Asymptotic Models of Navier-Stokes Equations:

Applications in Biomecanics

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Aim

- simplification of Navier Stokes equations
- thanks to asymptotic theory:

  "Boundary Layer"

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Starting from Navier Stokes (Axi)

- we simplify NS to a Reduced set of equations
  - which contains the physical scales,
  - the most important phenomena
- much more simple set of equations: Integral equations (1D)
- cross comparisons in some cases of NS/ RNSP/ Integral

Prandtl 04
Golstein 48

paradox of upstream influence

- *Triple Deck*

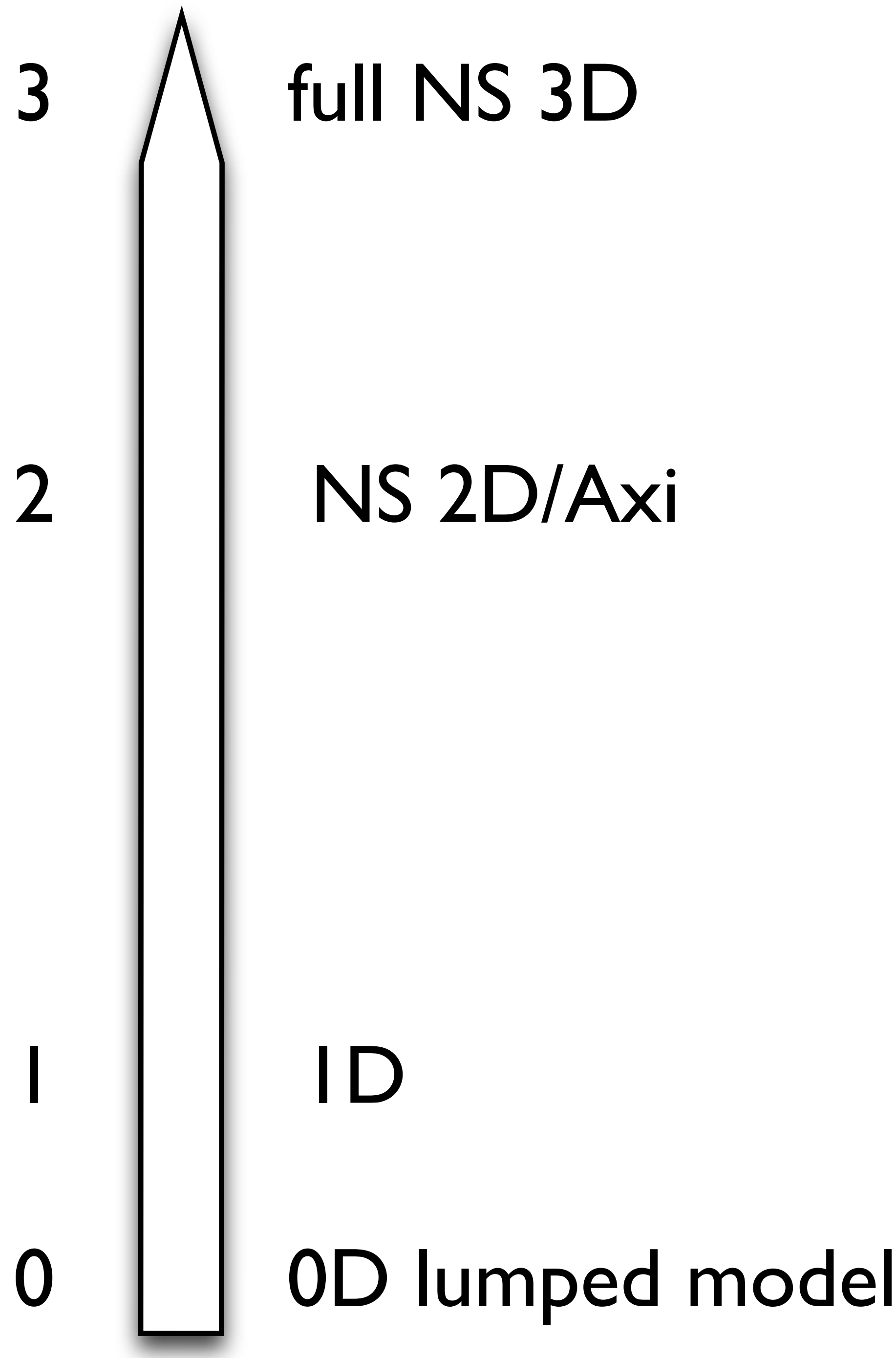
Lighthill
Stewartson Neiland Messiter 69
Smith

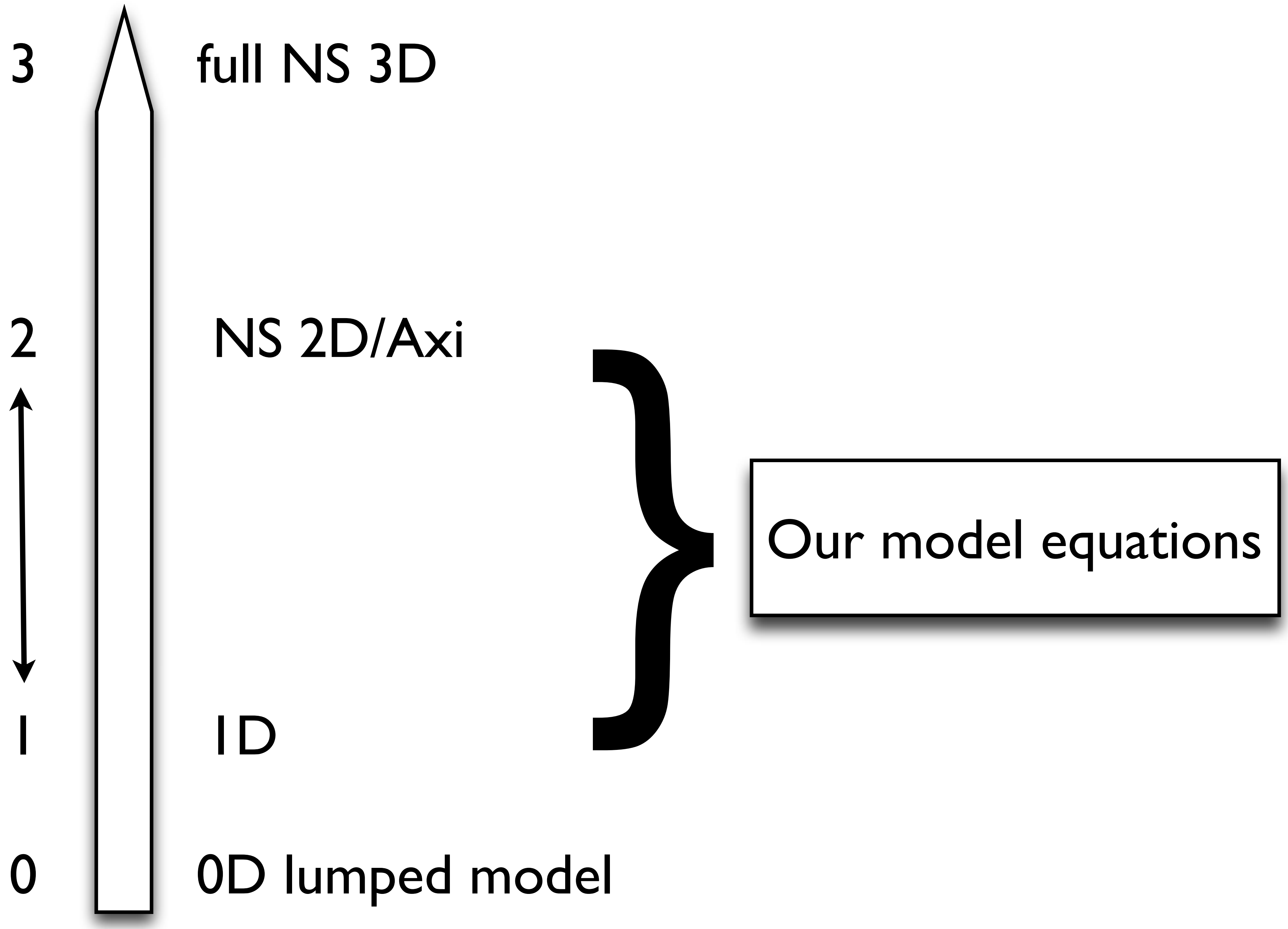
- *Interactive Boundary Layer / Viscous Inviscid Interactions*

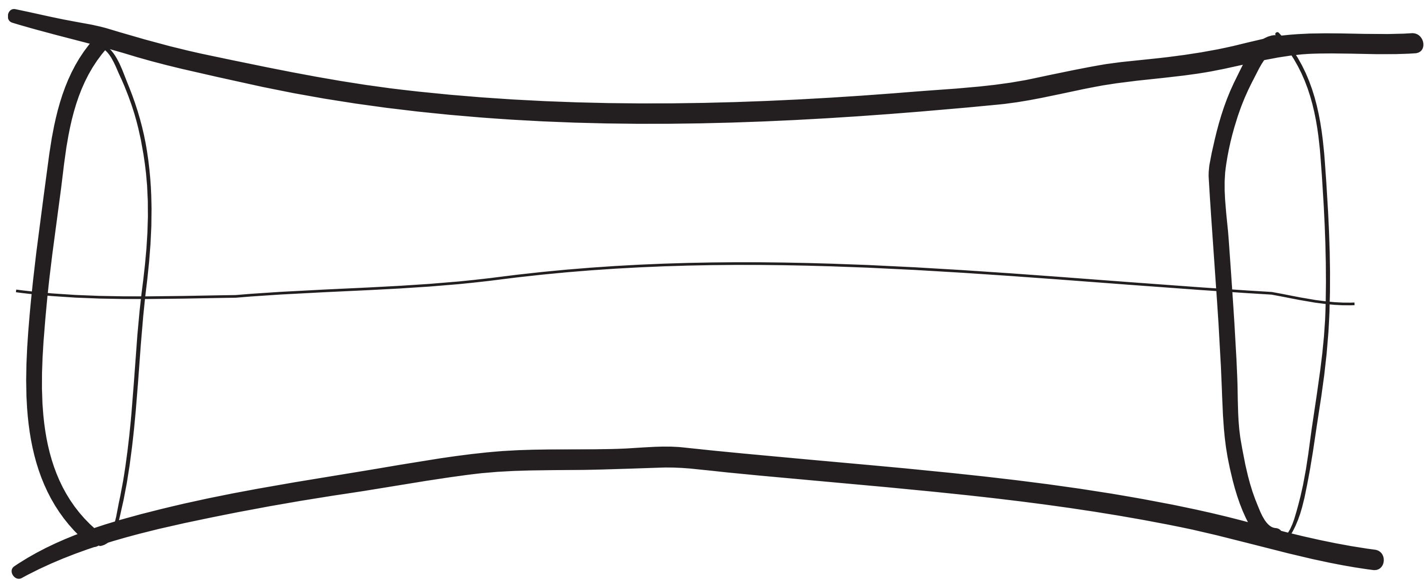
Le Balleur 78, Carter 79, Cebeci 70s
Veldman 81

- *Boundary layer Asymptotics*

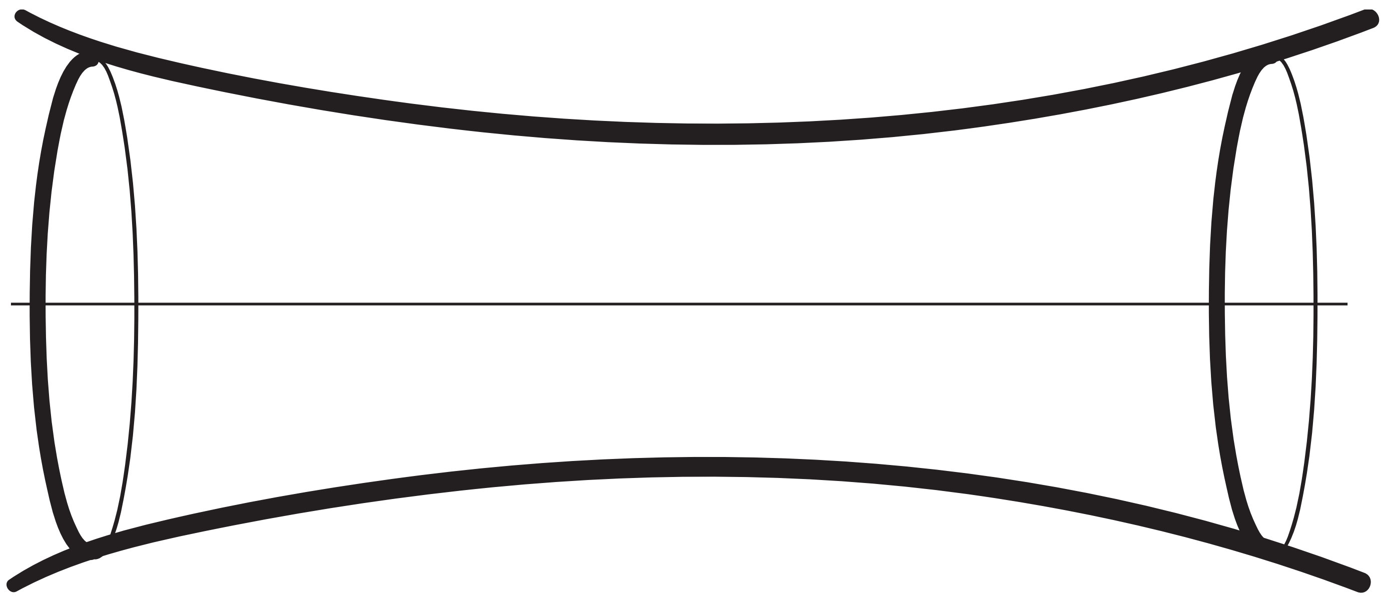
Sychev, Ruban, Sychev, Korelev, 98
Sobey 00
Cebeci Cousteix 01
Mauss Cousteix 07 (SCEM)


3
full NS 3D
2
NS 2D/Axi
1
1D
0
0D lumped model

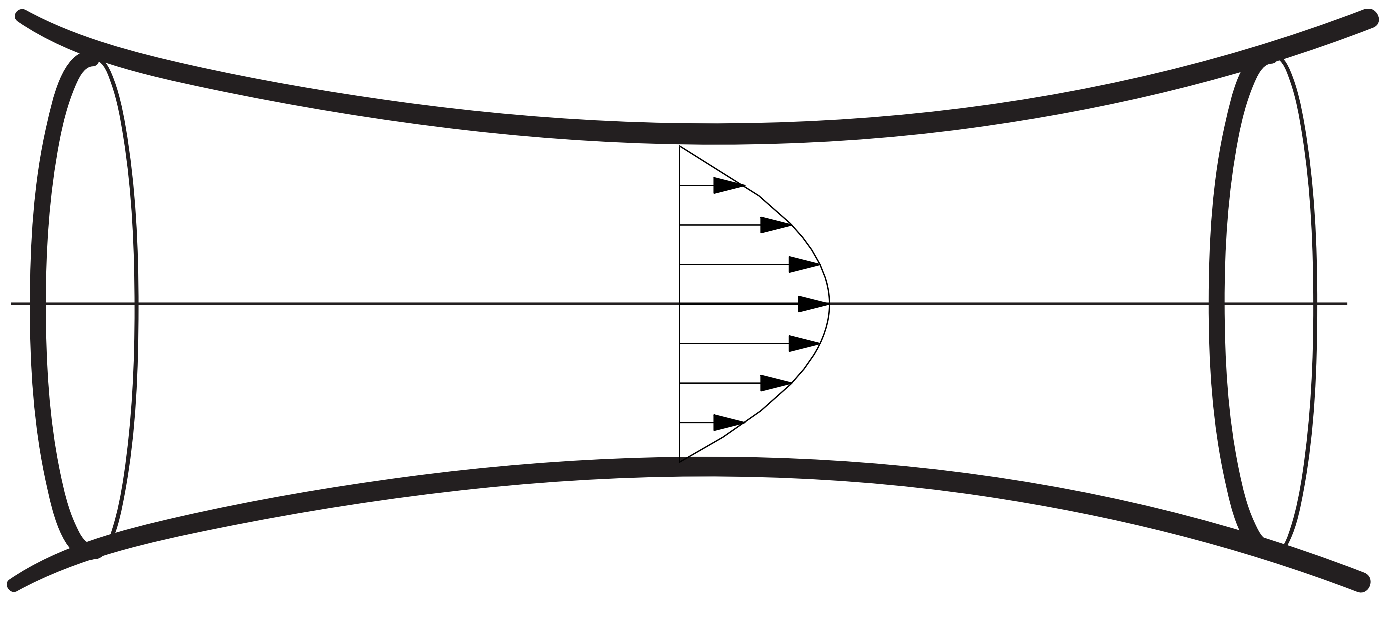

3
full NS 3D
2
NS 2D/Axi
1
1D
0
0D lumped model
Our model equations



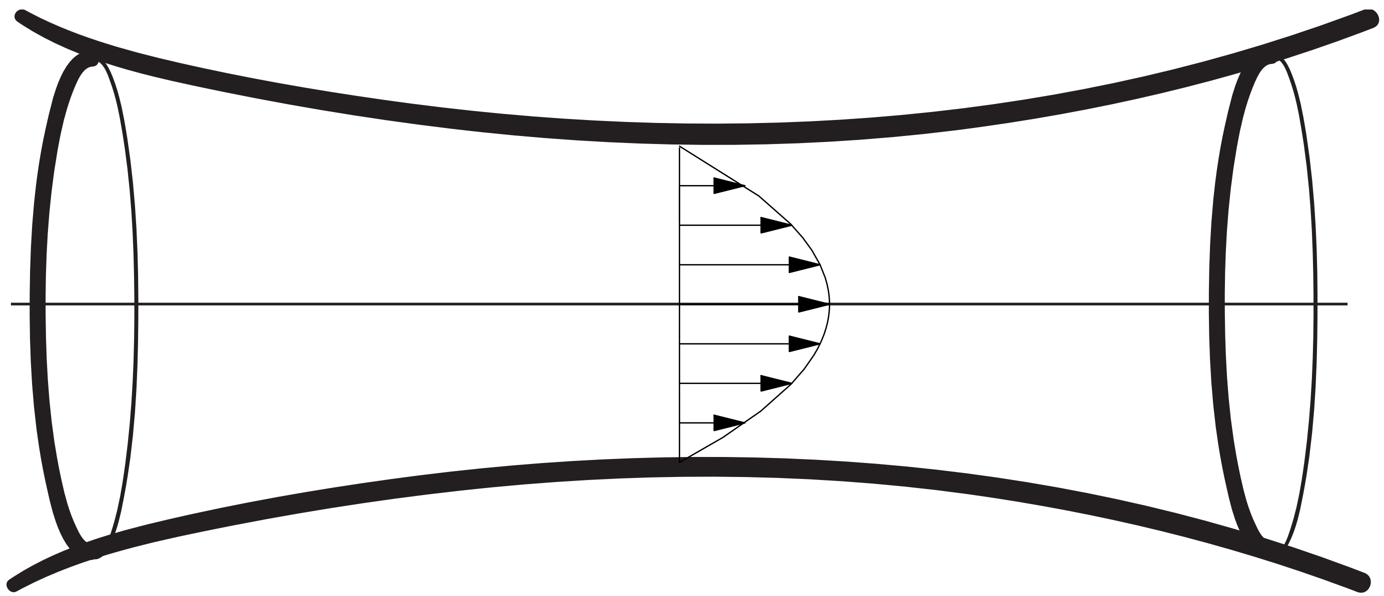
reality?



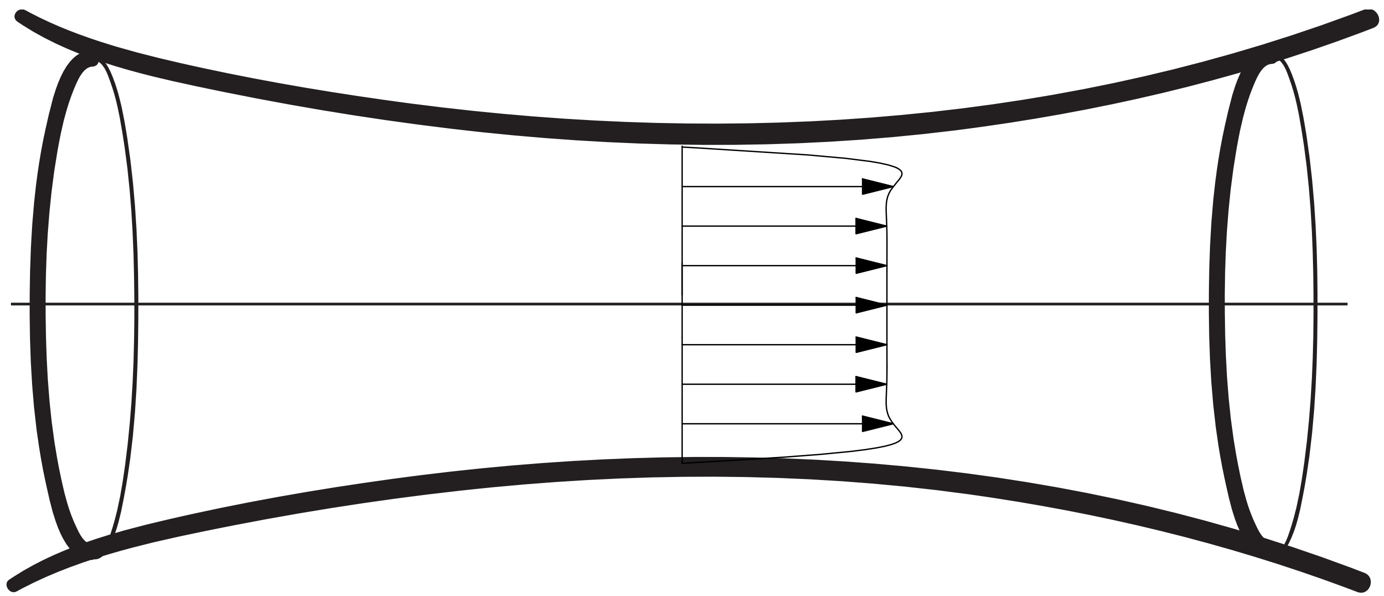
straight pipe, smooth walls, symmetry



Interactive Boundary Layer



Interactive Boundary Layer



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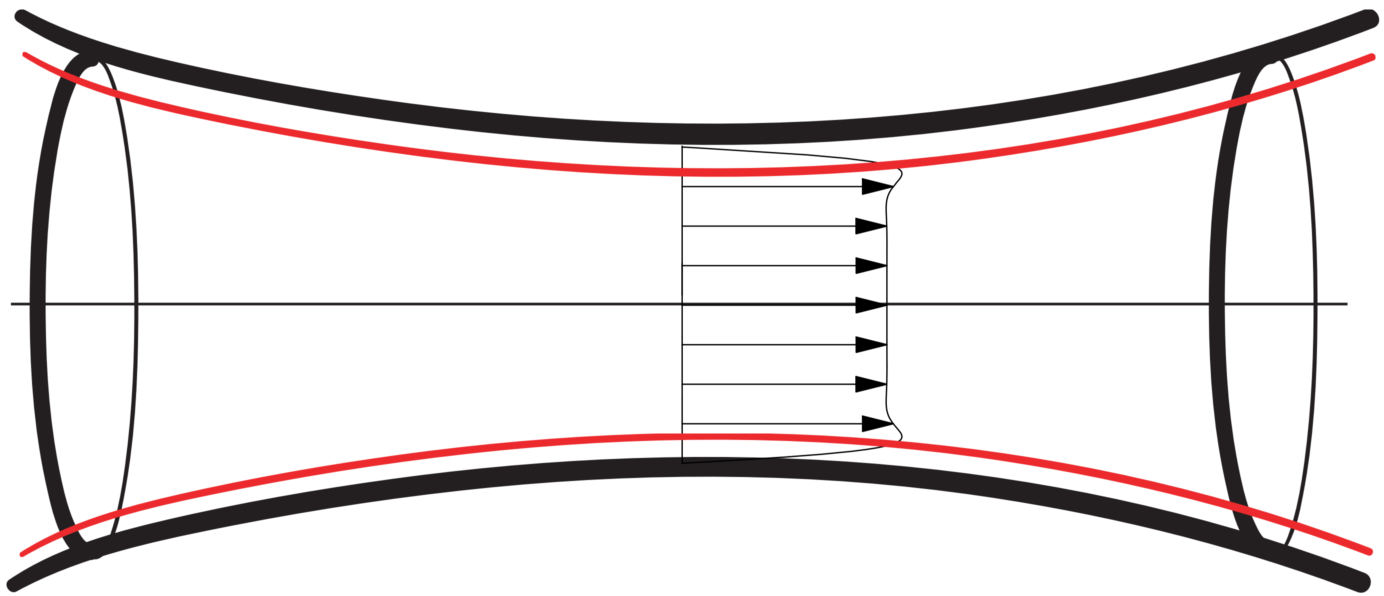

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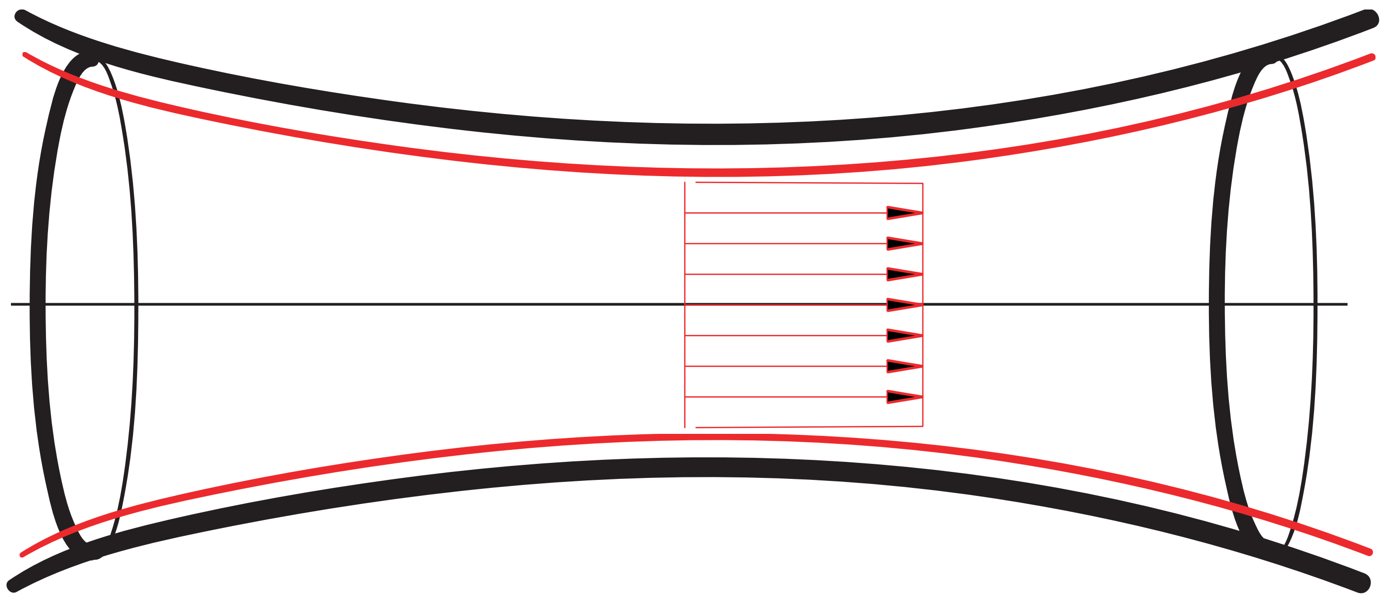

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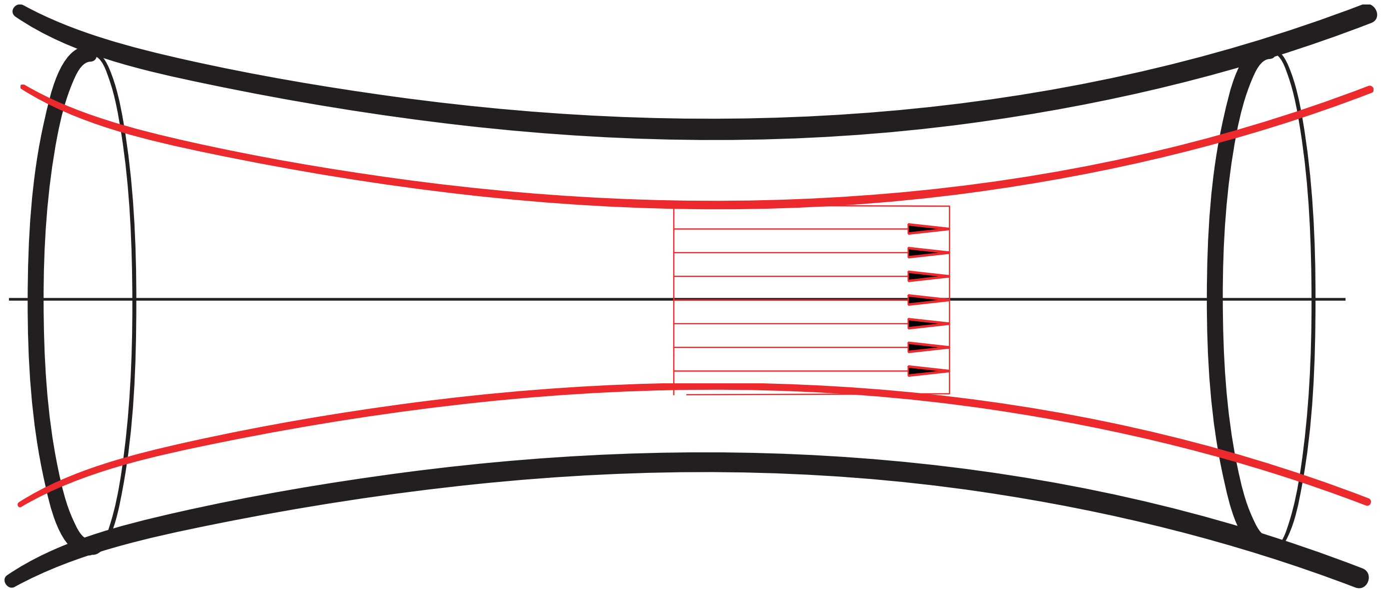
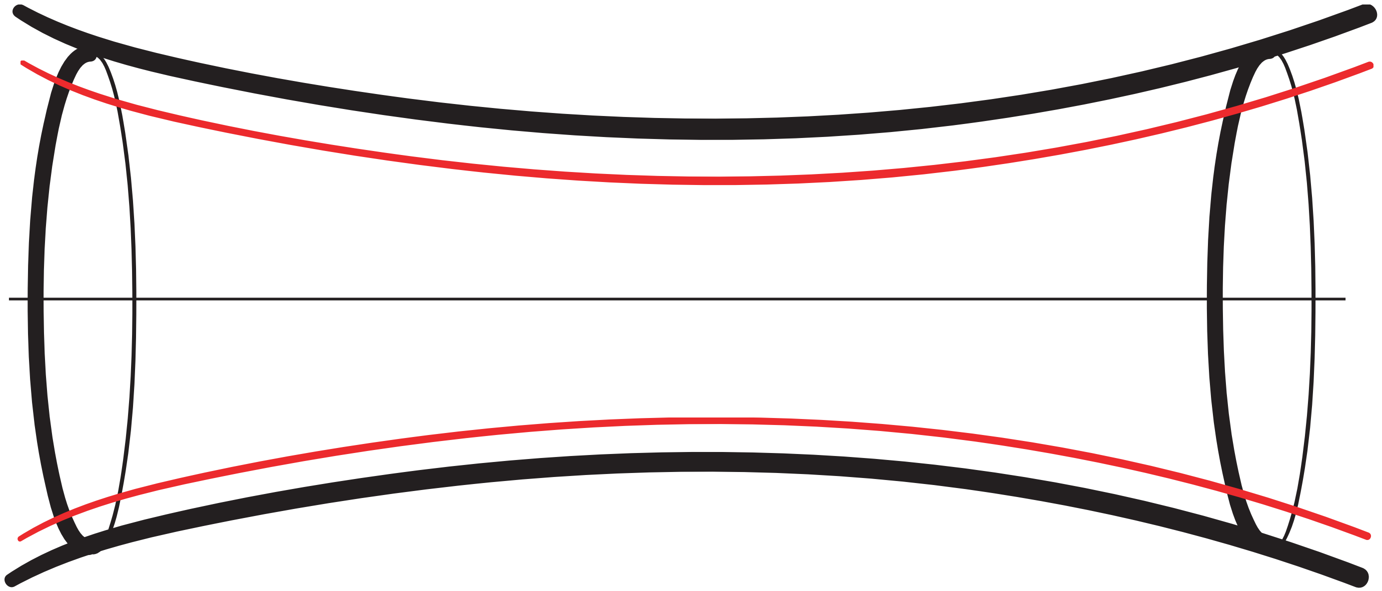
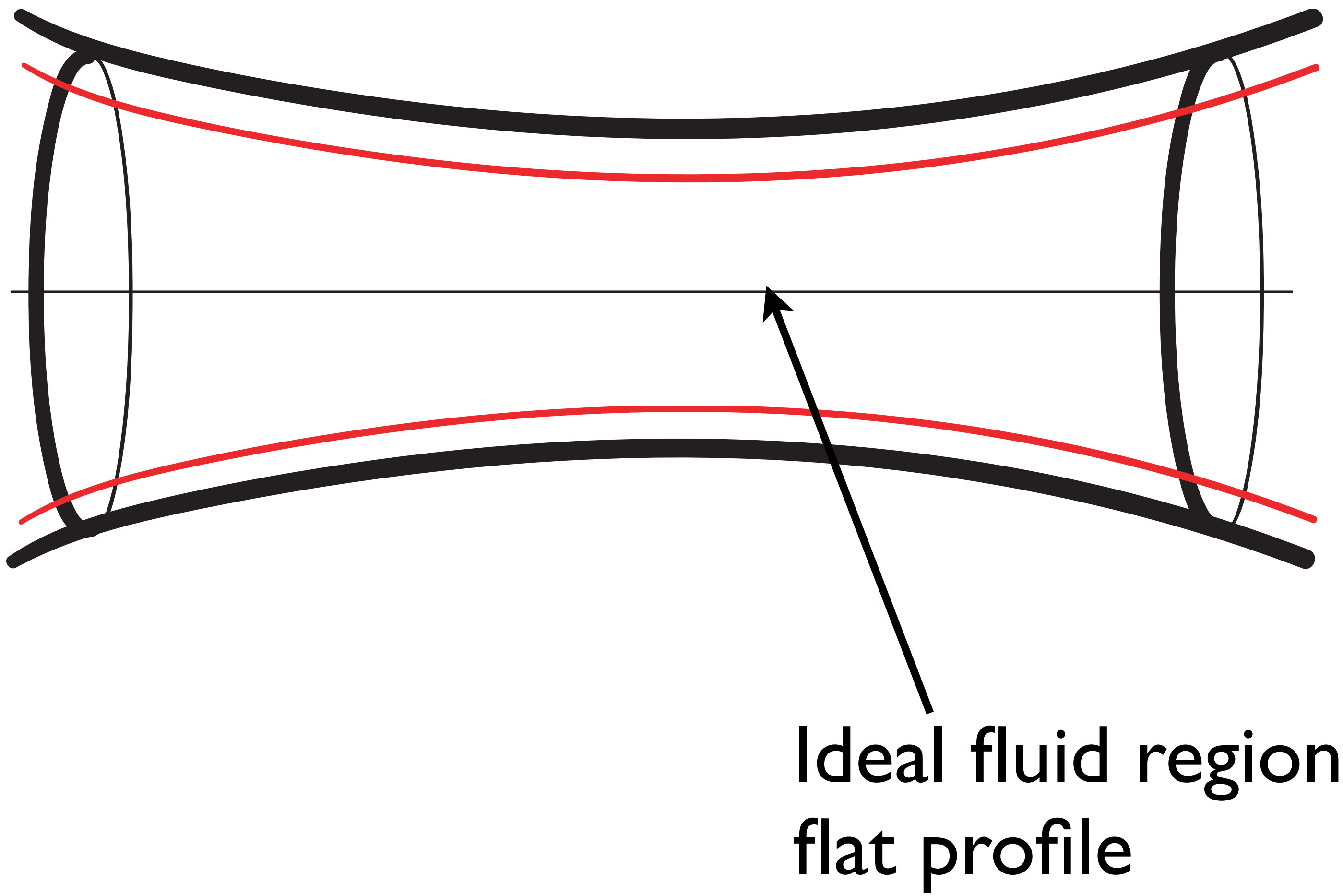


Interactive Boundary Layer



Interactive Boundary Layer



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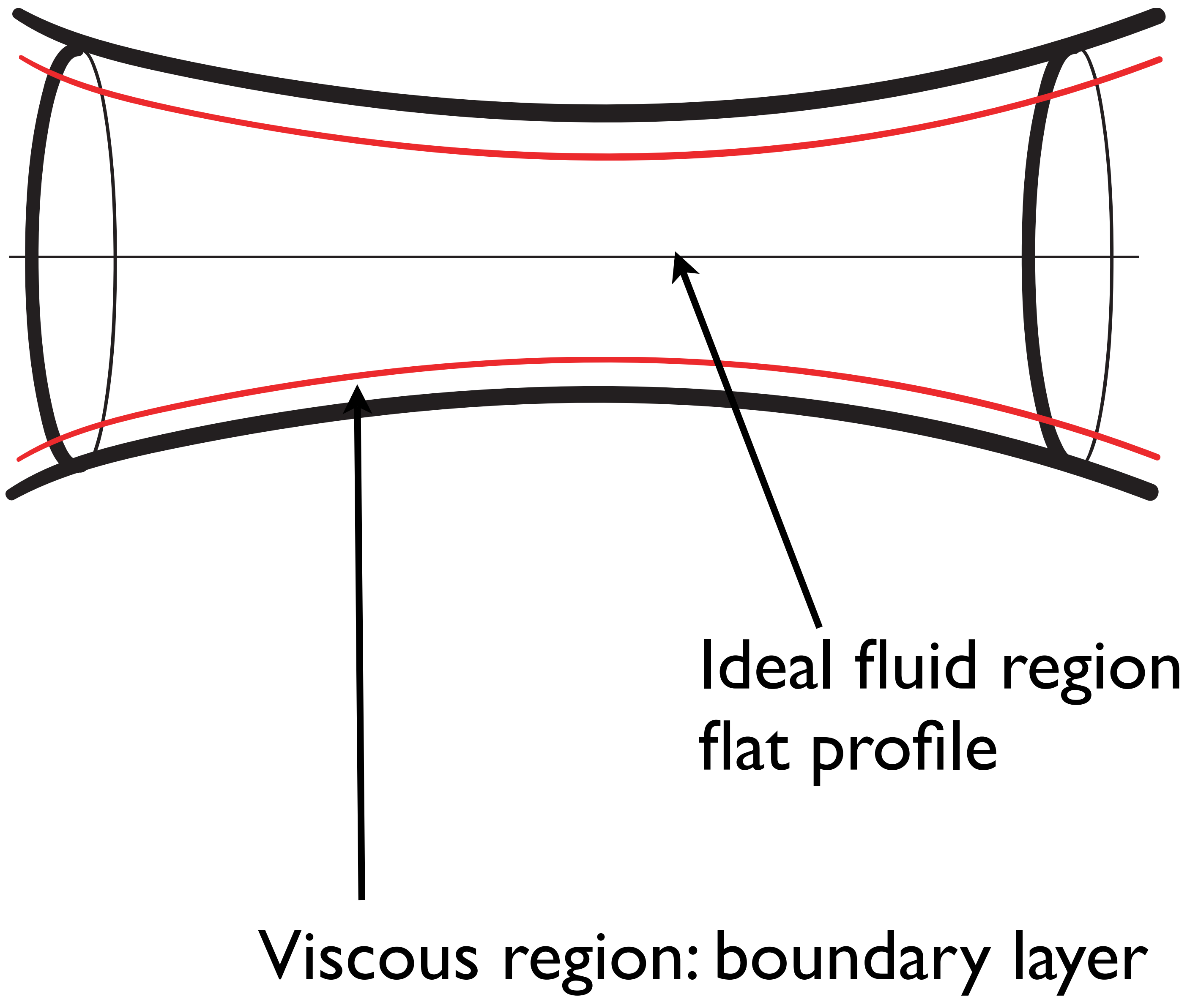
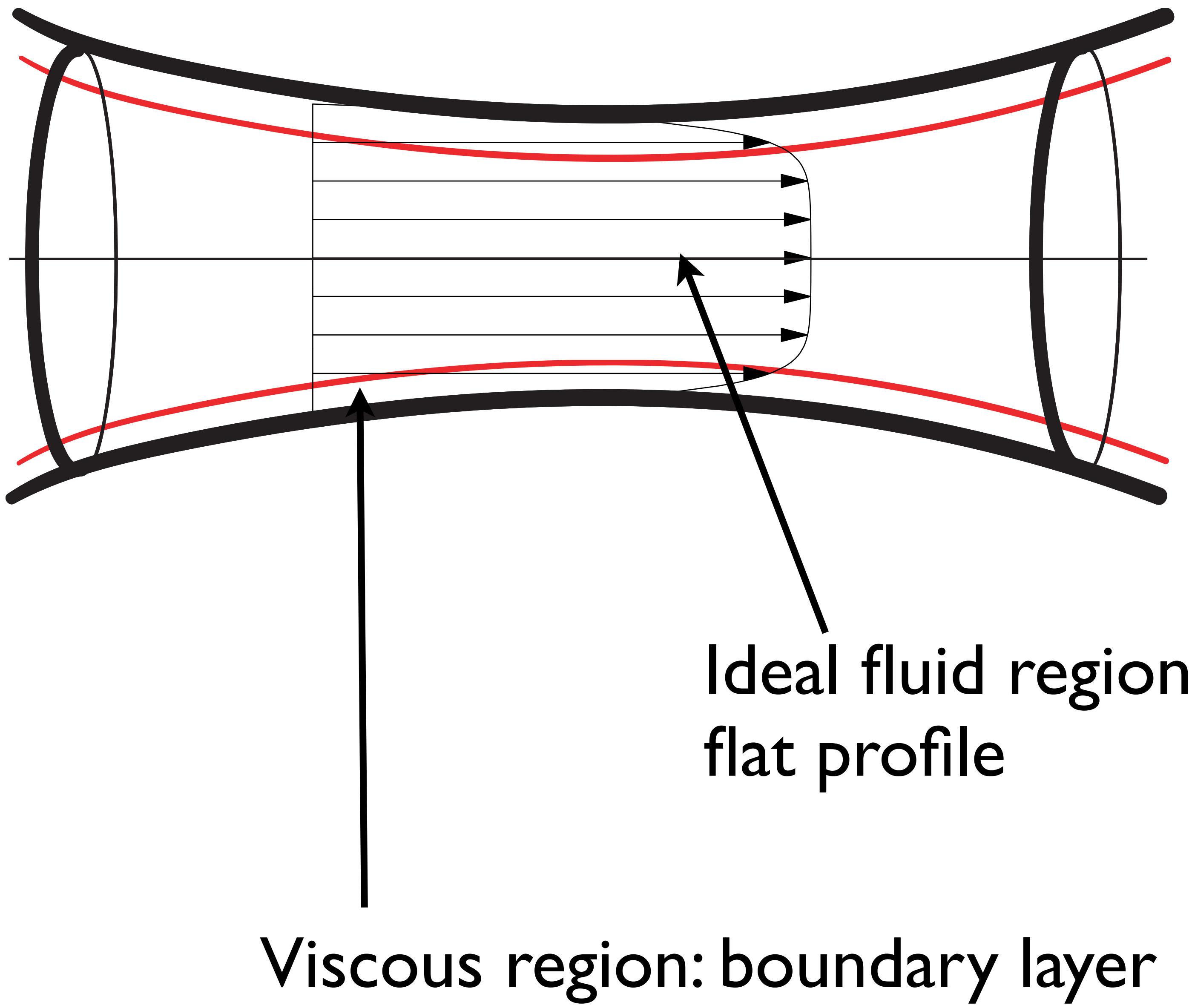
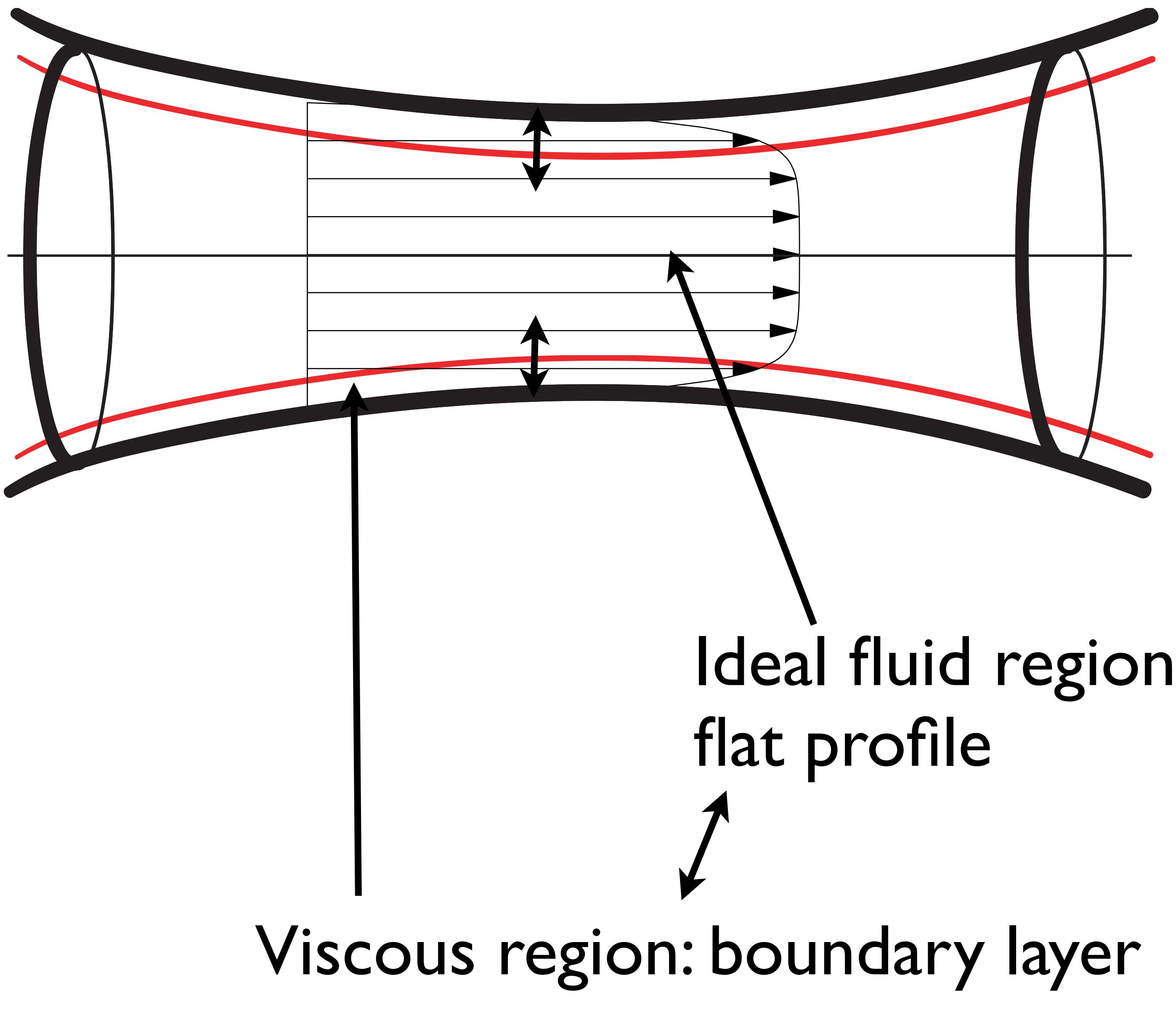


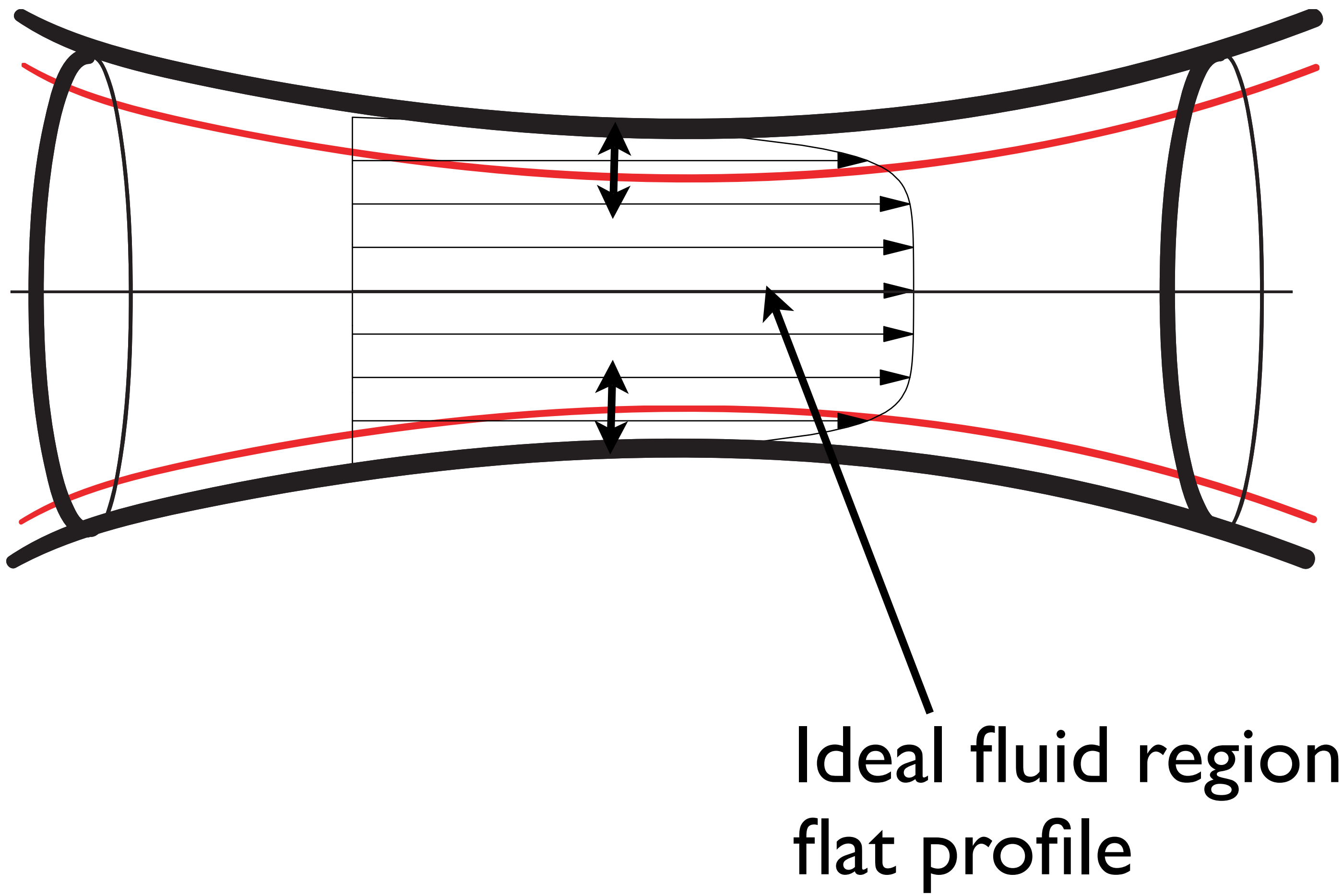
Interactive Boundary Layer



Interactive Boundary Layer

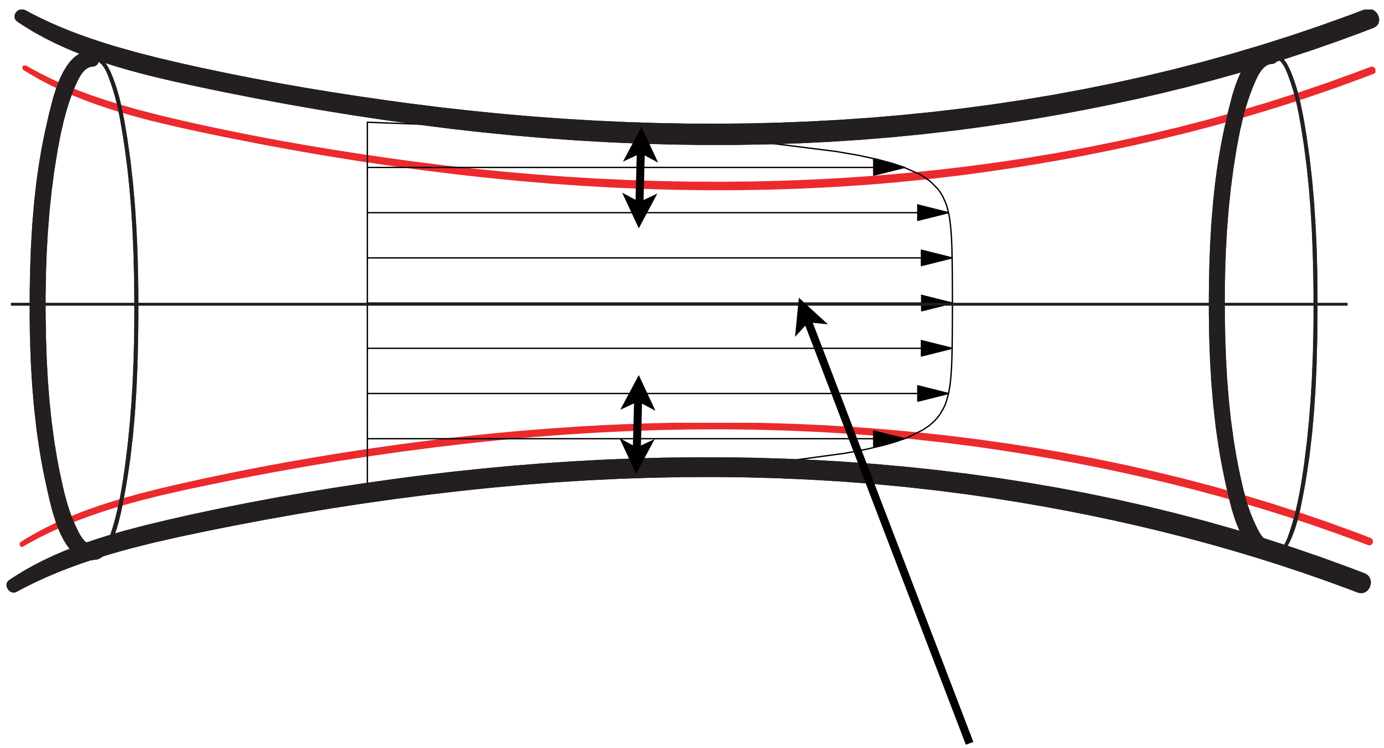


Interactive Boundary Layer



steady/ or large convective acceleration

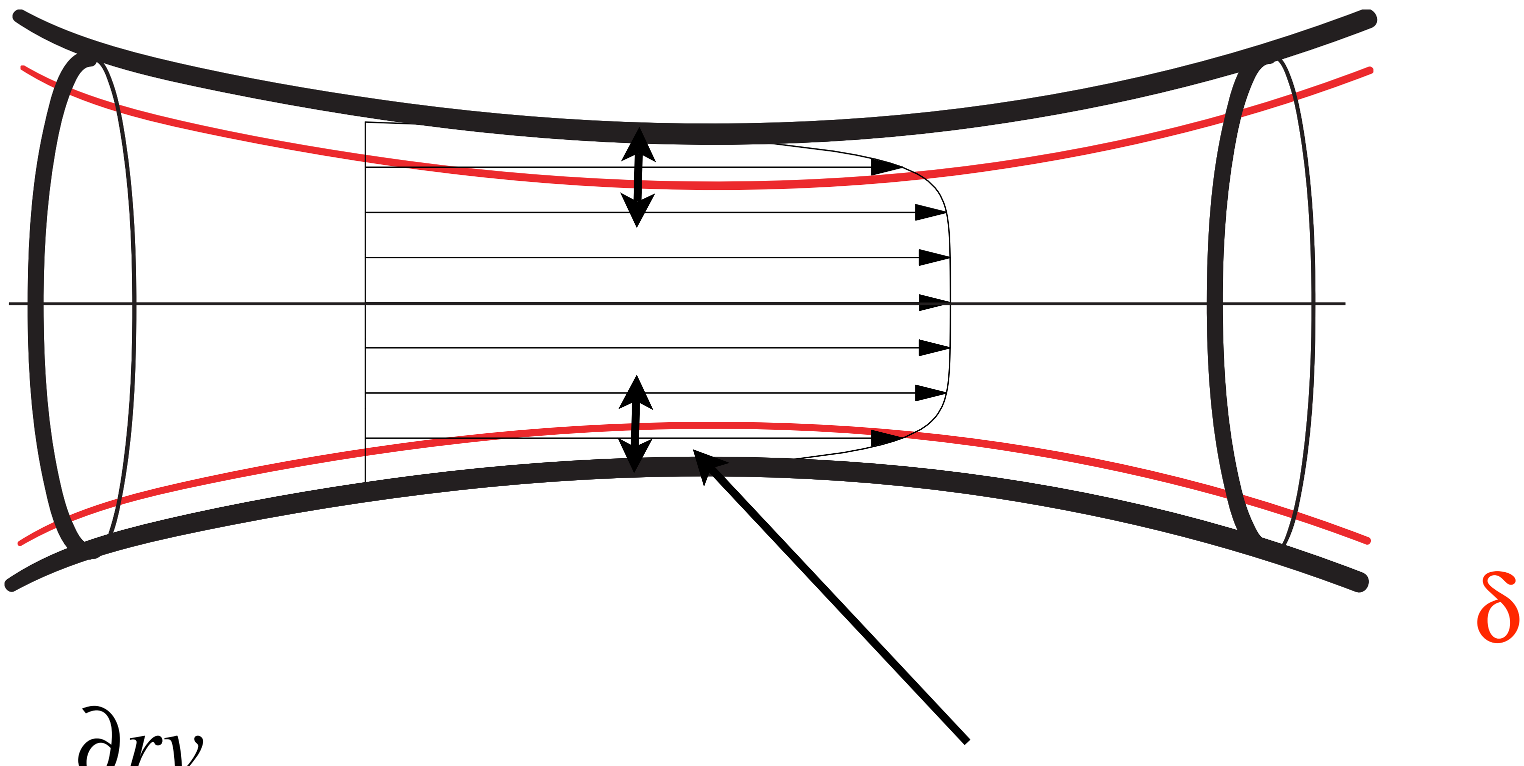
Interactive Boundary Layer



Ideal fluid region
flat profile

$$U_e S = cst$$

Interactive Boundary Layer



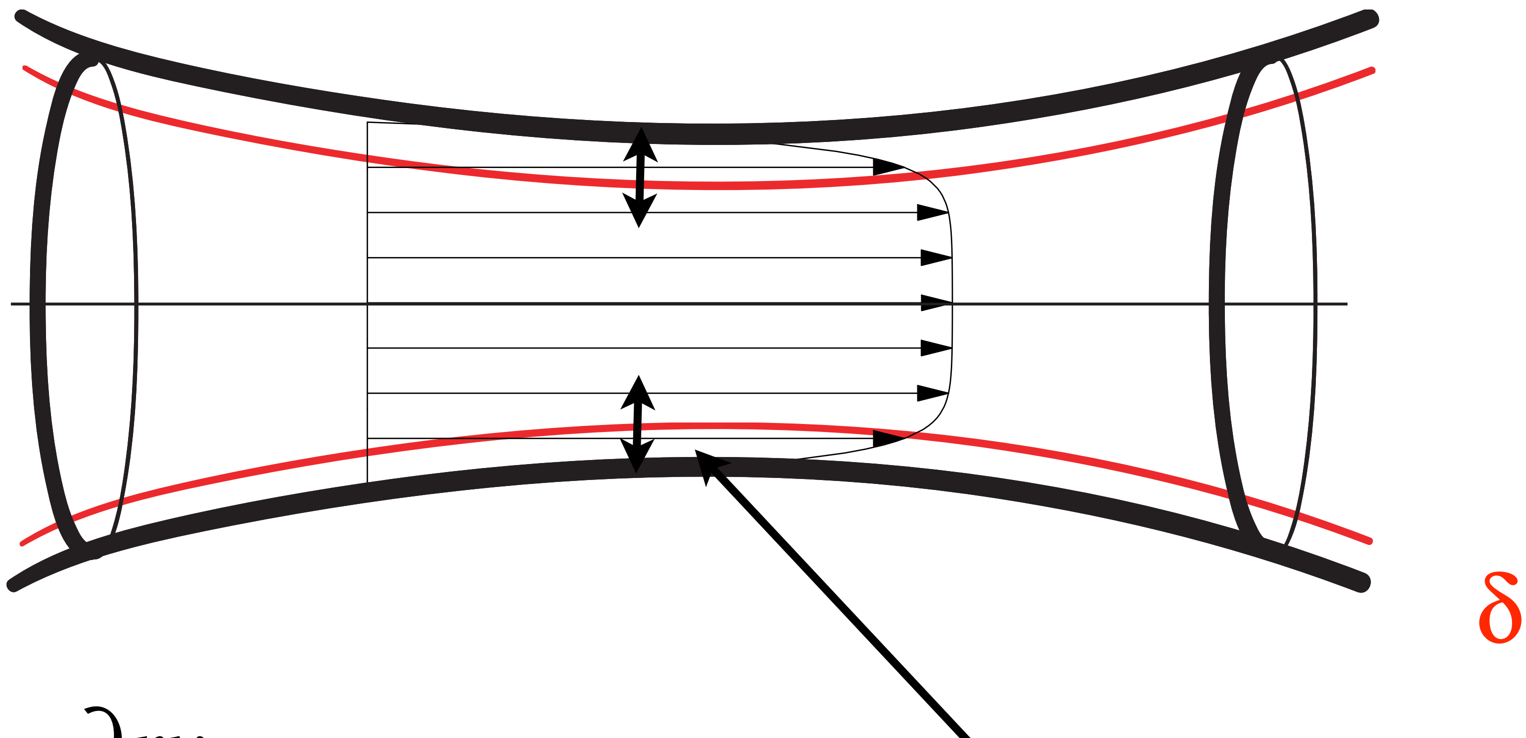
$$\frac{\partial u}{\partial x} + \frac{\partial r v}{r \partial r} = 0$$

$$\frac{\partial u}{\partial t} + u\frac{\partial}{\partial x}u + v\frac{\partial}{\partial r}u = -\frac{\partial p}{\rho \partial x} + \nu \frac{\partial}{r\partial r} r \frac{\partial u}{\partial r} \quad + \ldots$$

X X

steady/ or large convective acceleration

Interactive Boundary Layer

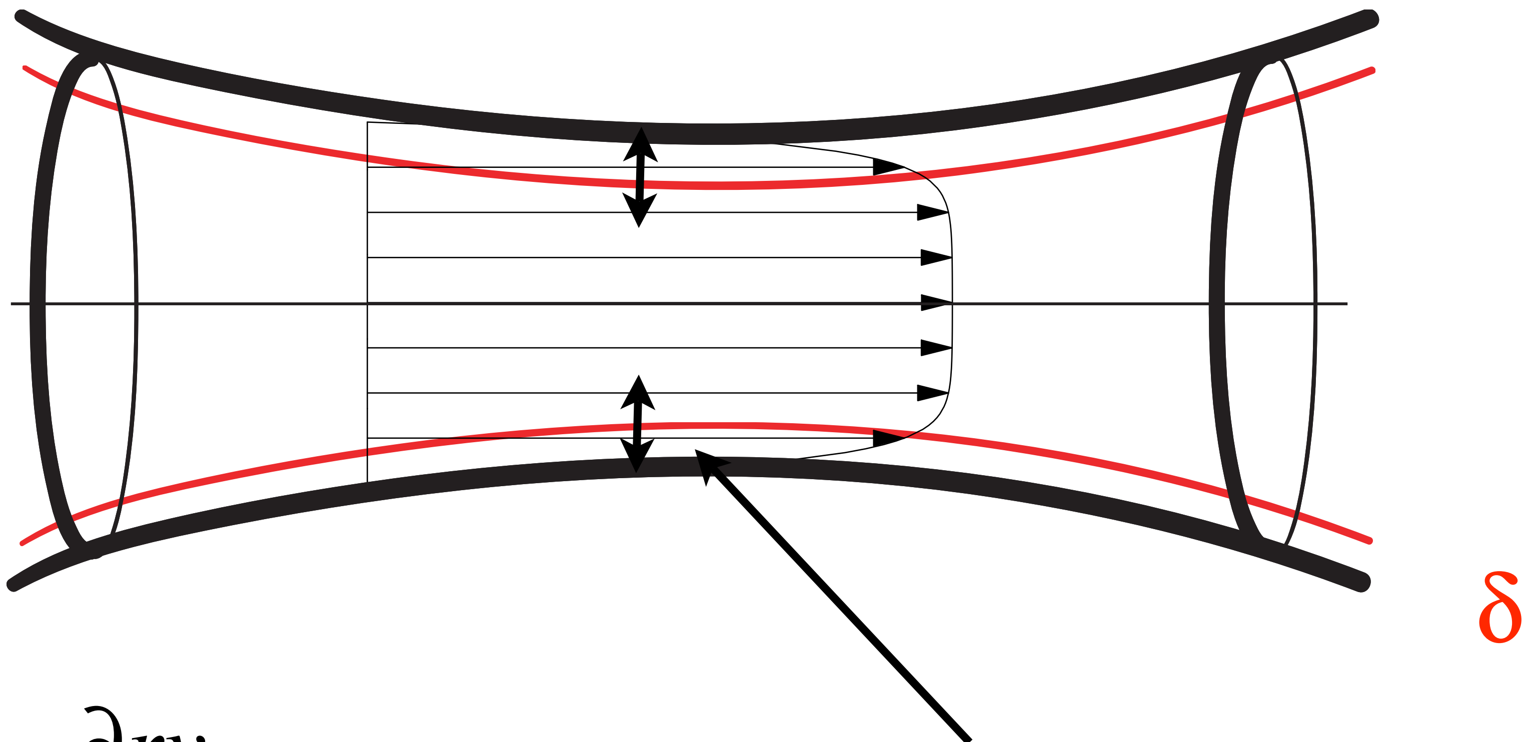


$$\frac{\partial u}{\partial x} + \frac{\partial rv}{r\partial r} = 0$$

$$\boxed{\frac{U_0^2}{\lambda}} = -\frac{\partial p}{\rho \partial x} + \boxed{\frac{\nu}{U_0 \lambda}\frac{\lambda^2}{\delta^2}\frac{U_0^2}{\lambda}} \quad 0 = -\frac{\partial p}{\rho \partial r}$$

steady/ or large convective acceleration

Interactive Boundary Layer



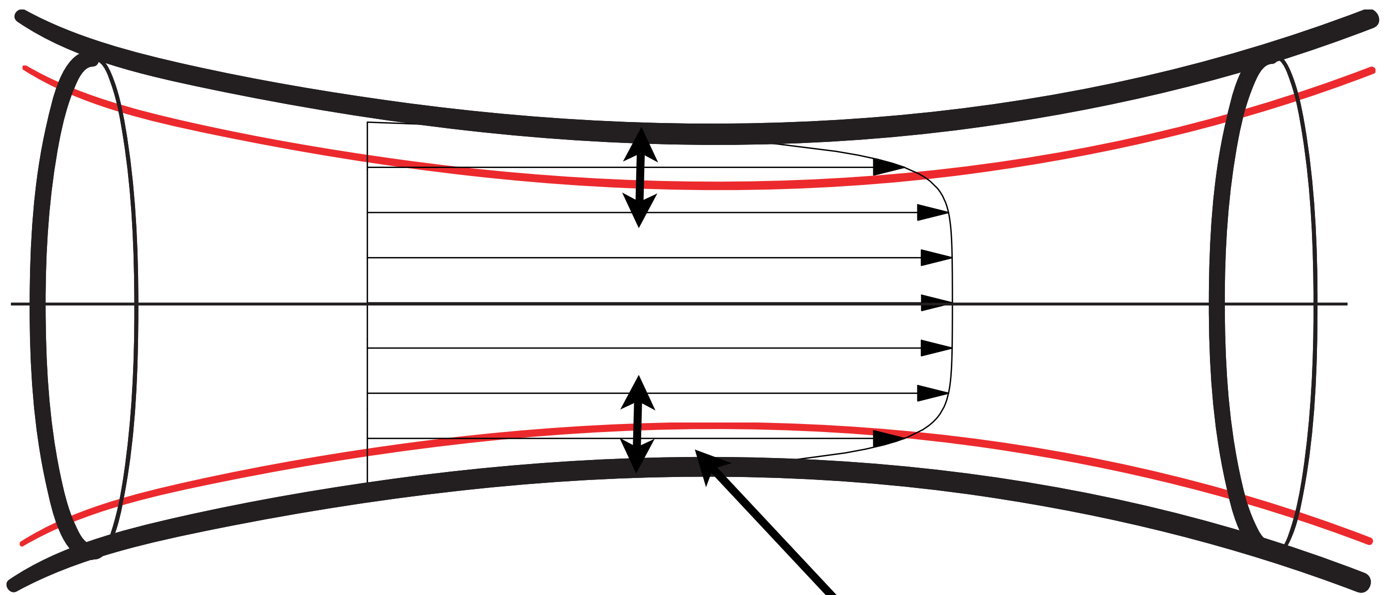
$$\frac{\partial u}{\partial x} + \frac{\partial r v}{r \partial r} = 0$$

Viscous region: boundary layer

$$\boxed{\frac{U_0^2}{\lambda}} = -\frac{\partial p}{\rho \partial x} + \boxed{\frac{1}{Re}\frac{\lambda^2}{\delta^2}\frac{U_0^2}{\lambda}} \qquad 0 = -\frac{\partial p}{\rho \partial r}$$

steady/ or large convective acceleration

Interactive Boundary Layer



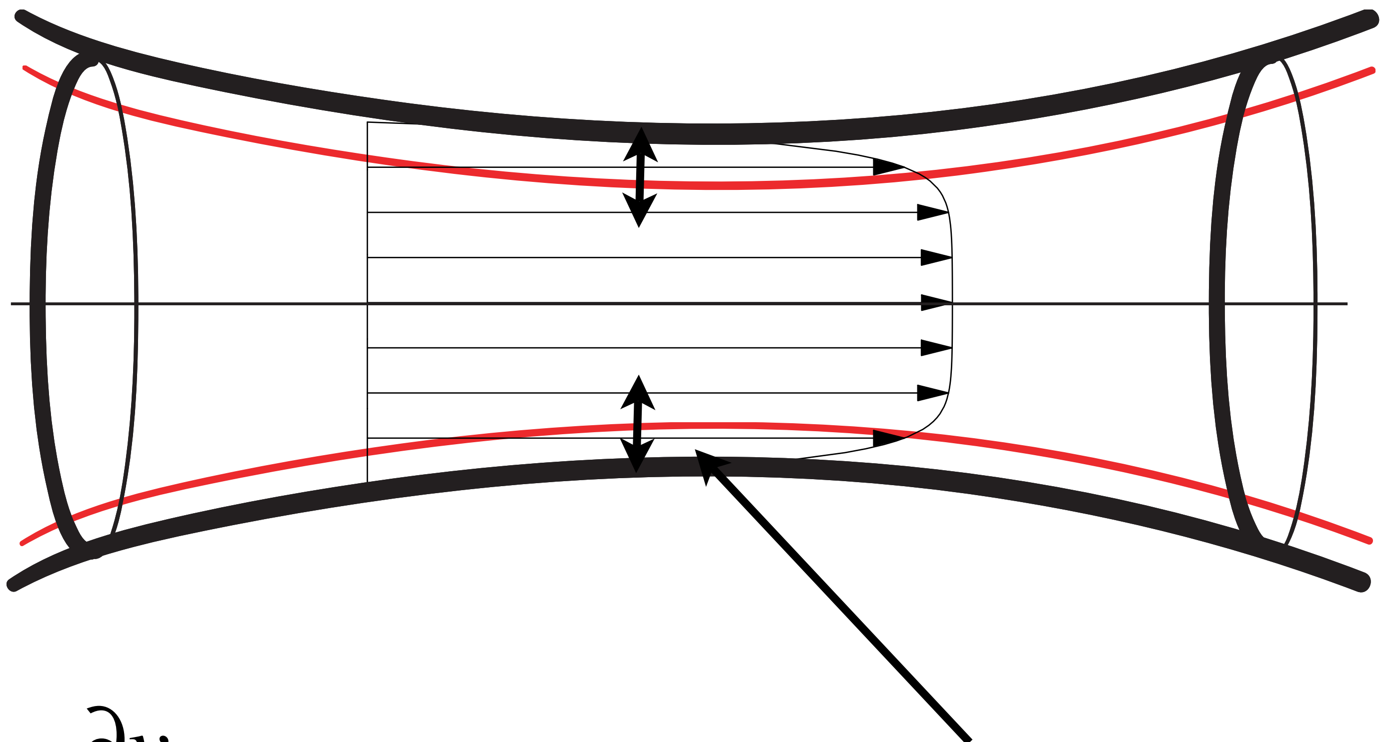
$$\delta \sim \frac{\lambda}{Re^{1/2}}$$

$$\frac{\partial u}{\partial x} + \frac{\partial rv}{r\partial r} = 0$$

Viscous region: boundary layer

$$\boxed{\frac{U_0^2}{\lambda}} = -\frac{\partial p}{\rho \partial x} + \boxed{\frac{1}{Re}\frac{\lambda^2}{\delta^2}\frac{U_0^2}{\lambda}} \quad 0 = -\frac{\partial p}{\rho \partial r}$$

Interactive Boundary Layer

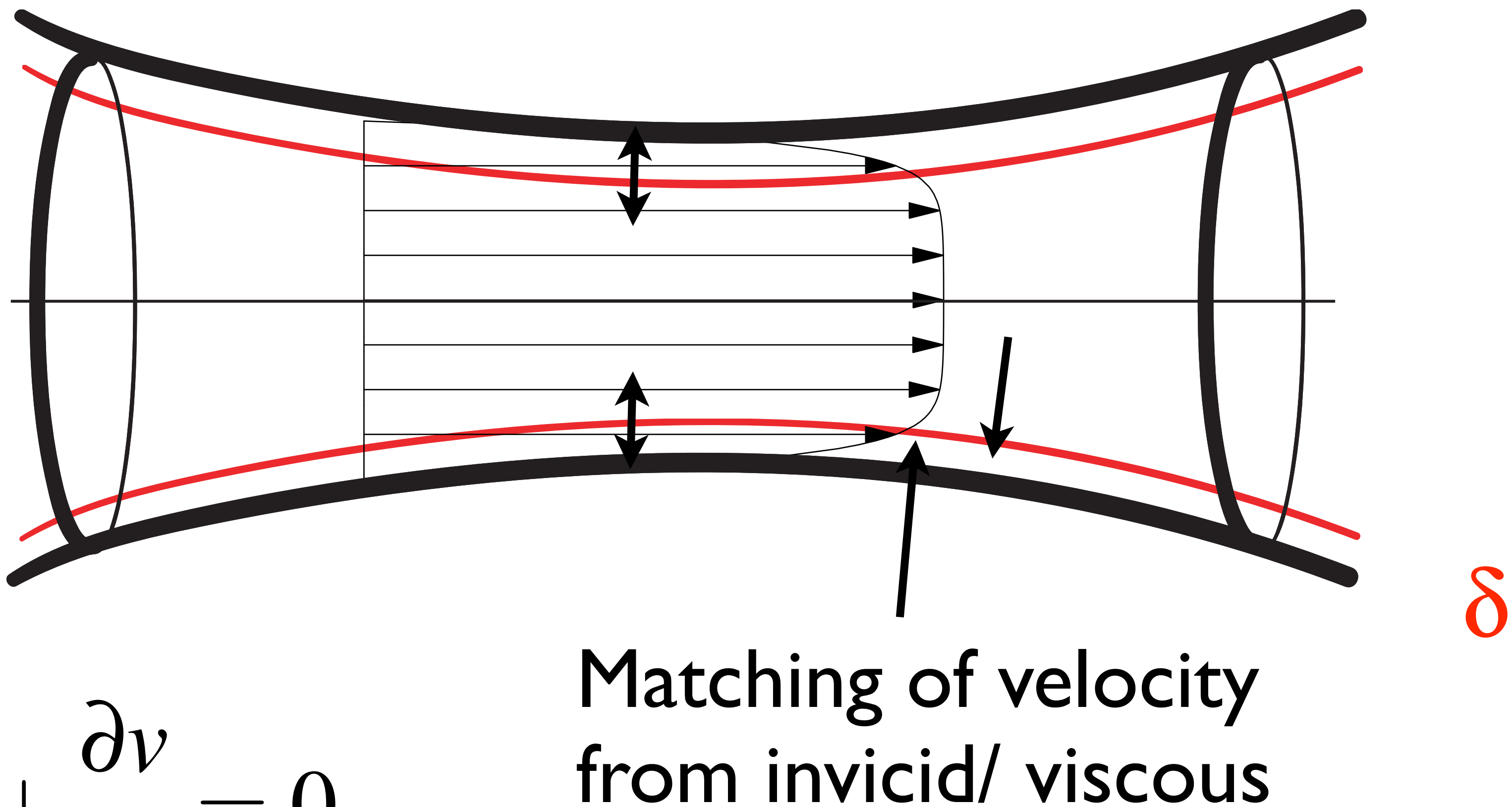


$$\delta \sim \frac{\lambda}{Re^{1/2}}$$

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial n} = 0$$

$$u\frac{\partial}{\partial x}u + v\frac{\partial}{\partial n}u = -\frac{\partial p}{\partial x} + \frac{\partial^2}{\partial n^2}u \qquad 0 = -\frac{\partial p}{\partial n}$$

Interactive Boundary Layer



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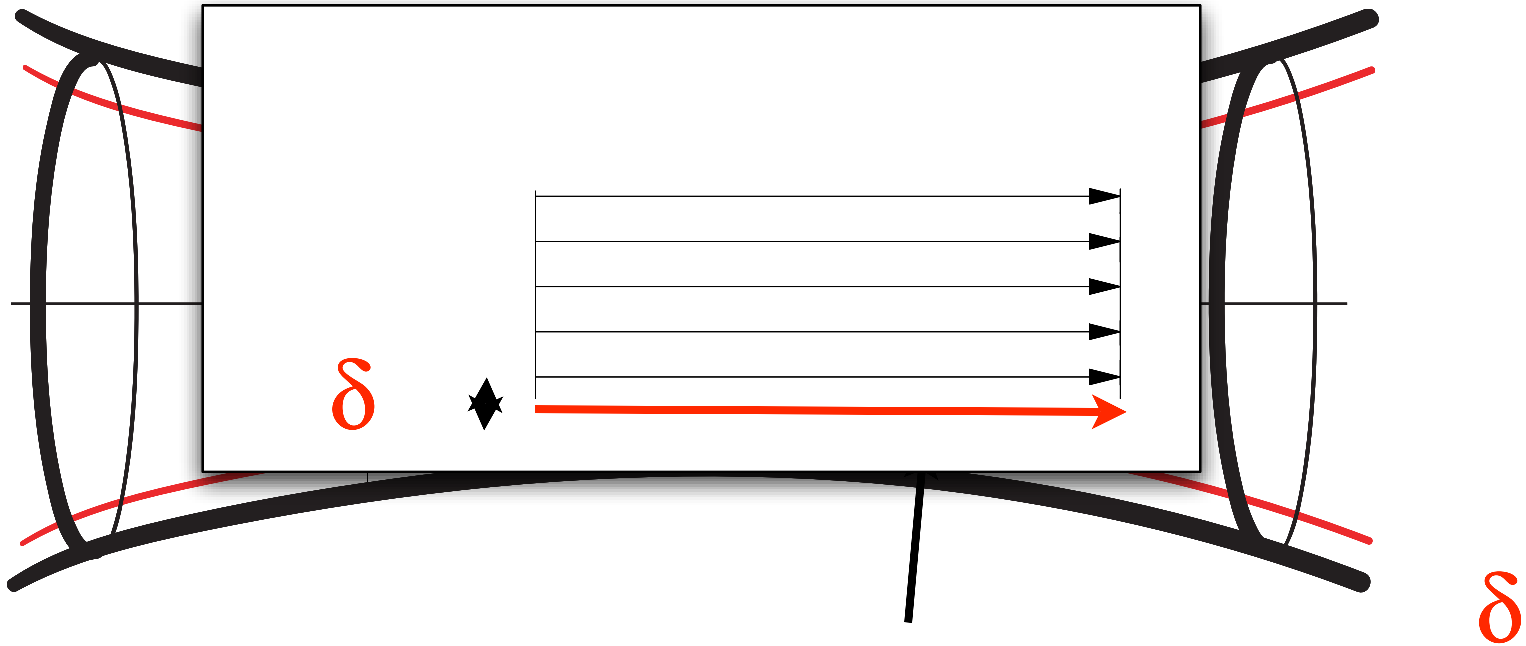
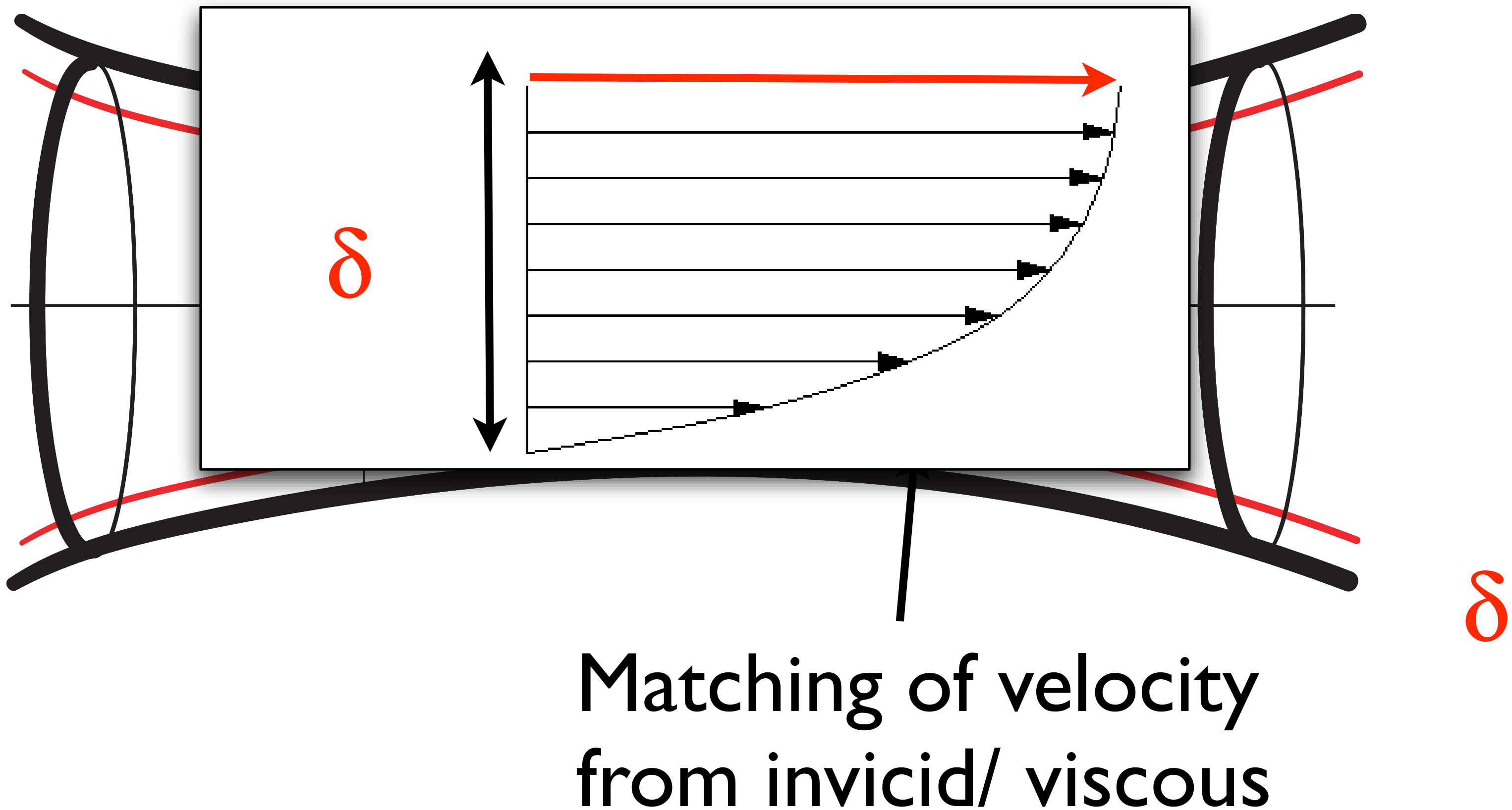
Interactive Boundary Layer



