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[Contrôle de connaissances](#)



[Programmation détaillée](#)

dernière mise à jour : 03/12/2007 par ortiz



MF204 : Transferts thermiques et massiques dans les fluides

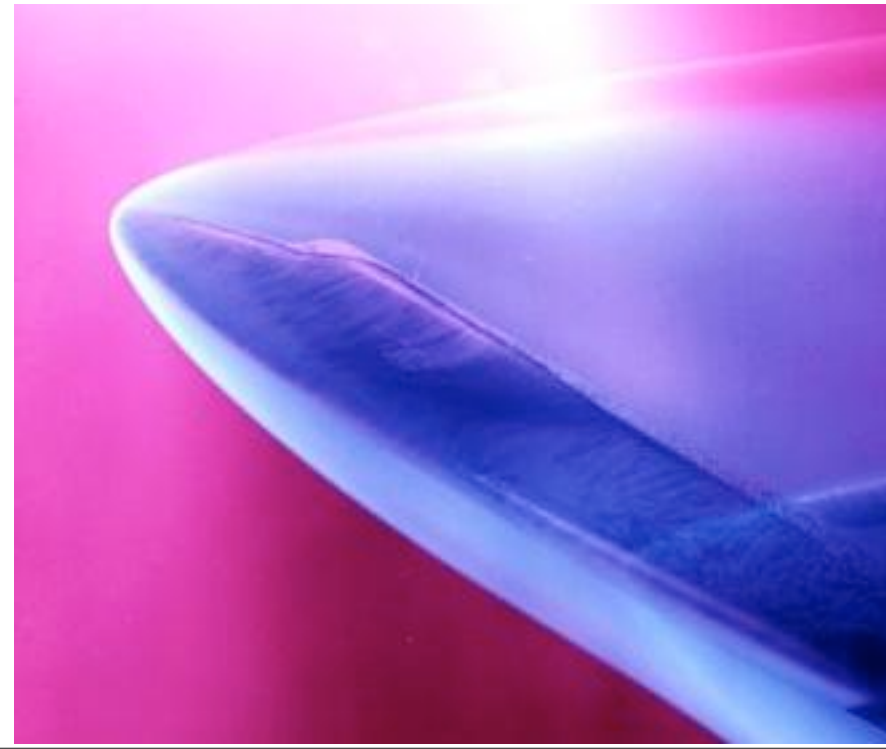
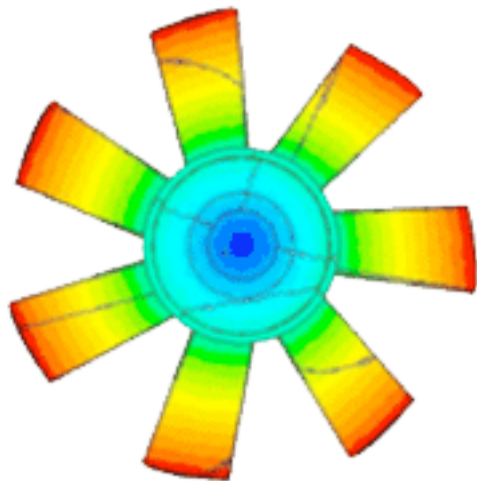
Année : 2A		Module : voie	Crédits ECTS : 2
Professeurs :		Pierre-Yves LAGREE	
Maîtres de conférences :		Pierre-Yves LAGREE ; ANNE PLANCHETTE	
DATE	HEURES	TYPE SEANCE	PROGRAMME DE LA SEANCE
22 01 2008	08:30 09:30	Cours magistral	Rappels de conduction, coefficient d'échange (équation de la chaleur) (équation de la chaleur) thermodynamique des processus irréversibles Rappels de conduction. Le coefficient d'échange.
22 01 2008	09:45 11:45	Petite classe	
29 01 2008	8:30 9:30	Cours magistral	Convection forcée Convection forcée
29 01 2008	9:45 11:45	Petite classe	
05 02 2008	8:30 9:30	Cours magistral	Convection forcée suite et fin
05 02 2008	9:45 11:45	Petite classe	
12 02 2008	08:30 09:30	Cours magistral	Convection Naturelle Convection libre
12 02 2008	09:45 11:45	Petite classe	
19 02 2008	08:30 09:30	Cours magistral	Convection forcée turbulente Turbulence
19 02 2008	09:45 11:45	Petite classe	
04 03 2008	08:30 09:30	Cours magistral	Transferts de masse Convection massique
04 03 2008	09:45 11:45	Petite classe	
11 03 2008	08:30 11:30	Contrôle	Contrôle de connaissances
		Petite classe	

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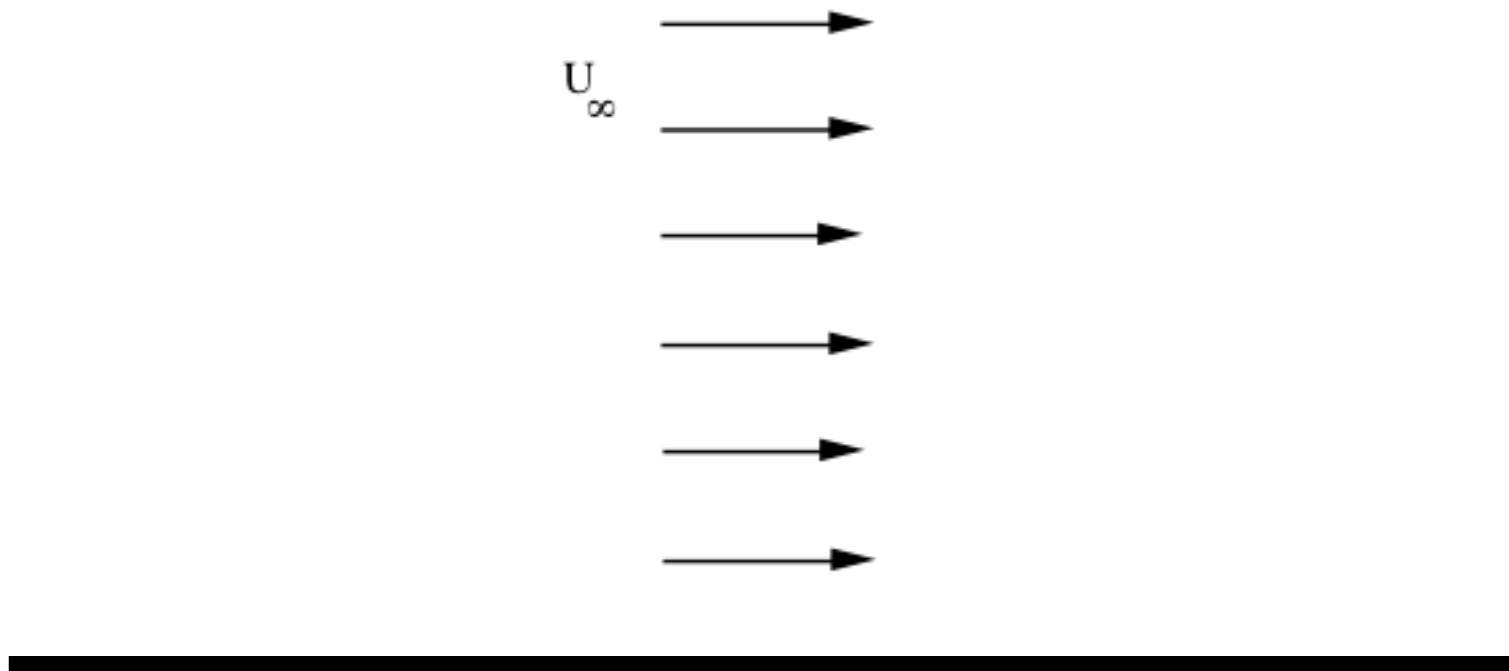
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<http://www.imm.jussieu.fr/~lagree/COURS/ENSTA/>

