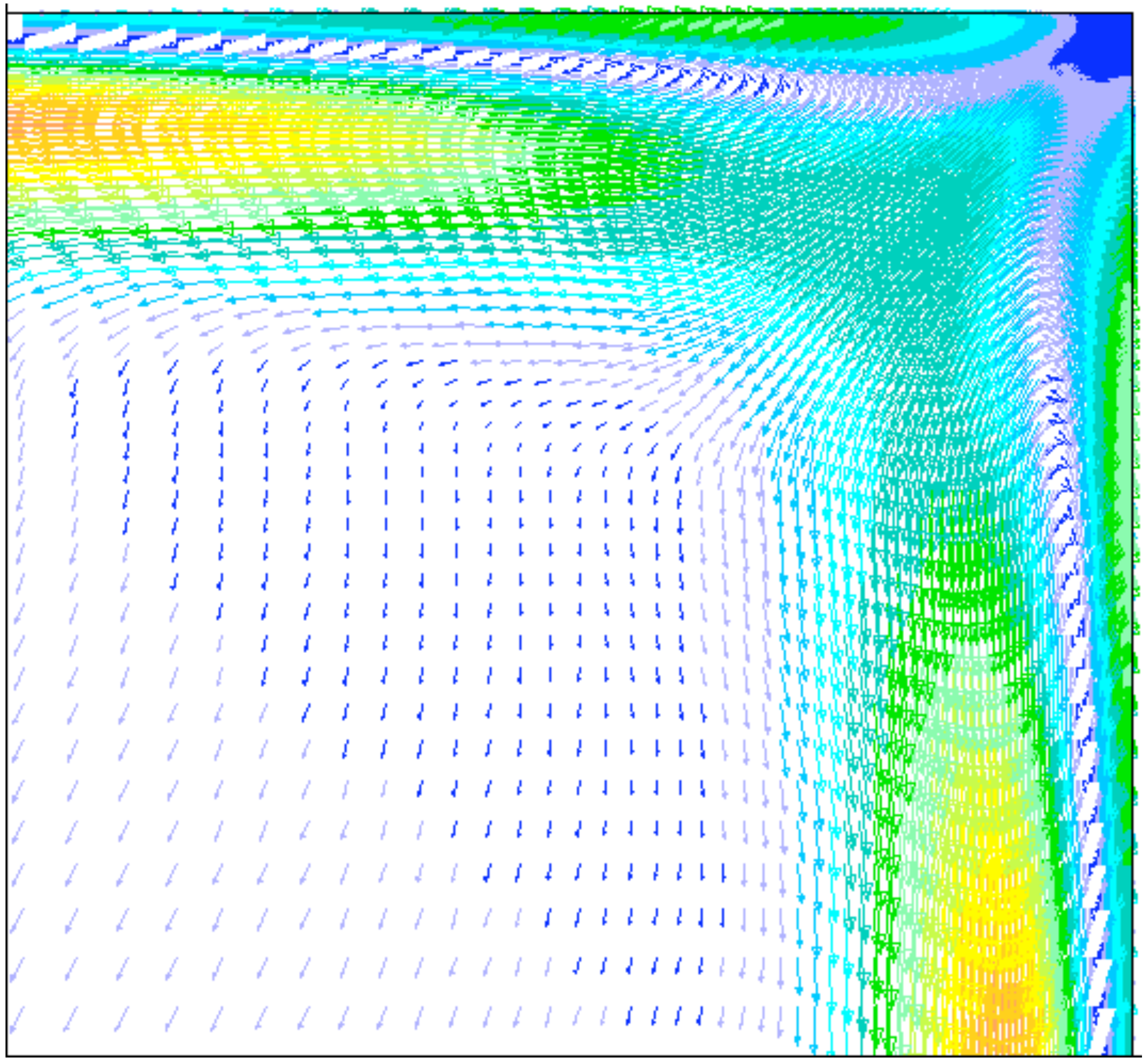
	d_1/L_s	d_2/L_s	f_1	f_2
A	0.42	0.75	0.50	0.58
B	0.33	0.75	0.50	0.58
C	0.33	0.75	0.58	0.65

