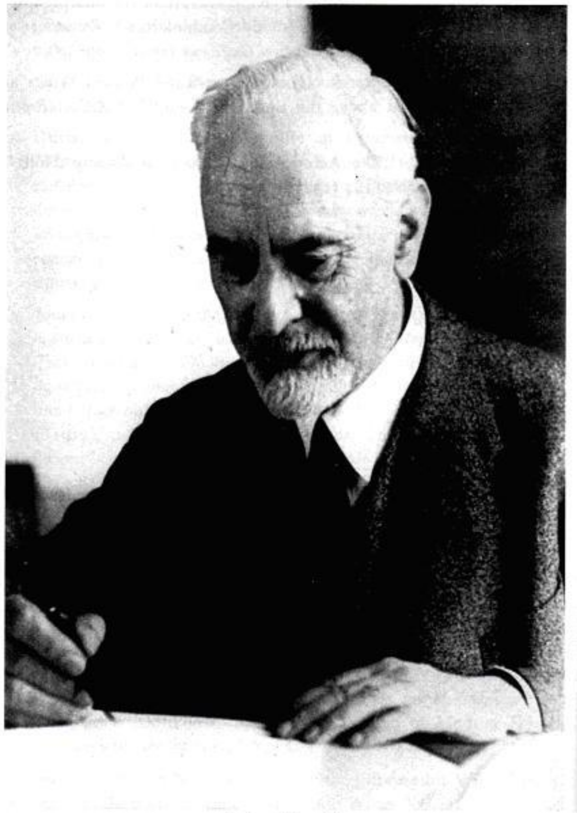
- Fenômenos de Transporte I - 2020

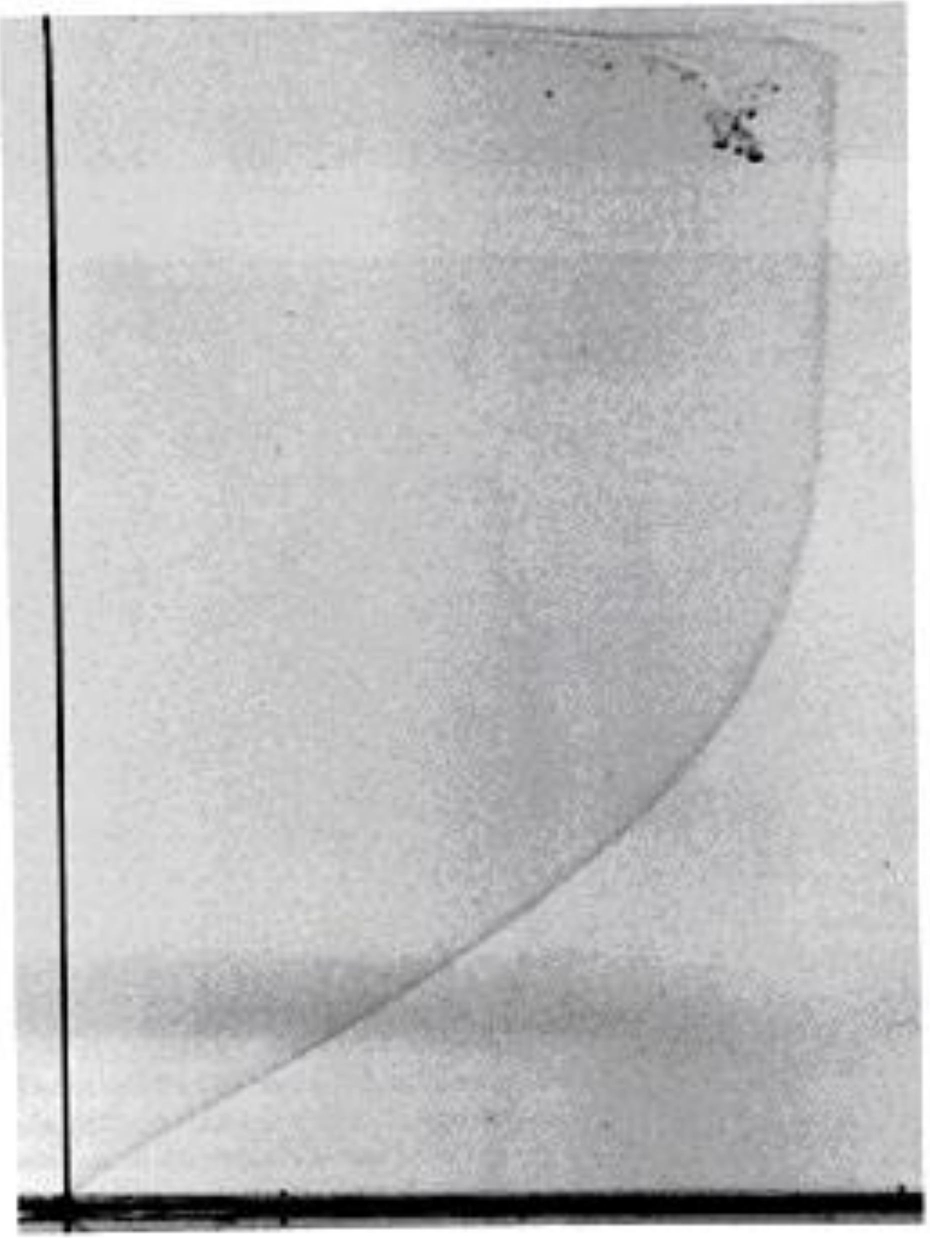
CAMADA LIMITE LAMINAR

- EXERCÍCIOS



Ludwig Prandtl

Perfil de Velocidades- Camada Limite



30. Blasius boundary-layer profile on a flat plate. The tangential velocity profile in the laminar boundary layer on a flat plate, discovered by Prandtl and calculated accurately by Blasius, is made visible by tellurium. Water is flowing at 9 cm/s. The Reynolds number is 500 based on distance from the leading edge, and the displacement thickness is about 5 mm. A fine tellurium wire perpendicular to the plate at the left is subjected to an electrical impulse of a few milliseconds duration. A chemical reaction produces a slender colloidal cloud, which drifts with the stream and is photographed a moment later to define the velocity profile. Photograph by F. X. Wortmann

