ESCOLA POLITÉCNICA DA UNIVERSIDADE DE SÃO PAULO

Turbulência fantástica

aantunha

titulo

Tudo que existe no universo é fruto do acaso e da necessidade

Demócrito 460 a 385 a.C.

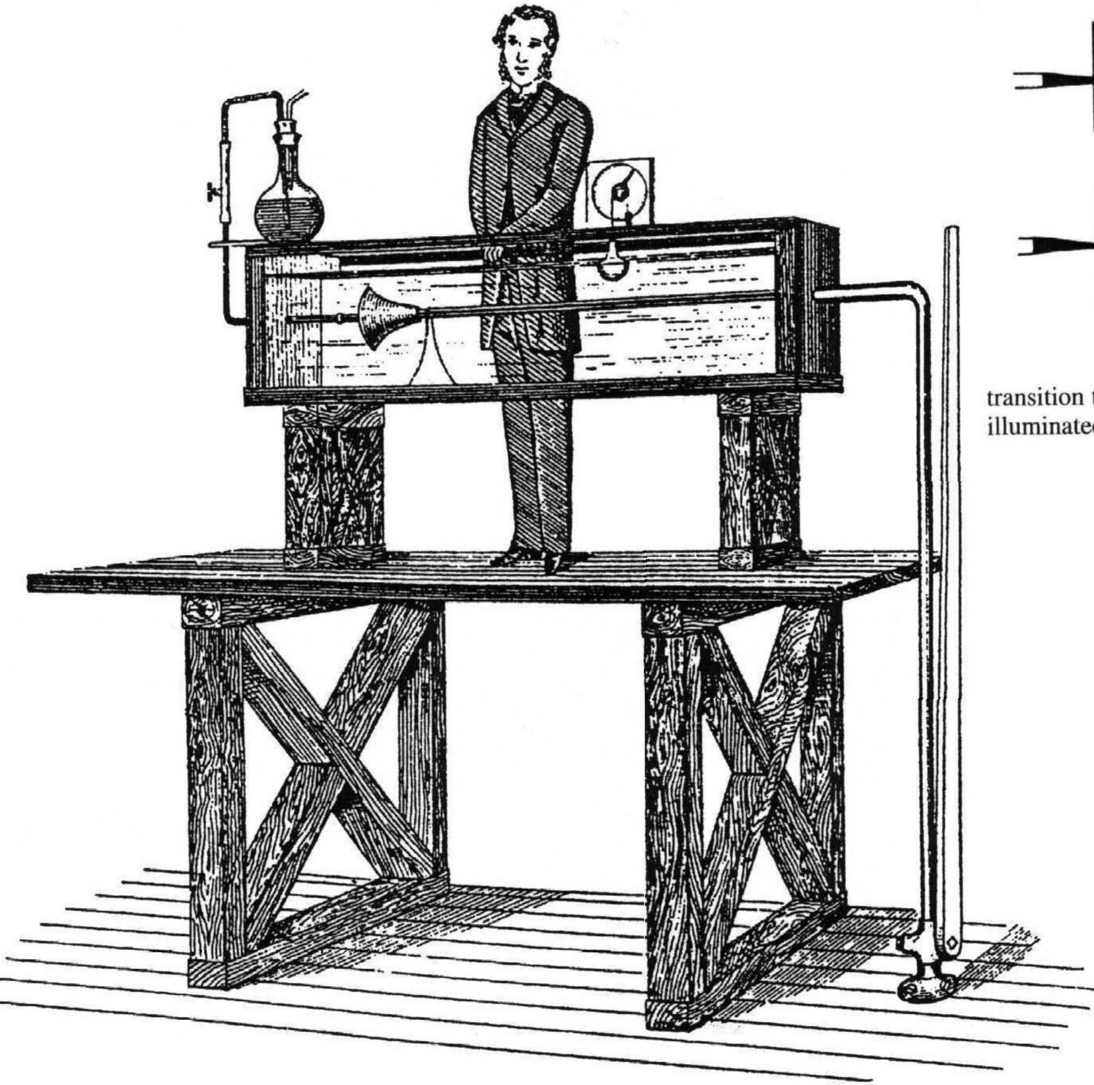
atomismo

da Vinci

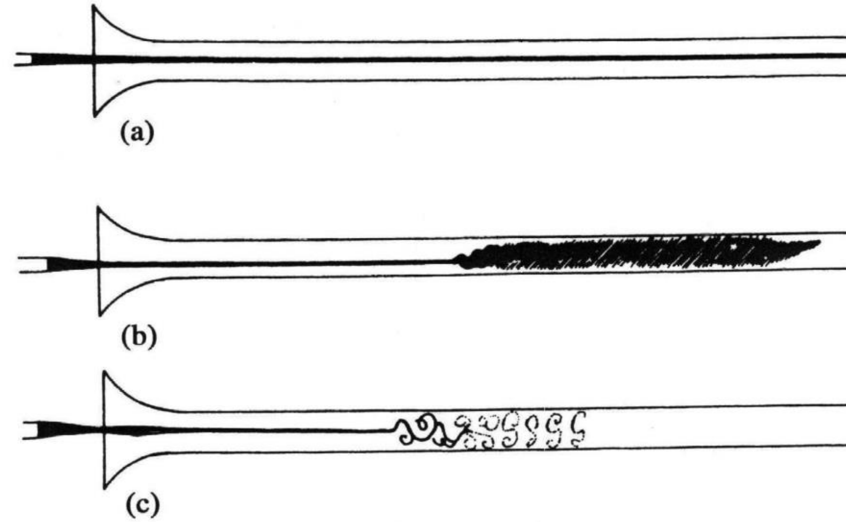
1452-1519


transition to turbulence
©2005 Pal & Basu

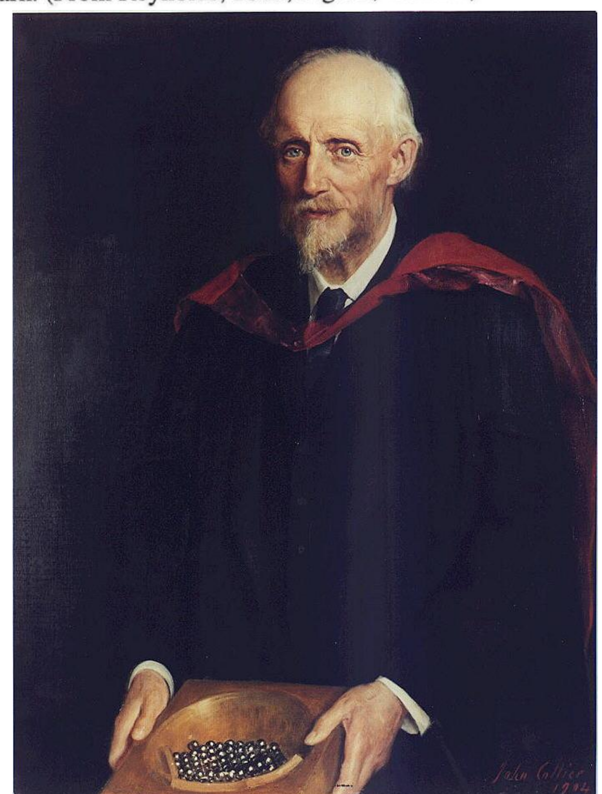