Secondary flow in corners





Secondary flow in corners

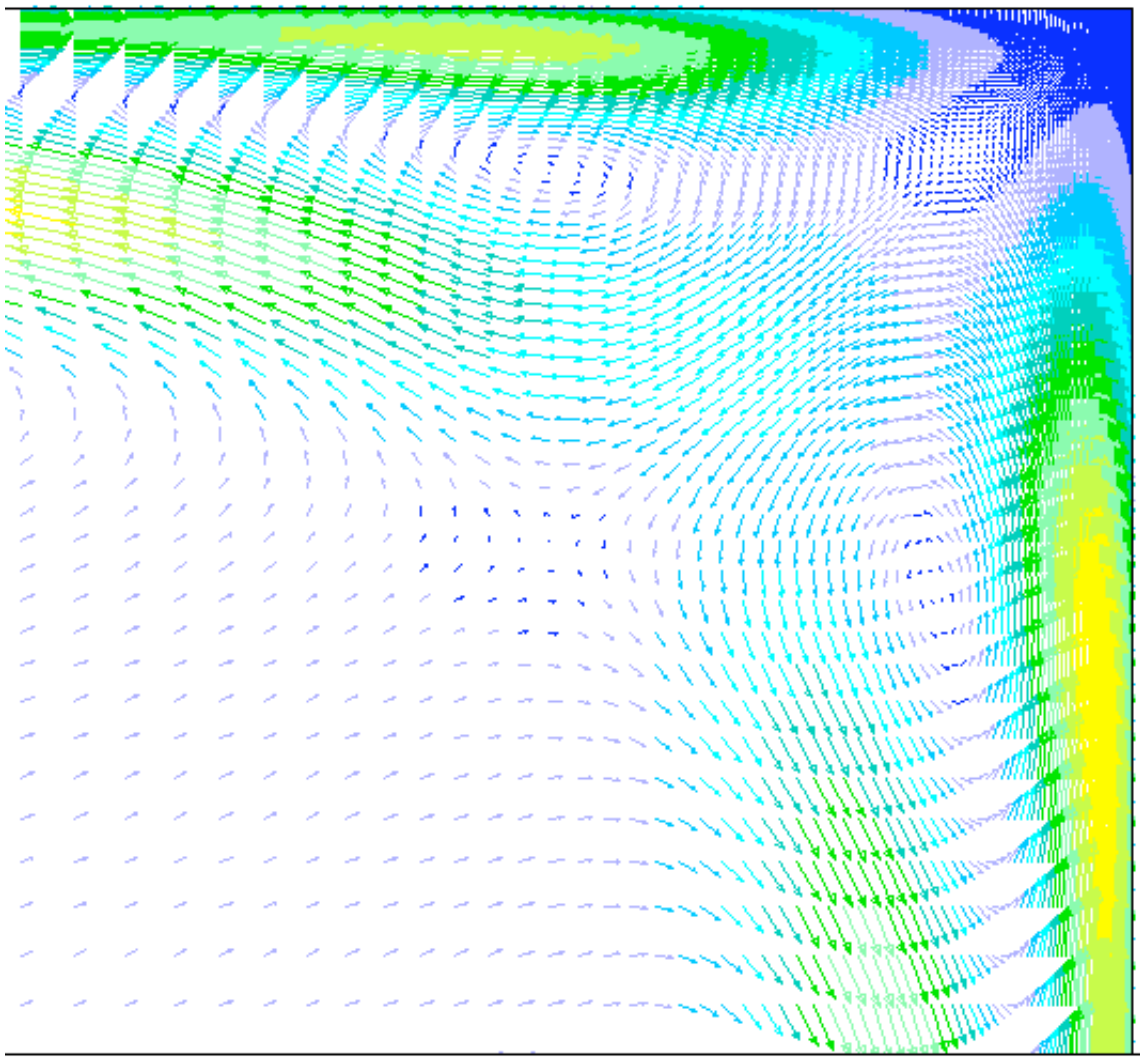


$x_t/L_t = 0$

$|V_{\max}| = 0.042U_t$

Bhatnagar and Recktenwald
ASME FED/HT 2004

Secondary flow in corners

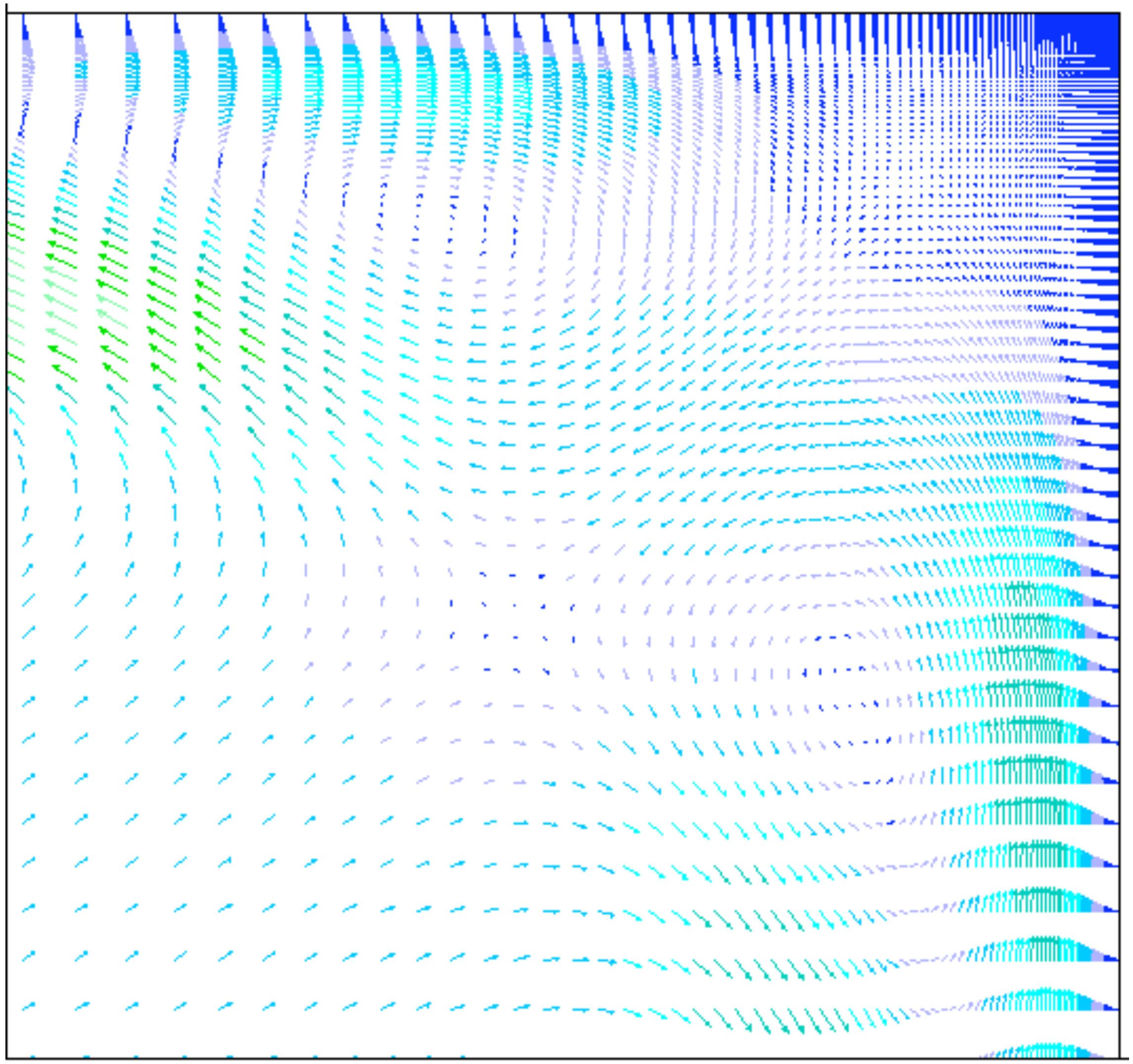