Solução de Blasius

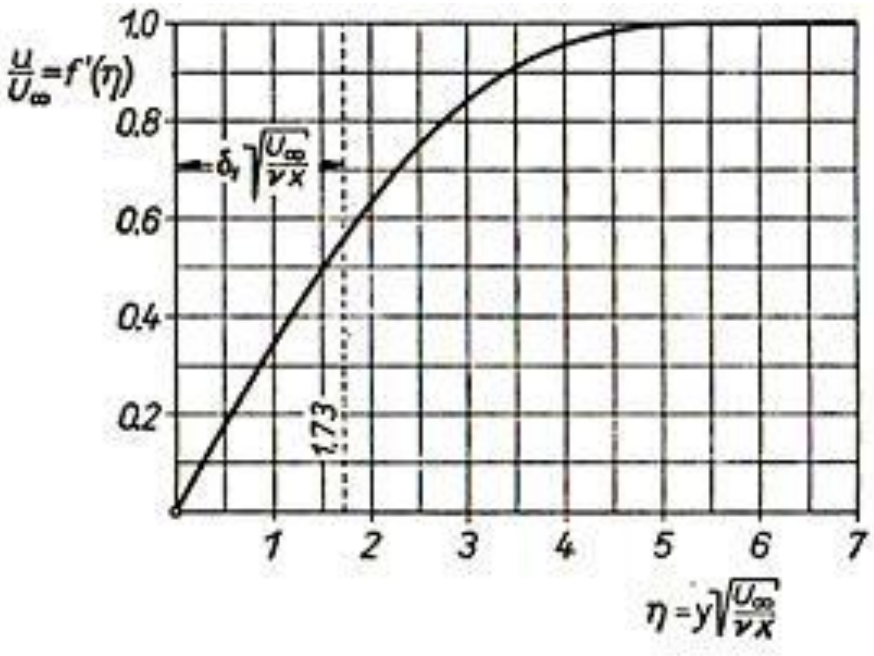


Fig. 7.7. Velocity distribution in the boundary layer along a flat plate, after Blasius [2]

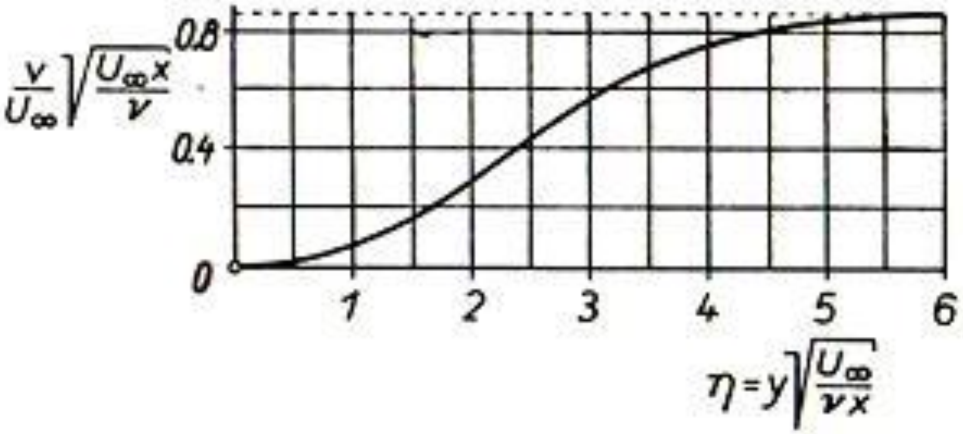
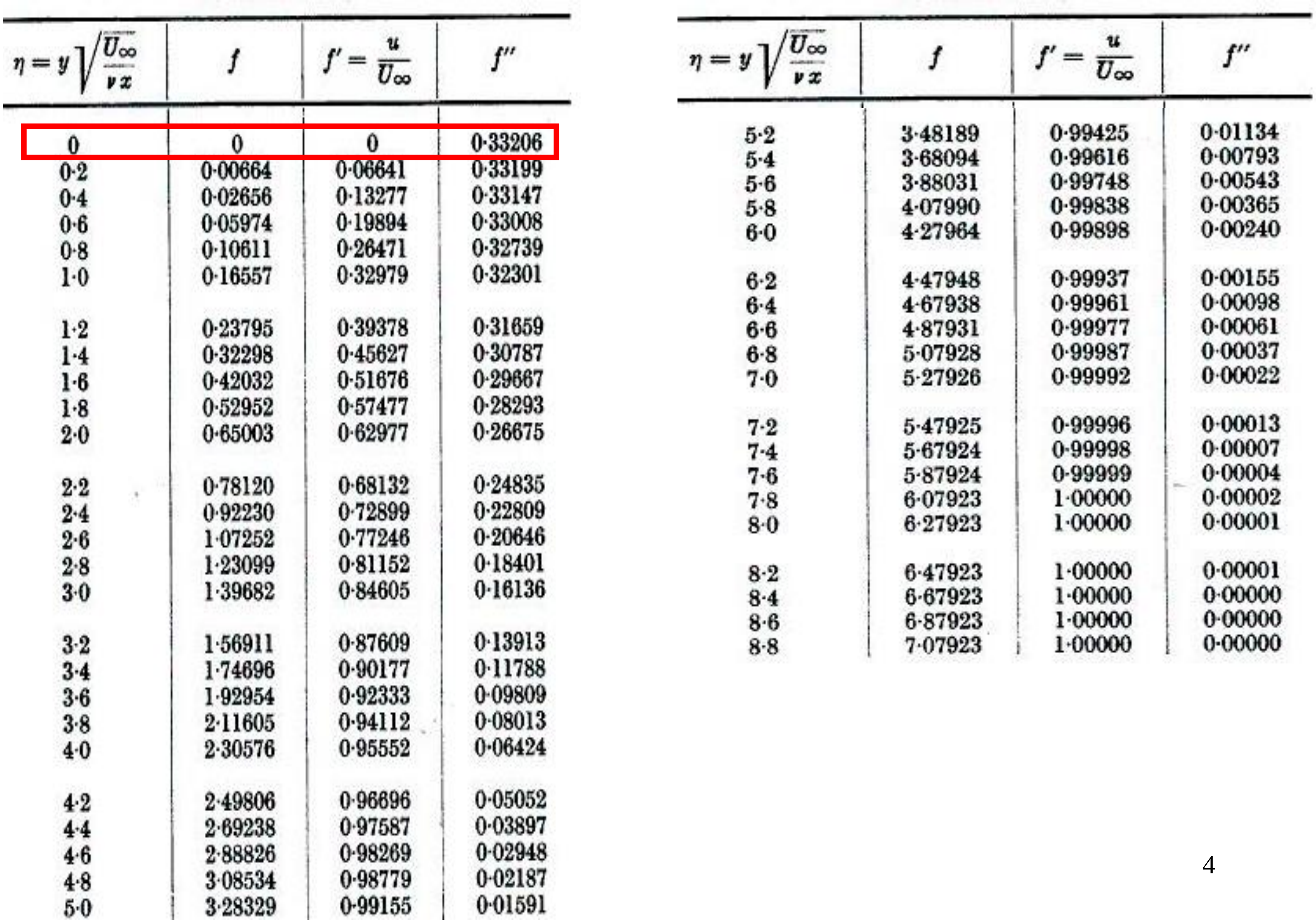