Matching of velocity
from invicid/ viscous

U_e at the wall

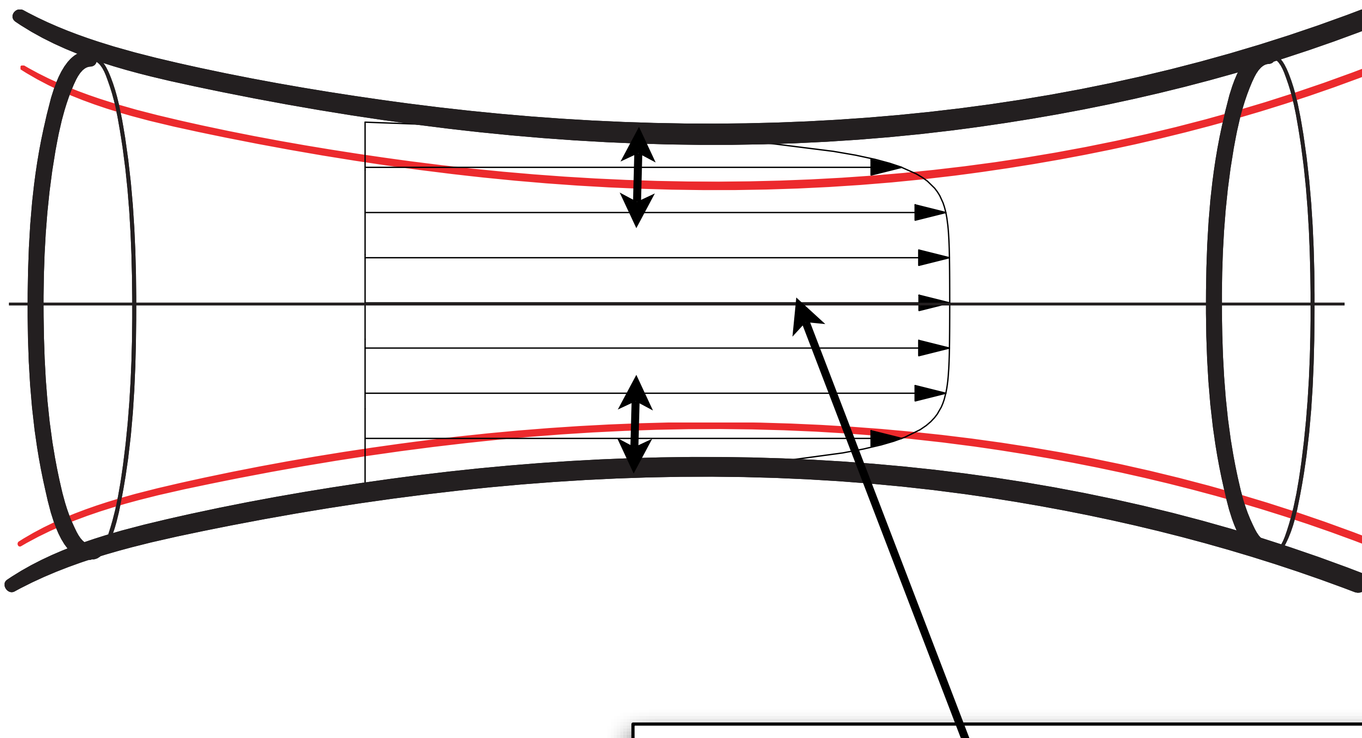
Interactive Boundary Layer



U_e at the wall

is the velocity at the edge of the boundary layer $u(x, \infty)$
at "infinity"

classical Boundary Layer

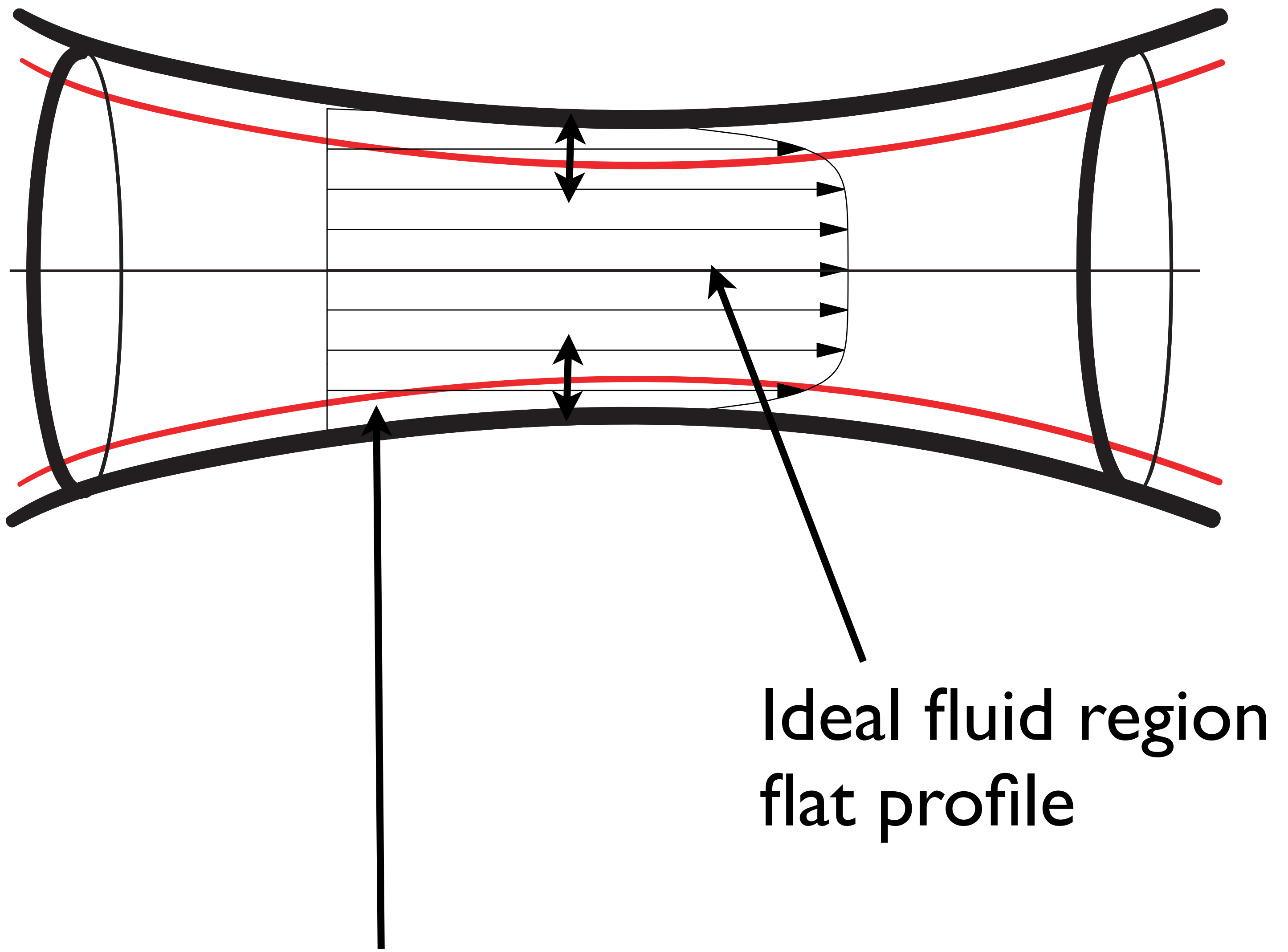


$$U_e(1-(f \qquad))^2 = 1$$

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial n} = 0 \qquad u(x,\infty) = U_e$$

$$u\frac{\partial}{\partial x}u + v\frac{\partial}{\partial n}u = \frac{dU_e}{dx} + \frac{\partial^2}{\partial n^2}u$$

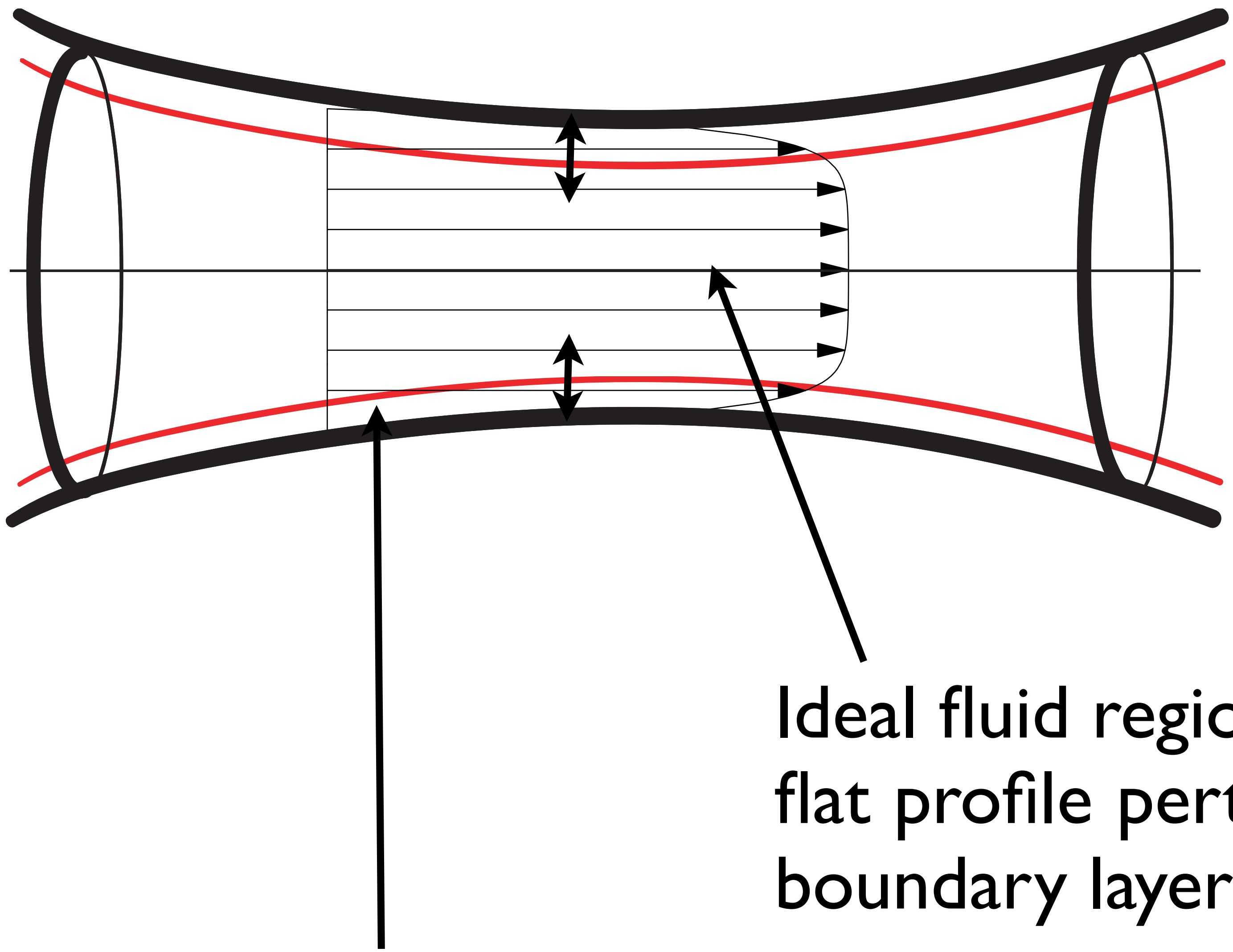
Interactive Boundary Layer



$$\delta_1 = \int_0^\infty (1 - \frac{u}{U_e}) dn$$

displacement of stream lines

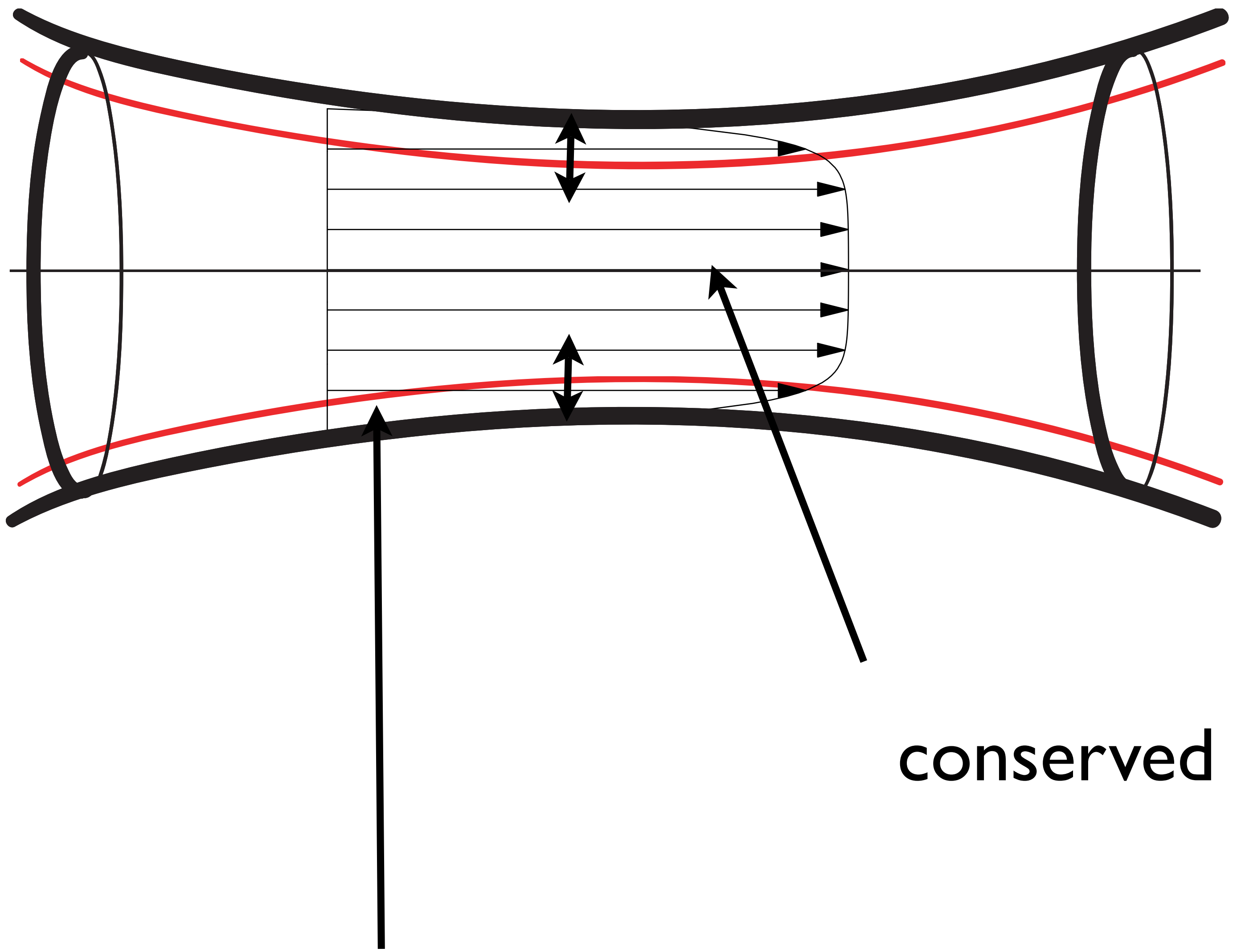
Interactive Boundary Layer



Ideal fluid region
flat profile perturbed by the
boundary layer thickness

$$\delta_1 = \int_0^\infty (1 - \frac{u}{U_e}) dn$$

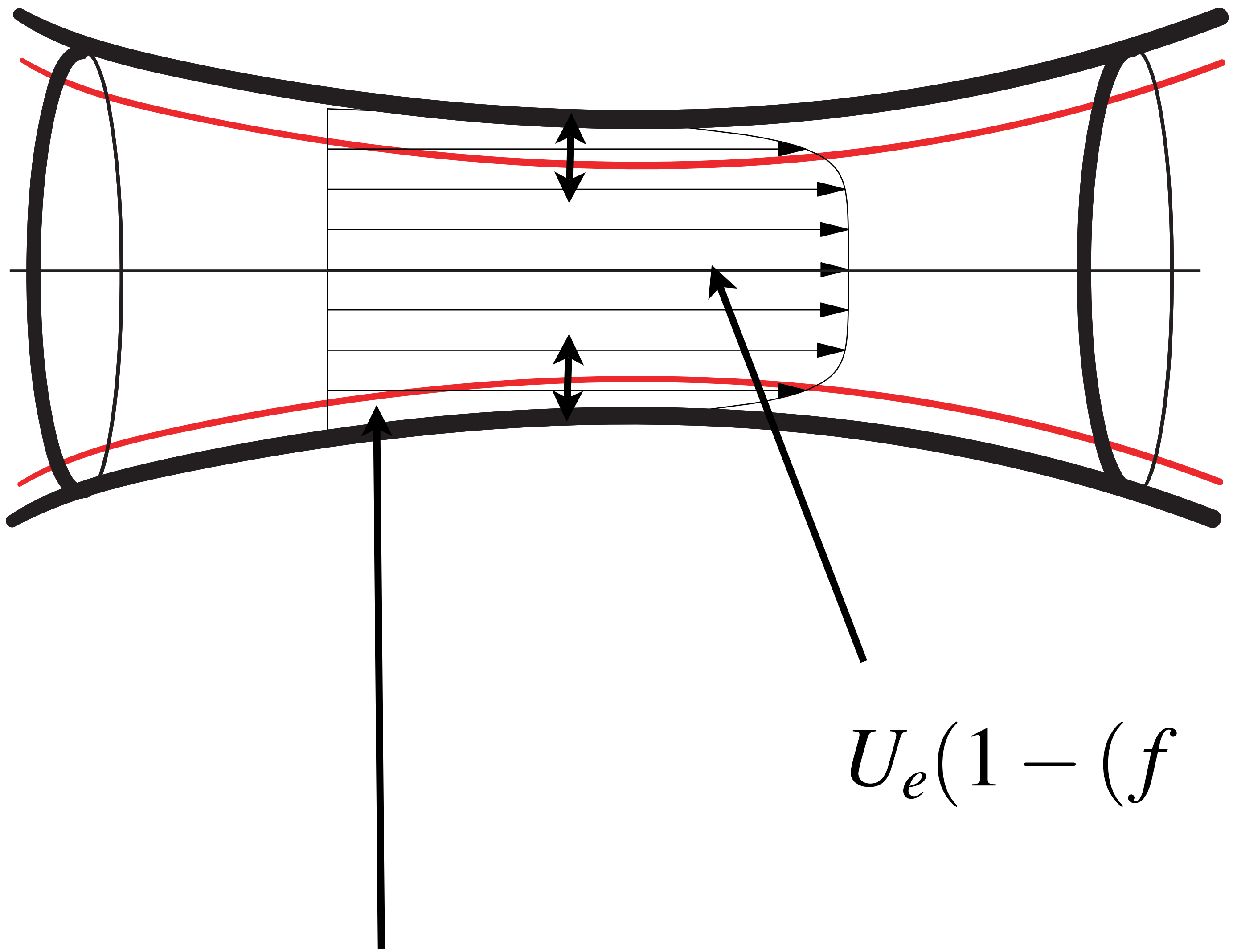
Interactive Boundary Layer



conserved flux

$$\delta_1 = \int_0^\infty \left(1 - \frac{u}{U_e}\right) dn$$

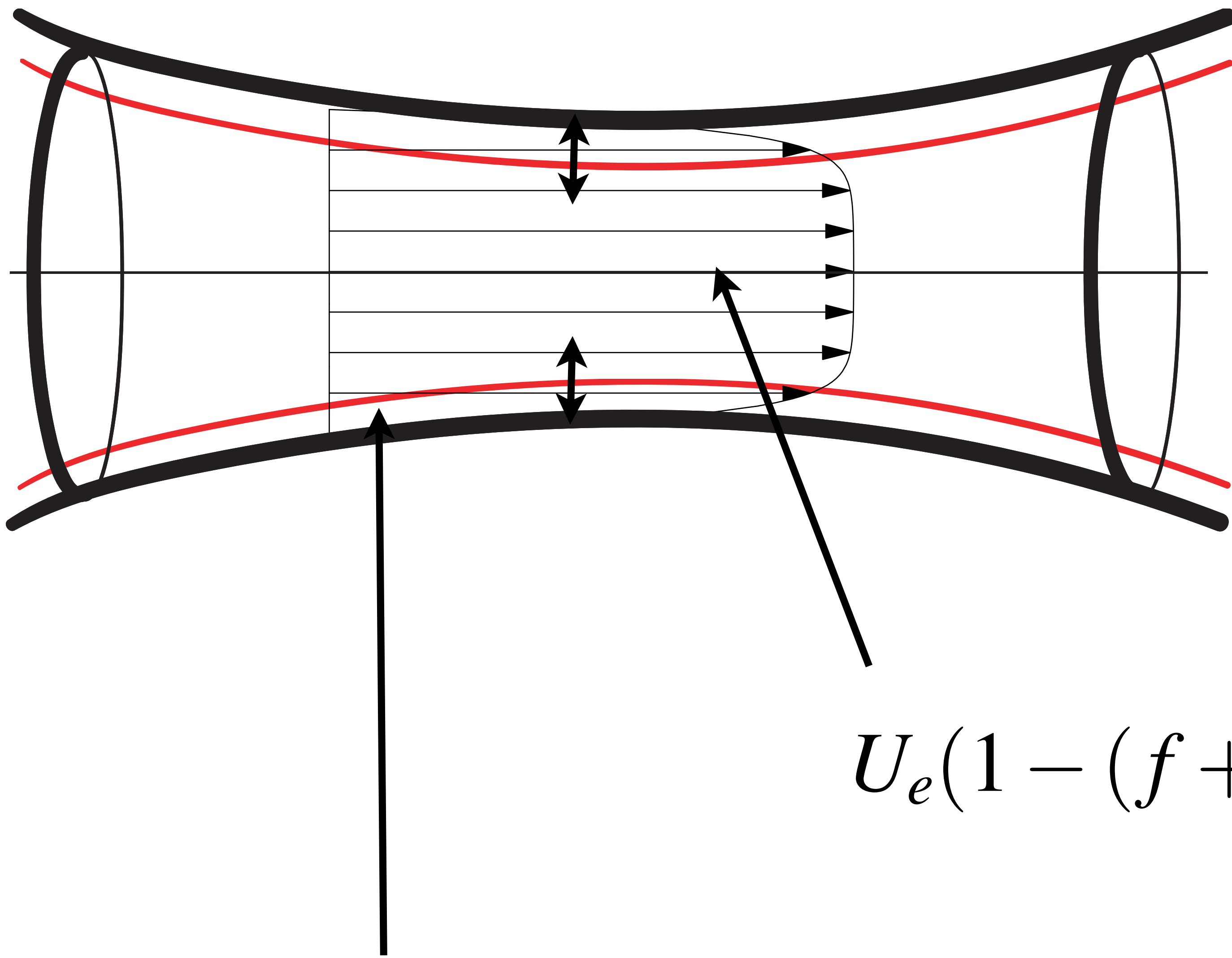
Interactive Boundary Layer



$$U_e(1-(f \qquad))^2 = 1$$

$$\delta_1 = \int_0^\infty (1 - \frac{u}{U_e}) dn$$

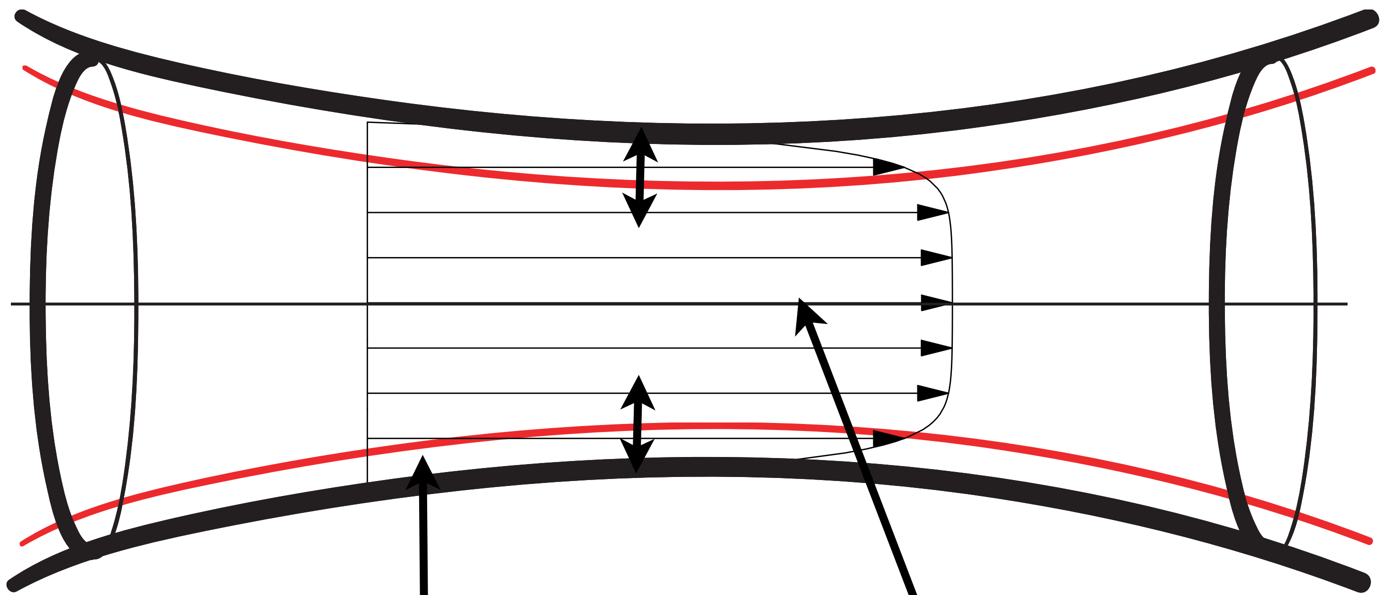
Interactive Boundary Layer



$$U_e(1-(f+\delta_1))^2 = 1$$

$$\delta_1 = \int_0^\infty (1 - \frac{u}{U_e}) dn$$

Interactive Boundary Layer



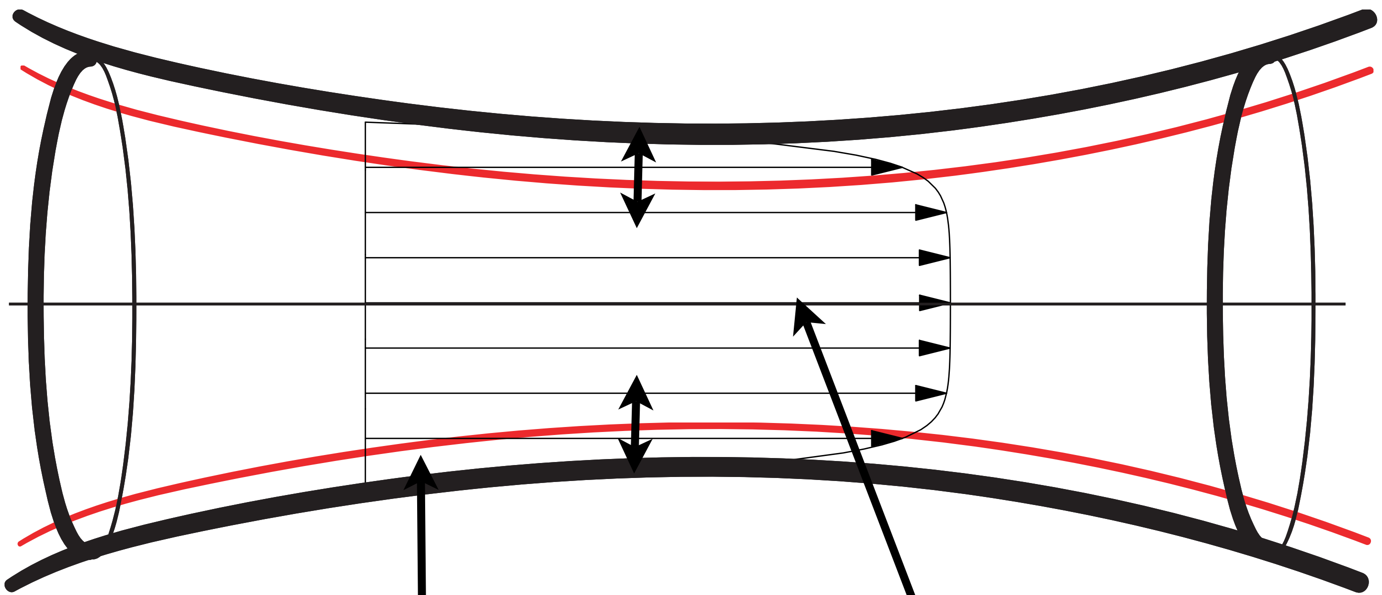
$$U_e(1-(f+\delta_1))^2 = 1$$

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial n} = 0$$

$$u\frac{\partial}{\partial x}u + v\frac{\partial}{\partial n}u = \frac{dU_e}{dx} + \frac{\partial^2}{\partial n^2}u$$

$$\delta_1 = \int_0^\infty (1-\frac{u}{U_e})dn$$

Interactive Boundary Layer



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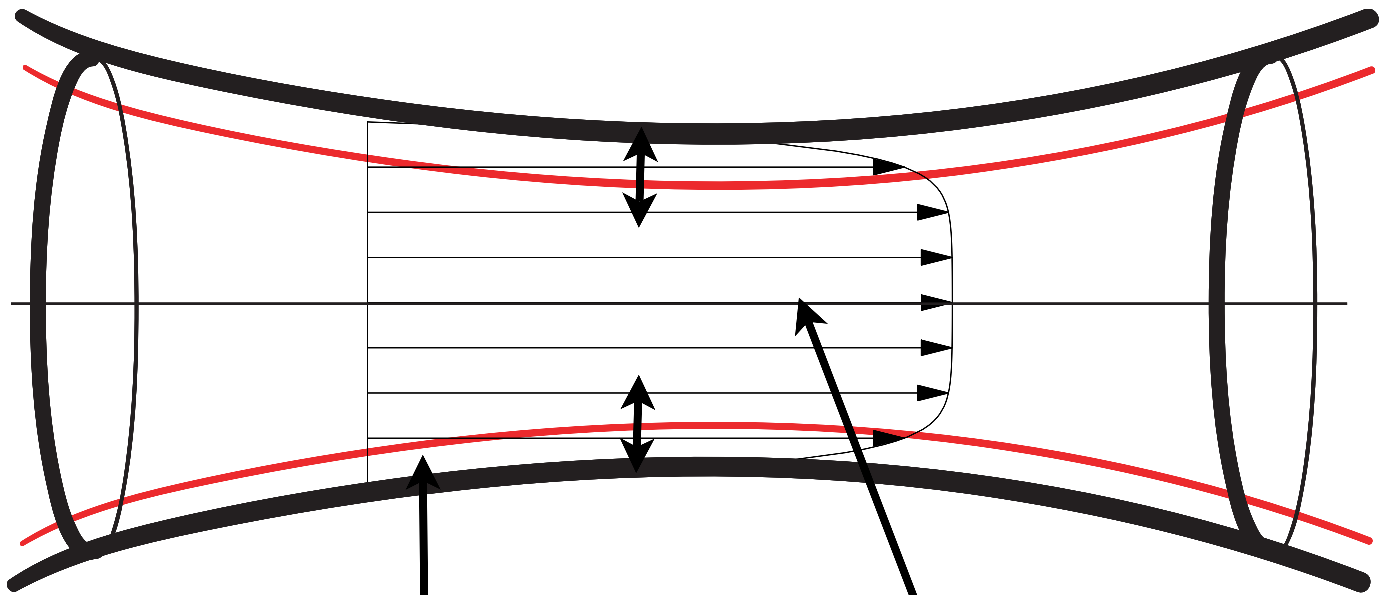
Interactive Boundary Layer



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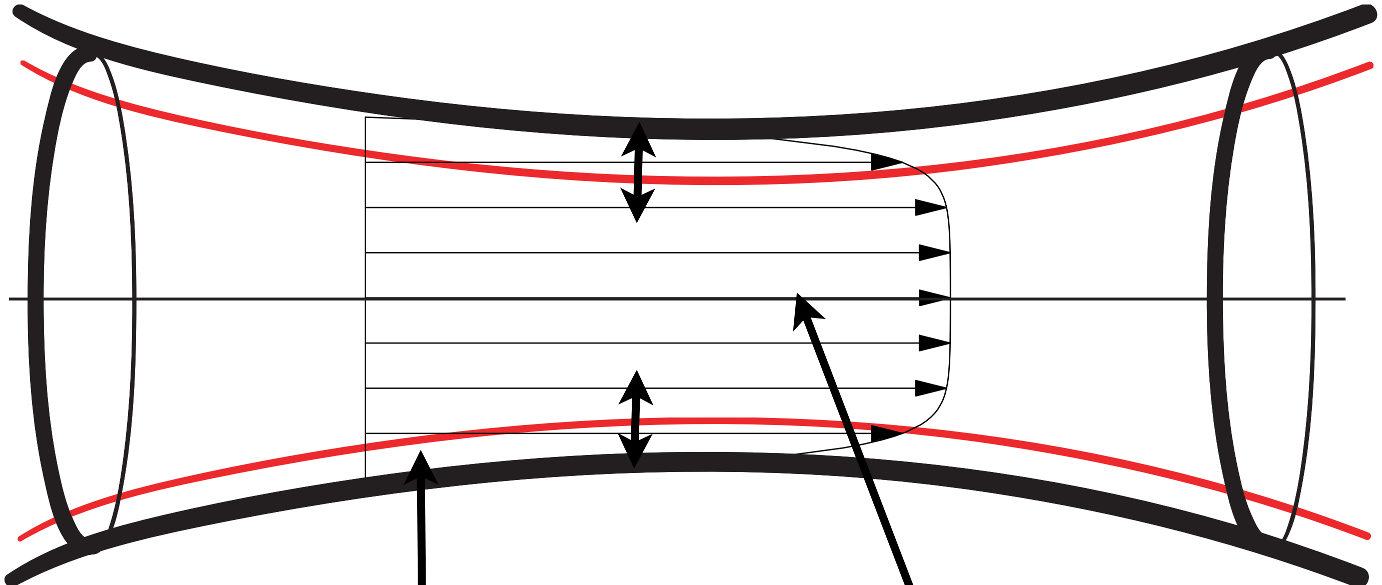
Interactive Boundary Layer



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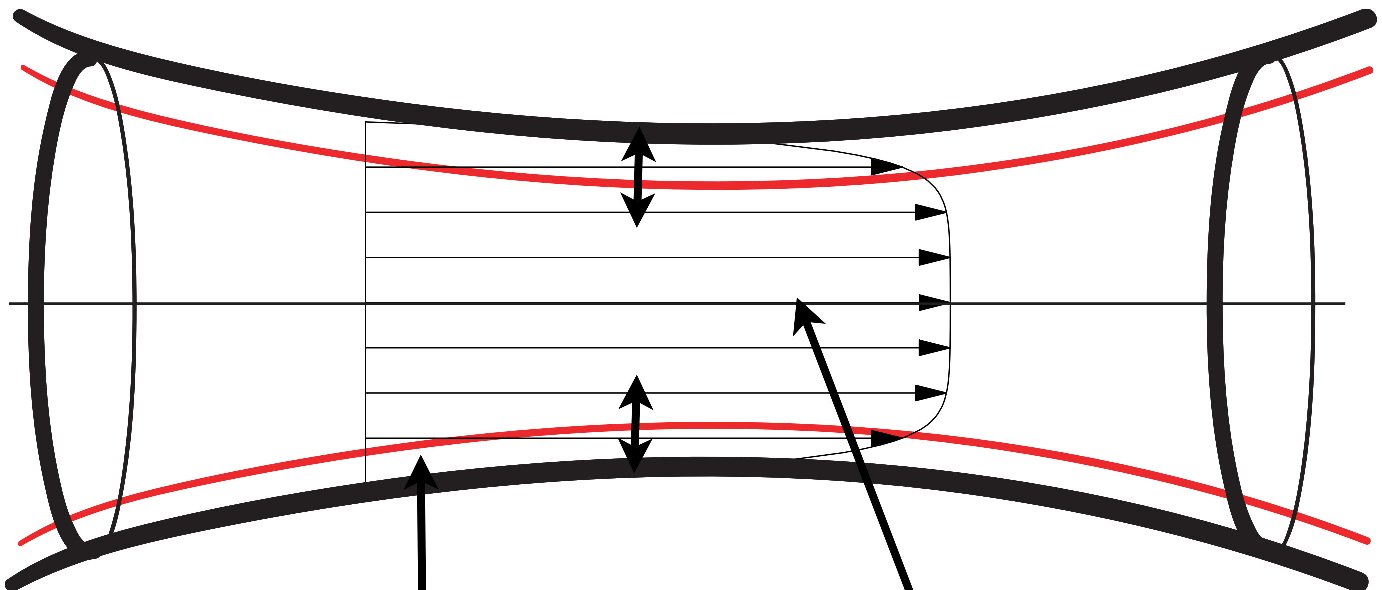
$$\delta_1 = \int_0^\infty \left(1-\frac{u}{U_e}\right)dn$$

Interactive Boundary Layer



Coupled System to solve

$$U_e(1-(f+\delta_1))^2 = 1$$

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial n} = 0 \qquad u(x,\infty) = U_e$$

$$u\frac{\partial}{\partial x}u + v\frac{\partial}{\partial n}u = \frac{dU_e}{dx} + \frac{\partial^2}{\partial n^2}u$$

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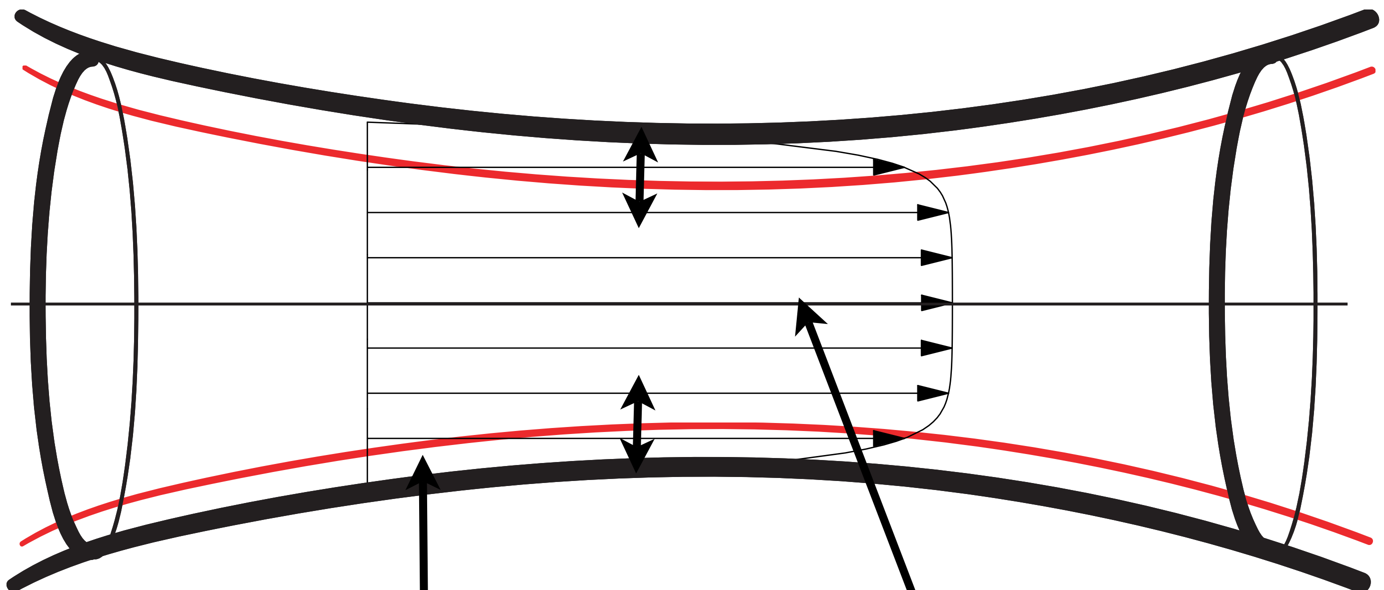

Coupled System to solve

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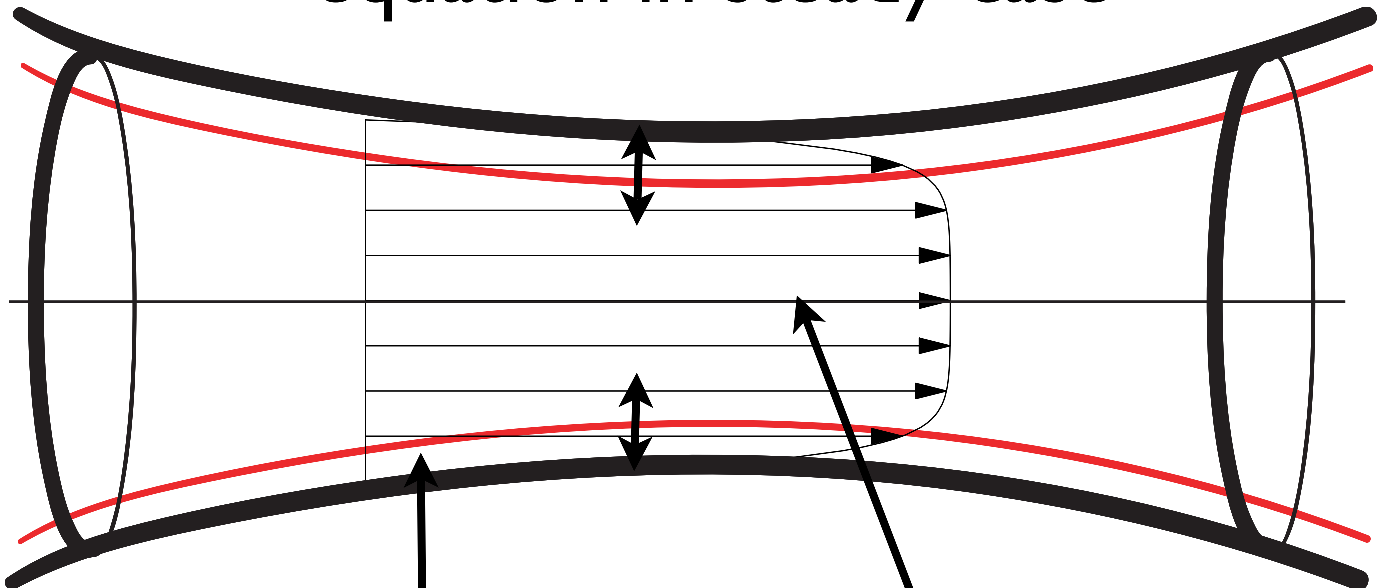
$$\int_0^\infty \; dn$$

$$\delta_1 = \int_0^\infty (1 - \frac{u}{U_e})dn$$

Integral resolution equation in steady case

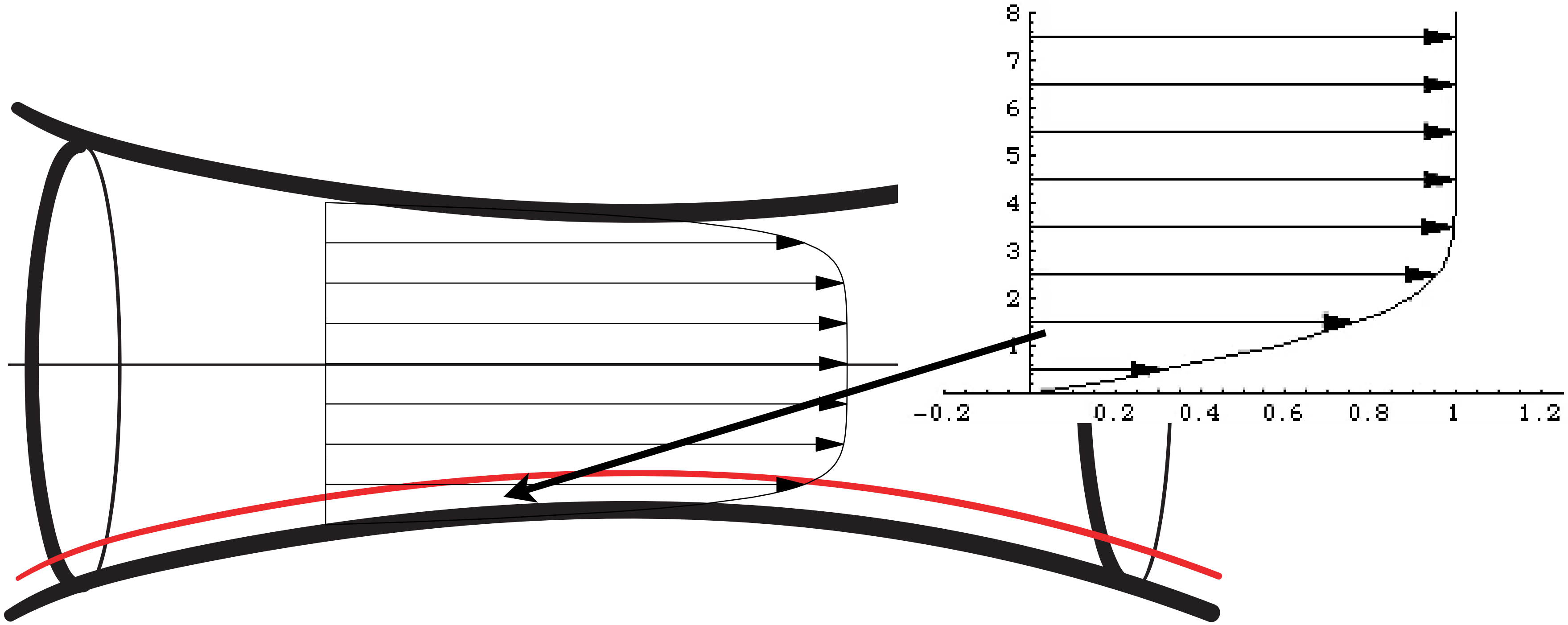


Coupled System to solve

$$U_e(1-(f+\delta_1))^2 = 1$$

$$\frac{d}{dx}\left(\frac{\delta_1}{H}\right) + \frac{\delta_1}{U_e}\left(1+\frac{2}{H}\right)\frac{dU_e}{dx} = \frac{f_2 H}{\delta_1 U_e}$$

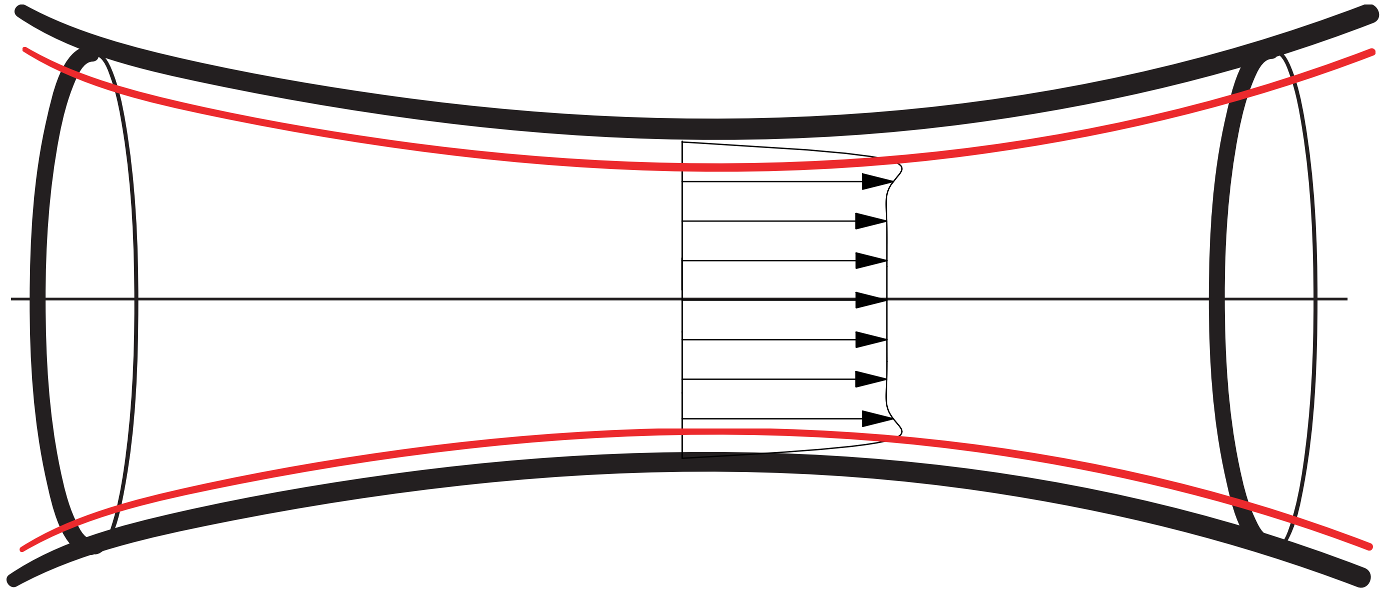
$$\delta_1 = \int_0^\infty \left(1-\frac{u}{U_e}\right)dn$$



Choice of the family of simple profiles

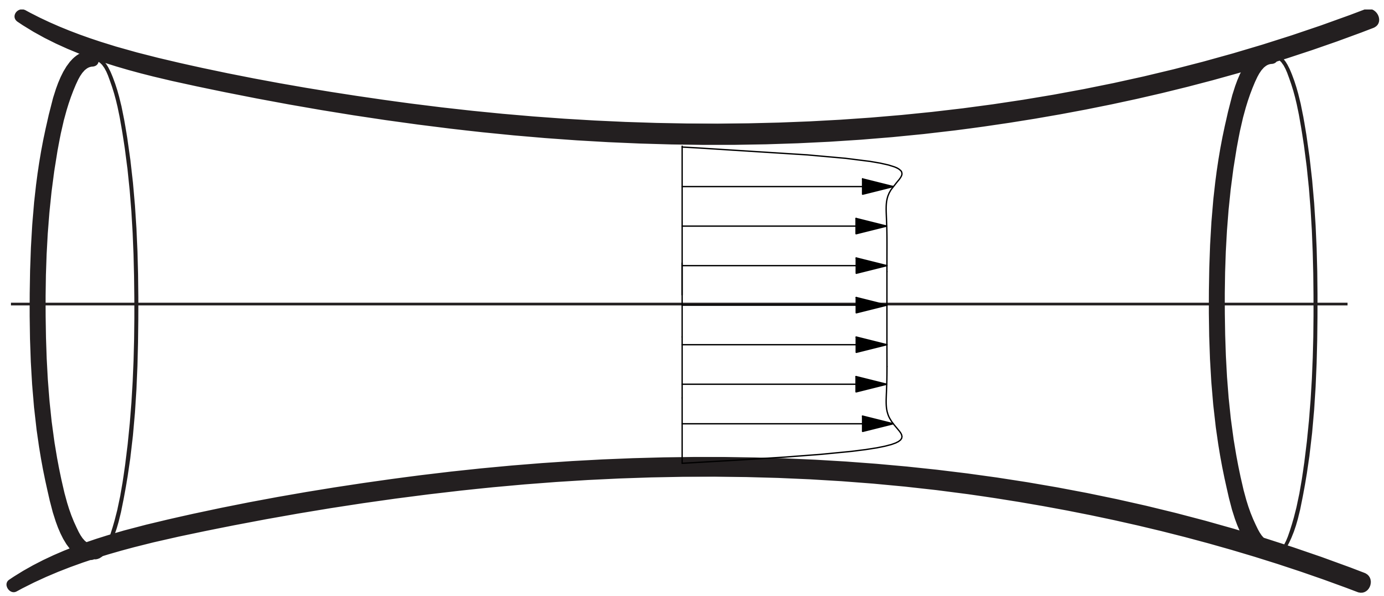
In a steady flow it is natural to use Falkner Skan

Interactive Boundary Layer

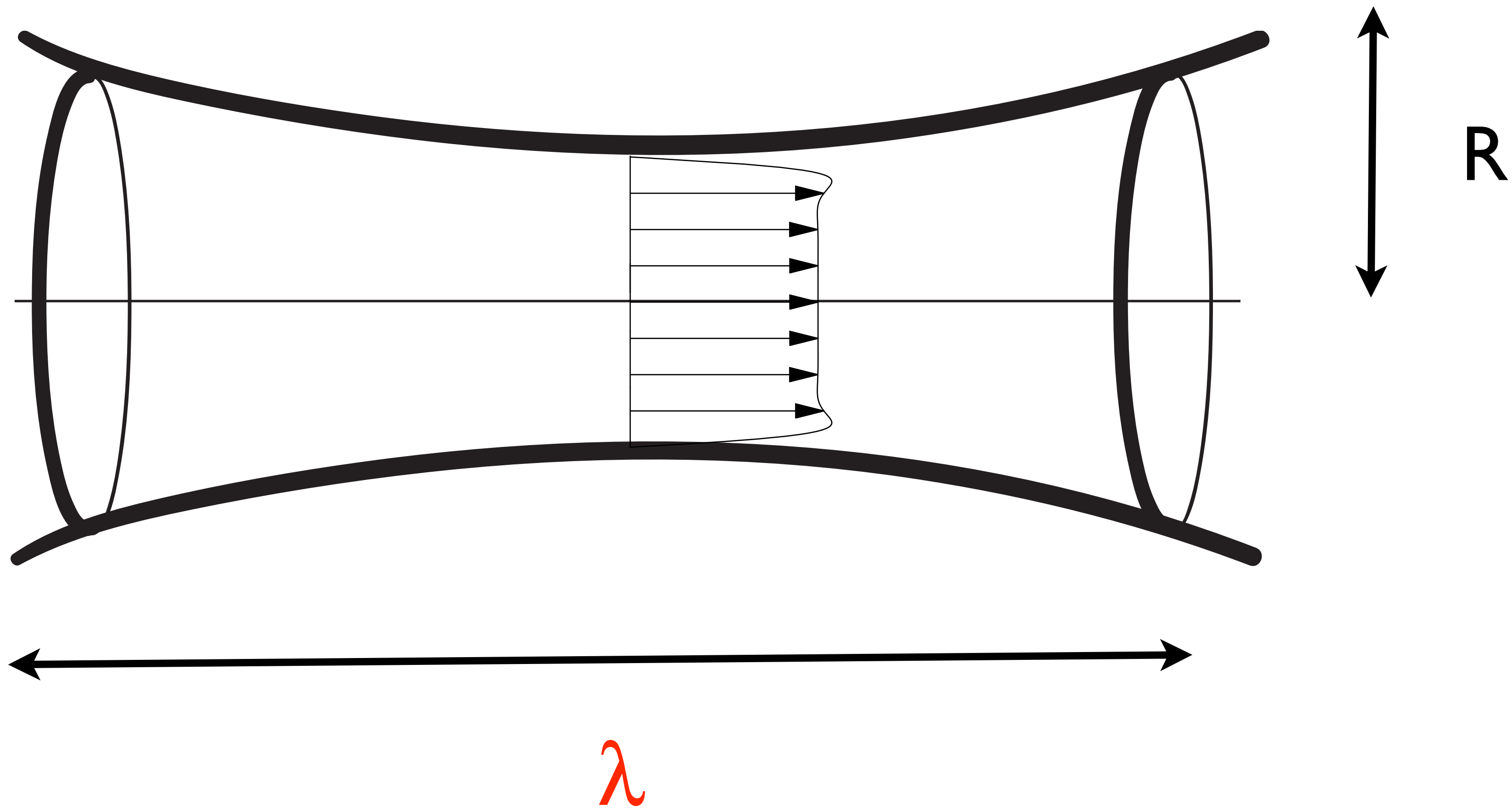


IBL is included in a larger system: RNSP

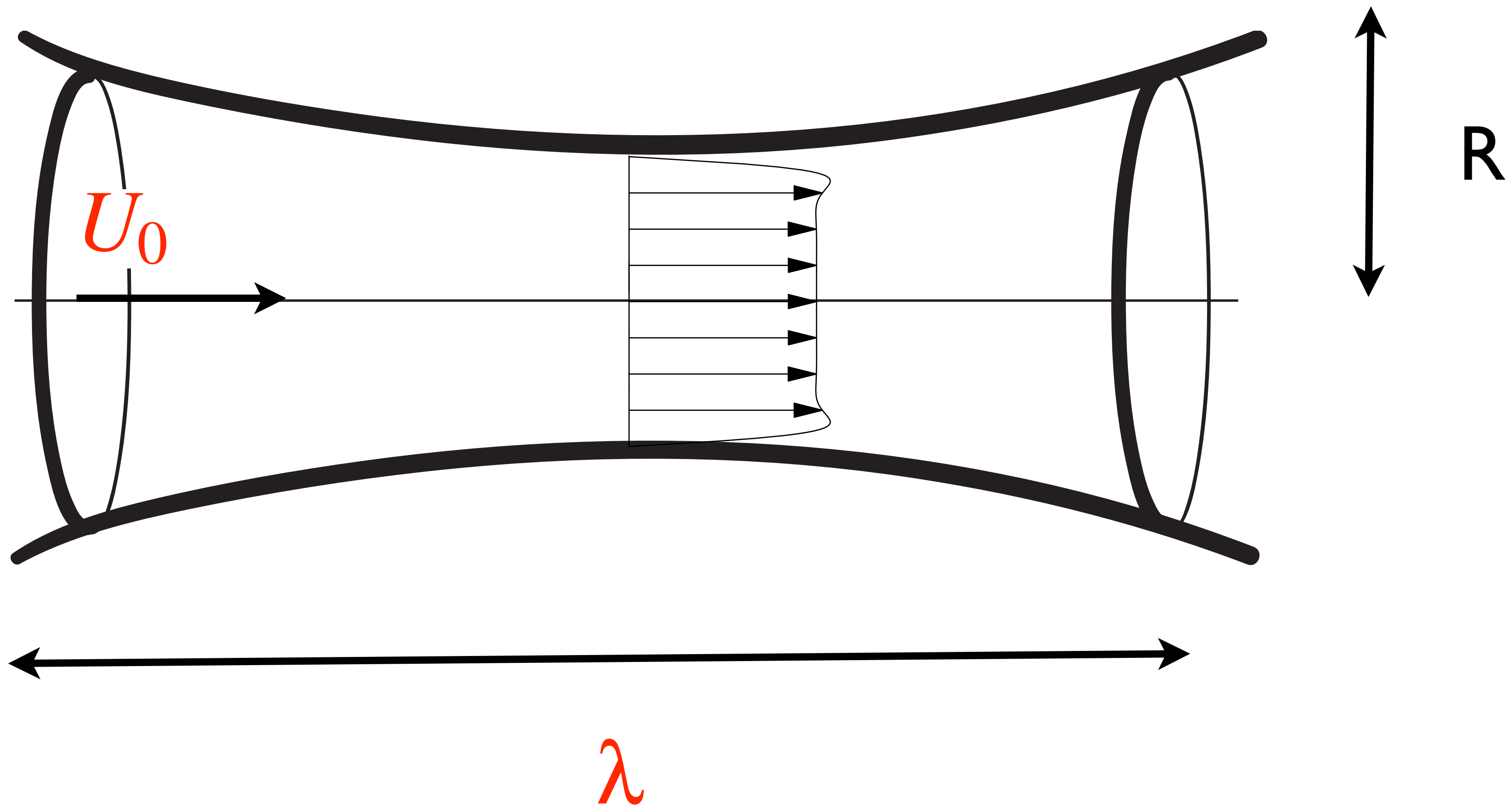
RNSP Equations



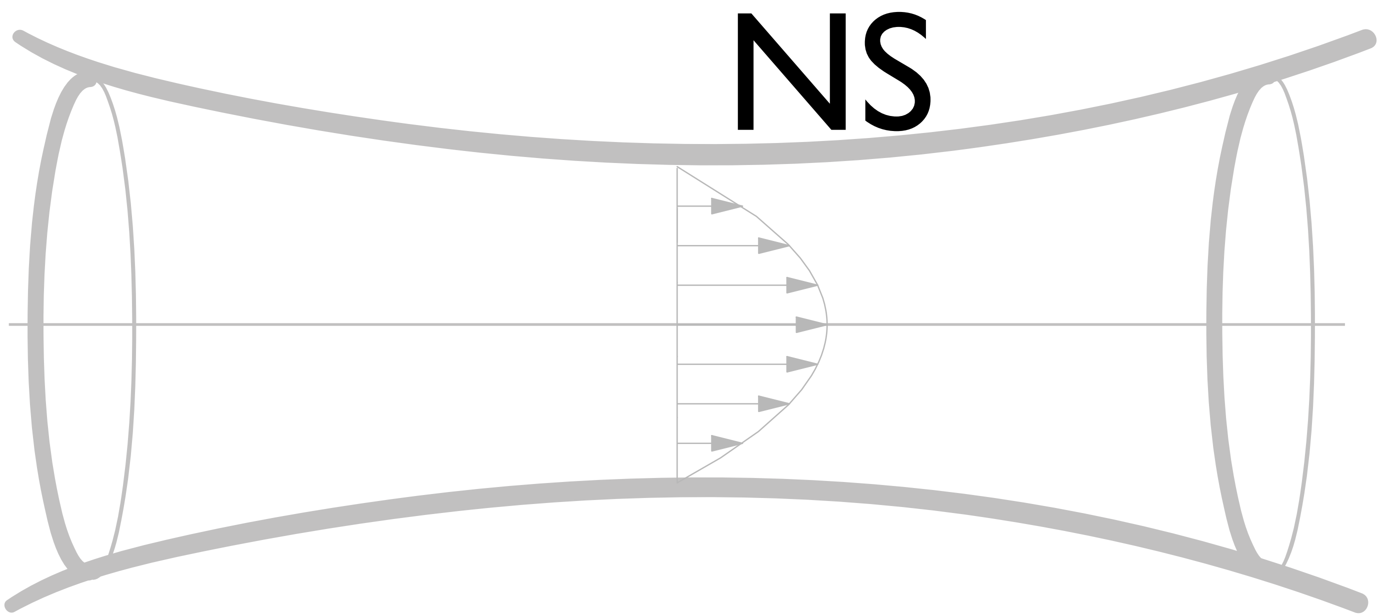
- simplified set
- deduced from orders of magnitude



$R << \lambda$



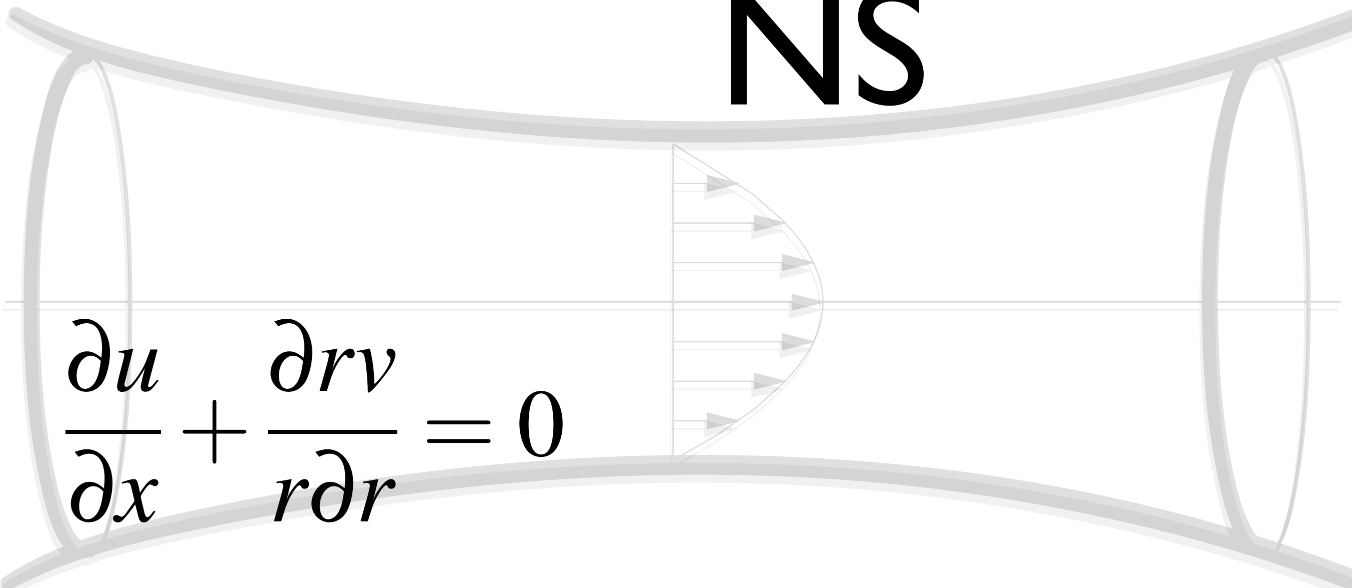
U_0
R
λ



$$\frac{\partial u}{\partial t} + u\frac{\partial}{\partial x}u + v\frac{\partial}{\partial r}u = -\frac{\partial p}{\rho \partial x} + \nu\frac{\partial^2}{\partial x^2}u + \nu\frac{\partial}{r\partial r}r\frac{\partial u}{\partial r}$$

$$\frac{\partial v}{\partial t} + u\frac{\partial}{\partial x}v + v\frac{\partial}{\partial r}v = -\frac{\partial p}{\rho \partial r} + \nu\frac{\partial^2}{\partial x^2}v + \nu\frac{\partial}{r\partial r}r\frac{\partial v}{\partial r}$$

NS



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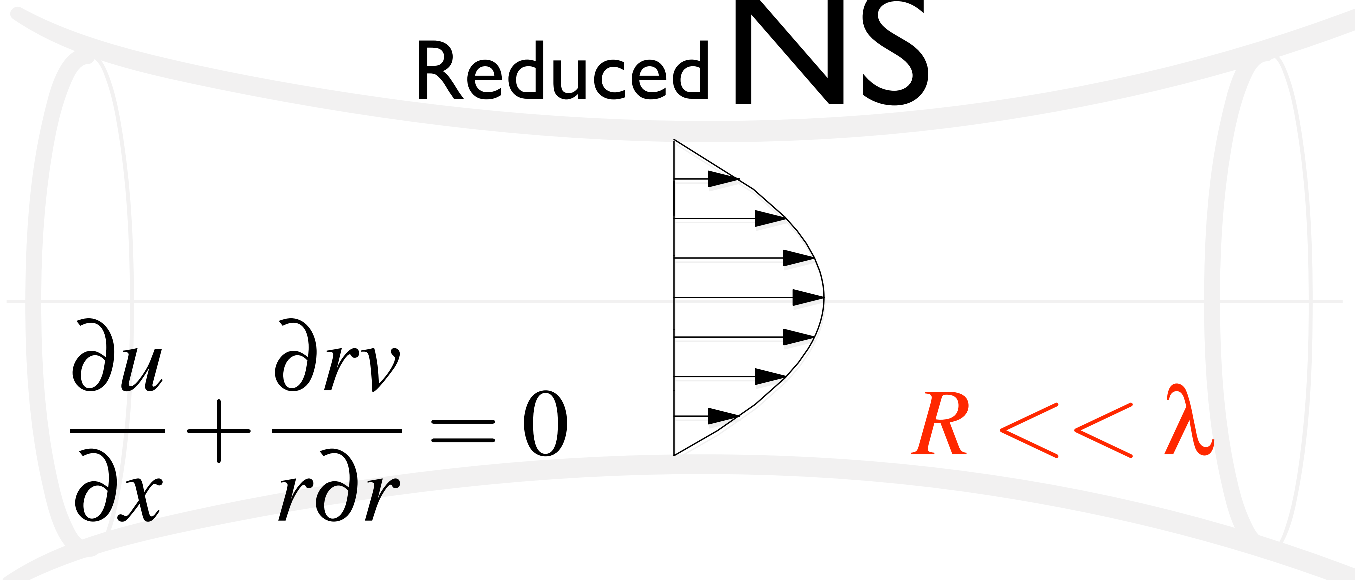
Reduced NS



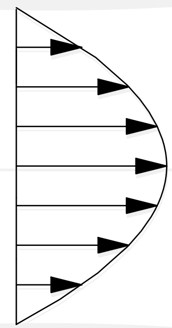
$$\frac{\partial u}{\partial x} + \frac{\partial rv}{r\partial r} = 0$$

$R << \lambda$

$$\frac{\partial u}{\partial t} + u\frac{\partial}{\partial x}u + v\frac{\partial}{\partial r}u = -\frac{\partial p}{\rho\partial x} + \nu\cancel{\frac{\partial^2}{\partial x^2}}u + \nu\frac{\partial}{r\partial r}r\frac{\partial u}{\partial r}$$

$$\frac{\partial v}{\partial t} + u\frac{\partial}{\partial x}v + v\frac{\partial}{\partial r}v = -\frac{\partial p}{\rho\partial r} + \nu\cancel{\frac{\partial^2}{\partial x^2}}v + \nu\frac{\partial}{r\partial r}r\frac{\partial v}{\partial r}$$

RNS/P



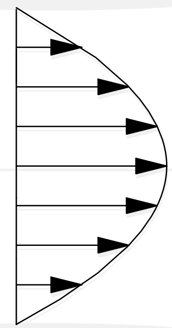
$$\frac{\partial u}{\partial x} + \frac{\partial r v}{r \partial r} = 0$$

$$R << \lambda \qquad V \sim U_0 \frac{R}{\lambda}$$

$$\frac{\partial u}{\partial t} + u\frac{\partial}{\partial x}u + v\frac{\partial}{\partial r}u = -\frac{\partial p}{\rho \partial x} + \nu \frac{\partial^2}{\partial x^2}u + \nu \frac{\partial}{r\partial r} r \frac{\partial u}{\partial r}$$

$$\frac{\partial v}{\partial t} + u\frac{\partial}{\partial x}v + v\frac{\partial}{\partial r}v = -\frac{\partial p}{\rho \partial r} + \nu \frac{\partial^2}{\partial x^2}v + \nu \frac{\partial}{r\partial r} r \frac{\partial v}{\partial r}$$

RNS/P



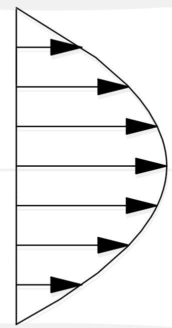
$$\frac{\partial u}{\partial x} + \frac{\partial rv}{r\partial r} = 0$$

$$R << \lambda \qquad V \sim U_0 \frac{R}{\lambda}$$

$$\frac{\partial u}{\partial t} + u\frac{\partial}{\partial x}u + v\frac{\partial}{\partial r}u = -\frac{\partial p}{\rho\partial x} + \nu\cancel{\frac{\partial^2}{\partial x^2}}u + \nu\frac{\partial}{r\partial r}r\frac{\partial u}{\partial r}$$

$$\frac{\partial v}{\partial t} + u\frac{\partial}{\partial x}v + v\frac{\partial}{\partial r}v = -\frac{\partial p}{\rho\partial r} + \nu\cancel{\frac{\partial^2}{\partial x^2}}v + \nu\frac{\partial}{r\partial r}r\frac{\partial v}{\partial r}$$

RNS/P



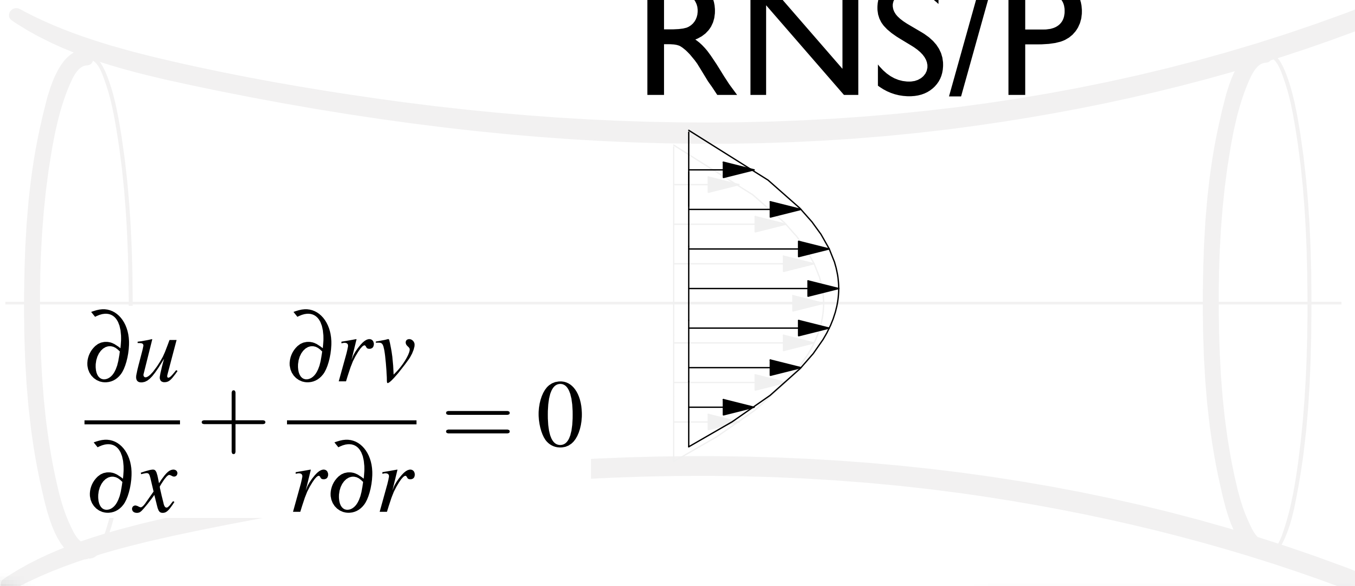
$$\frac{\partial u}{\partial x} + \frac{\partial r v}{r \partial r} = 0$$

$$R << \lambda \qquad V \sim U_0 \frac{R}{\lambda}$$

$$\frac{\partial u}{\partial t} + u\frac{\partial}{\partial x}u + v\frac{\partial}{\partial r}u = -\frac{\partial p}{\rho \partial x} + \nu \cancel{\frac{\partial^2}{\partial x^2}}u + \nu\frac{\partial}{r\partial r}r\frac{\partial u}{\partial r}$$

$$\cancel{\frac{\partial v}{\partial t}} + u\cancel{\frac{\partial}{\partial x}}v + v\cancel{\frac{\partial}{\partial r}}v = -\frac{\partial p}{\rho \partial r} + \nu \cancel{\frac{\partial^2}{\partial x^2}}v + \nu\frac{\partial}{r\partial r}\cancel{r\frac{\partial v}{\partial r}}$$

RNS/P

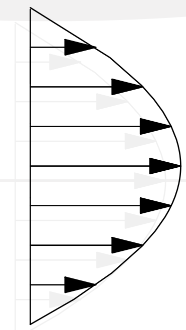


$$\frac{\partial u}{\partial x} + \frac{\partial rv}{r\partial r} = 0$$

$$\frac{\partial u}{\partial t} + u\frac{\partial}{\partial x}u + v\frac{\partial}{\partial r}u = -\frac{\partial p}{\rho\partial x} + \nu\frac{\partial}{r\partial r}r\frac{\partial u}{\partial r}$$

$$0 = -\frac{\partial p}{\rho\partial r}$$

RNS/P



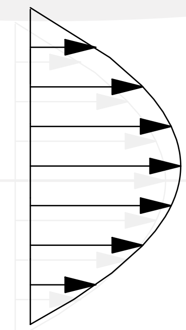
$$\frac{\partial u}{\partial x} + \frac{\partial r v}{r \partial r} = 0$$

$$\nu \frac{1}{\omega R^2}$$

$$\frac{\partial u}{\partial t} + u \frac{\partial}{\partial x} u + v \frac{\partial}{\partial r} u = -\frac{\partial p}{\rho \partial x} + \nu \frac{\partial}{r \partial r} r \frac{\partial u}{\partial r}$$

$$0 = -\frac{\partial p}{\rho \partial r}$$

RNS/P



$$\frac{\partial u}{\partial x} + \frac{\partial r v}{r \partial r} = 0$$

$$\alpha = R\sqrt{\frac{\omega}{\nu}}$$

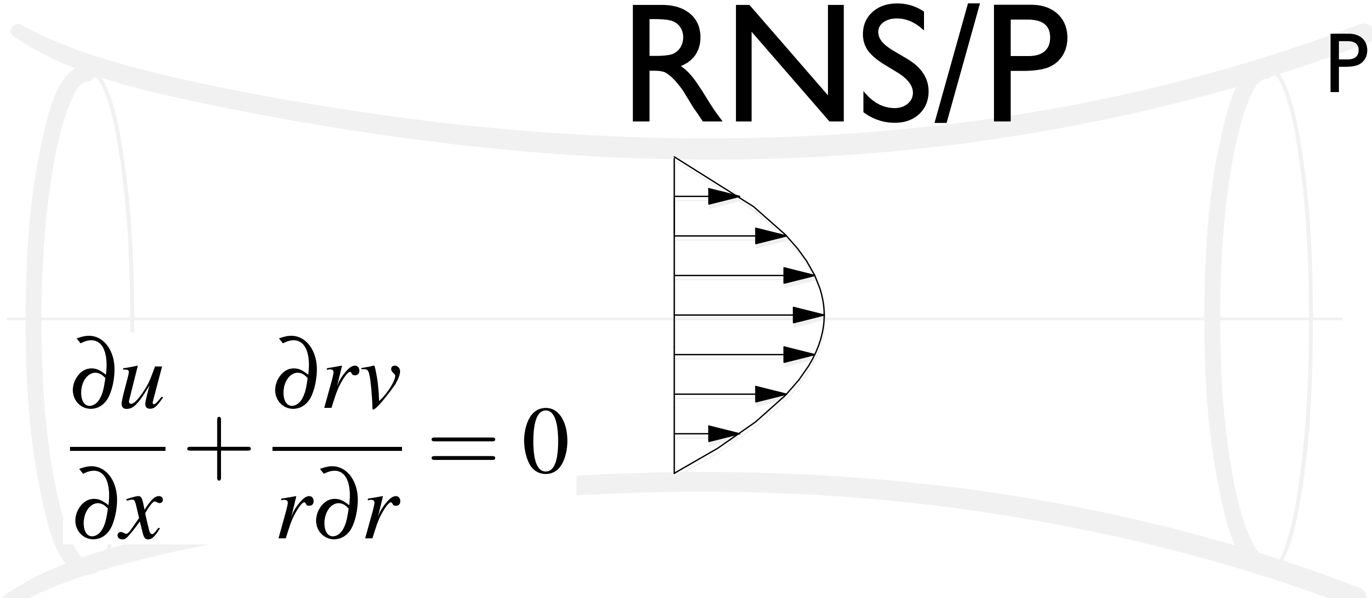
$$\frac{\partial u}{\partial t} + u\frac{\partial}{\partial x}u + v\frac{\partial}{\partial r}u = -\frac{\partial p}{\rho \partial x} + \nu\frac{\partial}{r \partial r}r\frac{\partial u}{\partial r}$$

$$0 = -\frac{\partial p}{\rho \partial r}$$

1/(Womersley)^2

RNS/P

Prandtl



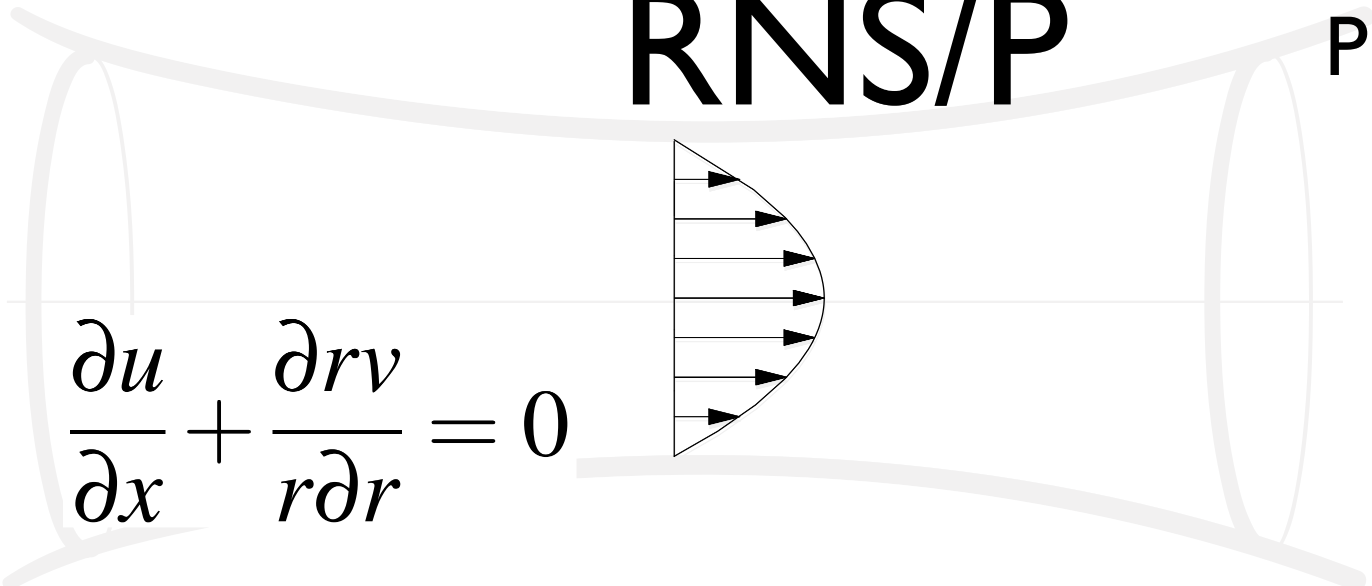
$$\frac{\partial u}{\partial x} + \frac{\partial r v}{r \partial r} = 0$$

$$\frac{\partial u}{\partial t} + u\frac{\partial}{\partial x}u + v\frac{\partial}{\partial r}u = -\frac{\partial p}{\rho \partial x} + \nu \frac{\partial}{r \partial r} r \frac{\partial u}{\partial r}$$

$$0 = -\frac{\partial p}{\rho \partial r}$$

RNS/P

Prandtl

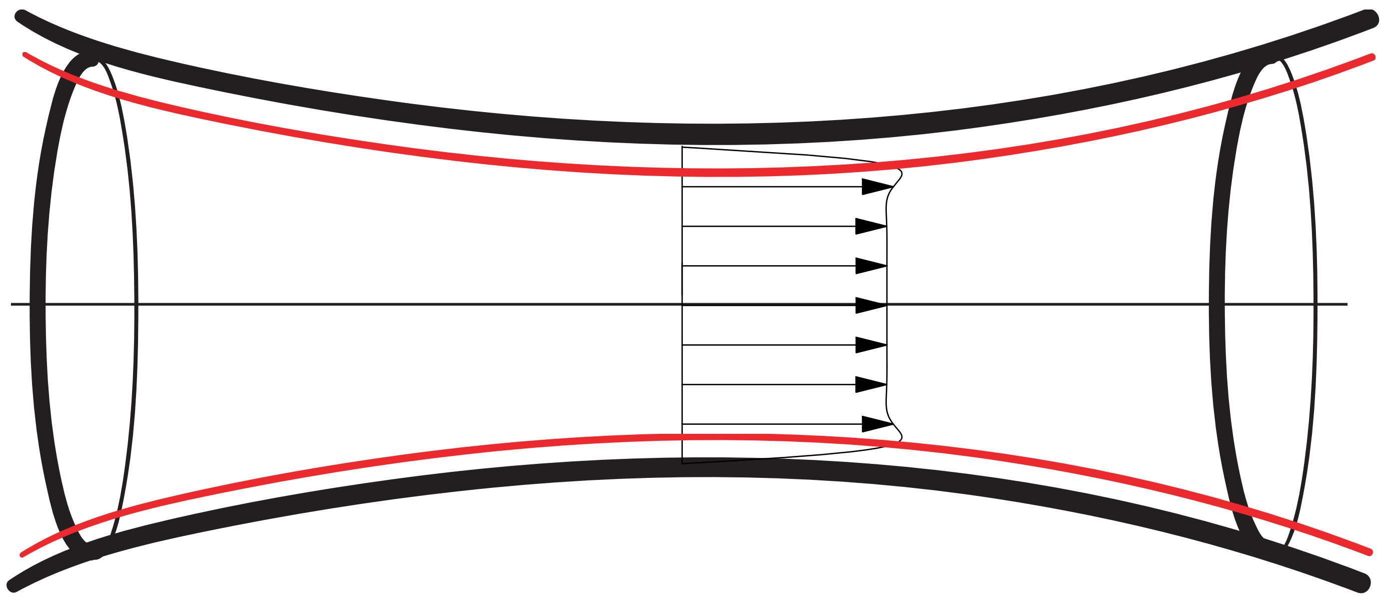


$$\frac{\partial u}{\partial x} + \frac{\partial r v}{r \partial r} = 0$$

$$u\frac{\partial}{\partial x}u + v\frac{\partial}{\partial r}u = -\frac{\partial p}{\rho \partial x} + \nu \frac{\partial}{r \partial r} r \frac{\partial u}{\partial r}$$