Convection forcée externe

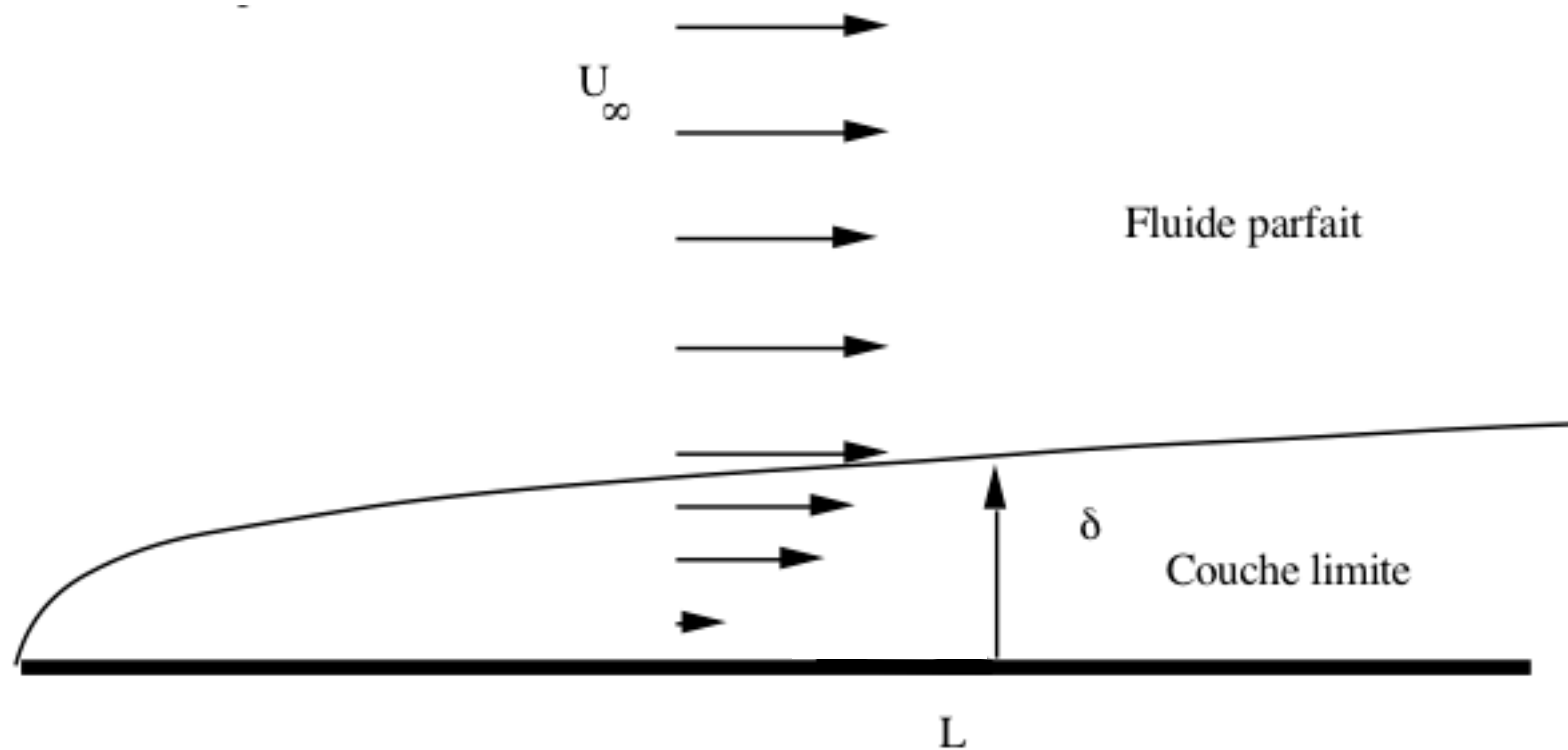


fluide parfait



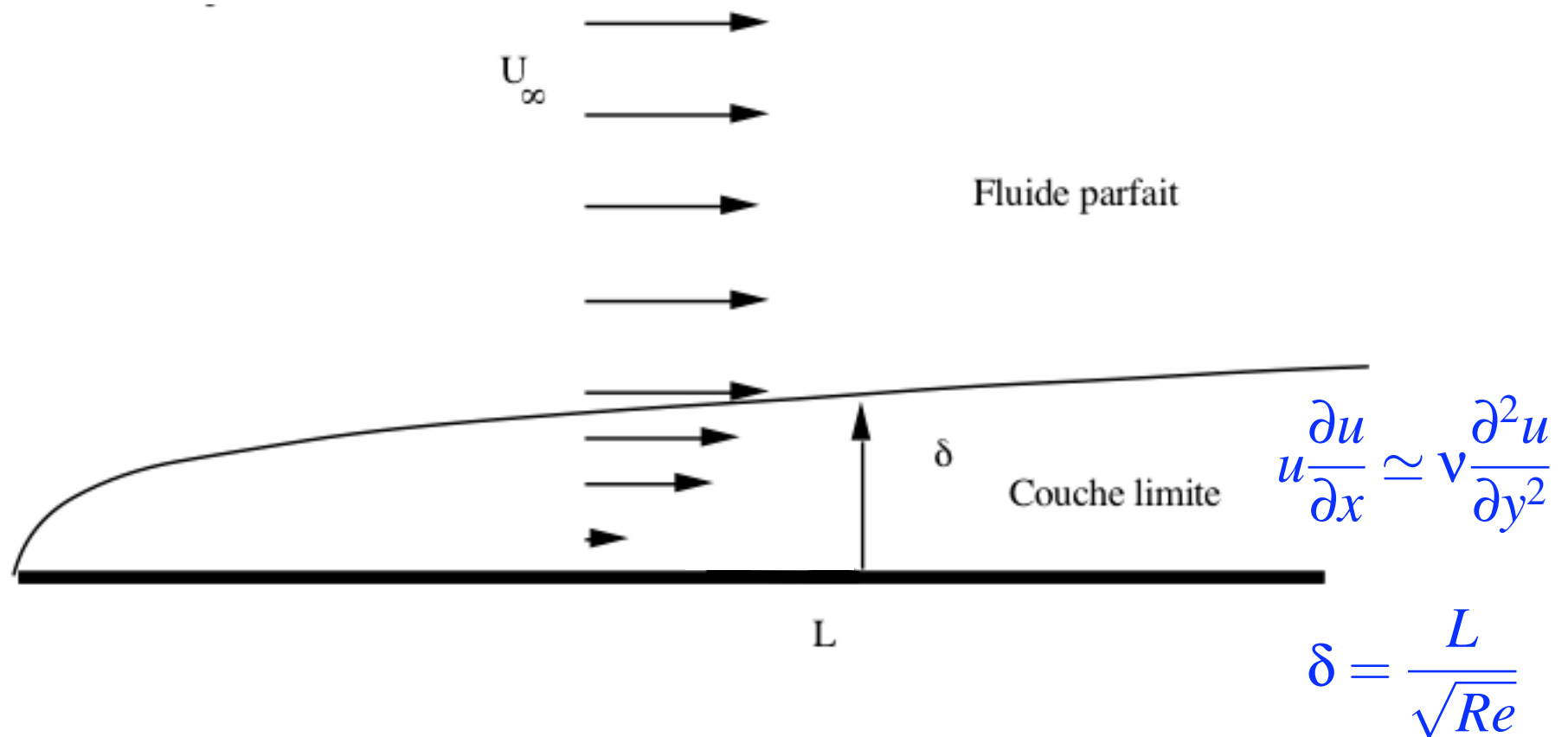
fluide parfait

couche limite



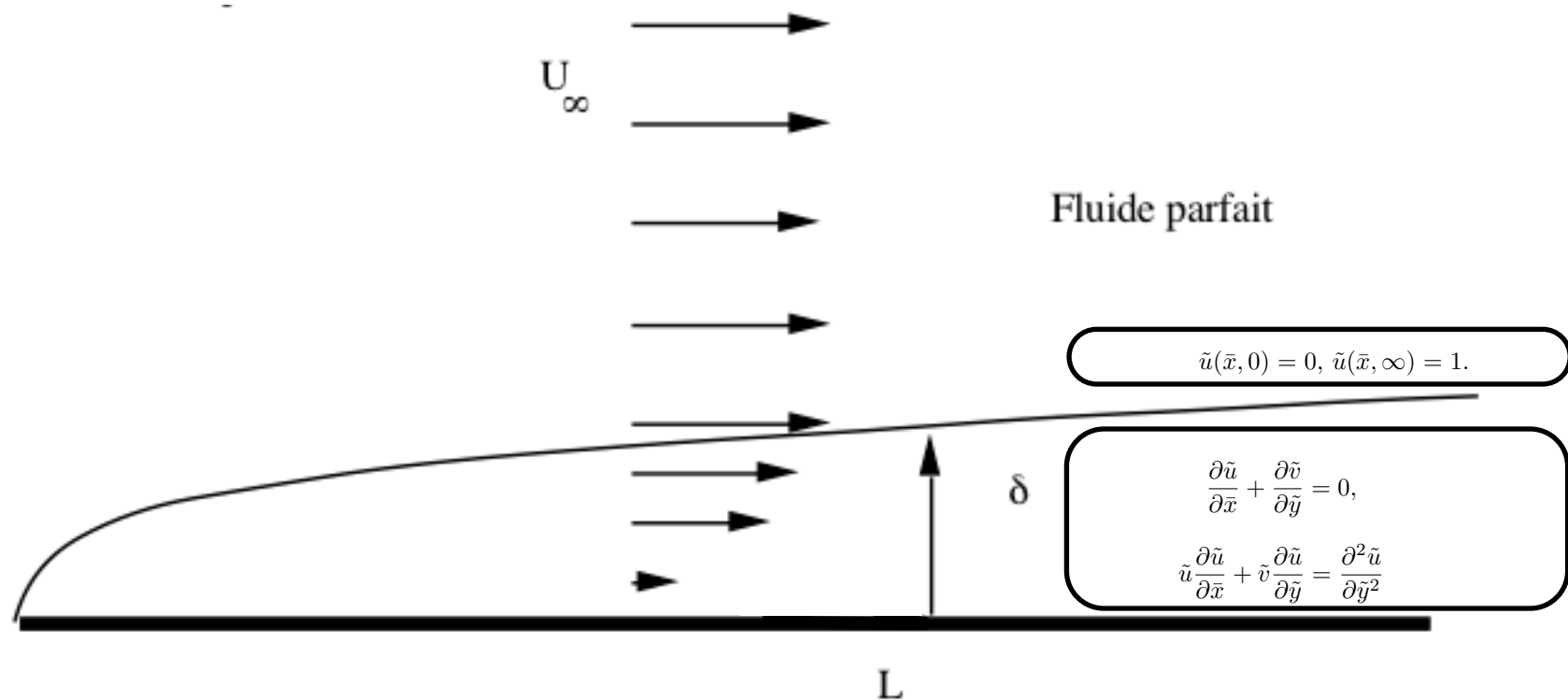
fluide parfait

couche limite

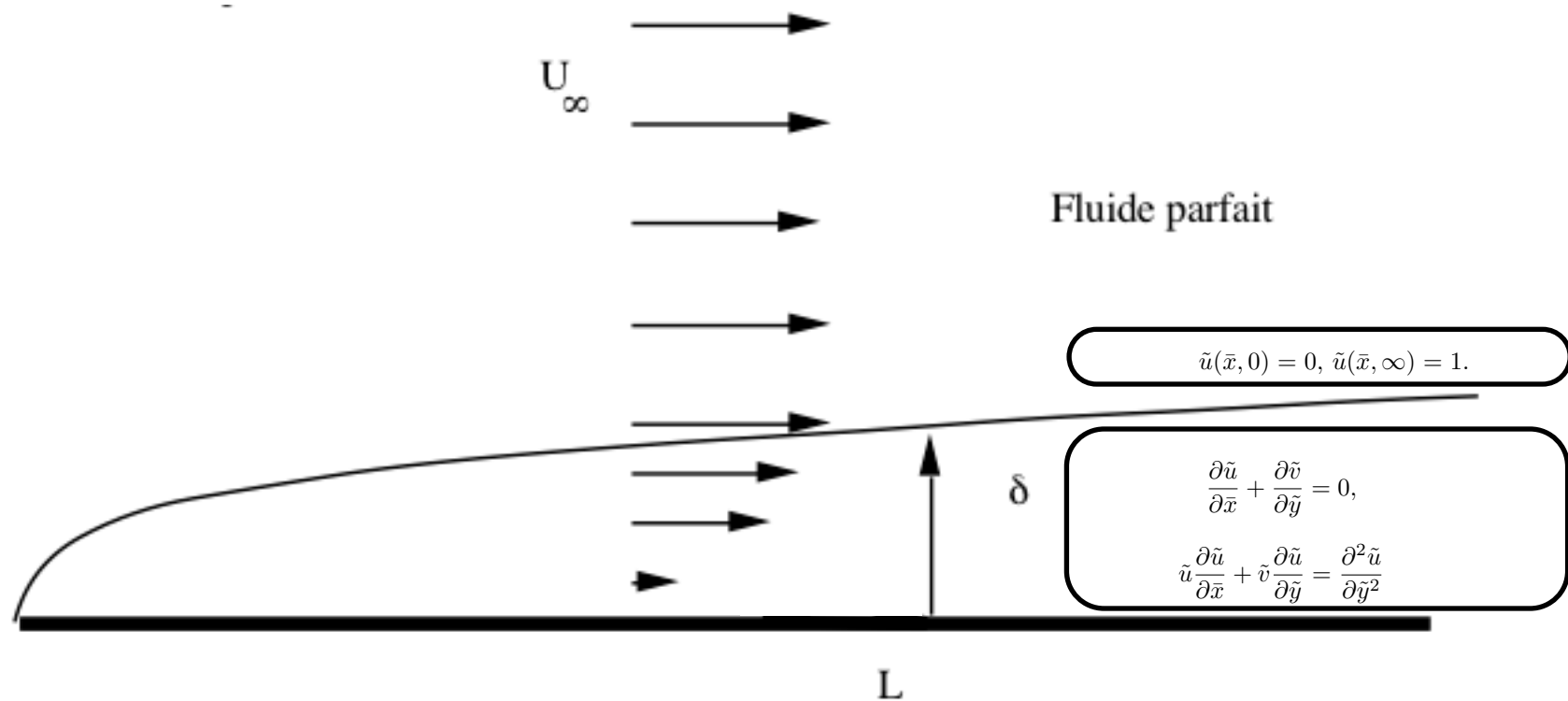


fluide parfait

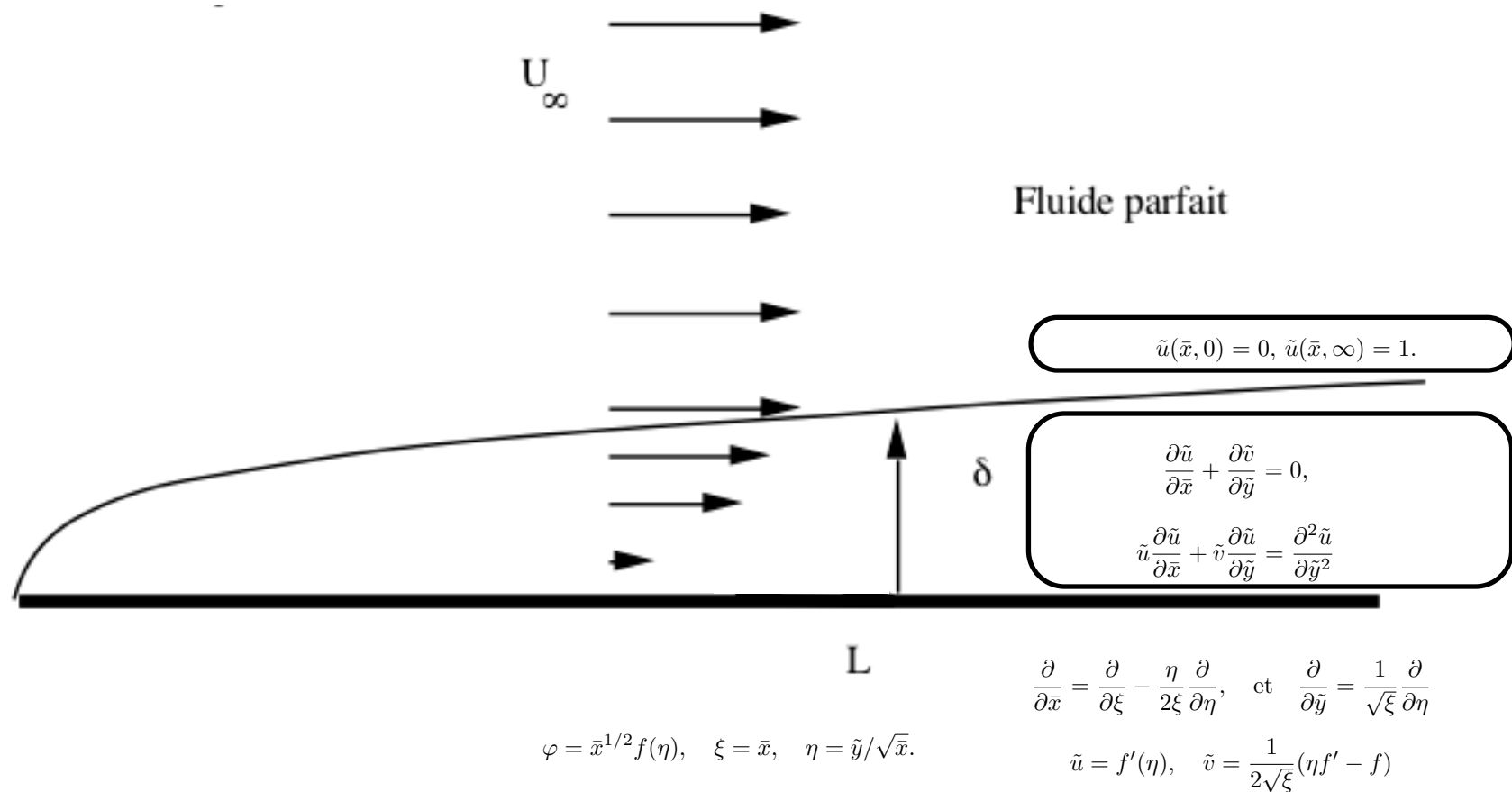
couche limite



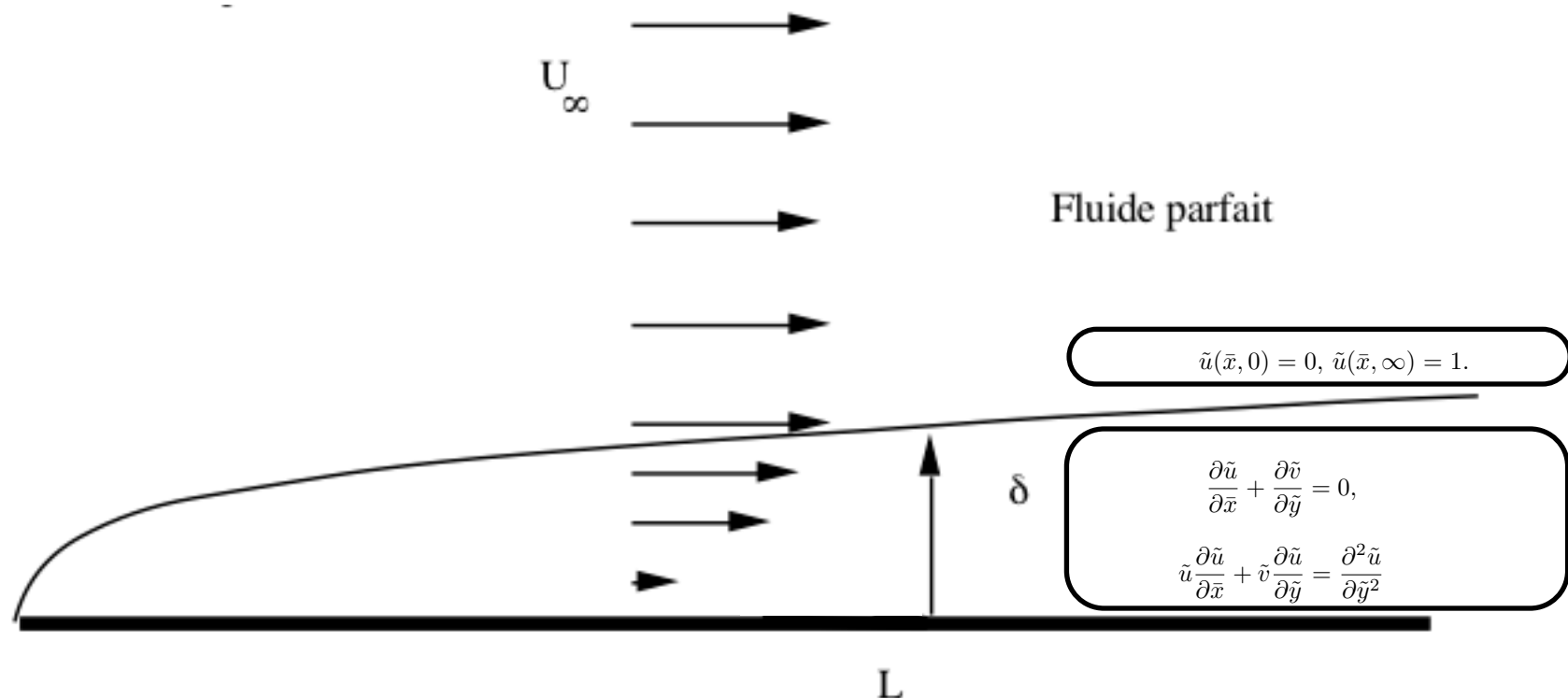
couche limite



couche limite



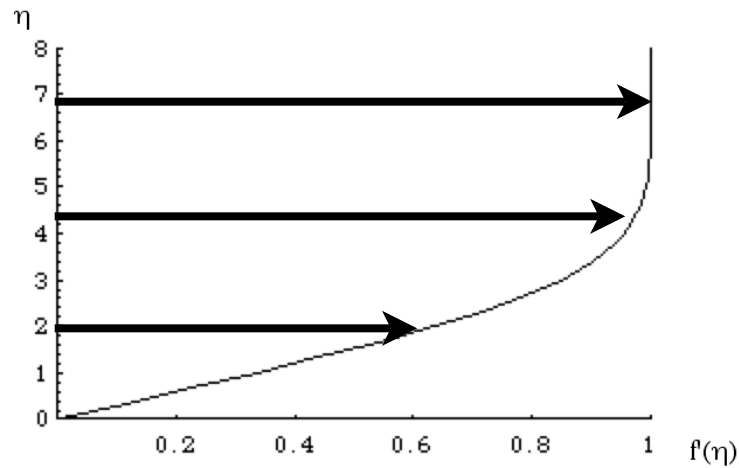
couche limite



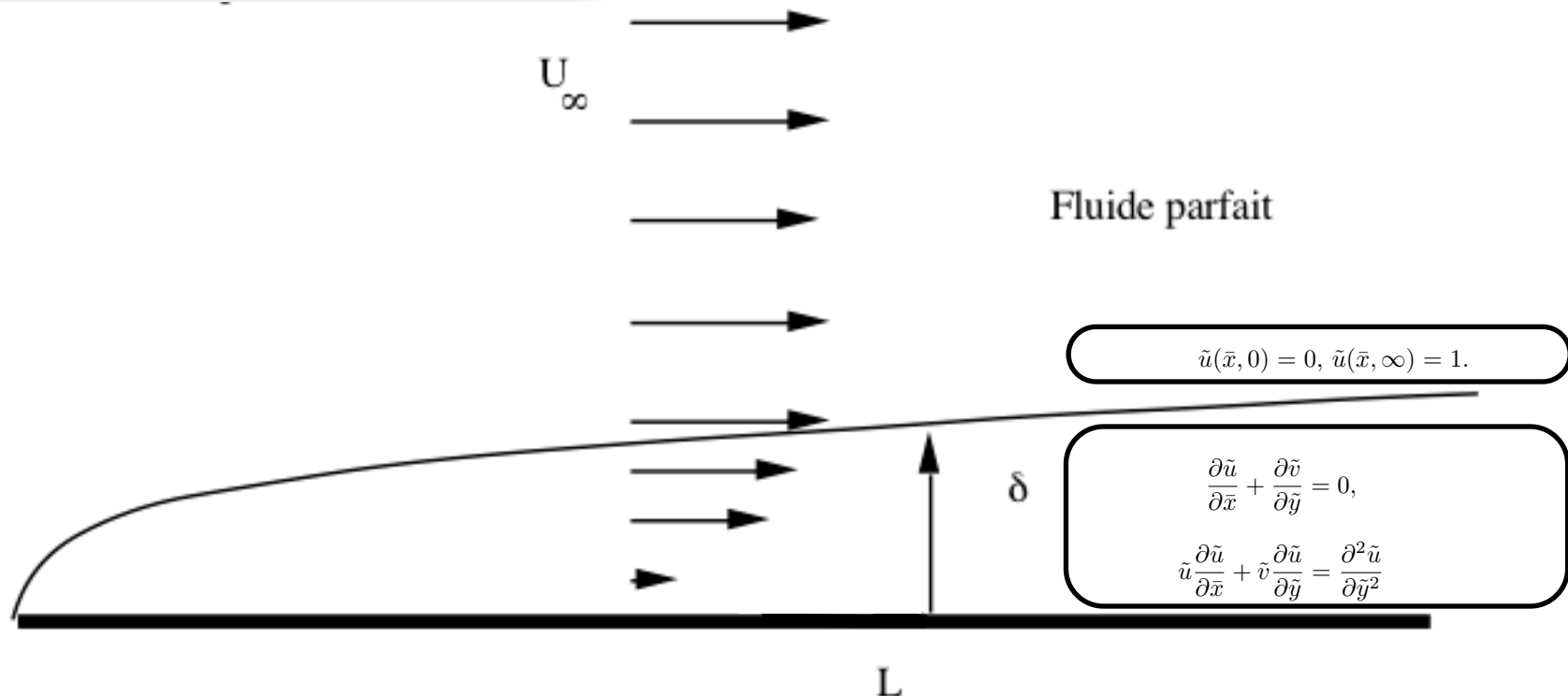
La partie dynamique admet la solution de Blasius bien connue:

$$2f''' + f f'' = 0 \text{ avec } f(0) = f'(0) = 0 \text{ et } f'(\infty) = 1. \quad f'(0) = 0.332,$$

couche limite



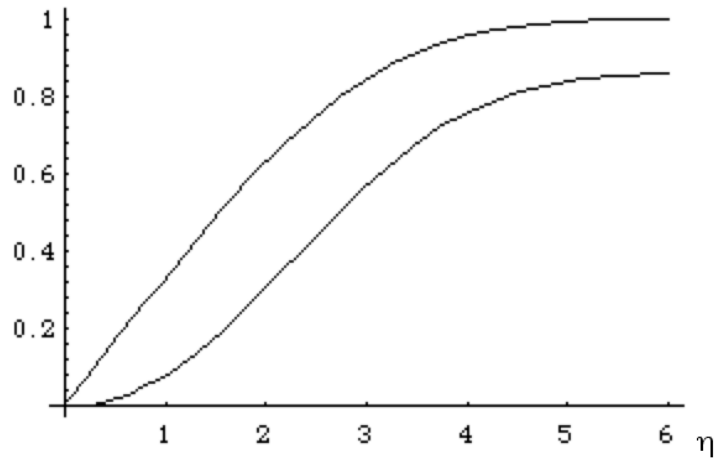
profil de vitesse: f' en abscisse, η en ordonnée.



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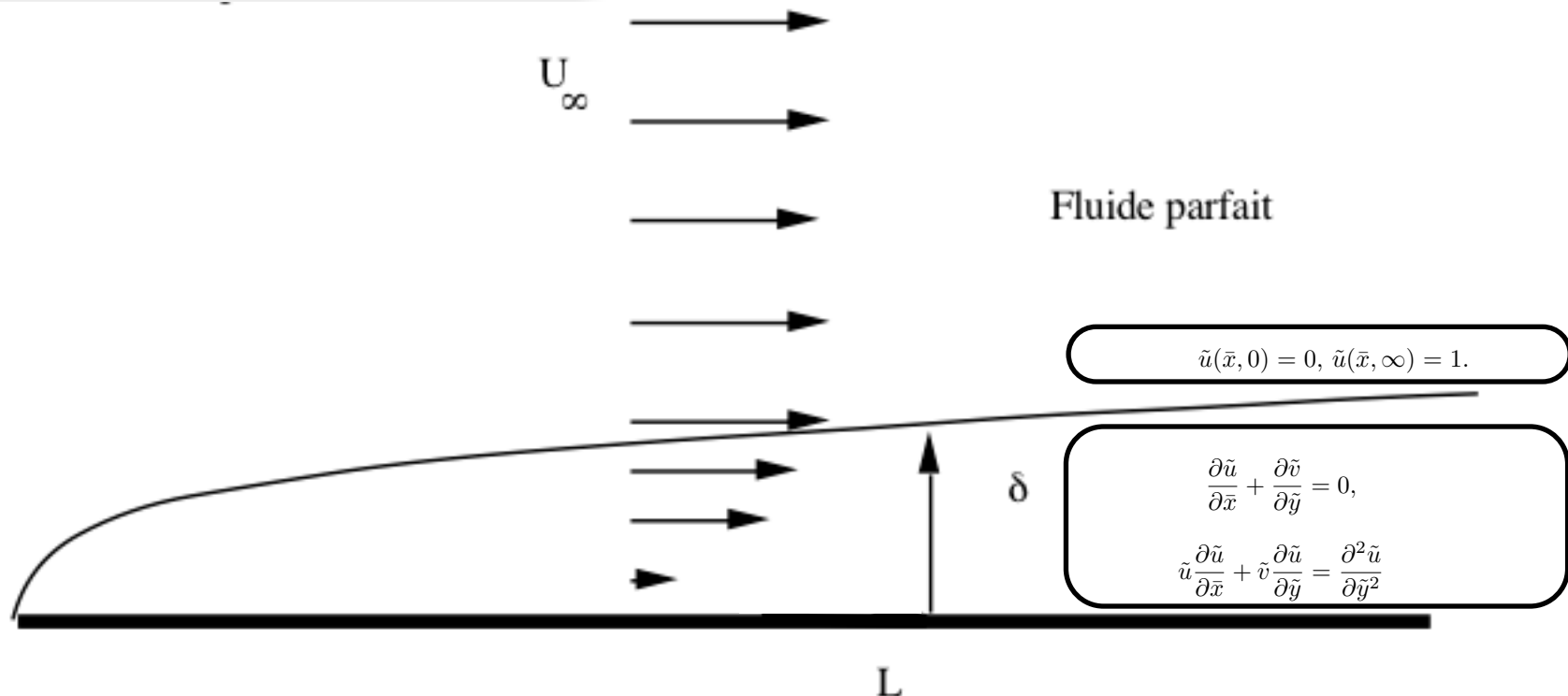
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$u(\eta)$ et $(\eta f' + f)/2$



vitesse longitudinale et transversale.

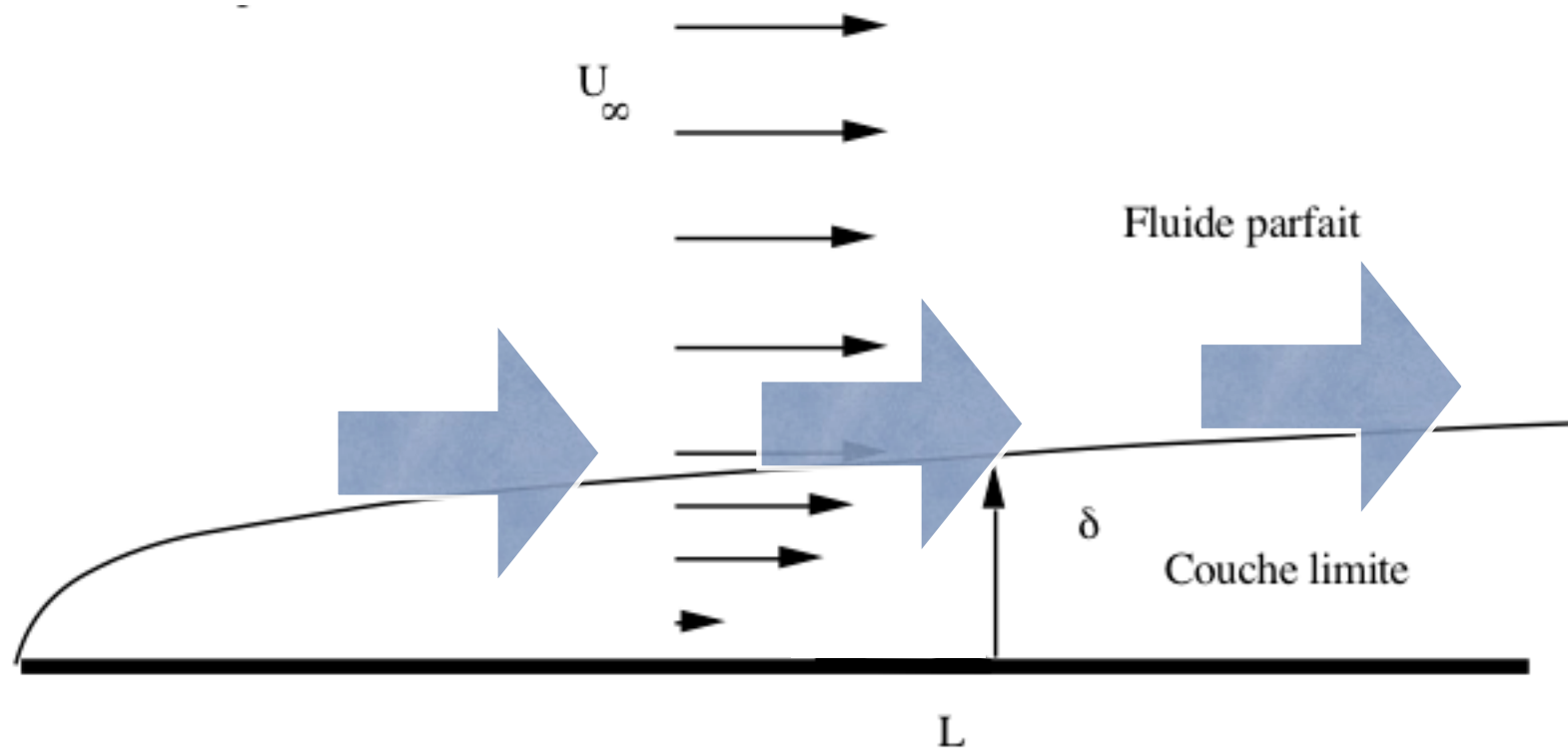
couche limite



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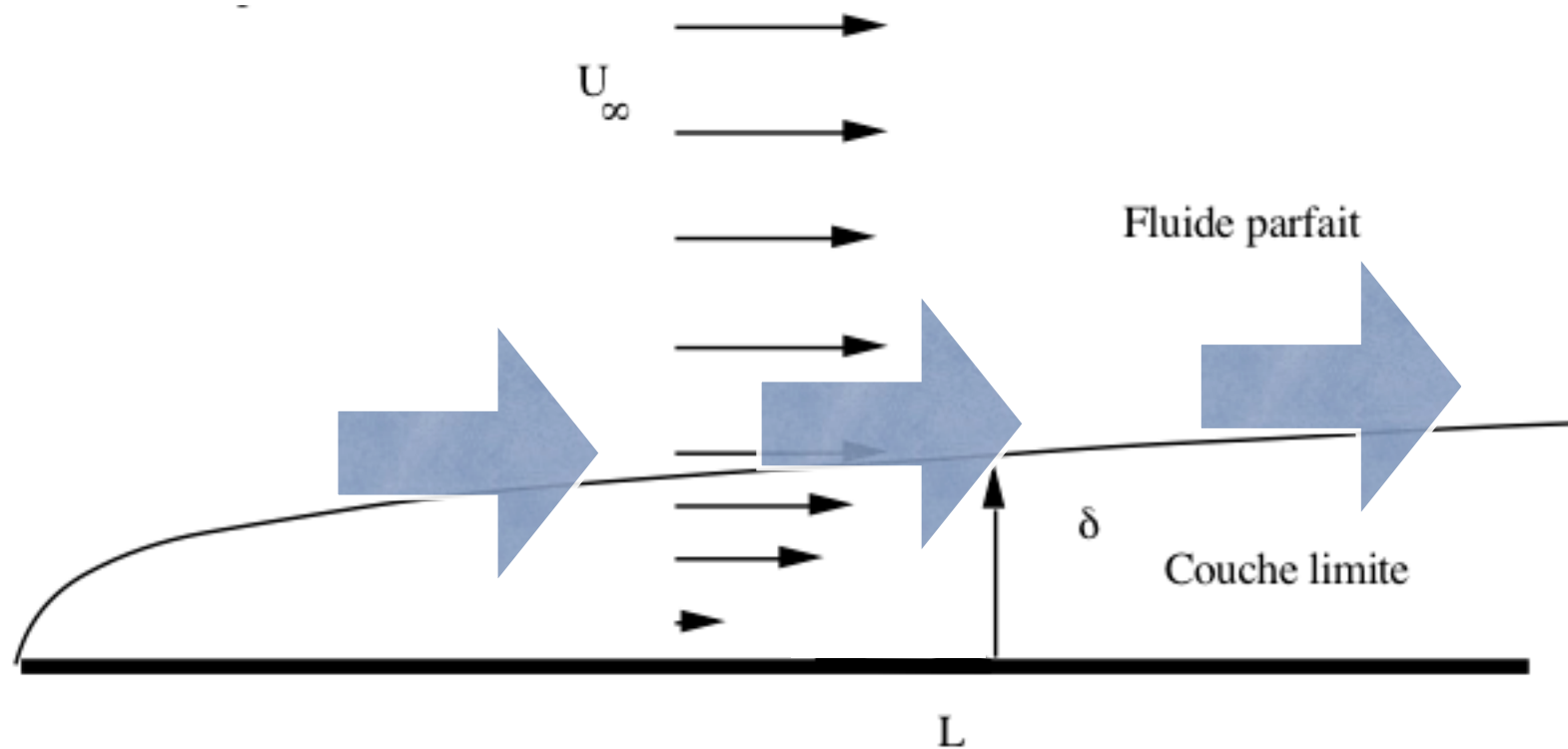
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fluide parfait $\longrightarrow$ couche limite



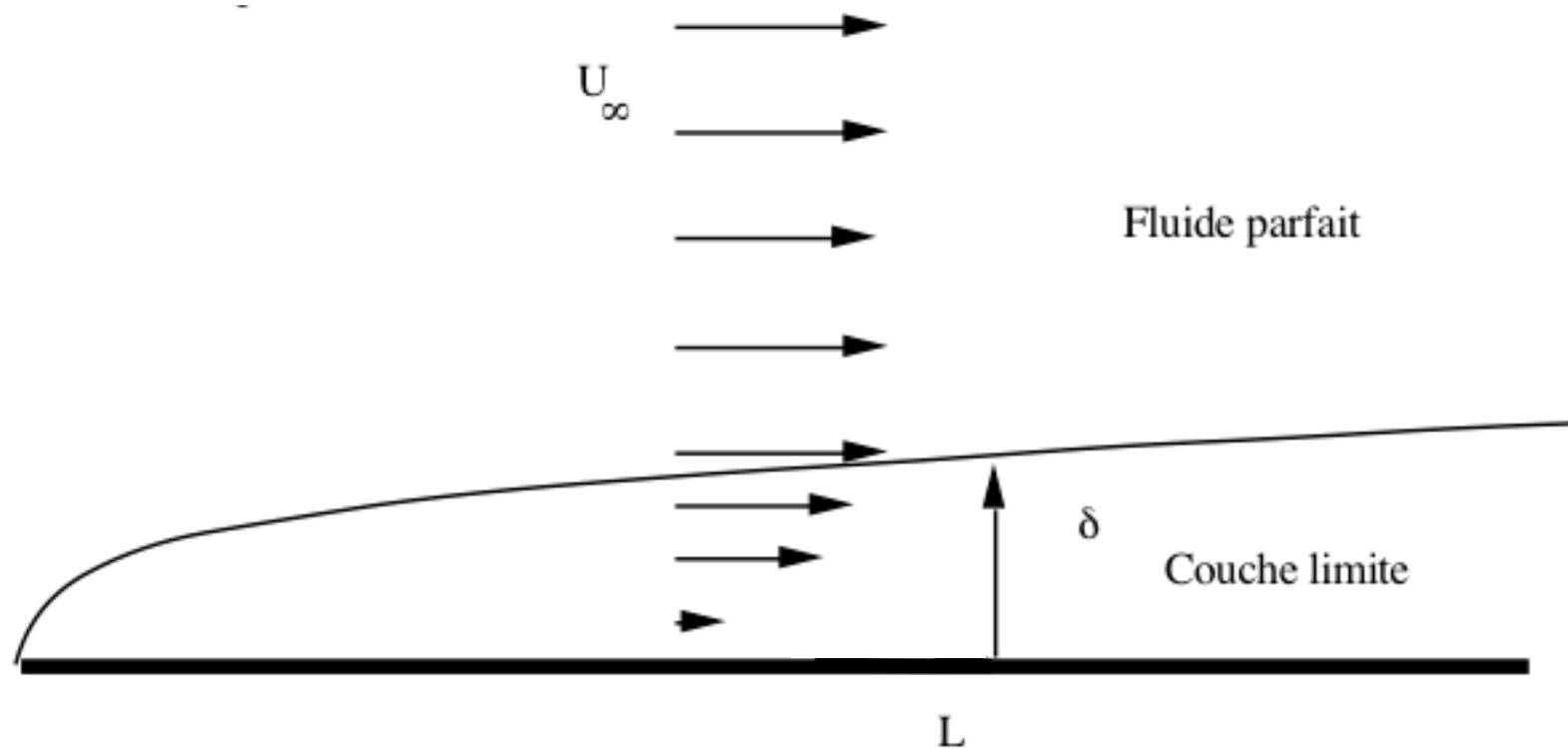
$$\begin{cases} \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \\ u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} = -\frac{\partial p}{\partial x} + \frac{\partial^2 u}{\partial y^2} \\ 0 = -\frac{\partial p}{\partial y} \end{cases}$$

+ cond. lim.