Fig. 7.8. The transverse velocity component in the boundary layer along a flat plate

$$u = U\frac{d\,f(\eta)}{d\eta}$$

$$v = \frac{1}{2}\sqrt{\frac{\nu\,U}{x}}\left(\eta\frac{d\,f(\eta(}{d\eta} - f(\eta(\right)$$

Solução de Blasius



$\eta = y\sqrt{\frac{U_\infty}{\nu x}}$	f	$f' = \frac{u}{U_\infty}$	f''
0	0	0	0·33206
0·2	0·00664	0·06641	0·33199
0·4	0·02656	0·13277	0·33147
0·6	0·05974	0·19894	0·33008
0·8	0·10611	0·26471	0·32739
1·0	0·16557	0·32979	0·32301
1·2	0·23795	0·39378	0·31659
1·4	0·32298	0·45627	0·30787
1·6	0·42032	0·51676	0·29667
1·8	0·52952	0·57477	0·28293
2·0	0·65003	0·62977	0·26675
2·2	0·78120	0·68132	0·24835
2·4	0·92230	0·72899	0·22809
2·6	1·07252	0·77246	0·20646
2·8	1·23099	0·81152	0·18401
3·0	1·39682	0·84605	0·16136
3·2	1·56911	0·87609	0·13913
3·4	1·74696	0·90177	0·11788
3·6	1·92954	0·92333	0·09809
3·8	2·11605	0·94112	0·08013
4·0	2·30576	0·95552	0·06424
4·2	2·49806	0·96696	0·05052
4·4	2·69238	0·97587	0·03897
4·6	2·88826	0·98269	0·02948
4·8	3·08534	0·98779	0·02187
5·0	3·28329	0·99155	0·01591
5·2	3·48189	0·99425	0·01134
5·4	3·68094	0·99616	0·00793
5·6	3·88031	0·99748	0·00543
5·8	4·07990	0·99838	0·00365
6·0	4·27964	0·99898	0·00240
6·2	4·47948	0·99937	0·00155
6·4	4·67938	0·99961	0·00098
6·6	4·87931	0·99977	0·00061
6·8	5·07928	0·99987	0·00037
7·0	5·27926	0·99992	0·00022
7·2	5·47925	0·99996	0·00013
7·4	5·67924	0·99998	0·00007
7·6	5·87924	0·99999	0·00004
7·8	6·07923	1·00000	0·00002
8·0	6·27923	1·00000	0·00001
8·2	6·47923	1·00000	0·00001
8·4	6·67923	1·00000	0·00000
8·6	6·87923	1·00000	0·00000
8·8	7·07923	1·00000	0·00000

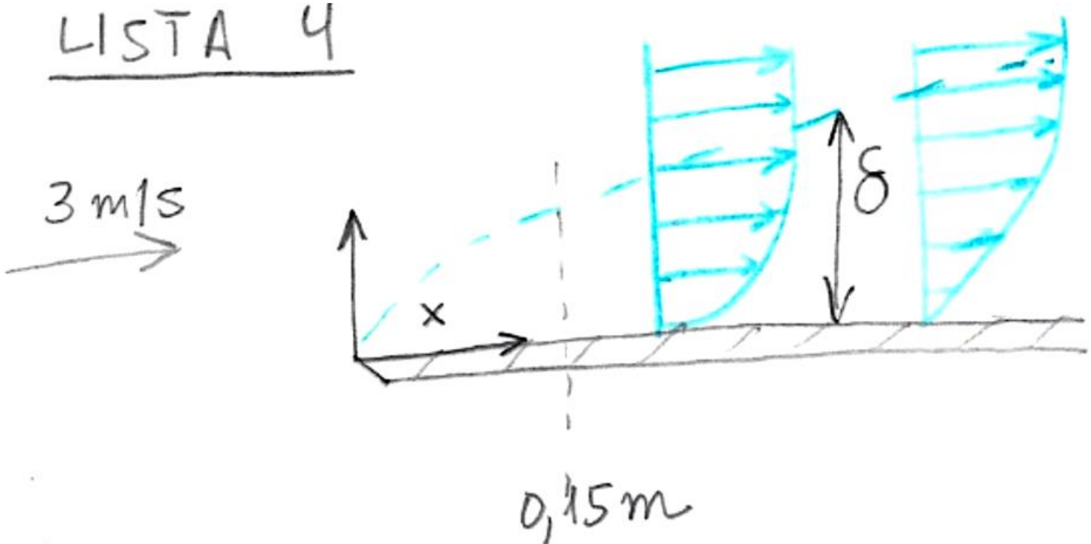
(1) Estimar a espessura da camada limite para o escoamento sobre uma placa plana horizontal, com velocidade de aproximação constante de 3 m/s, na posição distantede0,15 m da borda de ataque, admitida com incidência nula, considerando-se os seguintes casos:

Caso	Fluido	Densidade (kg/m^3)	Viscosidade (cP)	Difusividade de quant. de mov. (m^2/s)
a	Água	1000	1	1×10^{-6}
b	Ar	1	0,02	2×10^{-5}
c	Glicerina	1260	1500	$1,19 \times 10^{-3}$

Resposta: (a) $\delta_a = 0,0011$ *m; (b)* $\delta_b = 0,005$ *m; (c)* $\delta_c = 0,0386$ *m.*

1)

LISTA 4



a) água

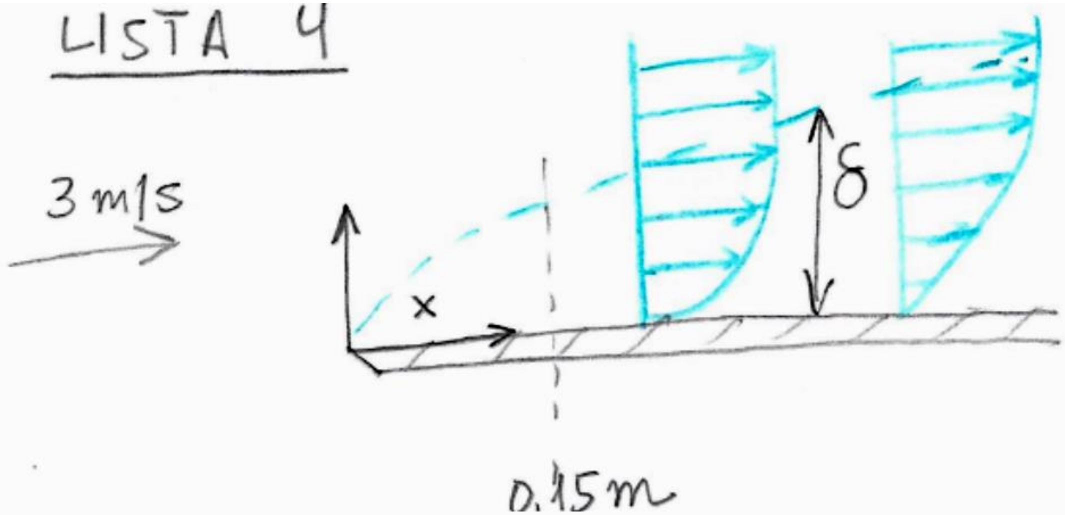
$\rho = 1000\ kg/m^3$ $\quad \mu = 1cP \quad \nu = 10^{-6}$

$$Re = \frac{\rho V x}{\mu} = \frac{Vx}{\nu} = \frac{3 \times 0,15}{10^{-6}} = 4,5.10^{5}$$

$$\frac{\delta}{x} = \frac{5}{\sqrt{Re_x}} = \frac{5}{\sqrt{4,5.10^{5}}} = 7,45.10^{-3}$$

$$\delta = 7,45.10^{3} . 0,15 = \underline{1,1.10^{-3}\ m}$$

1) LISTA 4



b) ar

$Re = 2{,}25 \cdot 10^{4}$

$\underline{\delta = 5 \cdot 10^{-3}\ m}$

c) glicerina

$Re = 378$

$\underline{\delta = 38{,}6 \cdot 10^{-3}\ m}$

$\delta_{glicerina} > \delta_{ar} > \delta_{água}$

1) Extra - $C_D = ?$

$$C_D = \frac{0{,}664}{\sqrt{Re_x}}$$

$$C_D \text{ água} = \frac{0{,}664}{\sqrt{4{,}5 \cdot 10^{+5}}} = 9{,}9 \cdot 10^{-4}$$

$$C_D \text{ ar} = \frac{0{,}664}{\sqrt{2{,}25 \cdot 10^{4}}} = 4{,}4 \cdot 10^{-3}$$

$$C_D \text{ glic} = \frac{0{,}664}{\sqrt{378}} = 3{,}41 \cdot 10^{-2}$$

C_D glicerina > $C_{D\,ar}$ > C_D água

τ_w ?

$$\tau_w = \frac{1}{2}\rho U^2 \cdot C_D$$

$$\tau_{w\,\text{água}} = \frac{1}{2} \cdot 1000 \cdot 3^2 \cdot 9{,}9 \cdot 10^{-4} = 4{,}45 \text{ Pa}$$

$$\tau_{\text{ar}} = \frac{1}{2} \cdot 1 \cdot 3^2 \cdot 4{,}4 \cdot 10^{-3} = 0{,}02 \text{ Pa}$$