Osborne Reynolds
1842 1912



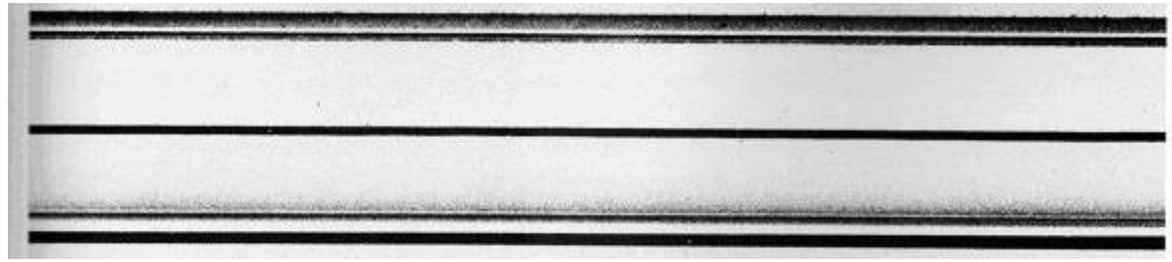
The configuration of Reynolds's experiment on flow along a pipe.



Sketches of (a) laminar flow in a pipe, indicated by a dye streak; (b) transition to turbulent flow in a pipe; and (c) transition to turbulent flow as seen when illuminated by a spark. (From Reynolds, 1883, Figs. 3, 4 and 5.)