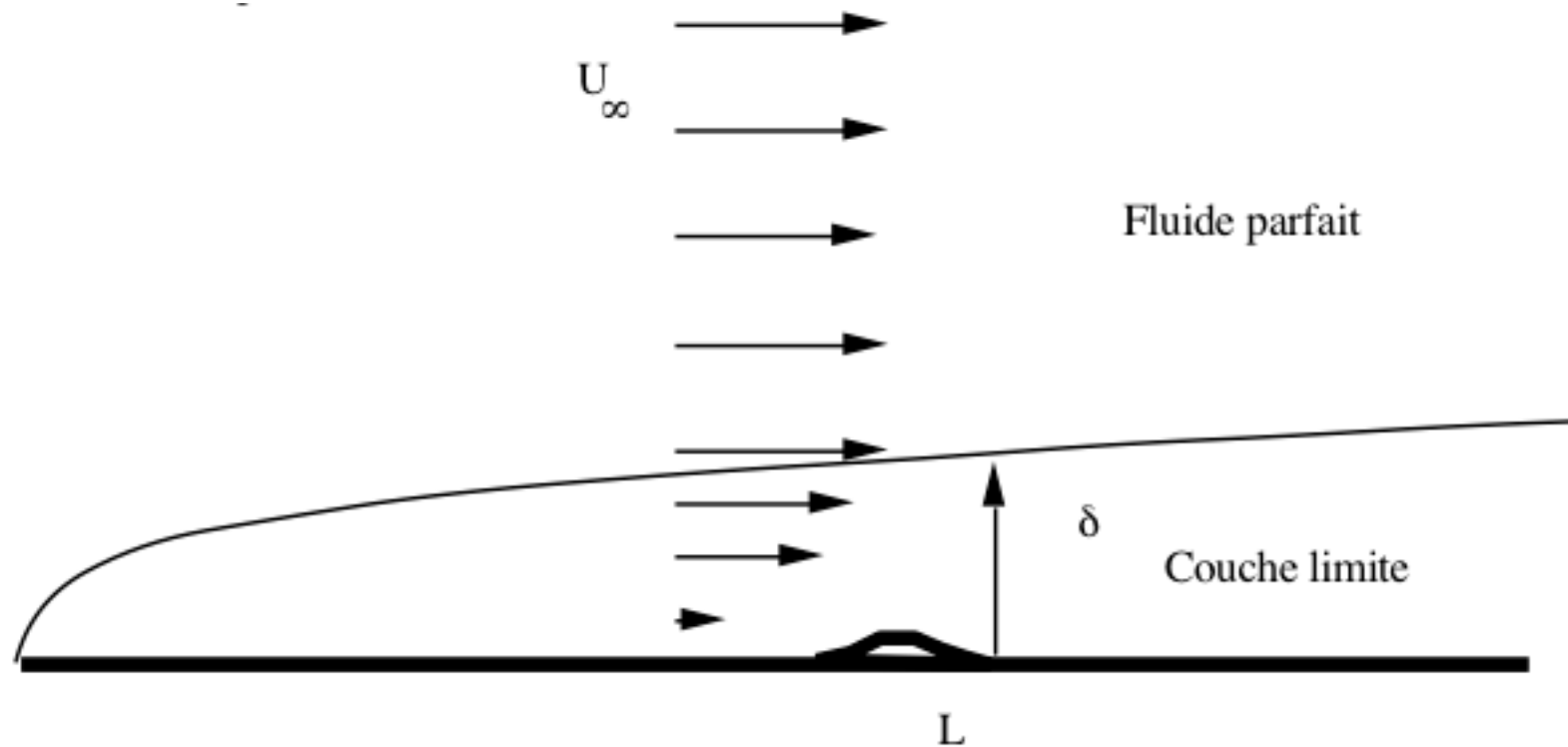
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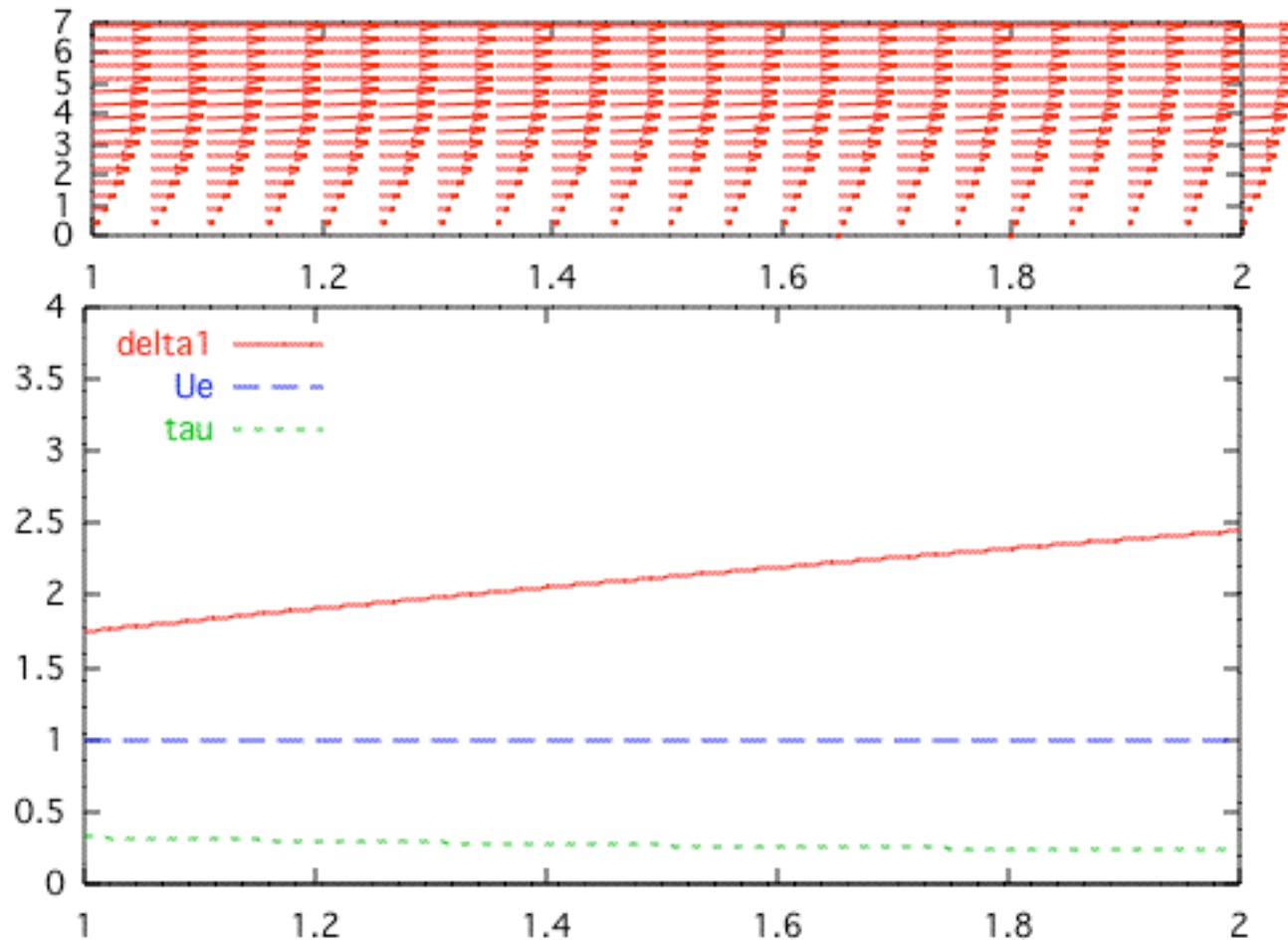
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$$\delta_1 = \int_0^{\infty} \left(1 - \frac{u}{U_{\infty}}\right) dy$$

épaisseur de déplacement



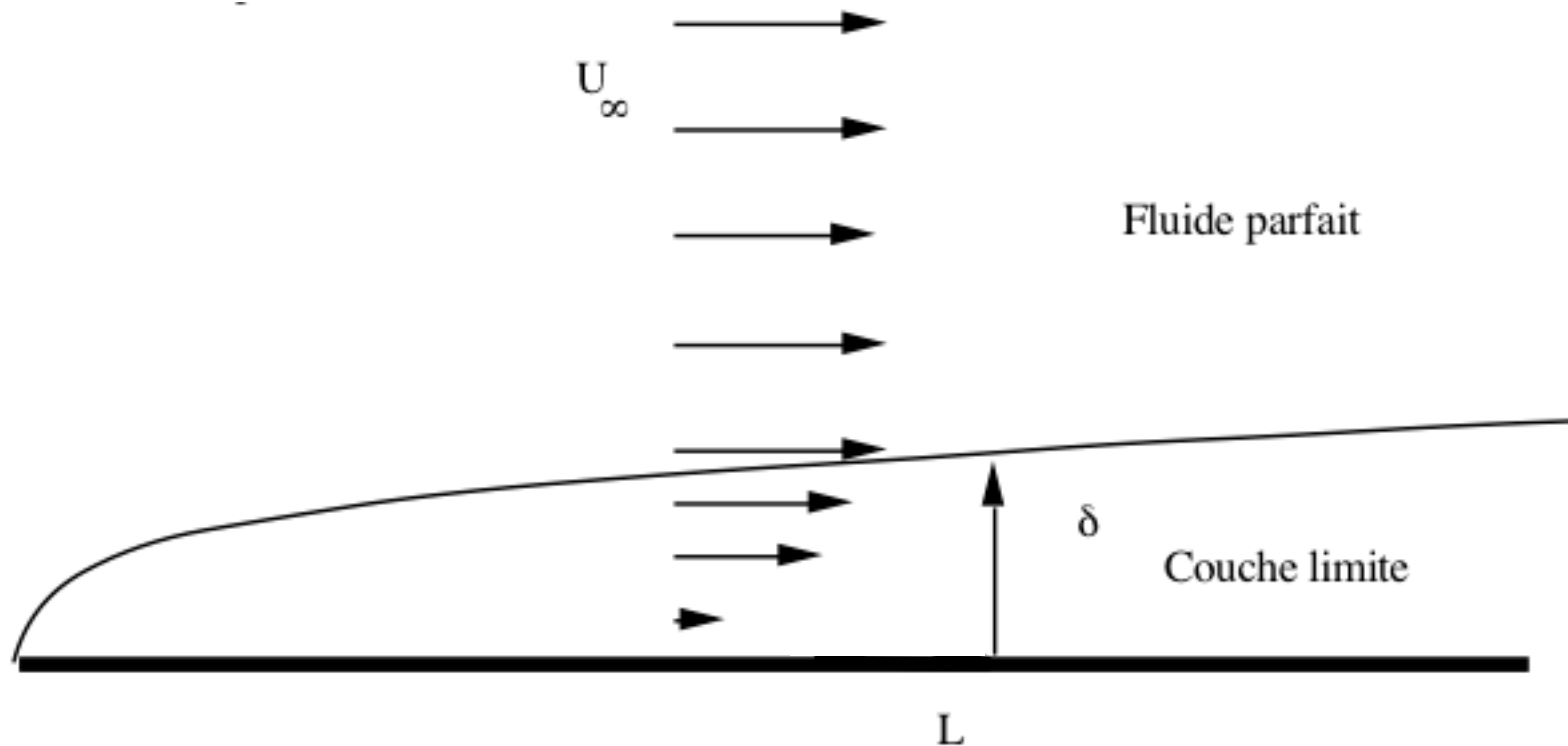
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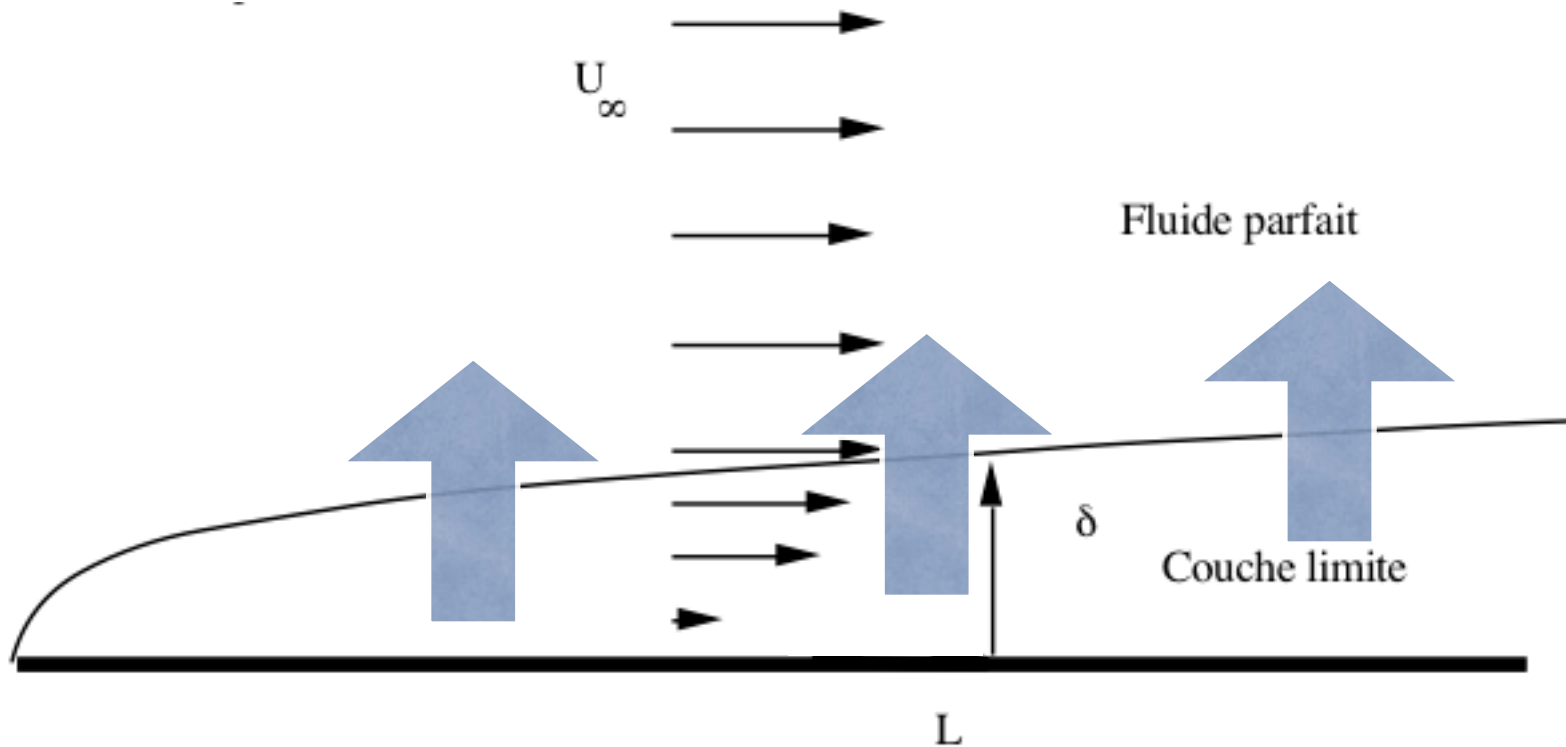
épaisseur de déplacement





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

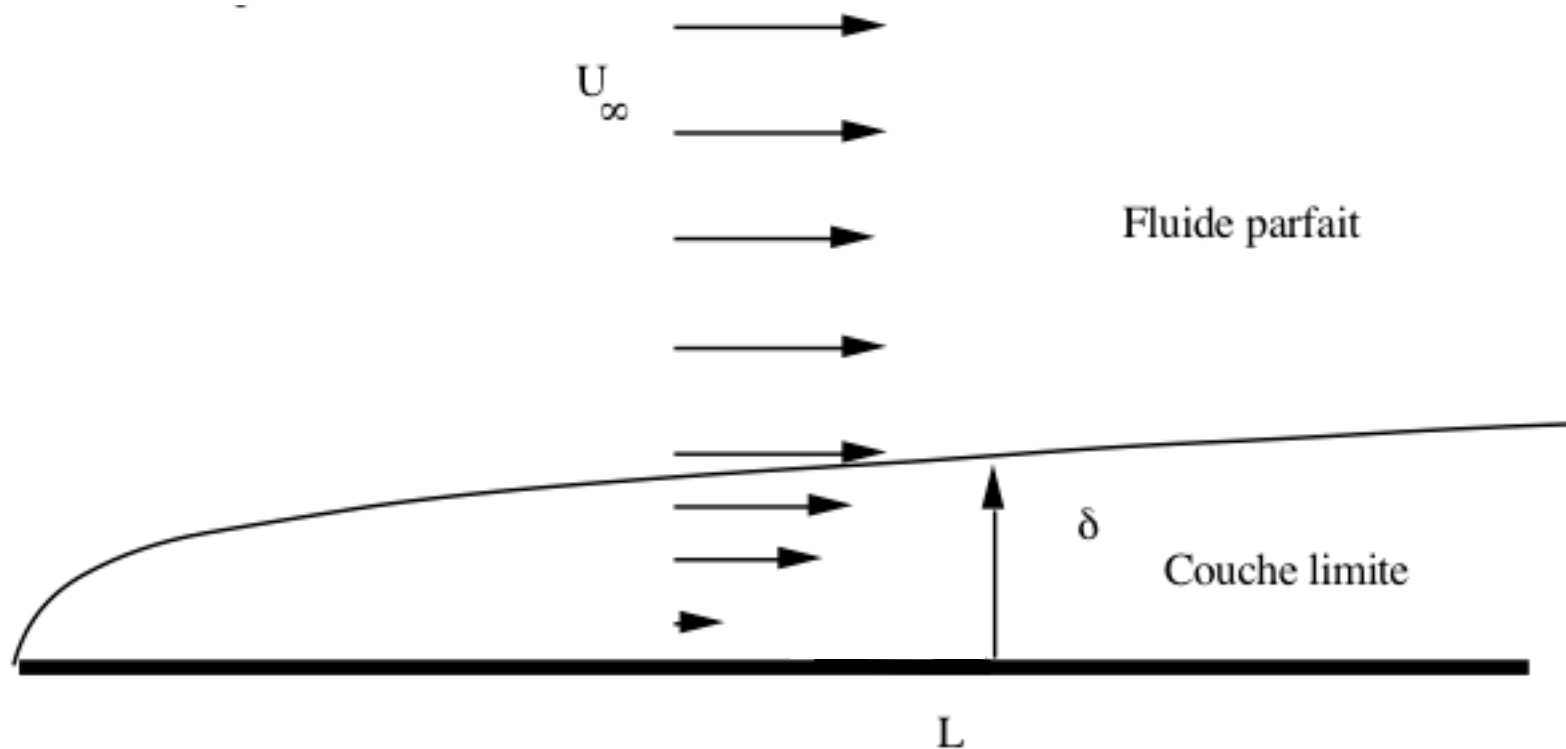
effet de second ordre



Interactive Boundary Layer

$$u_e = 1 + \frac{1}{\pi} \int \frac{\frac{\partial \delta_1}{\partial x}}{x - \xi} d\xi$$

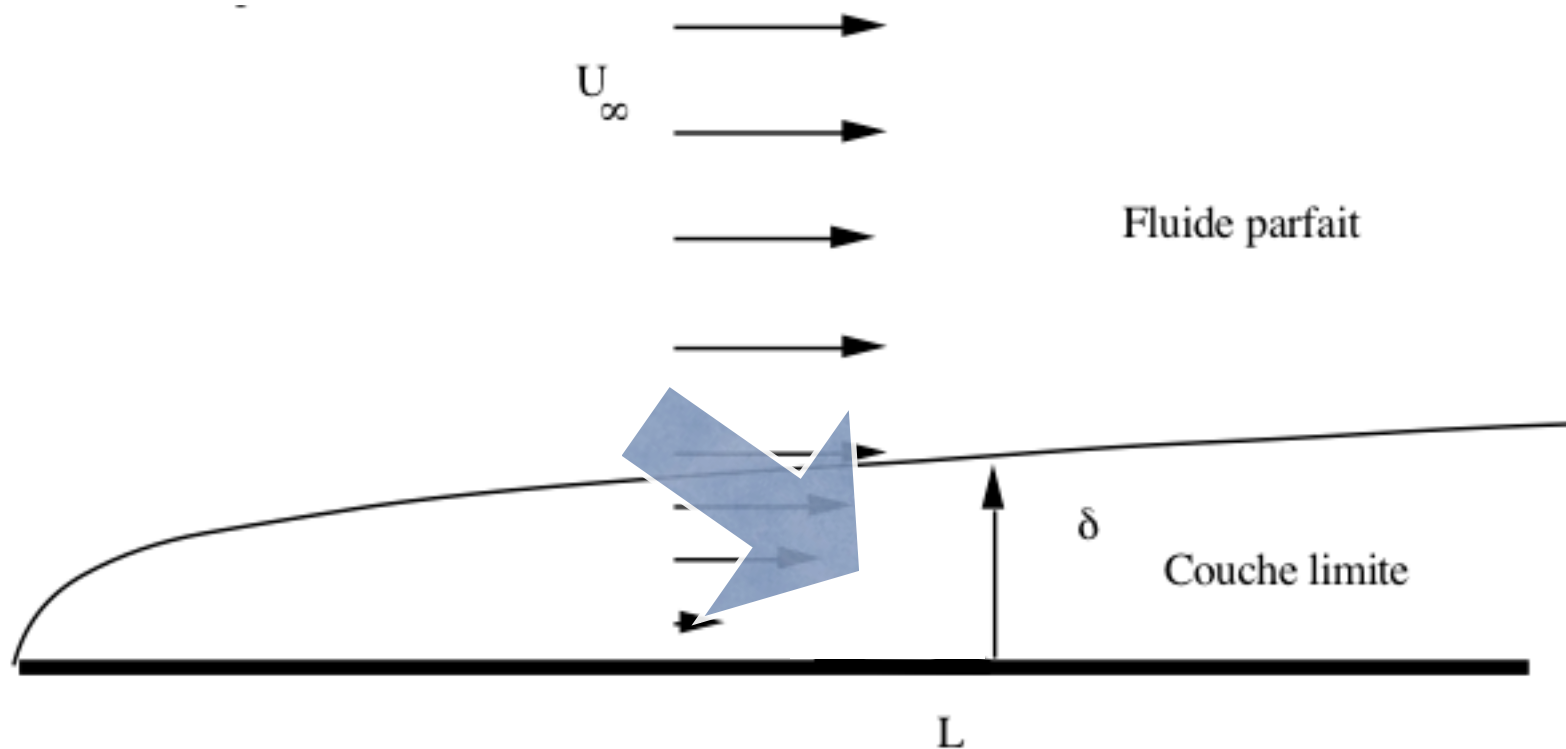
interaction forte



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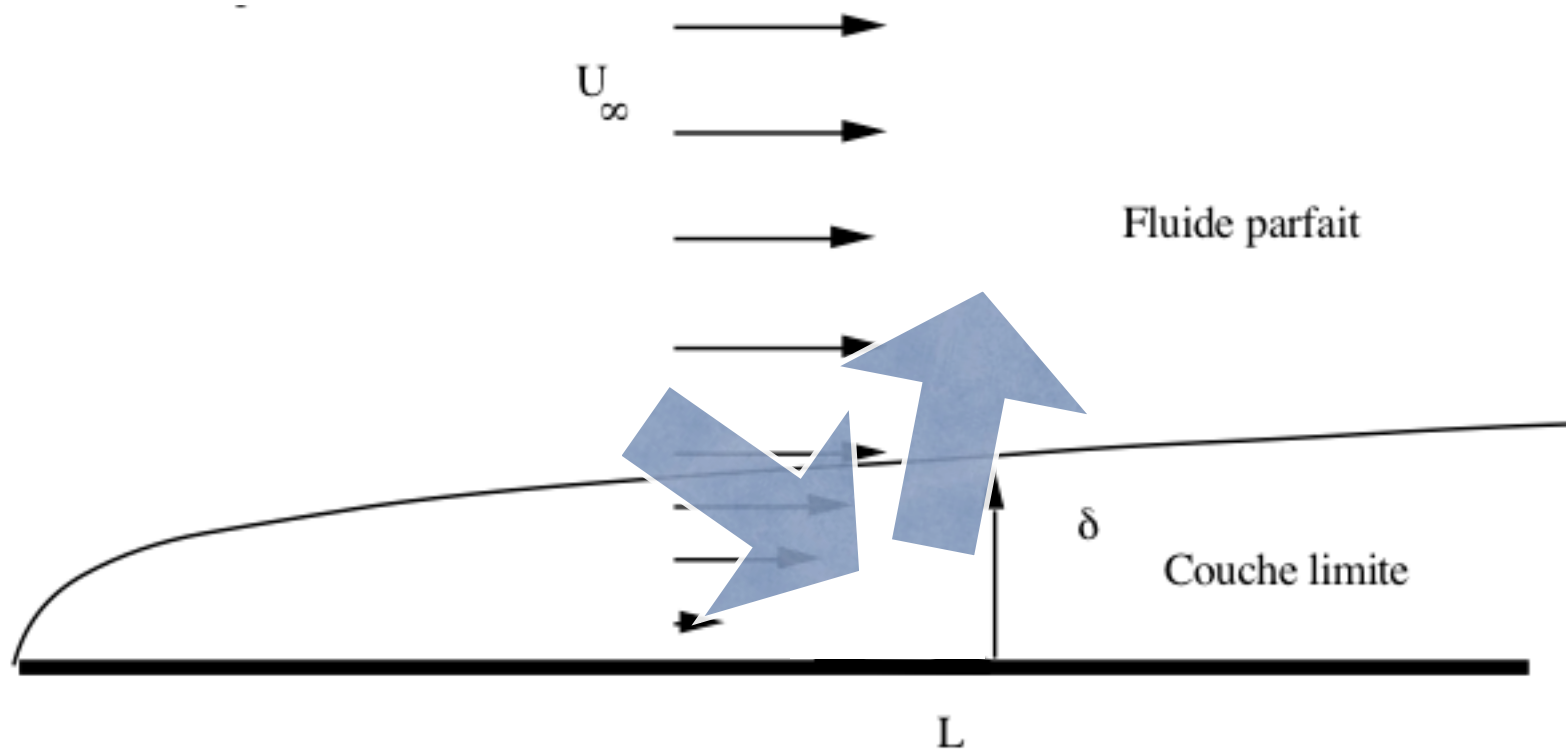
interaction forte