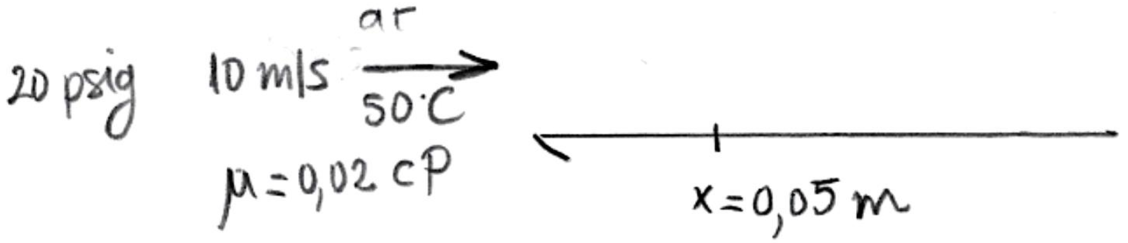
$$\tau_{\text{glicerina}} = \frac{1}{2} \cdot 1260 \cdot 3^2 \cdot 3{,}41 \cdot 10^{-2} = 193{,}3 \text{ Pa}$$

$$\tau_{\text{glicerina}} > \tau_{w\,\text{água}} \gg \tau_{\text{ar}}$$

(8) Ar a 50ºC e 20 psig (viscosidade = 0,02 cP) escoa sobre uma placa horizontal de incidência nula, com uma velocidade de aproximação uniforme de 10 m/s.

(a) Determinar, usando a solução exata de Blasius, as componentes de velocidade v_x e v_y no ponto dado por x = 0,05 m e y = δ/2, onde x é a direção de escoamento, y é a direção normal à placa e δ é a espessura da camada limite nessa posição. (b) Determinar a força de atrito numa placa de comprimento igual a 10 m (medido na direção de escoamento a partir da borda de ataque) e largura também de 10 m.

Resposta: (a) $v_x = 7{,}2$ *m/s,* $v_y = 0{,}017$ *m/s; (b) F = 35,1 N.*



$$20 \text{ psig} \rightarrow (20+14{,}7)\,\text{psia} \rightarrow 2{,}36 \text{ atm}$$

$$\rho = \frac{PM}{RT} = \frac{2{,}36 \cdot 29}{0{,}082 \cdot 323} = 2{,}582 \text{ kg/m}^3$$

$$Re = \frac{\rho v x}{\mu} = \frac{2{,}582 \cdot 10 \cdot 0{,}05}{0{,}02 \cdot 10^{-3}} = 64550$$

$$\delta = \frac{5x}{\sqrt{Re_x}} = \frac{0{,}25}{\sqrt{64550}} = 10^{-3} \text{ m}$$

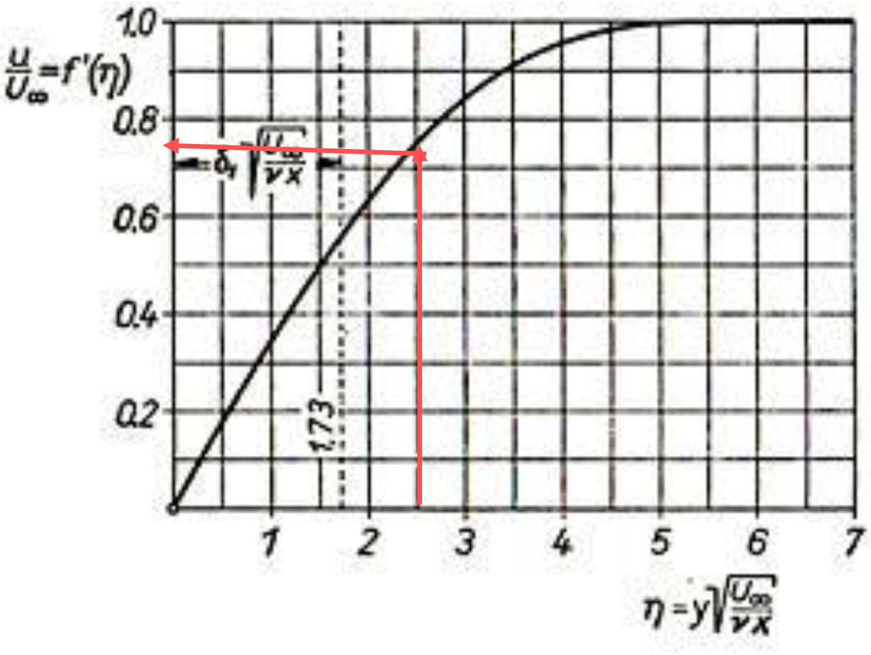
$$\delta = \frac{5x}{\sqrt{Re_x}} = \frac{0{,}25}{\sqrt{64550}} = 10^{-3}\ m$$

$$y = \delta/2 = 5.10^{-4}\ m \quad e \quad x = 0{,}05\ m$$

$$\eta = y\sqrt{\frac{u_0}{\nu x}} = 5.10^{-4}\sqrt{\frac{10}{7{,}75.10^{-6} \cdot 0{,}05}} = 2{,}5$$