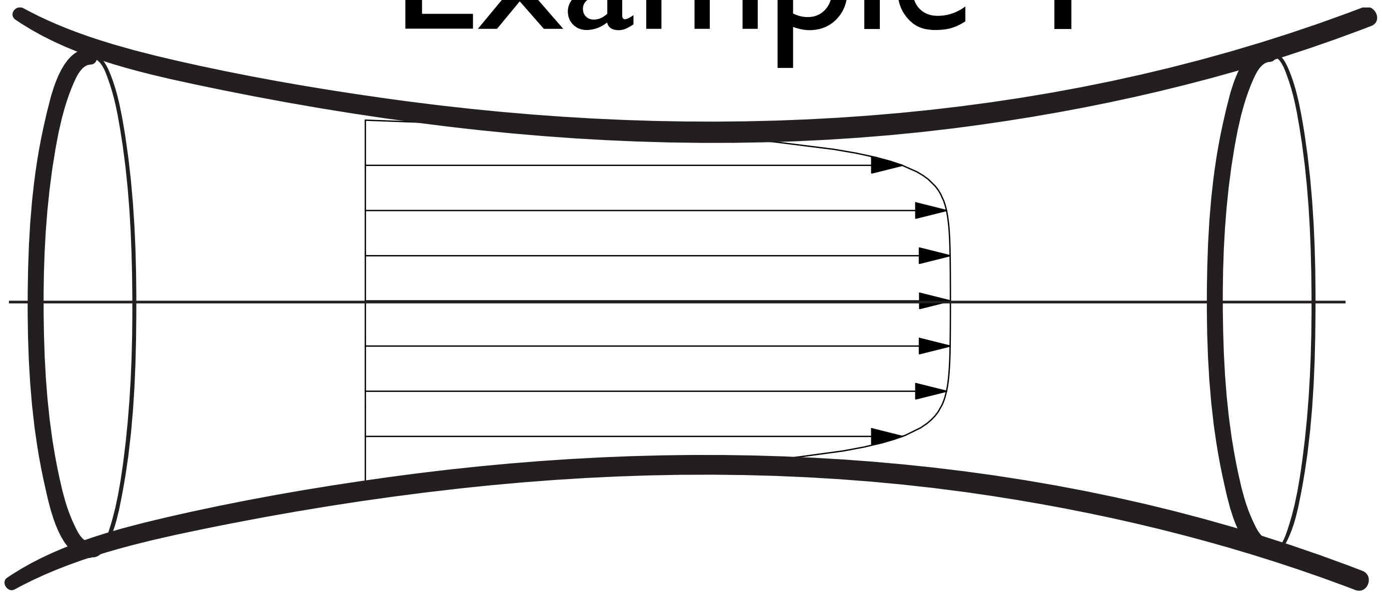
$$0 = -\frac{\partial p}{\rho \partial r}$$

Interactive Boundary Layer

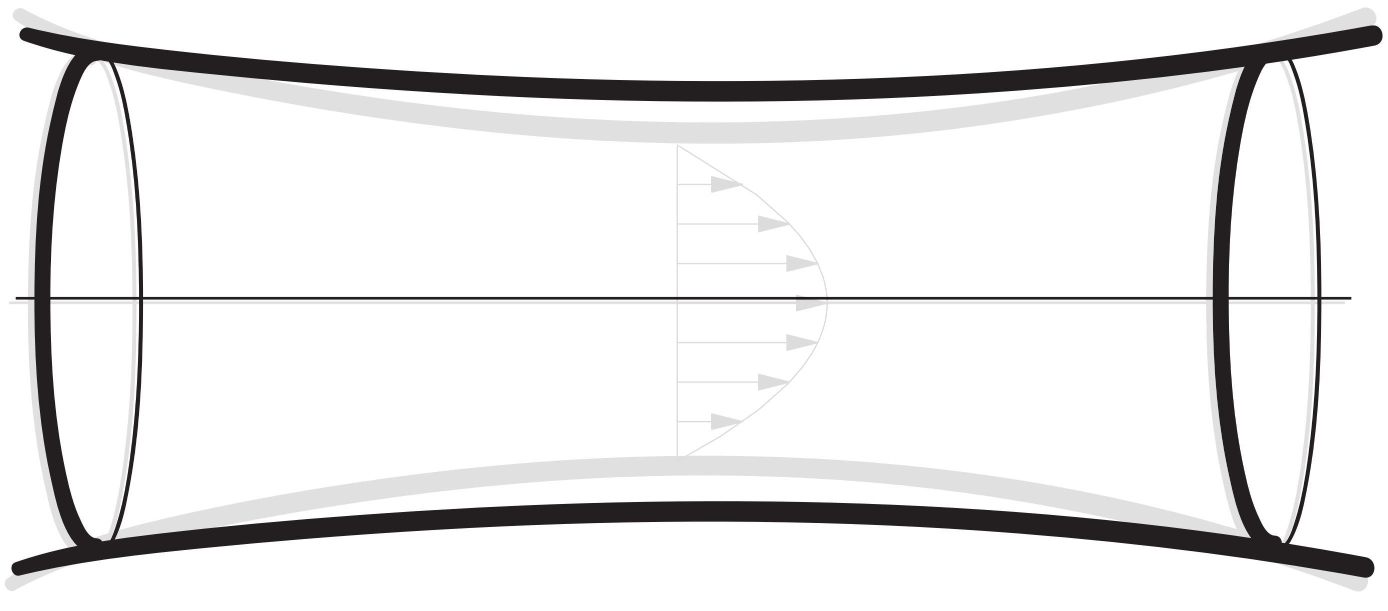


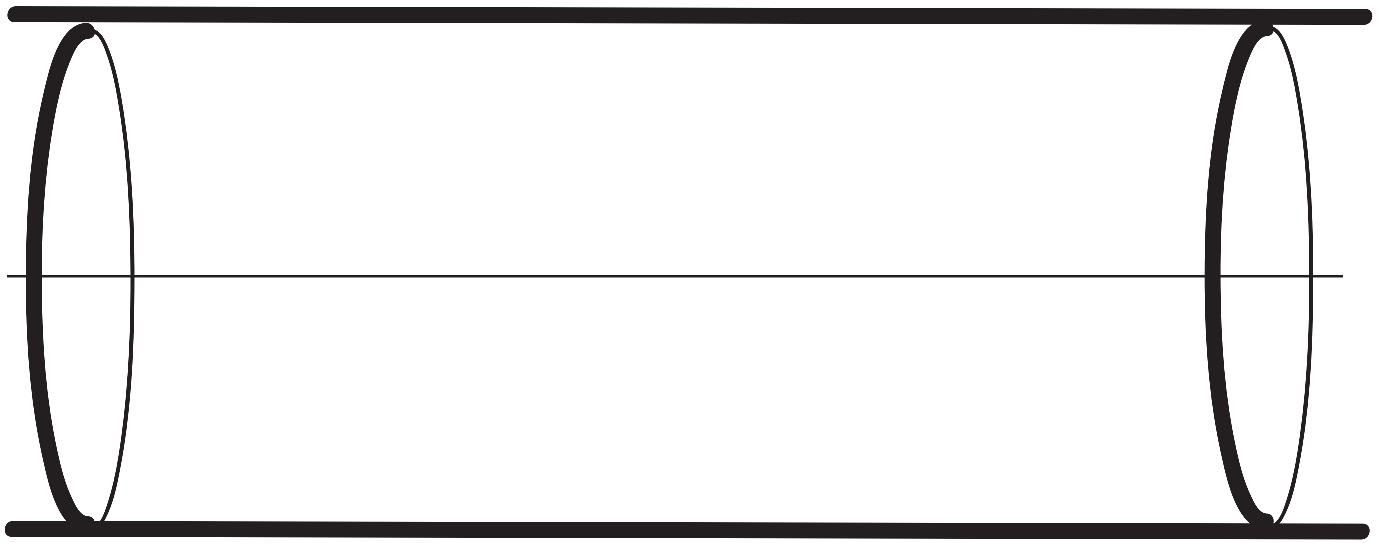
IBL is included in RNSP

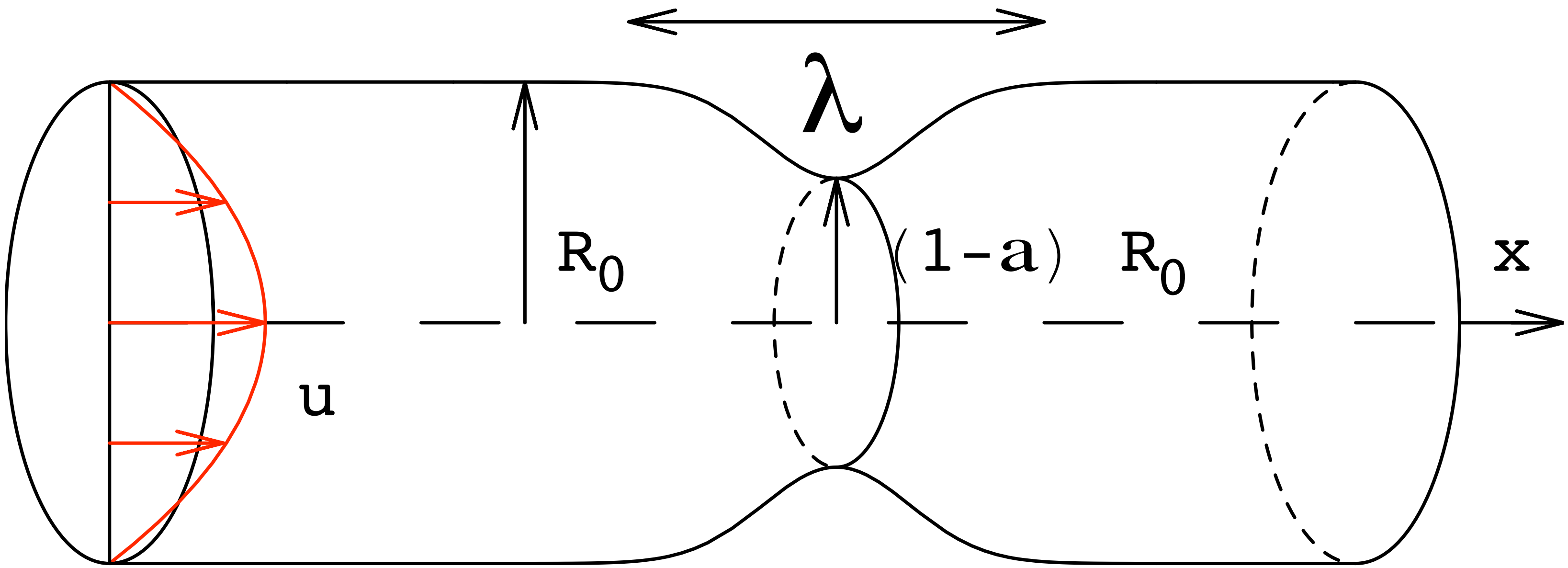
Example 1



- Flow in a stenozed vessel
- steady, rigid wall

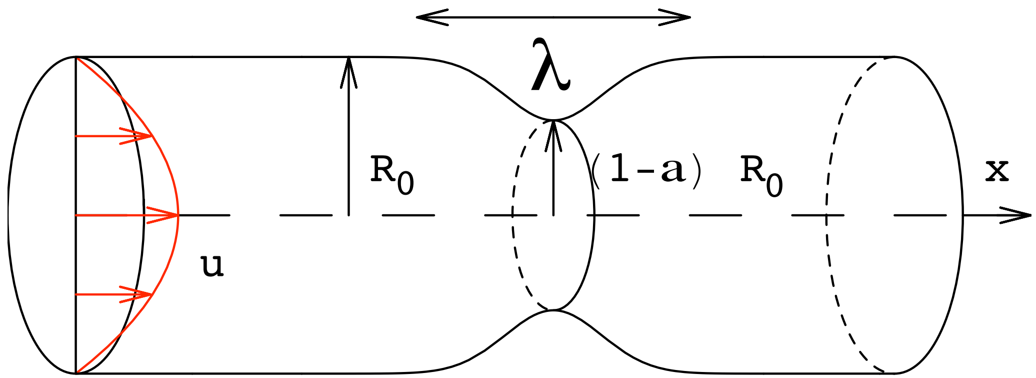






λ
R0
(1-a) R0
x
u

RNSP Scales

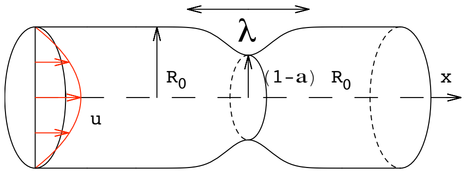


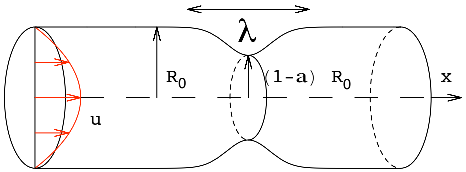
Using:

$x^* = xR_0Re$, $r^* = rR_0$, $u^* = U_0u$, $v^* = \frac{U_0}{Re}v$,
$p^* = p_0^* + \rho_0 U_0^2 p$ and $\tau^* = \frac{\rho U_0^2}{Re}\tau$

the following partial differential system is obtained from Navier Stokes as $Re \to \infty$:

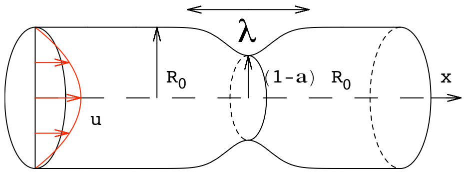
RNSP: Reduced Navier Stokes/ Prandtl System





RNSP: Reduced Navier Stokes/ Prandtl System

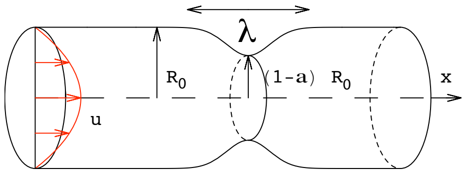
$$
\begin{aligned}
\frac{\partial}{\partial x}u + \frac{\partial}{r\partial r}rv &= 0, \\
(u\frac{\partial}{\partial x}u + v\frac{\partial}{\partial r}u) &= -\frac{\partial p}{\partial x} + \frac{\partial}{r\partial r}(r\frac{\partial}{\partial r}u), \\
0 &= -\frac{\partial p}{\partial r}.
\end{aligned}
$$



RNSP: Reduced Navier Stokes/ Prandtl System

$$\begin{aligned}
\frac{\partial}{\partial x}u + \frac{\partial}{r\partial r}rv &= 0, \\
(u\frac{\partial}{\partial x}u + v\frac{\partial}{\partial r}u) &= -\frac{\partial p}{\partial x} + \frac{\partial}{r\partial r}(r\frac{\partial}{\partial r}u), \\
0 &= -\frac{\partial p}{\partial r}.
\end{aligned}$$

$+$ The boundary conditions.



RNSP: Reduced Navier Stokes/ Prandtl System

$$
\begin{aligned}
\frac{\partial}{\partial x}u + \frac{\partial}{r\partial r}rv &= 0, \\
(u\frac{\partial}{\partial x}u + v\frac{\partial}{\partial r}u) &= -\frac{\partial p}{\partial x} + \frac{\partial}{r\partial r}(r\frac{\partial}{\partial r}u), \\
0 &= -\frac{\partial p}{\partial r}.
\end{aligned}
$$

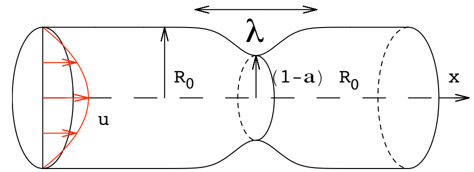
- axial symmetry ($\partial_r u = 0$ and $v = 0$ at $r = 0$),

- no slip condition at the wall ($u = v = 0$ at $r = 1 - f(x)$),

- the entry velocity profiles ($u(0, r)$ and $v(0, r)$) are given

- *no* output condition in $x_{out} = \frac{x^*_{out}}{R_0 Re}$

- streamwise marching, even when flow separation.

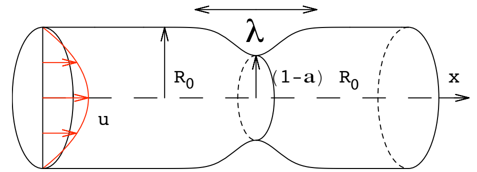


RNSP: Reduced Navier Stokes/ Prandtl System

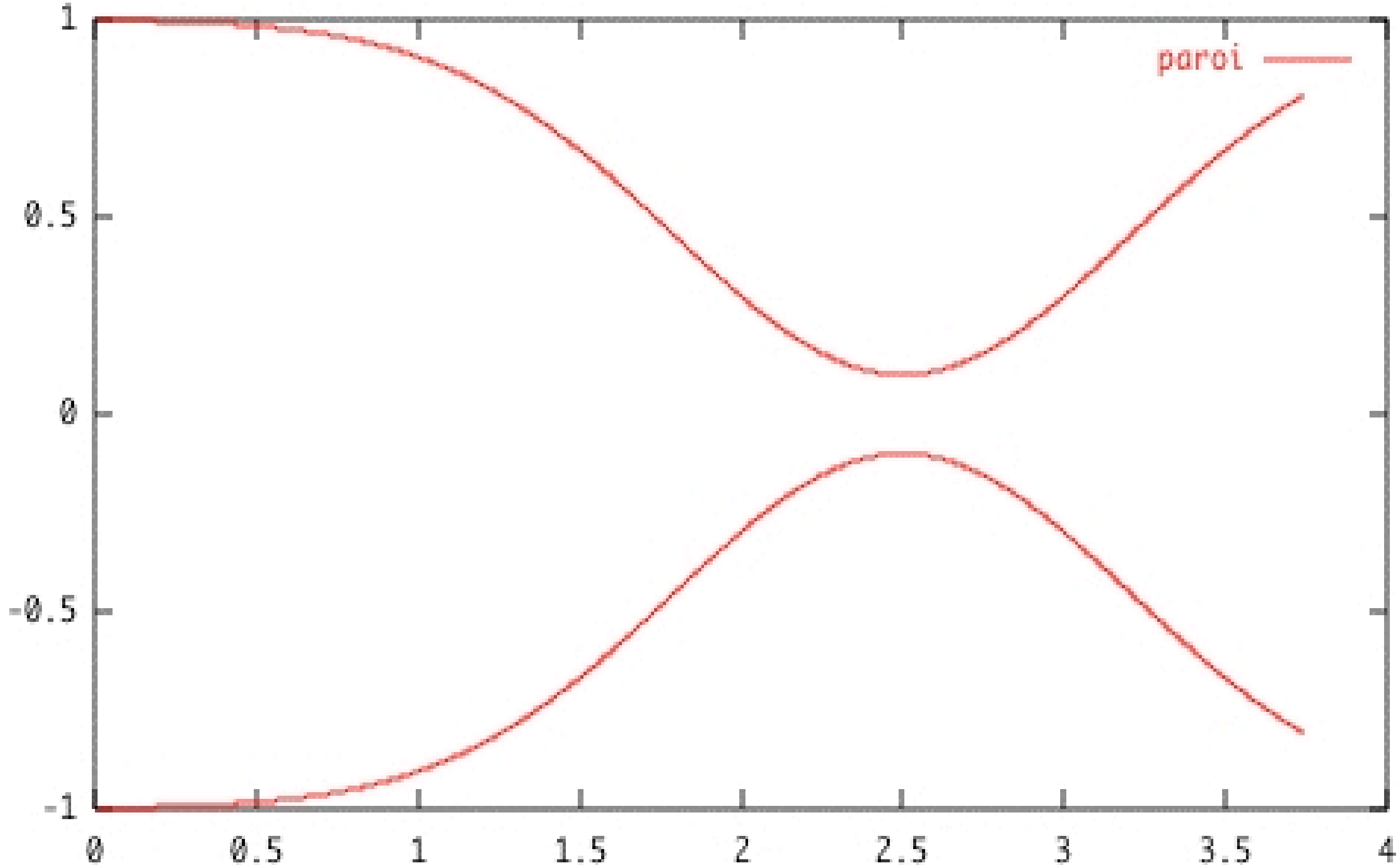
$$
\begin{aligned}
\frac{\partial}{\partial x}u + \frac{\partial}{r\partial r}rv &= 0, \\
(u\frac{\partial}{\partial x}u + v\frac{\partial}{\partial r}u) &= -\frac{\partial p}{\partial x} + \frac{\partial}{r\partial r}(r\frac{\partial}{\partial r}u), \\
0 &= -\frac{\partial p}{\partial r}.
\end{aligned}
$$

Parabolic Problem - Marching Problem

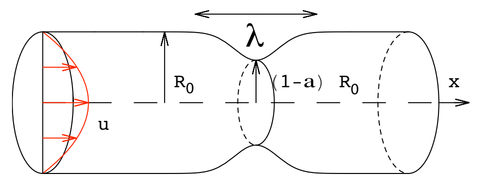
- axial symmetry ($\partial_r u = 0$ and $v = 0$ at $r = 0$),
- no slip condition at the wall ($u = v = 0$ at $r = 1 - f(x)$),
- the entry velocity profiles ($u(0, r)$ and $v(0, r)$) are given
- *no* output condition in $x_{out} = \frac{x^*_{out}}{R_0 Re}$
- streamwise marching, even when flow separation.



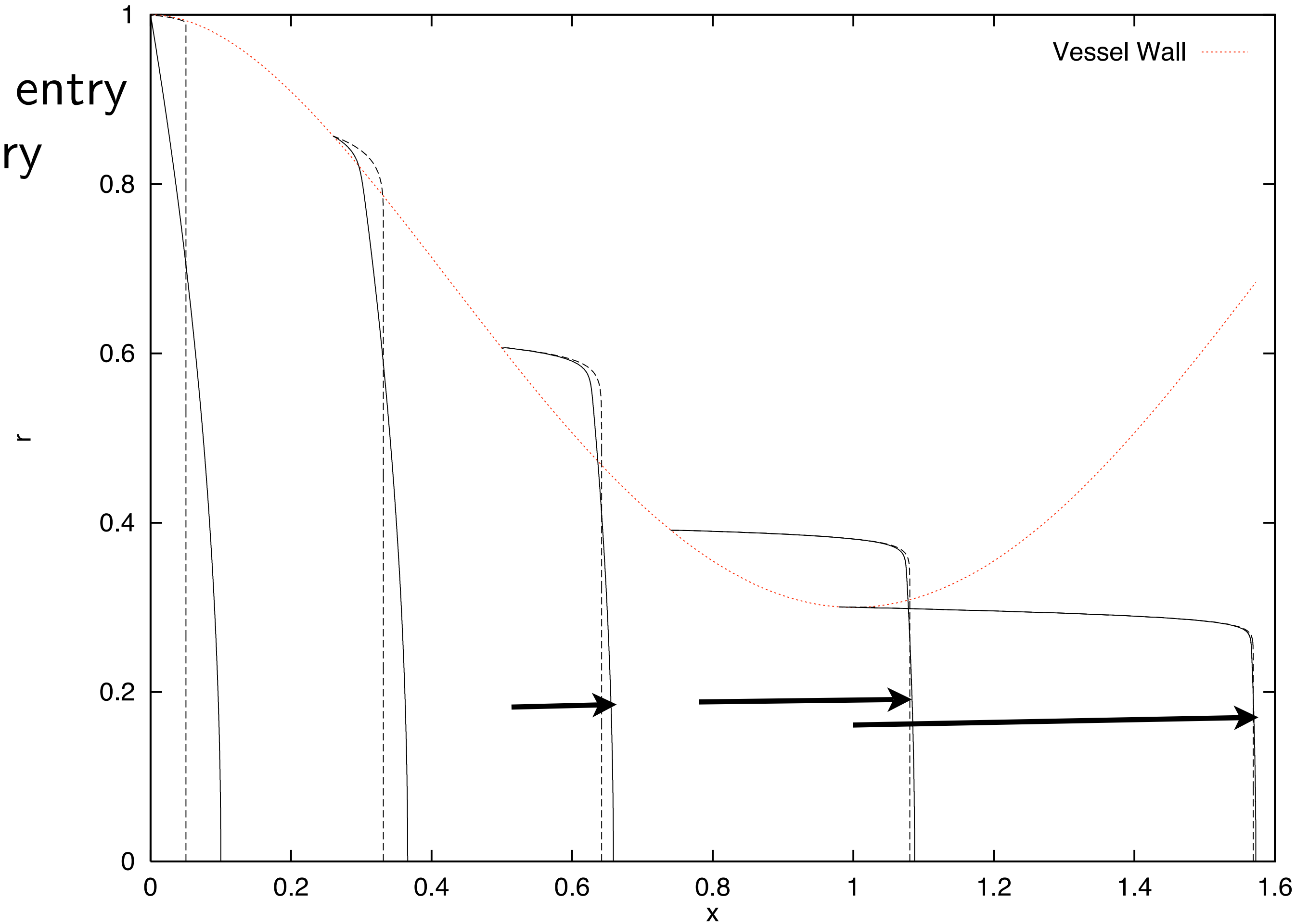
λ
R_0
(1-a) R_0
x
u

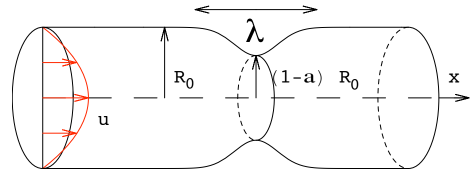


paroi
1
0.5
0
-0.5
-1
0
0.5
1
1.5
2
2.5
3
3.5
4

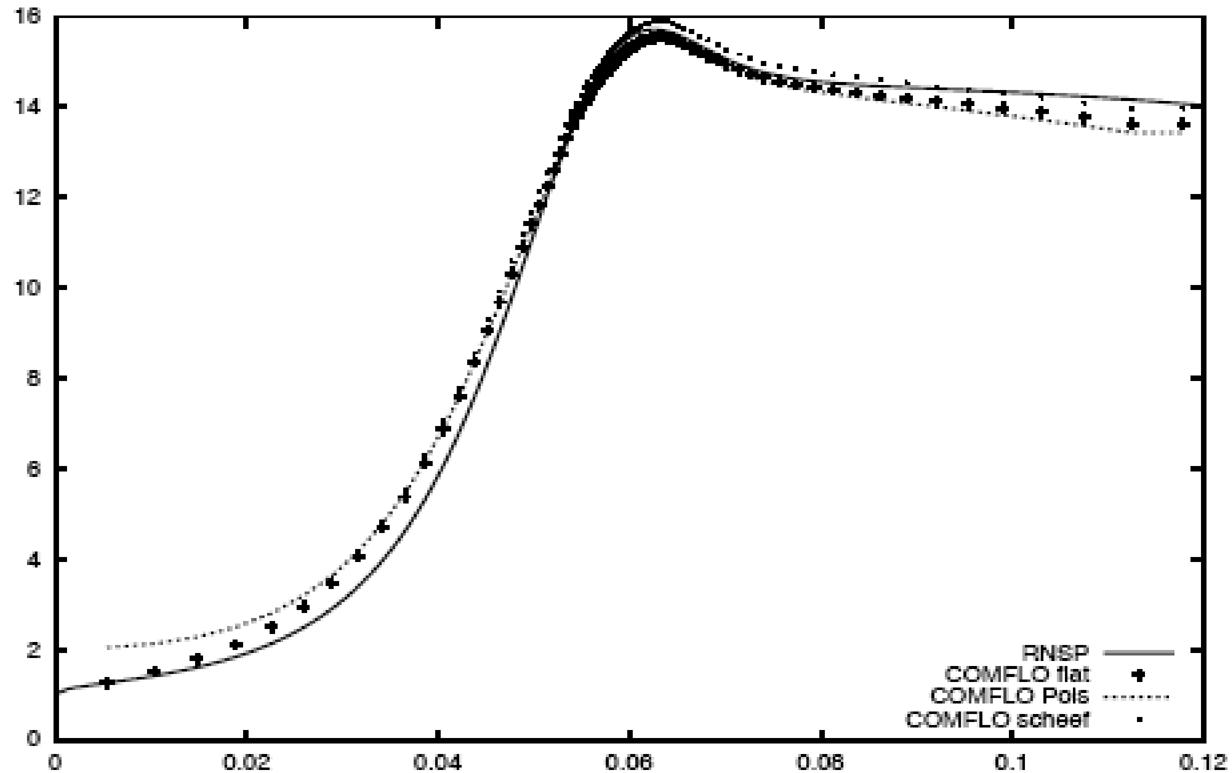


Evolution of the velocity profile along the convergent part of a 70% stenosis $(Re = 500)$;
solid line: Poiseuille entry
broken line: flat entry

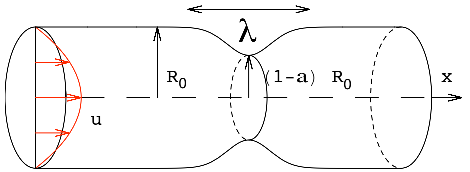




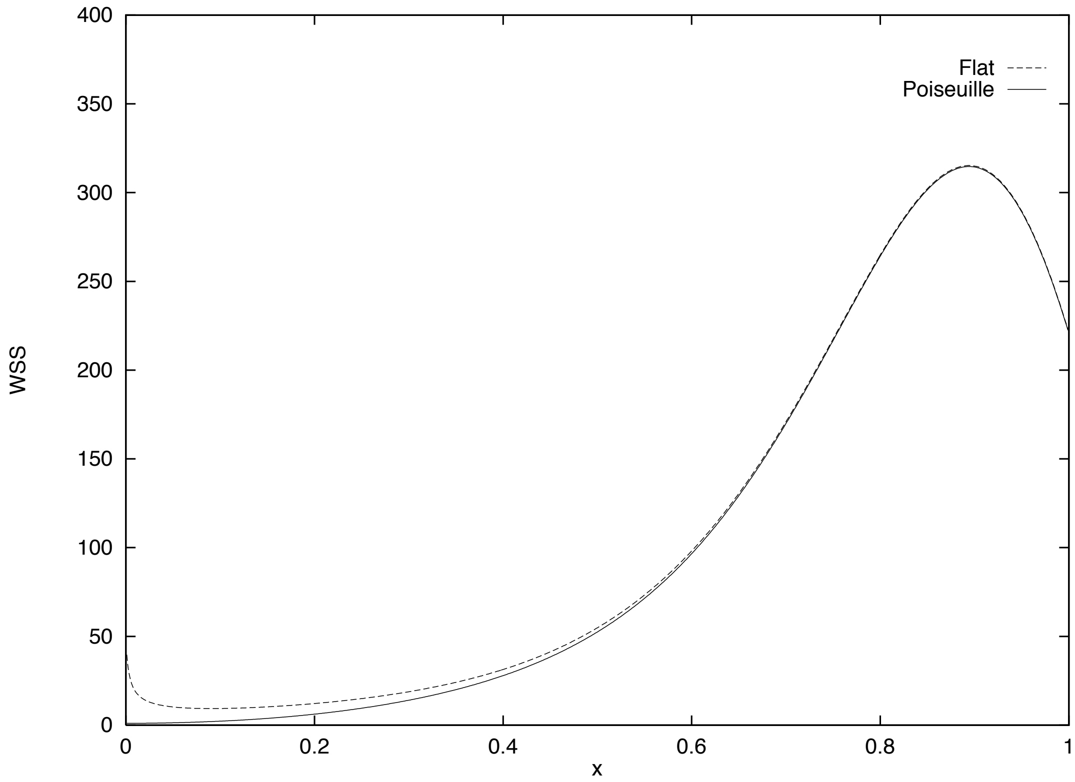
Testing asymmetry in the entry profile



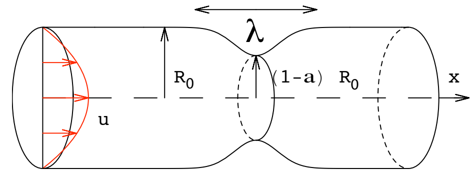
The velocities in the middle for Comflo and RNS.
Comflo uses here 50X50X100 points. Dimensionless scales!

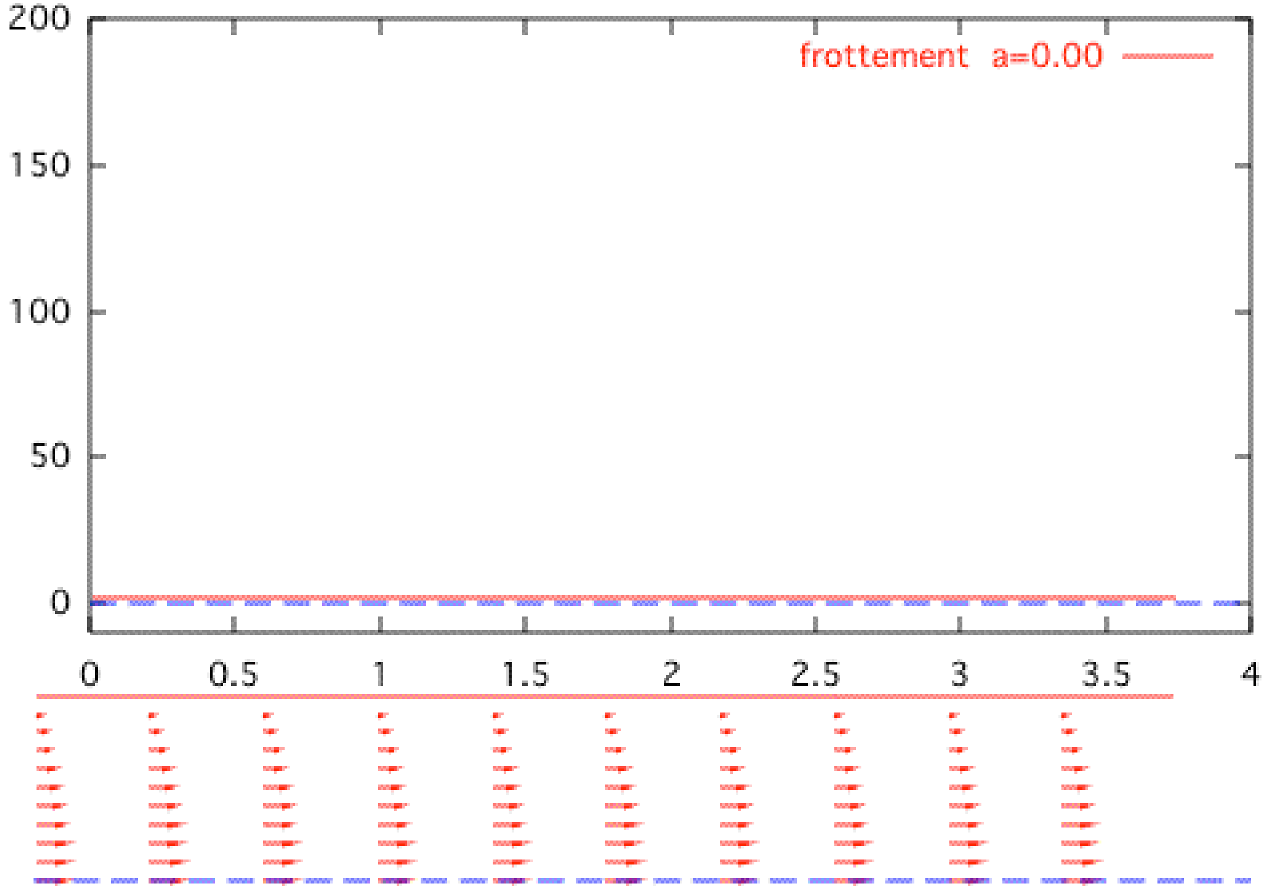


Wall Shear Stress

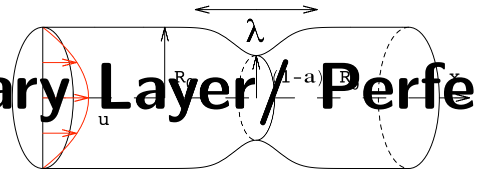


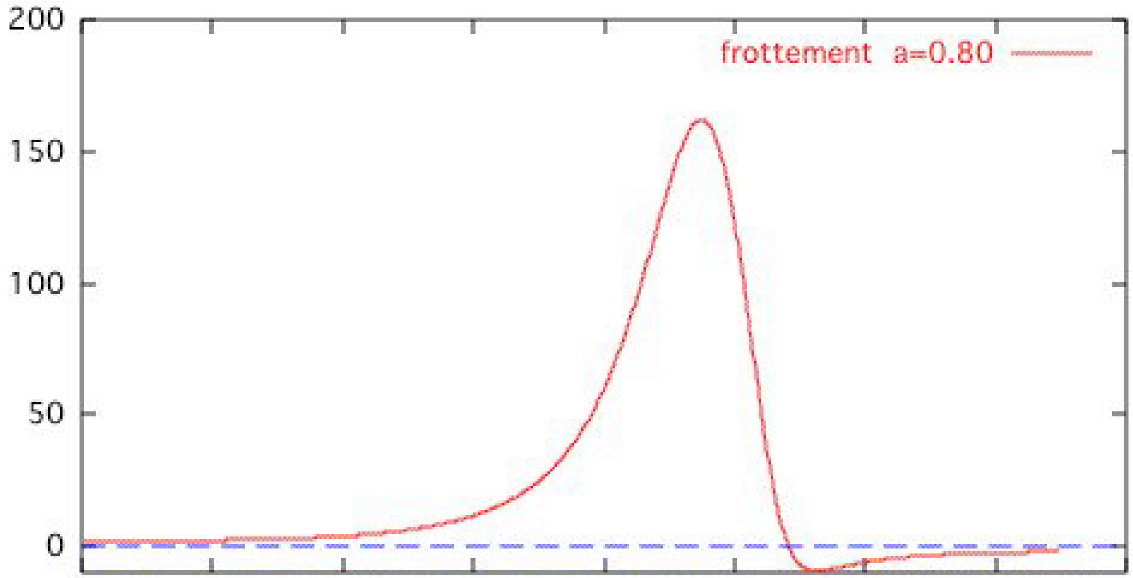
Evolution of the WSS distribution along the convergent part of a 70% stenosis ($Re = 500$) ; solid line: Poiseuille entry profile ; broken line: flat entry profile.

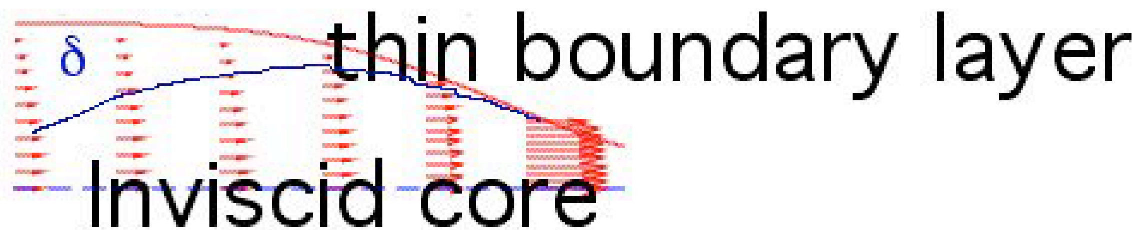

λ
R0
(1-a) R0
x
u

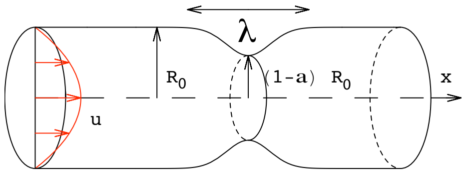

frottement a=0.00
200
150
100
50
0
0
0.5
1
1.5
2
2.5
3
3.5
4

Boundary Layer / Perfect Fluid

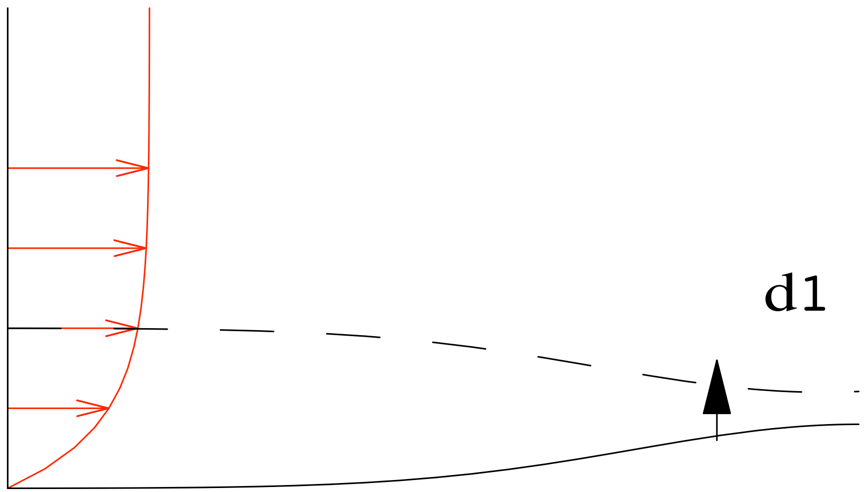




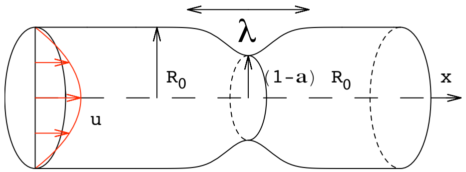




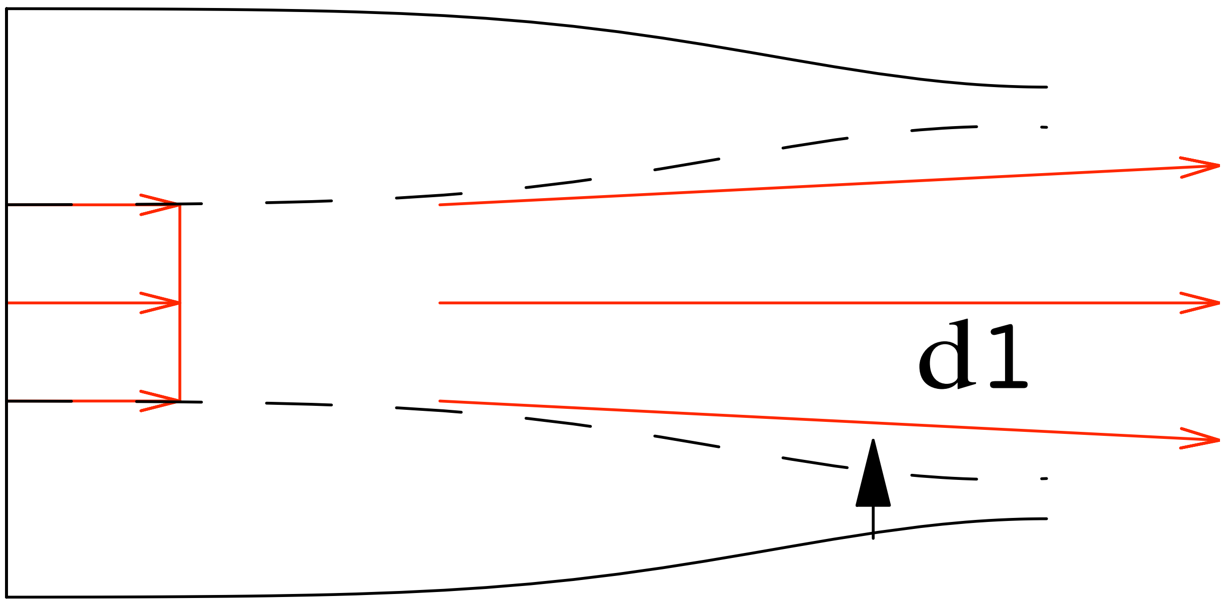
Boundary Layer/ Perfect Fluid



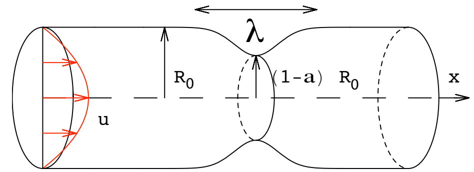
The boundary layer is generated near the wall
δ_1 is the displacement thickness.



Boundary Layer/ Perfect Fluid



The displacement thickness acts as a "new" wall!
→Interacting Boundary Layer (IBL)



RNSP/ IBL

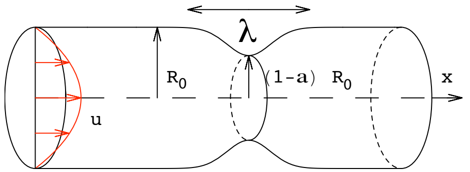
After rescalling:
$r = R(\bar{x}) - (\lambda/Re)^{-1/2}\bar{y}$, $u = \bar{u}$, $v = (\lambda/Re)^{1/2}\bar{v}$ and $x - x_b = (\lambda/Re)\bar{x}$, $p = \bar{p}$, where x_b is the position of the bump, the RNSP(x) set gives the final IBL (interacting Boundary Layer) problem as follows:

$$\frac{\partial \bar{u}}{\partial \bar{x}} + \frac{\partial \bar{v}}{\partial \bar{n}} = 0$$

$$(\bar{u}\frac{\partial \bar{u}}{\partial \bar{x}} + \bar{v}\frac{\partial \bar{u}}{\partial \bar{n}}) = \bar{u}_e \frac{d\bar{u}_e}{d\bar{s}} + \frac{\partial}{\partial \bar{n}}\frac{\partial \bar{u}}{\partial \bar{n}}$$

with: $\bar{u}(\bar{x},0) = 0$, $\bar{v}(\bar{x},0) = 0$ $\bar{u}(\bar{x},\infty) = u_e$, where $\bar{\delta}_1 = \int_0^\infty (1 - \frac{\bar{u}}{\bar{u}_e})d\bar{n}$, and

$$\bar{u}_e = \frac{1}{(R^2 - 2((\lambda/Re)^{-1/2})\bar{\delta}_1)}.$$



IBL integral: 1D equation

$$\frac{d}{d\bar{x}}(\frac{\bar{\delta}_1}{H}) = \bar{\delta}_1(1+\frac{2}{H})\frac{d\bar{u}_e}{d\bar{x}} + \frac{f_2 H}{\bar{\delta}_1 \bar{u}_e},$$
$$\bar{u}_e = \frac{1}{(R^2 - 2(\lambda/Re)^{-1/2}\bar{\delta}_1)}.$$

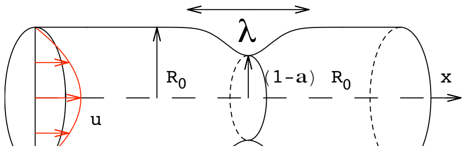
To solve this system, a closure relationship linking H and f_2 to the velocity and the displacement thickness is needed.

Defining $\Lambda_1 = \bar{\delta}_1^2 \frac{d\bar{u}_e}{d\bar{x}}$,

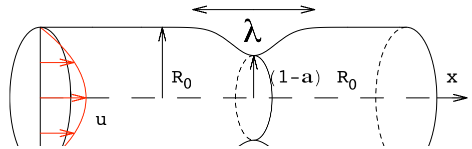
the system is closed from the resolution of the Falkner Skan system as follows:

if $\Lambda_1 < 0.6$ then $H = 2.5905exp(-0.37098\Lambda_1)$, else $H = 2.074$.

From H,f_2 is computed as $f_2 = 1.05(-H^{-1} + 4H^{-2})$.

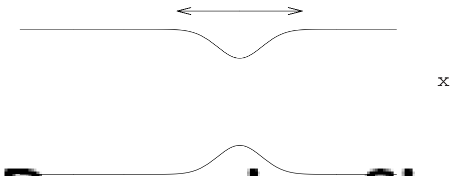


IBL integral: 1D equation Simplified Shear Stress



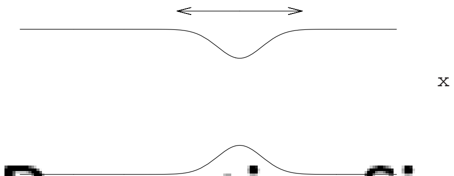
IBL integral: 1D equation Simplified Shear Stress

- variation of velocity (flux conservation)



IBL integral: 1D equation Simplified Shear Stress

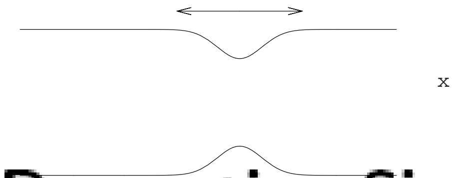
- variation of velocity (flux conservation) $U_0 \to U_0/(1-\alpha-\delta_1)^2$



IBL integral: 1D equation Simplified Shear Stress

- variation of velocity (flux conservation) $U_0 \to U_0/(1-\alpha-\delta_1)^2$

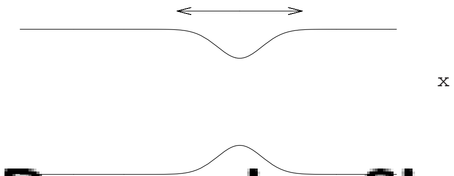
- acceleration: boundary layer $\delta_1 \simeq \frac{\lambda}{\sqrt{Re_\lambda}}$,



IBL integral: 1D equation Simplified Shear Stress

- variation of velocity (flux conservation) $U_0 \to U_0/(1-\alpha-\delta_1)^2$

- acceleration: boundary layer $\delta_1 \simeq \frac{\lambda}{\sqrt{Re_\lambda}}$, with $Re_\lambda = \frac{\lambda U_0}{(1-\alpha)^2\nu} = \frac{Re\lambda}{(1-\alpha)^2}$

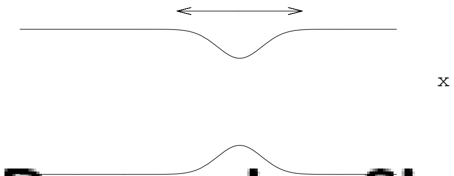


IBL integral: 1D equation Simplified Shear Stress

- variation of velocity (flux conservation) $U_0 \to U_0/(1-\alpha-\delta_1)^2$

- acceleration: boundary layer $\delta_1 \simeq \frac{\lambda}{\sqrt{Re_\lambda}}$, with $Re_\lambda = \frac{\lambda U_0}{(1-\alpha)^2 \nu} = \frac{Re \lambda}{(1-\alpha)^2}$

- WSS = (variation of velocity)/(boundary layer thickness)



IBL integral: 1D equation Simplified Shear Stress

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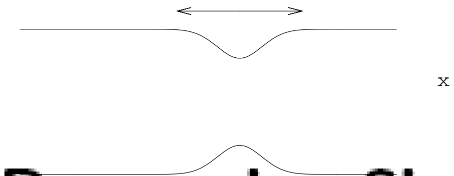
- WSS = (variation of velocity)/(boundary layer thickness) $= \frac{(Re/\lambda)^{1/2}}{(1-\alpha)^3}$



IBL integral: 1D equation Simplified Shear Stress

- variation of velocity (flux conservation) $U_0 \rightarrow U_0/(1-\alpha-\delta_1)^2$

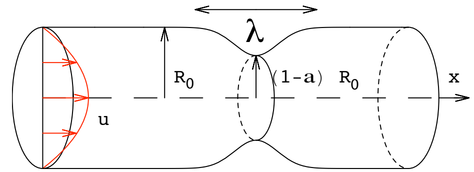
- acceleration: boundary layer $\delta_1 \simeq \frac{\lambda}{\sqrt{Re_\lambda}}$, with $Re_\lambda = \frac{\lambda U_0}{(1-\alpha)^2\nu} = \frac{Re\lambda}{(1-\alpha)^2}$

- WSS = (variation of velocity)/(boundary layer thickness) $= \frac{(Re/\lambda)^{1/2}}{(1-\alpha)^3}$

A simple formula as been settled:

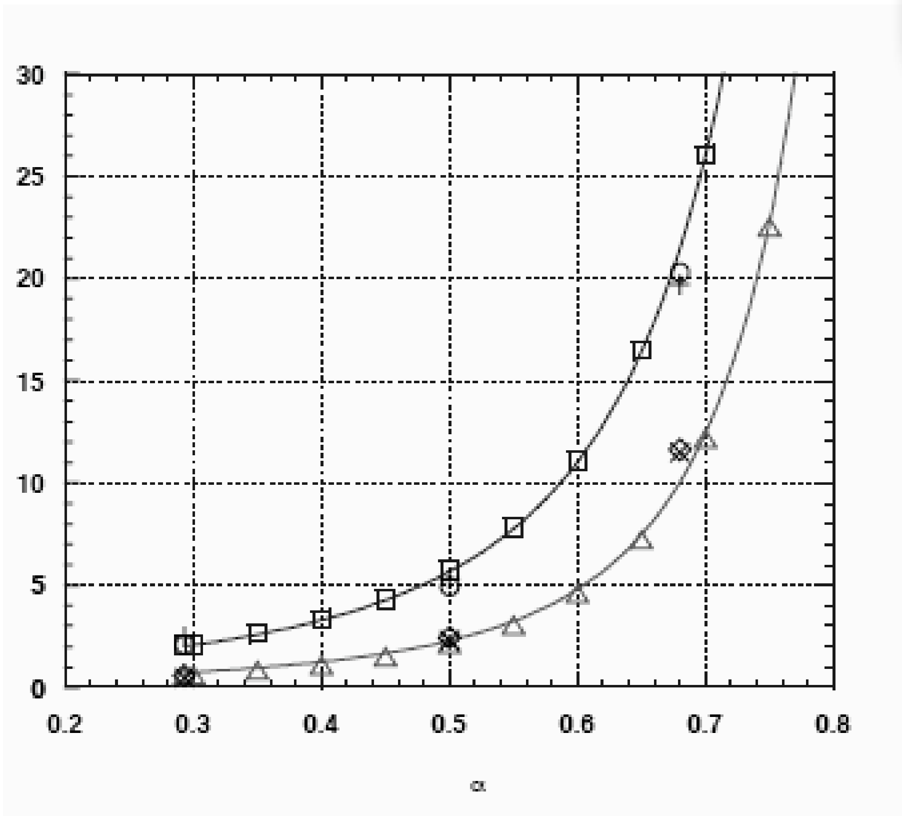
$$WSS = (\mu\frac{\partial u^*}{\partial y^*})/((\mu\frac{4U_0}{R})) \sim .22\frac{((Re/\lambda)^{1/2}+3)}{(1-\alpha)^3}$$

Reynolds number is no longer Re but $Re\lambda$ and $(Re/\lambda)^{1/2}$ is the inverse of the relative boundary layer thickness.



IBL integral: Comparison with Navier Stokes (Siegel et al. 1994)

a, b

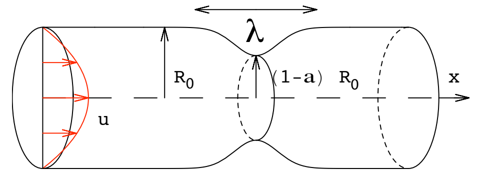


$$WSS = aRe^{1/2} + b$$

Coefficient a and b for the maximum WSS.
solid lines with △ and "square" : coefficient a and b obtained using the IBL integral method ;

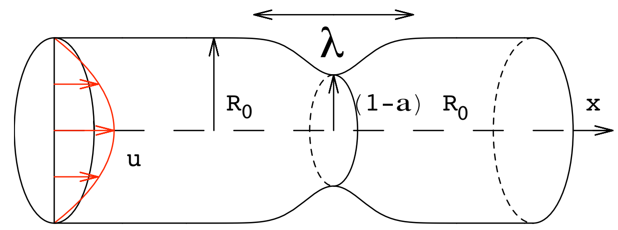
◇ : coefficient a derived from Siegel for $\lambda = 3$;
× : coefficient a derived from Siegel for $\lambda = 6$;
◯ : coefficient b derived from Siegel for $\lambda = 3$;
+ : coefficient b derived from Siegel for $\lambda = 6$.

$$WSS = (\mu\frac{\partial u}{\partial y})/(\mu\frac{4U_0}{R}) \simeq 0.22\frac{(Re/\lambda)^{1/2}+3}{(1-\alpha)^3}$$

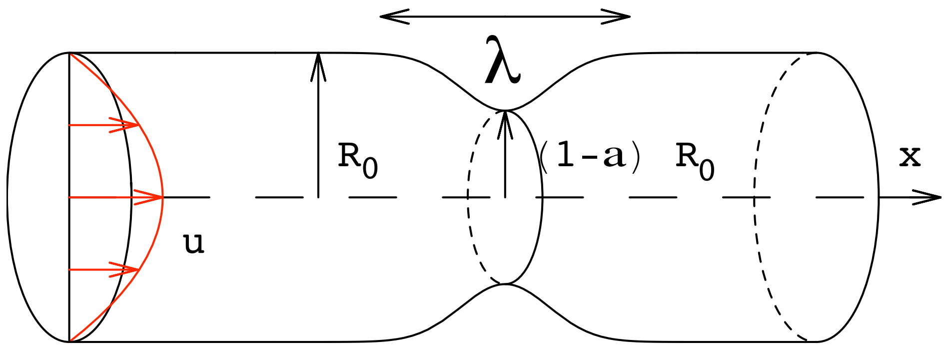


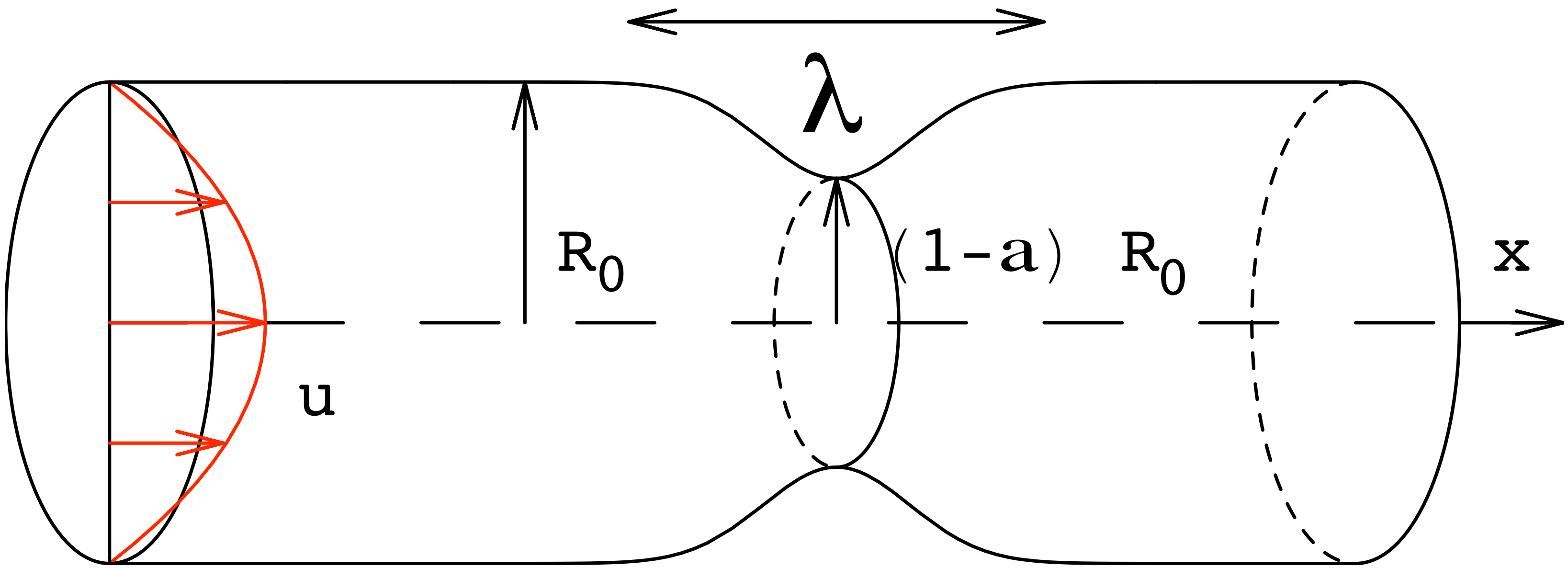
S. Lorthois, P.-Y. Lagrée, J.-P. Marc-Vergnes & F. Cassot. (2000):
"Maximal wall shear stress in arterial stenoses: Application to the internal carotid arteries",
Journal of Biomechanical Egineering, Volume 122, Issue 6, pp. 661-666.

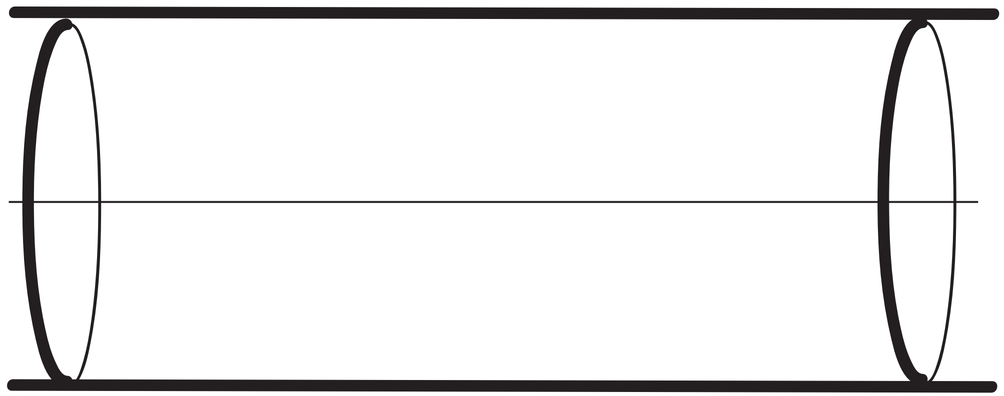
Lorthois S. & Lagrée P.-Y. (2000):
"Flow in a axisymmetric convergent: evaluation of maximum wall shear stress",
C. R. Acad. Sci. Paris, t328, Série II b, p33-40, 2000

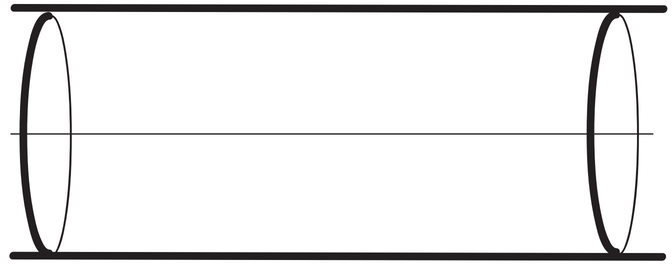


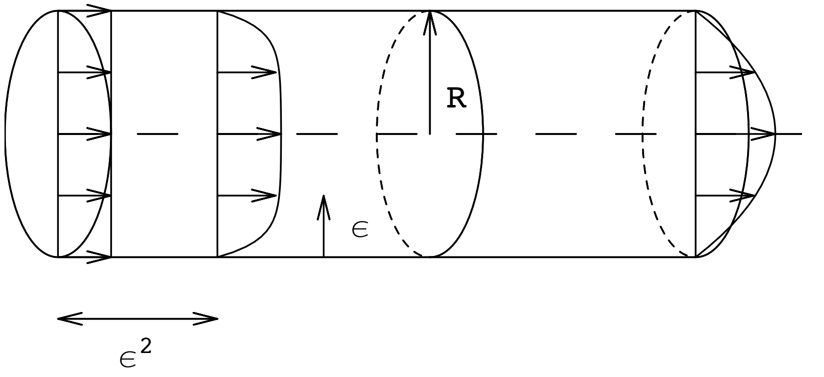
λ
R0
(1-a) R0
x
u

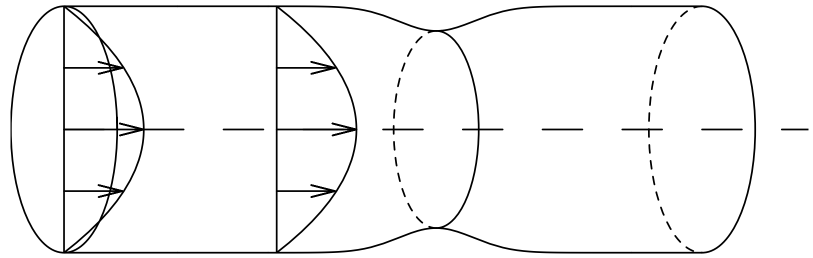

λ
R0
(1-a) R0
x
u

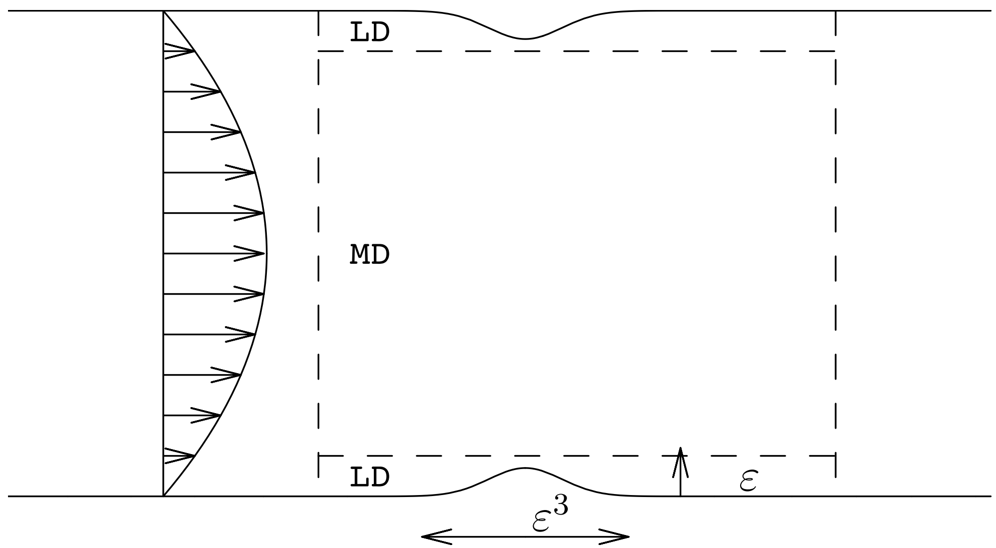

λ
R_0
(1-a) R_0
x
u





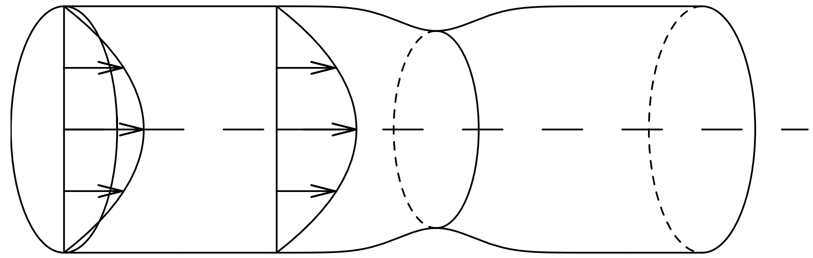

R
∈
∈2

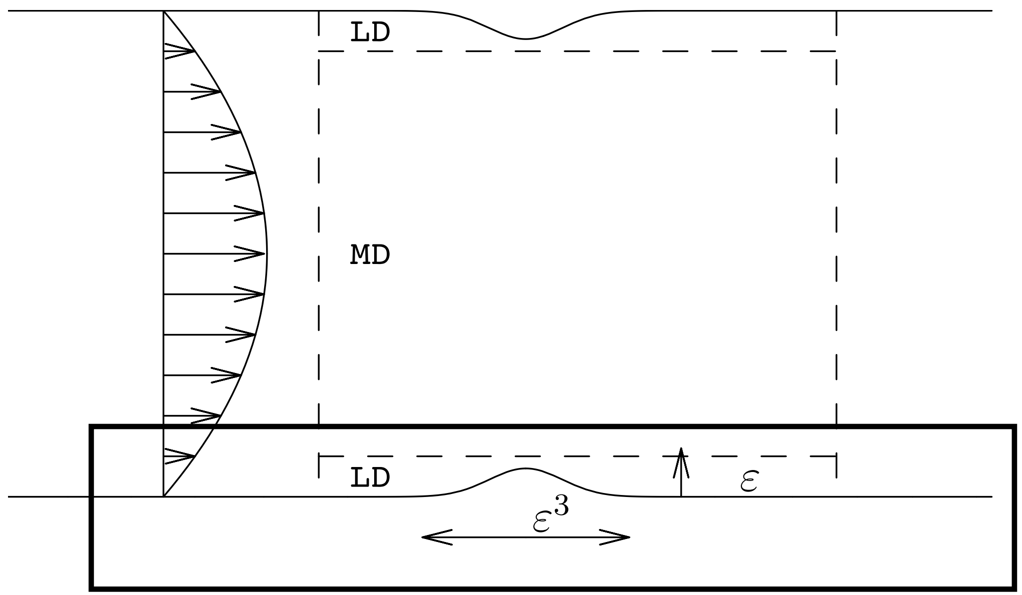




Double Deck

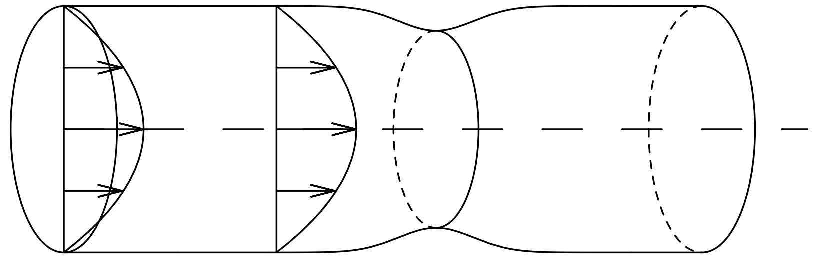
$A = 0$

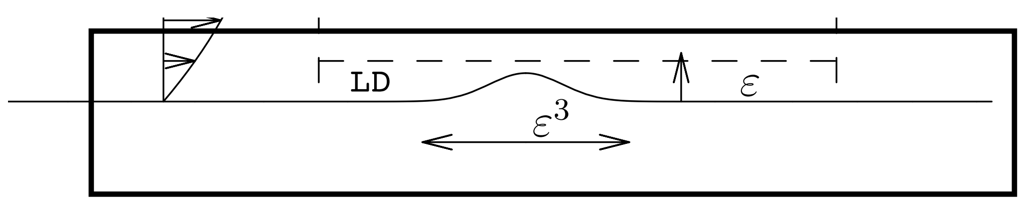




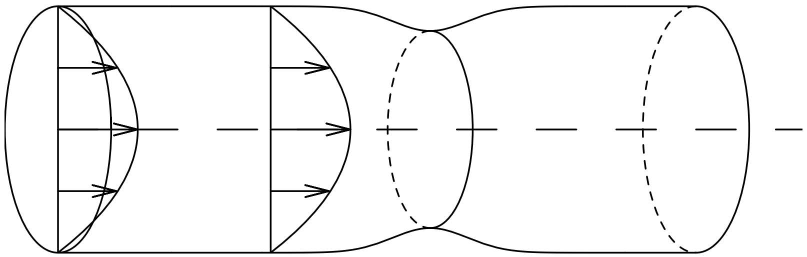
Double Deck

$A = 0$



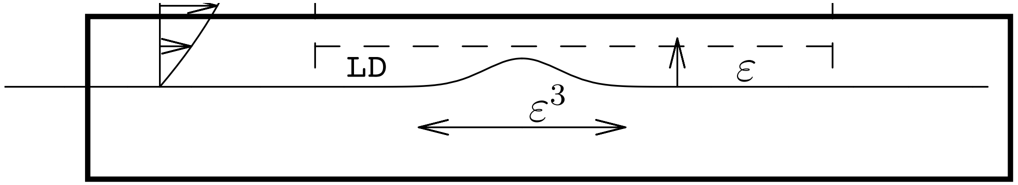


Double Deck

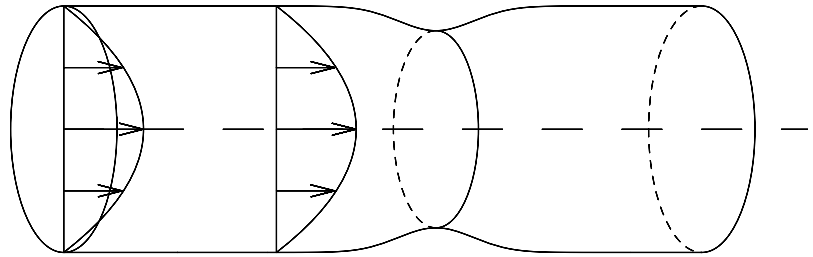


$$u = y \qquad\qquad u\frac{\partial}{\partial x}u \sim \frac{\partial^2}{\partial y^2}u$$

$$\frac{\varepsilon}{x_3}\bar{u}\frac{\partial}{\partial \bar{x}}\bar{u} \sim \frac{1}{\varepsilon^2}\frac{\partial^2}{\partial \bar{y}^2}\bar{u}$$



Double Deck



$$\frac{\partial}{\partial x}u + \frac{\partial}{\partial y}v = 0,$$

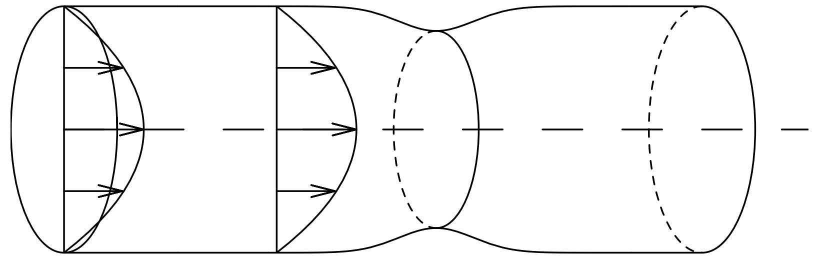
$$u\frac{\partial}{\partial x}u + v\frac{\partial}{\partial y}u = -\frac{d}{dx}p + \frac{\partial^2}{\partial y^2}u$$

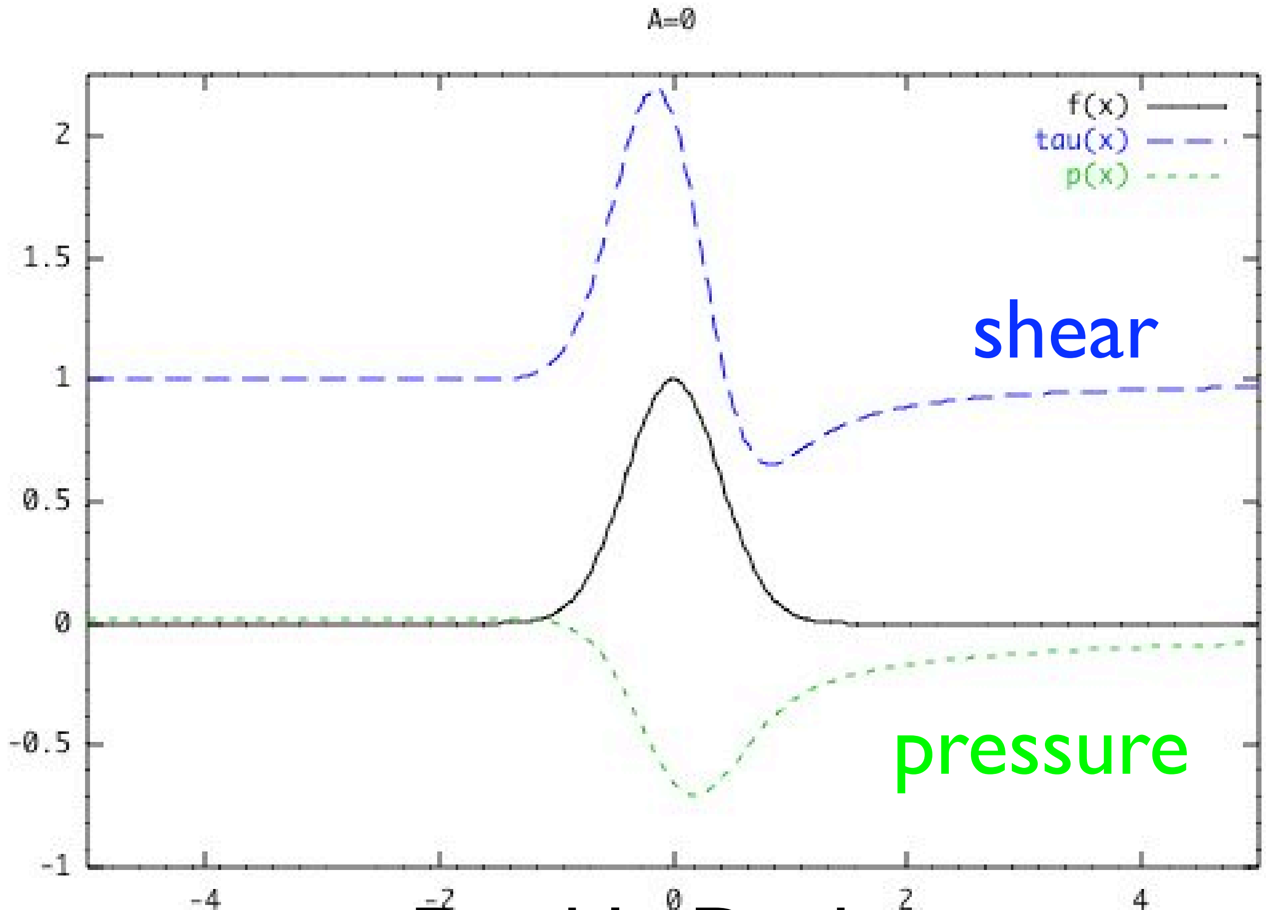
$$u(x, y = f(x)) = 0, \qquad v(x, y = f(x)) = 0$$

$$\lim_{y\to\infty} u(x,y) = y.$$

again the same equations
with differents scales and different boundary conditions

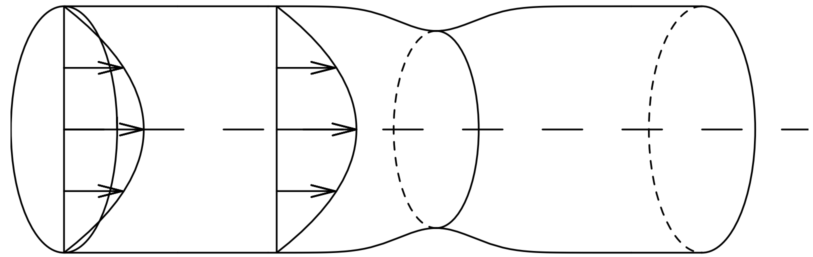
Double Deck





Double Deck

$A = 0$



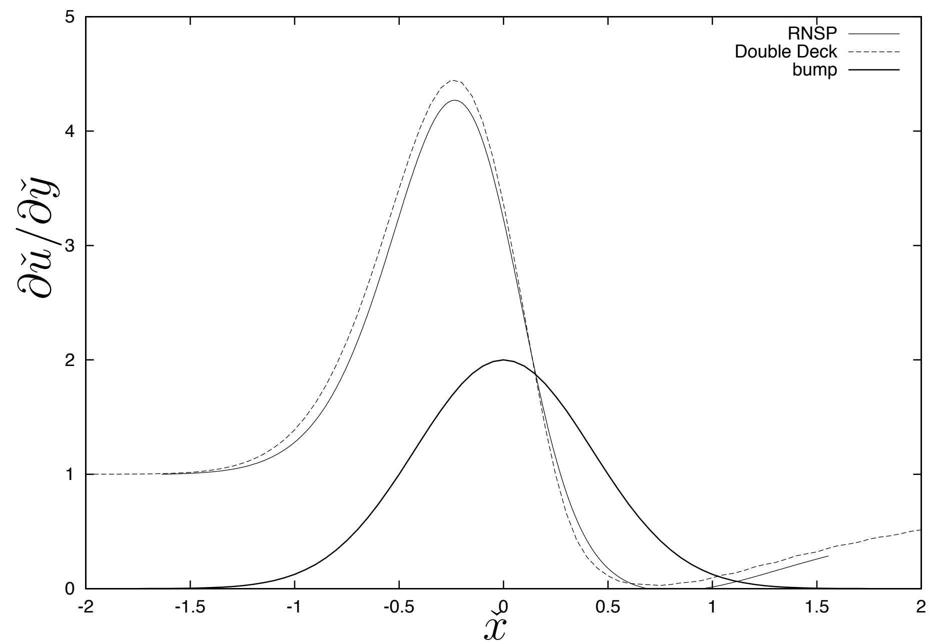
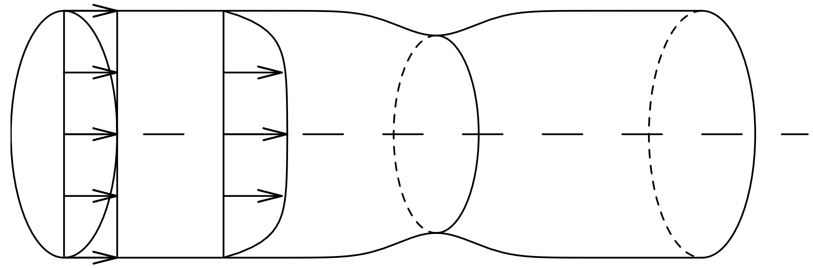
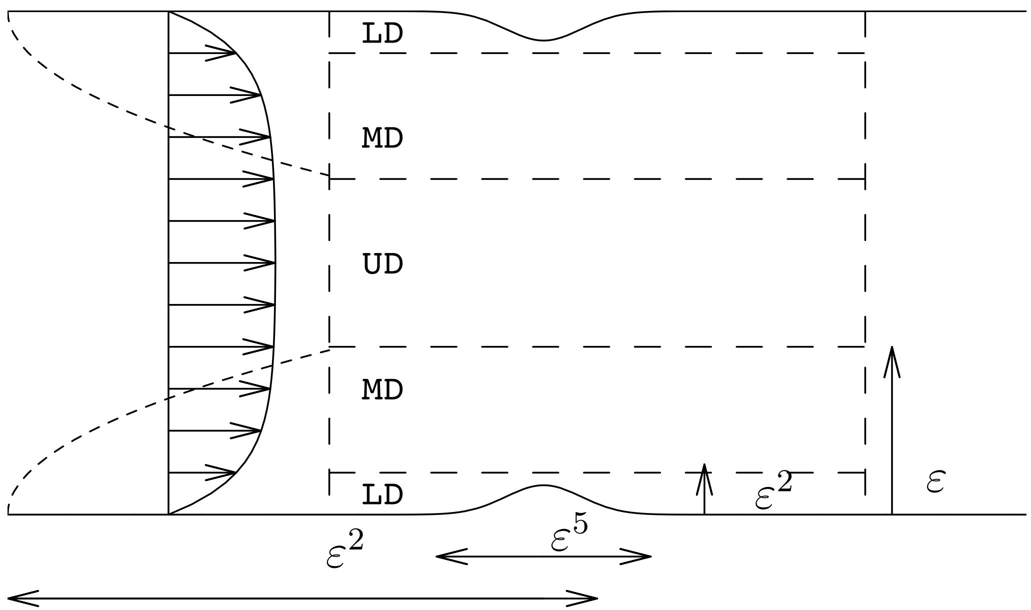


Fig. 12. **Longitudinal evolution of the WSS near the incipient separation case** for $x_l = 0.0125$. D.D. : Double Deck resolution ; RNSP : RNSP resolution rescaled in Double Deck scales.