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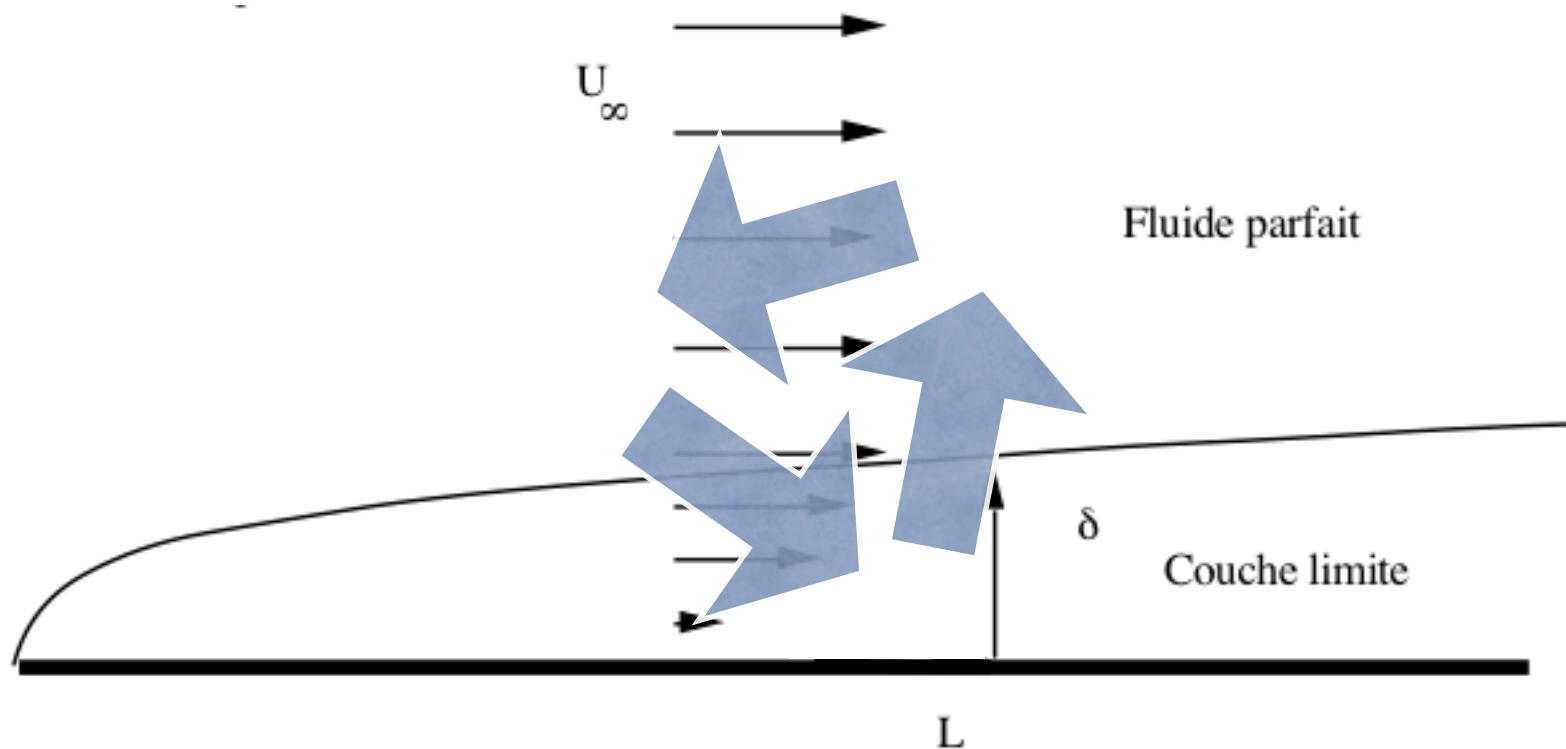
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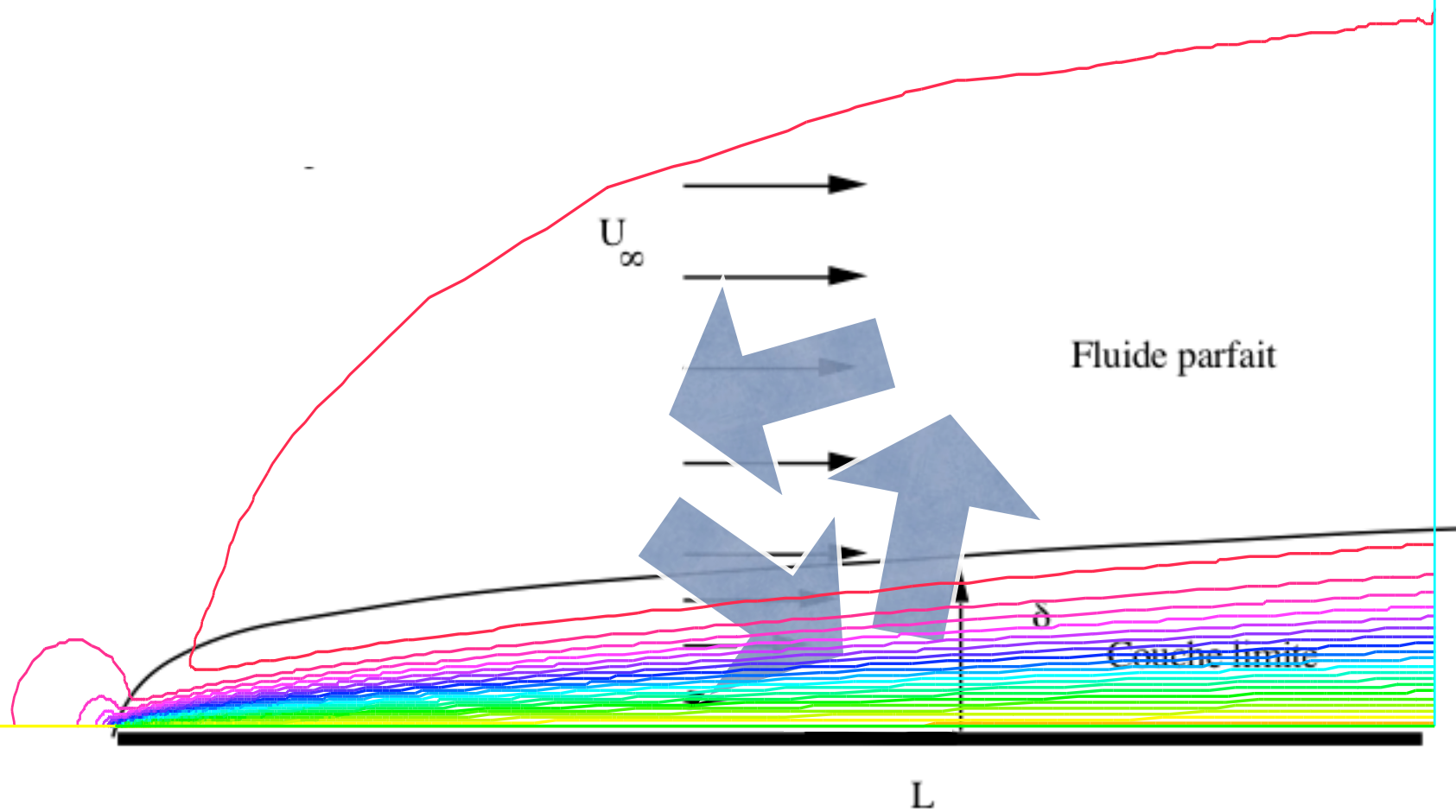


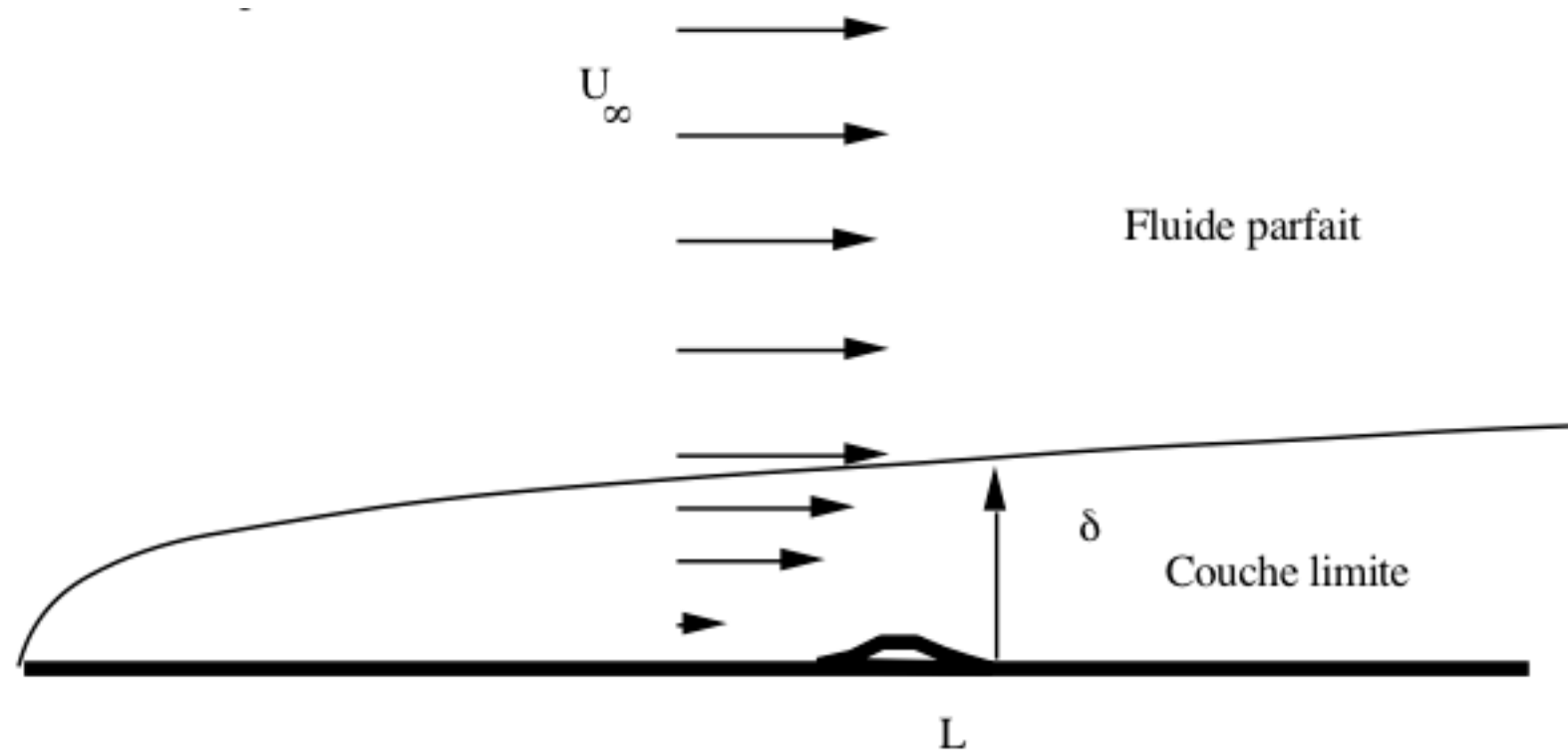
Interactive Boundary Layer

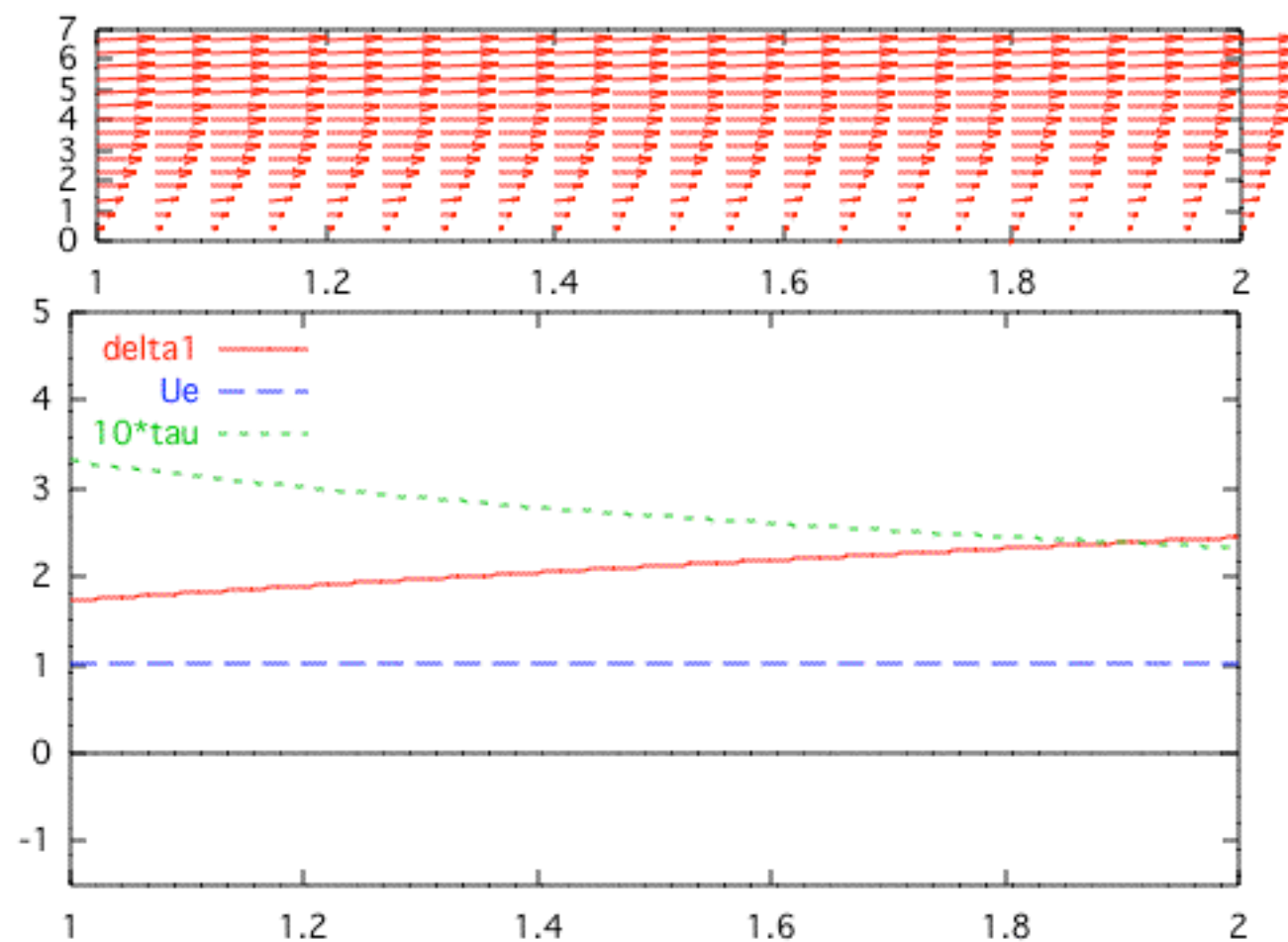
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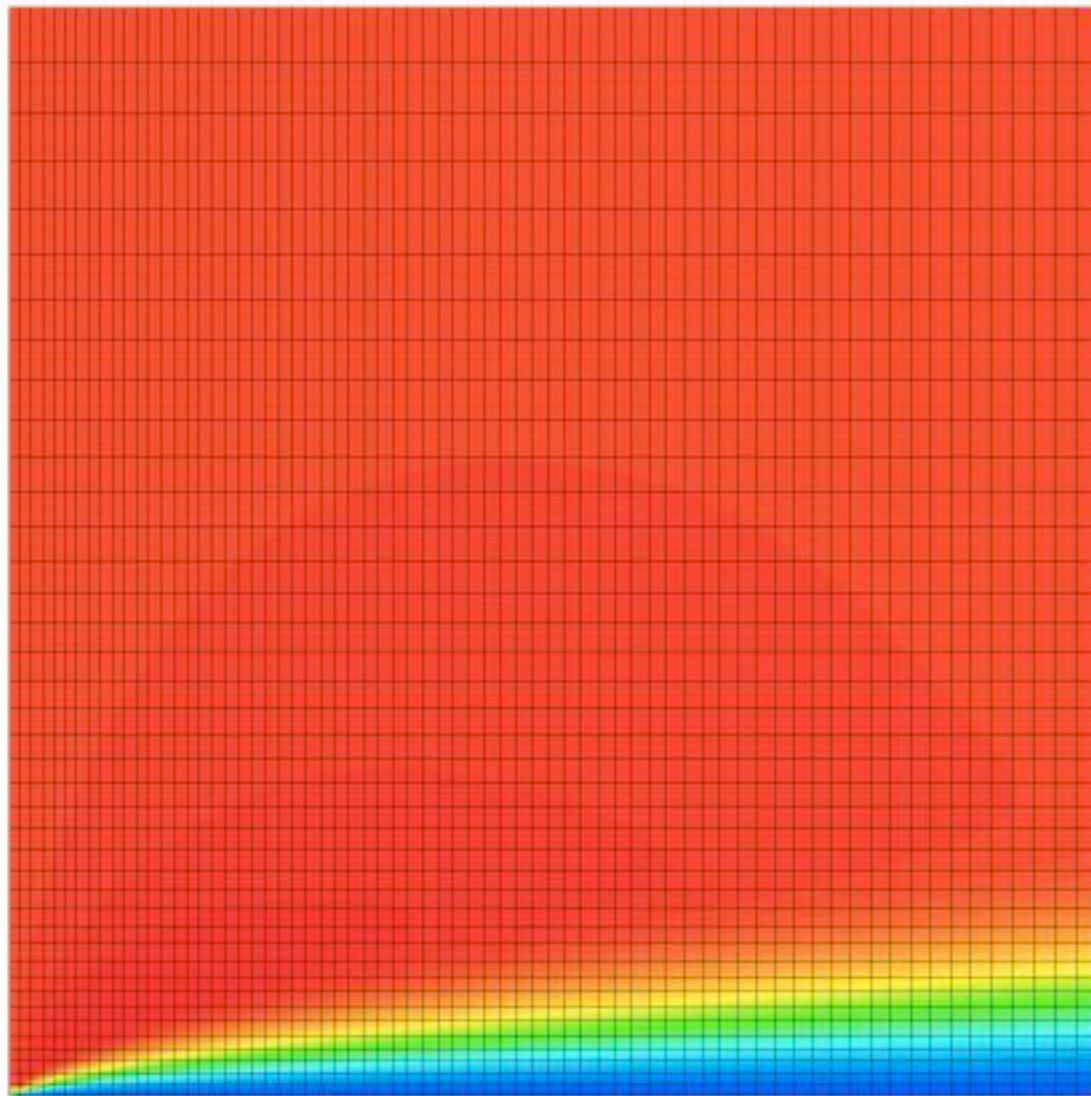
interaction forte





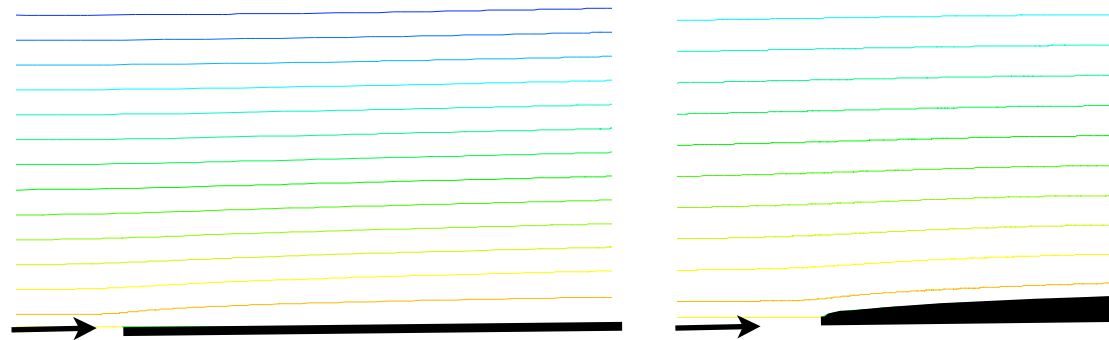




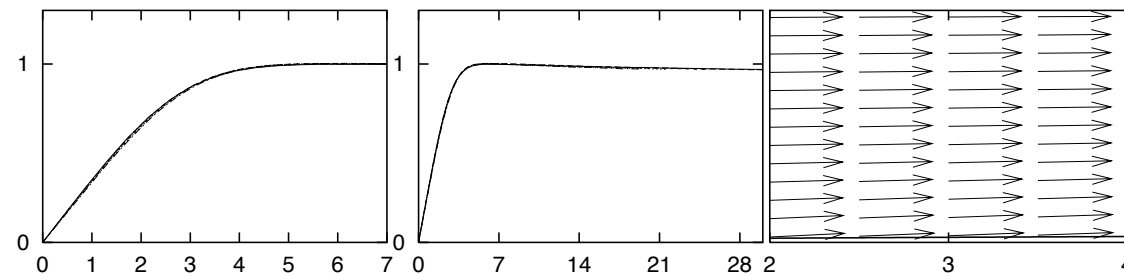


Navier Stokes par CASTEM

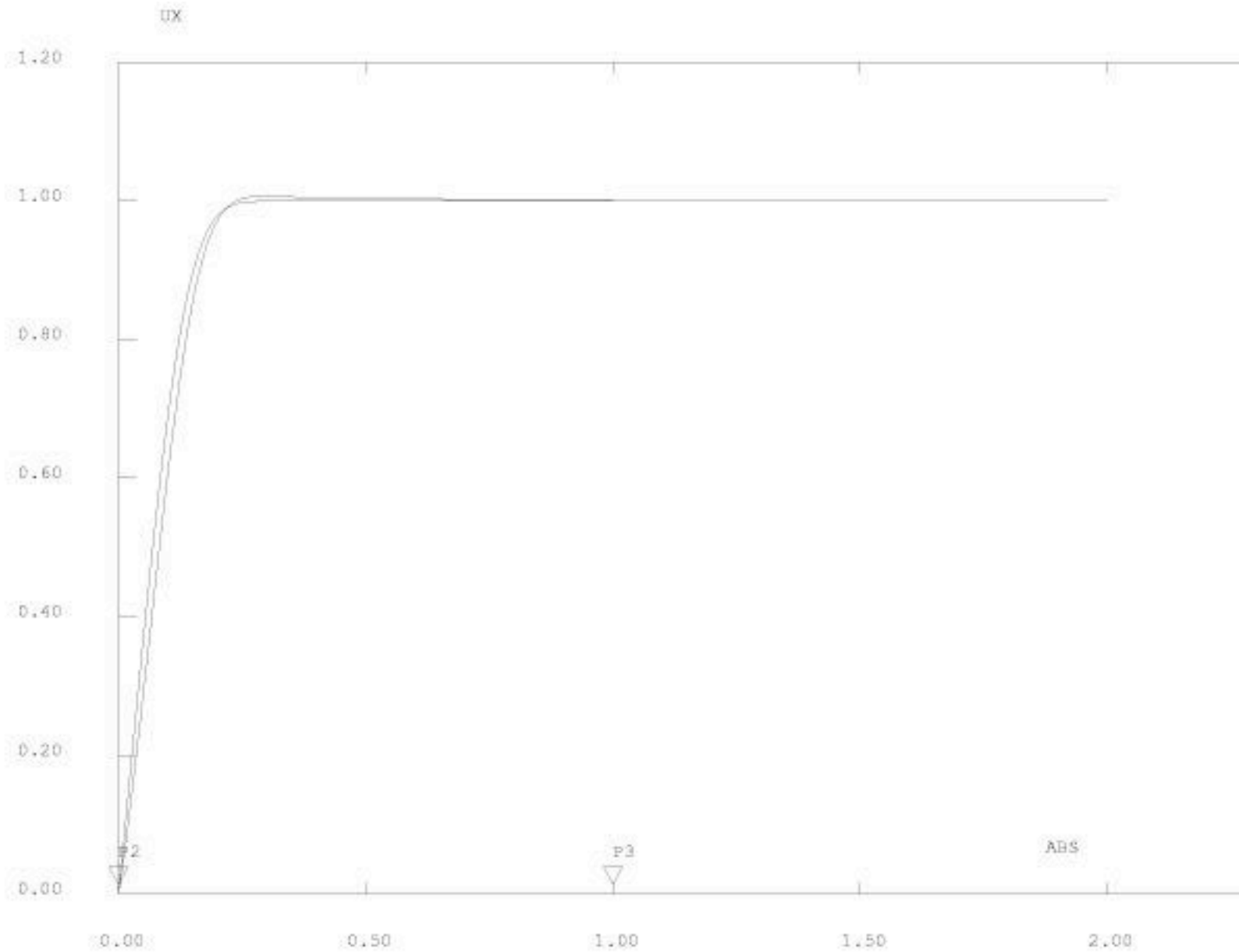
Re=500 Vitesse: iso U



- À gauche, calcul de Navier Stokes par FreeFem++ à $Re = 500$, tracé les lignes de courant. À droite, calcul de fluide parfait sur un corps en $1.7(Re)^{-1/2}\bar{x}^{1/2}$, on voit que les lignes de courant sont (presque) les mêmes, autrement dit on observe l'effet de soufflage de la couche limite sur le fluide parfait (effet de second ordre).