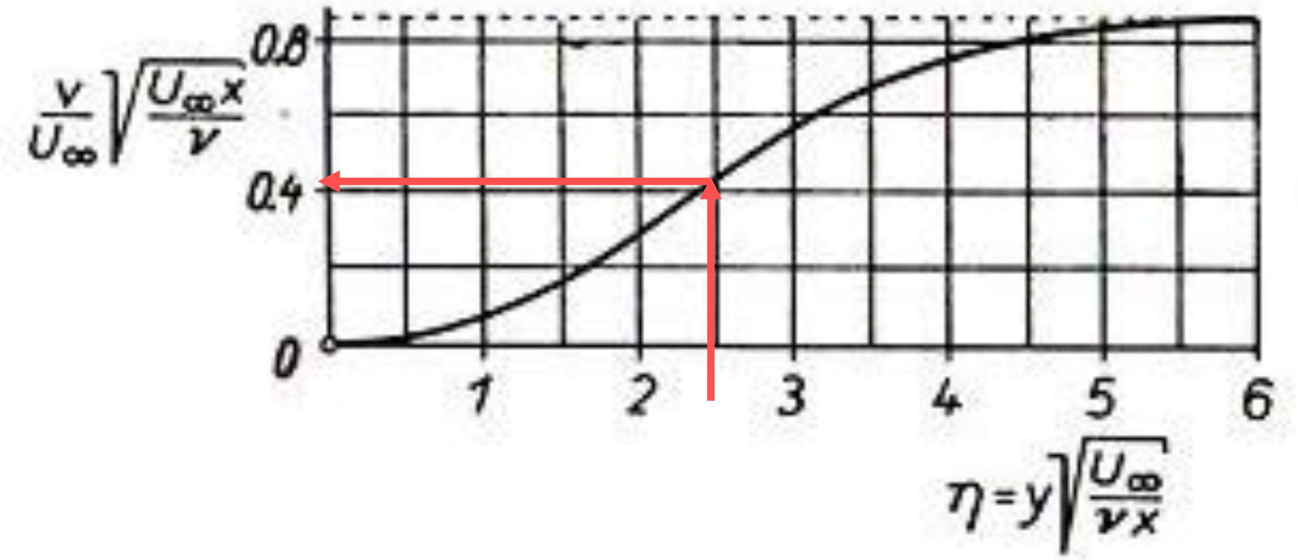
$$\nu = \mu/\rho = 7{,}75.10^{-6}$$

$$\frac{V_x}{u_0} = 0{,}75 = f'(\eta) \Rightarrow \boxed{V_x = 7{,}5\ m/s}$$

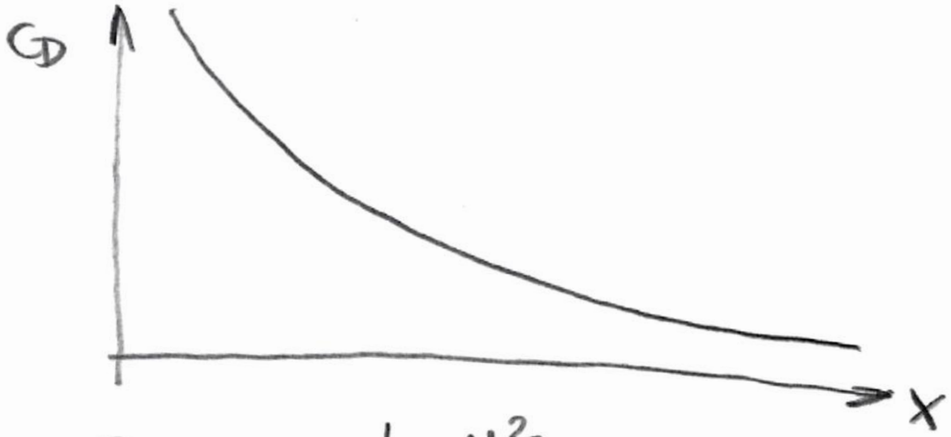


$$\frac{v_y}{u_0}\sqrt{\frac{u_0 x}{\nu}} \underset{\eta=2,5}{=} 0,42 = \frac{v_y}{10}\sqrt{\frac{10\times 0,05}{7,75.10^{-6}}}$$

$$\boxed{v_y = 0,017 \ m/s}$$



$$C_D = \frac{0{,}664}{\sqrt{Re_x}}$$



$$\tau_w = C_D \times \frac{1}{2} \rho U^2$$

$$\tau_w = \frac{0{,}332 \rho U^2}{\sqrt{\rho U x / \mu}} = 0{,}332 \mu U \sqrt{\frac{\rho U}{\mu x}}$$

$$F_w = \int^{w}\int^{L} \tau_w \cdot dx\, dz = \iint 0{,}332 \mu U \sqrt{\frac{\rho U}{\mu x}}\, dx\, dz$$

$$F_w = \int_0^w \int_0^L \tau_w \, . \, dx \, dz = \iint 0{,}332 \mu U \sqrt{\frac{\rho U}{\nu x}} \, dx \, dz$$

$$F_w = w \, . \left[0{,}332 \mu U \sqrt{\frac{\rho U}{\mu x}} \; 2 . \sqrt{x} \right]_0^L$$

$$F_w = 0{,}664 \, w \mu U \sqrt{\frac{\rho U L}{\mu}}$$

$$F_w = 0{,}664 \, w \mu U \sqrt{Re_L}$$

ou $$\overline{C_D} = \frac{F_w}{w . L . \frac{1}{2} \rho U^2} = 1{,}328 \sqrt{\frac{\mu}{\rho U L}} =$$

$$\overline{C_D} = 1{,}328 \, Re_L^{-1/2}$$

$$F_w = 0{,}664 . 10 . 0{,}02 . 10^{-3} . 10 \sqrt{\underbrace{\frac{2582 . 10 . 10}{902 . 10^{-3}}}_{1{,}3 . 10^7}}$$