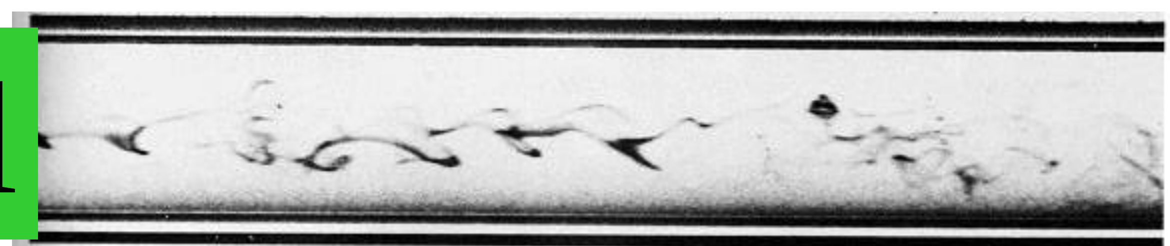
Reynolds experimento de 1883

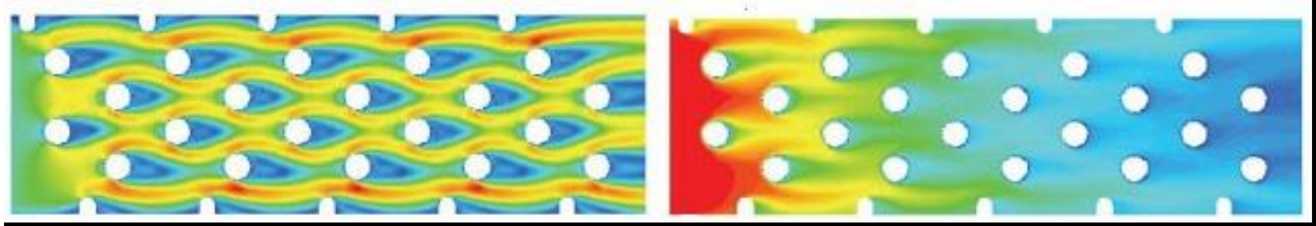


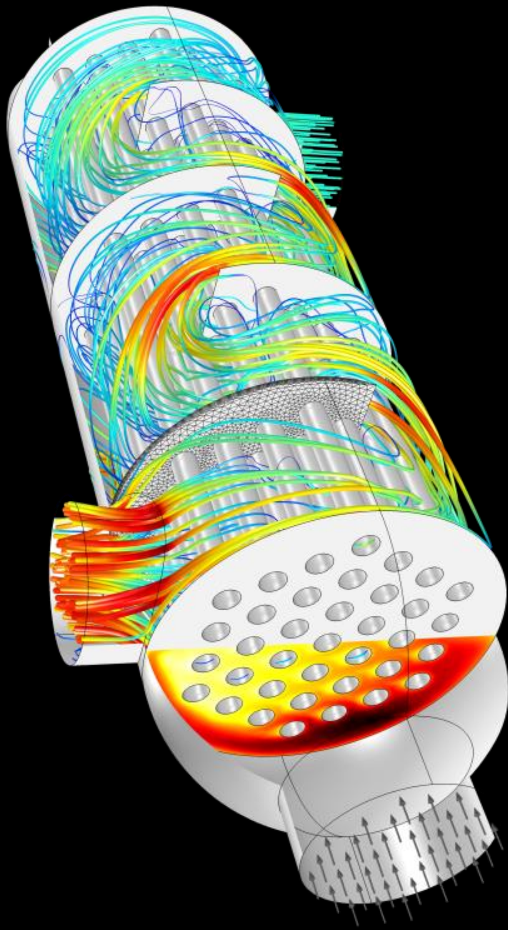
rotacional