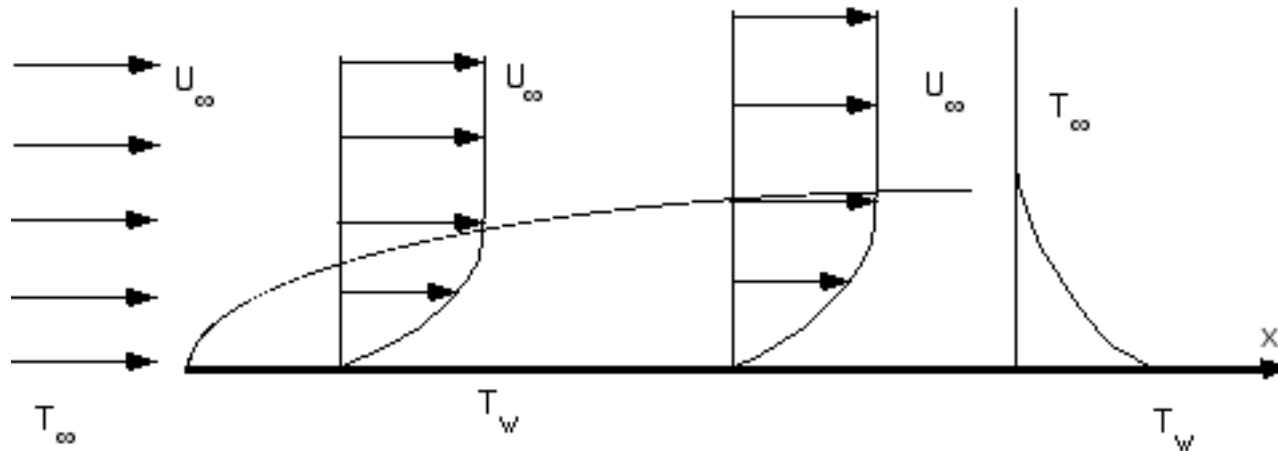
– Calcul de Navier Stokes par FreeFem++ à $Re = 500$, à gauche on retrouve bien le profil autosemblable de Blasius (par superposition parfaite de différents profils tracés en fonction de la variable de similitude $\bar{y}(Re/\bar{x})^{1/2}$). Au centre, si on regarde plus loin "que la couche limite" ces mêmes profils, on observe qu'il y a une décroissance de la vitesse. A droite, la vitesse de fluide parfait sur un corps en $1.7(Re)^{-1/2}\bar{x}^{1/2}$, on voit que la vitesse de fluide parfait décroît de la valeur de glissement à la valeur à l'infini lorsque l'on s'éloigne de la paroi. La surcroissance de vitesse (observée au centre et à droite) s'interprète comme un effet de second ordre.



Navier Stokes par CASTEM

$Re=500$
profil réduits // Blasius

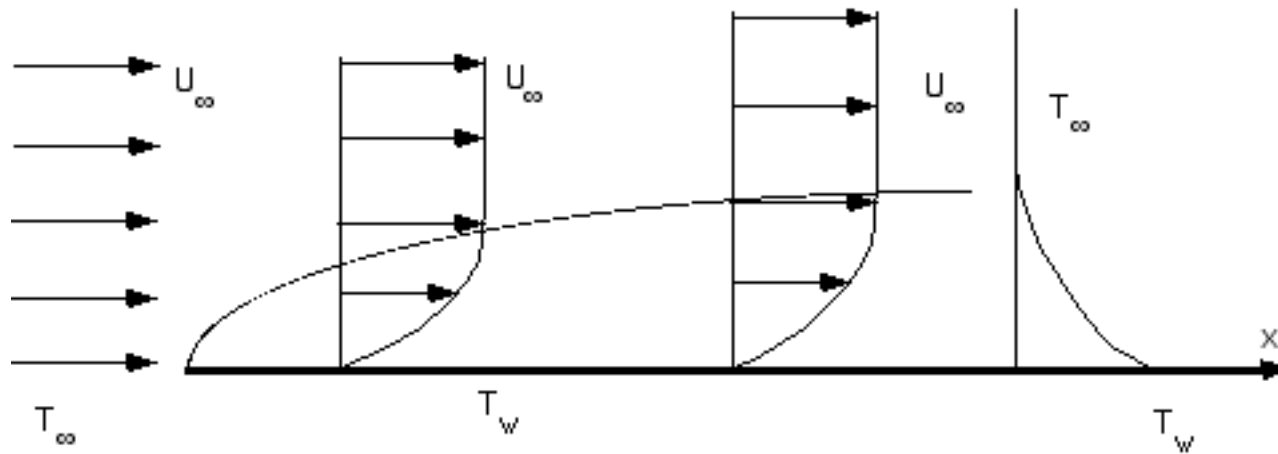
Couche limite dynamique et thermique incompressible sur une plaque plane



$$(\bar{\underline{u}} \cdot \bar{\underline{\nabla}}) \bar{T} = \frac{1}{Pe} \bar{\underline{\nabla}}^2 \bar{T} + 2 \frac{E}{R_\infty} \bar{\underline{D}} : \bar{\underline{D}},$$

température imposés sur la paroi, à l'infini

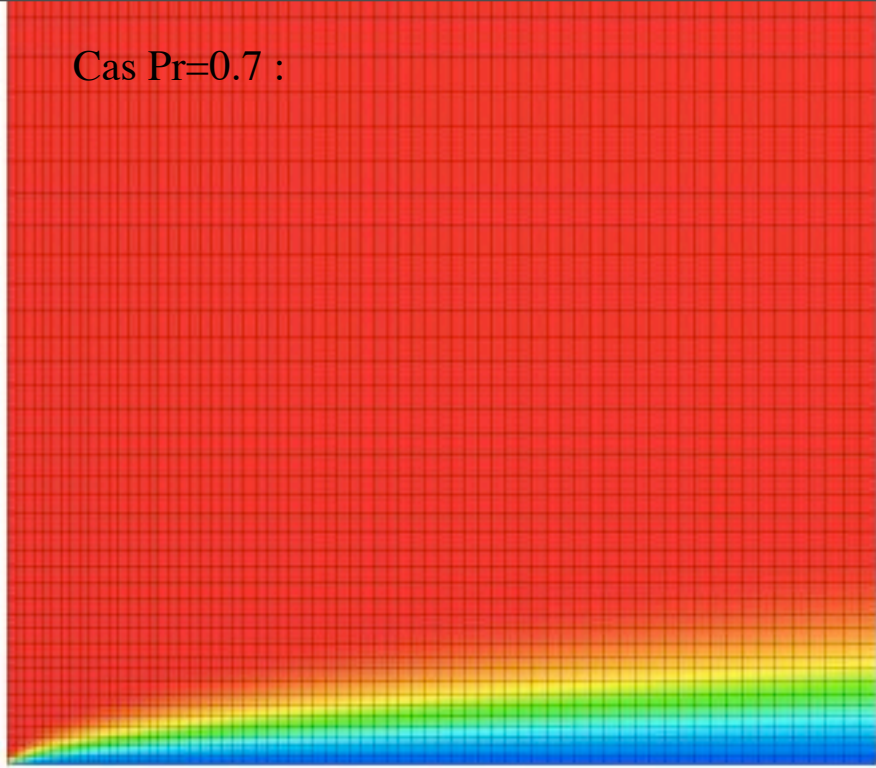
Couche limite dynamique et thermique incompressible sur une plaque plane



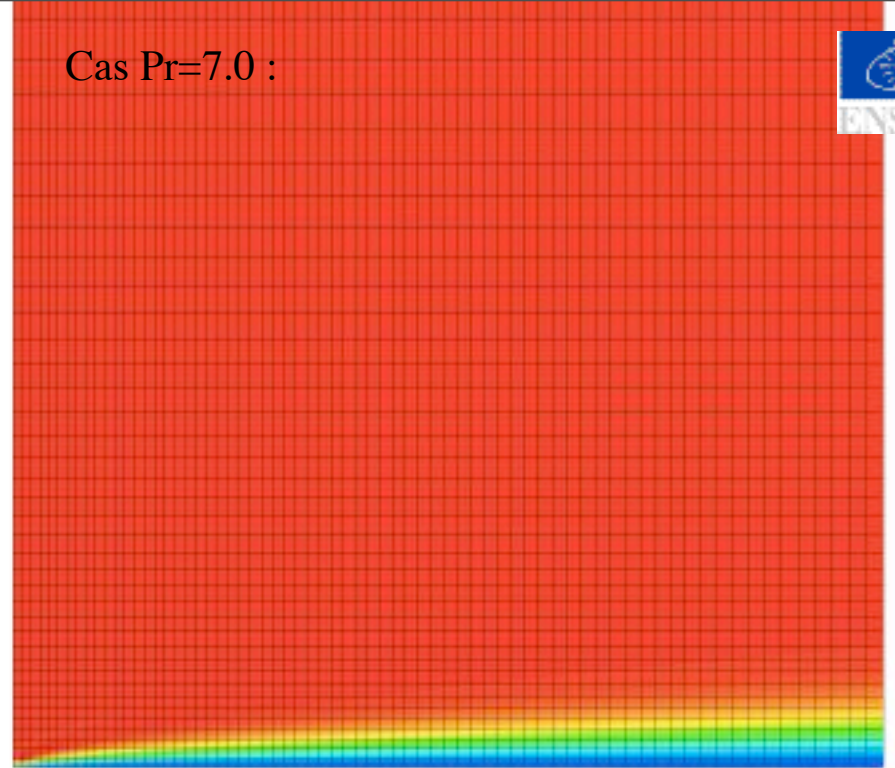
$$\tilde{u} \frac{\partial \tilde{T}}{\partial \tilde{x}} + \tilde{v} \frac{\partial \tilde{T}}{\partial \tilde{y}} = \frac{1}{Pr} \frac{\partial^2 \tilde{T}}{\partial \tilde{y}^2} + E \left(\frac{\partial \tilde{u}}{\partial \tilde{y}} \right)^2.$$

$$\tilde{T}(\tilde{x}, 0) = 1, \tilde{T}(\tilde{x}, \infty) = 0.$$

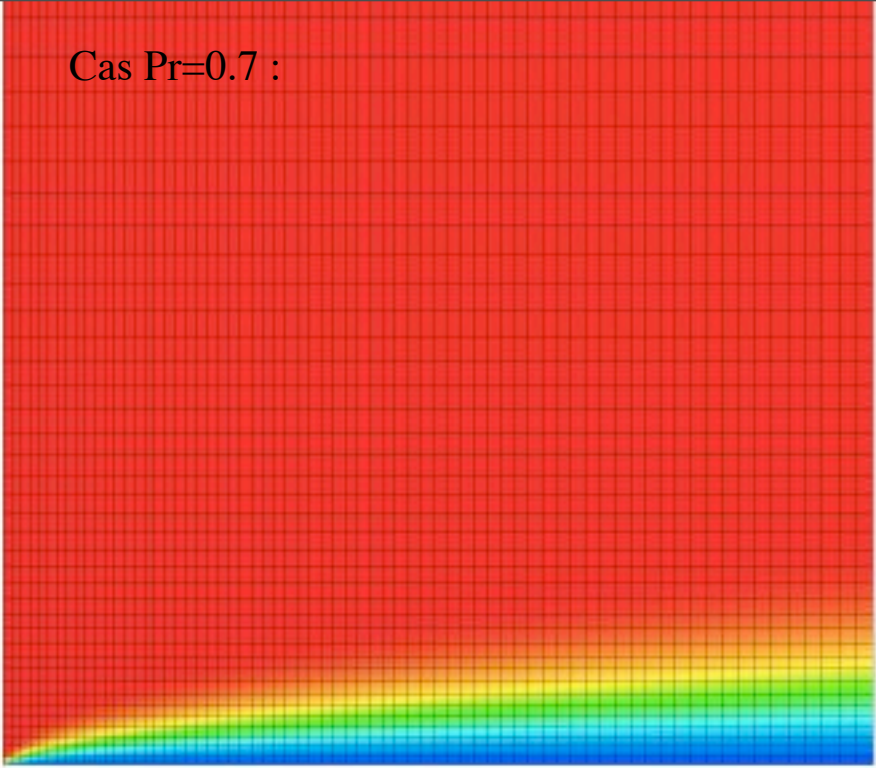
Cas $Pr=0.7$:



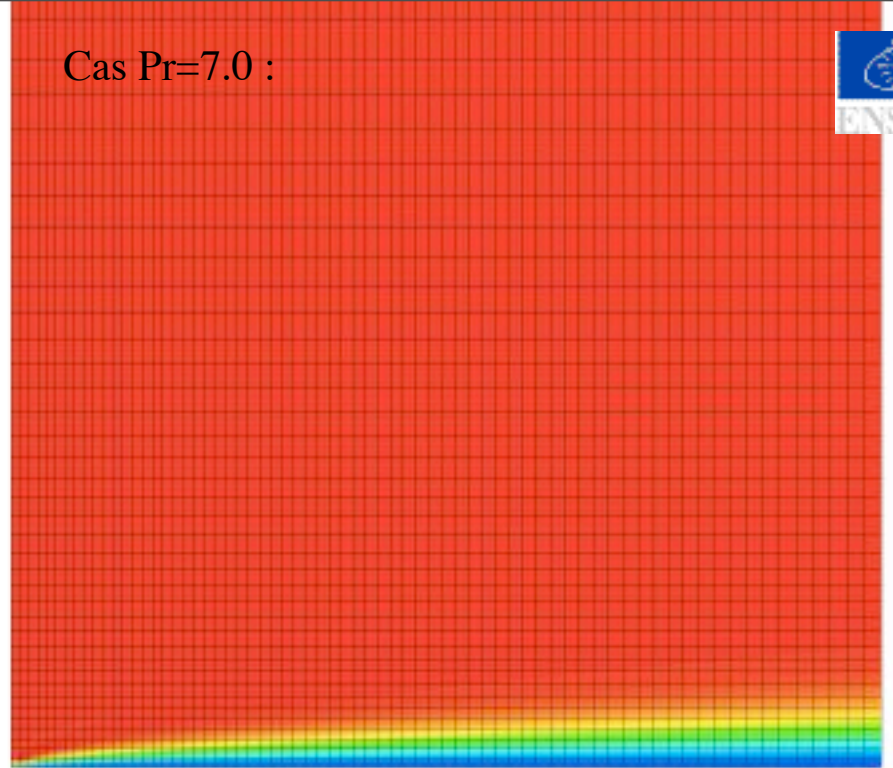
Cas $Pr=7.0$:



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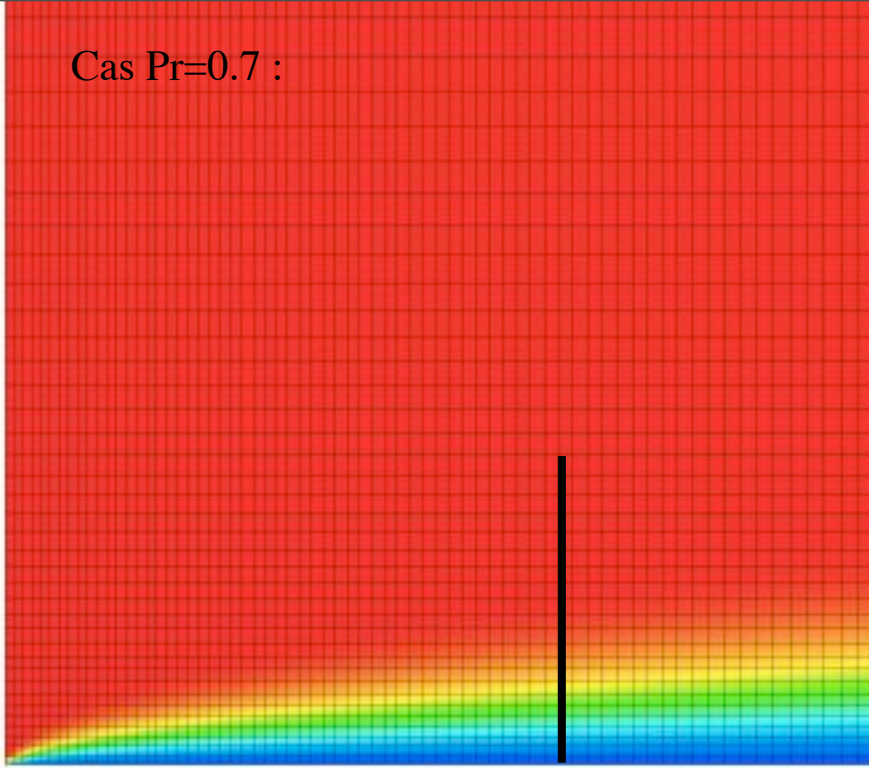
$$\tilde{T} = g(\eta).$$

$$2g'' + Prfg' + 2EPrf''^2 = 0.$$

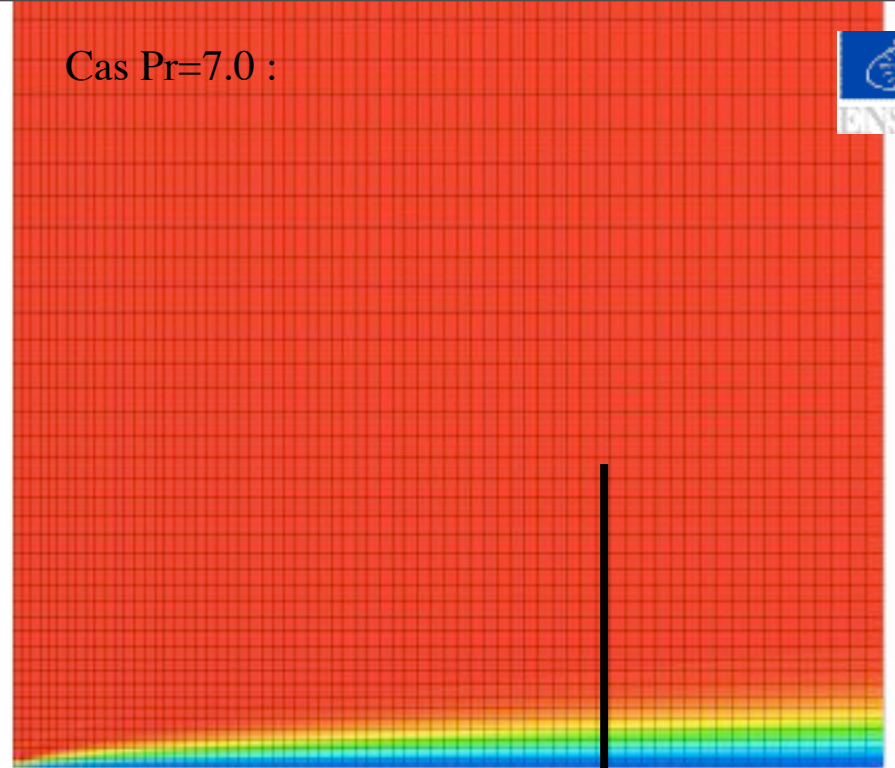
$$E = 0, \quad \begin{array}{ll} \text{à } Pr=0.7 & g'(0)=-0.293 \\ \text{à } Pr=1 & g'(0)=-0.332 \\ \text{à } Pr=7 & g'(0)=-0.646 \end{array}$$

$$g'(0) = -0.332Pr^{-1/3}$$

Cas $Pr=0.7$:



Cas $Pr=7.0$:



$$\tilde{T} = g(\eta).$$

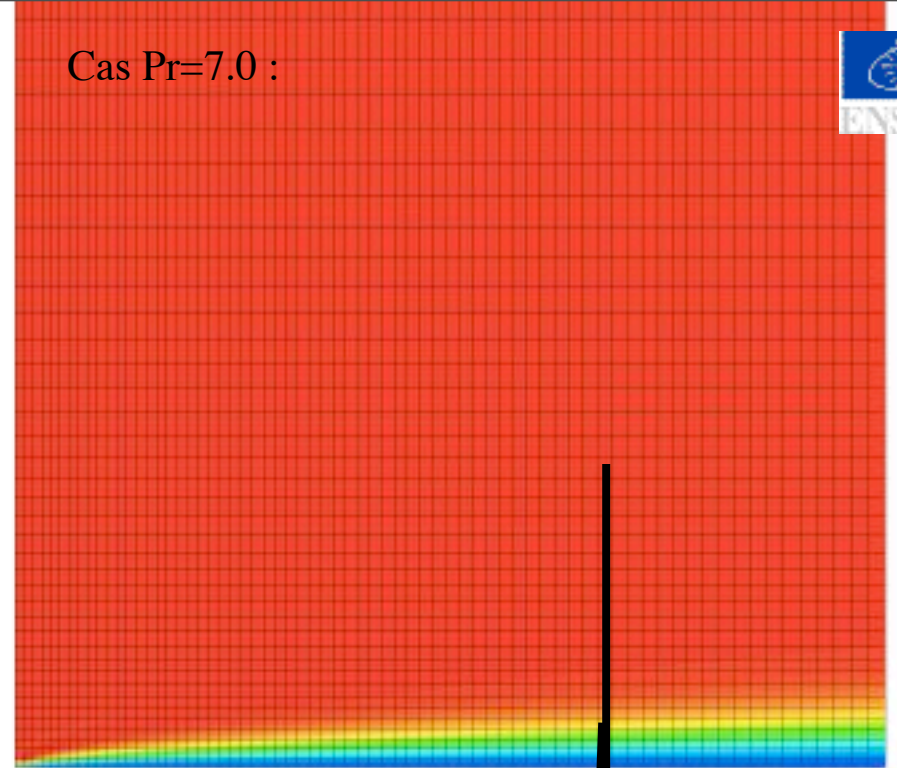
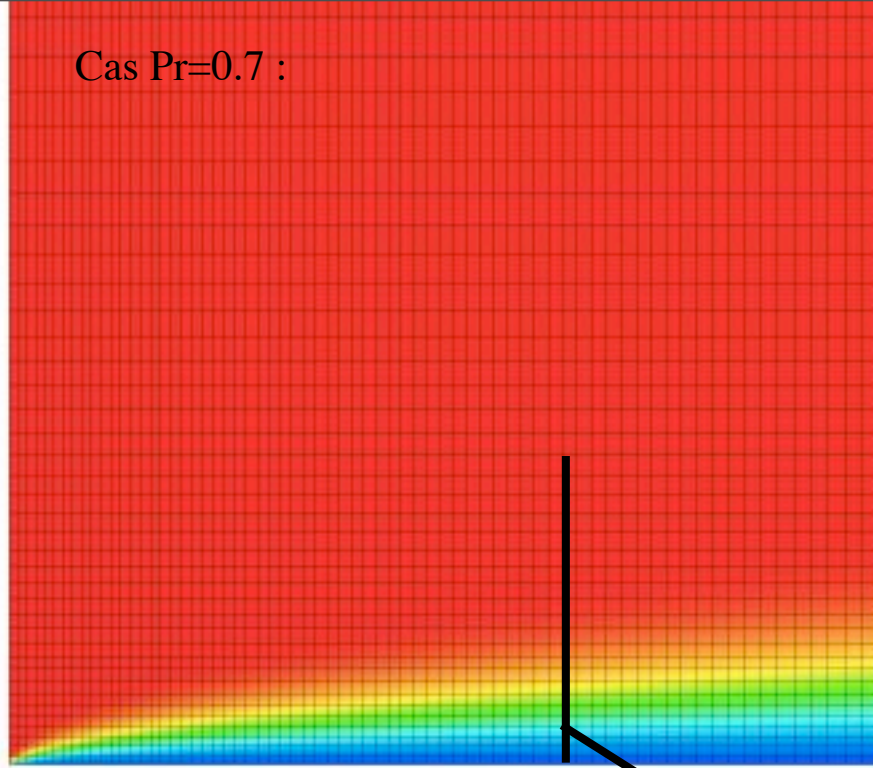
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2001 Education Recherche : GIBI FBCIT