$$\boxed{F_w = 4{,}77 \text{ N}} \quad ?$$

CAMADA LIMITE LAMINAR E TURBULENTA

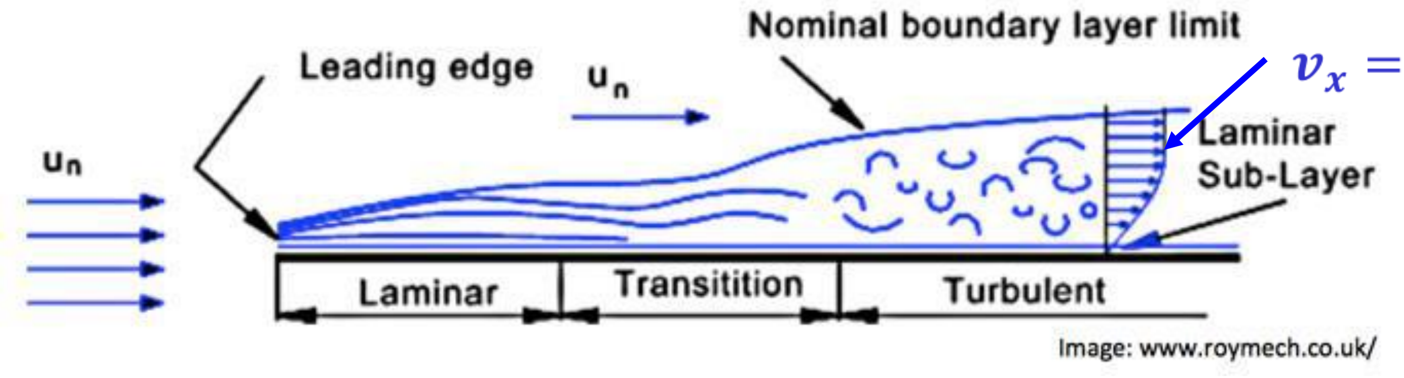
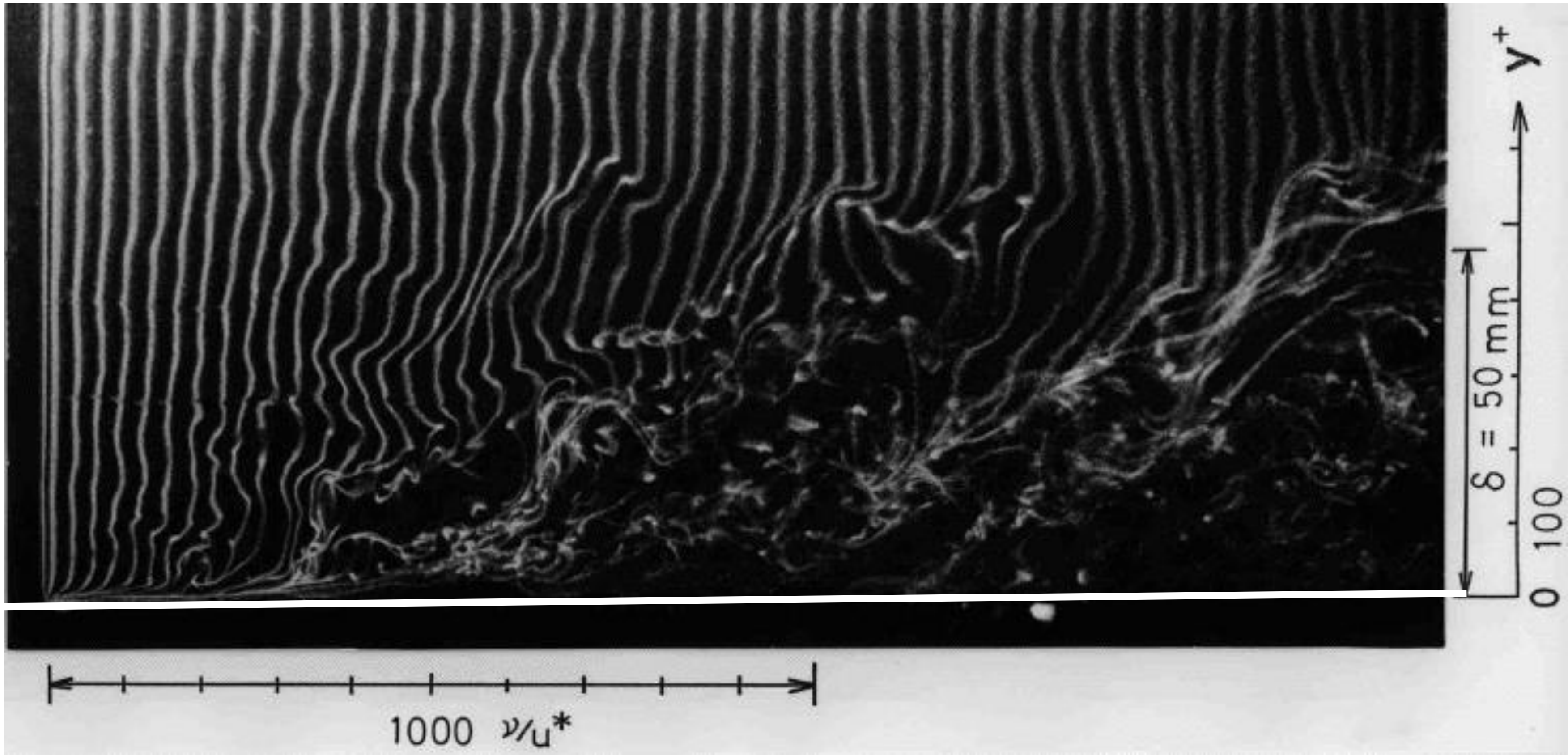

Nominal boundary layer limit
Leading edge
u_n
u_n
Laminar Sub-Layer
Laminar
Transitition
Turbulent