Double Deck

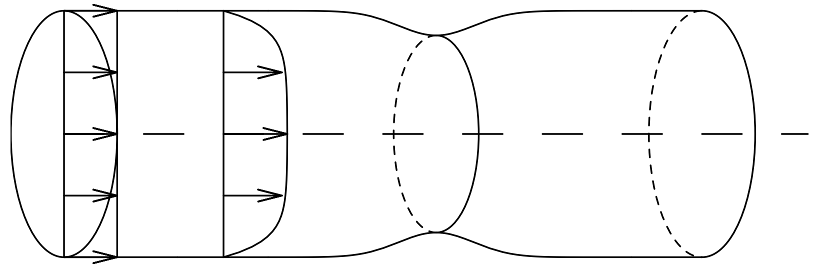
$A = 0$

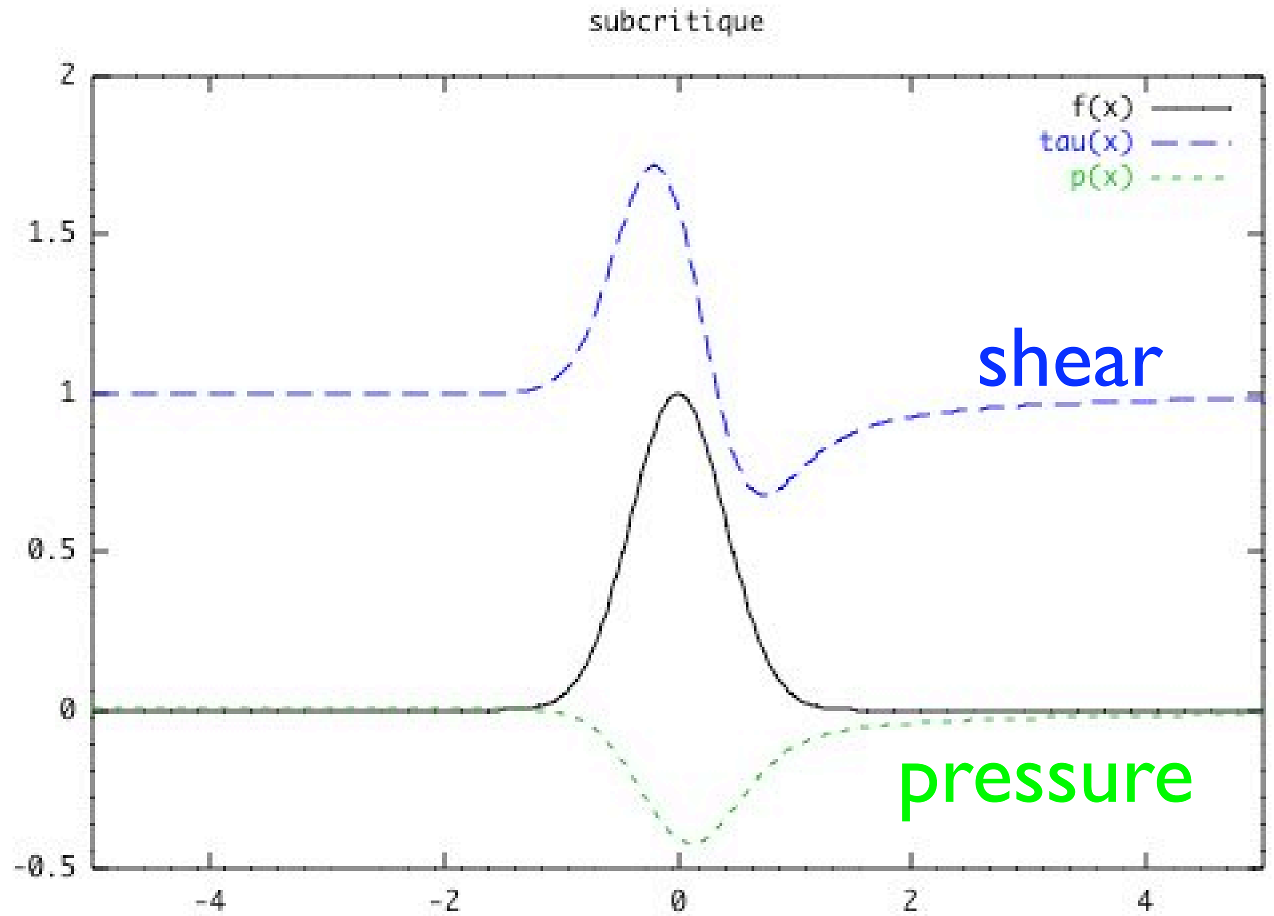




Triple Deck

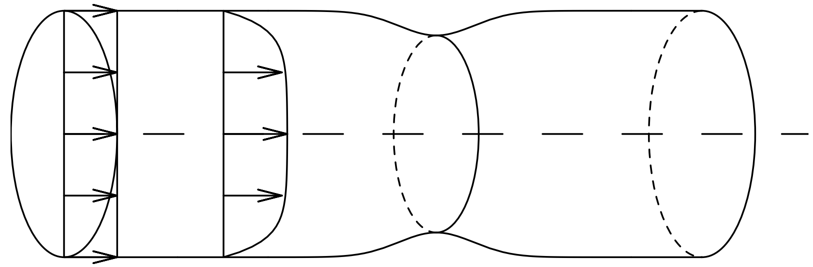
$p = A$





Triple Deck

$p = A$



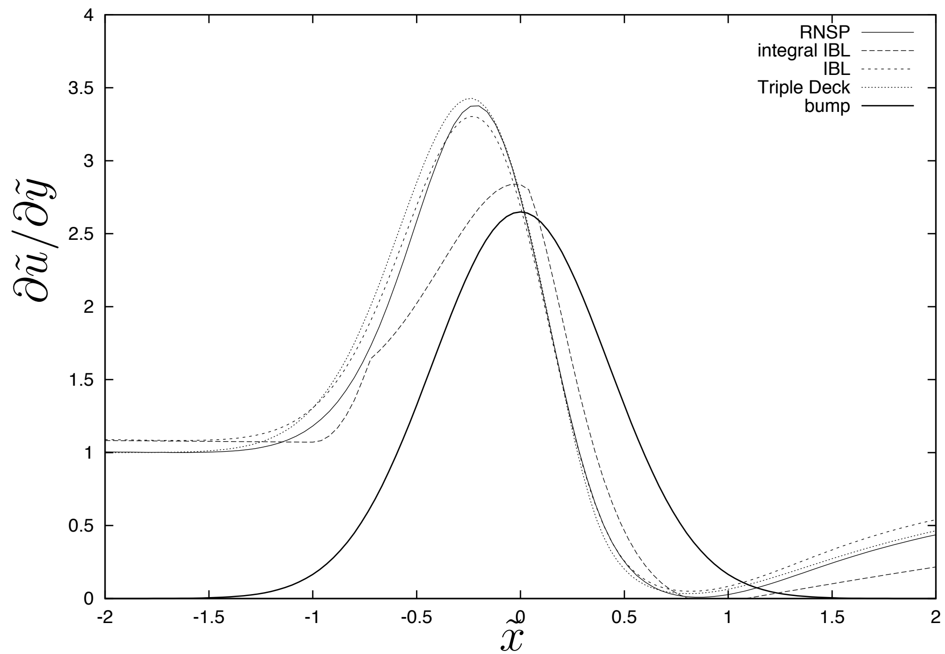
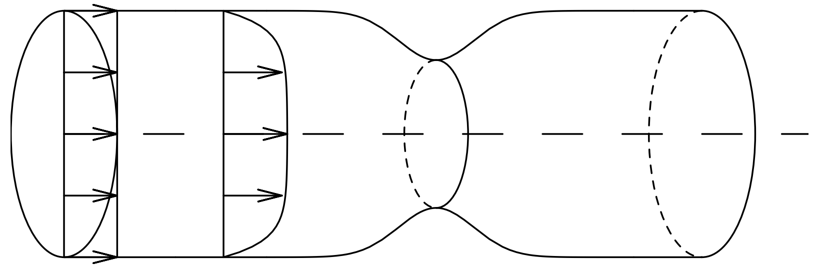


Fig. 9. **Longitudinal evolution of the WSS near the incipient separation case** RNSP, integral IBL, full IBL resolution (in RNSP variables, the bump is located in $x = 0.02$, and its width is 0.00125), and Triple Deck resolution. All the curves are rescaled in Triple Deck scales.

Triple Deck

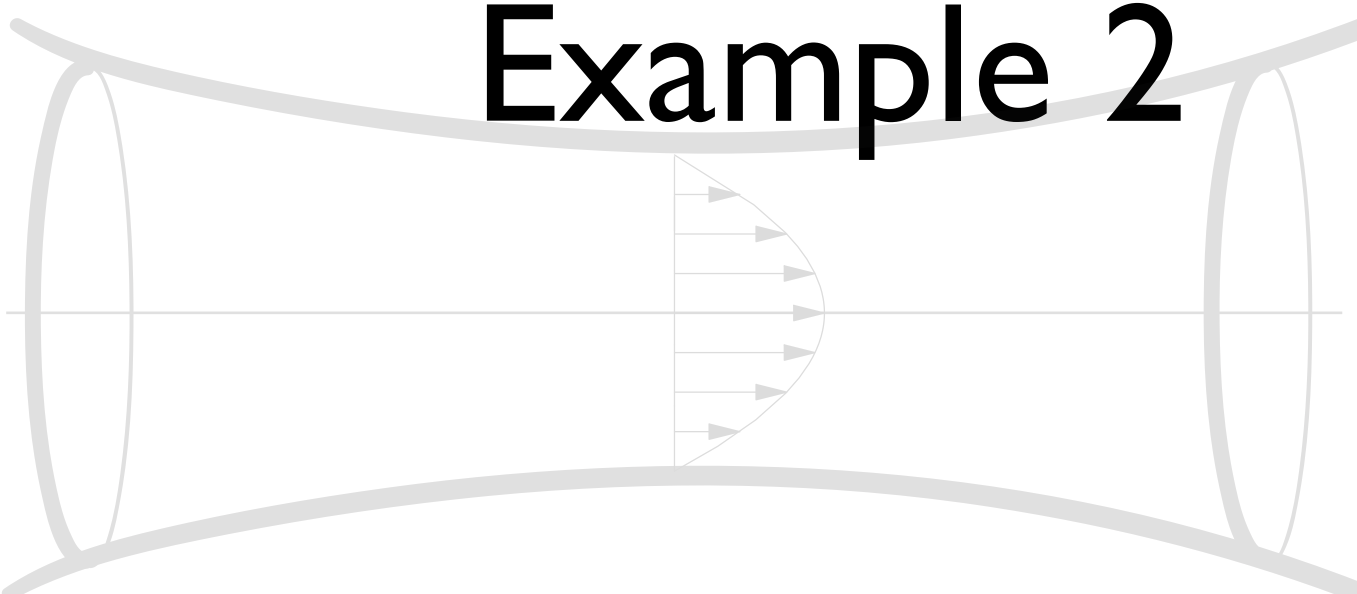
$$p = A$$



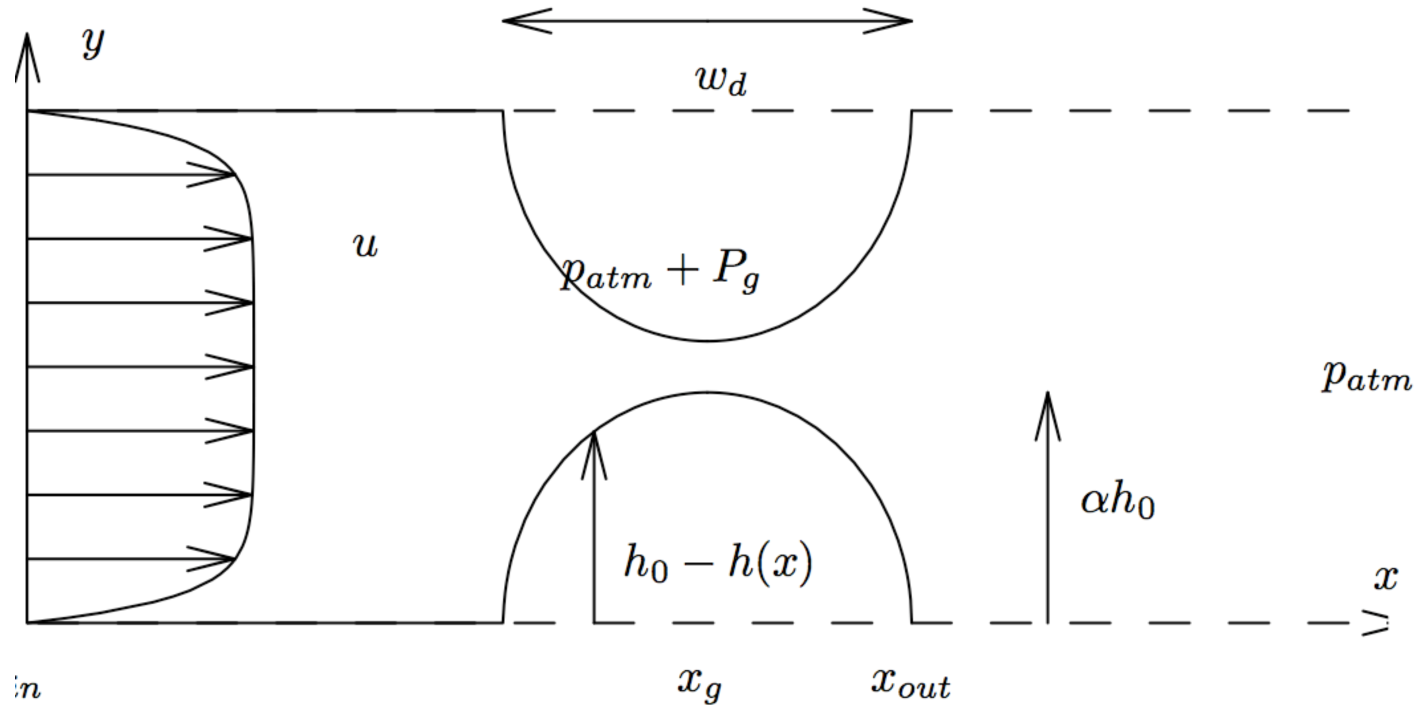
••••

P.-Y. Lagrée & S. Lorthois (2005):
"The RNS/Prandtl equations and their link with other asymptotic descriptions.
Application to the computation of the maximum value of the Wall Shear Stress in a pipe",
Int. J. Eng Sci., Vol 43/3-4 pp 352-378.

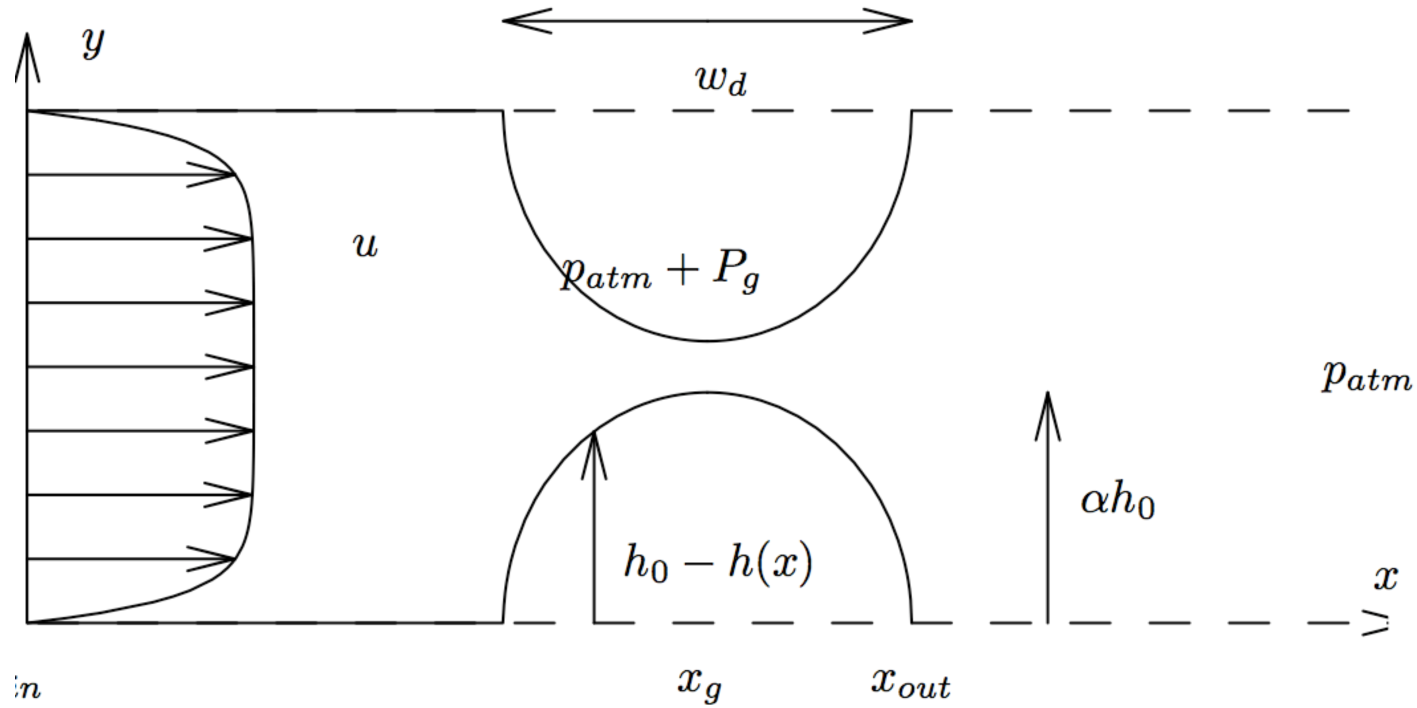
Example 2



- Flow in a 2D stenozed vessel
- steady, rigid wall



- Flow in a stenozed vessel
- steady, rigid wall

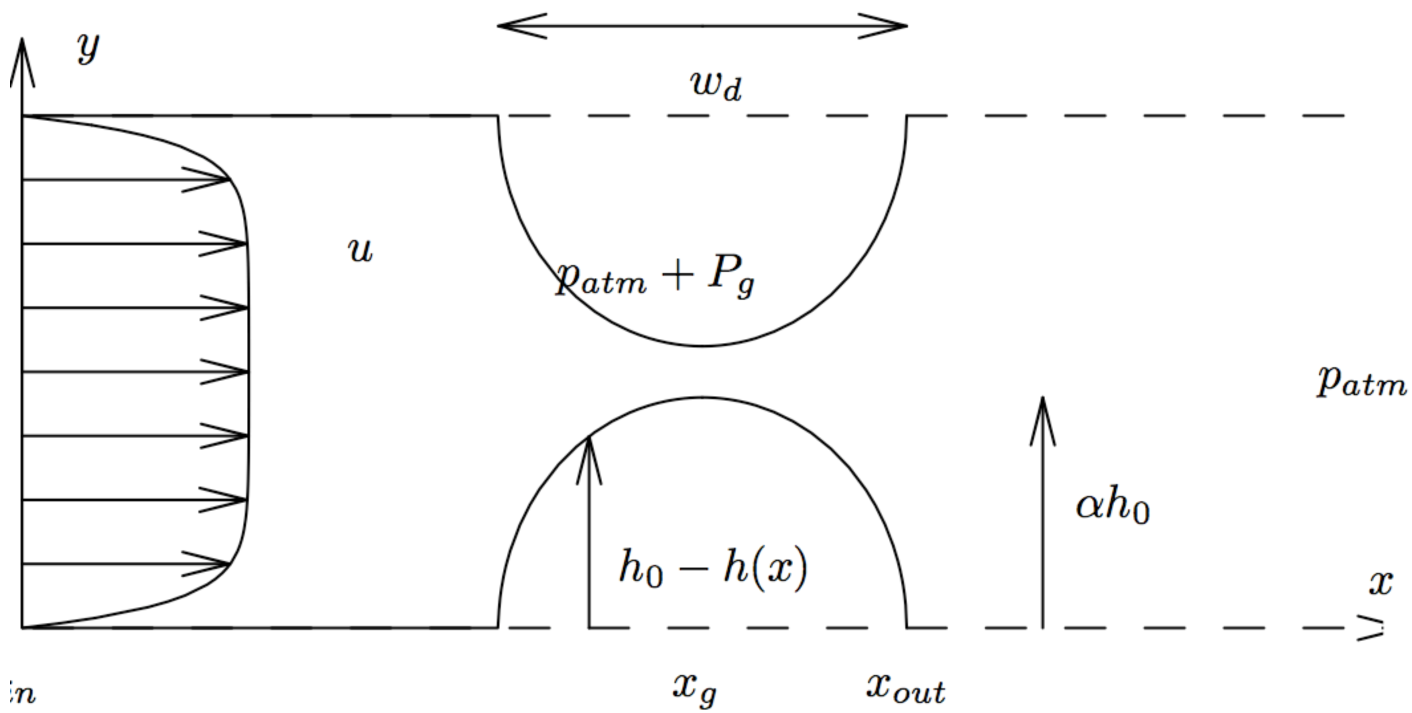


$$\frac{\partial}{\partial x}u + \frac{\partial}{\partial y}v = 0$$

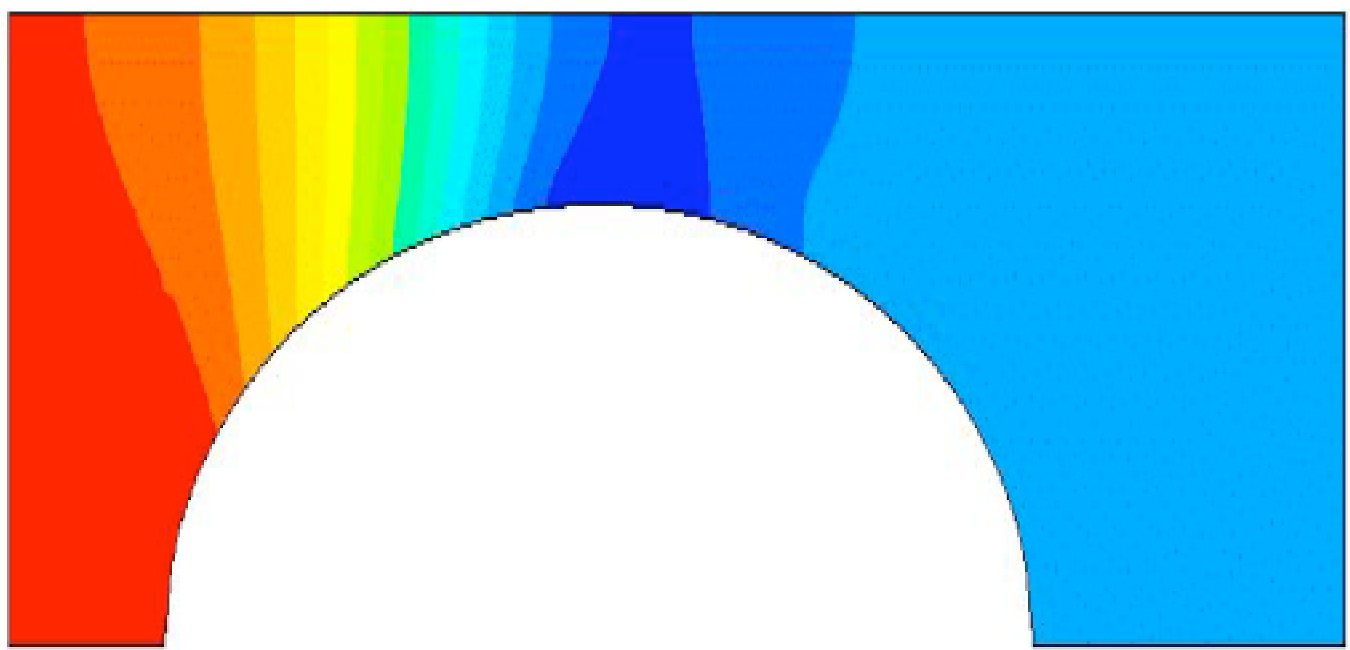
$$u\frac{\partial}{\partial x}u + v\frac{\partial}{\partial y}u = -\frac{\partial}{\partial x}p + \frac{\partial^2}{\partial y^2}u$$

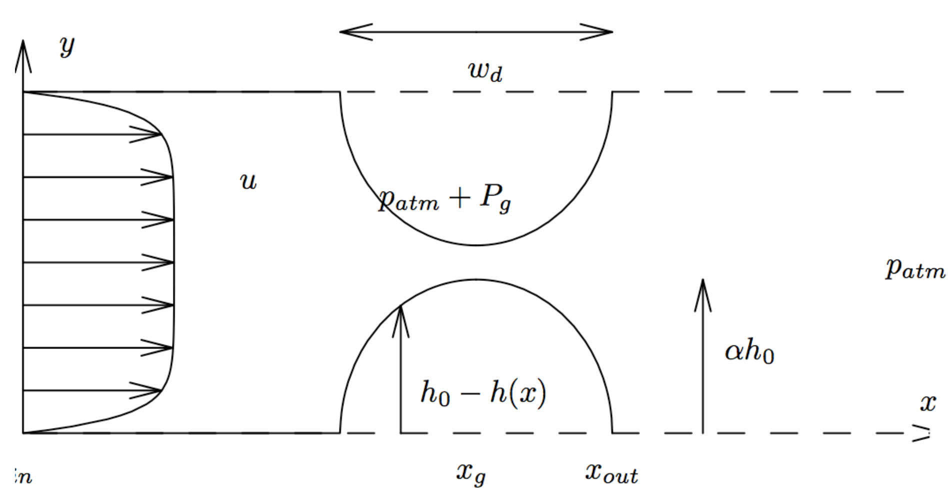
$$0 = -\frac{\partial}{\partial y}p$$

RNSP non dimensional



y
w_d
u
$p_{atm} + P_g$
p_{atm}
αh_0
$h_0 - h(x)$
x
x_g
x_{out}





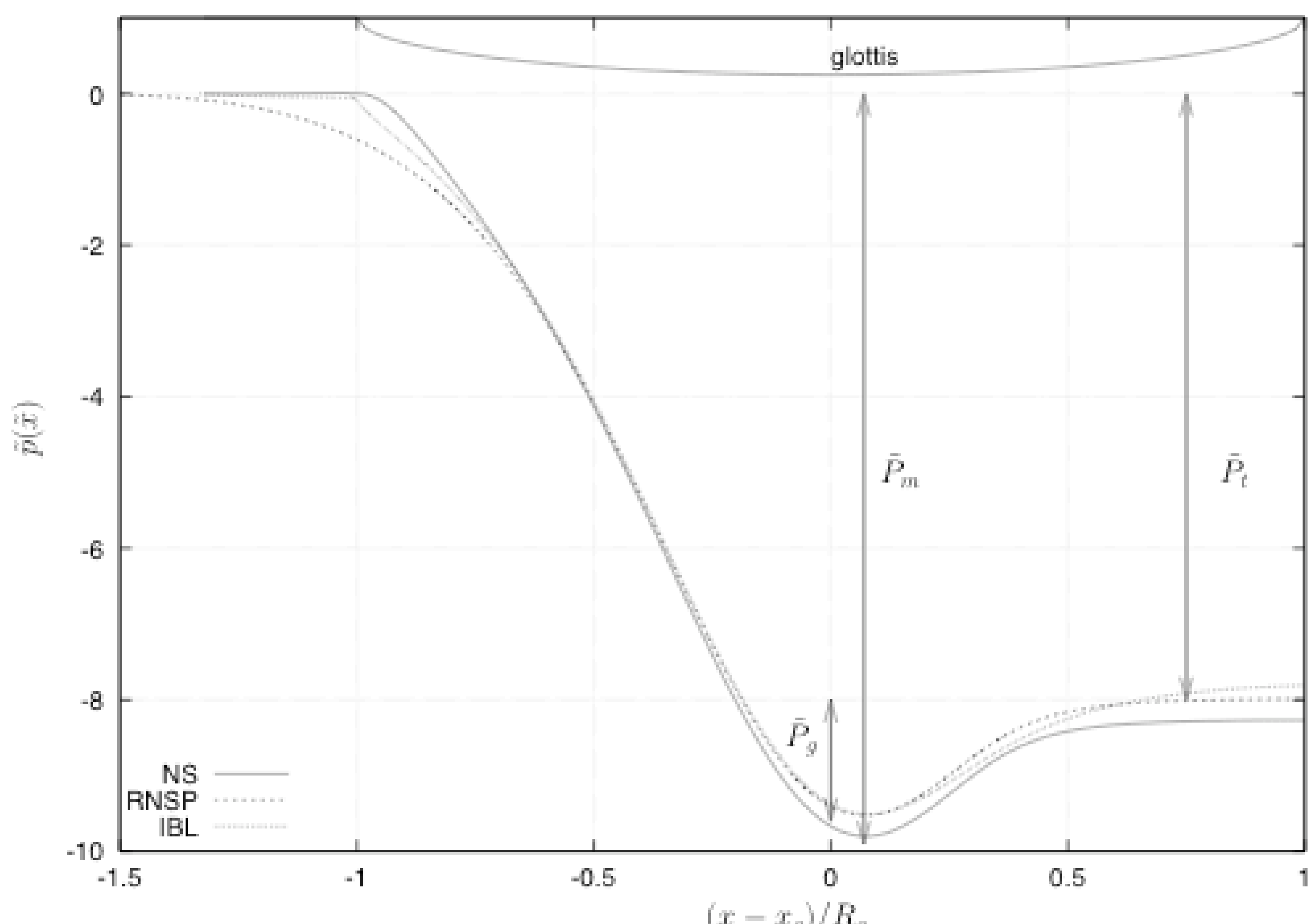
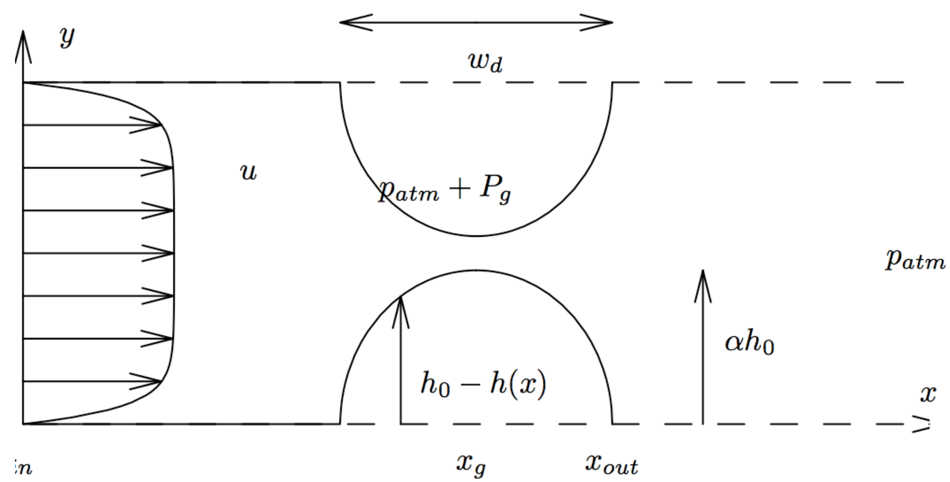


Fig. 2 A comparison between computed non-dimensional pressure for the three models (NS, IBL and RNSP, in this last case the wall has



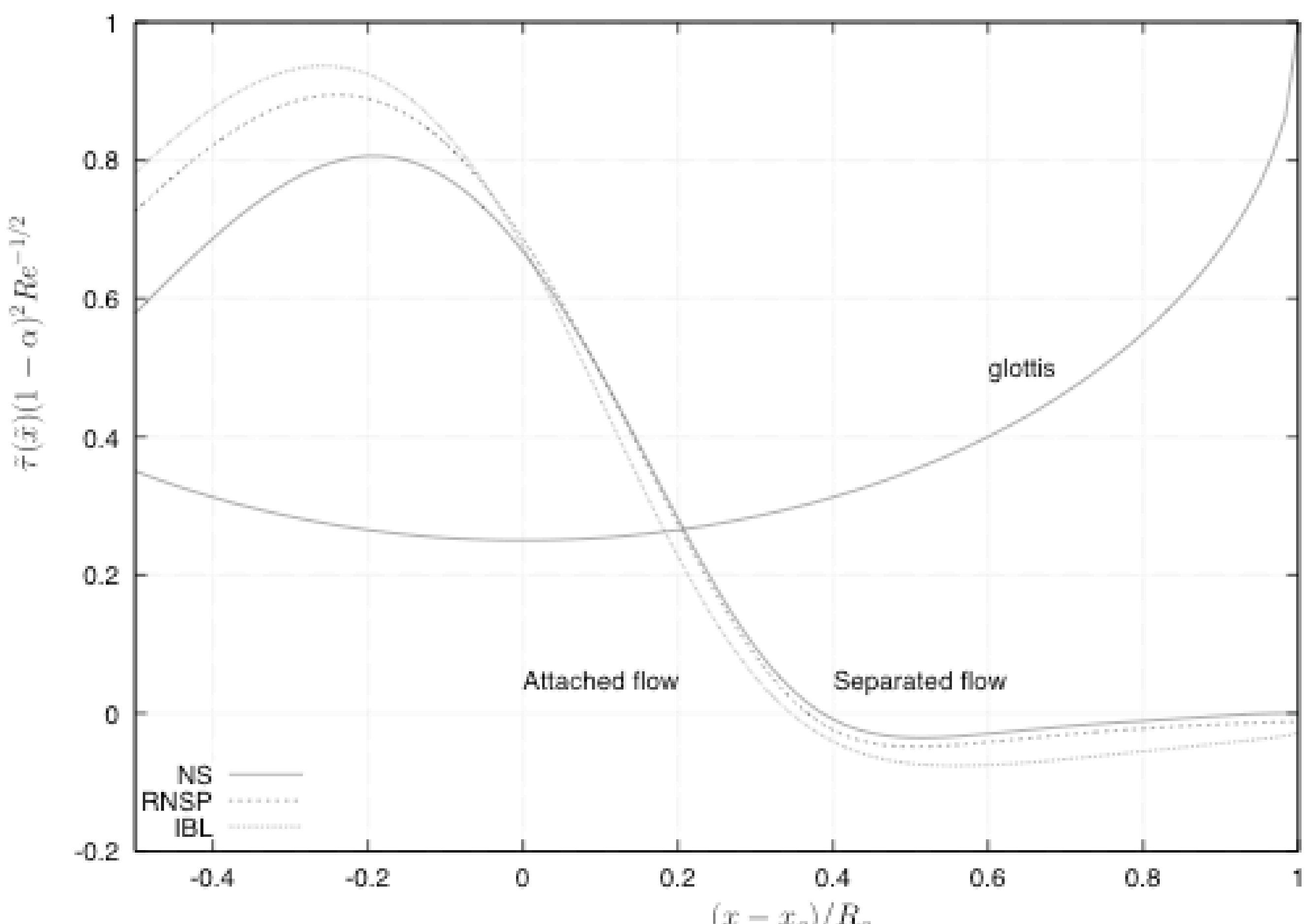
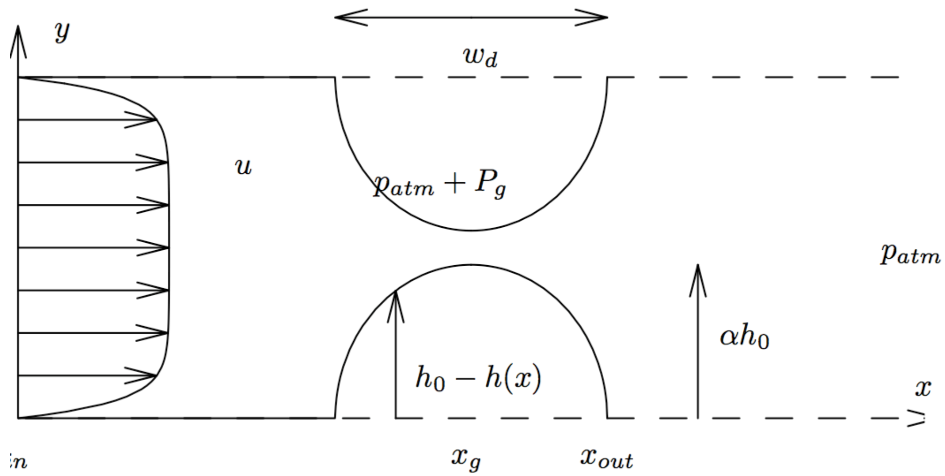


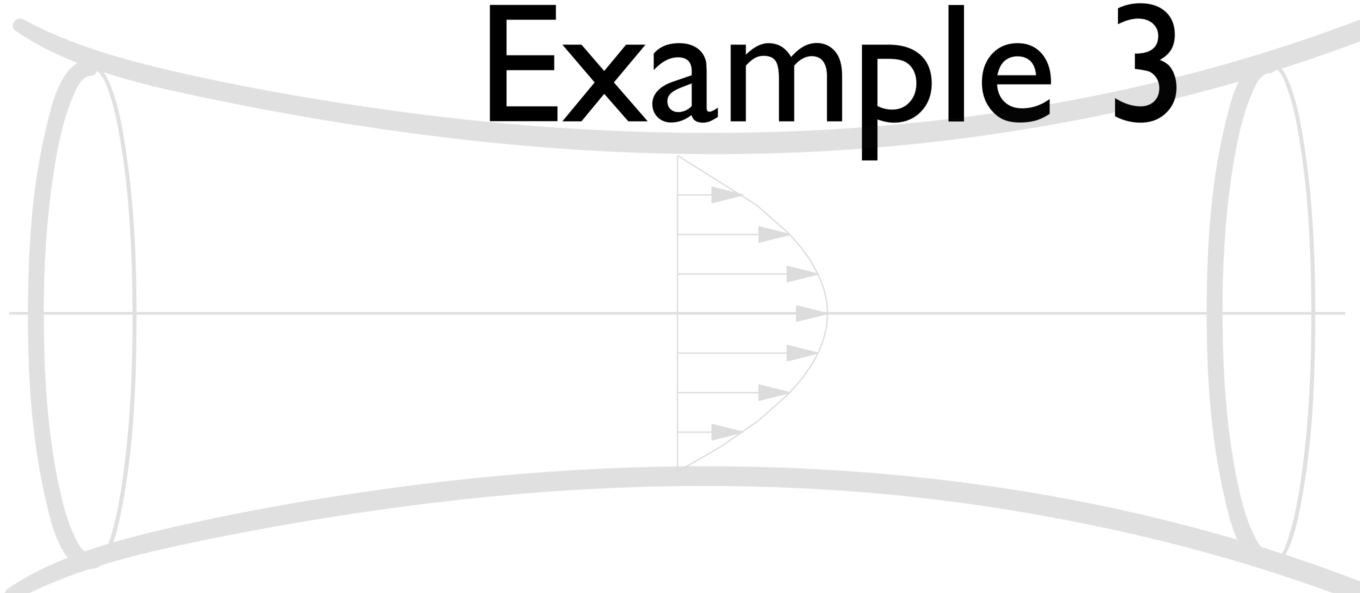
Fig. 4. A comparison between computed skin friction divided by $(0.47 + 2.07)(1-\alpha)^{-1}/\bar{\delta}_1 \sim (1-\alpha)^{-2} Re^{1/2}$ for the three models



P.-Y. Lagrée, E. Berger, M. Deverge, C. Vilain & A. Hirschberg (2005):
"Characterization of the pressure drop in a 2D symmetrical pipe: some asymptotical, numerical and experimental comparisons",
ZAMM: Z. Angew. Math. Mech. 85, No. 2, pp. 141-146.

M. Deverge, X. Pelorson, C. Vilain, P.-Y. Lagrée, F. Chentouf, J. Willems & A. Hirschberg (2003):
"Influence of the collision on the flow through in-vitro rigid models of the vocal folds".
J. Acoust. Soc. Am. 114 , pp. 3354 - 3362.

Example 3



- Flow in a stenozed vessel
- steady, rigid wall
- non symetrical case

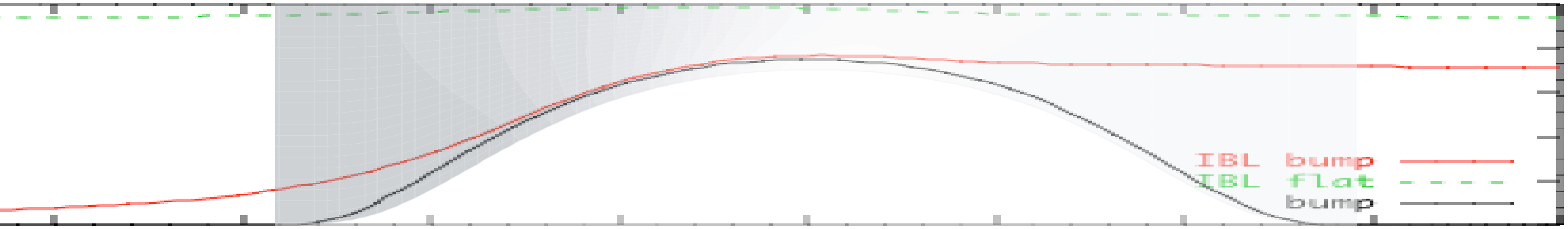
non symmetrical case

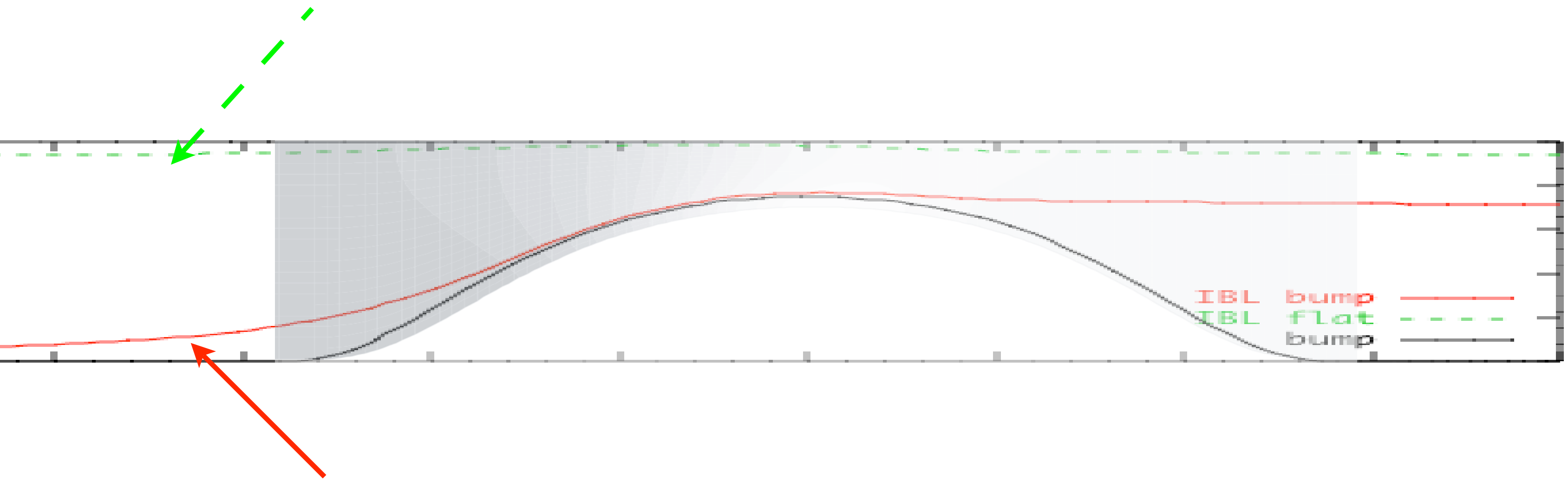
- RNSP
- modified integral method to take into account the transverse variation of pressure
- NS

non symmetrical case

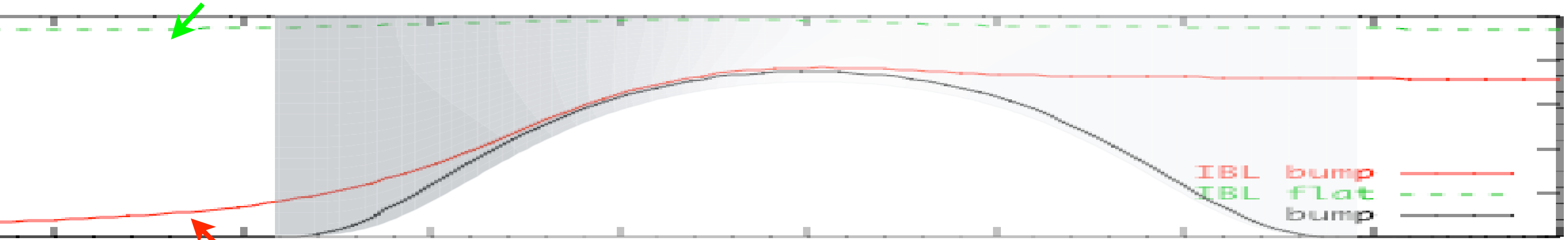
- RNSP
- modified integral method to take into account the transverse variation of pressure
- NS

non symmetrical case




IBL bump
IBL flat
bump

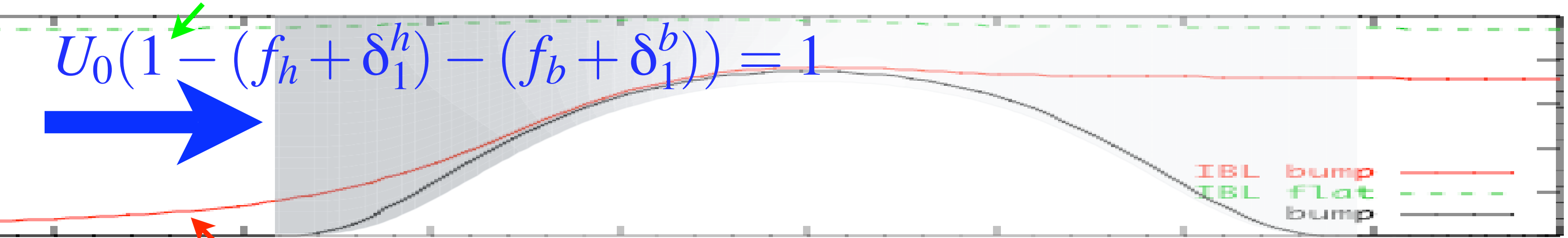
$$\frac{d}{dx}\left(\frac{\delta_1^h}{H}\right) + \frac{\delta_1^h}{u_e^h}\left(1+\frac{2}{H}\right)\frac{du_e^h}{dx} = \frac{f_2 H}{\delta_1^h u_e^h}, \qquad \delta_1^h = F(p_e^h)$$



$$\frac{d}{dx}\left(\frac{\delta_1^b}{H}\right) + \frac{\delta_1^b}{u_e^b}\left(1+\frac{2}{H}\right)\frac{du_e^b}{dx} = \frac{f_2 H}{\delta_1^b u_e^b}, \qquad \delta_1^b = F(p_e^b)$$

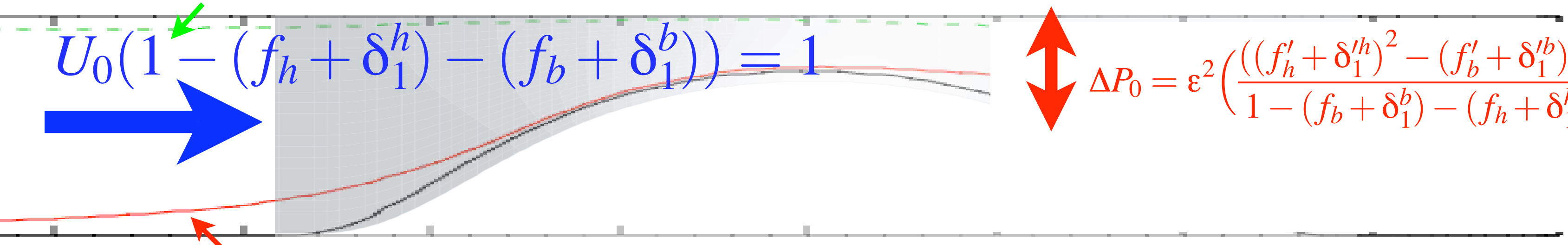
$$\frac{d}{dx}\left(\frac{\delta_1^h}{H}\right) + \frac{\delta_1^h}{u_e^h}\left(1 + \frac{2}{H}\right)\frac{du_e^h}{dx} = \frac{f_2 H}{\delta_1^h u_e^h}, \qquad \delta_1^h = F(p_e^h)$$

$$U_0(1 - (f_h + \delta_1^h) - (f_b + \delta_1^b)) = 1$$



$$\frac{d}{dx}\left(\frac{\delta_1^b}{H}\right) + \frac{\delta_1^b}{u_e^b}\left(1 + \frac{2}{H}\right)\frac{du_e^b}{dx} = \frac{f_2 H}{\delta_1^b u_e^b}, \qquad \delta_1^b = F(p_e^b)$$

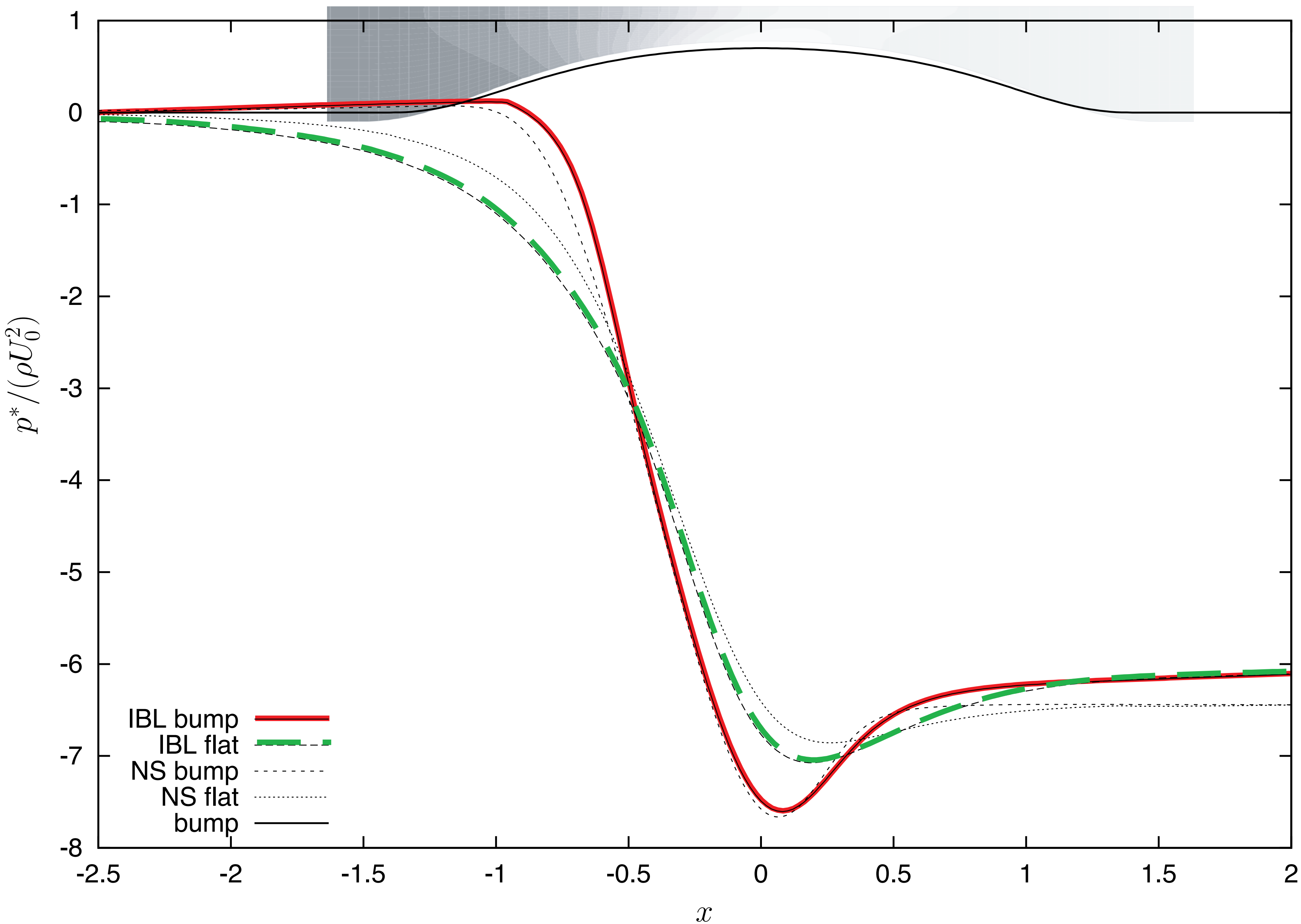
$$\frac{d}{dx}\left(\frac{\delta_1^h}{H}\right)+\frac{\delta_1^h}{u_e^h}\left(1+\frac{2}{H}\right)\frac{du_e^h}{dx}=\frac{f_2 H}{\delta_1^h u_e^h},\qquad \delta_1^h=F(p_e^h)$$



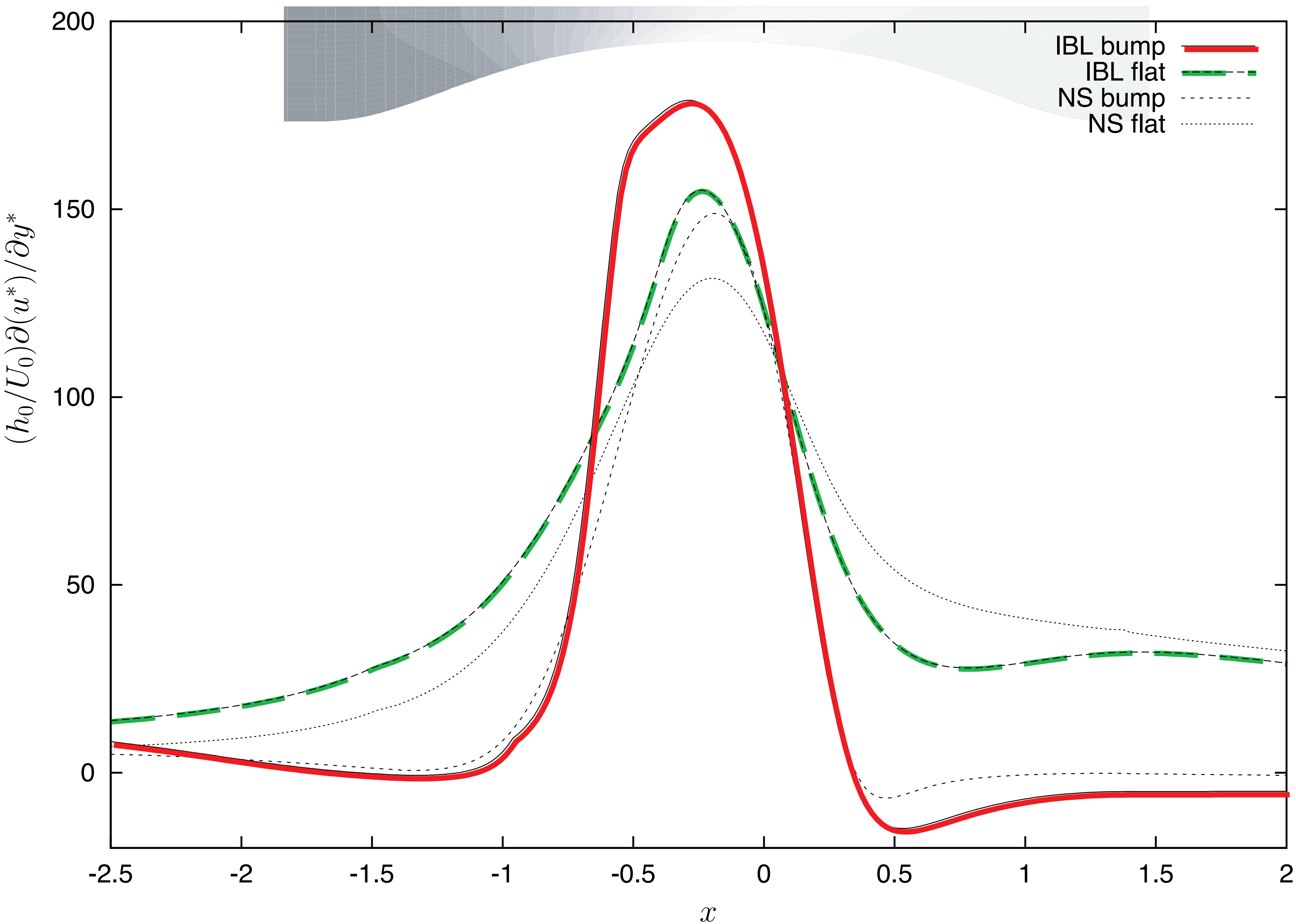
$$U_0(1-(f_h+\delta_1^h)-(f_b+\delta_1^b))=1$$

$$\Delta P_0=\varepsilon^2\left(\frac{((f_h'+\delta_1'^h)^2-(f_b'+\delta_1'^b)^2)}{1-(f_b+\delta_1^b)-(f_h+\delta_1^h)}+\frac{(f_h''+\delta_1''^h-f_b''-\delta_1''^b)}{2}\right).$$

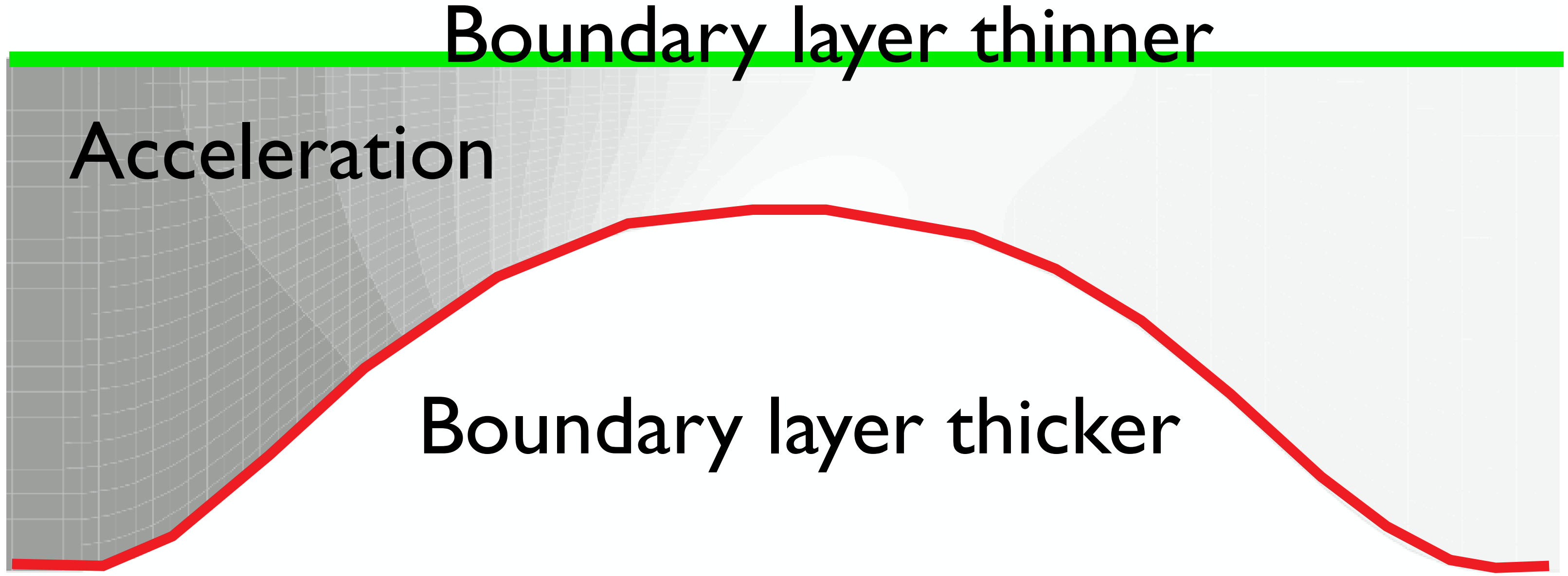
$$\frac{d}{dx}\left(\frac{\delta_1^b}{H}\right)+\frac{\delta_1^b}{u_e^b}\left(1+\frac{2}{H}\right)\frac{du_e^b}{dx}=\frac{f_2 H}{\delta_1^b u_e^b},\qquad \delta_1^b=F(p_e^b)$$

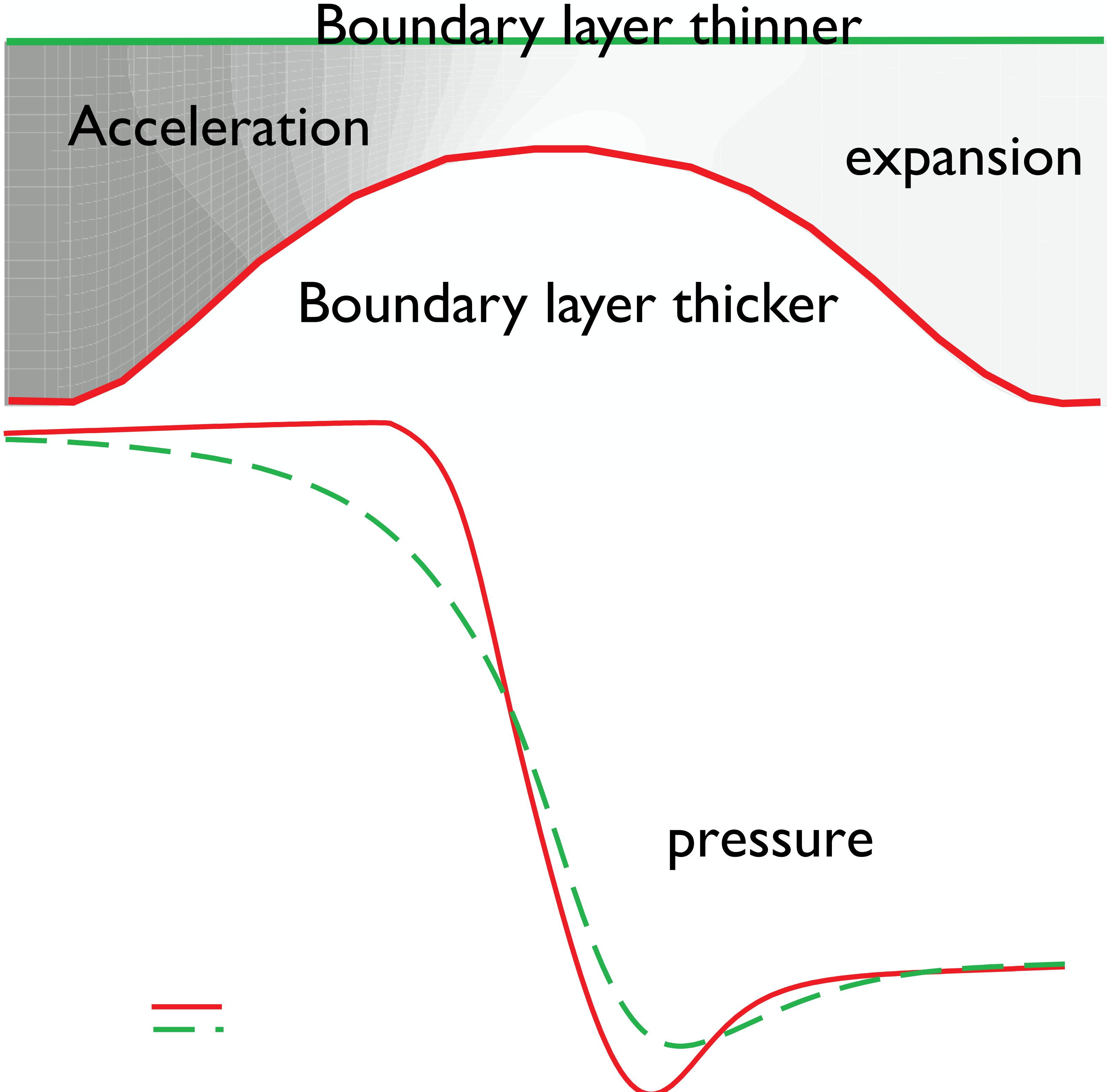


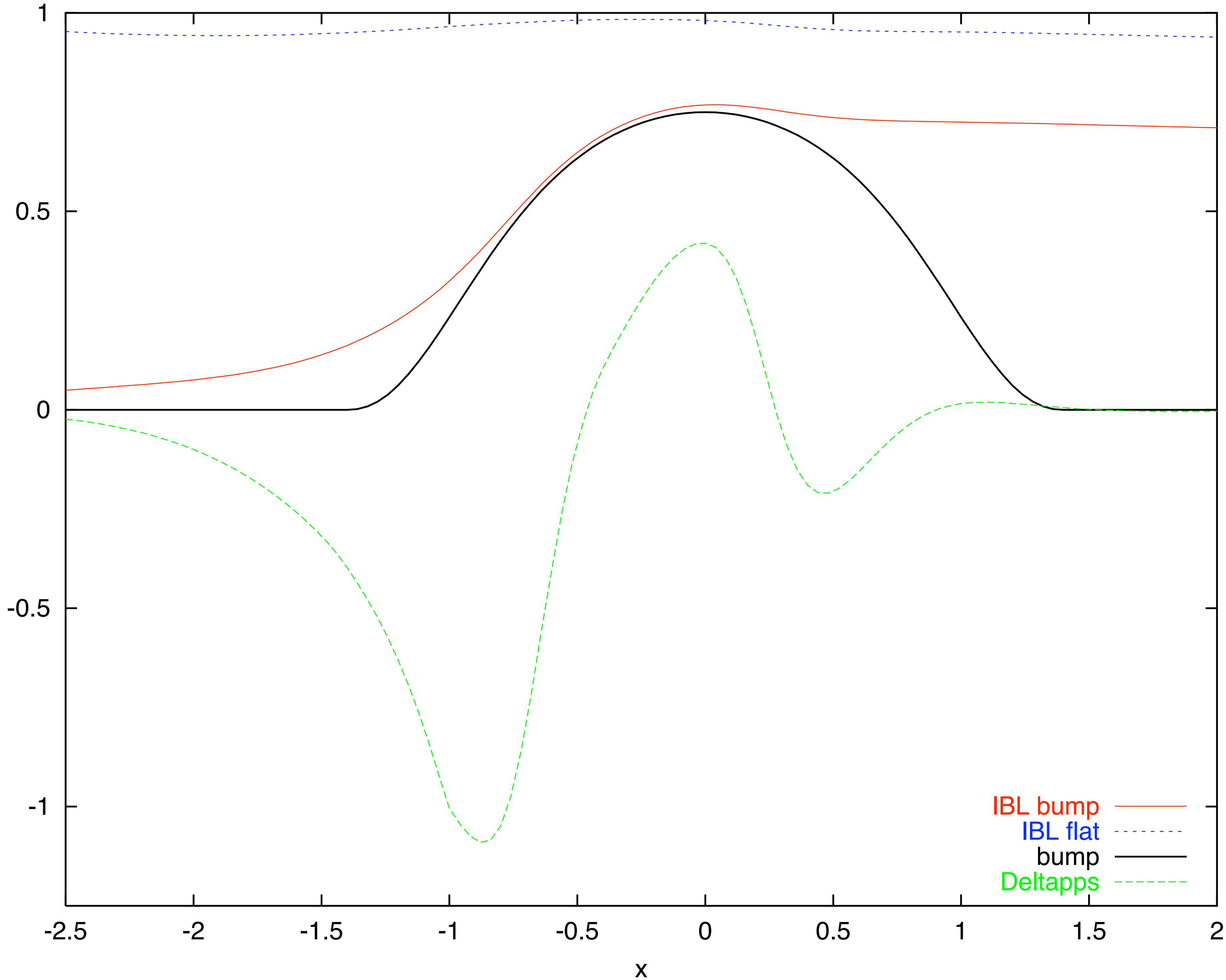
$p^*/(\rho U_0^2)$
x
1
0
-1
-2
-3
-4
-5
-6
-7
-8
-2.5
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
IBL bump
IBL flat
NS bump
NS flat
bump



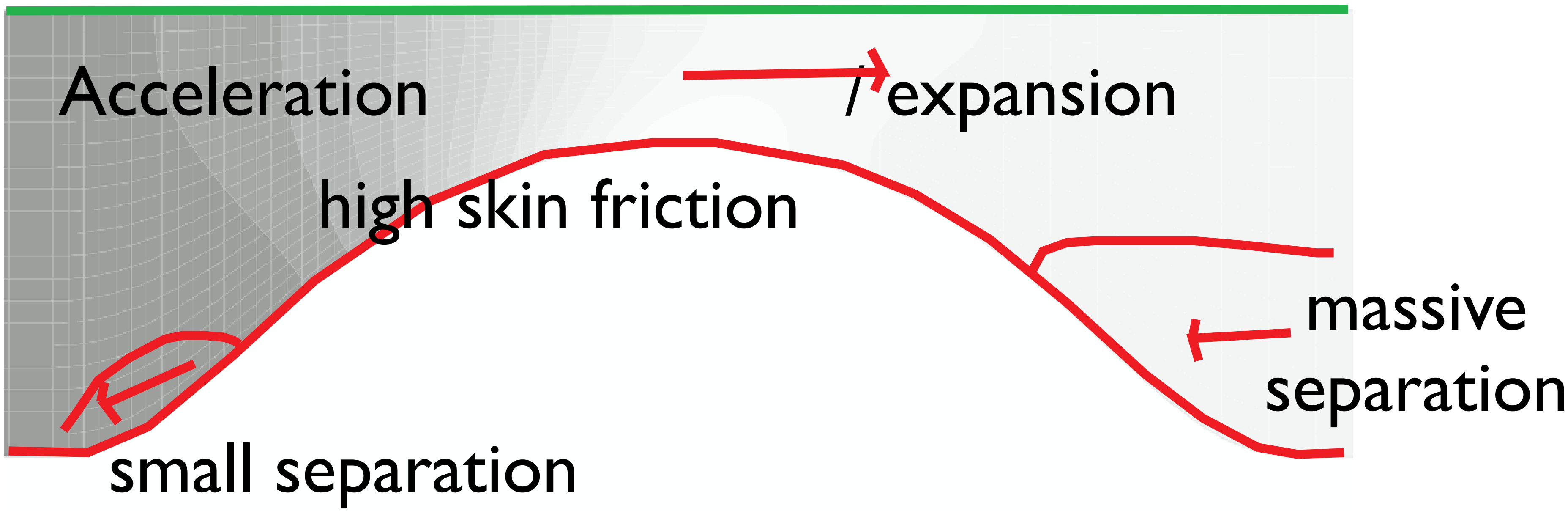
IBL bump
IBL flat
NS bump
NS flat
200
150
100
50
0
-2.5
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
$(h_0/U_0)\partial(u^*)/\partial y^*$
x


Boundary layer thinner
Acceleration
Boundary layer thicker


Boundary layer thinner
Acceleration
expansion
Boundary layer thicker
pressure



1
0.5
0
-0.5
-1
-2.5
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
x
IBL bump
IBL flat
bump
Deltapps

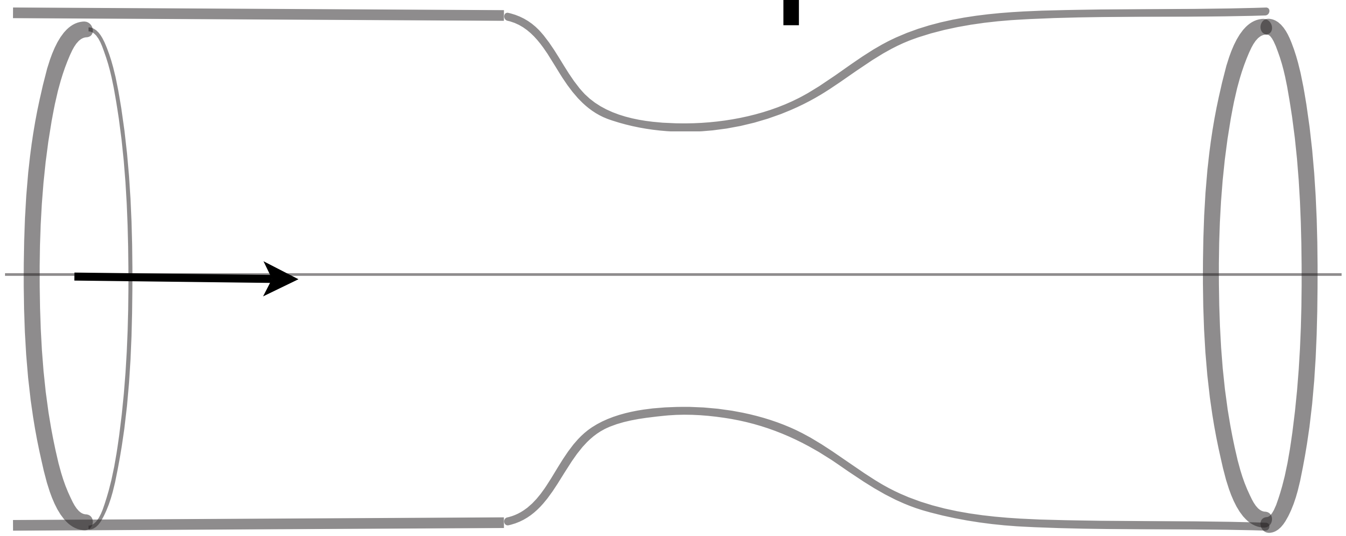


P.-Y. Lagrée, A. Van Hirtum & X. Pelorson (2007):
"Asymmetrical effects in a 2D stenosis".
European Journal of Mechanics - B/Fluids, Volume 26, Issue 1, January-February 2007, Pages 83-92