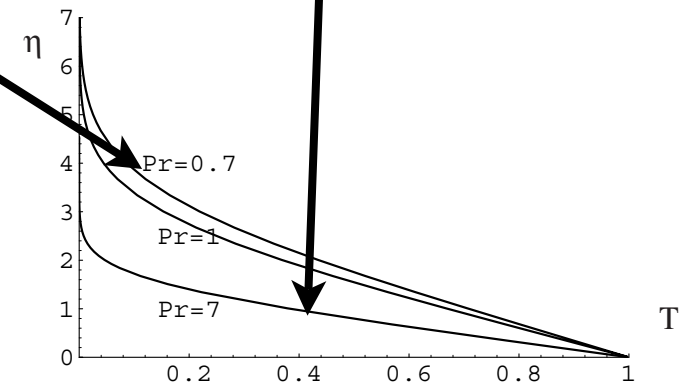
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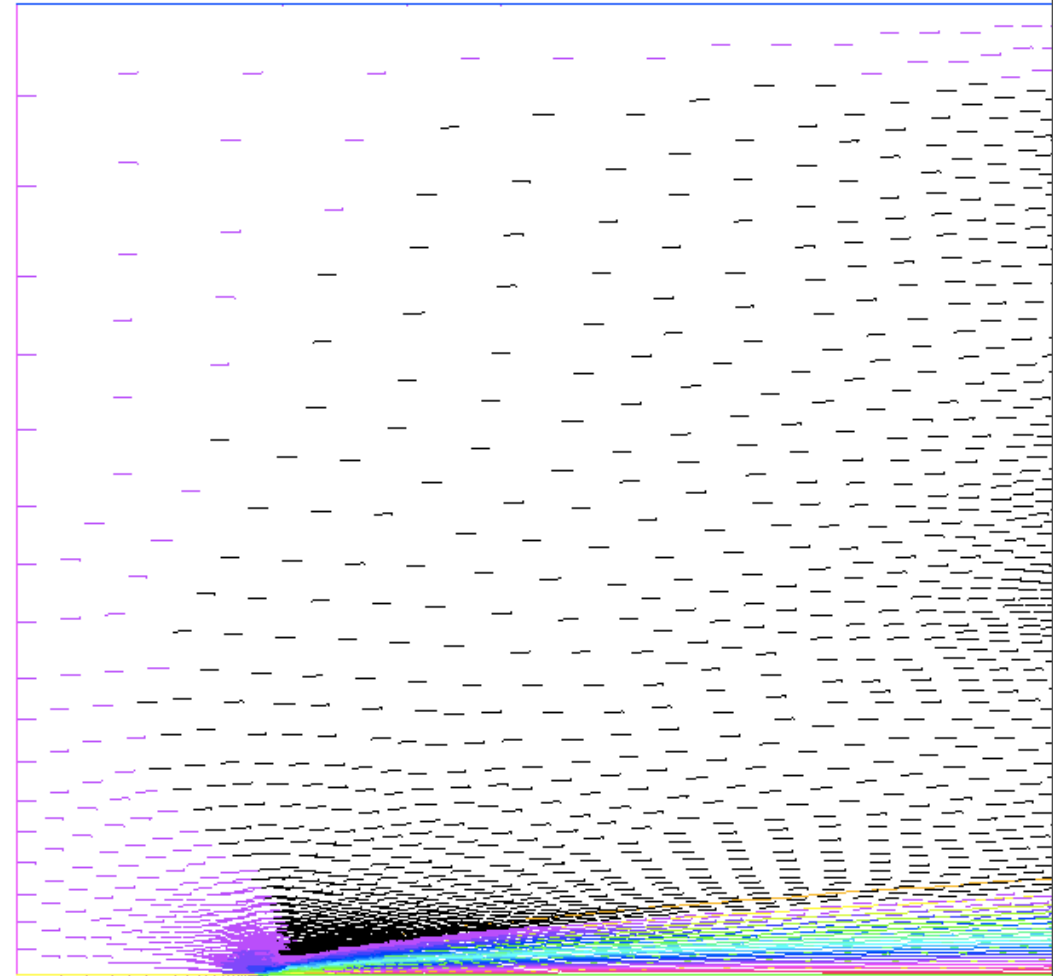
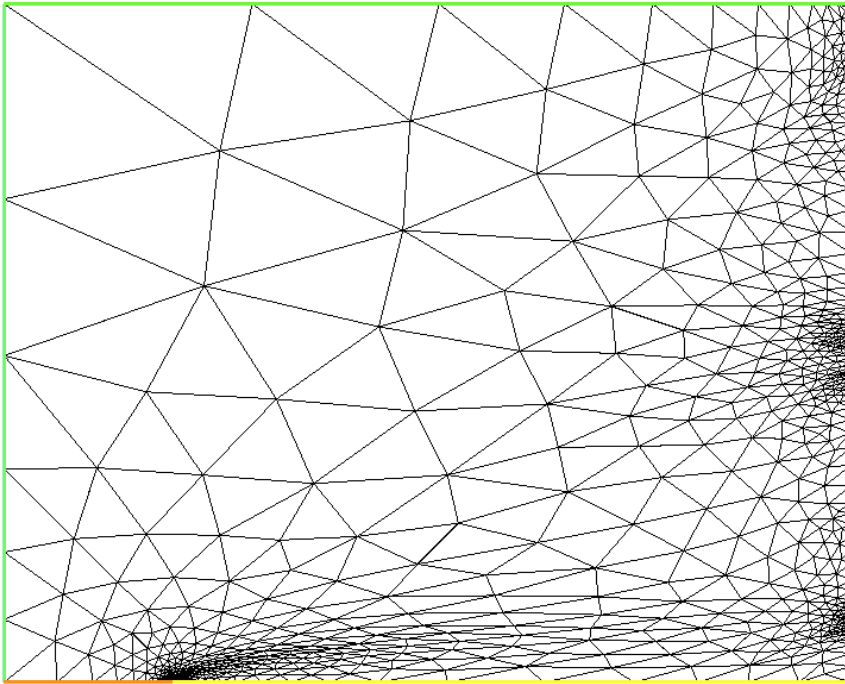
à $Pr=0.7$	$g'(0)=-0.293$
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à $Pr=7$	$g'(0)=-0.646$

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Cas Pr=0.7 :

Cas Pr=7.0 :



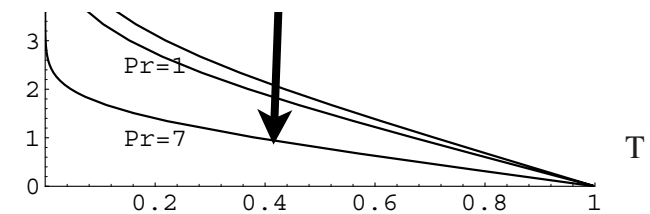
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$$2g'' + Prfg' + 2EPrf''^2$$

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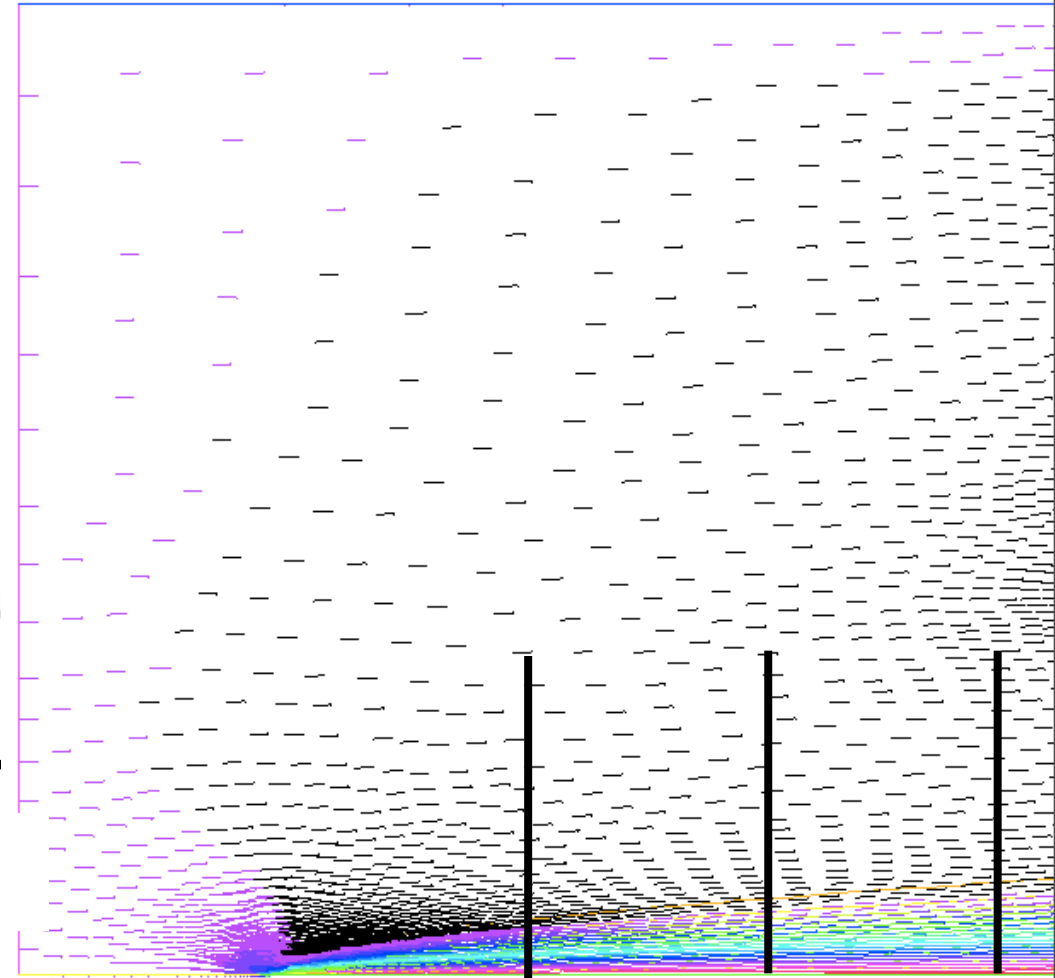
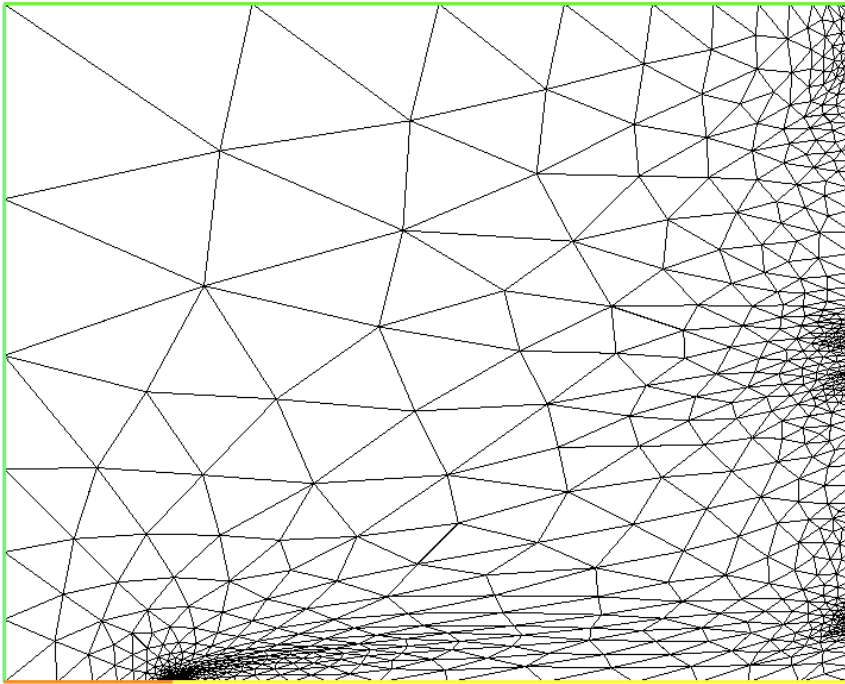
à $P_r=0.7$	$g'(0)=-0.293$
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Cas Pr=0.7 :

Cas Pr=7.0 :



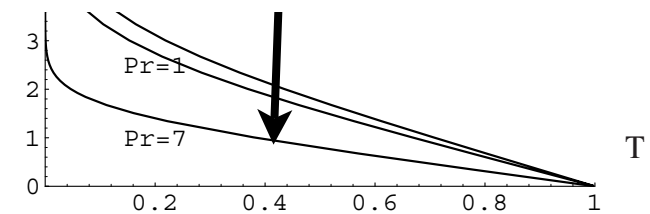
cas $E=0, Pr=1$ $\tilde{T} = g(\eta).$

$$2g'' + \eta f g' = 0$$

$E = 0,$

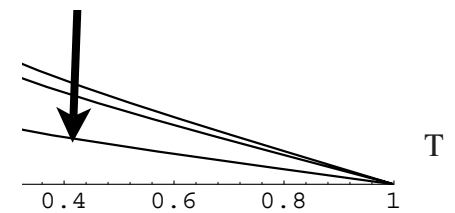
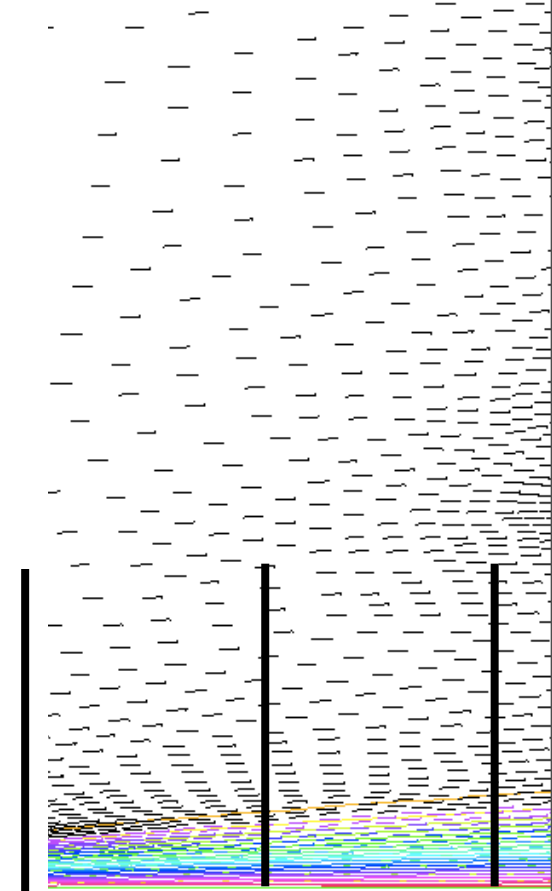
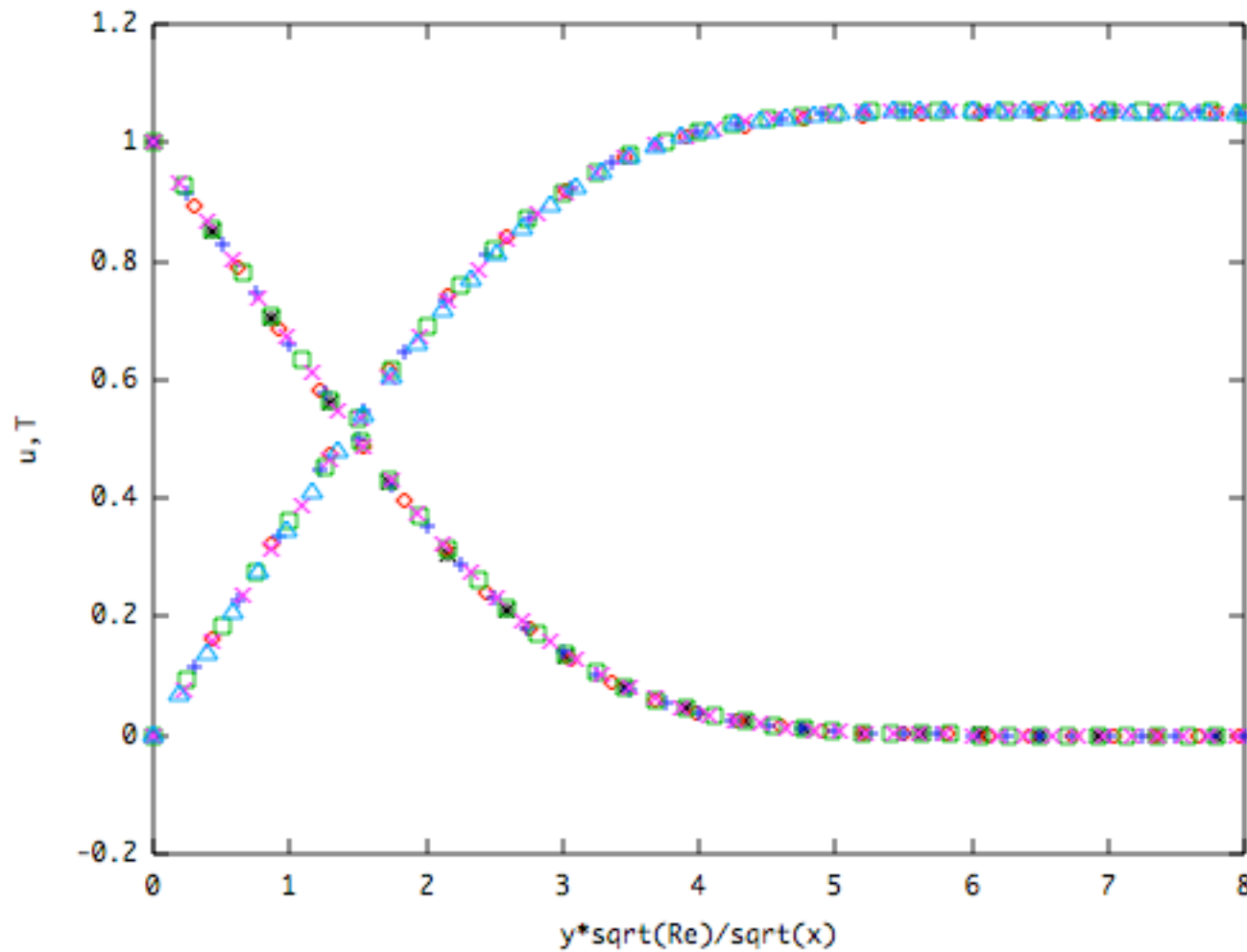
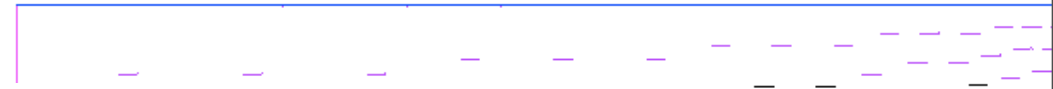
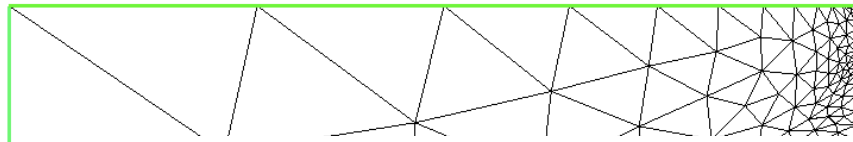
$\rightarrow Pr=0.7$	$g'(0)=-0.293$
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$$g'(0) = -0.332Pr^{-1/3}$$



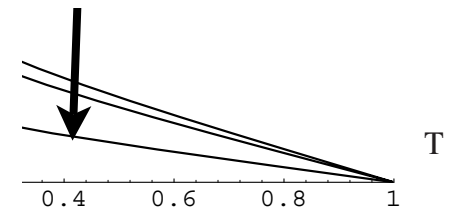
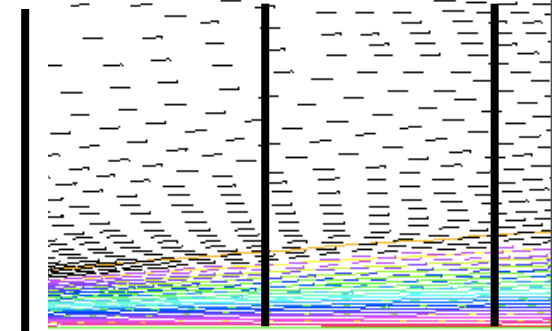
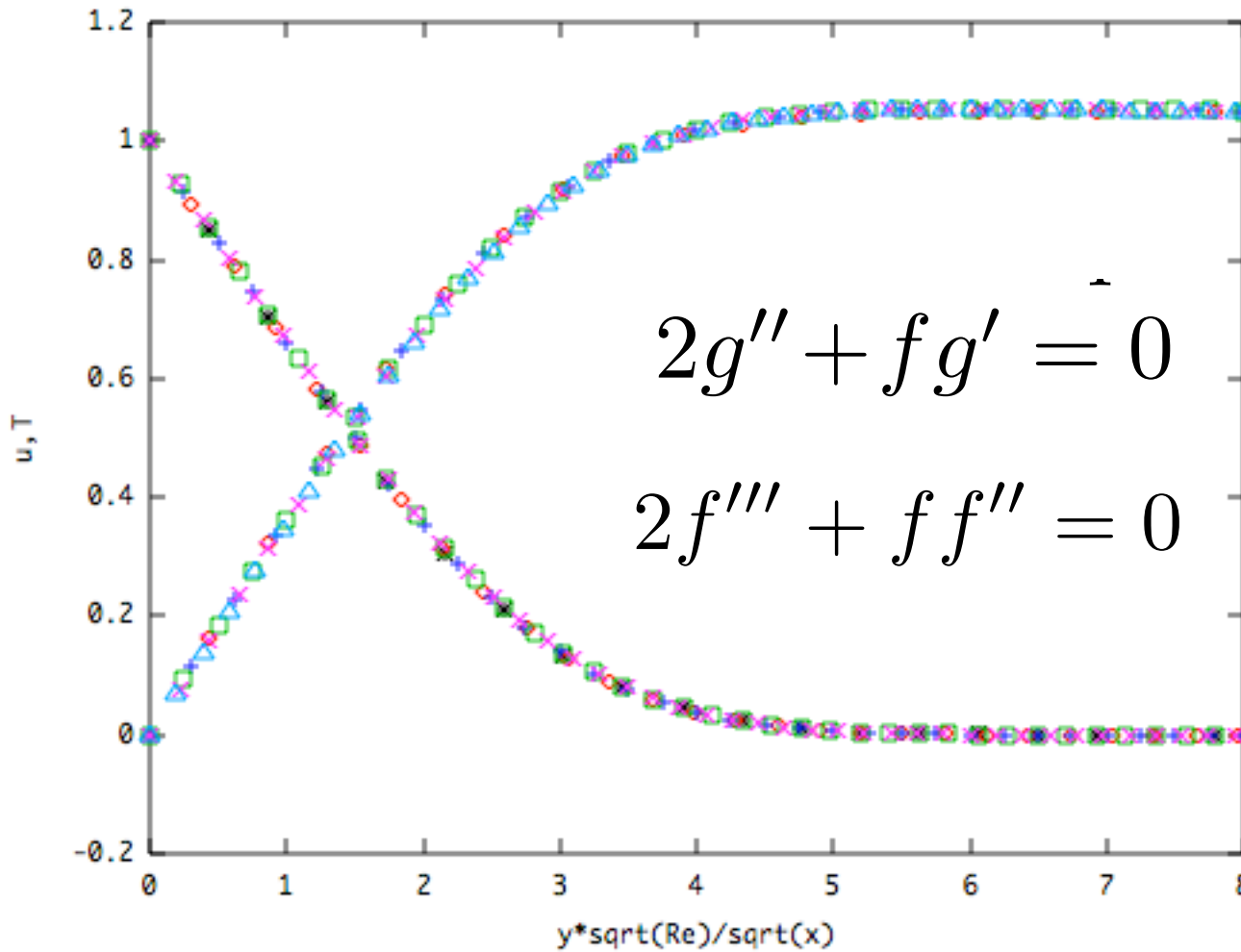
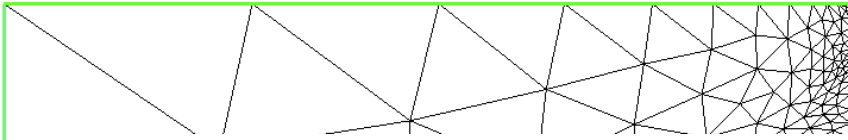
Cas Pr=0.7 :

Cas Pr=7.0 :



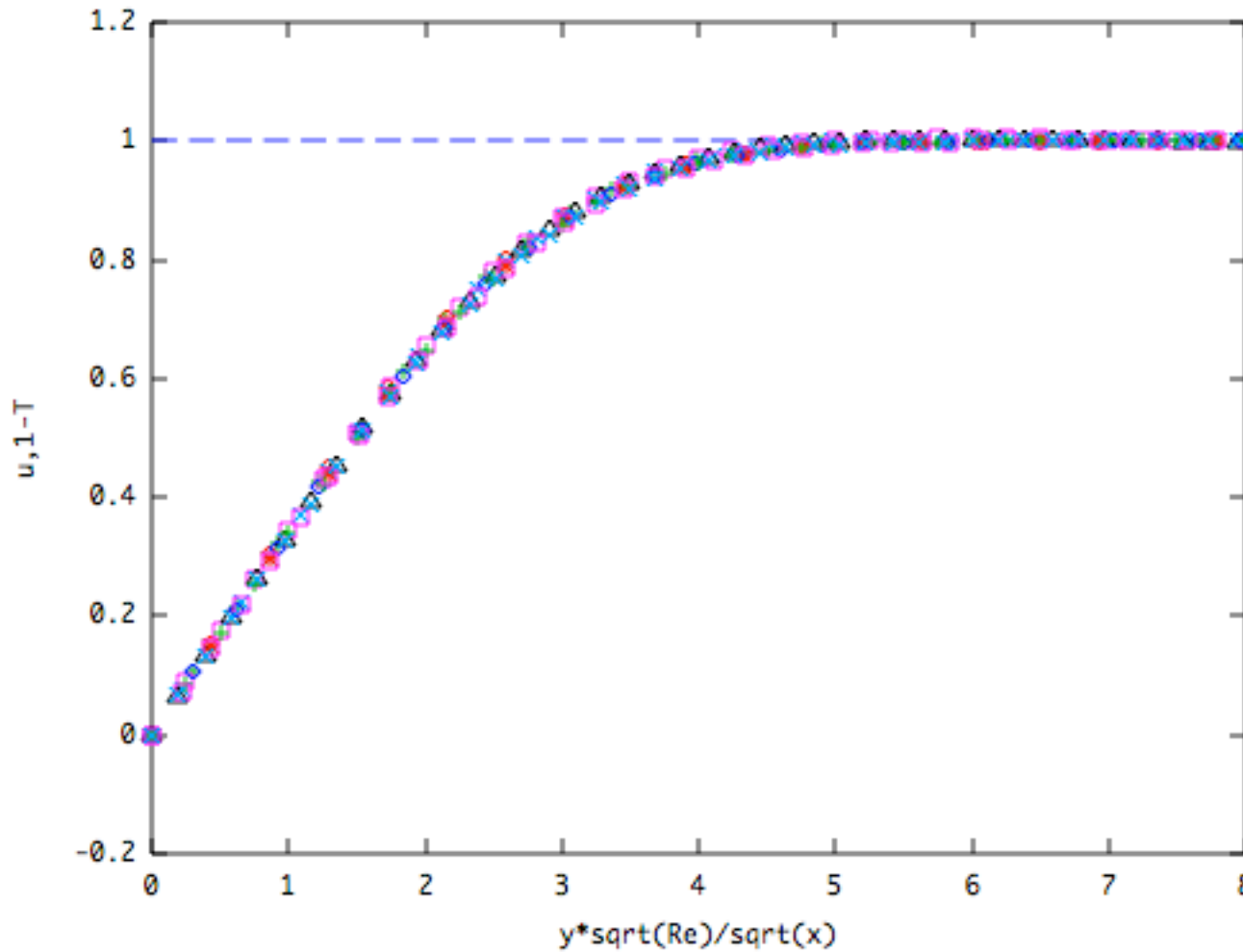
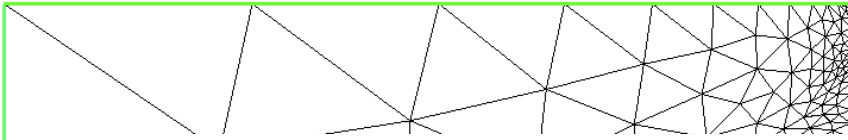
Cas Pr=0.7 :