$$x_t/L_t = 0.5$$

$$|V_{\max}| = 0.022U_t$$

Bhatnagar and Recktenwald
ASME FED/HT 2004

Secondary flow in corners



$x_t/L_t = 1$

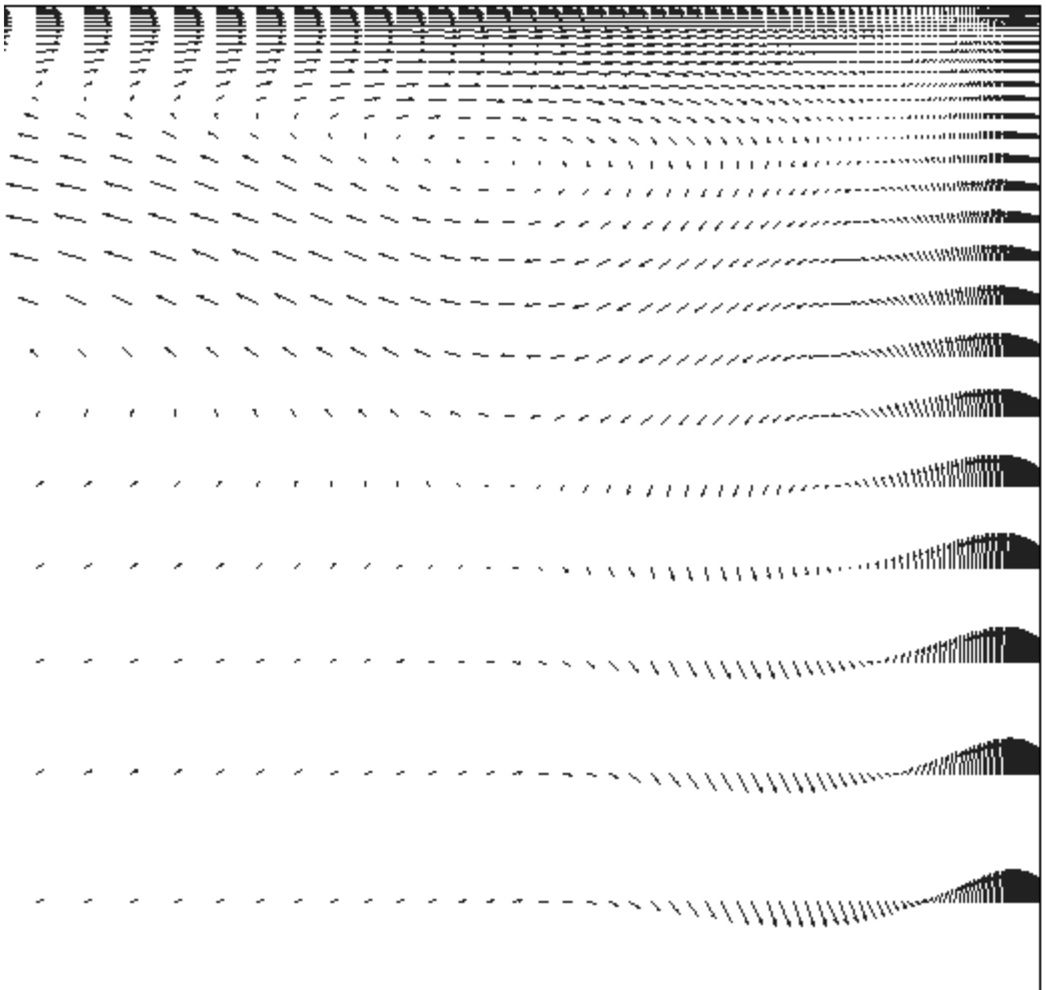
$|V_{\max}| = 0.014U_t$

Bhatnagar and Recktenwald
ASME FED/HT 2004

Conclusions

- Boundary layer and CFD analysis are complementary
- No separation predicted for $d/L_s < 0.35$ and $L_c/D_{\mathrm{hs}} = 0.81$
- Weak secondary flow in corners
- Wind tunnel is operating

The Team



Extra

100×100 Mesh in cross section