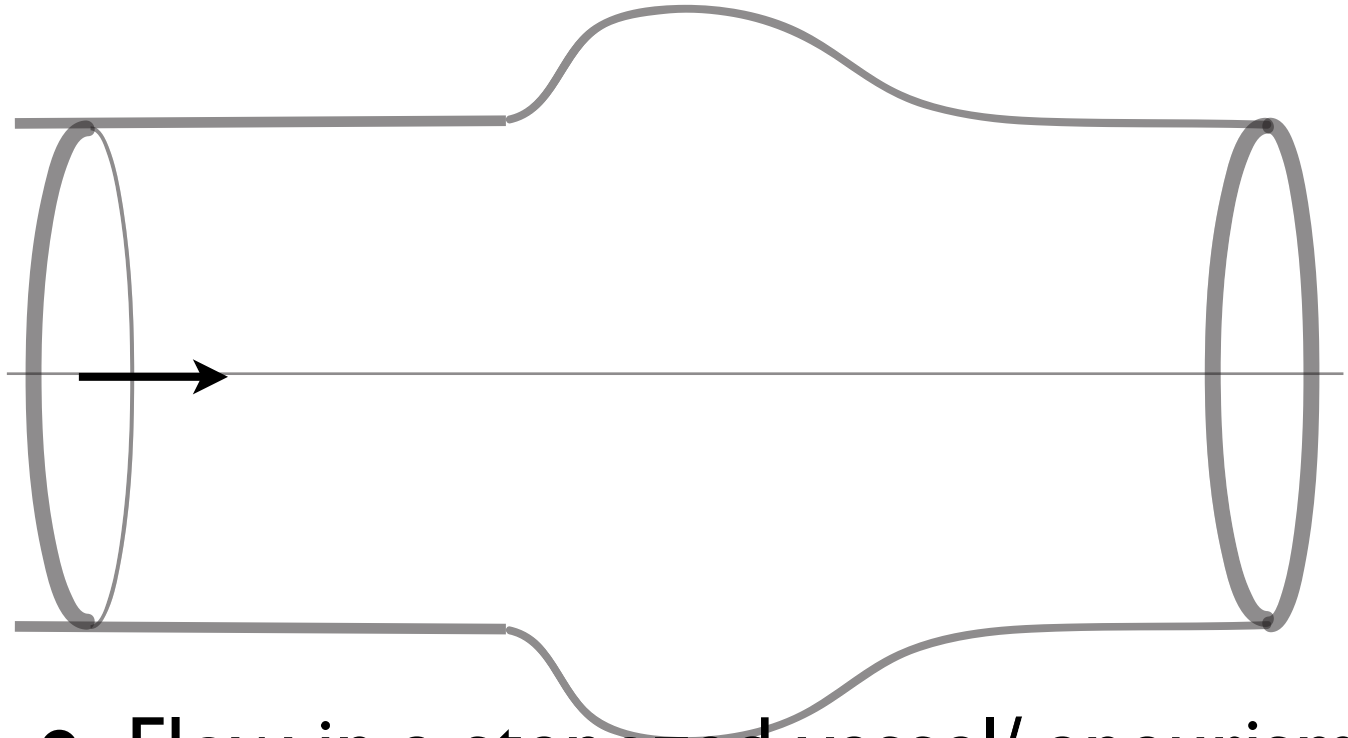
Example 4

- Flow in a stenozed vessel/ aneurism
- unsteady, rigid wall

Example 2

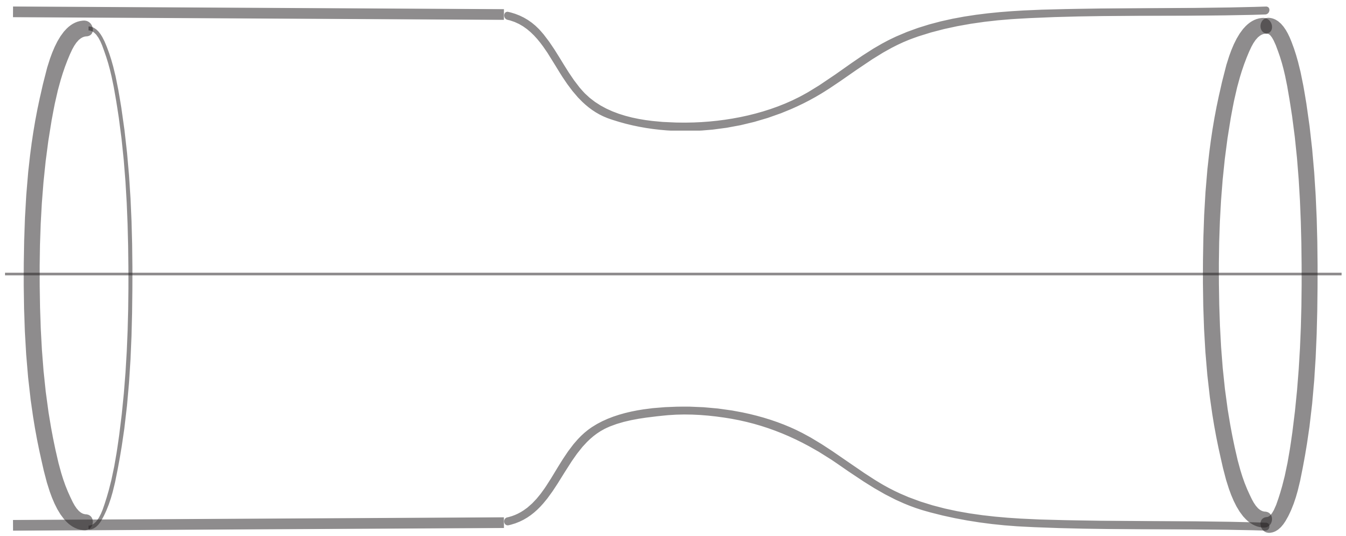


- Flow in a stenozed vessel/
- unsteady, rigid wall

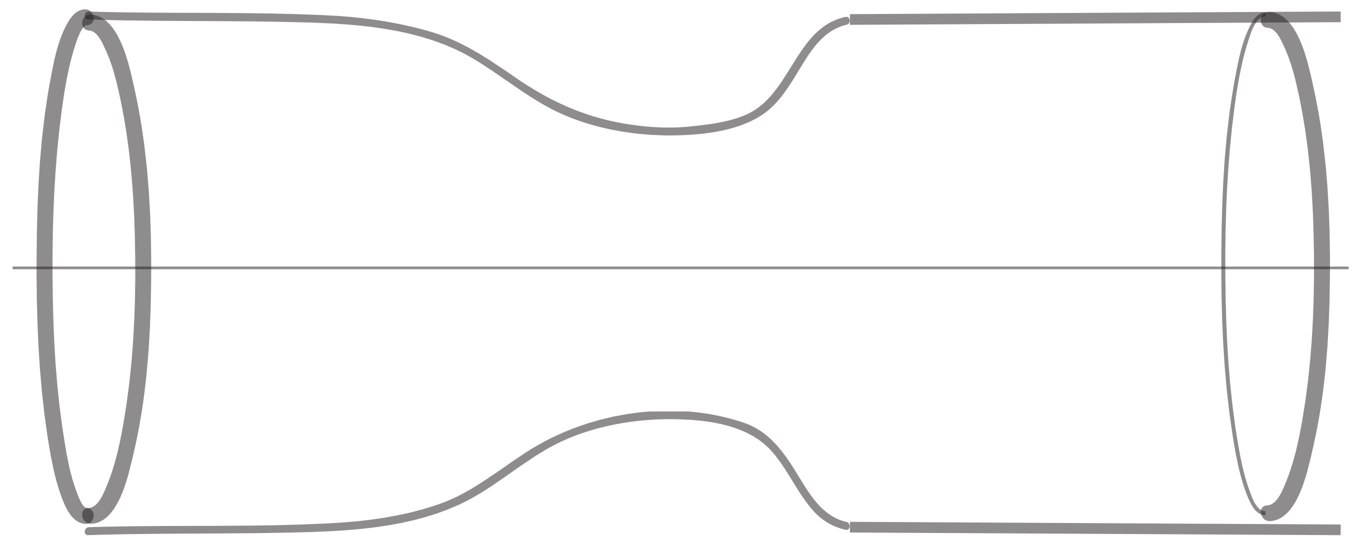


- Flow in a stenozed vessel/ aneurism
- unsteady, rigid wall

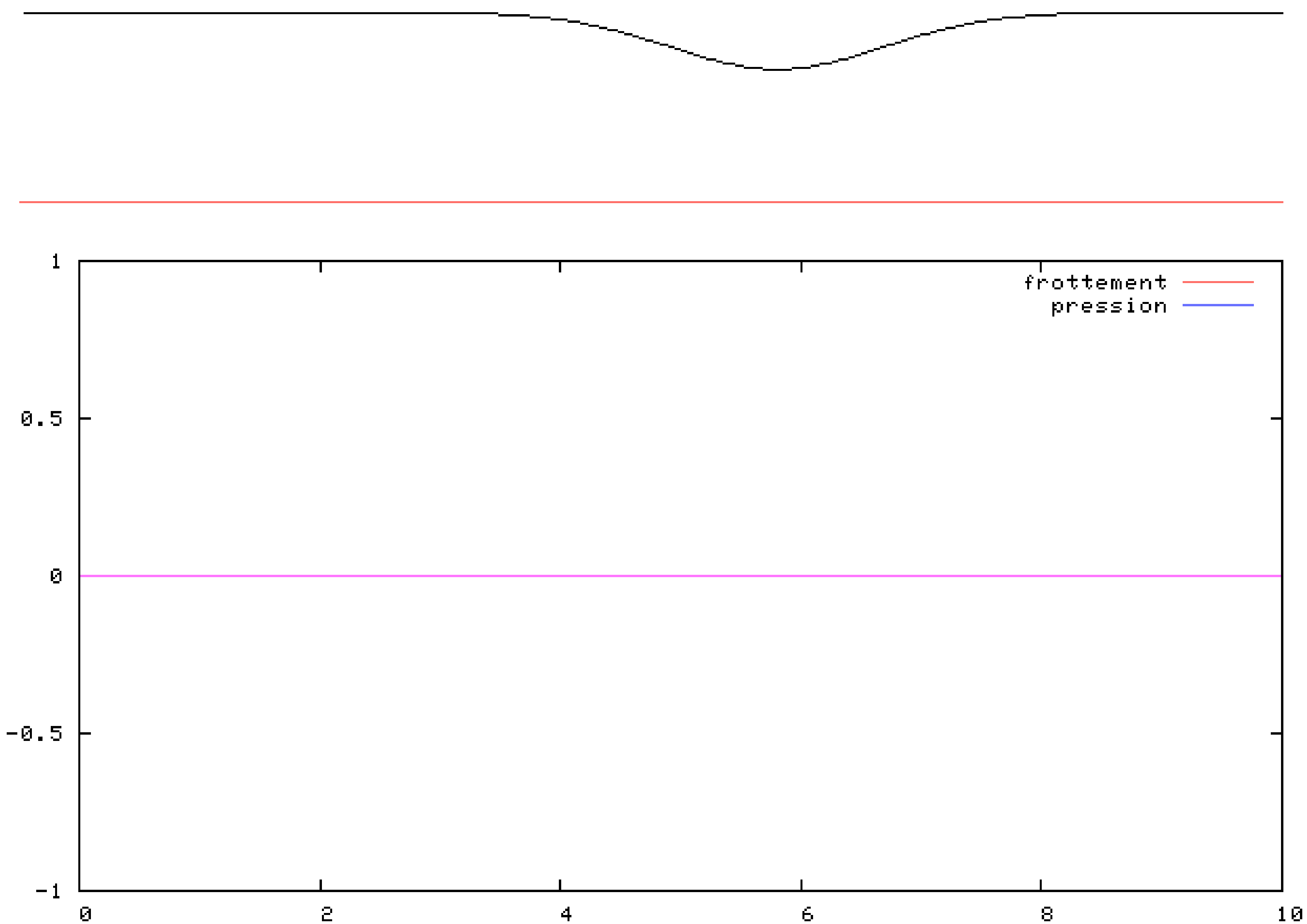
- Stenosis



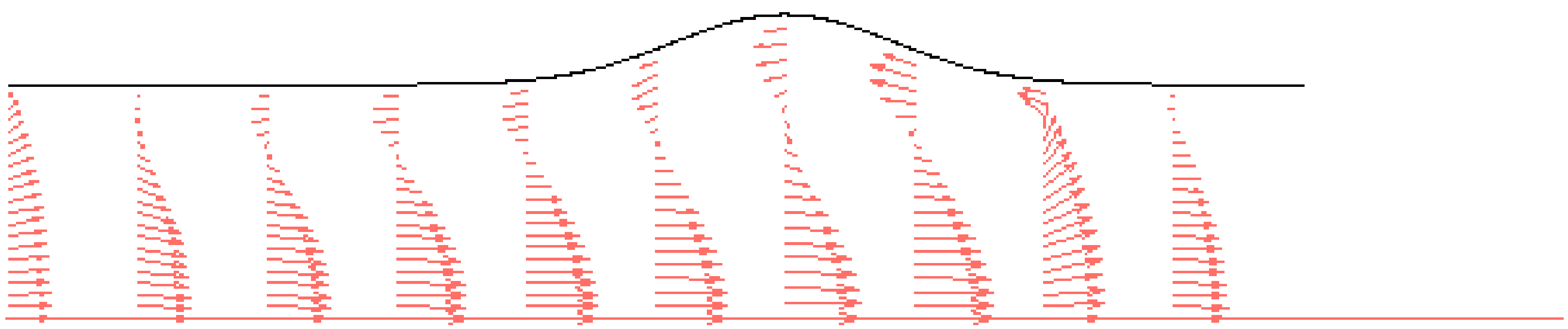
- Stenosis

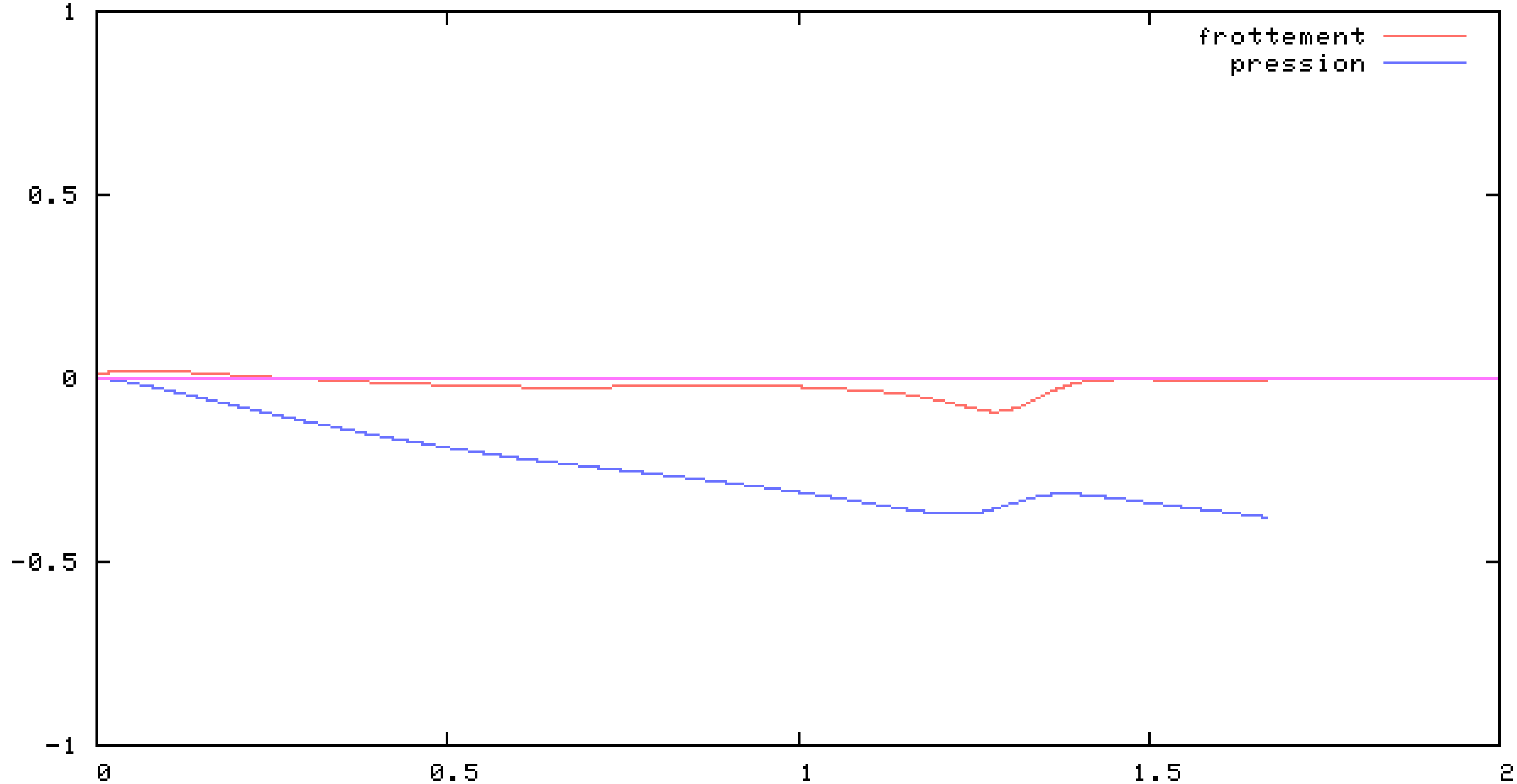


- Stenosis

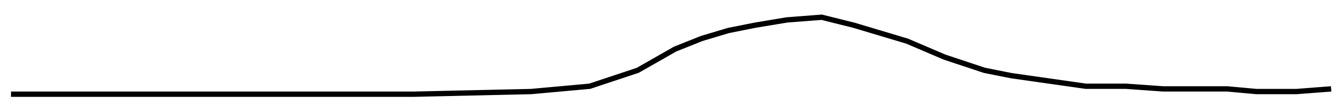


- Aneurism



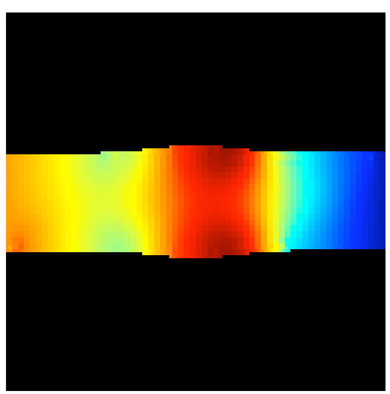


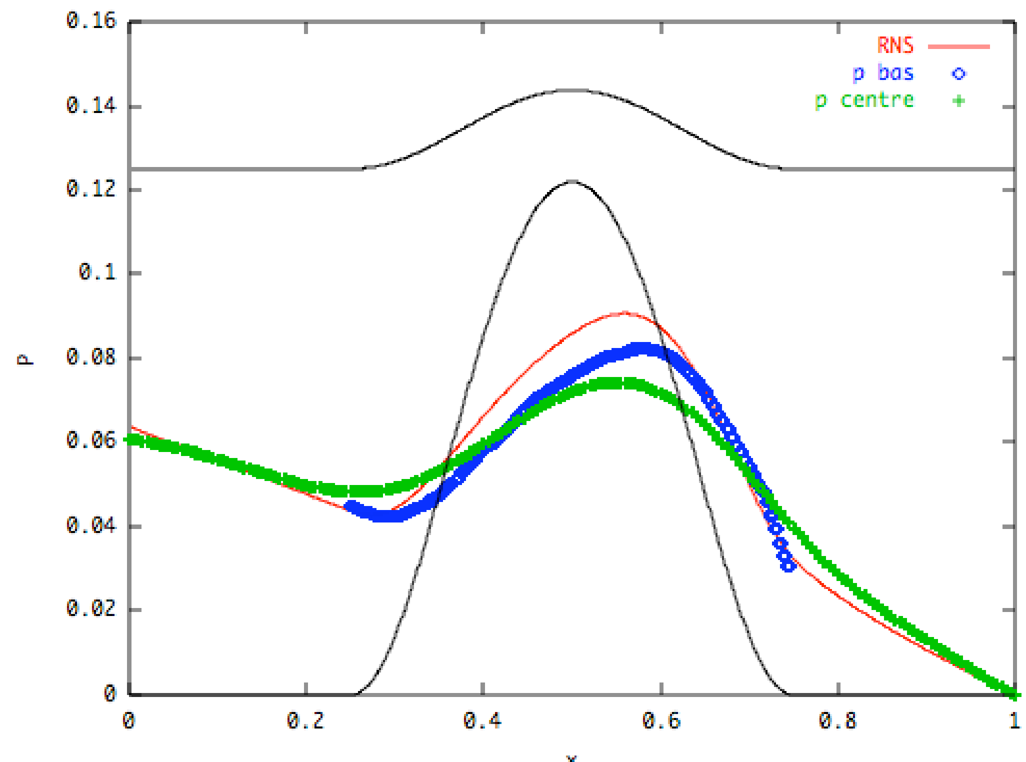
- Aneurism



- pressure distribution

Steady 2D



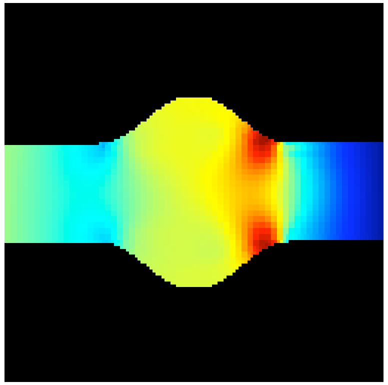


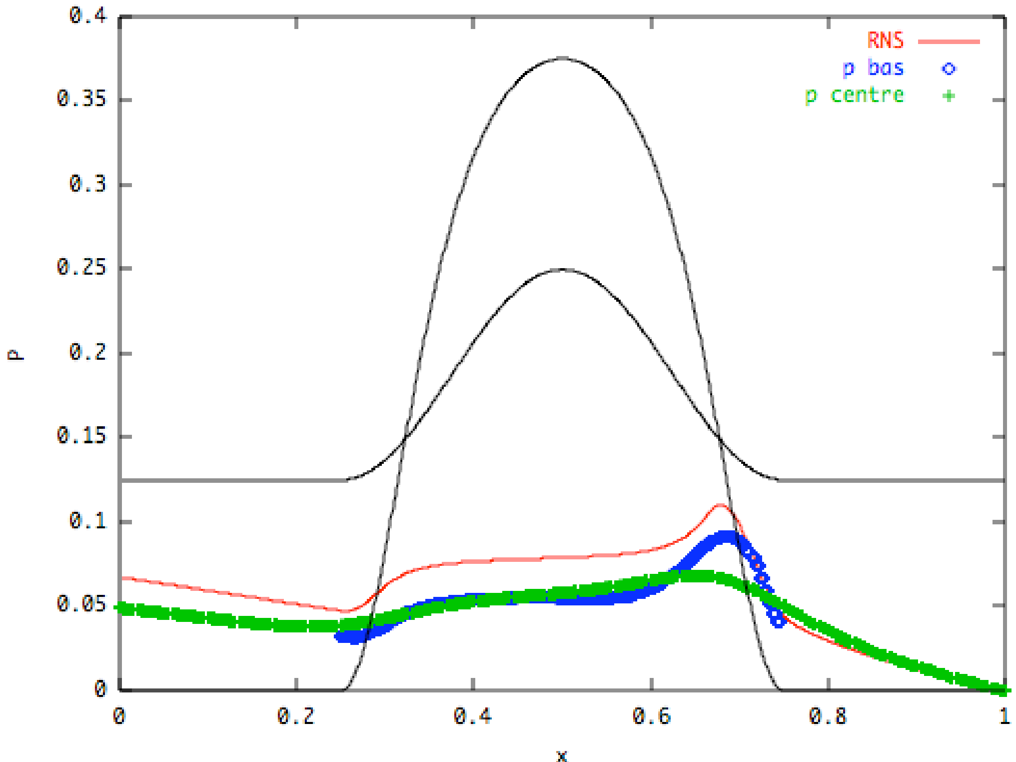
Comparaison gerris - RNS

- Aneurism

- pressure distribution

Steady 2D



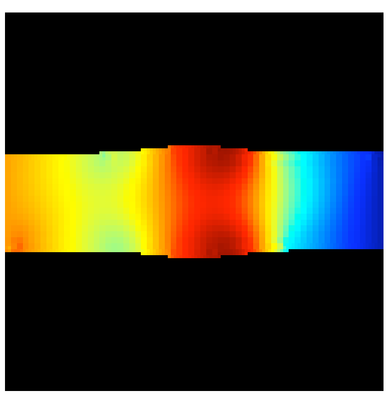


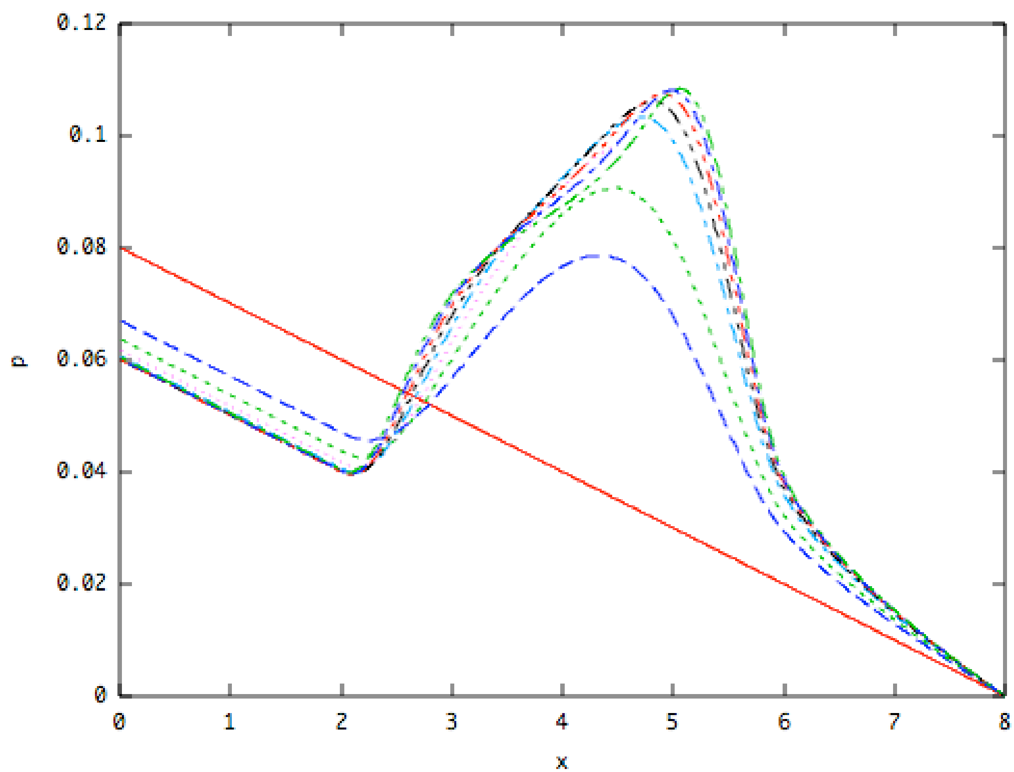
Comparaison gerris - RNS

- Aneurism

- ◆ pressure distribution

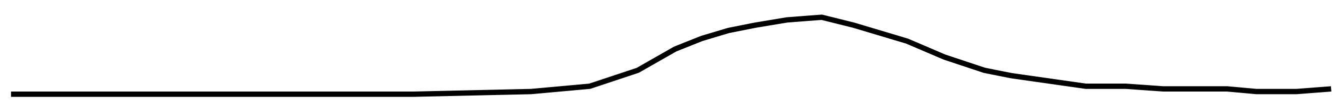
Steady 2D





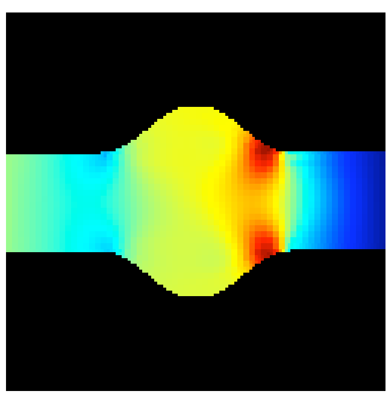
RNS

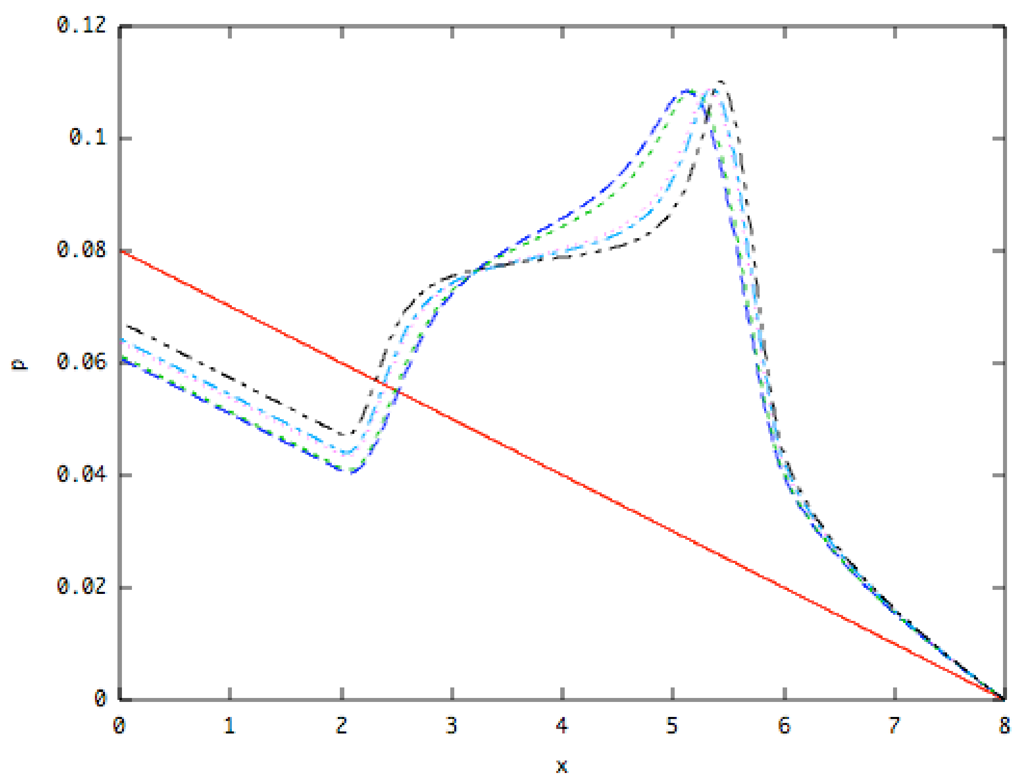
- Aneurism



- pressure distribution

Steady 2D



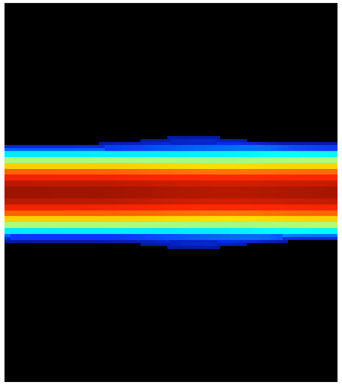


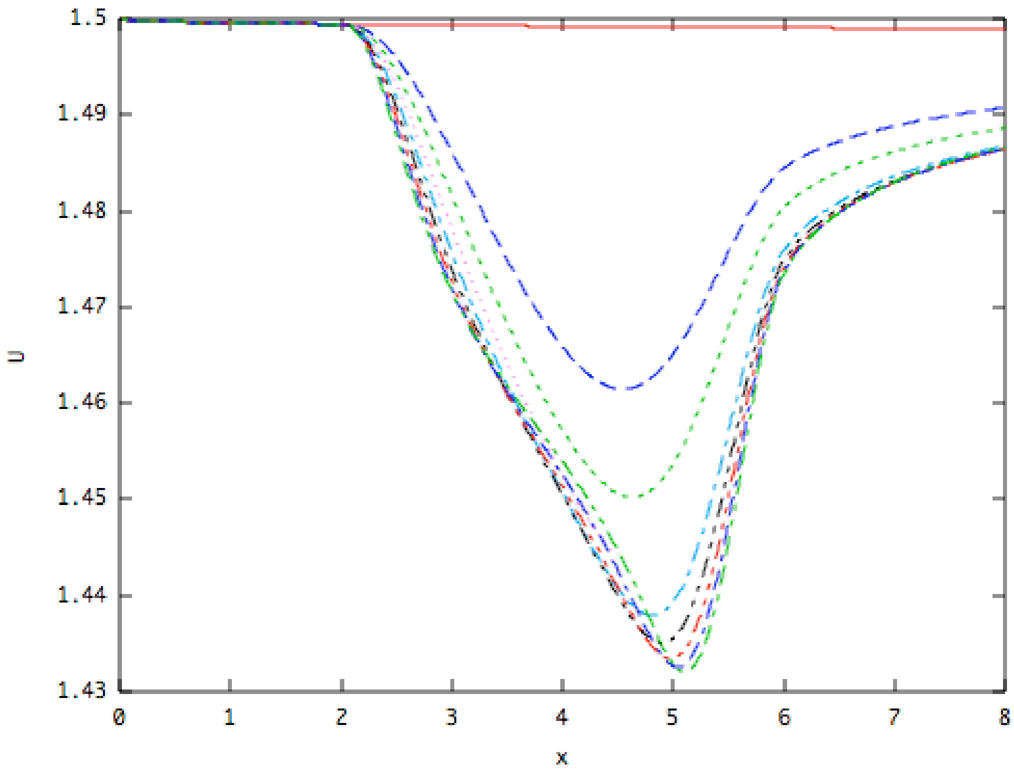
RNS

- Aneurism

- velocity distribution

Steady 2D



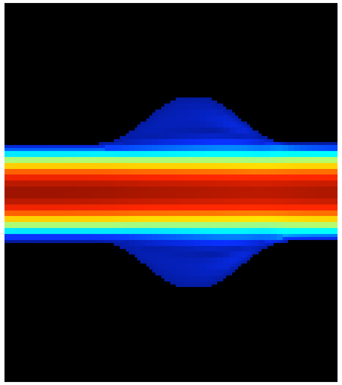


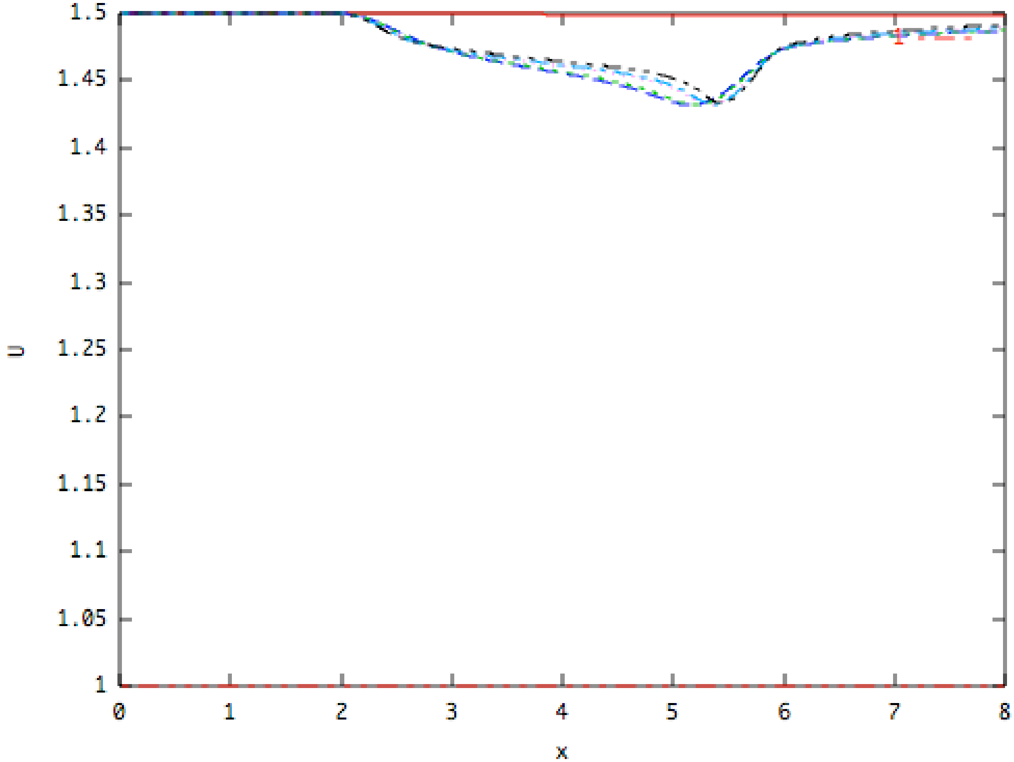
RNS

- Aneurism

- velocity distribution

Steady 2D



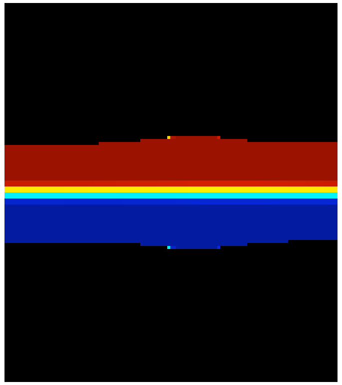


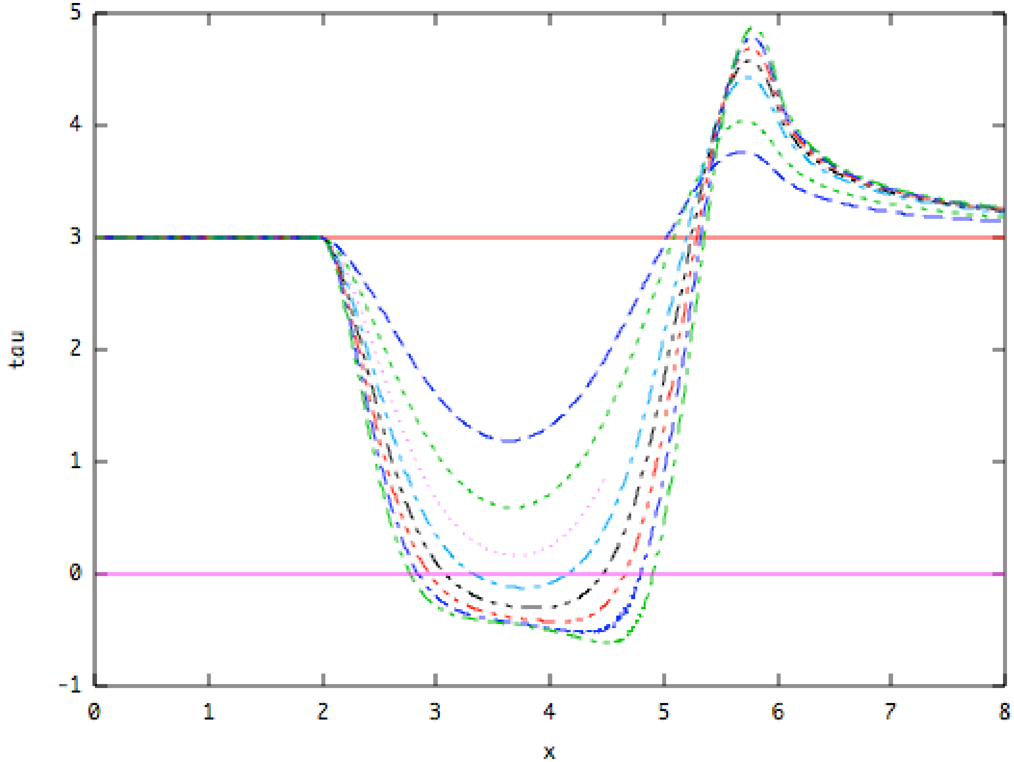
RNS

- Aneurism

- shear stress distribution

Steady 2D



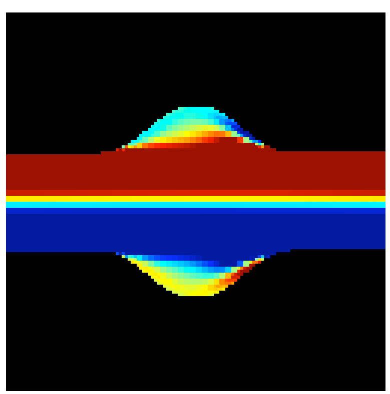


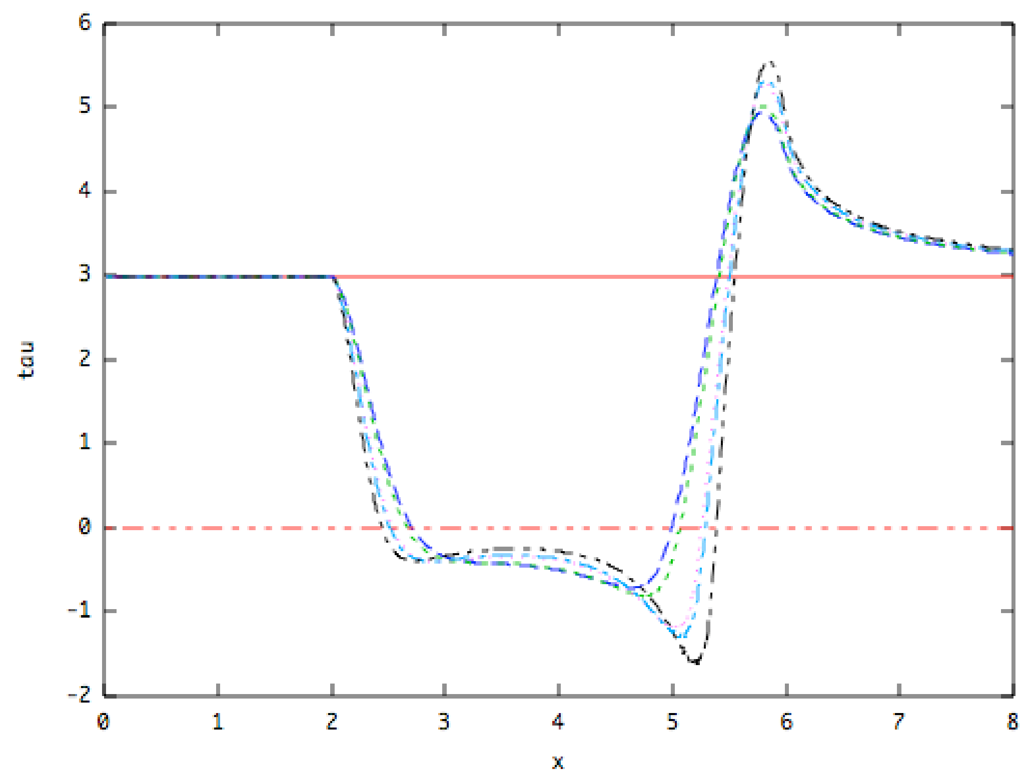
RNS

- Aneurism

- shear stress distribution

Steady 2D



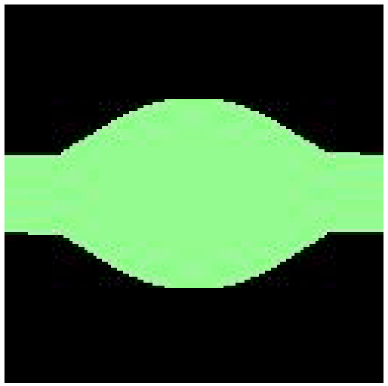


RNS

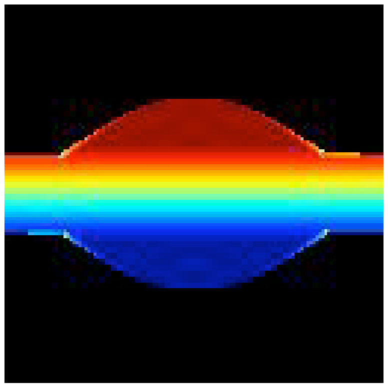
- Aneurism

- unsteady

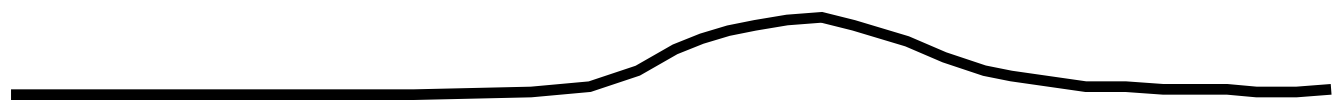
but still rigid

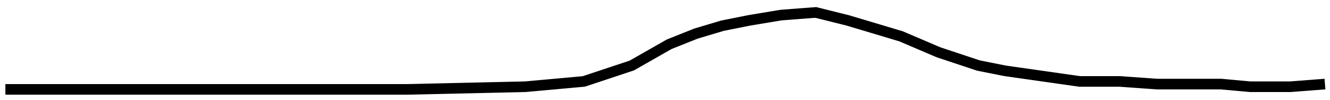


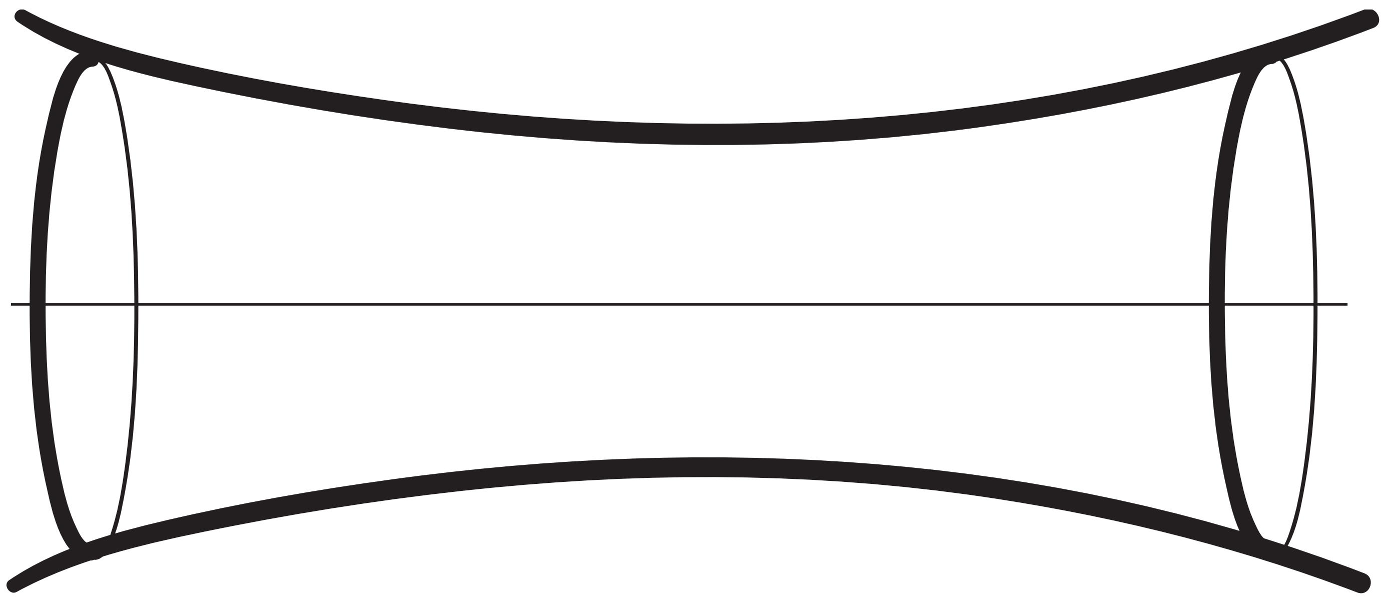
gerris imposed flux

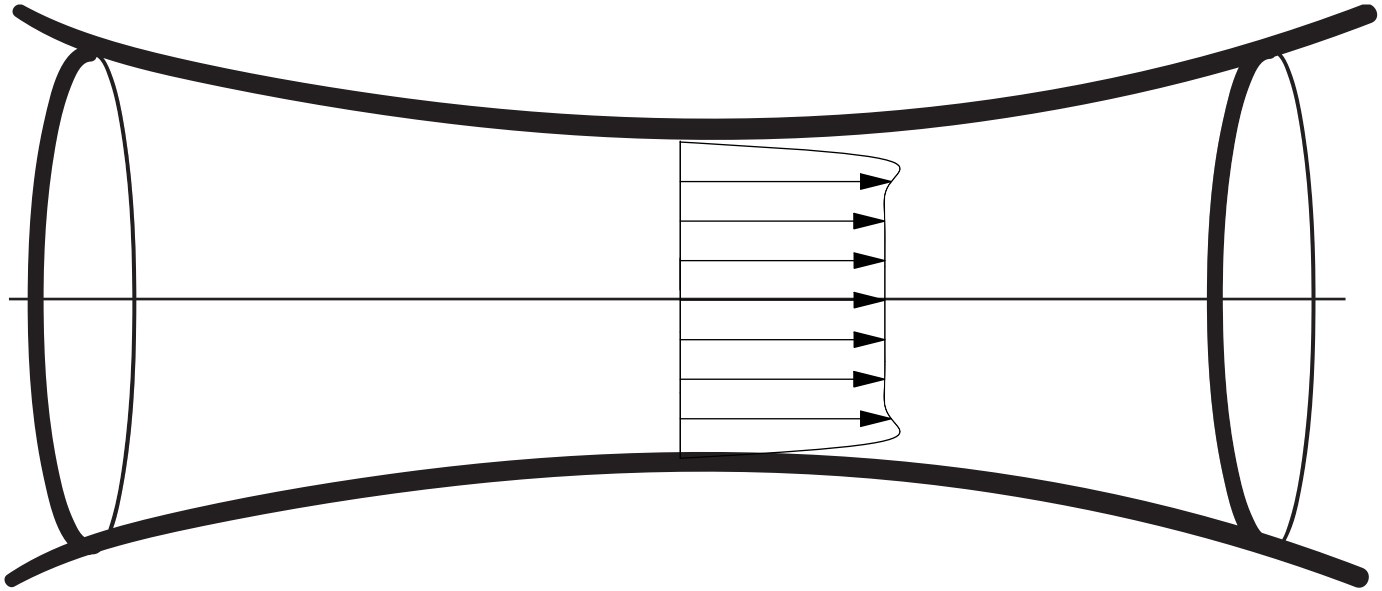


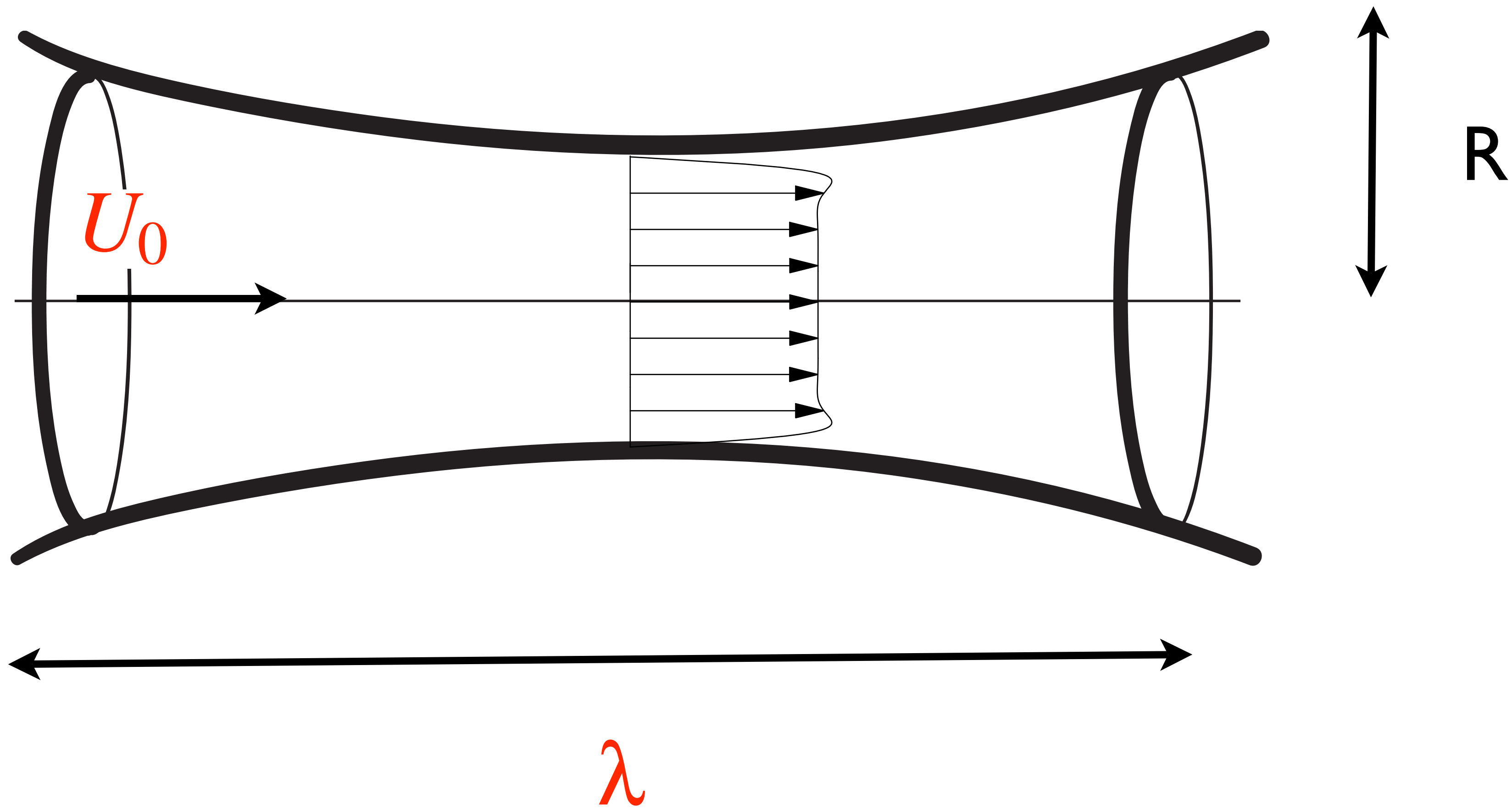
gerris imposed pressure



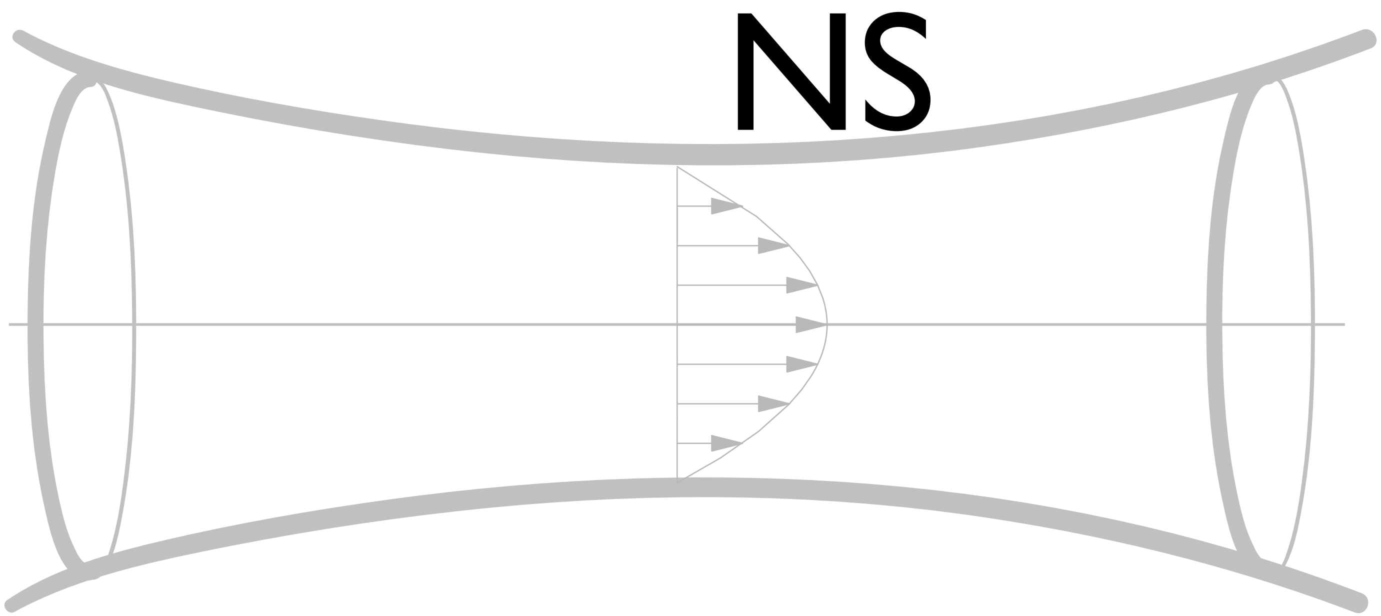








$$R << \lambda$$

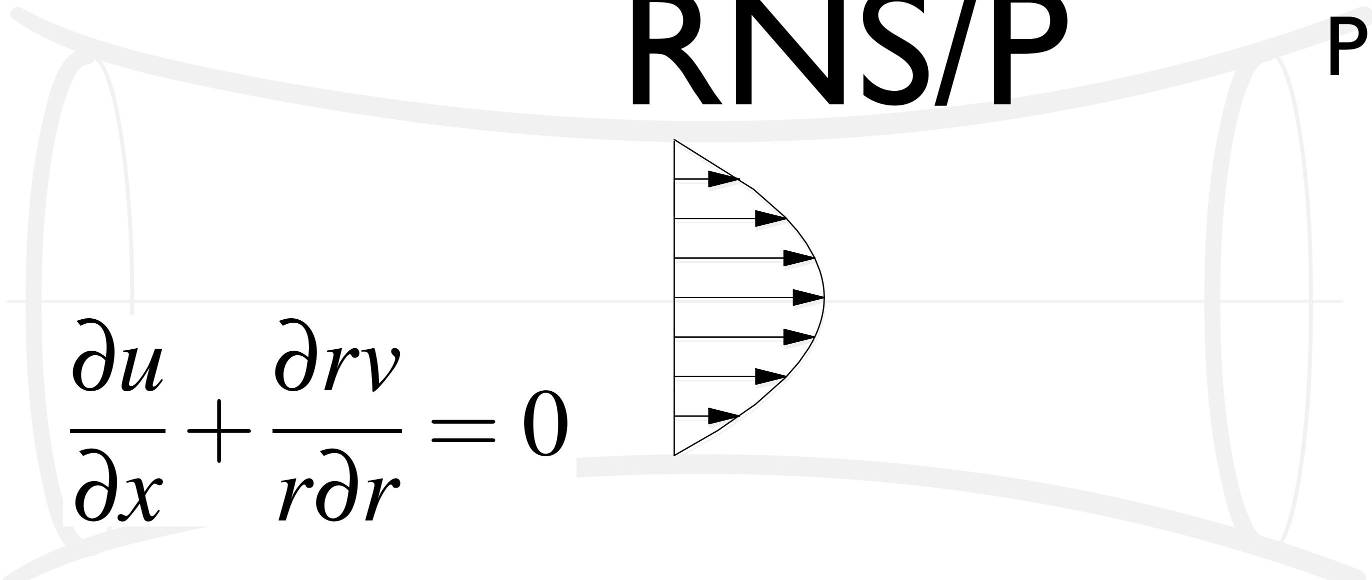


$$\frac{\partial u}{\partial t} + u\frac{\partial}{\partial x}u + v\frac{\partial}{\partial r}u = -\frac{\partial p}{\rho \partial x} + \nu\frac{\partial^2}{\partial x^2}u + \nu\frac{\partial}{r\partial r}r\frac{\partial u}{\partial r}$$

$$\frac{\partial v}{\partial t} + u\frac{\partial}{\partial x}v + v\frac{\partial}{\partial r}v = -\frac{\partial p}{\rho \partial r} + \nu\frac{\partial^2}{\partial x^2}v + \nu\frac{\partial}{r\partial r}r\frac{\partial v}{\partial r}$$

RNS/P

Prandtl

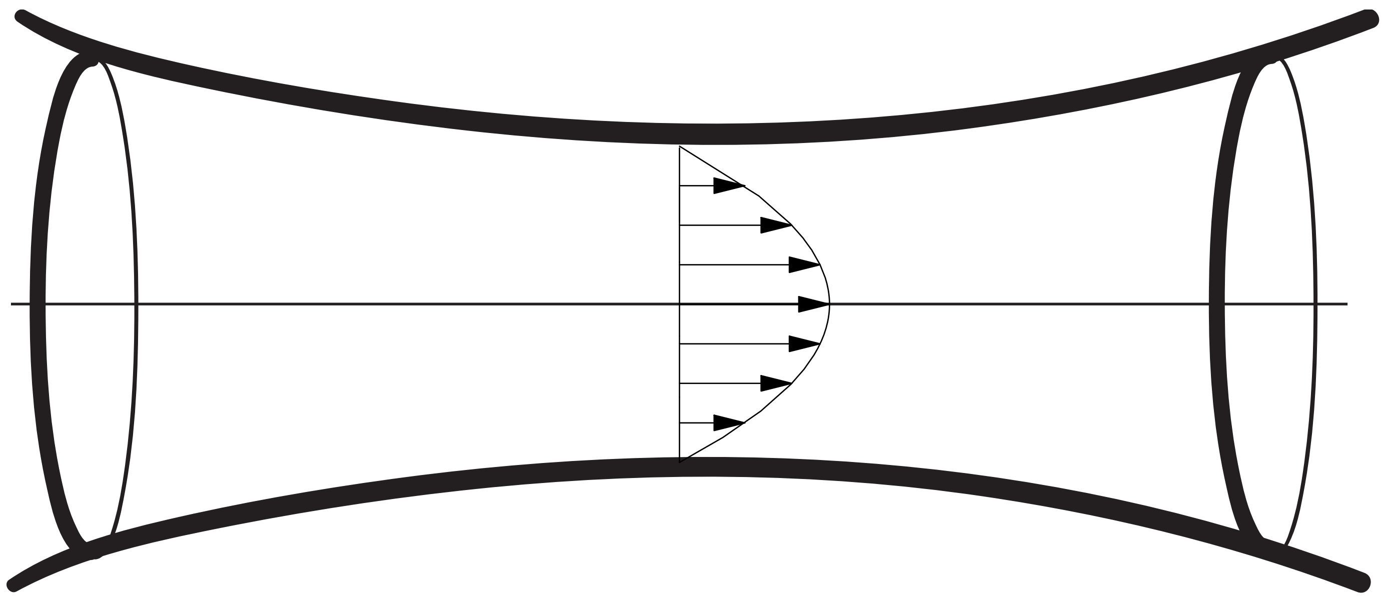


$$\frac{\partial u}{\partial x} + \frac{\partial r v}{r \partial r} = 0$$

$$\frac{\partial u}{\partial t} + u\frac{\partial}{\partial x}u + v\frac{\partial}{\partial r}u = -\frac{\partial p}{\rho \partial x} + \nu \frac{\partial}{r \partial r} r \frac{\partial u}{\partial r}$$

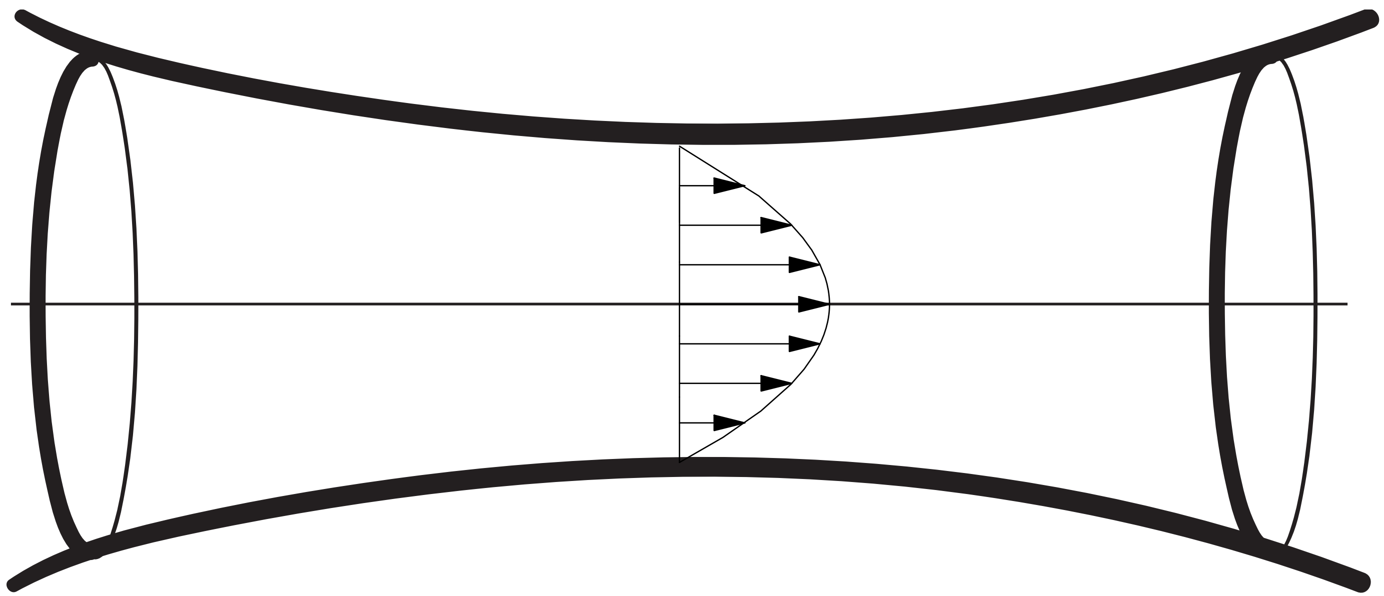
$$0 = -\frac{\partial p}{\rho \partial r}$$

Boundary conditions



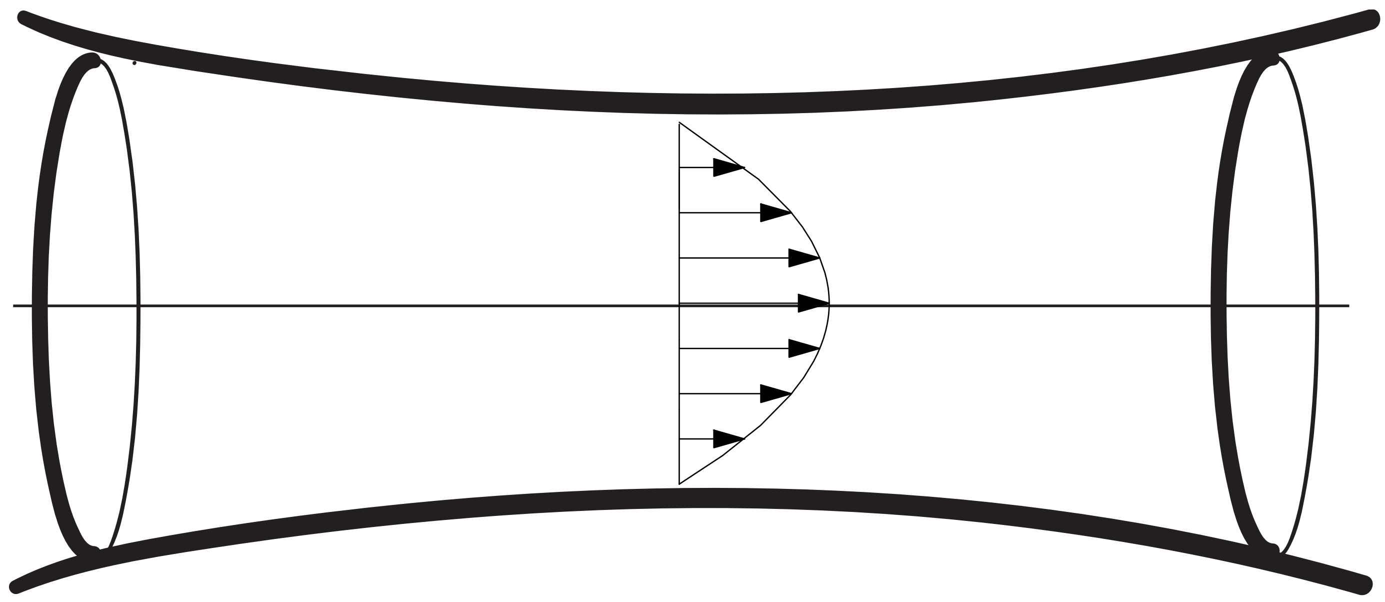
Rigid wall: $u = v = 0$

Boundary conditions



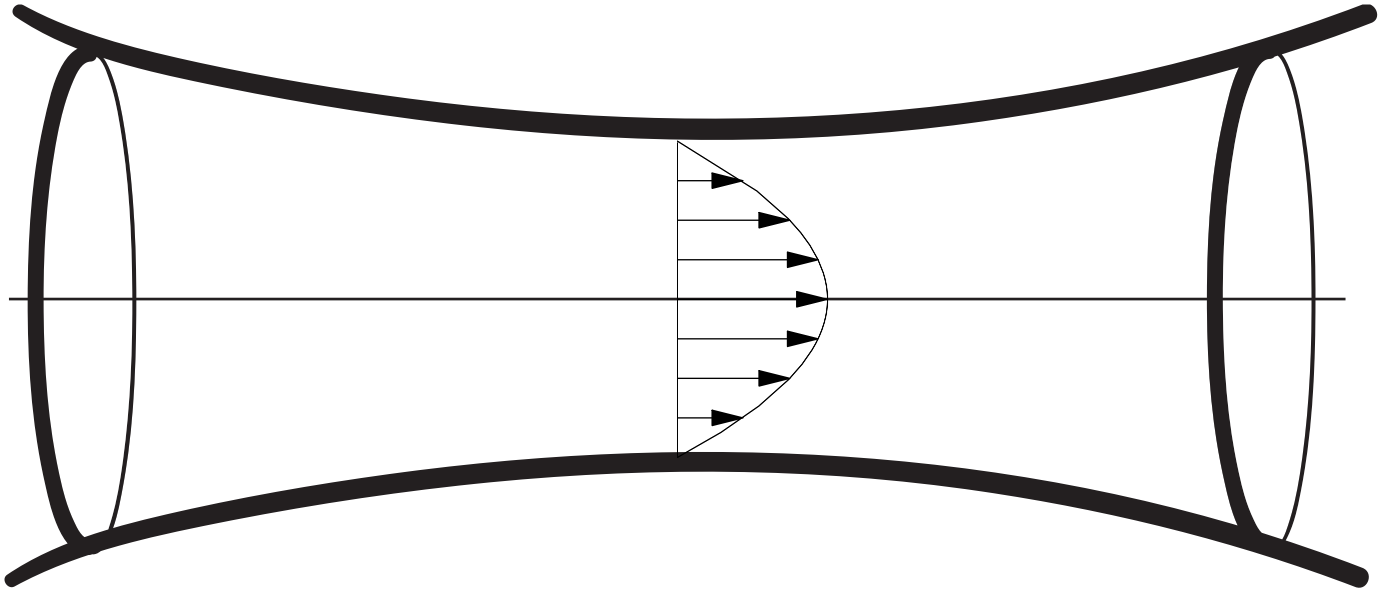
moving wall

Boundary conditions



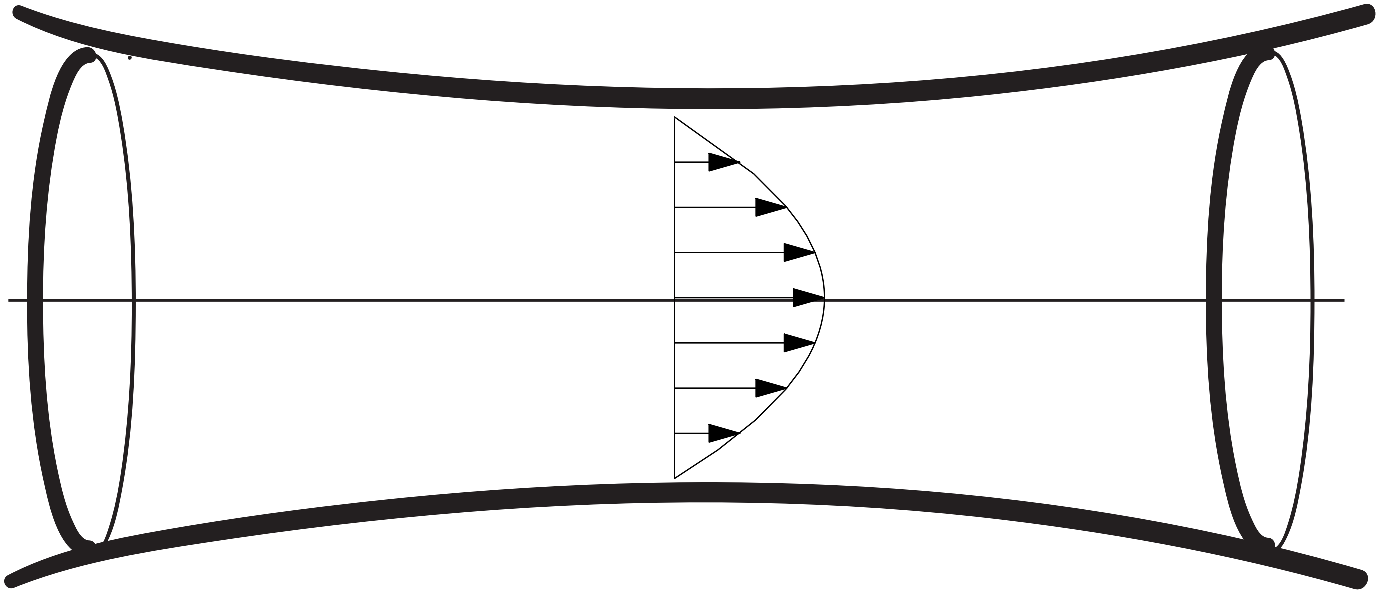
moving wall

Boundary conditions



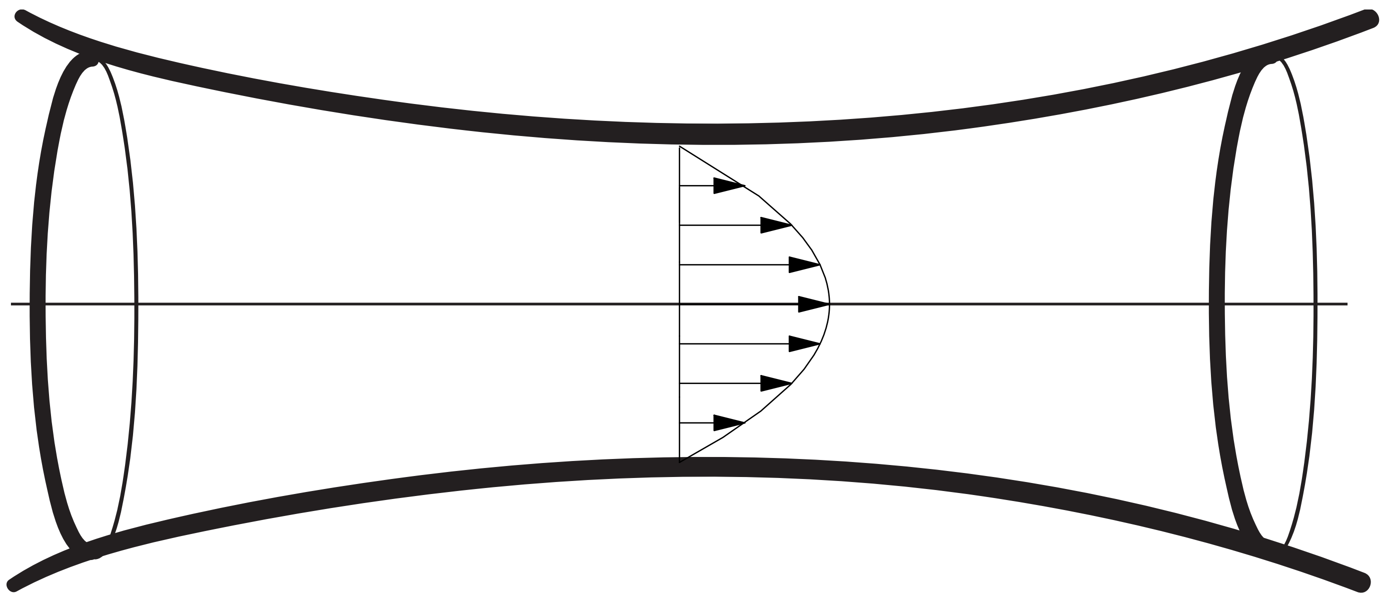
moving wall

Boundary conditions



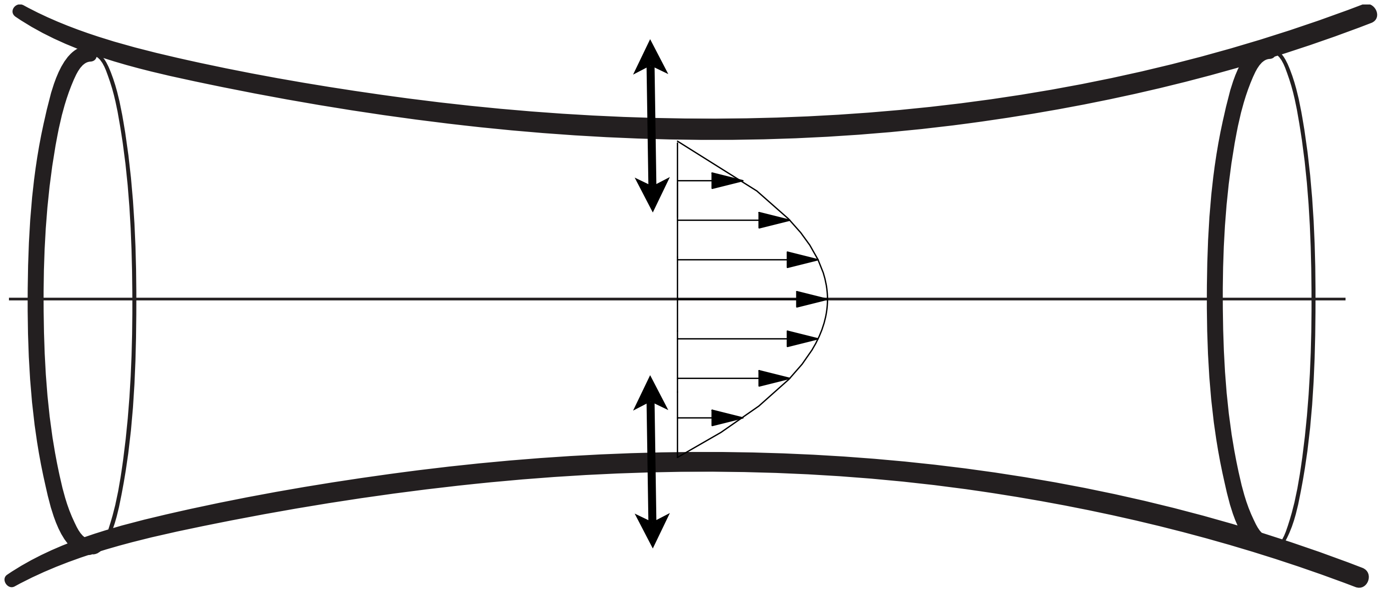
moving wall

Boundary conditions



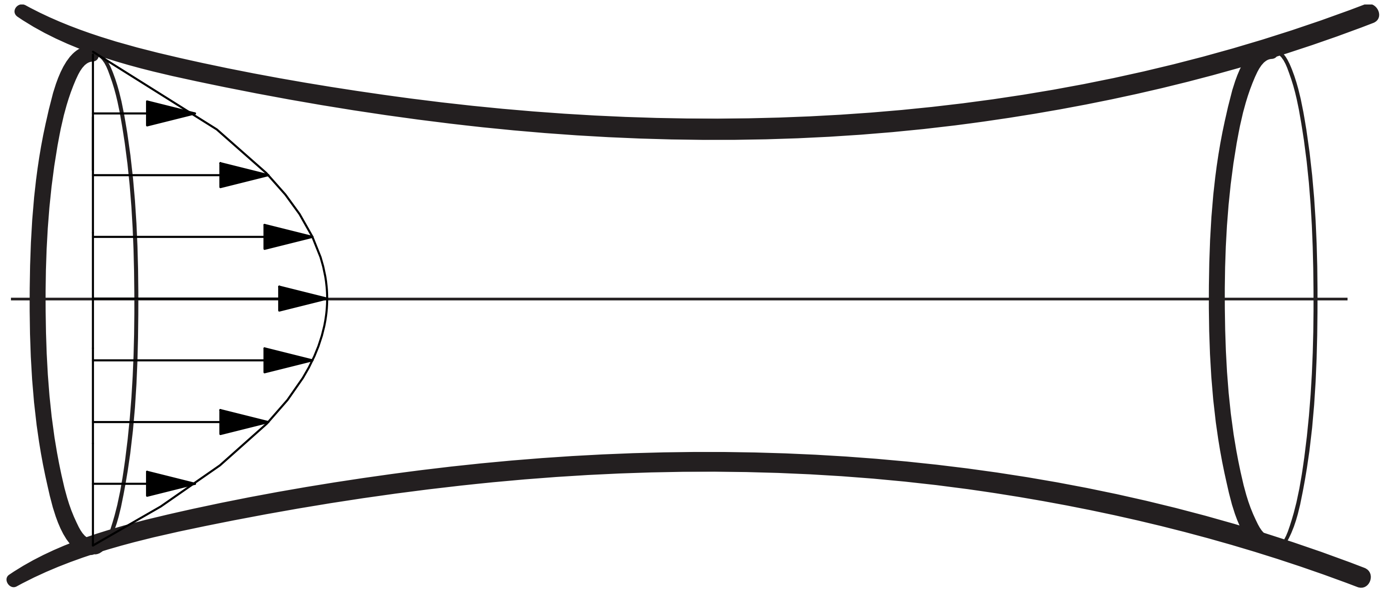
moving wall

Boundary conditions



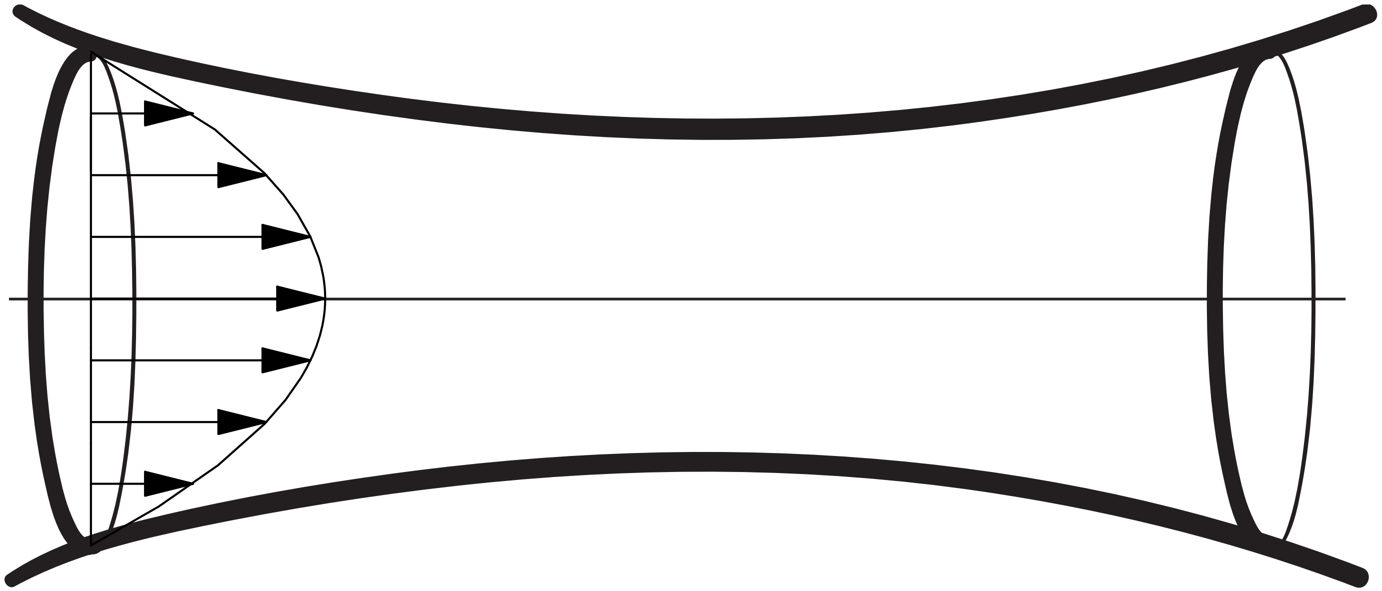
moving wall $$v = \frac{\partial R}{\partial t}$$

Boundary conditions



First given profile:

Boundary conditions

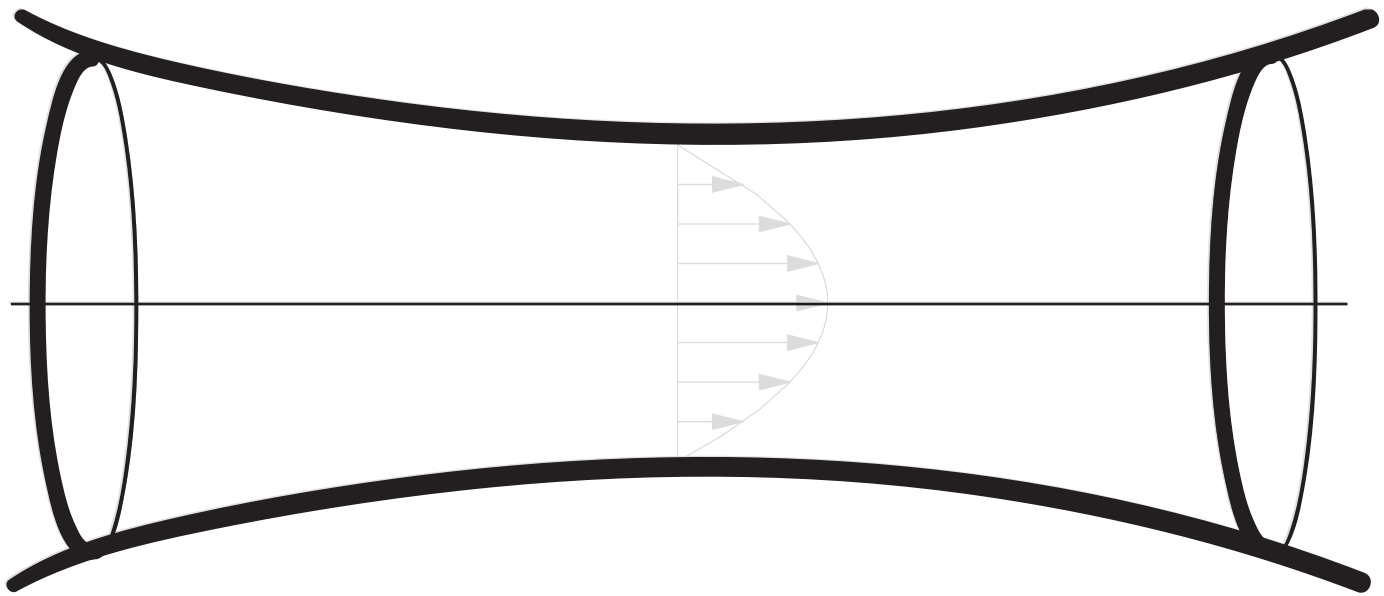


First given profile:

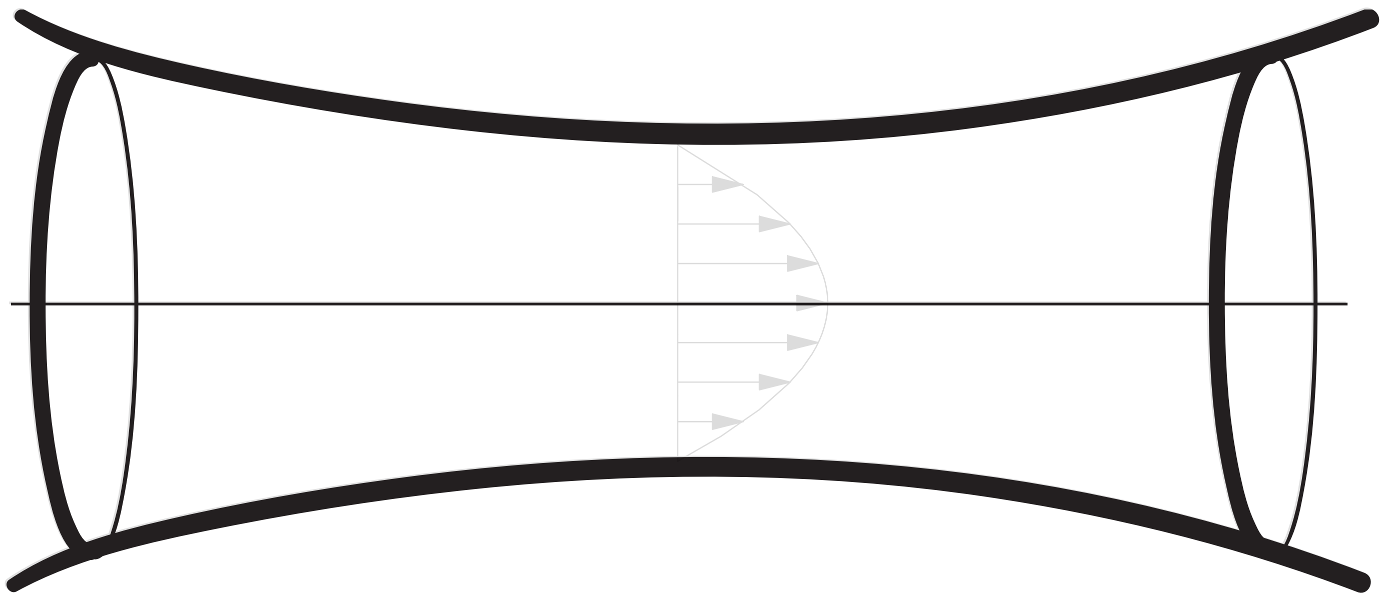
marching procedure

→

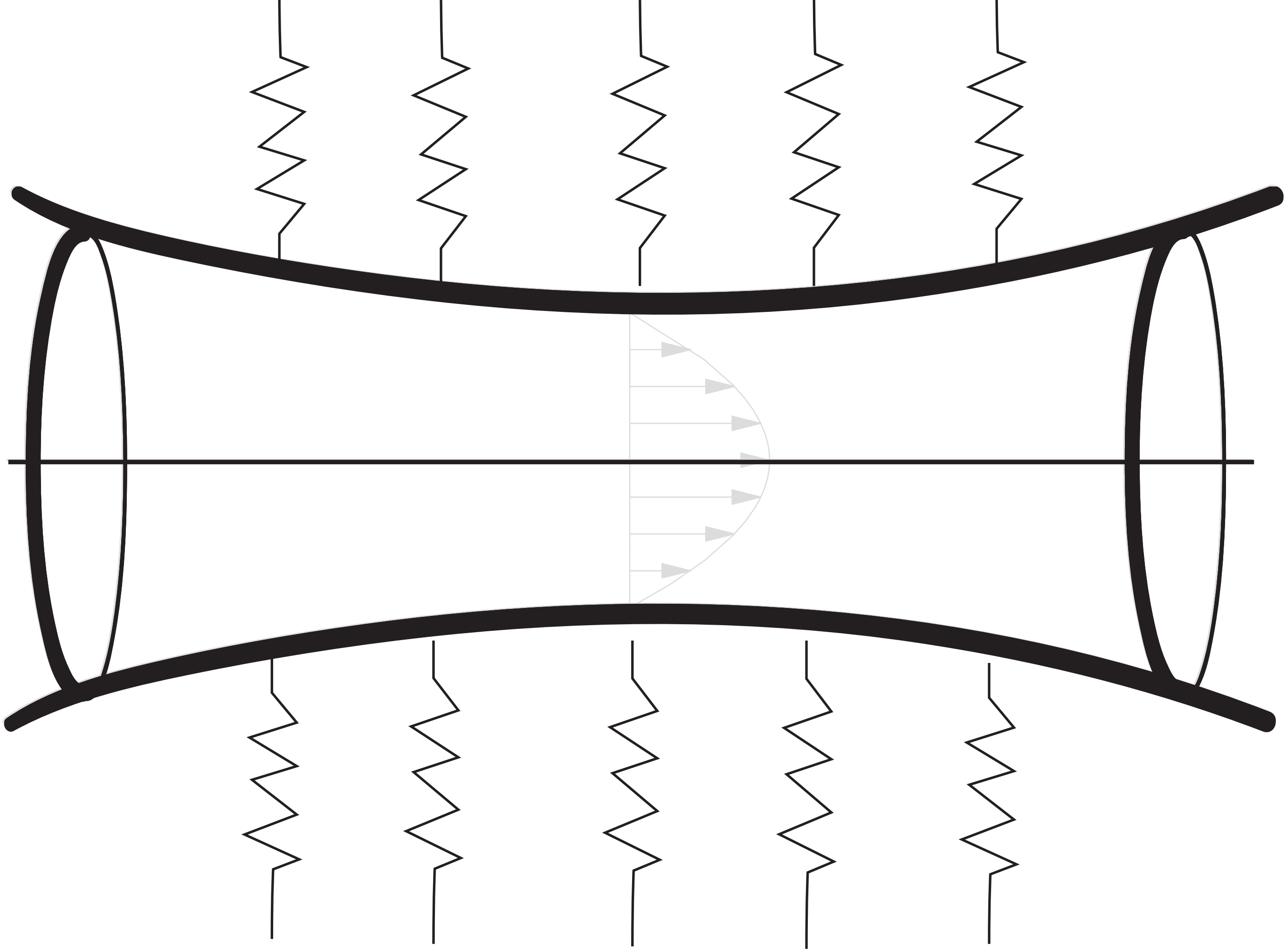
distribution of pressure is a result



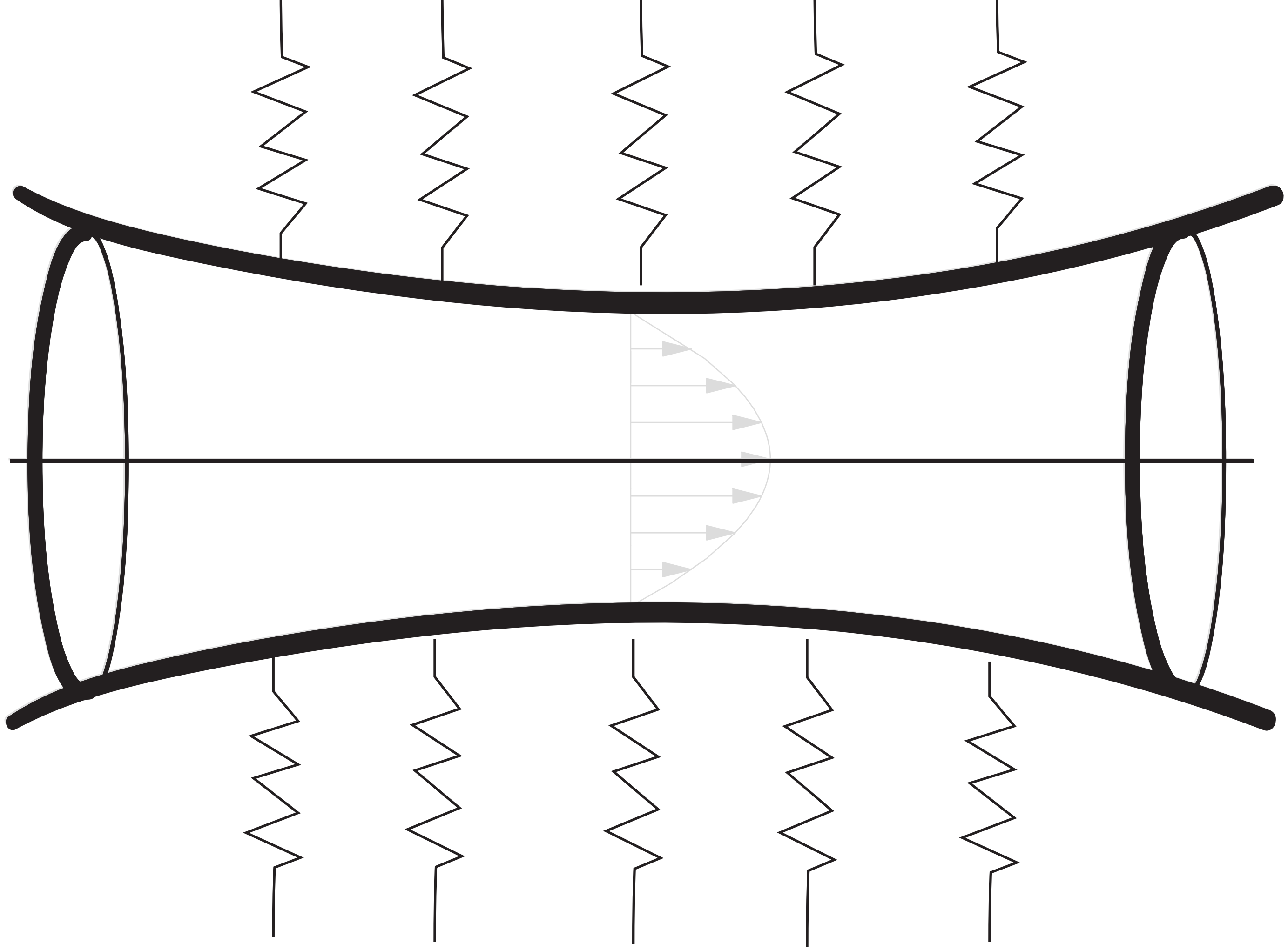
Up to now, the wall was rigid

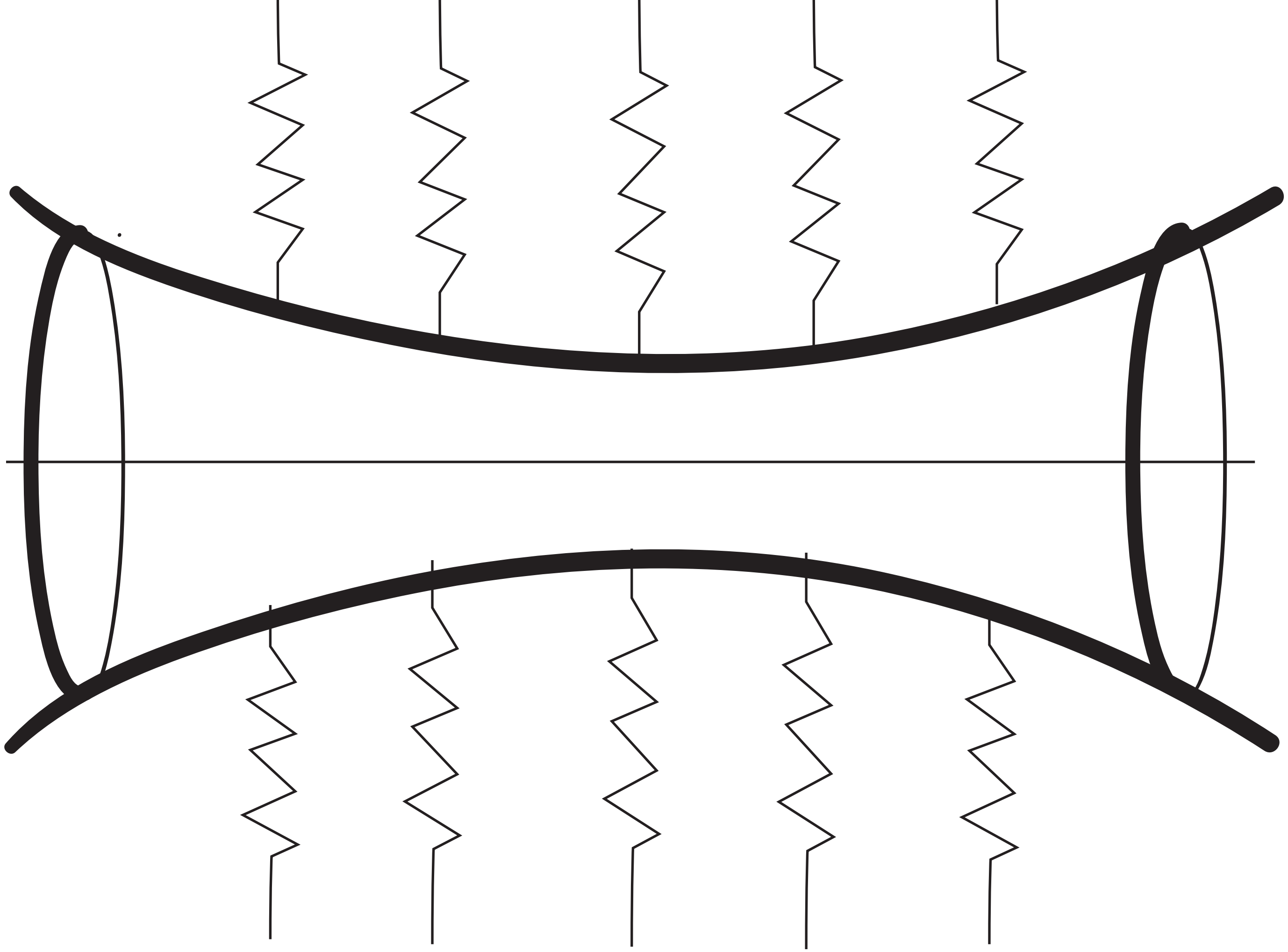


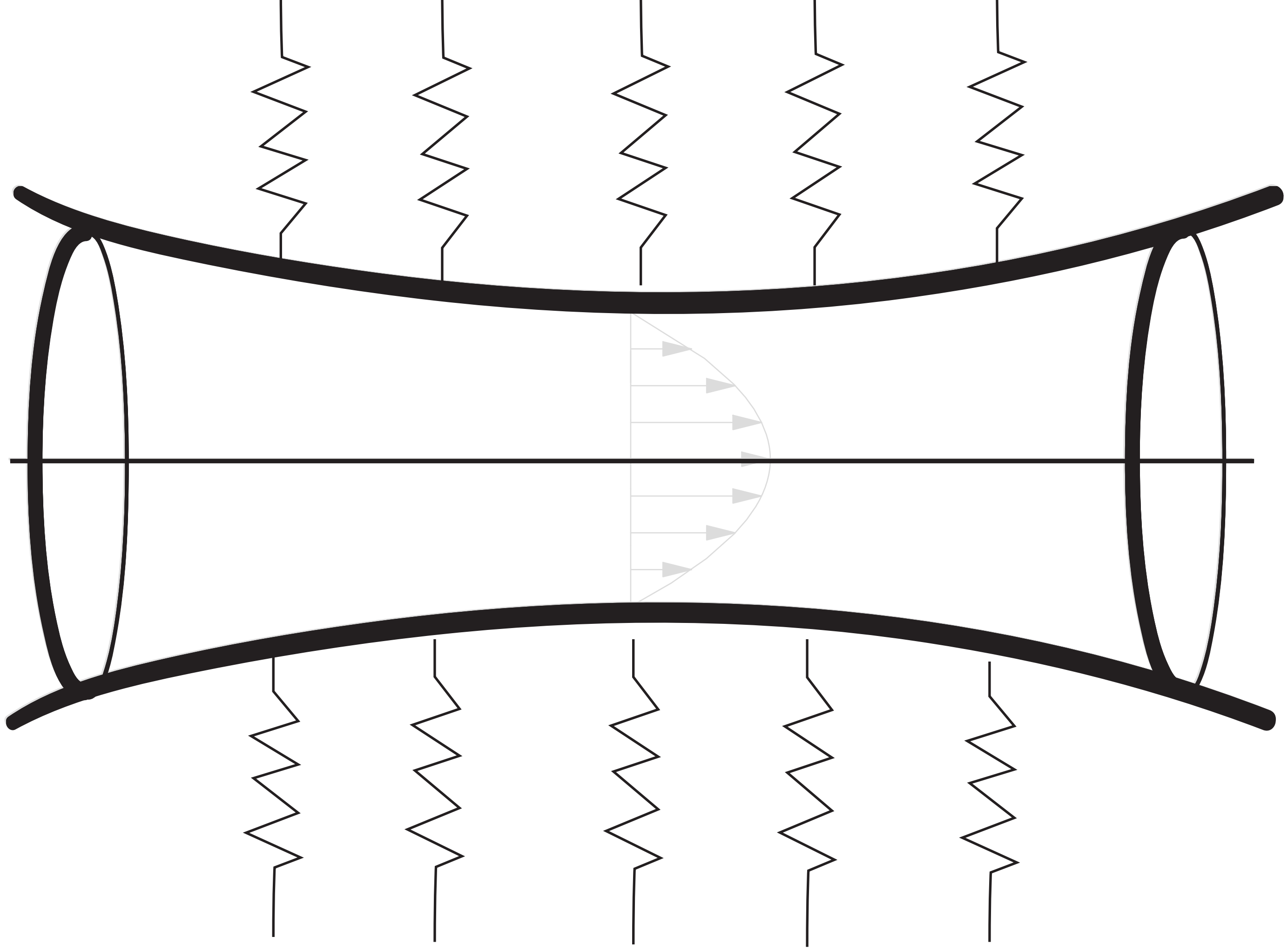
we use a simple elastic model

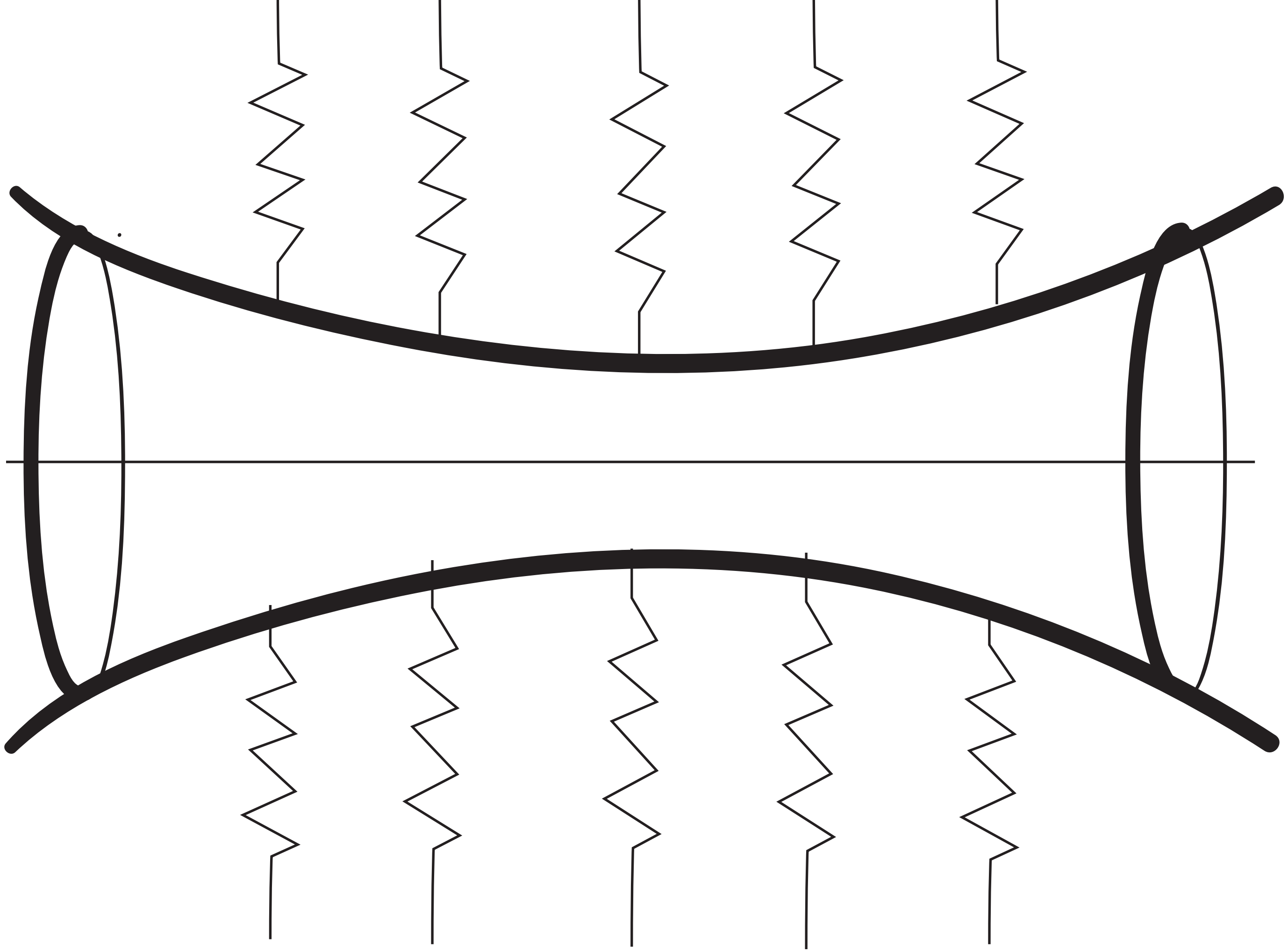


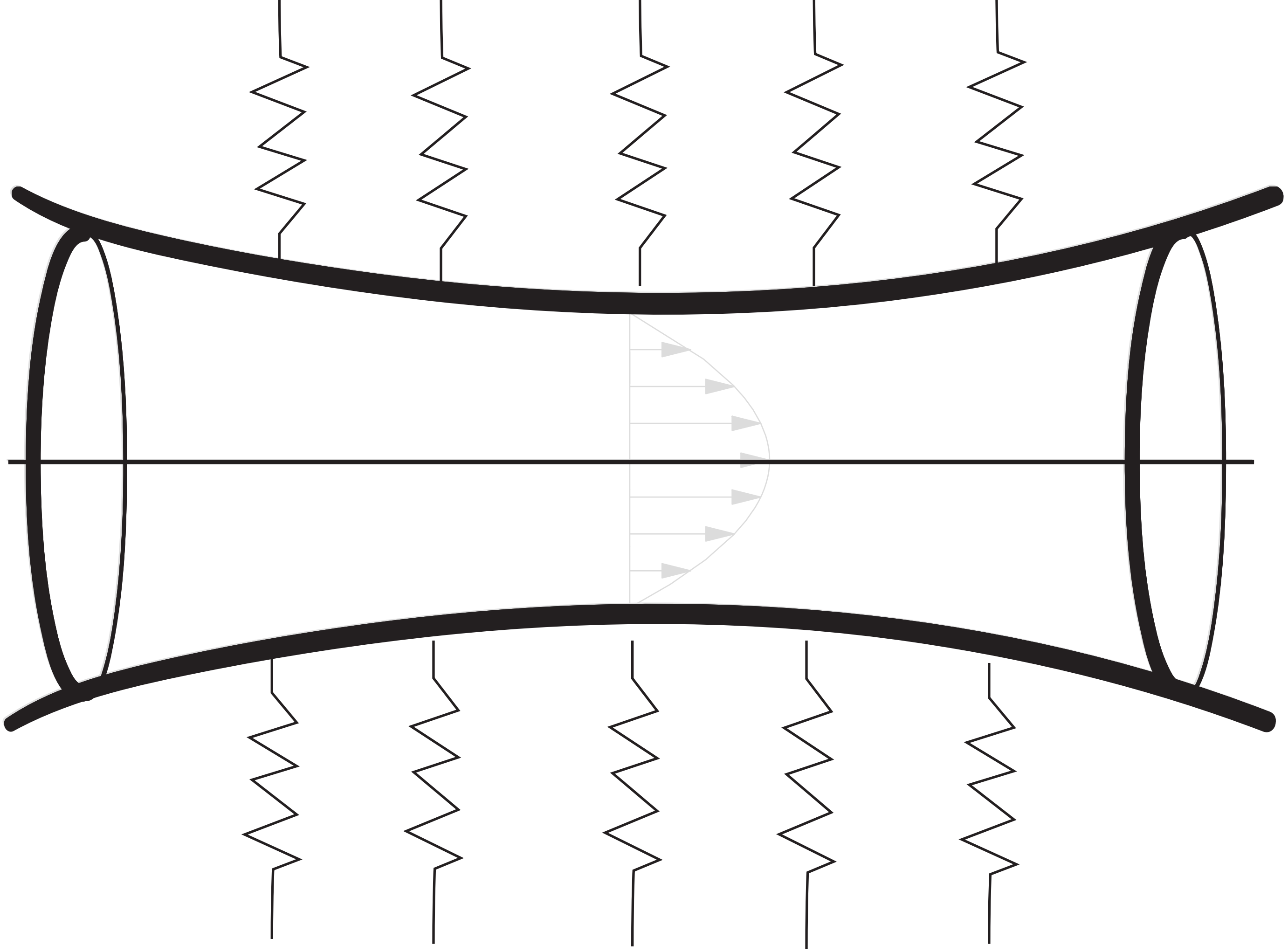
we use a simple elastic model



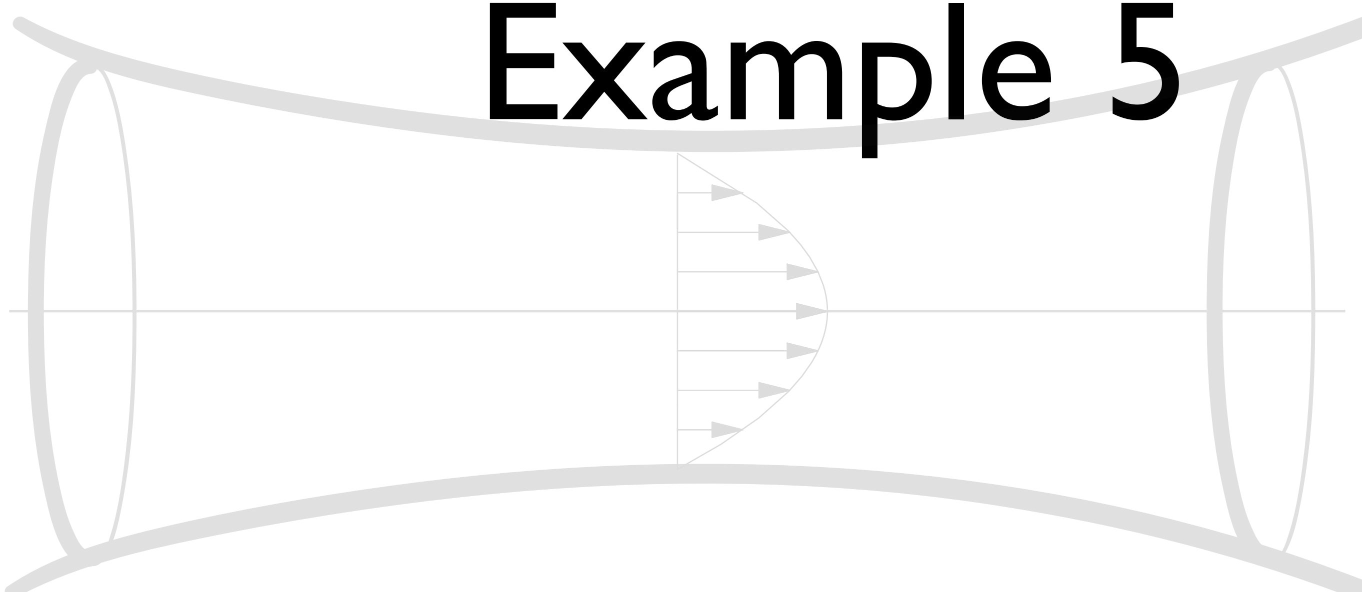




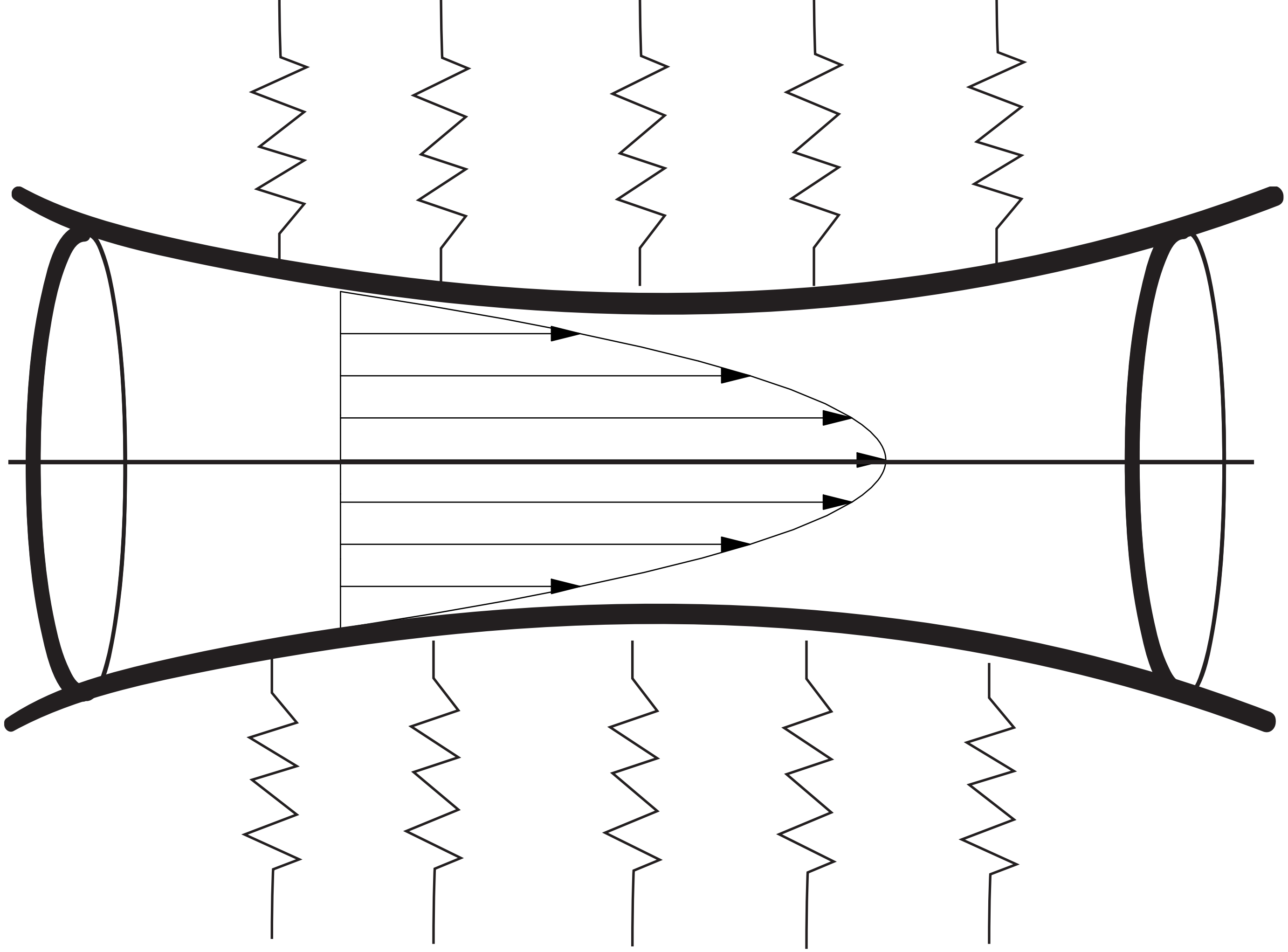




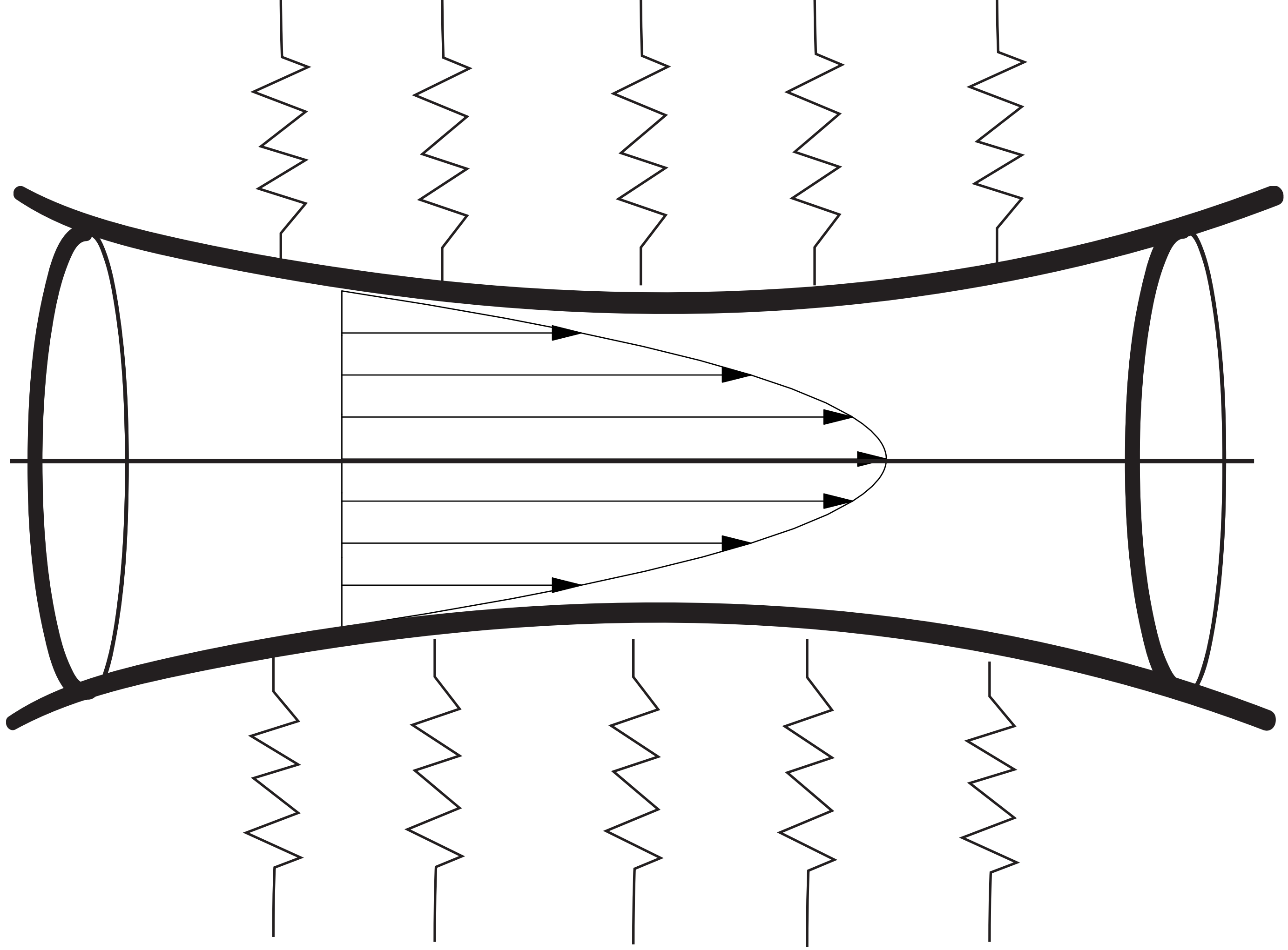
Example 5



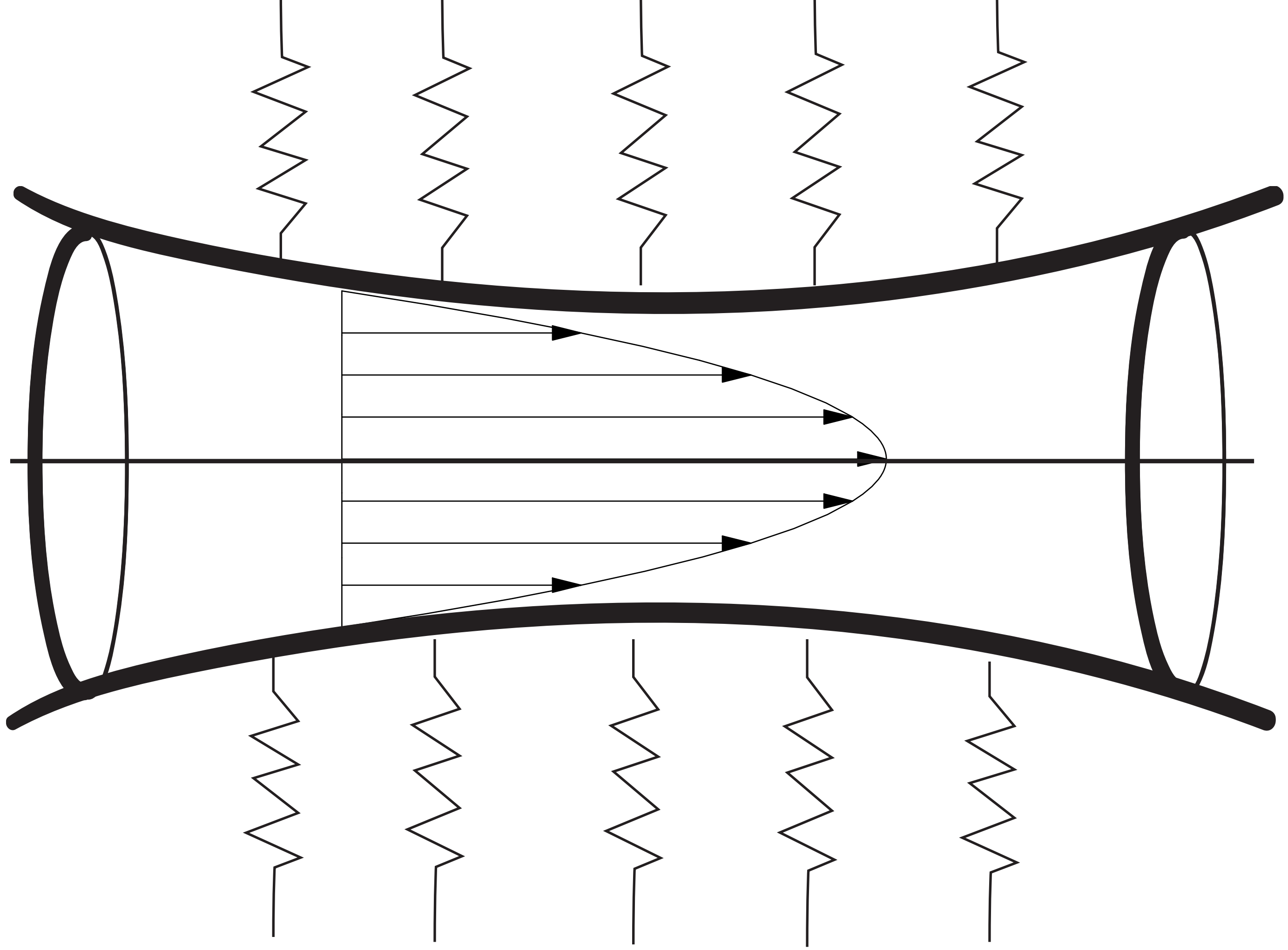
- Flow in a collapsible tube
- unsteady, elastic wall, no inertia



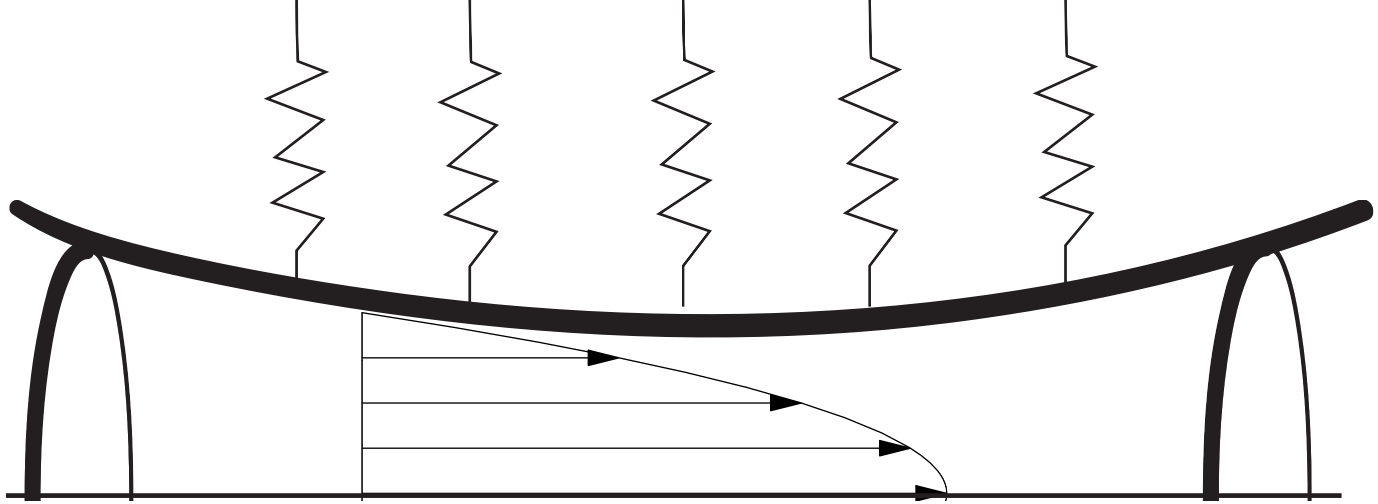
Collapsible tube

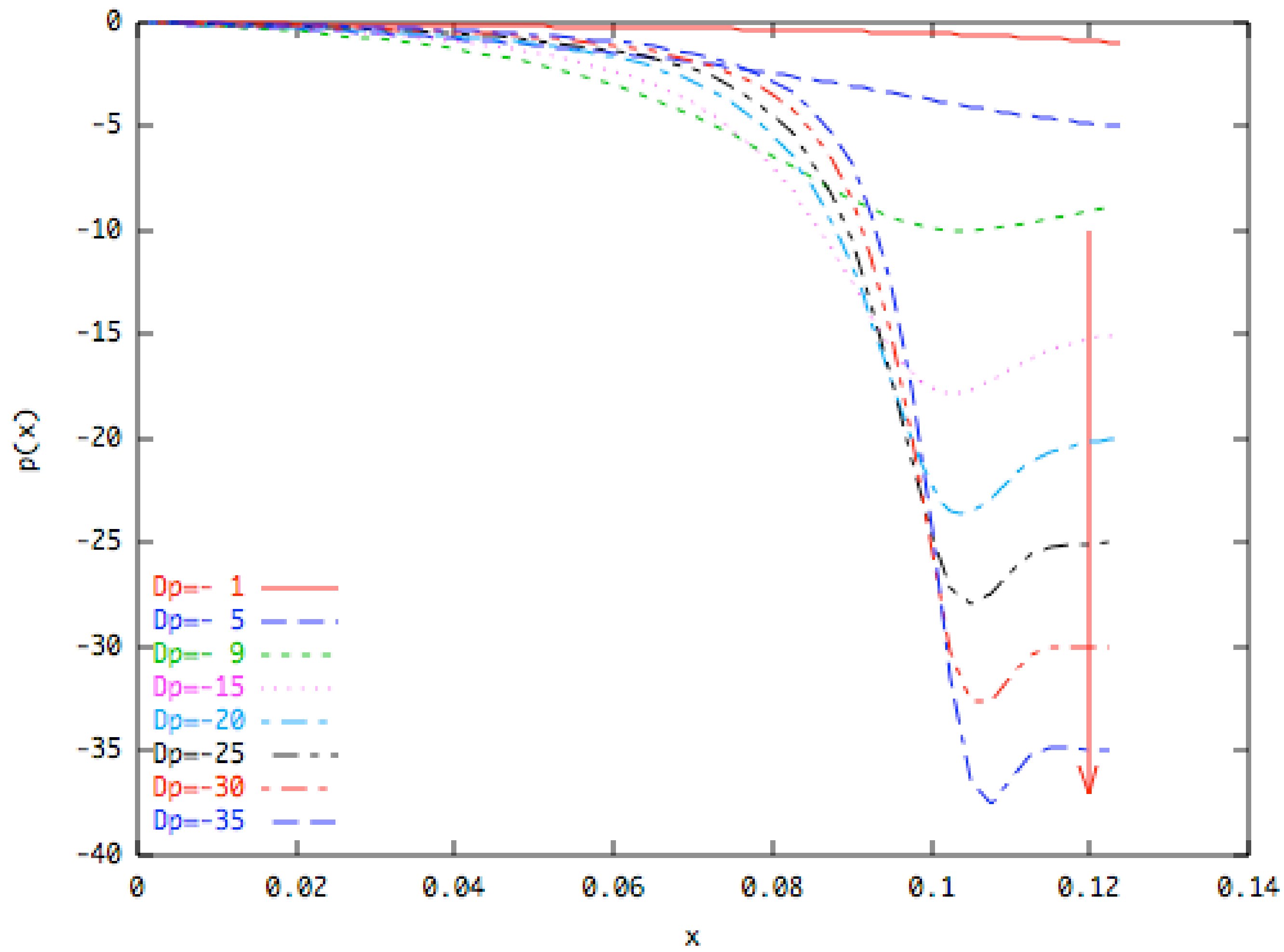


R^n gives p^{n+1}

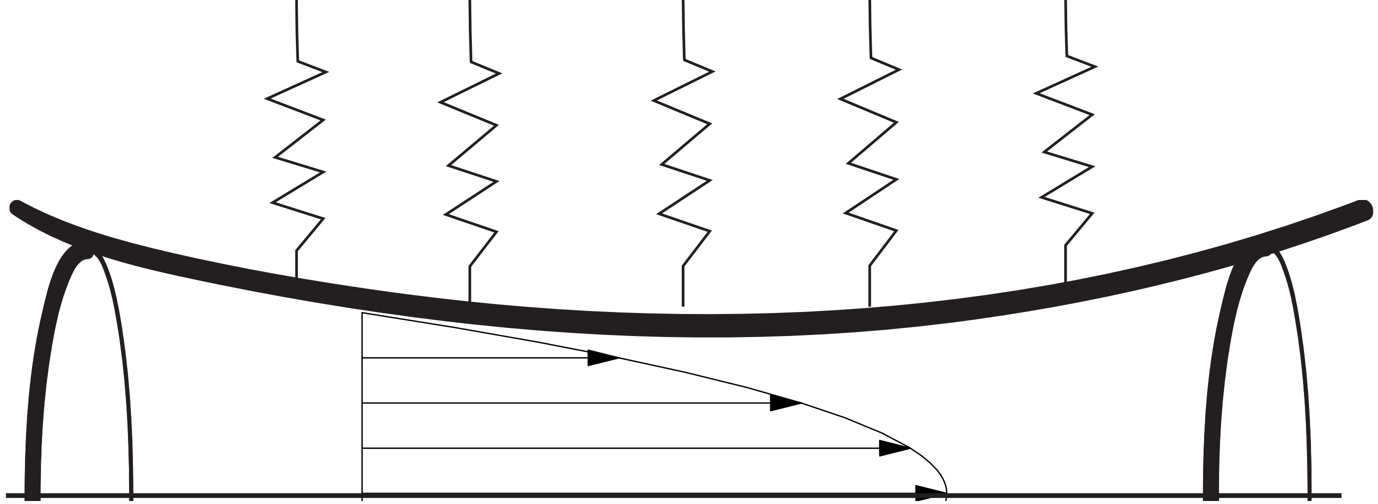


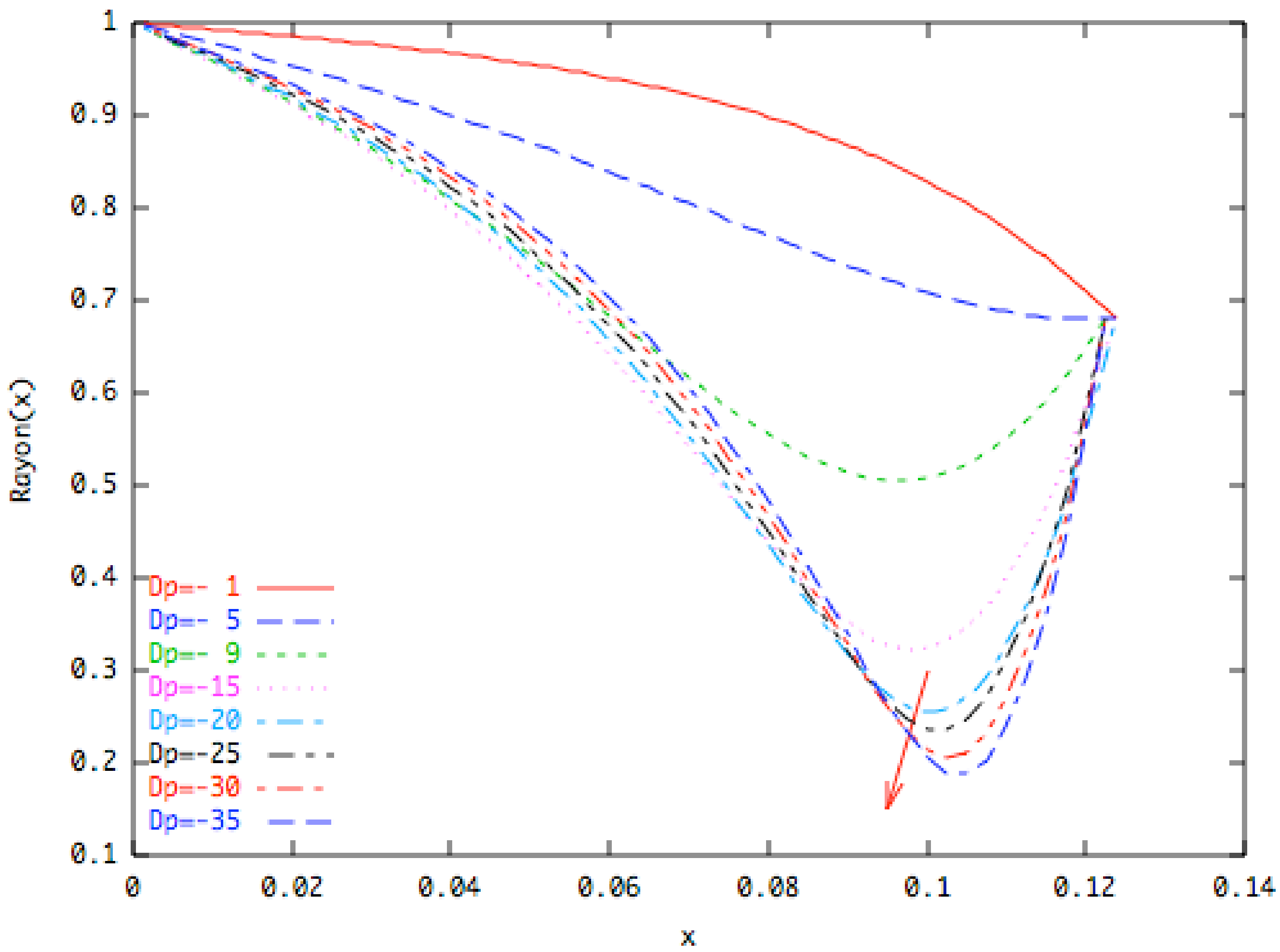
R^n gives p^{n+1} $\longrightarrow$ $p^{n+1} = k(R^{n+1} - 1)$



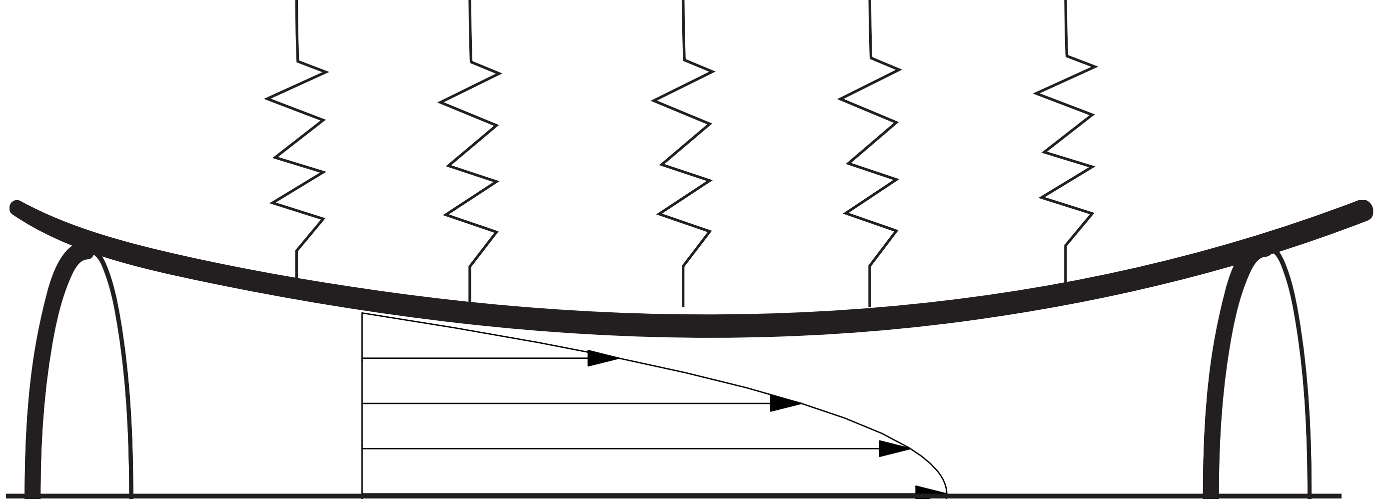


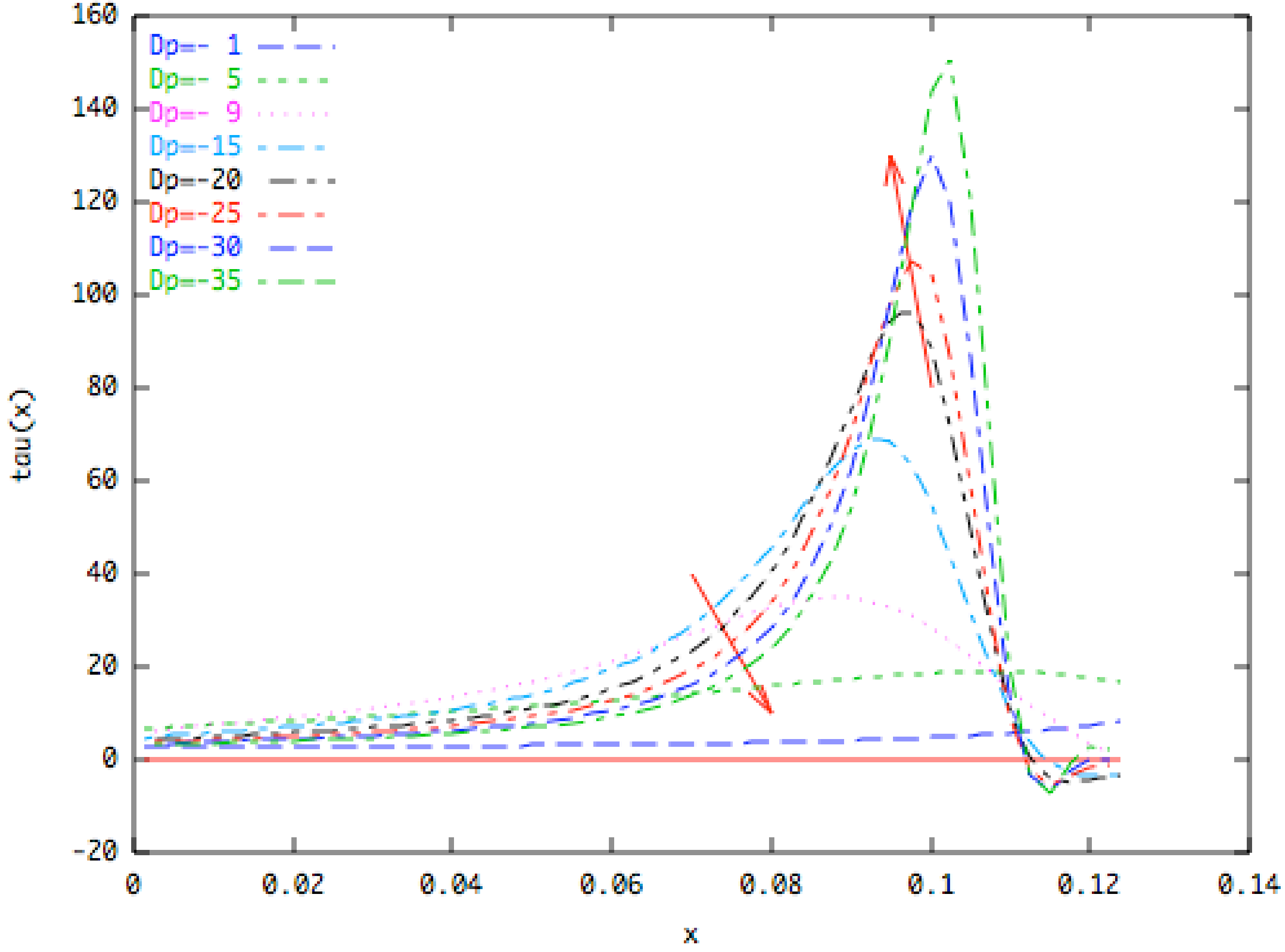
Dp=- 1
Dp=- 5
Dp=- 9
Dp=-15
Dp=-20
Dp=-25
Dp=-30
Dp=-35
p(x)
x
0
-5
-10
-15
-20
-25
-30
-35
-40
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14



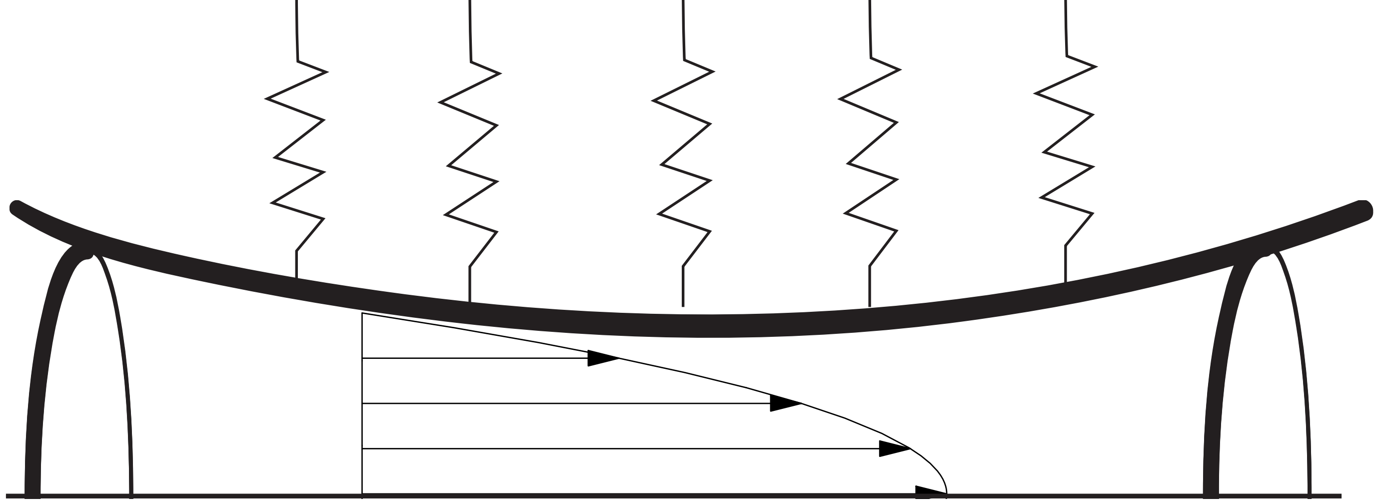


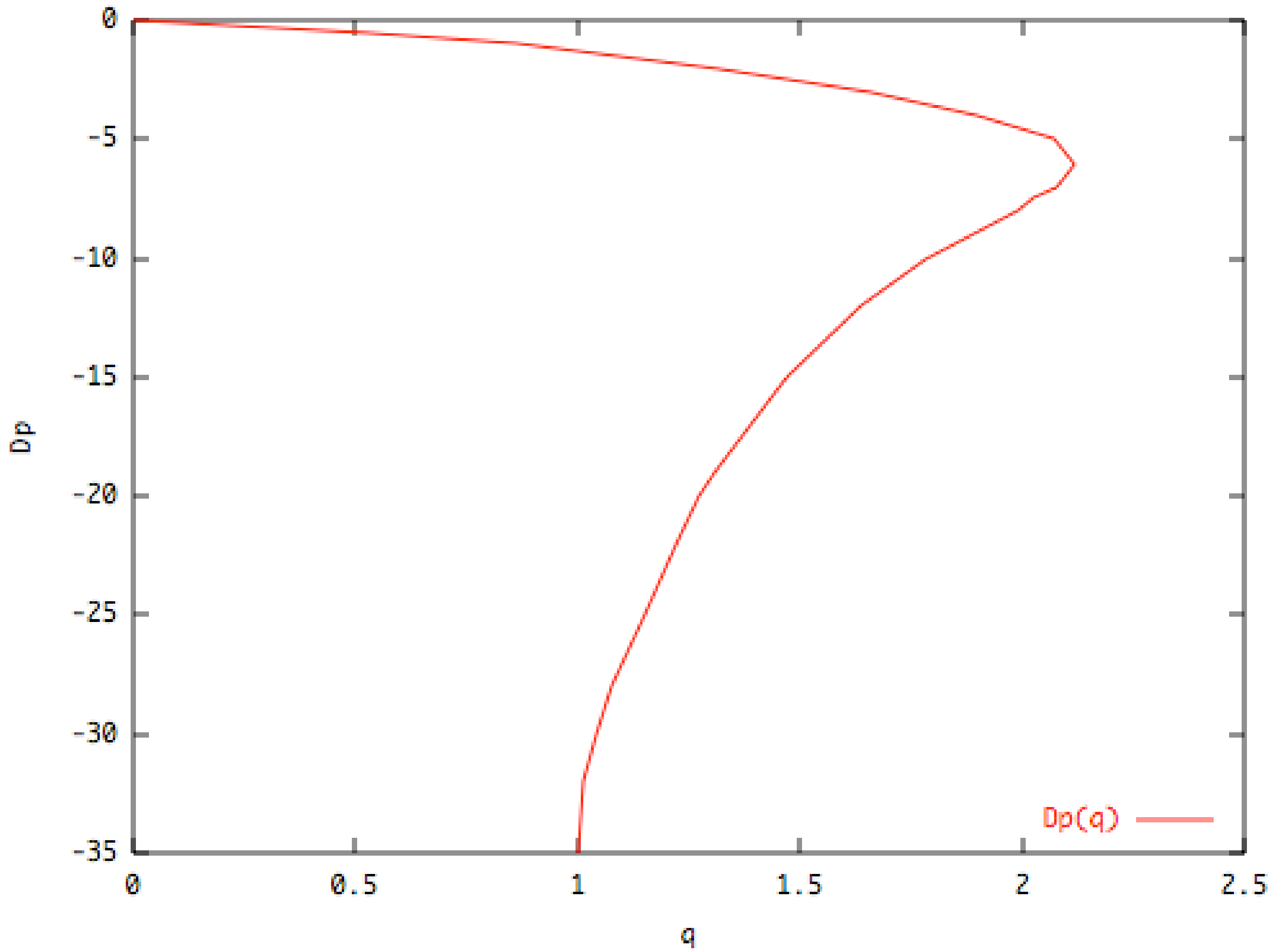
Rayon(x)
x
Dp=- 1
Dp=- 5
Dp=- 9
Dp=-15
Dp=-20
Dp=-25
Dp=-30
Dp=-35





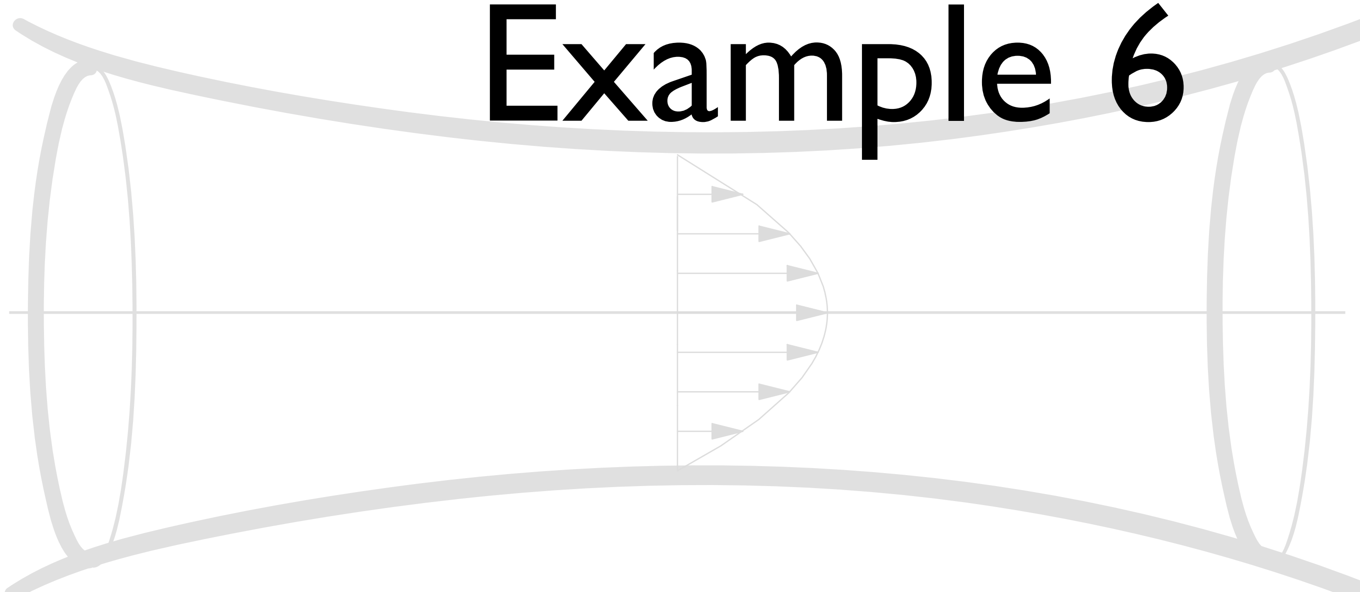
Dp=- 1
Dp=- 5
Dp=- 9
Dp=-15
Dp=-20
Dp=-25
Dp=-30
Dp=-35
tau(x)
x
160
140
120
100
80
60
40
20
0
-20
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14



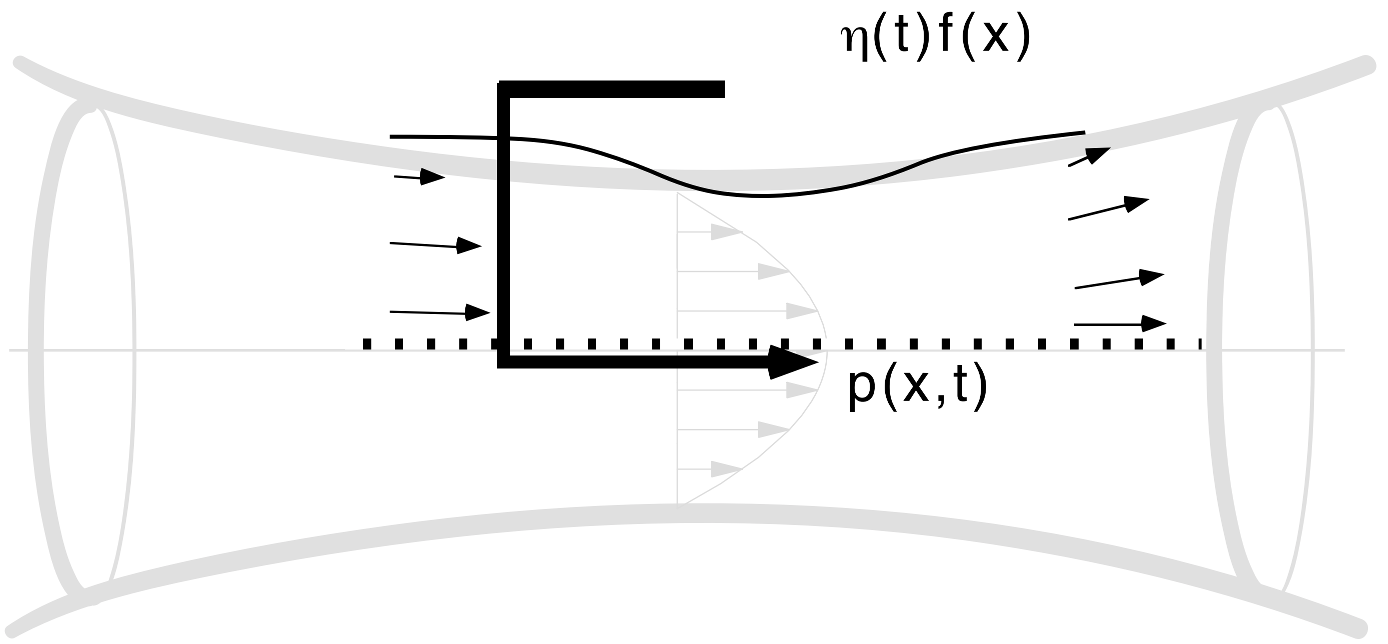


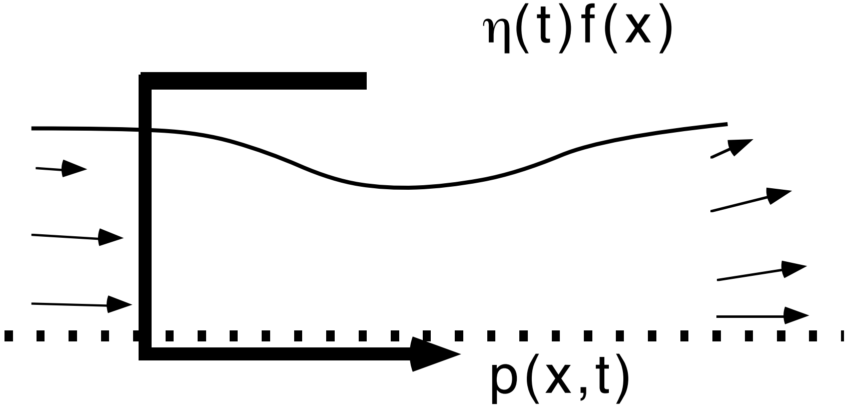
0
-5
-10
-15
-20
-25
-30
-35
Dp
0
0.5
1
1.5
2
2.5
q
Dp(q)

Example 6

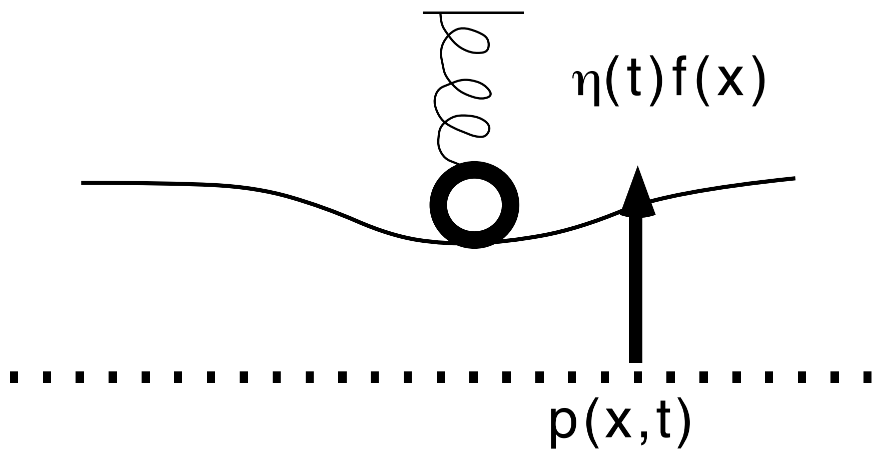


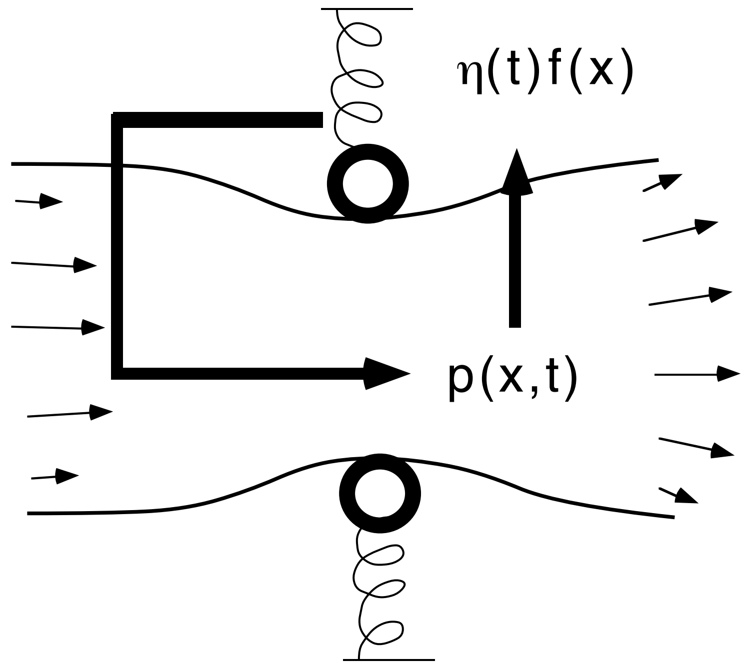
- flow with elastic wall with mass (glottis)

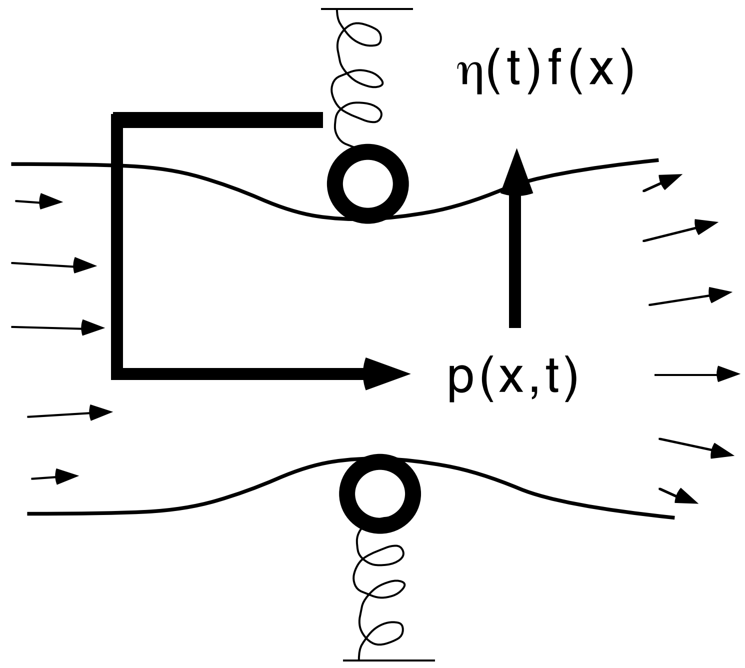

η(t)f(x)
p(x,t)



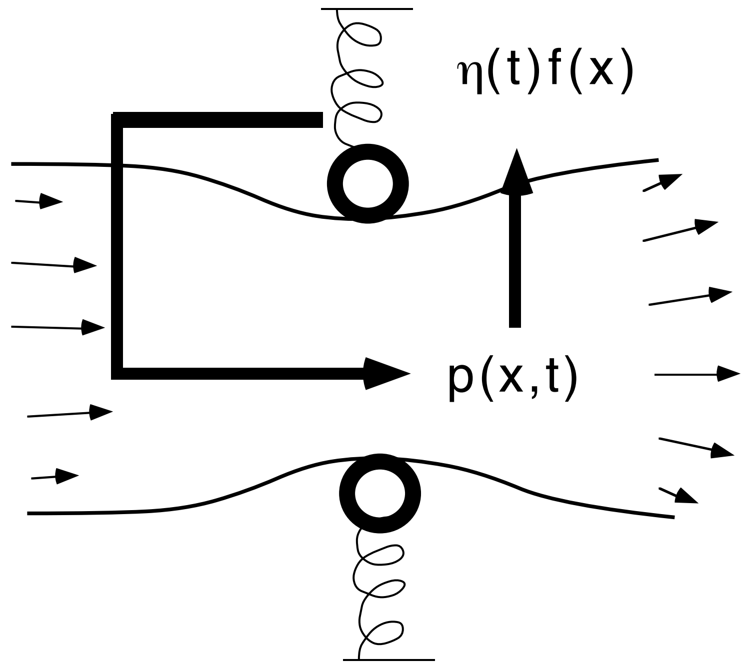
η(t)f(x)
p(x,t)


η(t)f(x)
p(x,t)

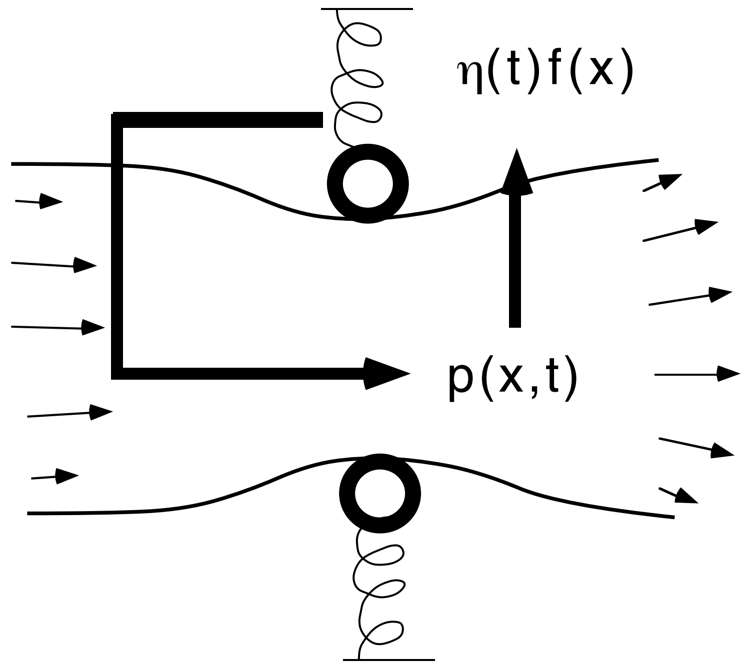

η(t)f(x)
p(x,t)



$$\mu\frac{\partial^2\eta}{\partial t^2}+k\eta=-p$$

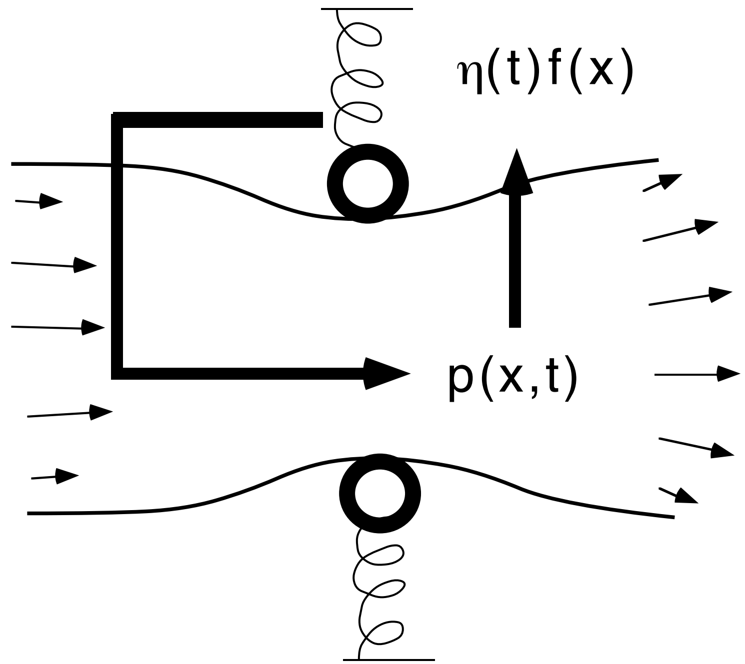


Newmark method for the spring:
prediction/ correction



Newmark method for the spring: prediction/ correction

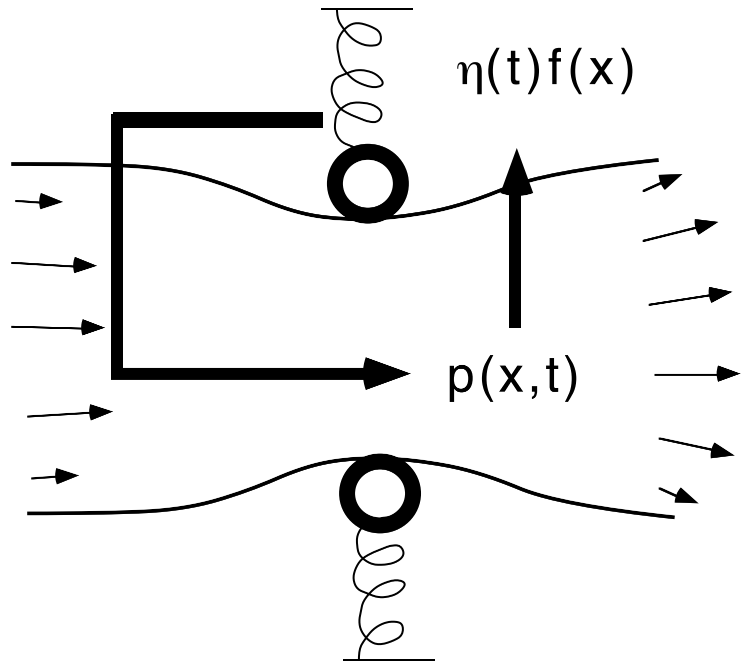
$$\eta^n, \frac{\partial \eta^n}{\partial t} \xrightarrow{\text{fluid}} p$$