Cas Pr=7.0 :

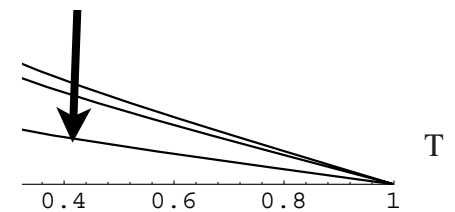
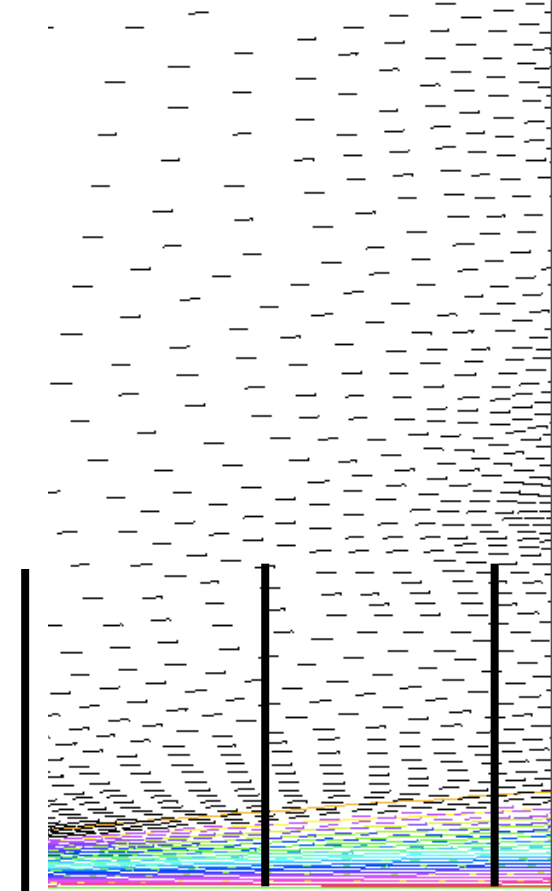


Cas Pr=0.7 :

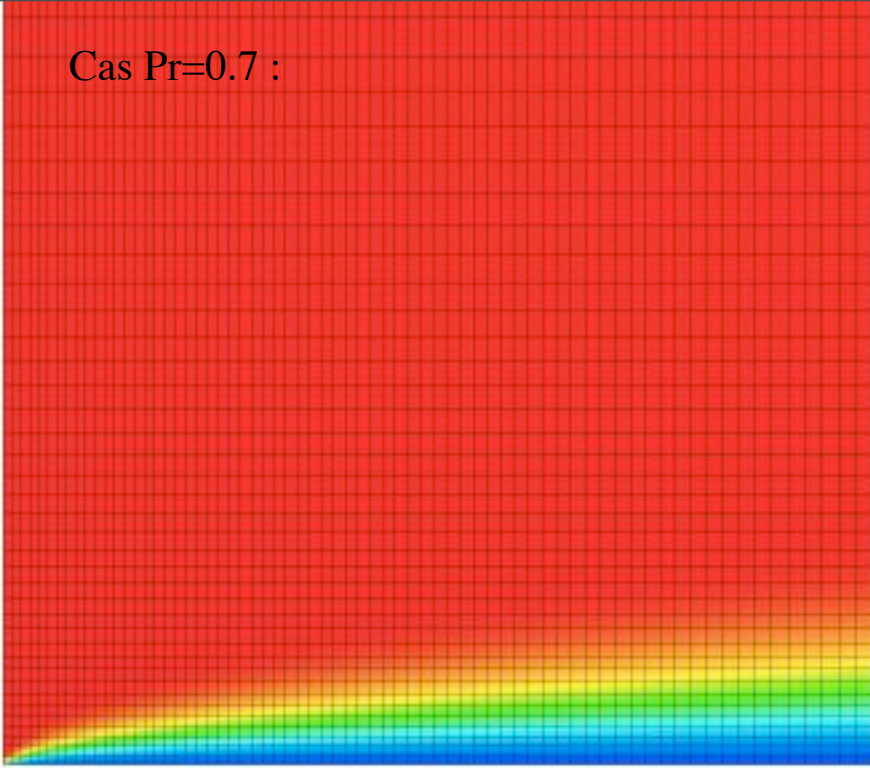
Cas Pr=7.0 :



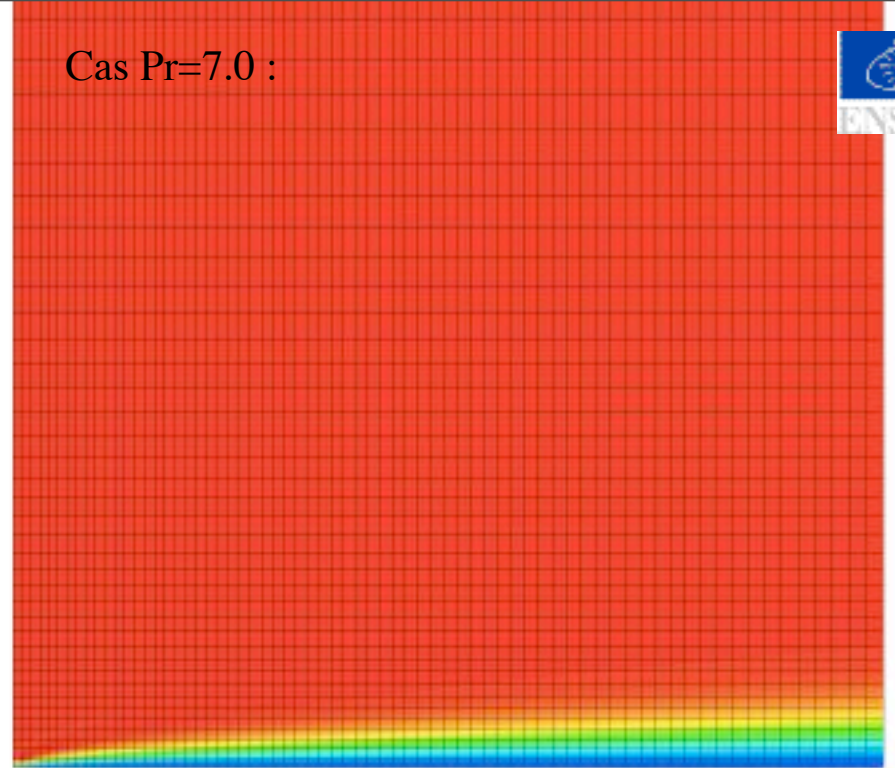
$$u = f' = 1 - T$$



Cas $Pr=0.7$:



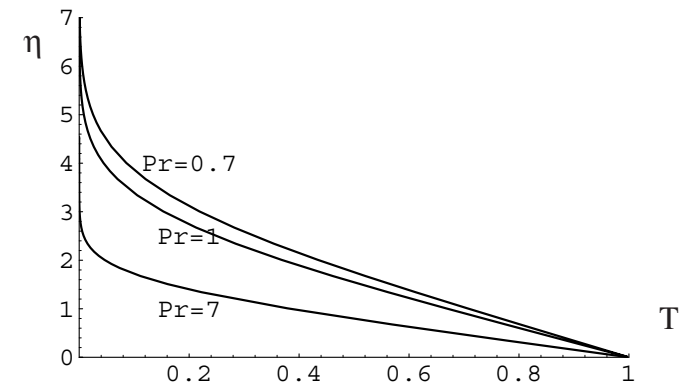
Cas $Pr=7.0$:



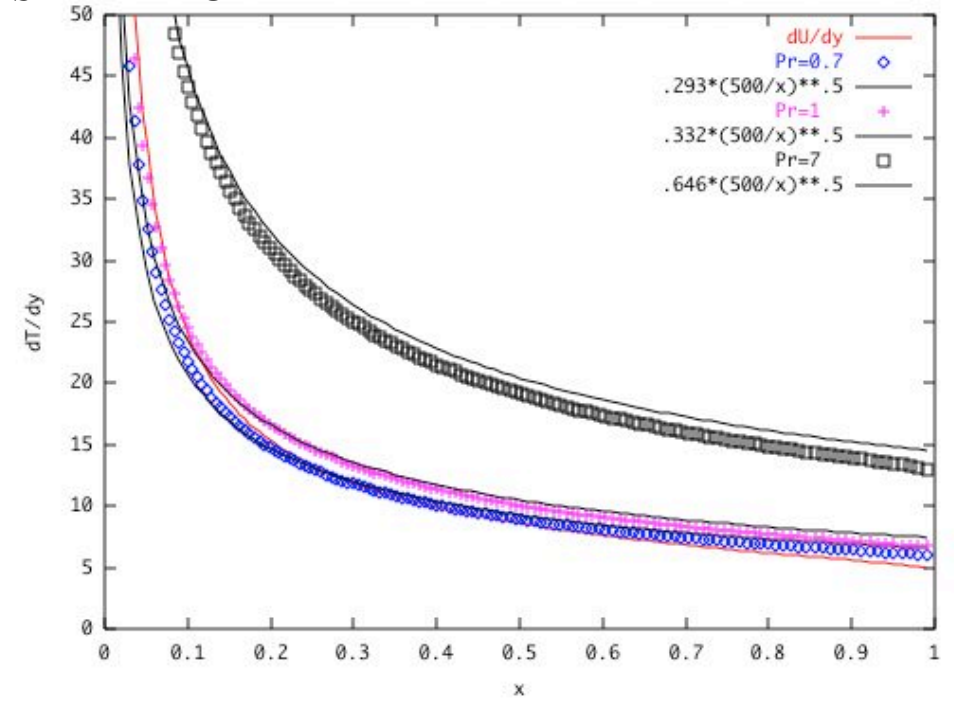
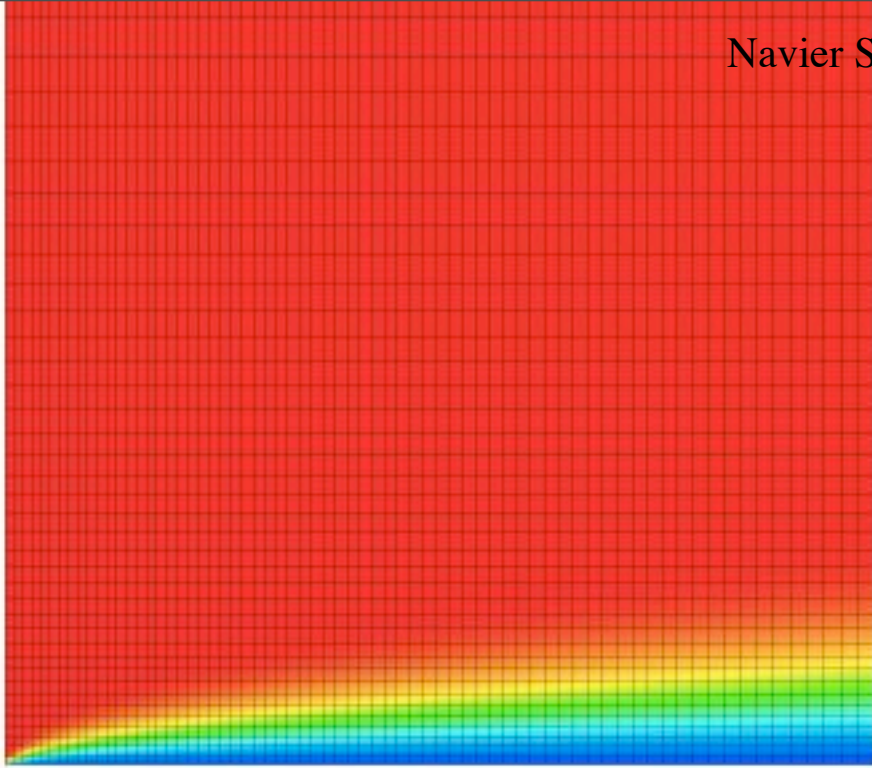
$$\phi = 0.332 Pr^{1/3} k L^{-1} R_{\infty}^{1/2} \frac{T_w - T_{\infty}}{\bar{x}^{1/2}}$$

$$Nu = \frac{\phi L}{k(T_w - T_{\infty})}$$

$$Nu_x = 0.332 Pr^{1/3} R_x^{1/2}.$$



Navier Stokes par CASTEM: FLUX

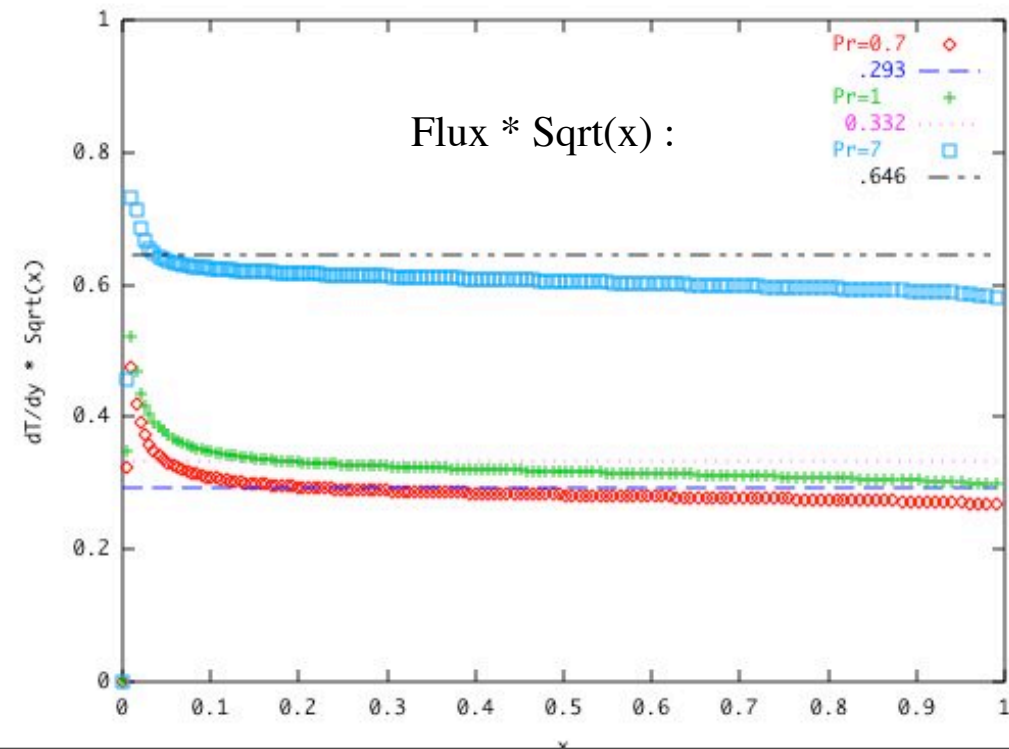


001 Education Recherche : GIBI FBCIT

$$\phi = 0.332Pr^{1/3}kL^{-1}R_{\infty}^{1/2}\frac{T_w - T_{\infty}}{\bar{x}^{1/2}}$$

$$Nu = \frac{\phi L}{k(T_w - T_{\infty})}$$

$$Nu_x = 0.332Pr^{1/3}R_x^{1/2}.$$



Flux imposé

$$\tilde{u} \frac{\partial \tilde{T}}{\partial \tilde{x}} + \tilde{v} \frac{\partial \tilde{T}}{\partial \tilde{y}} = \frac{1}{Pr} \frac{\partial^2 \tilde{T}}{\partial \tilde{y}^2}$$

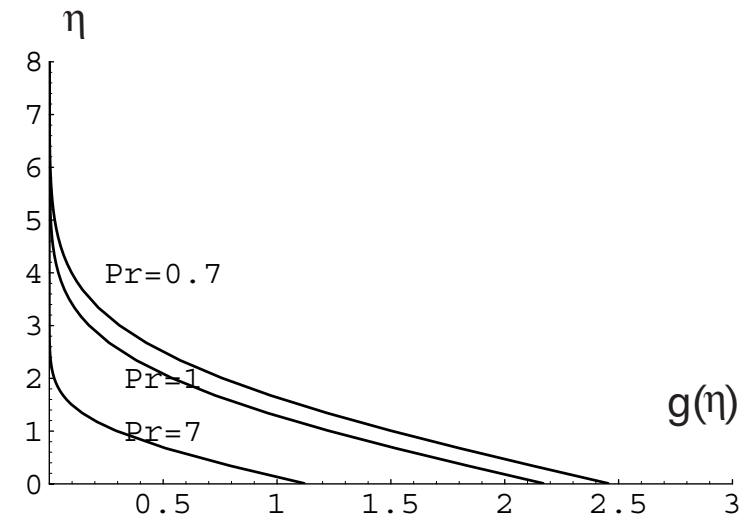
$$E = 0,$$

$$\phi = -g'(0)k(\Delta T)L^{-1}R_{\infty}^{1/2},$$

$$T = T_{\infty} + \Delta T \bar{x}^{1/2} g(\eta),$$

$$2g'' + Pr(fg' - f'g) = 0.$$

à $Pr=0.7$ $g(0)=2.464$
à $Pr=1.0$ $g(0)=2.1789$
à $Pr=7$ $g(0)=1.13$
grosso modo $g(0) \sim 2.18 Pr^{-1/3}$



- Profil $g(\eta)$ à différents Pr .

$$T = T_{\infty} + \frac{\phi}{k} 2.18 Pr^{-1/3} \bar{x}^{1/2}.$$

$$Nu = R_{\infty}^{1/2} (0.46 Pr^{1/3}) \bar{x}^{1/2}.$$

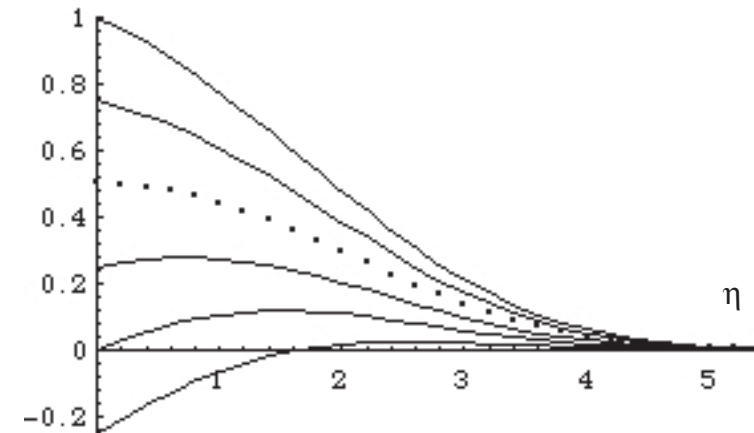
Température imposée

$$\tilde{u} \frac{\partial \tilde{T}}{\partial \bar{x}} + \tilde{v} \frac{\partial \tilde{T}}{\partial \tilde{y}} = \frac{1}{Pr} \frac{\partial^2 \tilde{T}}{\partial \tilde{y}^2} + E \left(\frac{\partial \tilde{u}}{\partial \tilde{y}} \right)^2.$$

$$\tilde{T}(\bar{x}, 0) = 1, \tilde{T}(\bar{x}, \infty) = 0.$$

Eckert non nul

$g(\eta)$



– la température fonction de la variable de similitude (le cas en pointillé est le cas adiabatique, ici comme $Pr=1$, $T_{aw}=0.5$).

$$g'' + \frac{Pr}{2} f g' + E Pr f''^2 = 0.$$

Résultats:

- tuyau

$$Nu_{approx} = 3.66 + \frac{0.127}{2L/(Pe_D D) + 0.0635(2L/(Pe_D D))^{1/3}}$$

- plaque

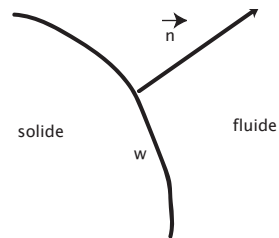
$$Nu_x = 0.332 Pr^{1/3} R_x^{1/2}.$$

$$Nu = R_\infty^{1/2} (0.46 Pr^{1/3}) \bar{x}^{1/2}.$$

cas plus compliqués

- Nu fonction Re, Pr

$$Nu = C Re^m Pr^n.$$



par définition du flux

$$\underline{q}_w = -k \left[\frac{\partial T}{\partial n} \right]_w \underline{n},$$

et

$$Nu = \frac{-k \partial T / \partial n}{(T_w - T_f)}$$

or par définition de h

$$\underline{q}_w = h(T_w - T_f) \underline{n}.$$

$$Nu_x = \frac{h(x)x}{k}.$$

(moyenne)

TABLE 7-1

Empirical correlations for the average Nusselt number for natural convection over surfaces

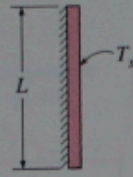
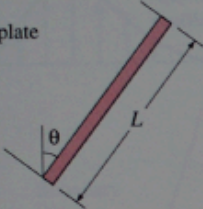
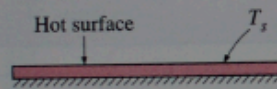
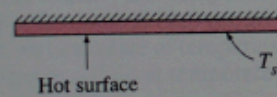
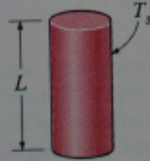
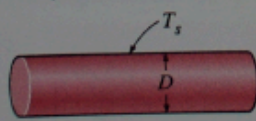
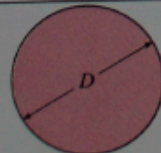
Geometry	Characteristic length δ	Range of Ra	Nu
Vertical plate 	L	10^4-10^9 10^9-10^{13} Entire range	$Nu = 0.59 Ra^{1/4}$ $Nu = 0.1 Ra^{1/3}$ $Nu = \left\{ 0.825 + \frac{0.387 Ra^{1/6}}{(1 + (0.492/Pr)^{9/16})^{4/5}} \right\}$ (complex but more accurate)
Inclined plate 	L		Use vertical plate equations as a first degree of approximation. Replace g by $g \cos \theta$ for $Ra < 10^9$
Horizontal plate (Surface area A and perimeter p) (a) Upper surface of a hot plate (or lower surface of a cold plate)  (b) Lower surface of a hot plate (or upper surface of a cold plate) 	A/p	10^4-10^7 10^7-10^{11} 10^5-10^{11}	$Nu = 0.54 Ra^{1/4}$ $Nu = 0.15 Ra^{1/3}$ $Nu = 0.27 Ra^{1/4}$
vertical cylinder 	L		A vertical cylinder can be treated as a vertical plate when $D \geq \frac{35L}{Gr^{1/4}}$
Horizontal cylinder 	D	$10^{-5}-10^{12}$	$Nu = \left\{ 0.6 + \frac{0.387 Ra^{1/6}}{(1 + (0.559/Pr)^{9/16})^{4/5}} \right\}$
Sphere 	$\frac{1}{2} \pi D$	$Ra \leq 10^{11}$ $(Pr \geq 0.7)$	$Nu = 2 + \frac{0.589 Ra^{1/4}}{(1 + (0.469/Pr)^{9/16})^{4/9}}$

TABLE 9-2

Nusselt numbers for fully developed velocity and temperature profiles in tubes of various cross sections

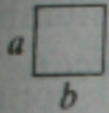
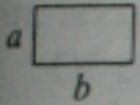
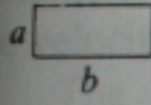
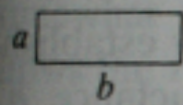
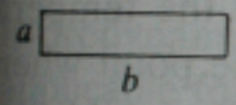
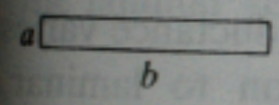
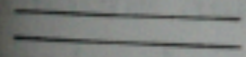
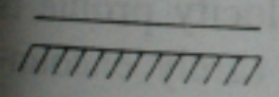
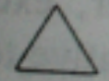
Cross-sectional shape	b/a	$Nu_{(H)}^\dagger$	$Nu_{(T)}$
		4.364	3.66
	1.0	3.61	2.98
	1.43	3.73	3.08
	2.0	4.12	3.39
	3.0	4.79	3.96
	4.0	5.33	4.44
	8.0	6.49	5.60
	∞	8.235	7.54
		5.385	4.86
		3.11	2.49

TABLE 7-2

Empirical correlations for the average Nusselt number for natural convection in enclosures (the character s as indicated on the respective diagram)