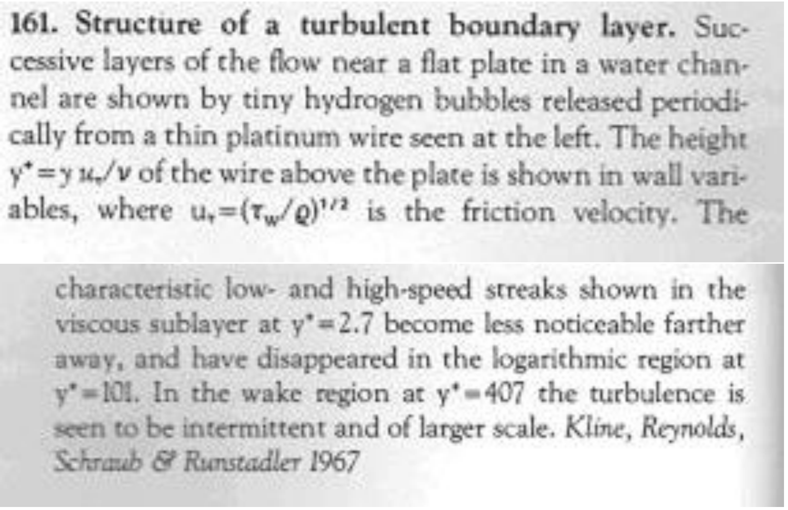
Image: www.roymech.co.uk/

$$v_x = U(y/\delta)^{1/7}$$

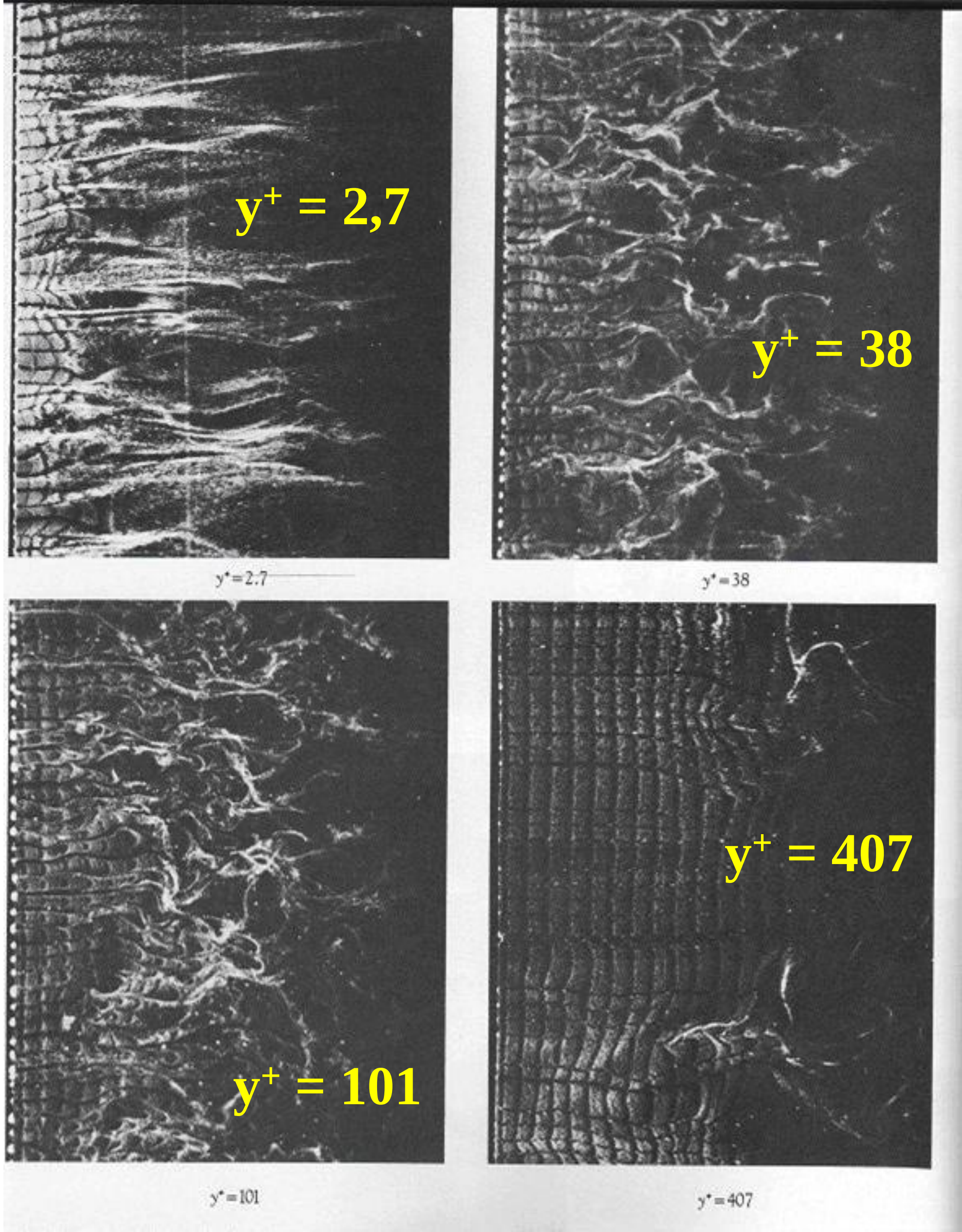
Camada Limite	Laminar	Turbulenta
$\dfrac{\delta}{x}$	$\dfrac{5}{Re_x{}^{1/2}}$	$\dfrac{0,376}{Re_x{}^{1/5}}$
$C_{D,local}$	$\dfrac{0,664}{Re_x{}^{1/2}}$	$\dfrac{0,0576}{Re_x{}^{1/5}}$
$C_{D,médio}$	$\dfrac{1,328}{Re_L{}^{1/2}}$	$\dfrac{0,072}{Re_L{}^{1/5}}$


y⁺
δ = 50 mm
0
100
1000 ν/u*

y+



161. Structure of a turbulent boundary layer. Successive layers of the flow near a flat plate in a water channel are shown by tiny hydrogen bubbles released periodically from a thin platinum wire seen at the left. The height $y^+ = y\, u_\tau/\nu$ of the wire above the plate is shown in wall variables, where $u_\tau = (\tau_w/\varrho)^{1/2}$ is the friction velocity. The characteristic low- and high-speed streaks shown in the viscous sublayer at $y^+ = 2.7$ become less noticeable farther away, and have disappeared in the logarithmic region at $y^+ = 101$. In the wake region at $y^+ = 407$ the turbulence is seen to be intermittent and of larger scale. *Kline, Reynolds, Schraub & Runstadler 1967*



$y^+ = 2.7$ $y^+ = 38$

$y^+ = 101$ $y^+ = 407$