Newmark method for the spring: prediction/ correction

$$\eta^n, \frac{\partial \eta^n}{\partial t} \xrightarrow{\text{fluid}} p \qquad \eta^e, \frac{\partial \eta^e}{\partial t}$$

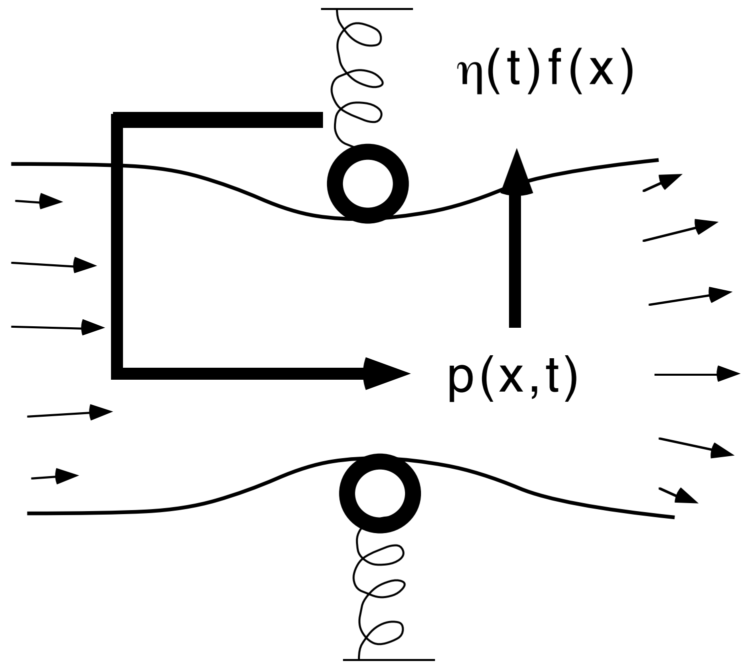
spring-prediction



Newmark method for the spring:
prediction/ correction

$$\eta^n, \frac{\partial \eta^n}{\partial t} \xrightarrow{\text{fluid}} p \qquad \eta^e, \frac{\partial \eta^e}{\partial t} \xrightarrow{\text{fluid}} p^e$$

spring-prediction

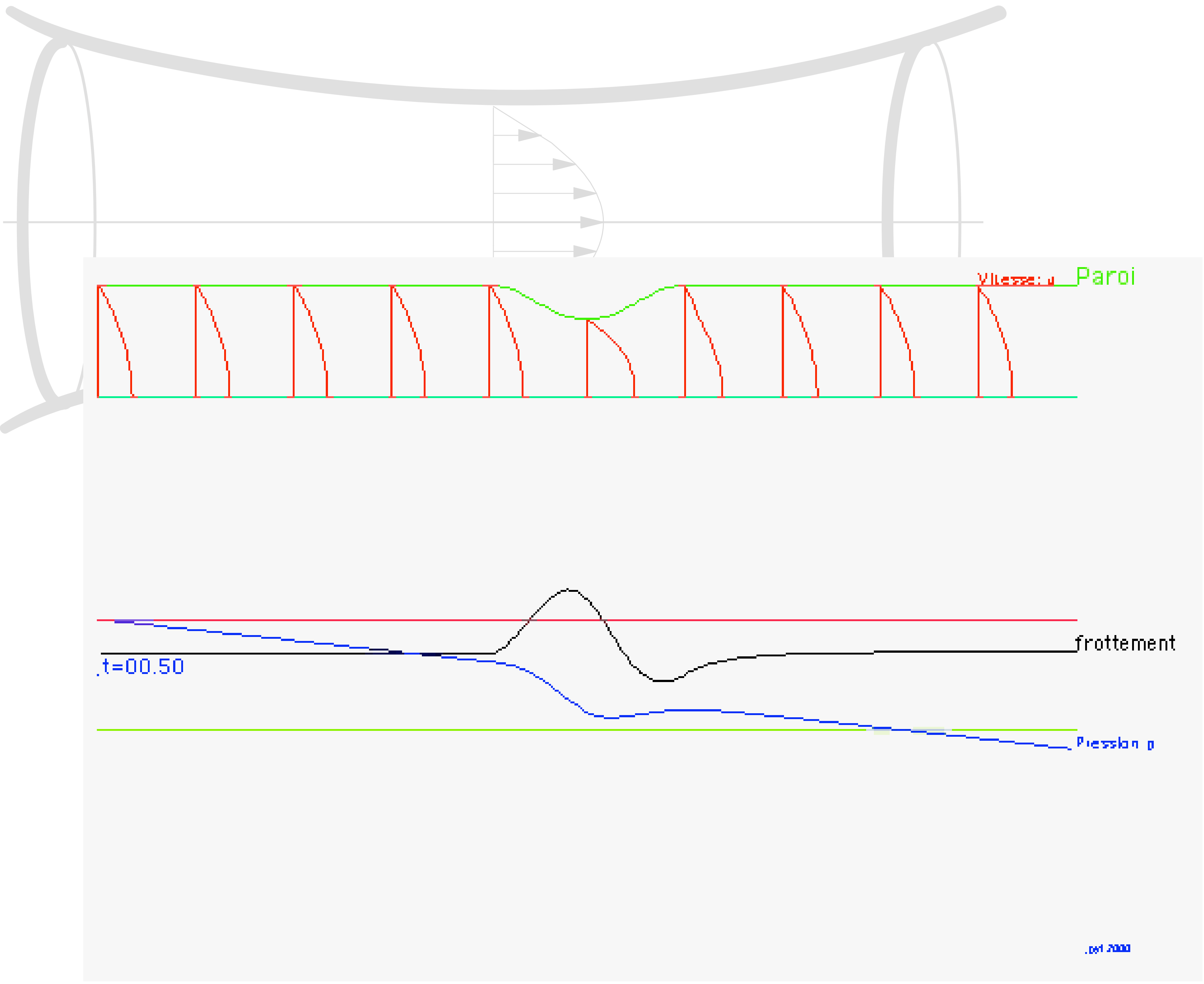


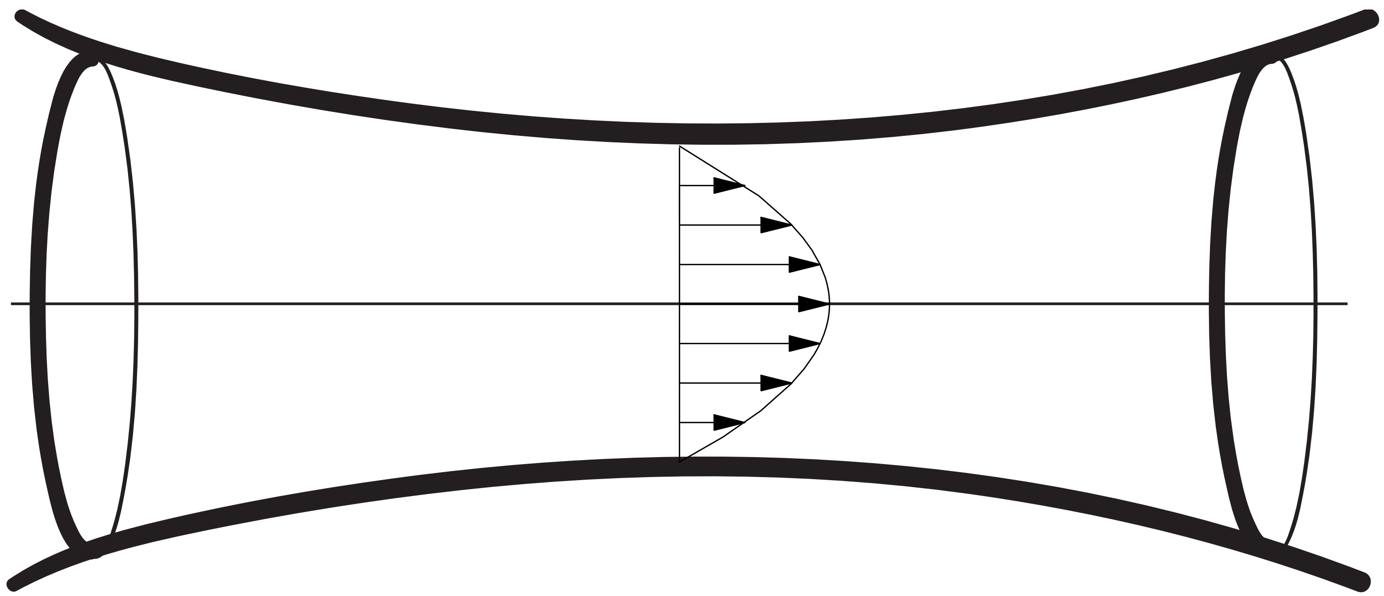
Newmark method for the spring:
prediction/ correction

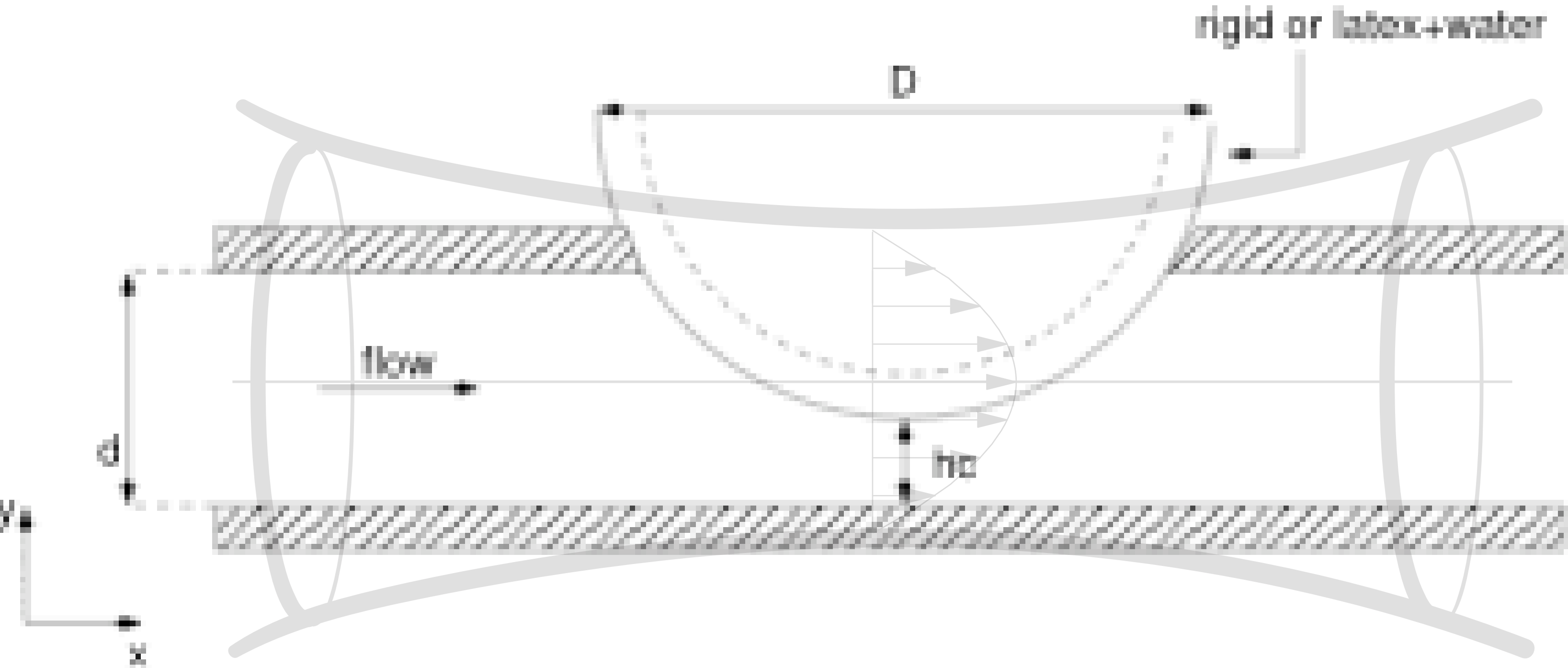
$$\eta^n, \frac{\partial \eta^n}{\partial t} \xrightarrow{\text{fluid}} p \qquad \eta^e, \frac{\partial \eta^e}{\partial t} \xrightarrow{\text{fluid}} p^e \qquad \eta^{n+1}, \frac{\partial \eta^{n+1}}{\partial t}$$

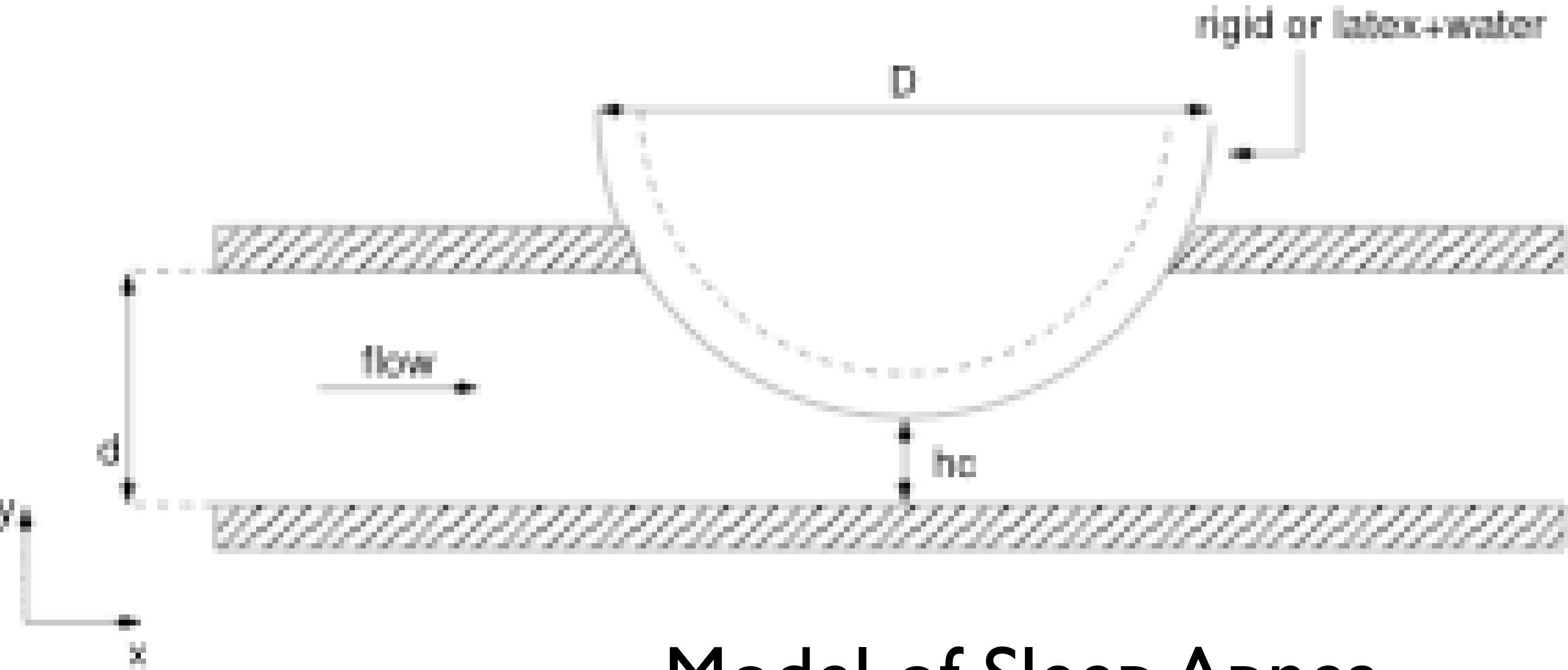
spring-prediction

spring- correction

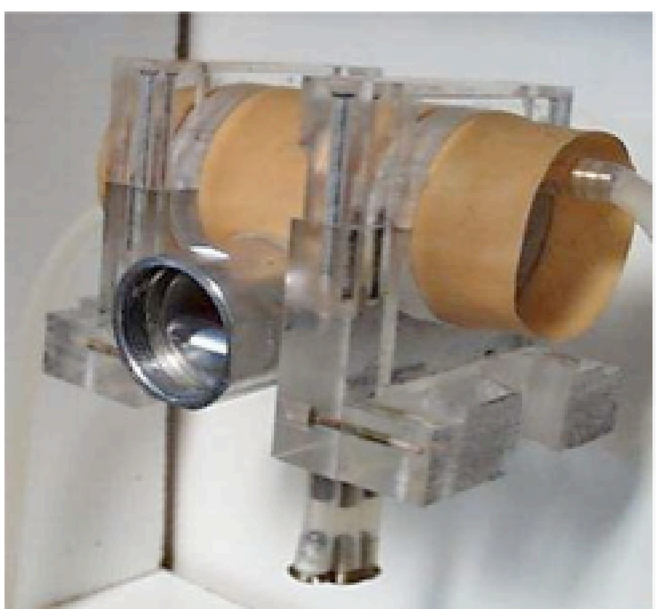

Paroi
frottement
t=00.50

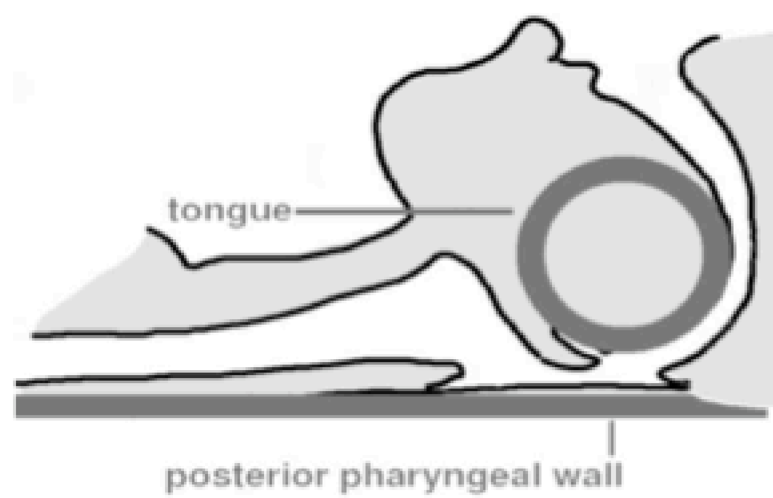


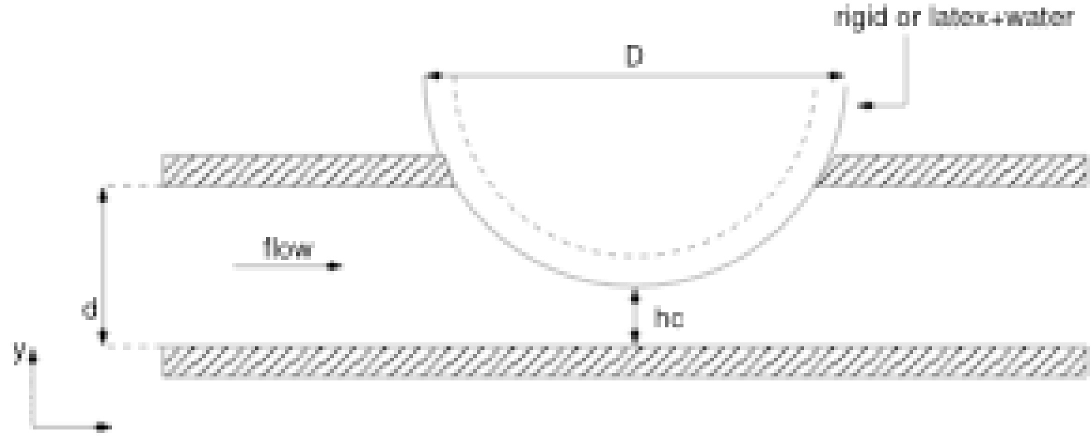

rigid or latex+water
D
flow
d
hc
y
x

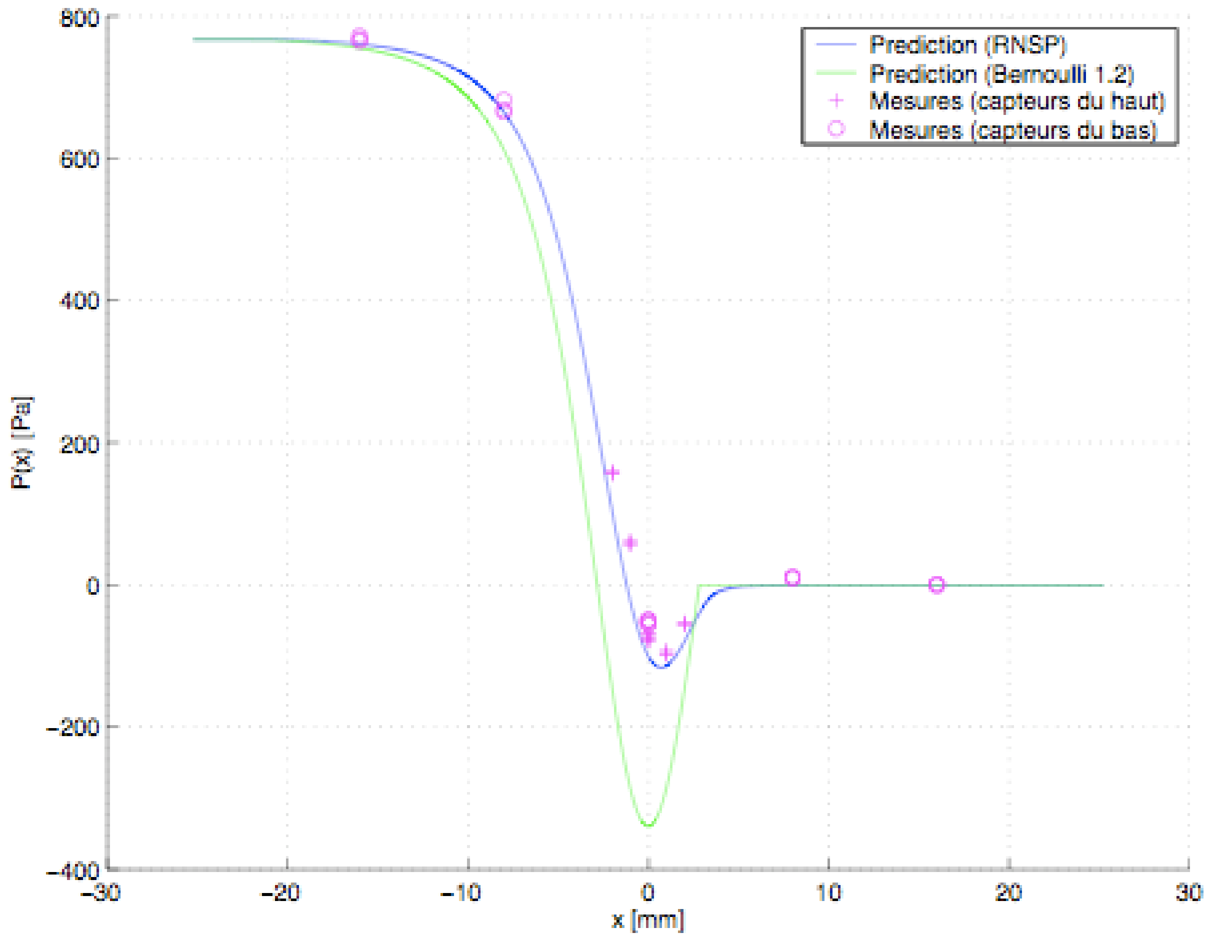


Model of Sleep Apnea



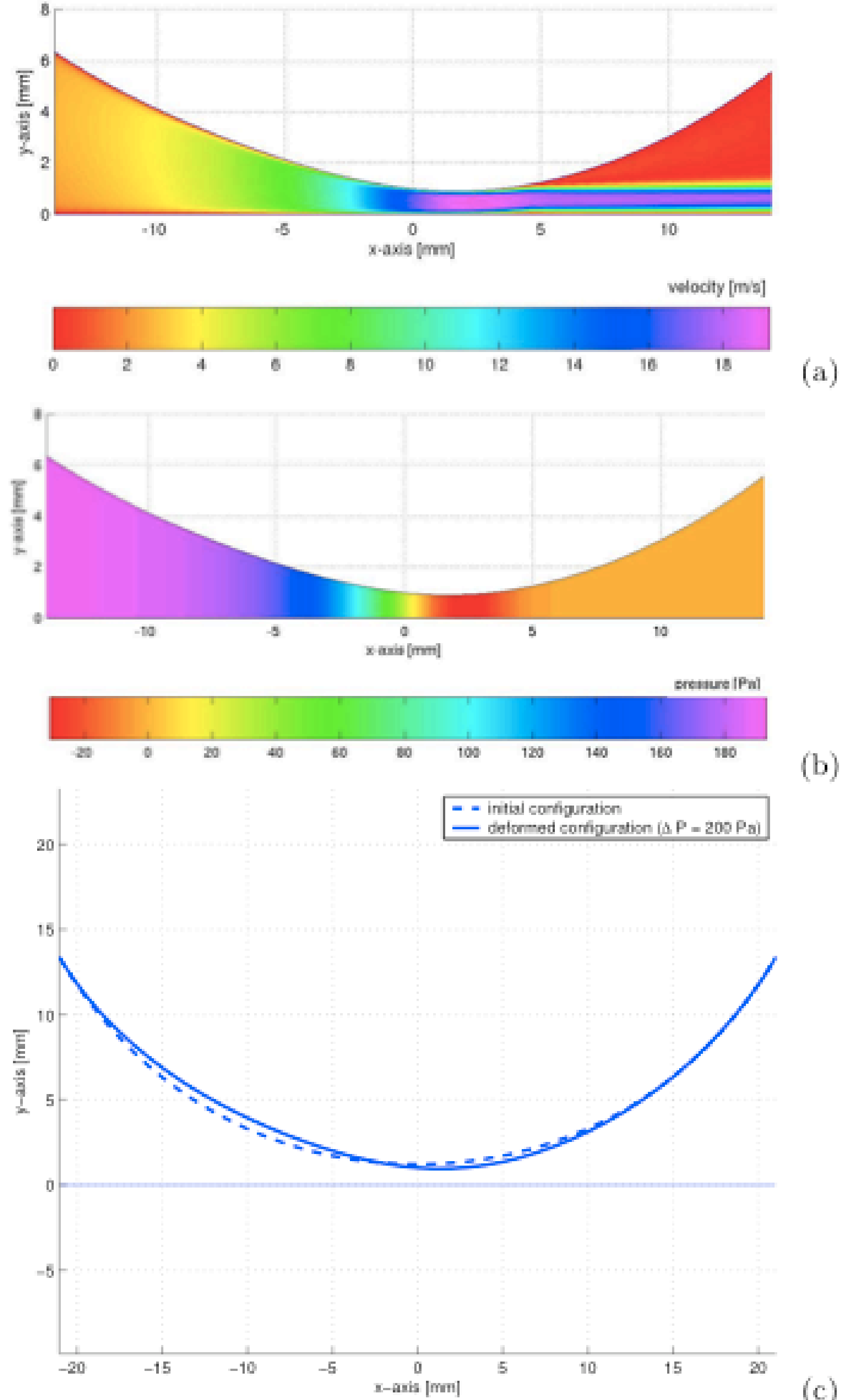



rigid or latex+water
D
flow
d
hc
y

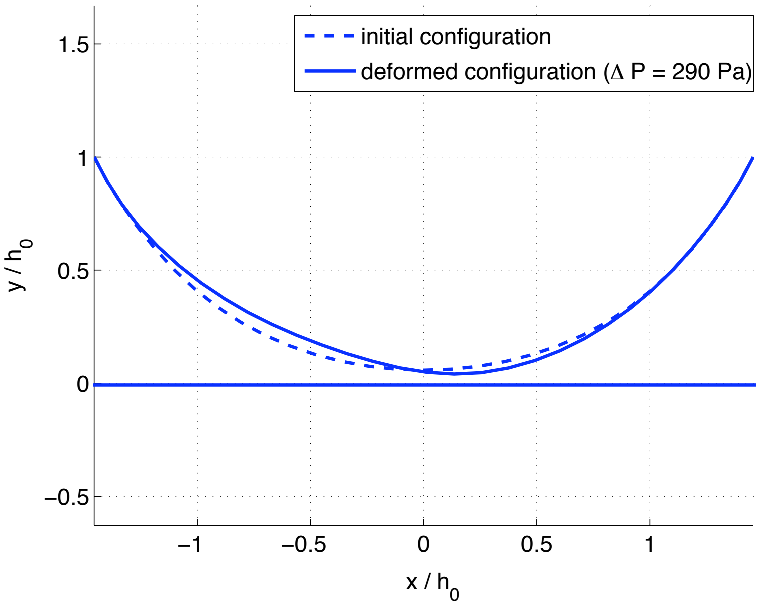

Prediction (RNSP)
Prediction (Bernoulli 1.2)
Mesures (capteurs du haut)
Mesures (capteurs du bas)
P(x) [Pa]
x [mm]
800
600
400
200
0
−200
−400
−30
−20
−10
0
10
20
30

rigid case

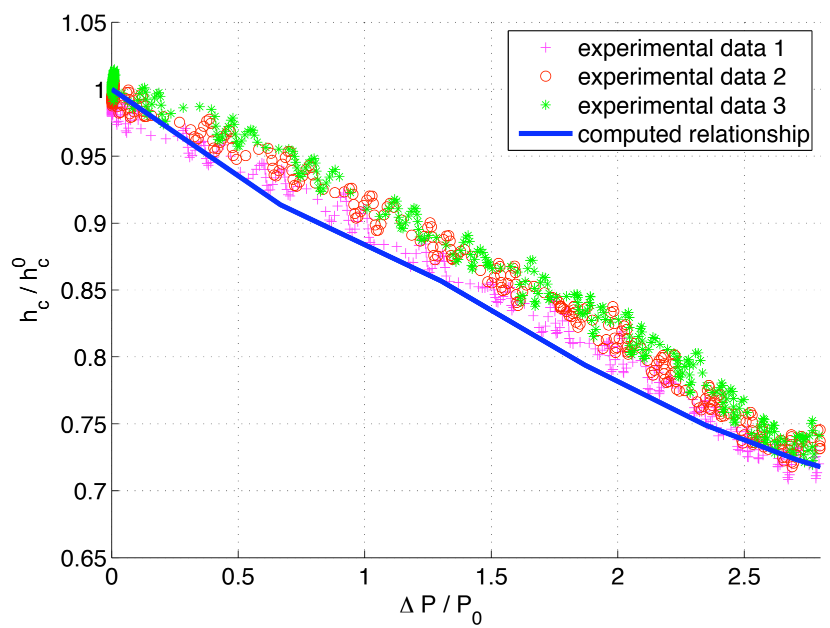
RNSP + Ansys

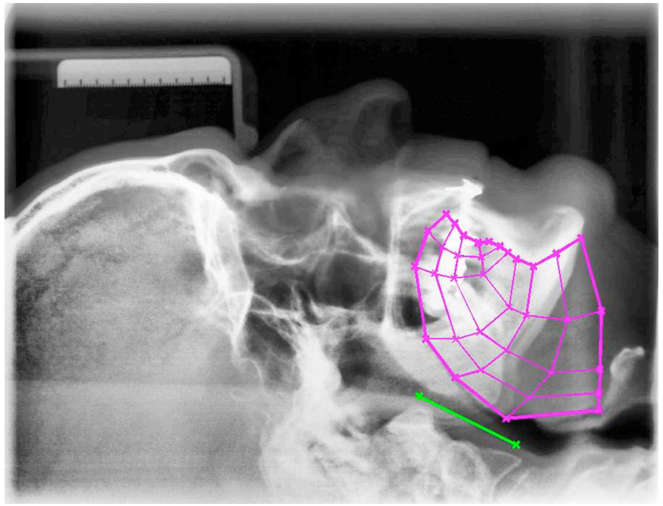


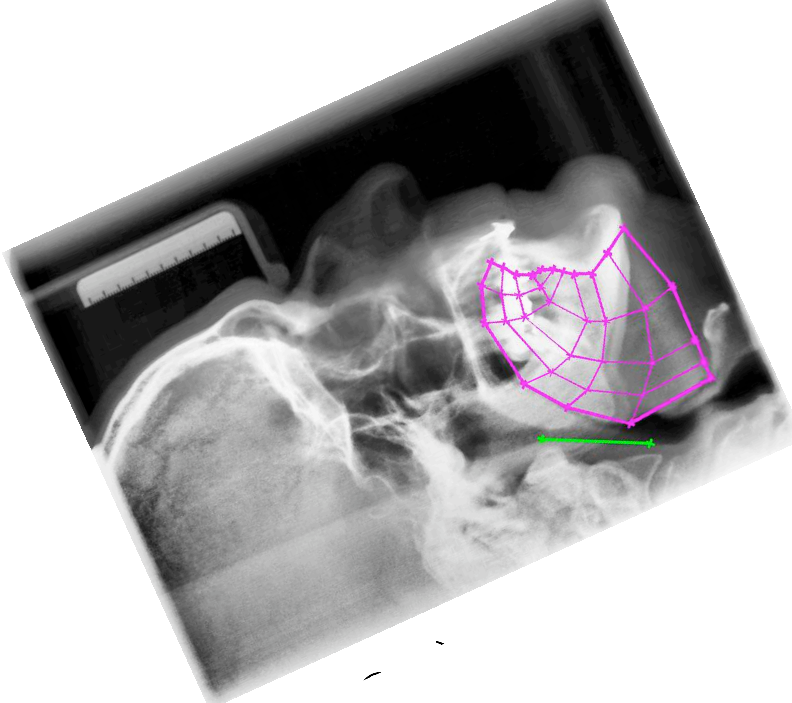
elastic wall

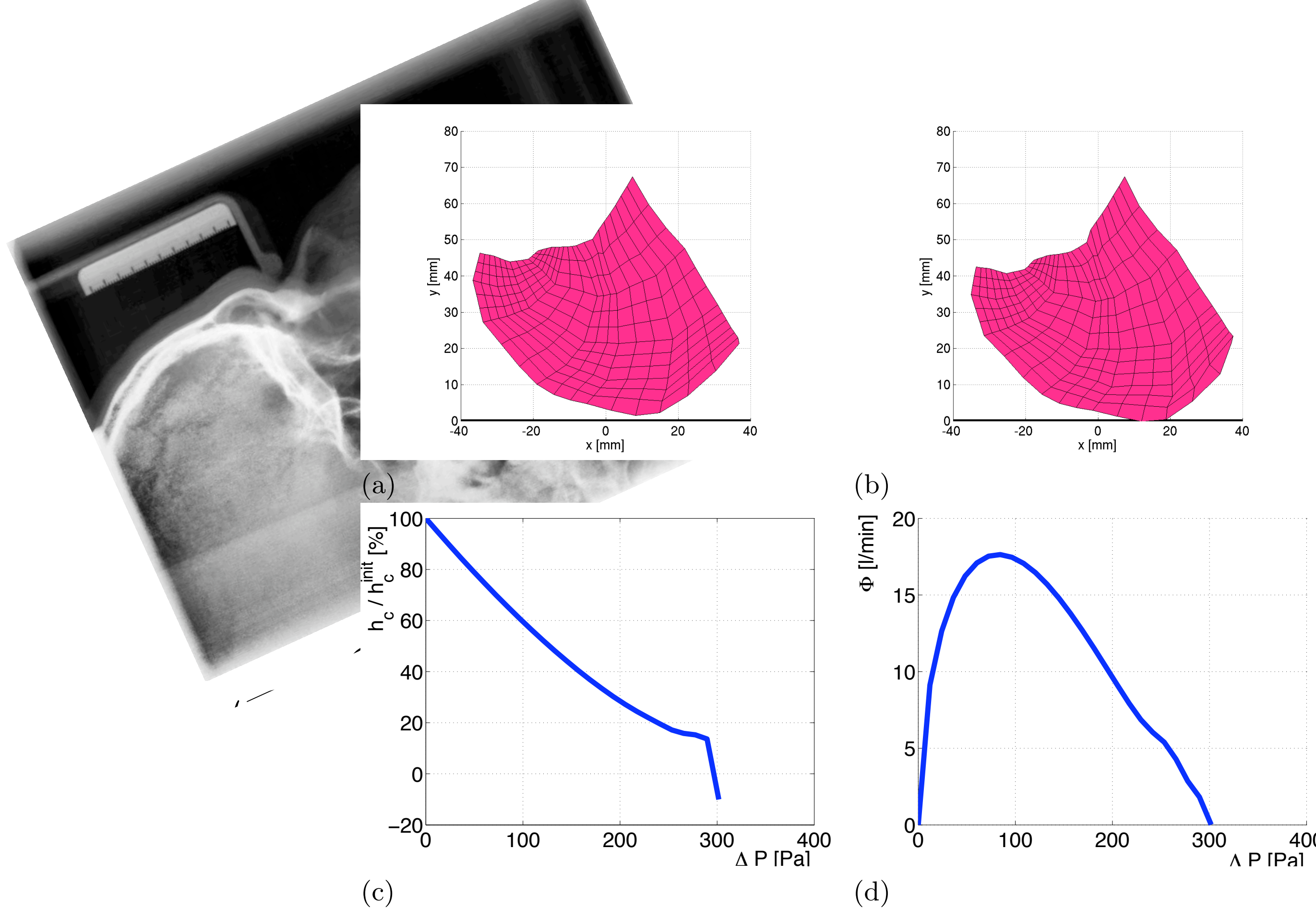


Simulation of a fluid-structure interaction, for $\Delta P = 290\ Pa$, $P_{ext} = 400\ Pa$ and $h_c = 0.87\ mm$.







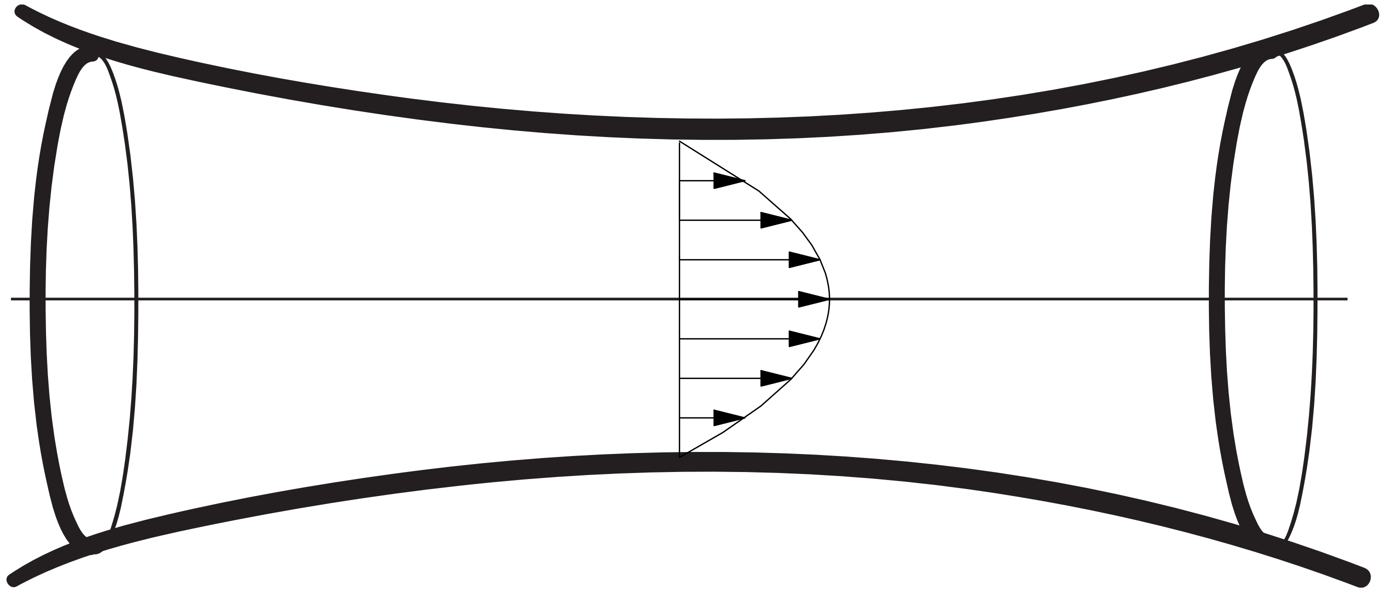


A. Van Hirtum, X. Pelorson & P.-Y. Lagrée (2005):
"In-vitro validation of some flow assumptions for the prediction of the pressure distribution during obstructive sleep apnea",
Medical & biological engineering & computing, no 43(1) pp. 162-171.

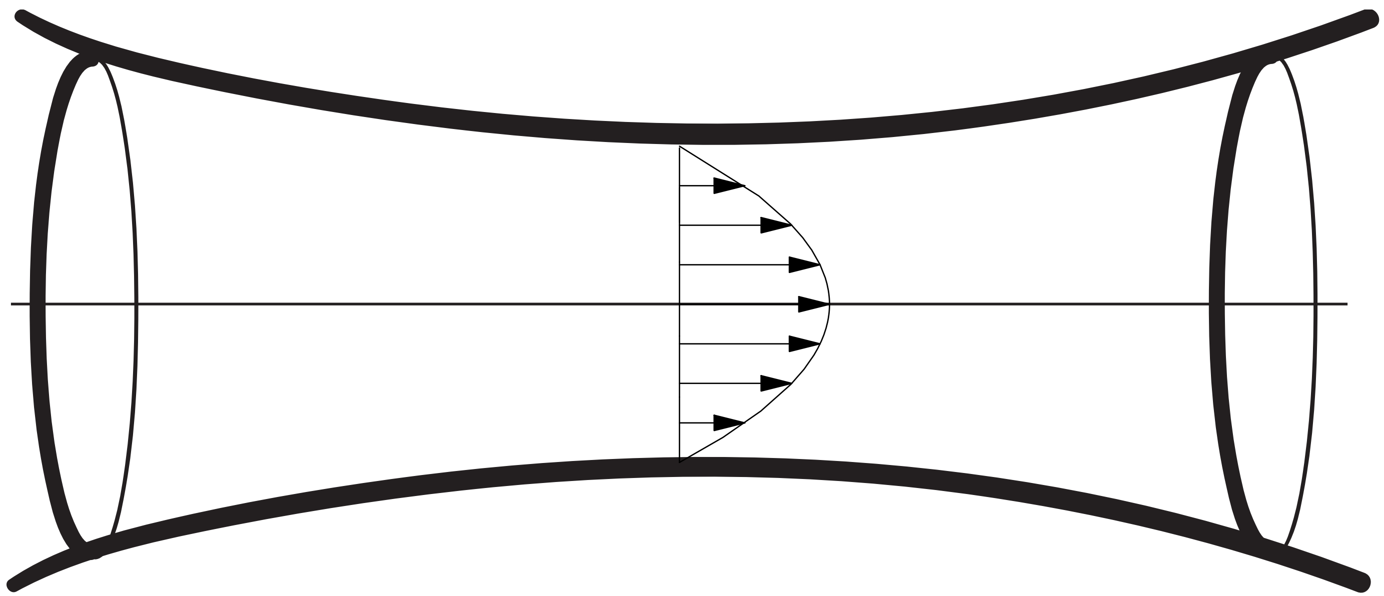
F. Chouly, A. Van Hirtum, X. Pelorson, Y. Payan, and P.-Y. Lagrée:
"An attempt to model Obstructive Sleep Apnea Syndrome: preliminary study" subm.

- 3D? Unsteady...

Integral resolution



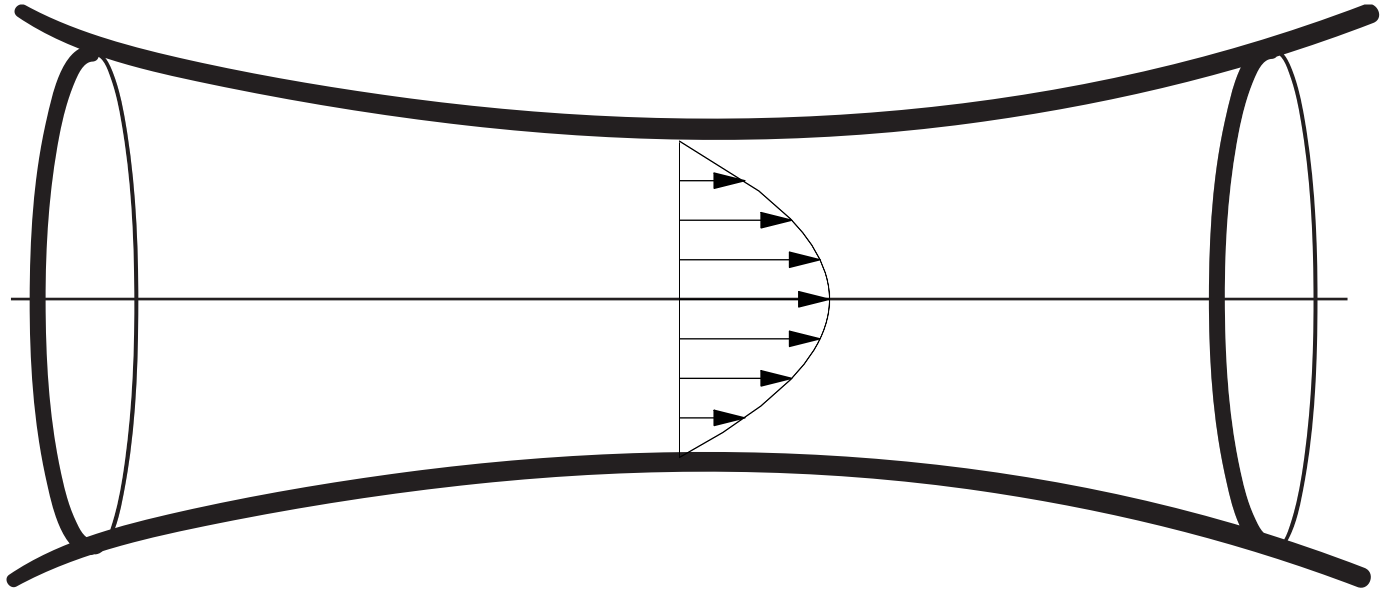
Integral resolution



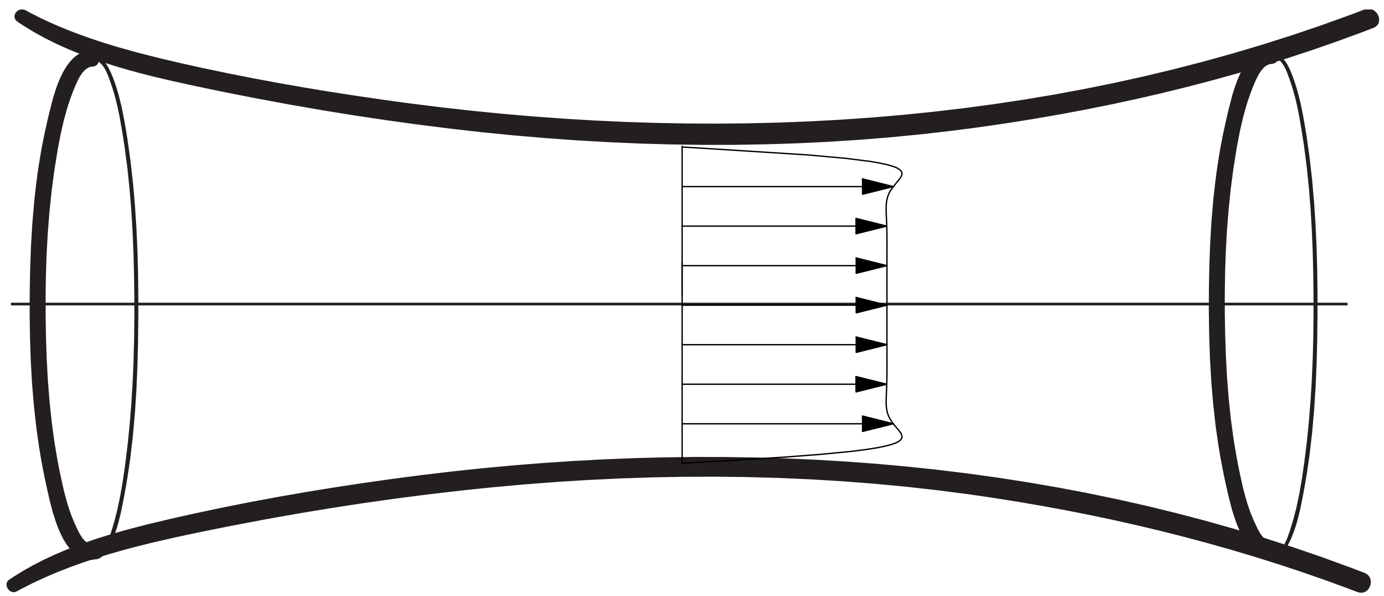
- integral system (1D) is included in RNSP

- we compute a more real profile

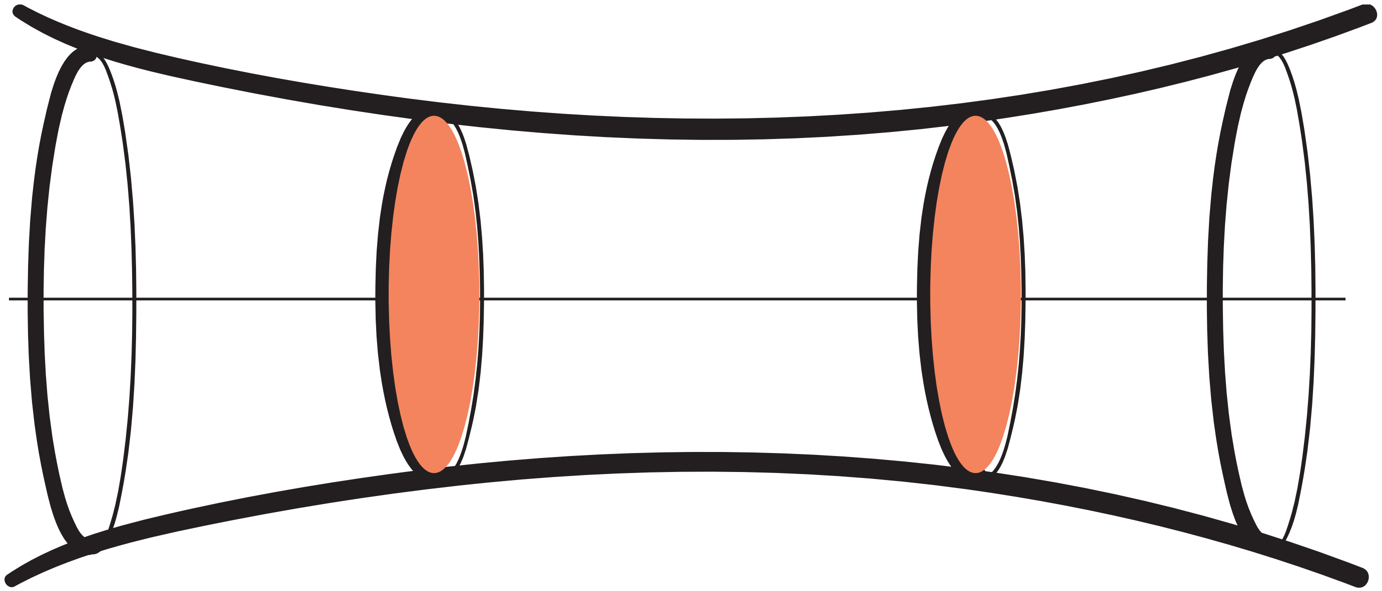
Integral resolution



Integral resolution

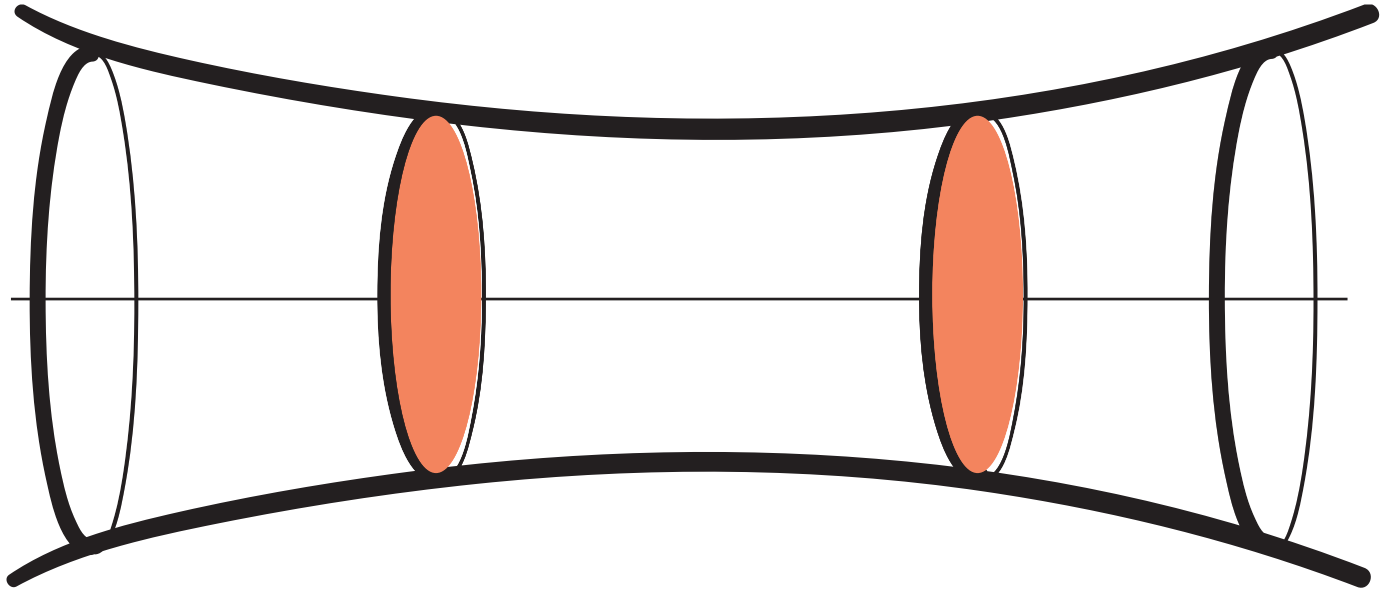


Integral resolution



$$Q = \int_0^R 2\pi r u dr$$

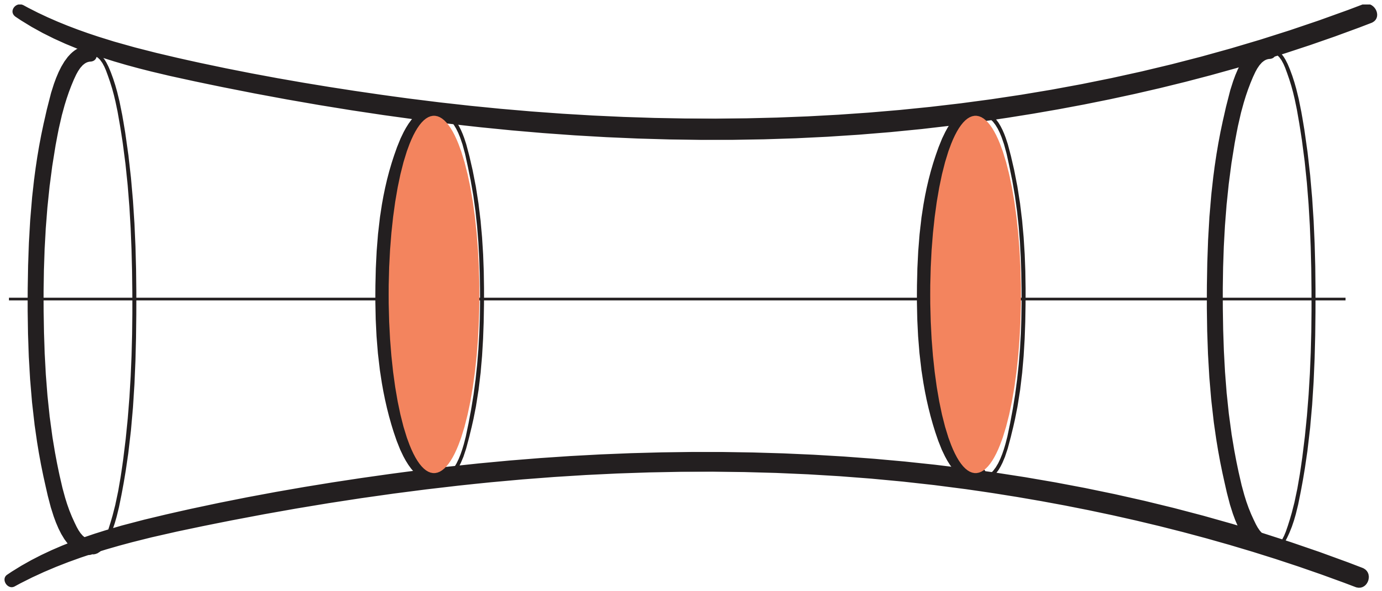
Integral resolution



$$Q = \int_0^R 2\pi r u dr$$

$$\frac{\partial u}{\partial x} + \frac{\partial r v}{r \partial r} = 0$$

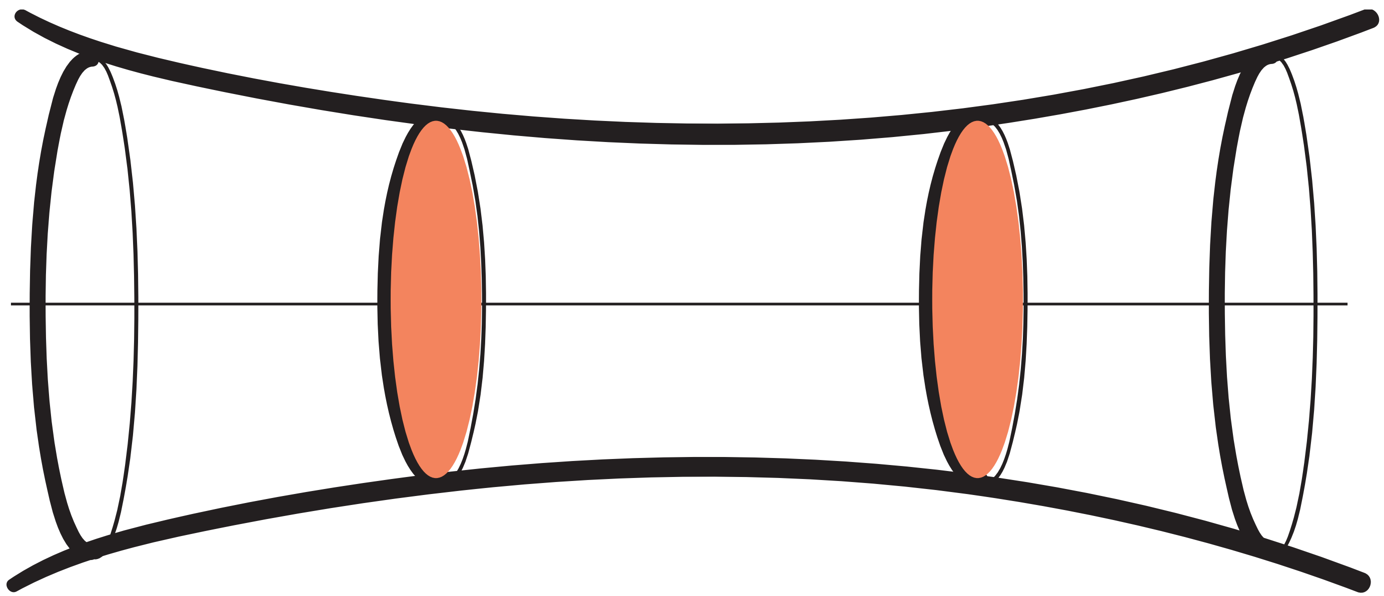
Integral resolution



$$Q = \int_0^R 2\pi r u dr$$

$$\int_0^R 2\pi r dr \cdot \left(\frac{\partial u}{\partial x} + \frac{\partial r v}{r \partial r} \right) = 0$$

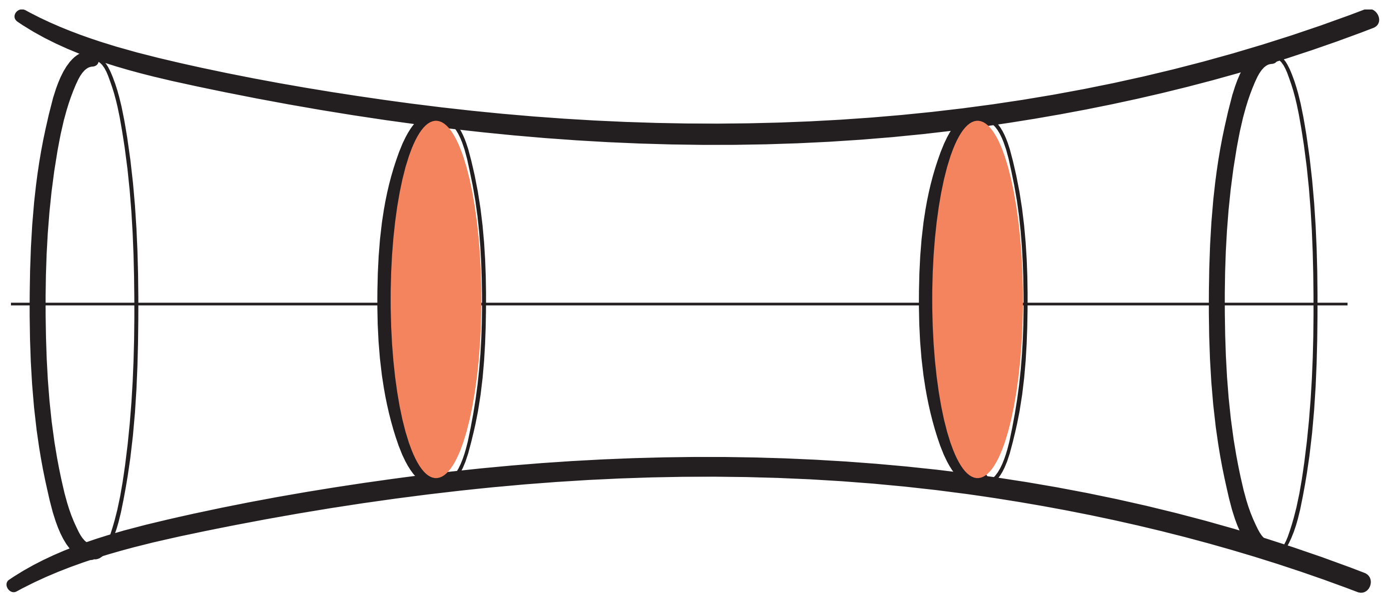
Integral resolution



$$Q = \int_0^R 2\pi r u dr$$

$$\int_0^R 2\pi r dr \cdot \left(\frac{\partial u}{\partial x} + \frac{\partial r v}{r \partial r} \right) = 0 \longrightarrow \frac{\partial (2\pi R^2)}{\partial t} + \frac{\partial Q}{\partial x} = 0$$

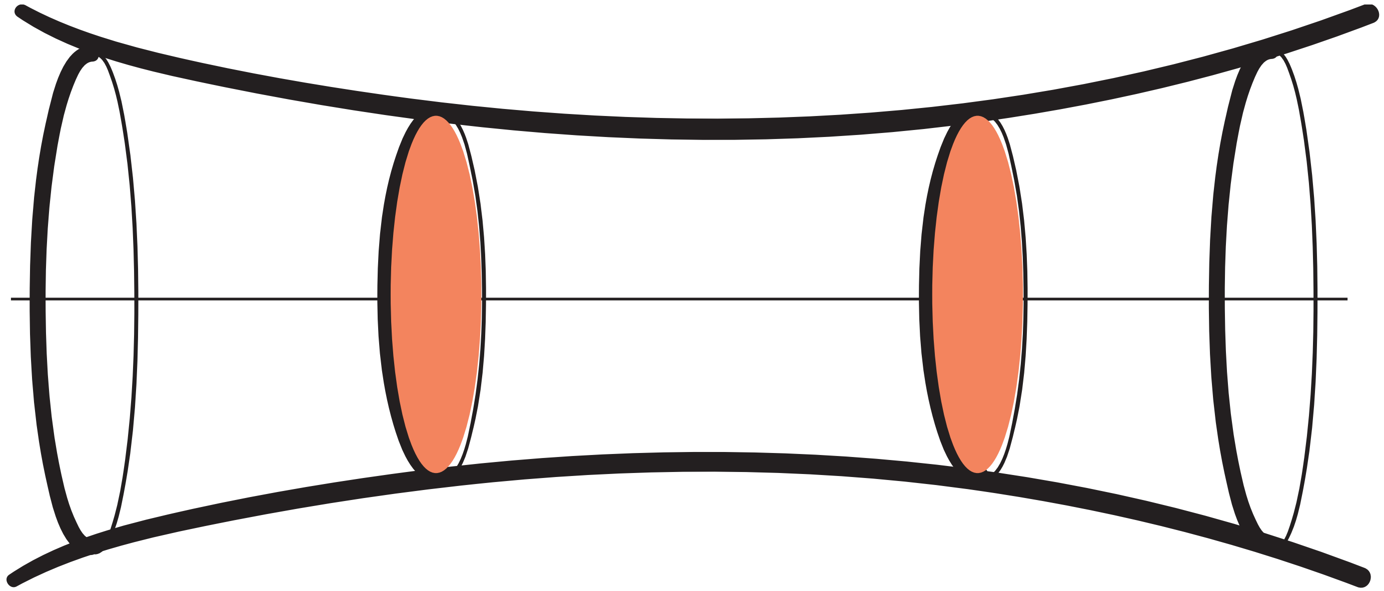
Integral resolution



$$Q = \int_0^R 2\pi r u dr$$

$$\frac{\partial(2\pi R^2)}{\partial t} + \frac{\partial Q}{\partial x} = 0$$

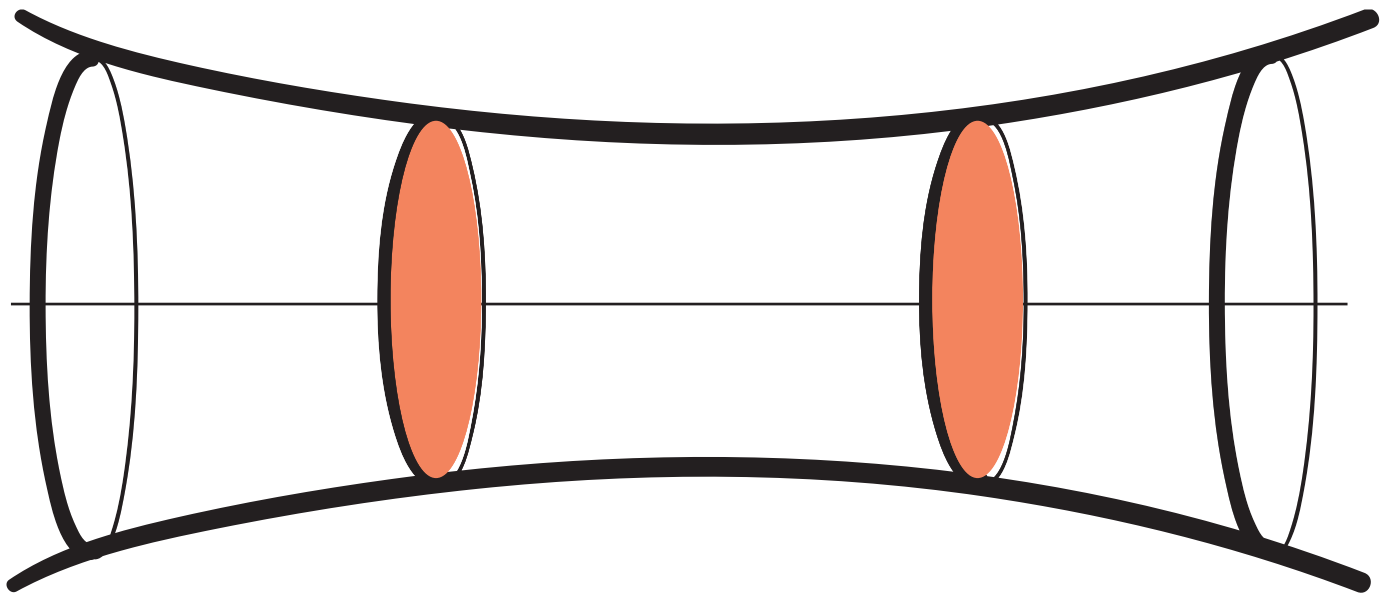
Integral resolution



$$Q = \int_0^R 2\pi r u dr$$

$$\tau = \frac{\partial u}{\partial r}$$

Integral resolution

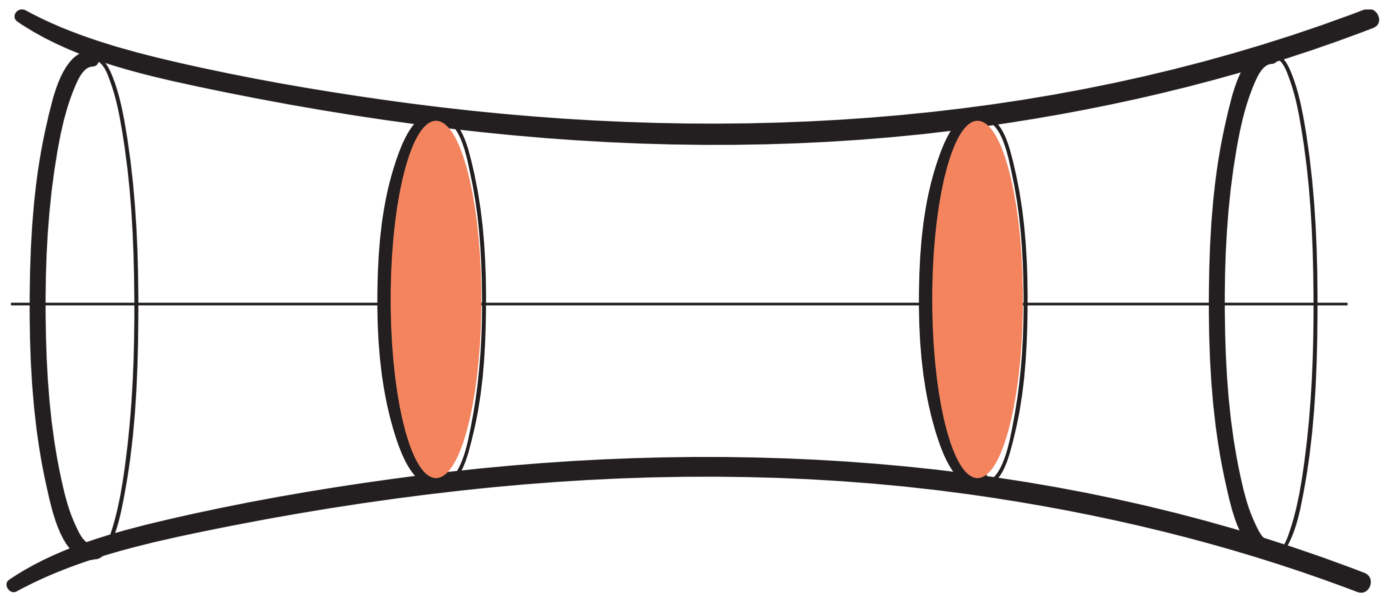


$$Q = \int_0^R 2\pi r u dr \qquad Q_2 = \int_0^R 2\pi r u^2 dr \qquad \tau = \frac{\partial u}{\partial r}$$

$$\int \left(\frac{\partial u}{\partial t} + u\frac{\partial}{\partial x}u + v\frac{\partial}{\partial r}u = -\frac{\partial p}{\rho \partial x} + \nu \frac{\partial}{r\partial r} r \frac{\partial u}{\partial r} \right)$$

$$0 = -\frac{\partial p}{\rho \partial r}$$

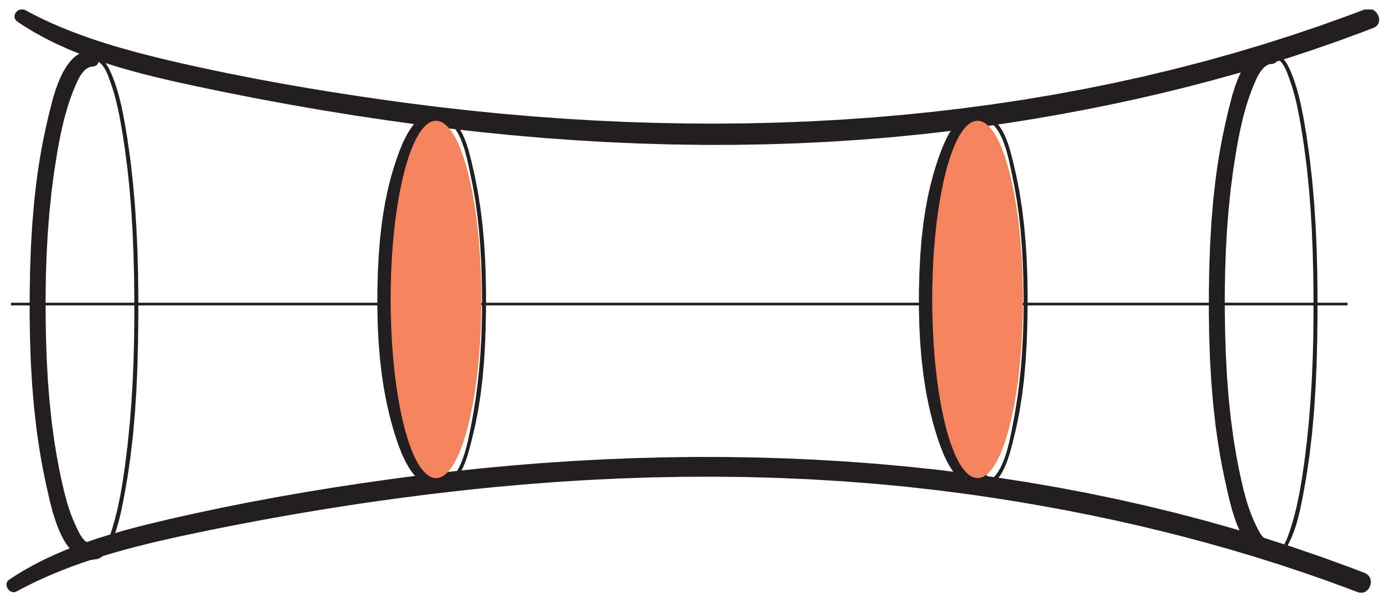
Integral resolution



$$Q = \int_0^R 2\pi r u dr \qquad Q_2 = \int_0^R 2\pi r u^2 dr \qquad \tau = \frac{\partial u}{\partial r}$$

$$\frac{\partial Q}{\partial t} + \frac{\partial Q_2}{\partial t} = -(2\pi R^2)\frac{\partial p}{\partial x} - \tau$$

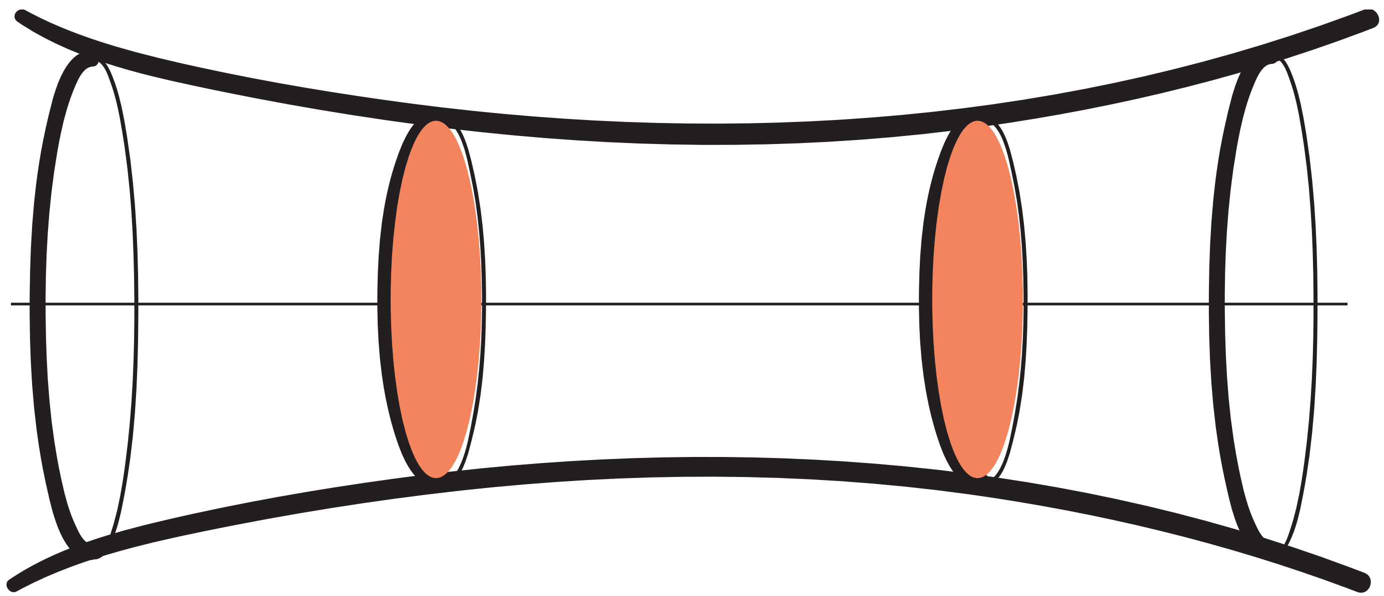
Integral resolution 1D equations



$$Q = \int_0^R 2\pi r u \, dr \qquad Q_2 = \int_0^R 2\pi r u^2 \, dr \qquad \tau = \frac{\partial u}{\partial r}$$

$$\frac{\partial (2\pi R^2)}{\partial t} + \frac{\partial Q}{\partial x} = 0 \qquad \frac{\partial Q}{\partial t} + \frac{\partial Q_2}{\partial t} = -(2\pi R^2)\frac{\partial p}{\partial x} - \tau$$

Integral resolution 1D equations

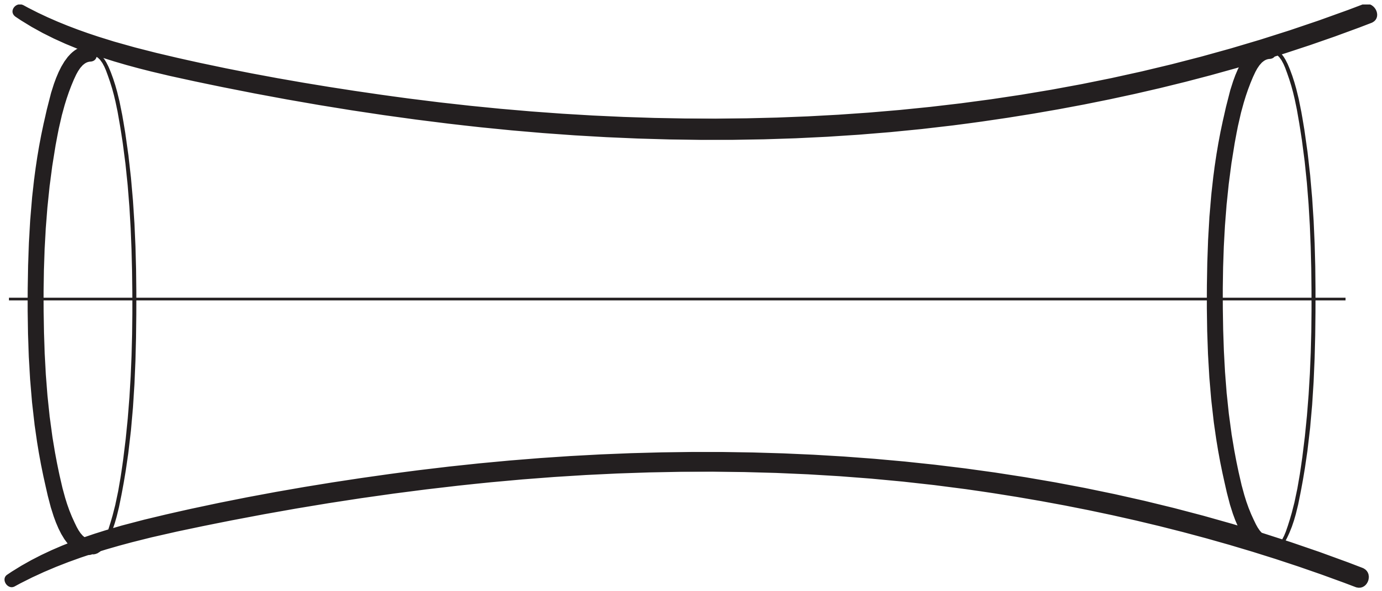


$$Q = \int_0^R 2\pi r u dr \qquad Q_2 = \int_0^R 2\pi r u^2 dr \qquad \tau = \frac{\partial u}{\partial r}$$

$$\frac{\partial (2\pi R^2)}{\partial t} + \frac{\partial Q}{\partial x} = 0 \qquad \frac{\partial Q}{\partial t} + \frac{\partial Q_2}{\partial t} = -(2\pi R^2)\frac{\partial p}{\partial x} - \tau$$

relation between pressure and Radius $p = k(R - R_0)$

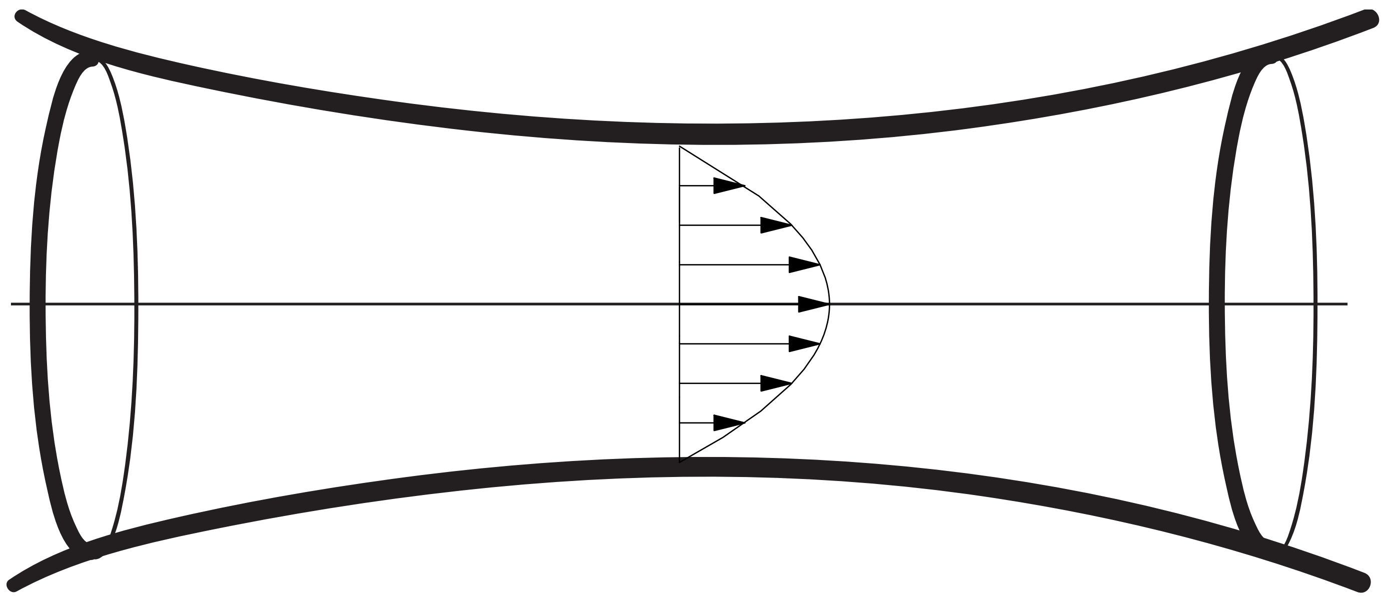
Integral resolution 1D equations



$$Q = \int_0^R 2\pi r u dr \qquad Q_2 = \int_0^R 2\pi r u^2 dr \qquad \tau = \frac{\partial u}{\partial r}$$