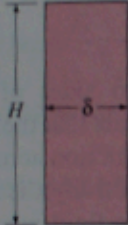
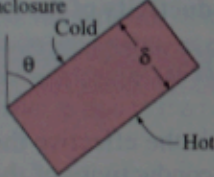
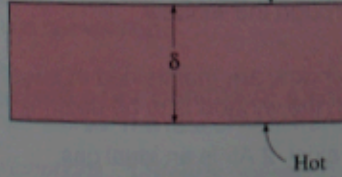
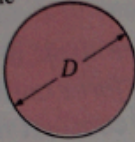
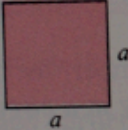
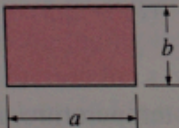
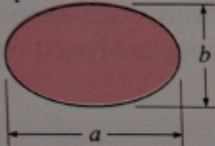
Geometry	Fluid	H/δ	Range of Pr	Range of Ra	Nusselt number
Vertical rectangular enclosure (or vertical cylindrical enclosure) 	Gas or liquid	—	—	$Ra < 2000$	$Nu = 1$
	Gas	11–42	0.5–2	$2 \times 10^3 - 2 \times 10^5$	$Nu = 0.197 Ra^{1/4}$
		11–42	0.5–2	$2 \times 10^5 - 10^7$	$Nu = 0.073 Ra^{1/3}$
	Liquid	10–40	1–20,000	$10^4 - 10^7$	$Nu = 0.42 Pr^{0.01} Ra^{1/4}$
		1–40	1–20	$10^6 - 10^9$	$Nu = 0.046 Ra^{1/3}$
Inclined rectangular enclosure 					Use the correlations for vertical enclosures as a first approximation for inclined enclosures by replacing g in the above correlations by $g \cos \theta$
Horizontal rectangular enclosure (hot surface at the top)	Gas or liquid	—	—	—	$Nu = 1$
Horizontal rectangular enclosure (hot surface at the bottom) 	Gas or liquid	—	—	$Ra < 1700$	$Nu = 1$
	Gas	—	0.5–2	$1.7 \times 10^3 - 7 \times 10^3$	$Nu = 0.059 Ra^{0.4}$
		—	0.5–2	$7 \times 10^3 - 3.2 \times 10^5$	$Nu = 0.212 Ra^{1/4}$
		—	0.5–2	$Ra > 3.2 \times 10^5$	$Nu = 0.061 Ra^{1/3}$
	Liquid	—	1–5000	$1.7 \times 10^3 - 6 \times 10^3$	$Nu = 0.012 Ra^{0.6}$
		—	1–5000	$6 \times 10^3 - 3.7 \times 10^4$	$Nu = 0.375 Ra^{0.2}$
		—	1–20	$3.7 \times 10^4 - 10^8$	$Nu = 0.13 Ra^{0.3}$
Concentric rectangular cylinders	Gas or liquid	—	1–5000	$6.3 \times 10^3 - 10^6$	$Nu = 0.11 Ra^{0.29}$
		—	1–5000	$10^6 - 10^8$	$Nu = 0.40 Ra^{0.20}$
Concentric spheres	Gas or liquid	—	0.7–4000	$10^2 - 10^9$	$Nu = 0.228 Ra^{0.226}$

TABLE 6-4

Nusselt number and friction factor for fully developed laminar flow in tubes of various cross-sections ($D_h = 4A_c/p$, $Re = \dot{V}_m D_h/\nu$, and $Nu = hD_h/k$)

Cross-section of tube	a/b or θ°	Nusselt number		Friction factor f
		$T_s = \text{const.}$	$\dot{q}_s = \text{const.}$	
Circle 	—	3.66	4.36	64.00/Re
Hexagon 	—	3.35	4.00	60.20/Re
Square 	—	2.98	3.61	56.92/Re
Rectangle 	a/b 1 2 3 4 6 8 ∞	2.98 3.39 3.96 4.44 5.14 5.60 7.54	3.61 4.12 4.79 5.33 6.05 6.49 8.24	56.92/Re 62.20/Re 68.36/Re 72.92/Re 78.80/Re 82.32/Re 96.00/Re
Ellipse 	a/b 1 2 4 8 16	3.66 3.74 3.79 3.72 3.65	4.36 4.56 4.88 5.09 5.18	64.00/Re 67.28/Re 72.96/Re 76.60/Re 78.16/Re
Triangle 	θ 10° 30° 60° 90° 120°	1.61 2.26 2.47 2.34 2.00	2.45 2.91 3.11 2.98 2.68	50.80/Re 52.28/Re 53.32/Re 52.60/Re 50.96/Re

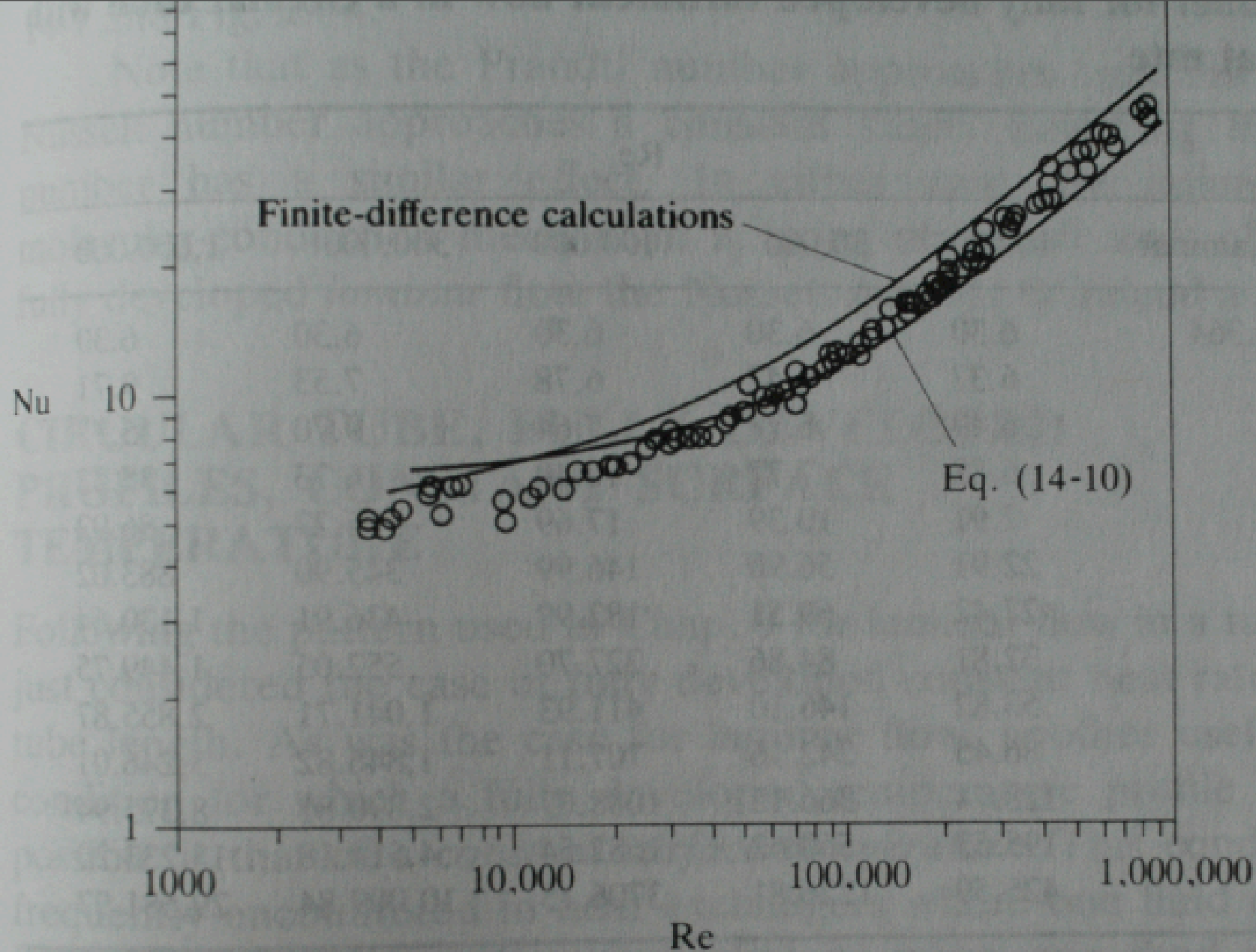


FIGURE 14-3

A comparison of the data of Skupinski *et al.*⁶ with Eq. (14-10) and with the results of direct integration of the energy equation. These data were obtained using an NaK mixture having a Prandtl number of 0.0153.

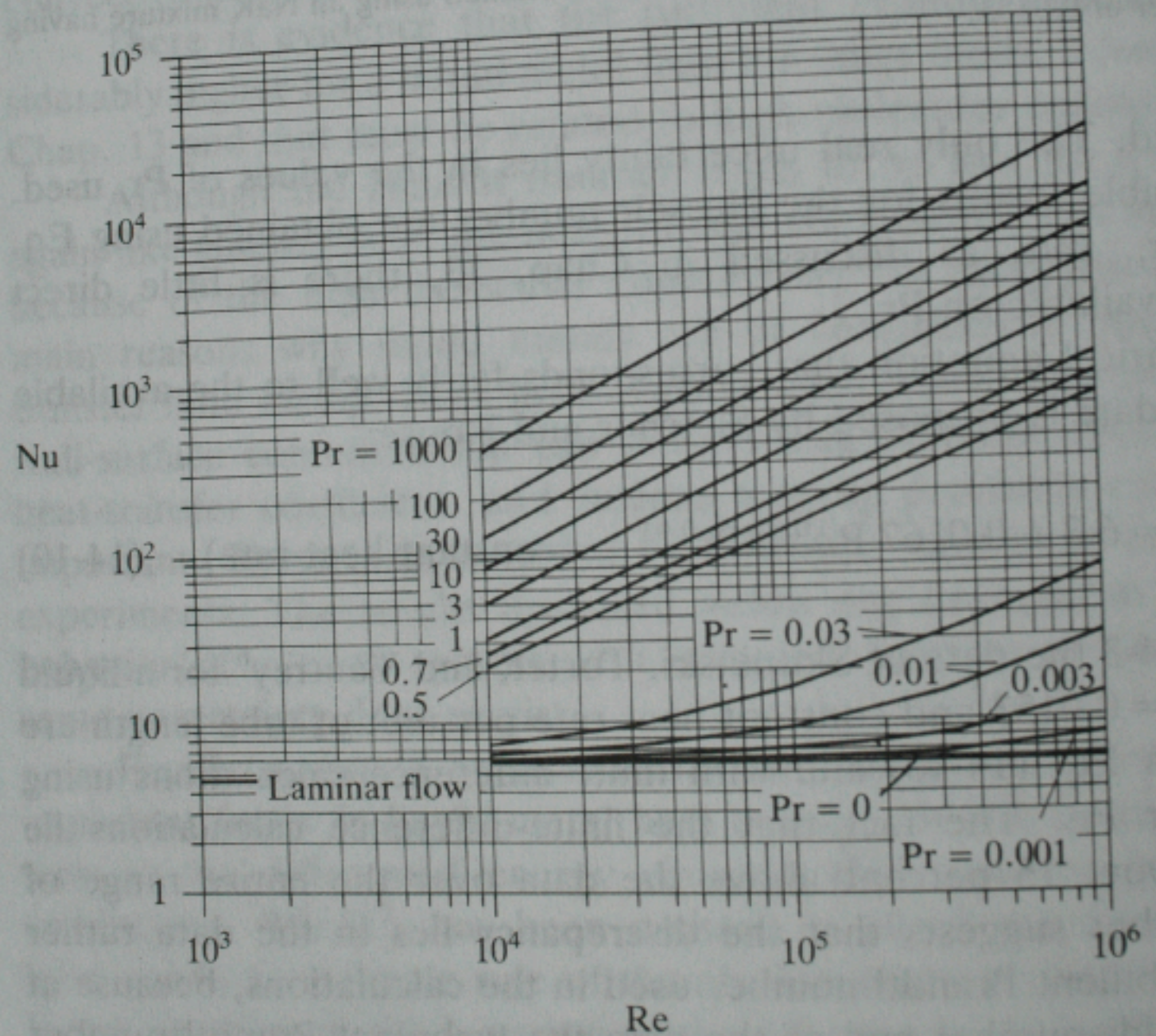
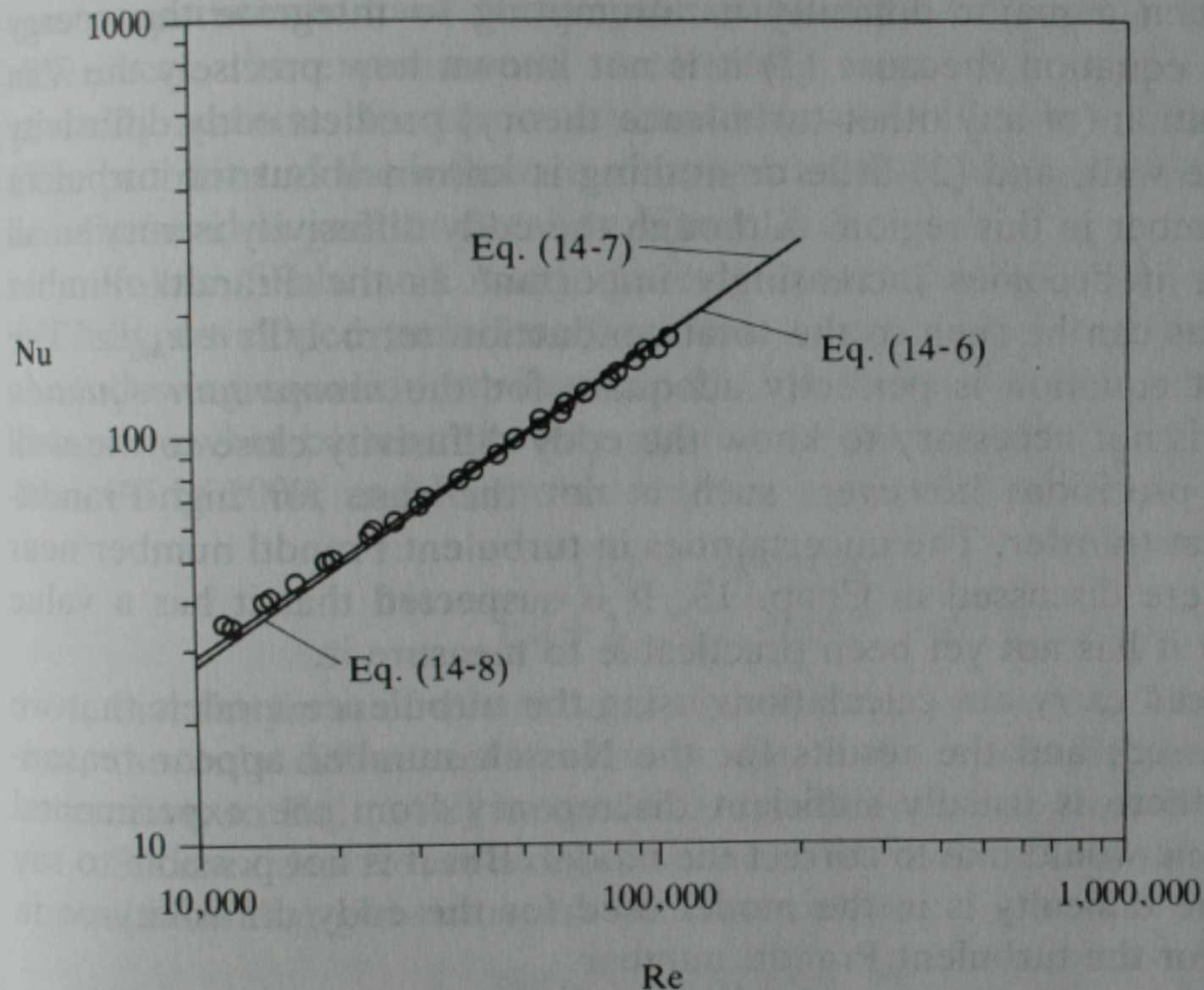
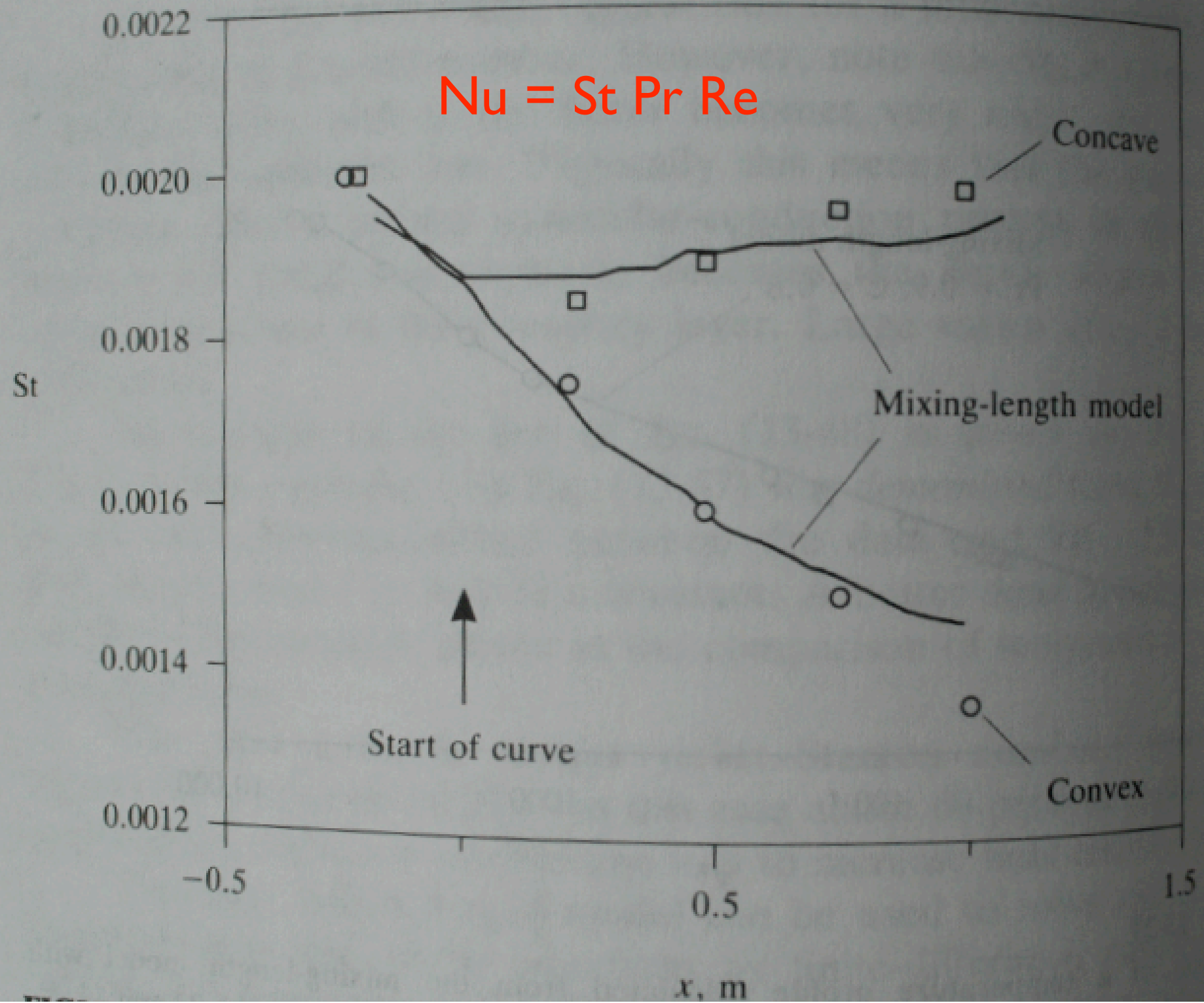


FIGURE 14-4

Nusselt number for fully developed velocity and temperature profiles; circular tube; constant heat rate.

**FIGURE 14-2**

Comparison of analysis with experiment for fully developed velocity and temperature profiles in a circular tube, constant heat rate (data of Kays and Leung,¹ for air, $Pr = 0.702$).



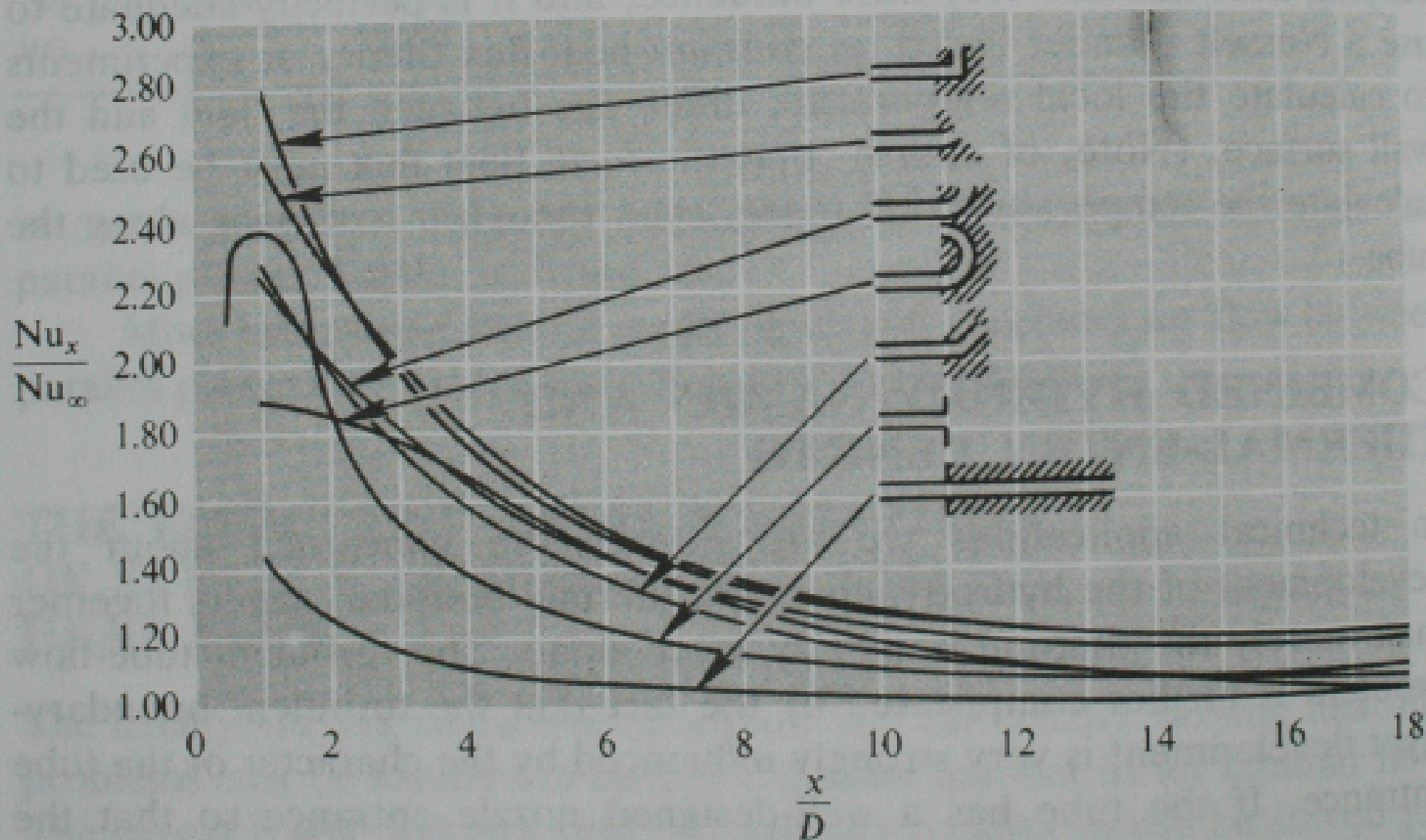


FIGURE 14-9

Measured local Nusselt numbers in the entry region of a circular tube for various entry configurations, air with constant surface temperature.¹⁸

stratégie pratique

écoulement à T fixé, calcul du flux...

calcul du solide

- équations dynamiques

$$\underline{\nabla} \cdot \underline{u} = 0.$$

$$\rho \left(\frac{\partial}{\partial t} \underline{u} + \underline{u} \cdot \underline{\nabla} \underline{u} \right) = -\underline{\nabla} p + \underline{f} + \mu \underline{\nabla}^2 \underline{u}.$$

- équation de la chaleur en incompressible

$$\rho c_p \left(\frac{\partial}{\partial t} T + \underline{u} \cdot \underline{\nabla} T \right) = k \underline{\nabla}^2 T + 2(\mu \underline{\underline{D}} : \underline{\underline{D}}) + r.$$

- conditions aux limites

adhérence à la paroi,
condition mixte du type :

$$-k \frac{\partial T}{\partial y} = h_e (T - T_e).$$

PC2



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Maîtres de conférences :		Pierre-Yves LAGREE ; Michael BAUDOIN	
DATE	HEURES	TYPE SEANCE	PROGRAMME DE LA SEANCE
23 01 2007	08:30 09:30	Cours magistral	Rappels de conduction, coefficient d'échange
23 01 2007	09:45 11:45	Petite classe	
30 01 2007	8:30 9:30	Cours magistral	Convection forcée
30 01 2007	9:45 11:45	Petite classe	
06 02 2007	8:30 9:30	Cours magistral	Convection forcée
06 02 2007	9:45 11:45	Petite classe	
13 02 2007	08:30 09:30	Cours magistral	Convection Naturelle
13 02 2007	09:45 11:45	Petite classe	
20 02 2007	08:30 09:30	Cours magistral	Convection forcée turbulente
20 02 2007	09:45 11:45	Petite classe	
06 03 2007	08:30 09:30	Cours magistral	Transferts de masse
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13 03 2007	08:30 11:30	Contrôle	Contrôle de connaissances
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