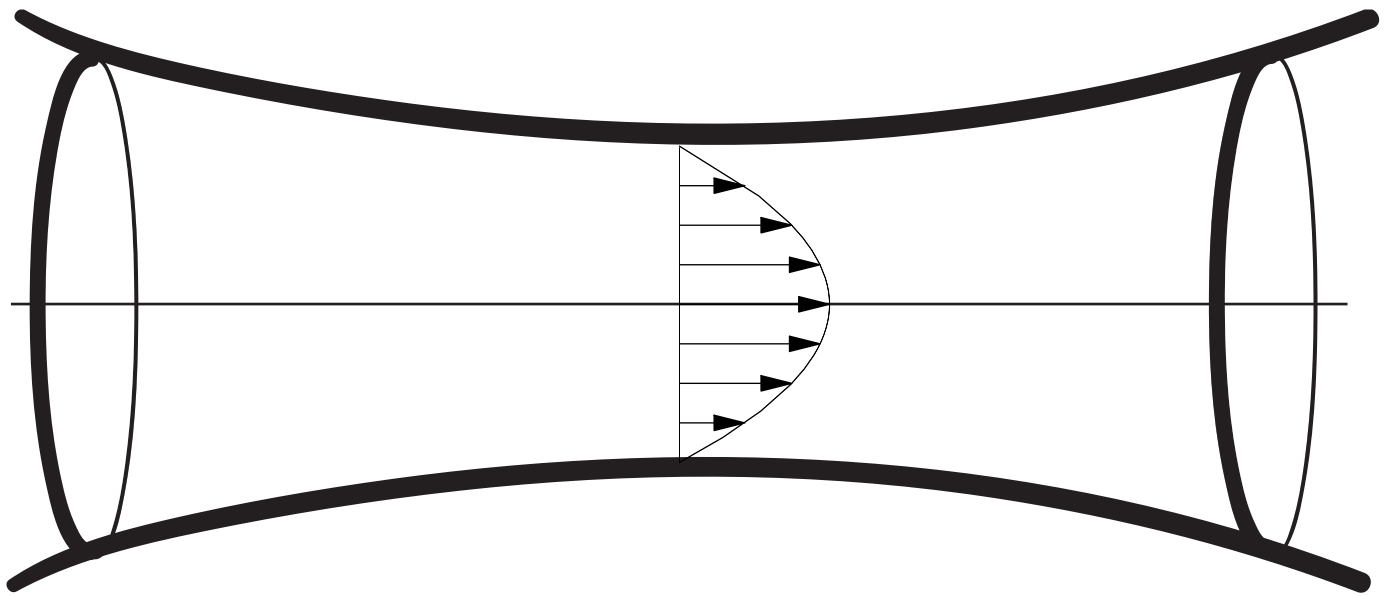
gives Q_2 as function of Q an τ as function Q

Integral resolution 1D equations



$$Q_2 = \int_0^R 2\pi r u^2 dr \qquad \tau = \frac{\partial u}{\partial r}$$

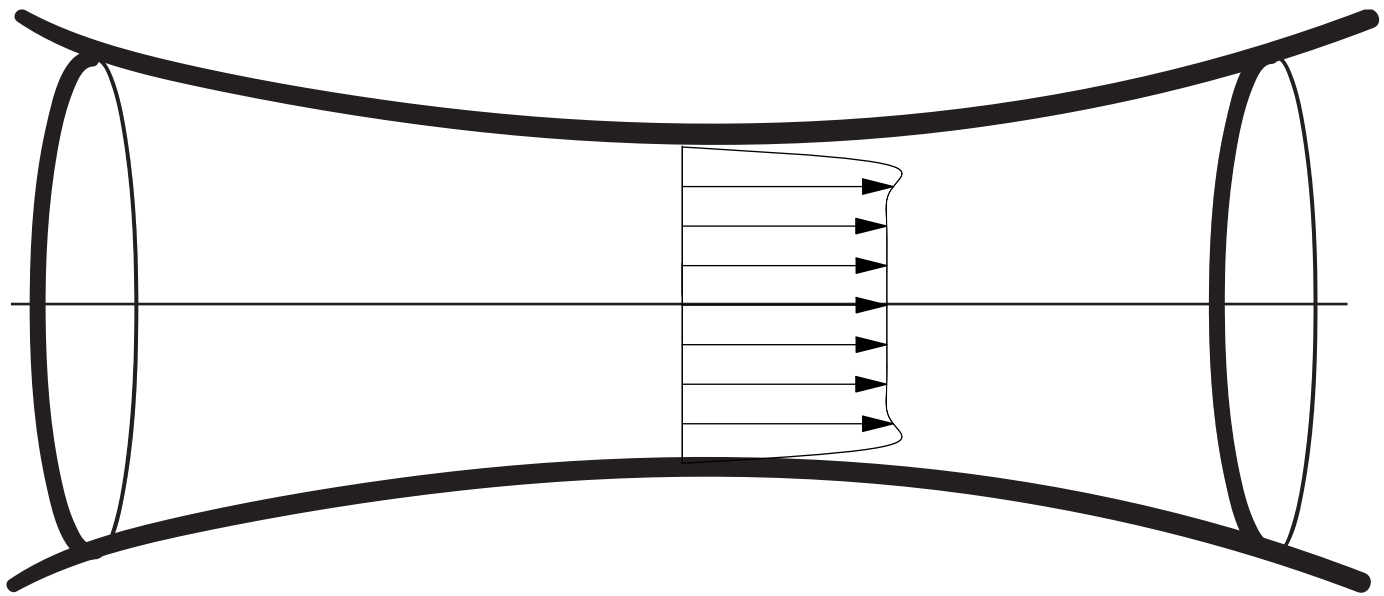
Integral resolution 1D equations



$$Q_2 = \int_0^R 2\pi r u^2 dr \qquad \tau = \frac{\partial u}{\partial r}$$

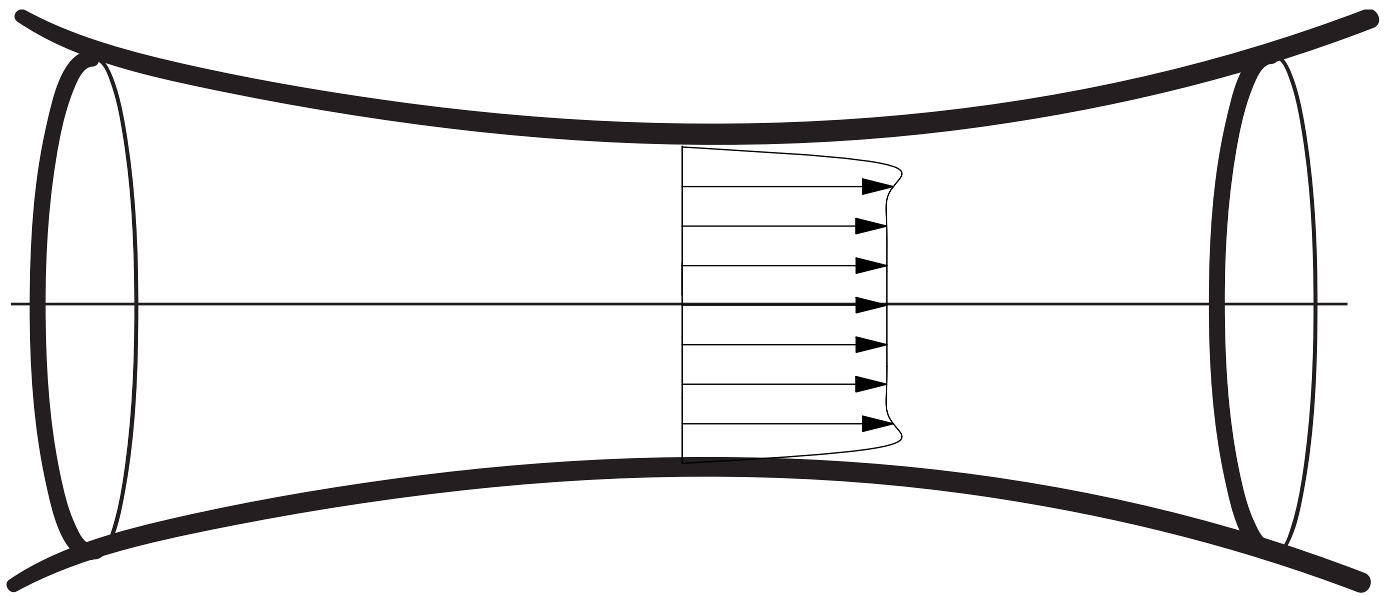
$$Q_2 = (\frac{4}{3})\frac{Q^2}{\pi R^2} \qquad \tau = (8\pi)\frac{Q}{\pi R^2}$$

Integral resolution 1D equations



$$Q_2 = \int_0^R 2\pi r u^2 dr \qquad \tau = \frac{\partial u}{\partial r}$$

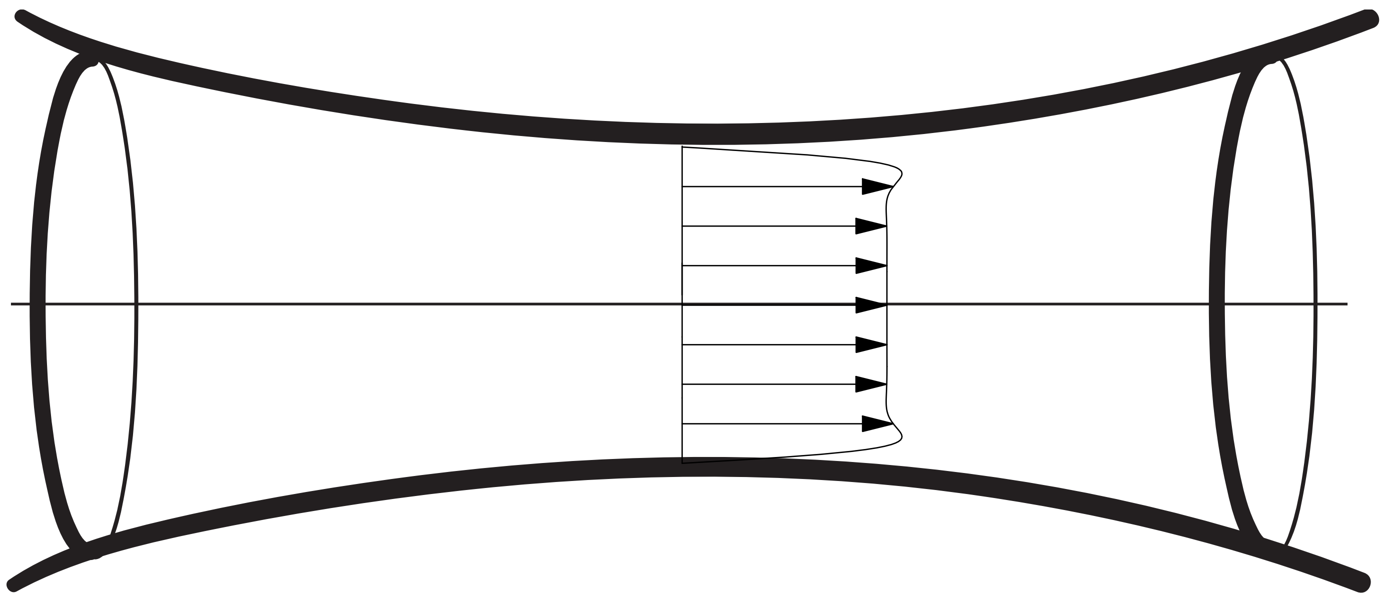
Integral resolution 1D equations



$$Q_2 = \int_0^R 2\pi r u^2 dr \qquad \tau = \frac{\partial u}{\partial r}$$

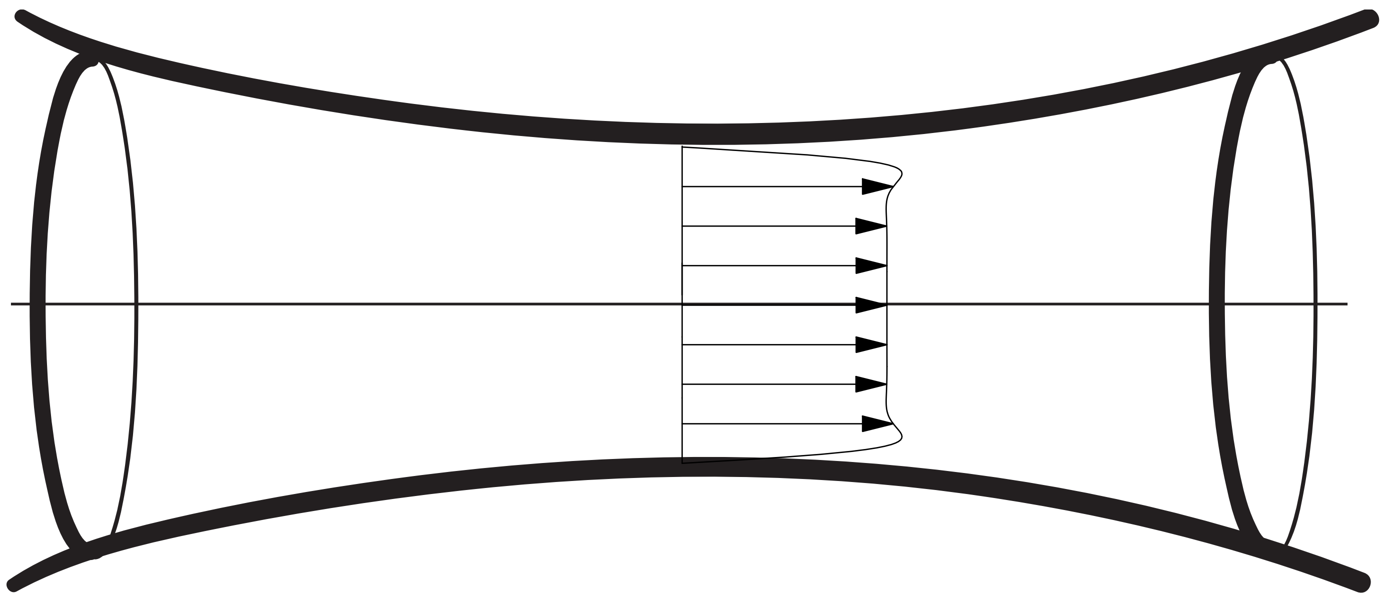
$$Q_2 = \frac{Q^2}{\pi R^2} \qquad \tau = F(Q)$$

Integral resolution 1D equations



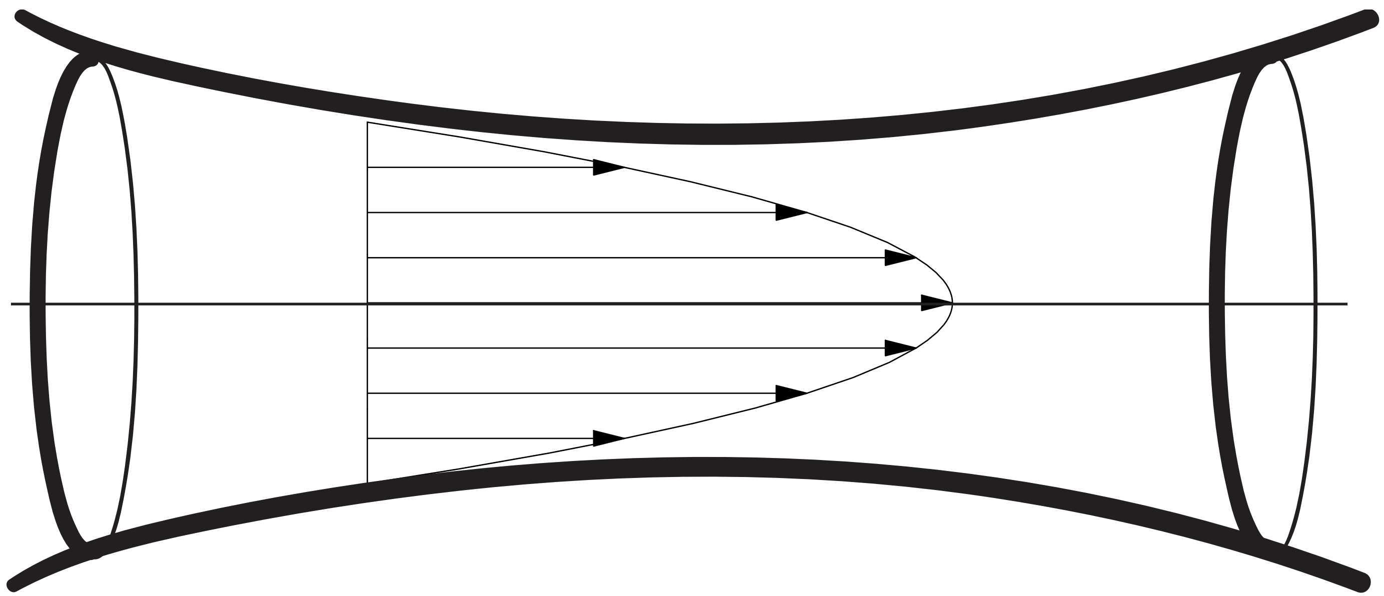
need of profile

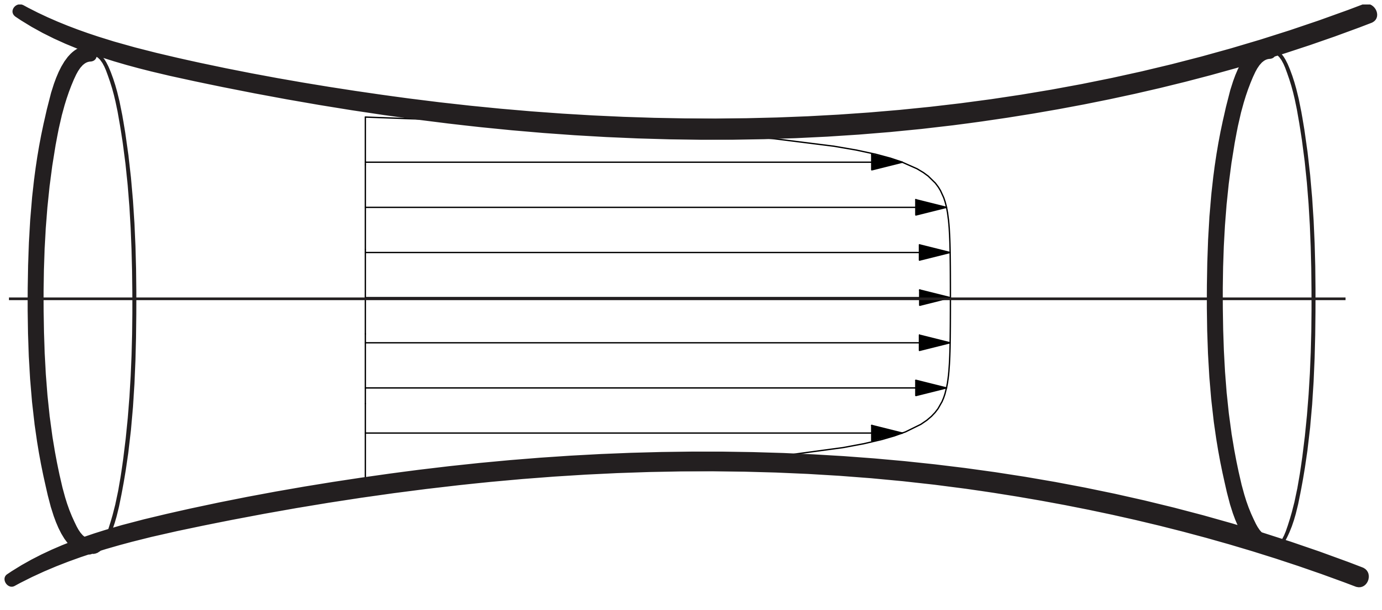
Integral resolution 1D equations

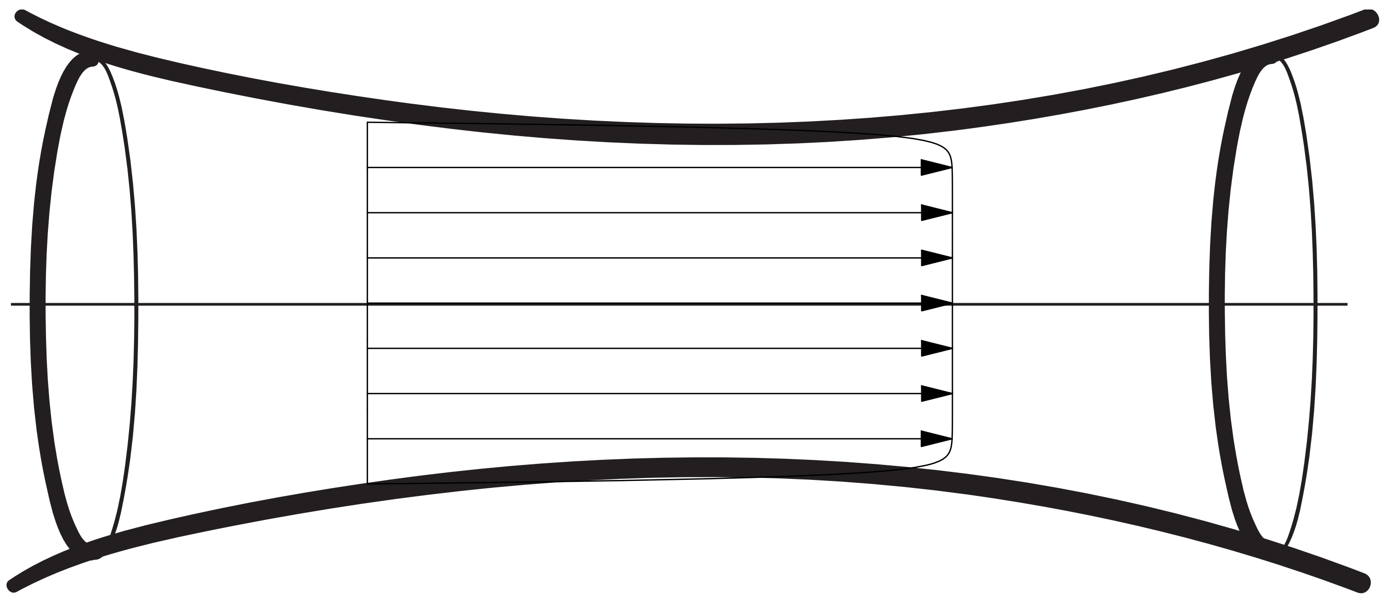


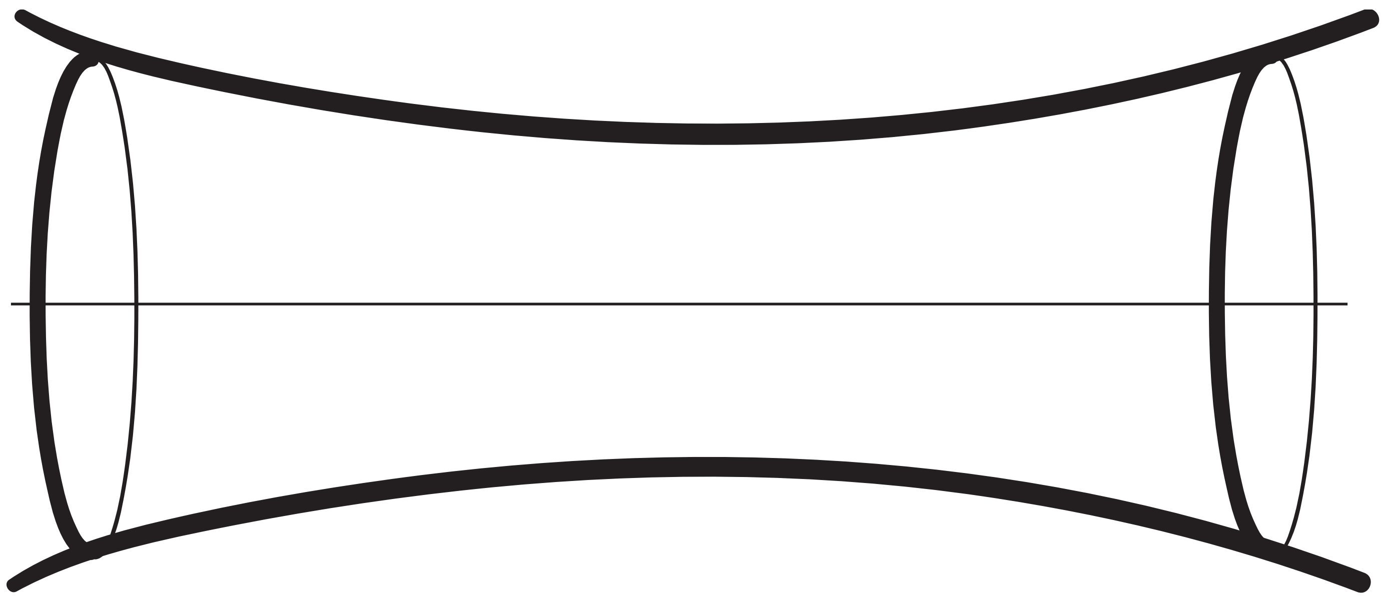
"usual" 1D equations are a simplification of RNSP

Choice of profiles

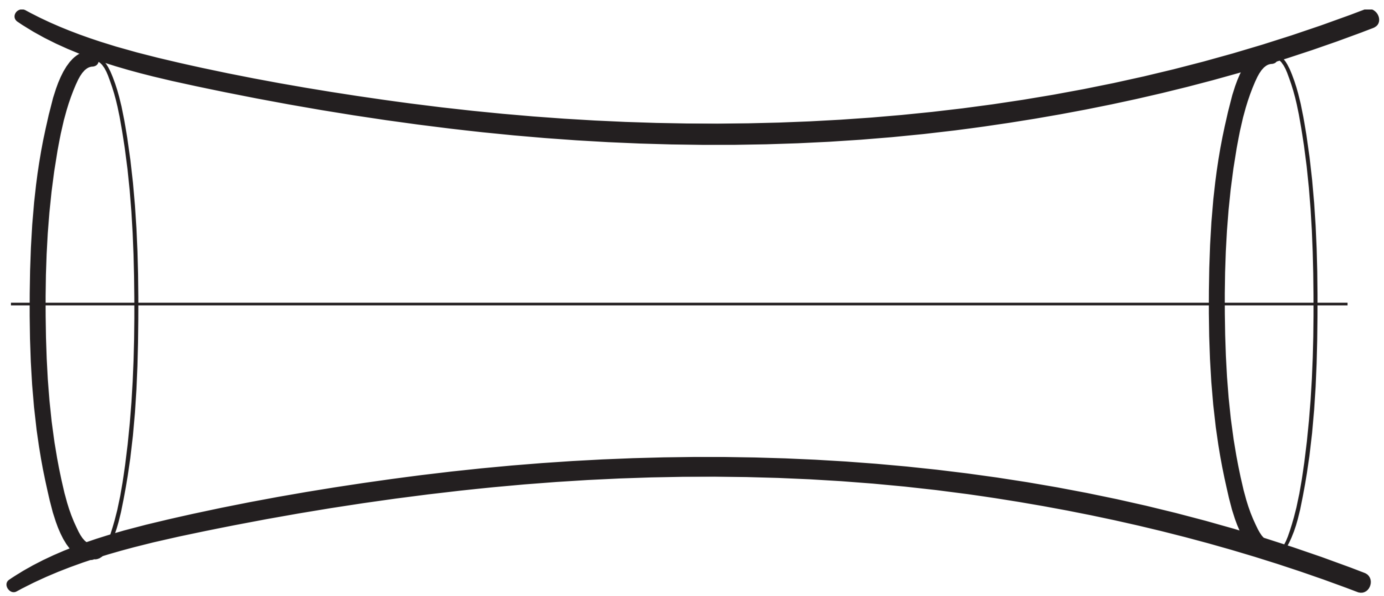








Choice of the family of simple profiles

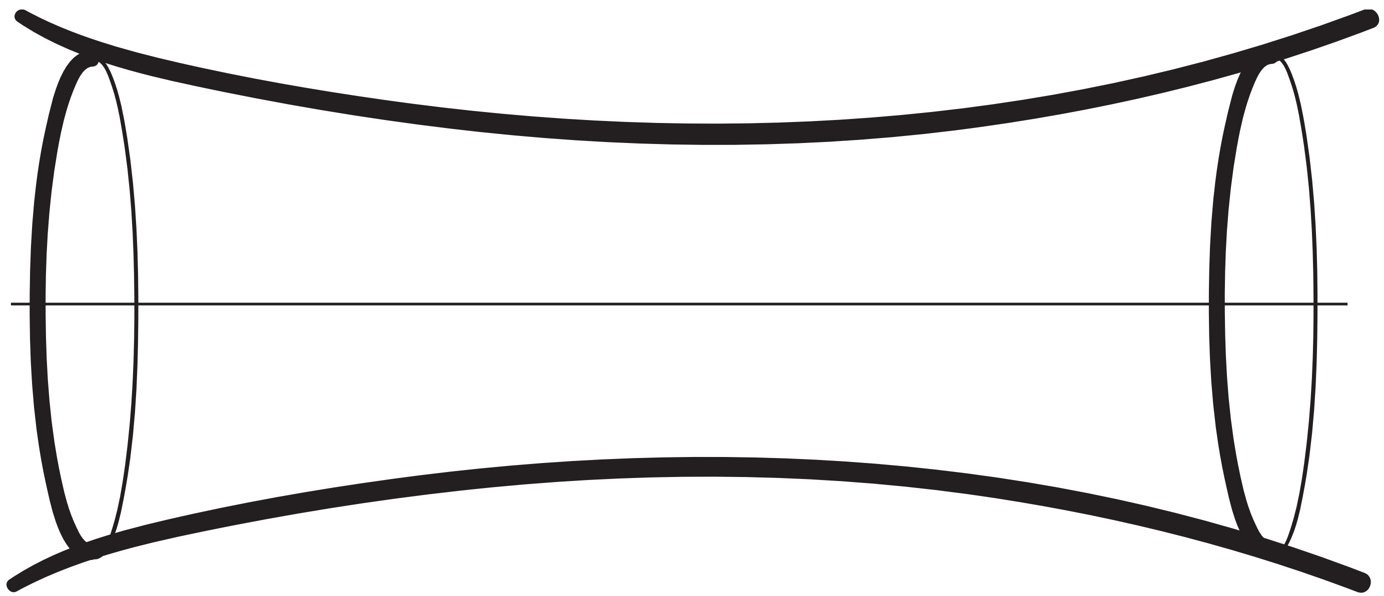


Choice of the family of simple profiles

In an unsteady flow it is natural to use Womersley

$$\frac{\partial u}{\partial t} + u\frac{\partial}{\partial x}u + v\frac{\partial}{\partial r}u = -\frac{\partial p}{\rho\partial x} + \nu\frac{\partial}{r\partial r}r\frac{\partial u}{\partial r}$$

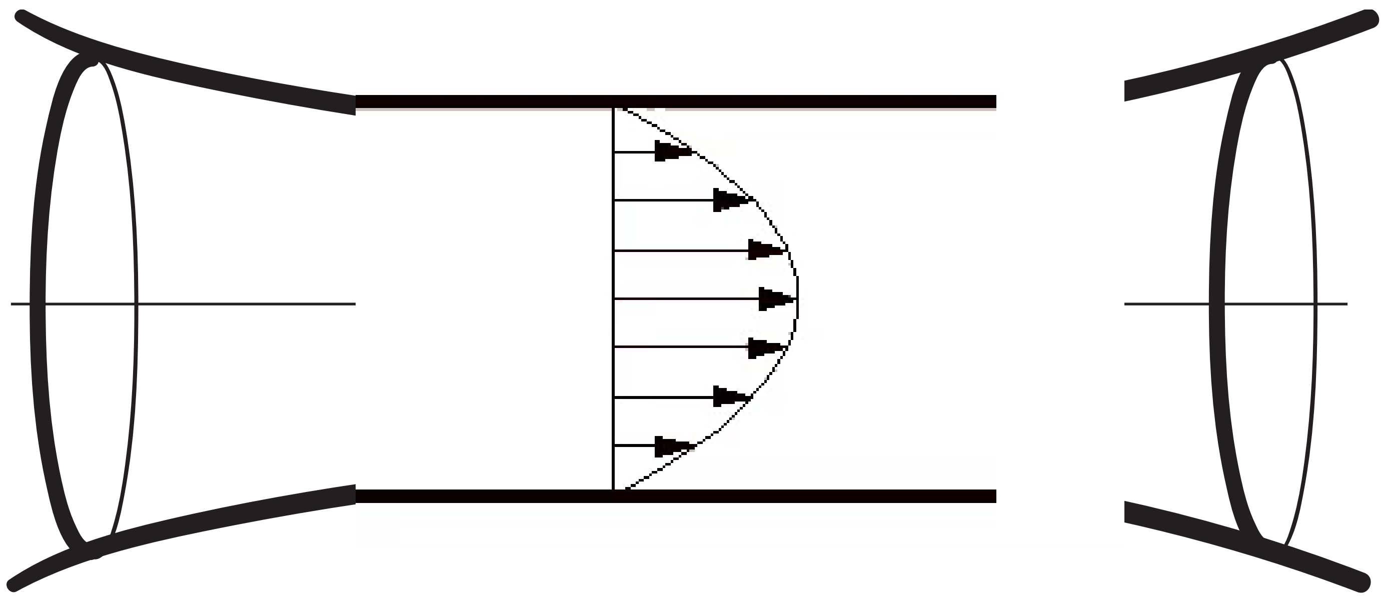
$$0 = -\frac{\partial p}{\rho\partial r}$$



Choice of the family of simple profiles

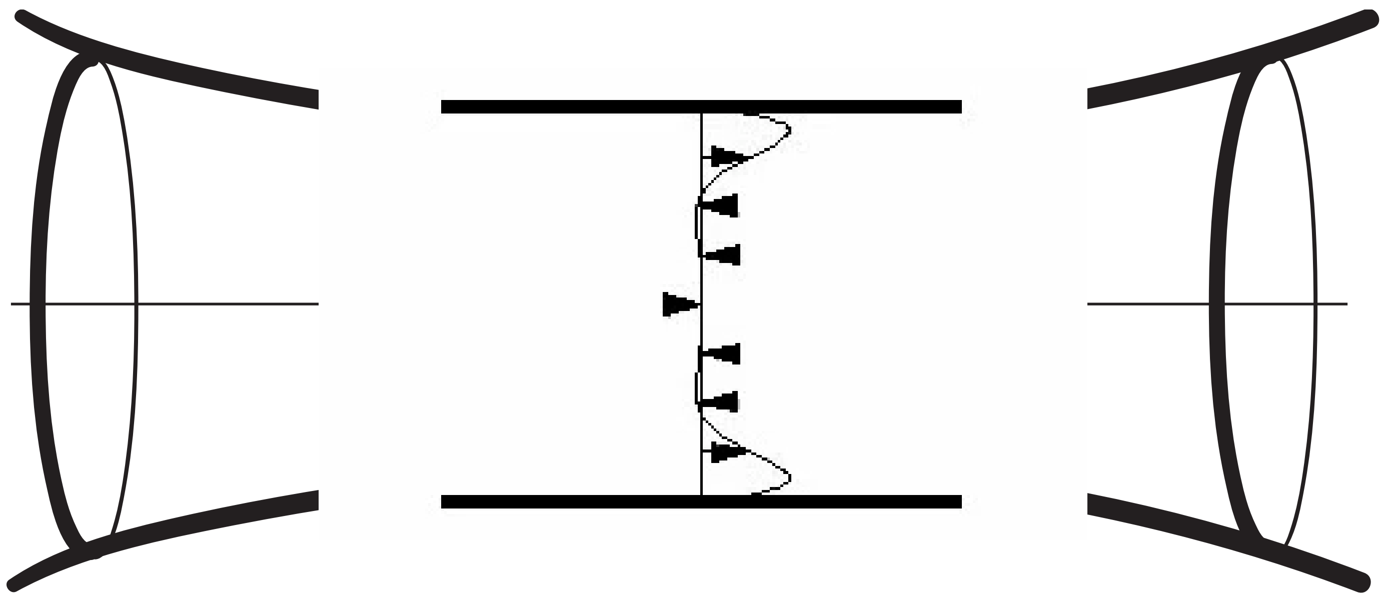
In an unsteady flow it is natural to use Womersley

Womersley profiles are solution of RNSP



Choice of the family of simple profiles

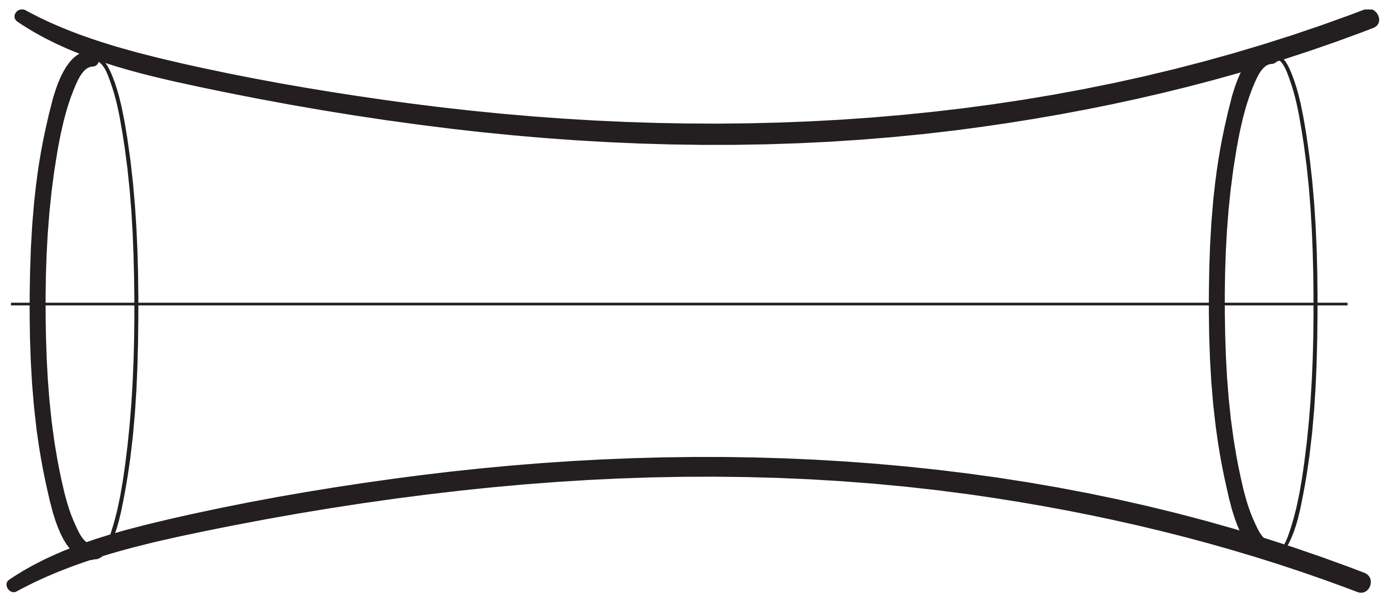
In an unsteady flow it is natural to use Womersley



Choice of the family of simple profiles

In an unsteady flow it is natural to use Womersley

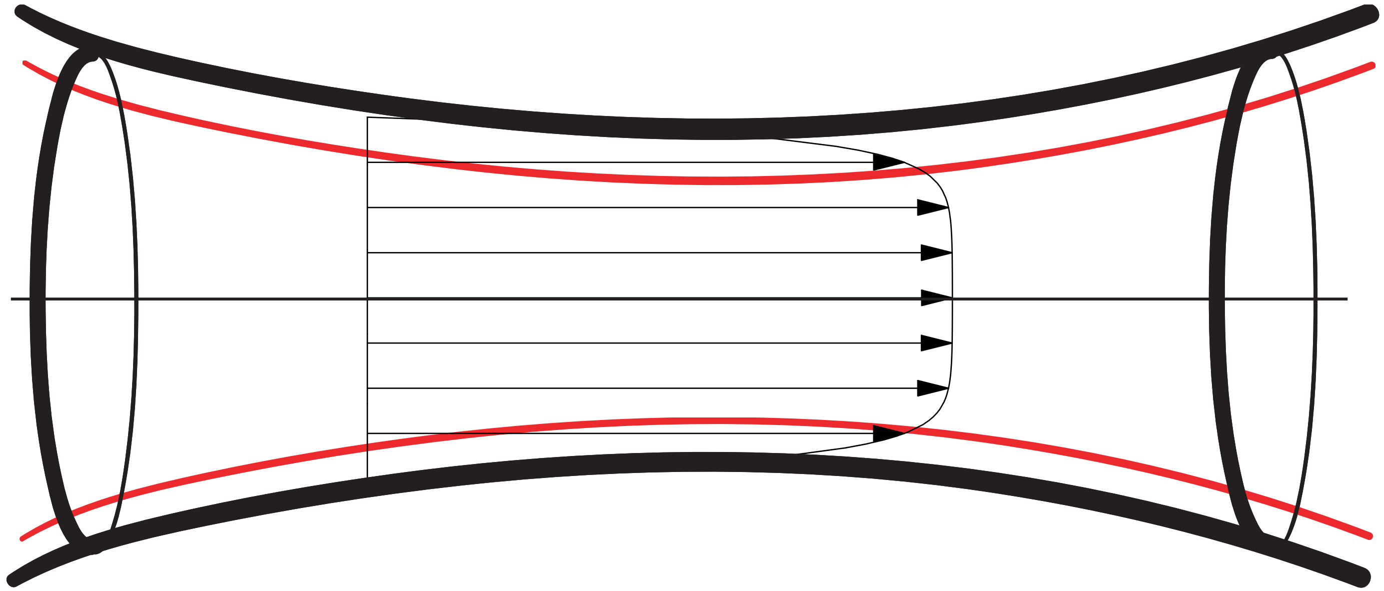
Integral resolution



$$Q = \int_0^R 2\pi r u dr \qquad Q_2 = \int_0^R 2\pi r u^2 dr \qquad \tau = \frac{\partial u}{\partial r}$$

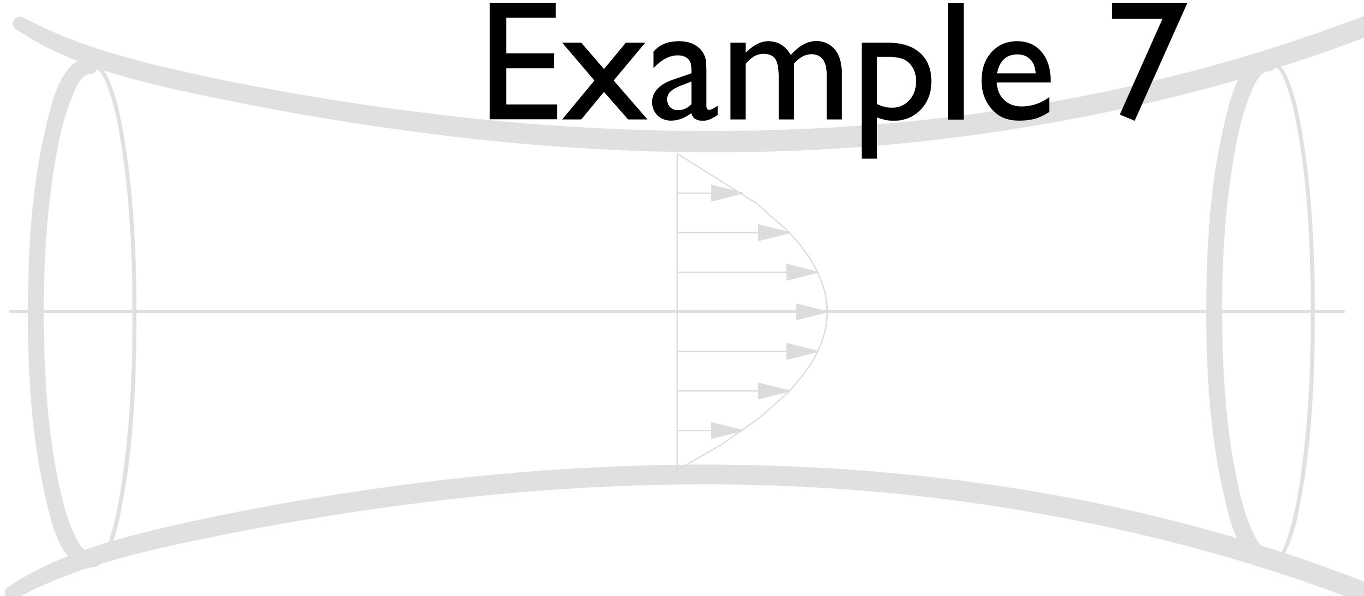
gives Q_2 as function of Q an τ as function Q

Integral resolution

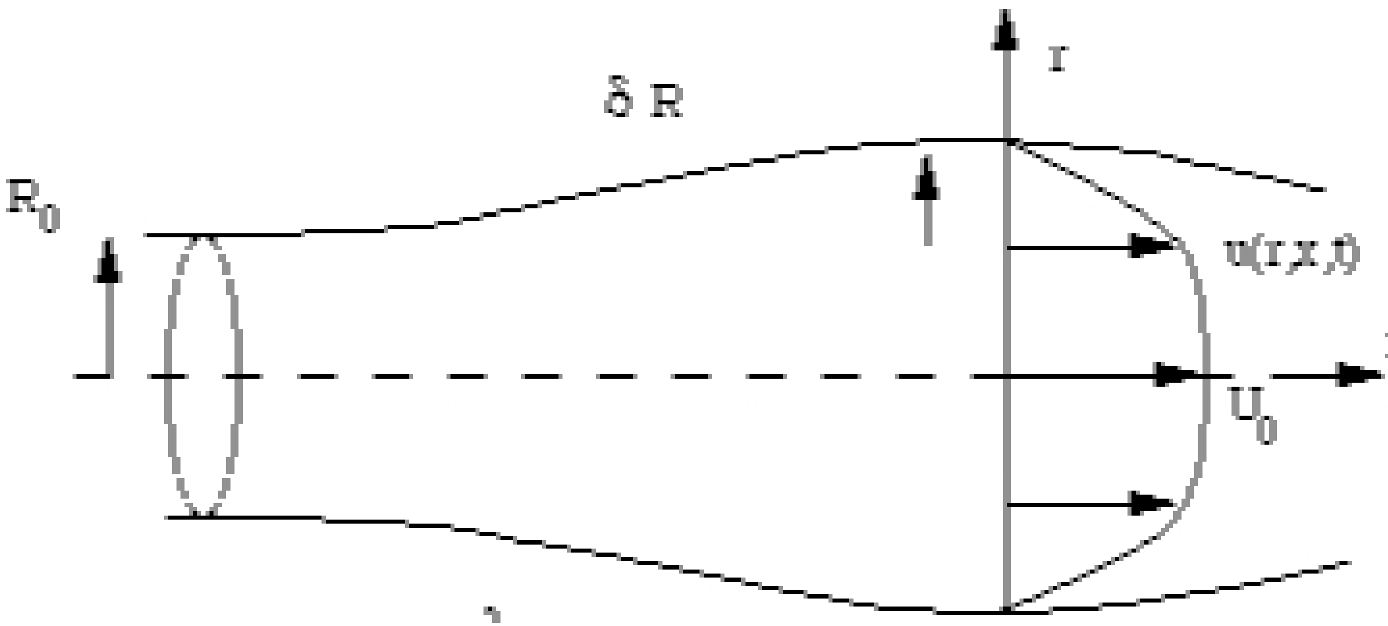


Numerical resolution: finite differences

Example 7



flow in arteries



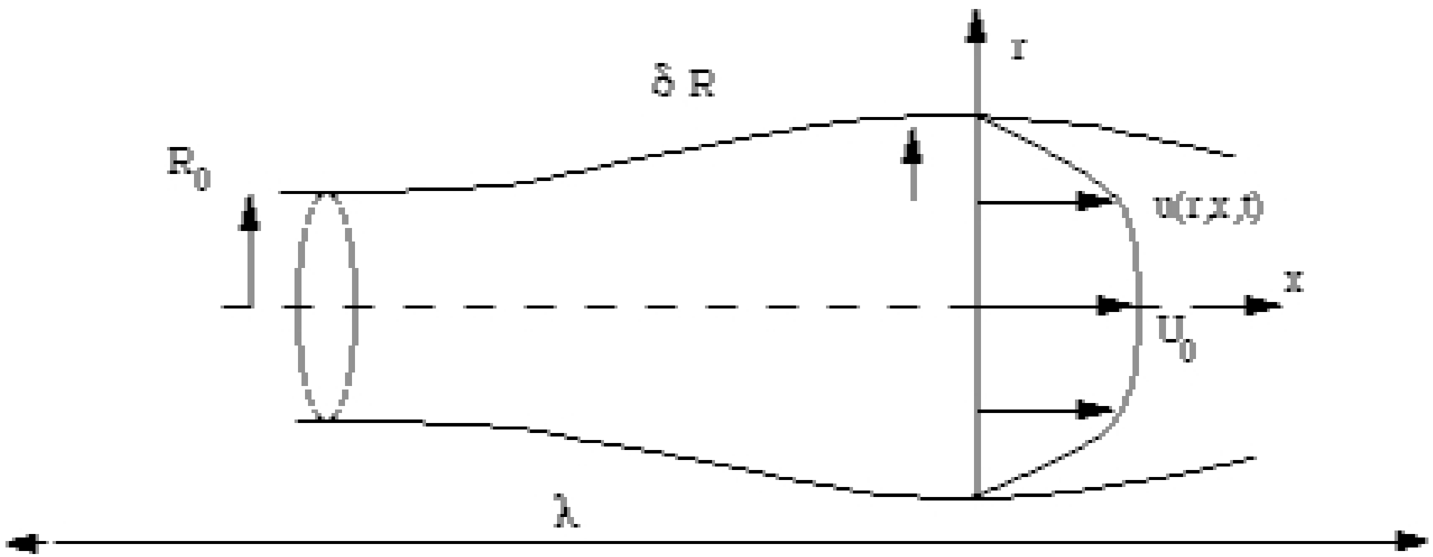
$$\frac{\partial}{\partial x}u + \frac{\partial}{r\partial r}rv = 0,$$

$$\frac{\partial u}{\partial t} + \varepsilon_2(u\frac{\partial}{\partial x}u + v\frac{\partial}{\partial r}u) = -\frac{\partial p}{\partial x} + \frac{2\pi}{\alpha^2}\frac{\partial}{r\partial r}(r\frac{\partial}{\partial r}u), 0 = -\frac{\partial p}{\partial r}.$$

$$\varepsilon_2 = \frac{\delta R}{R_0}, \qquad \alpha = R_0\sqrt{\frac{2\pi/T}{\nu}}$$

introducing wall elasticity: $p(x,t) = k(R(x,t) - R_0)$

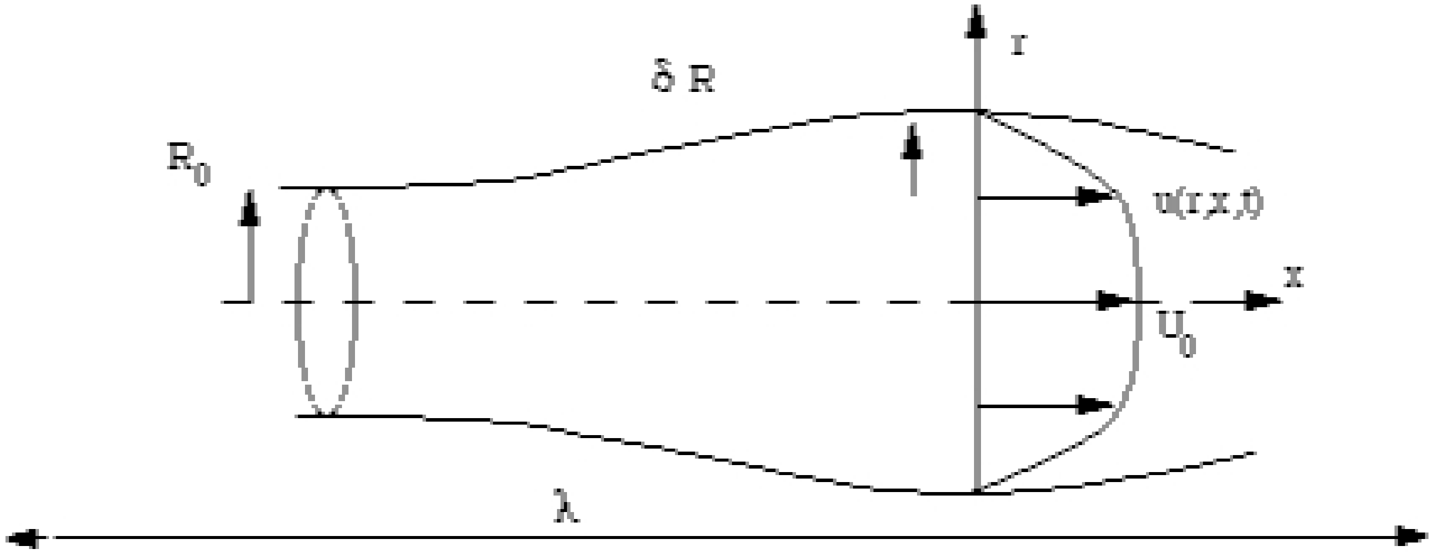
+ The boundary conditions: here hyperbolical ($R(x_{in},t)$ and $R(x_{out},t)$) given



week coupling

$$\frac{u^{n+1}-u^{n}}{\Delta t}+NL(u^{n})=-\frac{\partial p^{n}}{\rho\partial x}+\nu\frac{\partial}{r\partial r}r\frac{\partial u^{n+1}}{\partial r}$$

$$v^{n+1}(R^{n})=-\int_{0}^{R^{n}}\frac{r}{R^{n}}\frac{\partial u^{n+1}}{\partial x}dr$$



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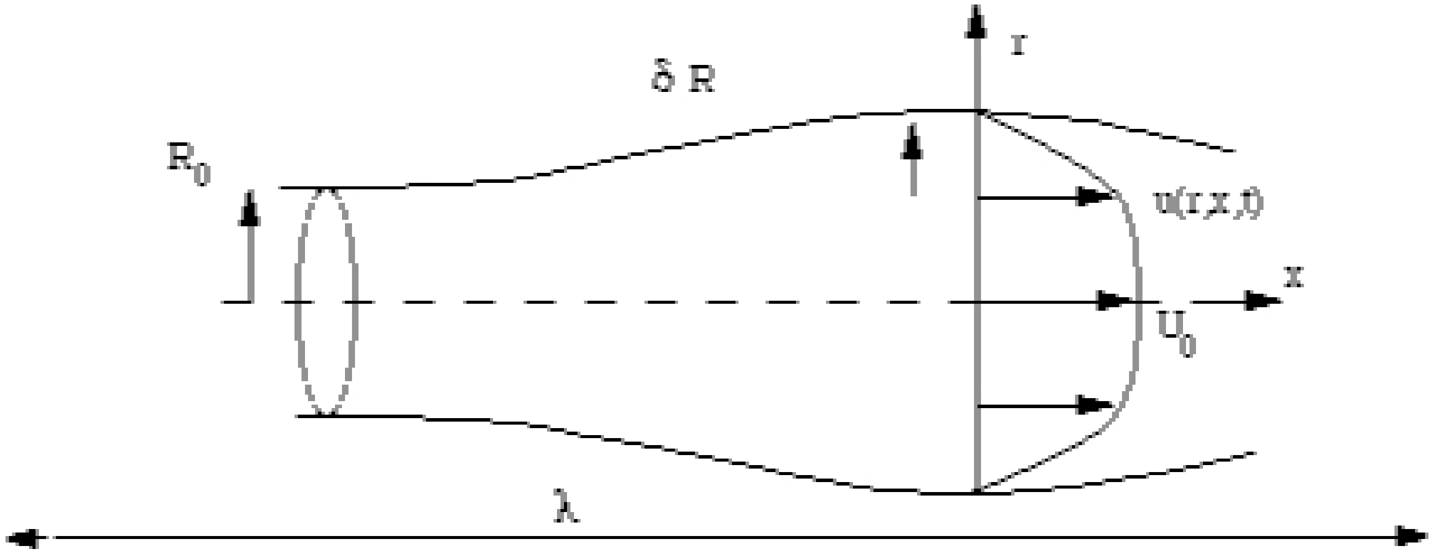
$$R^{n+1}=R^n+v^{n+1}(R^n)\Delta t$$



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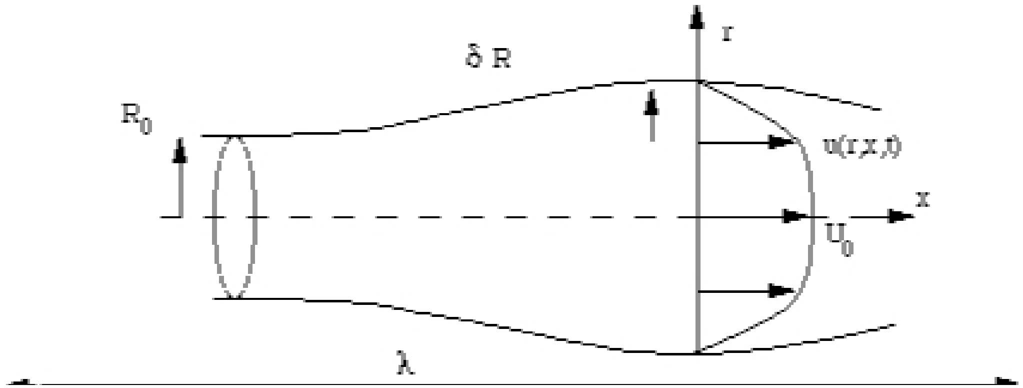
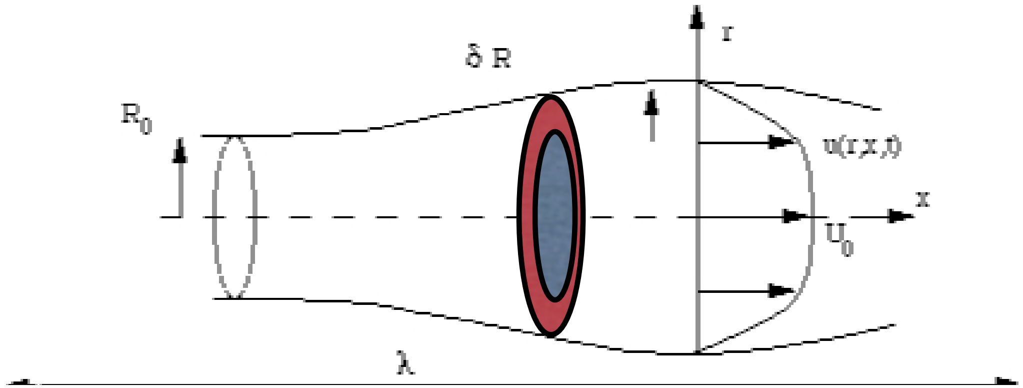
$$R^{n+1}=R^n+v^{n+1}(R^n)\Delta t \qquad p^{n+1}=k(R^{n+1}-R_0)$$



Flow in an elastic artery: integral relations

- new integral equations: adapting Von Kármán integral methods

The key is to integrate the equations with respect to the variable $\eta = r/R$ from the centre of the pipe to the wall $(0 \leq \eta \leq 1)$.



Flow in an elastic artery: integral relations

- new integral equations: adapting Von Kármán integral methods

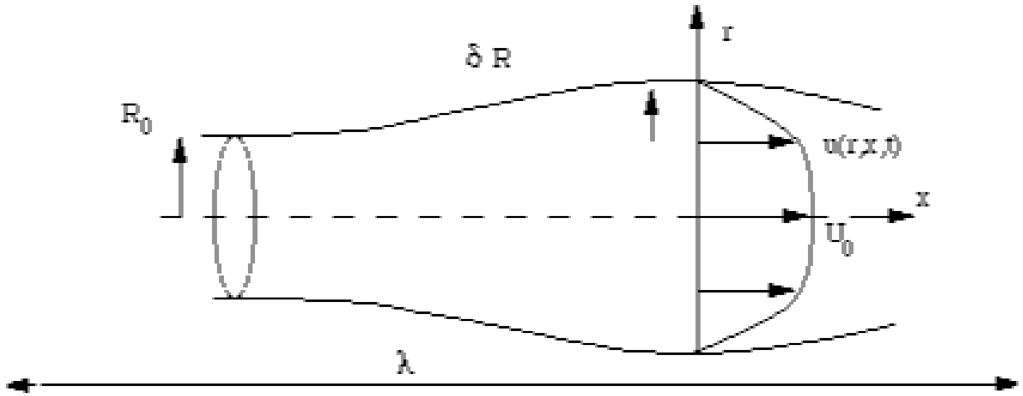
The key is to integrate the equations with respect to the variable $\eta = r/R$ from the centre of the pipe to the wall ($0 \leq \eta \leq 1$).

- U_0, the velocity along the axis of symmetry,

- q a kind of loss of flux (δ_1),

- Γ a kind of loss of momentum flux (δ_2):

$$U_0(x,t) = u(x, \eta = 0, t), \quad q = R^2(U_0 - 2\int_0^1 u\eta d\eta) \;\;\&\;\; \Gamma = R^2(U_0^2 - 2\int_0^1 u^2 \eta d\eta).$$



Flow in an elastic artery: integral relations

$$\frac{\partial R^2}{\partial t} + \varepsilon_2 \frac{\partial}{\partial x}(R^2 U_0 - q) = 0, \quad R = 1 + \varepsilon_2 h.$$

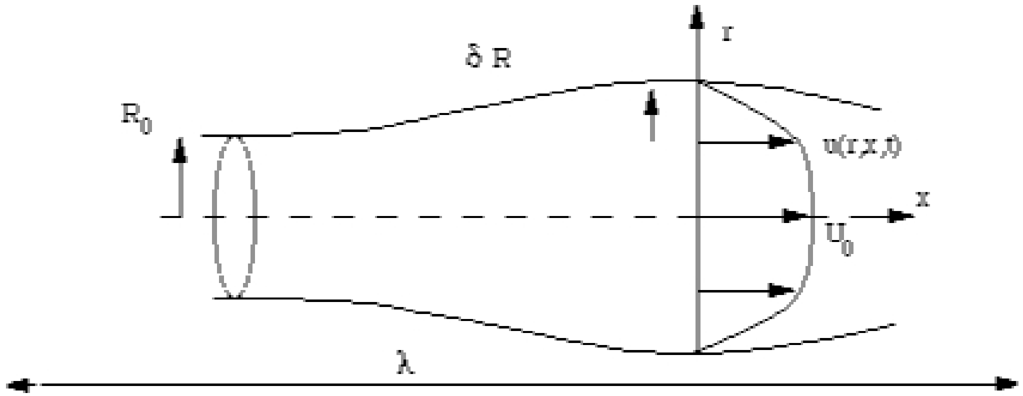
Integrating RNSP, with the help of the boundary conditions, we obtain the equation for $q(x,t)$:

$$\frac{\partial q}{\partial t} + \varepsilon_2 (\frac{\partial}{\partial x}\Gamma - U_0 \frac{\partial}{\partial x} q) = -2\frac{2\pi}{\alpha^2}\tau, \qquad \tau = (\frac{\partial u}{\partial \eta})|_{\eta=1} - (\frac{\partial^2 u}{\partial \eta^2})|_{\eta=0}.$$

From the same equation evaluated on the axis of symmetry (in $\eta = 0$), we obtain an equation for the velocity along the axis $U_0(x,t)$:

$$\frac{\partial U_0}{\partial t} + \varepsilon_2 U_0 \frac{\partial U_0}{\partial x} = -\frac{\partial p}{\partial x} + 2\frac{2\pi}{\alpha^2}\frac{\tau_0}{R^2}, \qquad \tau_0 = (\frac{\partial^2 u}{\partial \eta^2})|_{\eta=0}.$$

Boundary conditions ($h(x_{in}, t)$ and $h(x_{out}, t)$) given

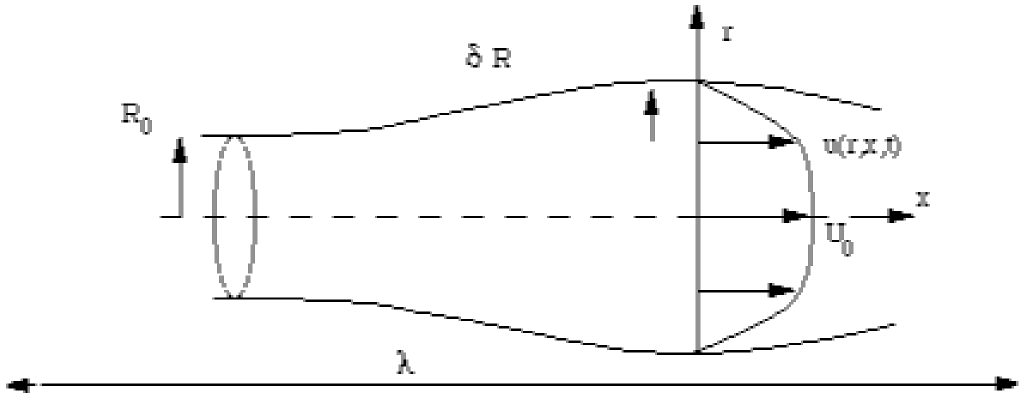


Closure

The two previous relations introduced the values of the friction in $\eta = 0$, the axis of symmetry: $((\frac{\partial^2 u}{\partial \eta^2})|_{\eta=0})$ and the skin friction in $\eta = 1$, at the wall: $((\frac{\partial u}{\partial \eta})|_{\eta=1})$.

- Information has been lost here, so we need a closure relation between (Γ, τ, τ_0) and (q, R, U_0).

- we have to imagine a velocity profile and deduce from it relations linking Γ, τ and τ_0 and q, U_0 et R.

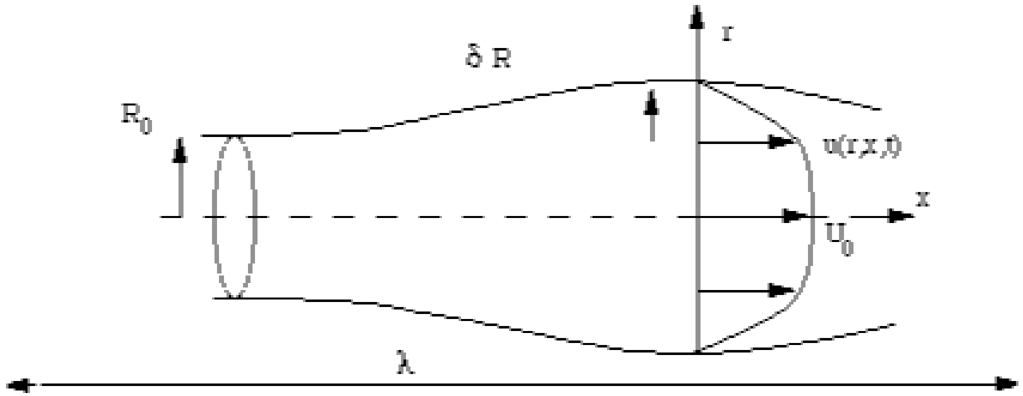


Closure: Womersley

• the most simple idea is to use the profiles from the analytical linearized solution given by Womersley (1955) for

$$(j_r + i j_i) = \left(\frac{1 - \dfrac{J_0(i^{3/2}\alpha\eta)}{J_0(i^{3/2}\alpha)}}{1 - \dfrac{1}{J_0(i^{3/2}\alpha)}} \right).$$

• assume that the velocity distribution in the following has the same dependence on η. It means that we suppose that the fundamental mode imposes the radial structure of the flow.

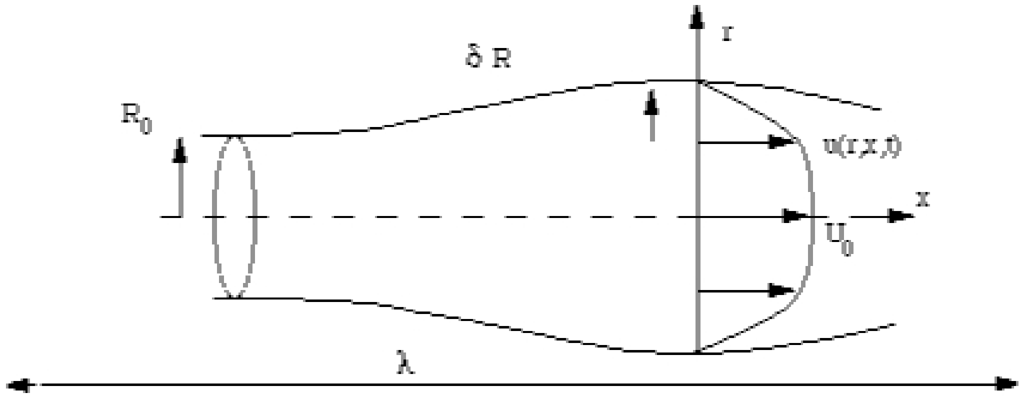


The coefficients of closure

- by integration/ derivation, we obtain:

$$\Gamma = \gamma_{qq}\frac{q^2}{R^2} + \gamma_{qu} q U_0 + \gamma_{uu} R^2 U_0^2, \quad \tau = \tau_q \frac{q}{R^2} + \tau_u U_0 \quad \tau_0 = \tau_{0q}\frac{q}{R^2} + \tau_{0u} U_0.$$

The coefficients $((\gamma_{qq}, \gamma_{qu}, \gamma_{uu}), (\tau_q, \tau_u), (\tau_{0q}, \tau_{0u}))$ are only functions of α.



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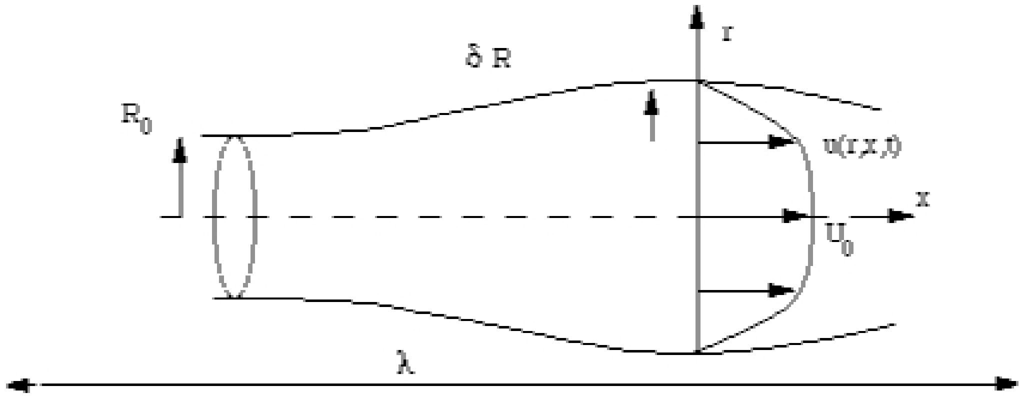
$$\begin{aligned}
\gamma_{uu} &= 1 - \int j_i^2/(\int j_i)^2 - (2\int j_r j_i)/\int j_i - \int j_r^2 + \\
&\quad +(2\int j_i^2 \int j_r)/(\int j_i)^2 + (2\int j_i j_r \int j_r)/\int j_i - \\
&\quad -(\int j_i^2 (\int j_r)^2)/(\int j_i), \\
\tau_{0u} &= \partial_\eta^2 j_{r\eta=0} + \partial_\eta^2 j_{i\eta=0}/\int j_i - (\partial_\eta^2 j_{i\eta=0} \int j_r)/\int j_i.
\end{aligned}$$



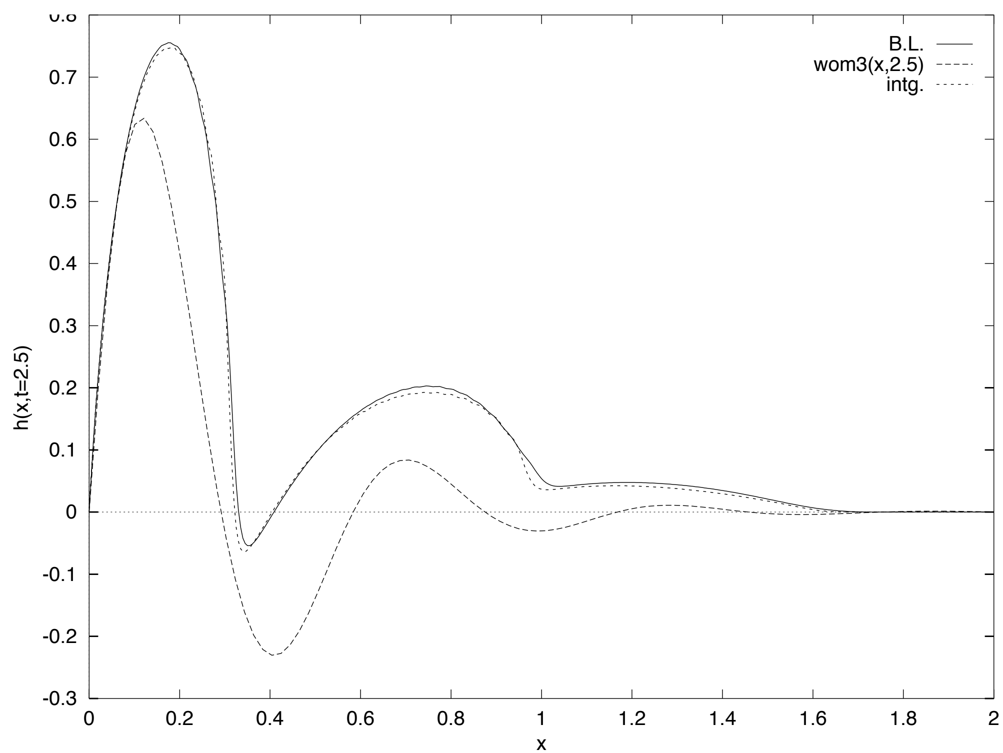
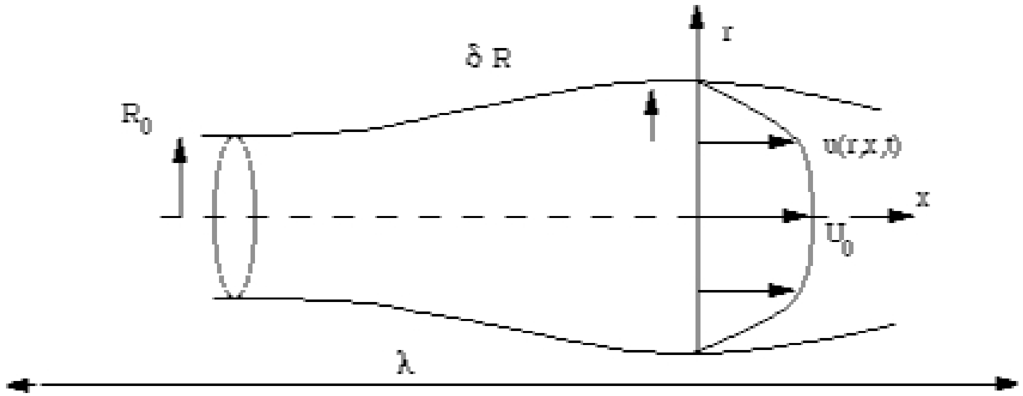


Figure 1: The displacement of the wall ($h(x, t = 2.5)$) as a function of x is plotted here at time $t = 2.5$. The dashed line (wom3(x,2.5)) is the Womersley solution (reference), the solid line (B.L.) is the result of the Boundary Layer code and the dots (intg) are the results of the integral method ($\alpha = 3$, $k_1 = 1$, $k_2 = 0$ and $\varepsilon_2 = 0.2$).



P.-Y. Lagrée (2000):
"An inverse technique to deduce the elasticity of a large artery ",
European Physical Journal, Applied Physics 9, pp. 153-163

Lagrée P-Y and Rossi M. (1996):
"Etude de l'écoulement du sang dans les artères: effets nonlinéaires et dissipatifs",
C. R. Acad. Sci. Paris, t322, Série II b, p401- 408, 1996.

Conclusion

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- real time simulation

F. Chouly, A. Van Hirtum, X. Pelorson, Y. Payan, and P.-Y. Lagrée:
"An attempt to model Obstructive Sleep Apnea Syndrome: preliminary study"

P.-Y. Lagrée, A. Van Hirtum & X. Pelorson (2007):
"Asymmetrical effects in a 2D stenosis".
European Journal of Mechanics - B/Fluids, Volume 26, Issue 1, January-February 2007, Pages 83-92

P.-Y. Lagrée & S. Lorthois (2005):
"The RNS/Prandtl equations and their link with other asymptotic descriptions. Application to the computation of the maximum value of the Wall Shear Stress in a pipe",
Int. J. Eng Sci., Vol 43/3-4 pp 352-378.

A. Van Hirtum, X. Pelorson & P.-Y. Lagrée (2005):
"In-vitro validation of some flow assumptions for the prediction of the pressure distribution during obstructive sleep apnea",
Medical & biological engineering & computing, no 43(1) pp. 162-171.

P.-Y. Lagrée, E. Berger, M. Deverge, C. Vilain & A. Hirschberg (2005):
"Characterization of the pressure drop in a 2D symmetrical pipe: some asymptotical, numerical and experimental comparisons",
ZAMM: Z. Angew. Math. Mech. 85, No. 2, pp. 141-146.

M. Deverge, X. Pelorson, C. Vilain, P.-Y. Lagrée, F. Chentouf, J. Willems & A. Hirschberg (2003):
"Influence of the collision on the flow through in-vitro rigid models of the vocal folds".
J. Acoust. Soc. Am. 114 , pp. 3354 - 3362.

S. Lorthois, P.-Y. Lagrée, J.-P. Marc-Vergnes & F. Cassot. (2000):
"Maximal wall shear stress in arterial stenoses: Application to the internal carotid arteries",
Journal of Biomechanical Egineering, Volume 122, Issue 6, pp. 661-666.

Lorthois S. & Lagrée P.-Y. (2000):
"Flow in a axisymmetric convergent: evaluation of maximum wall shear stress",
C. R. Acad. Sci. Paris, t328, Série II b, p33-40, 2000

P.-Y. Lagrée (2000):
"An inverse technique to deduce the elasticity of a large artery ",
European Physical Journal, Applied Physics 9, pp. 153-163

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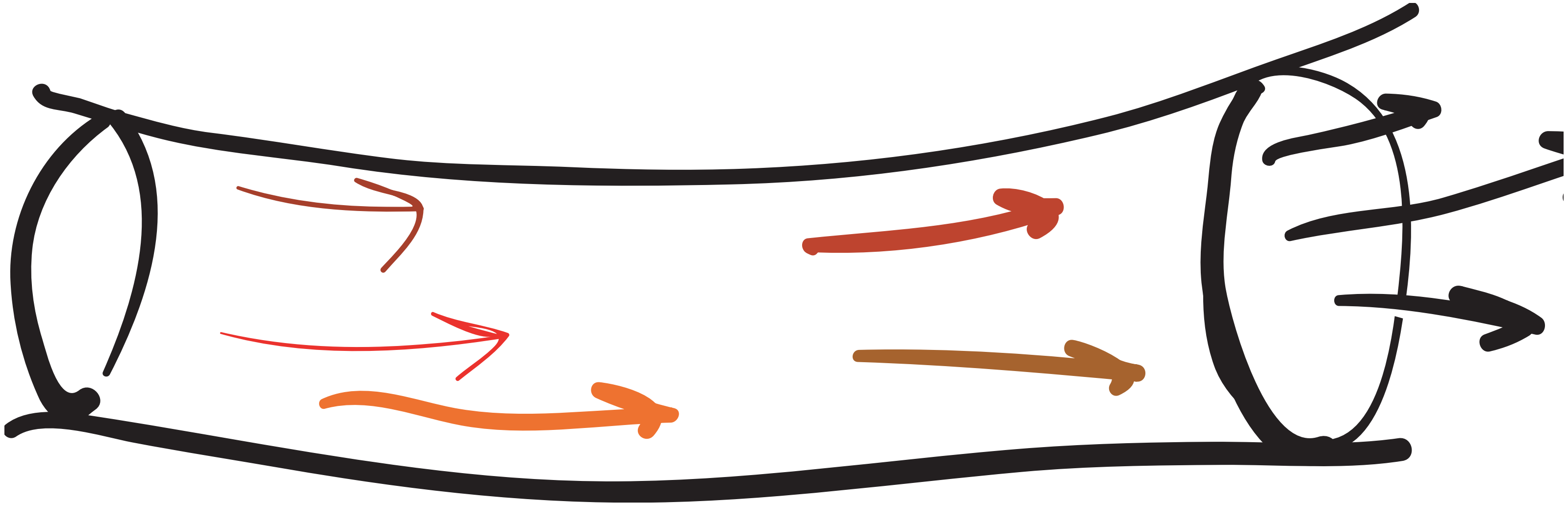
- Use Acrobat Reader 7.05 to see animations
- Updated version may be found here.



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