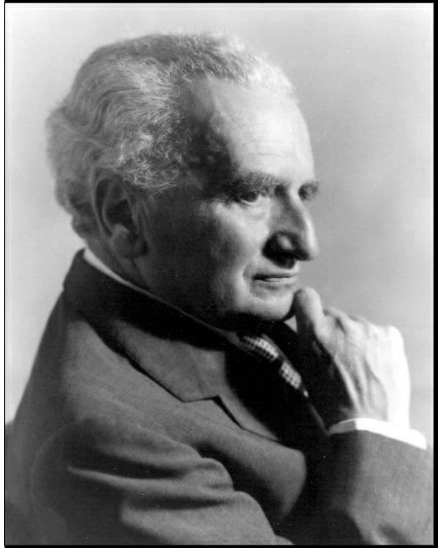
3D

irreversível

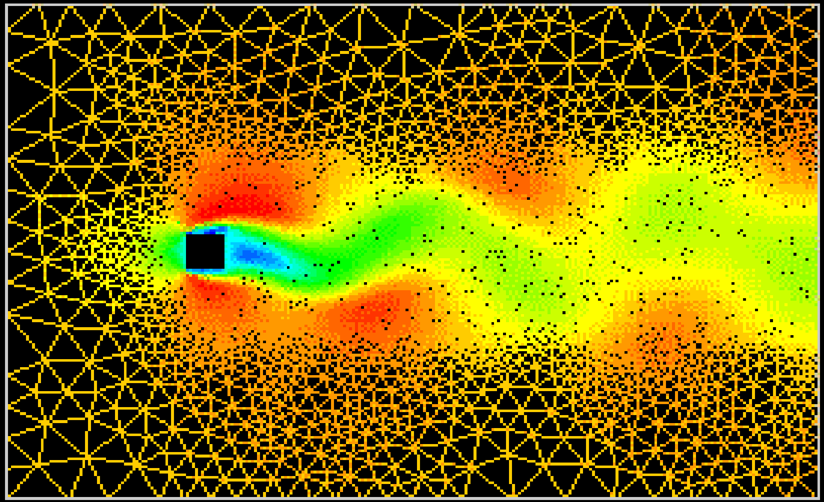


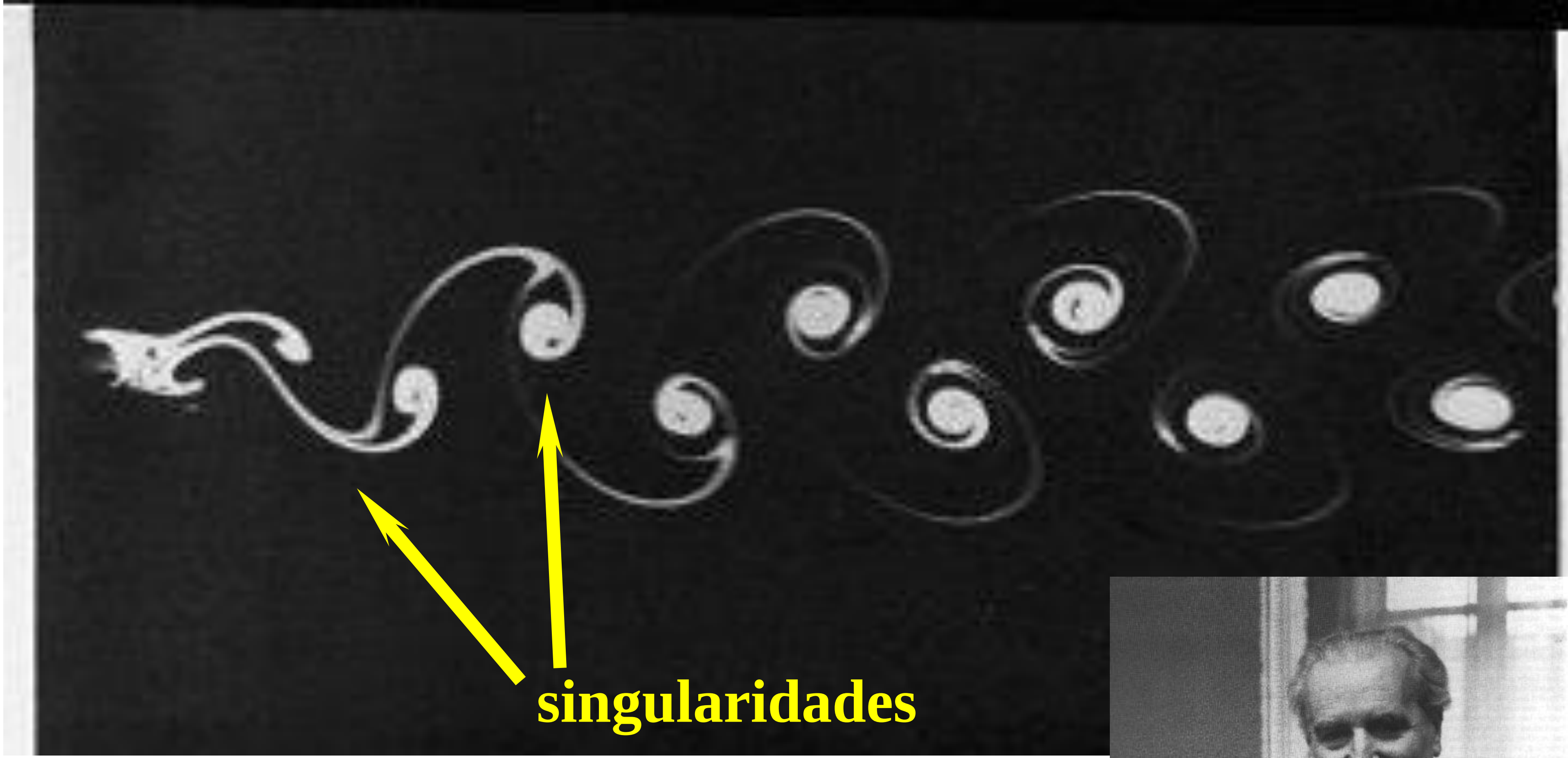






T. von Kármán
1881-1963

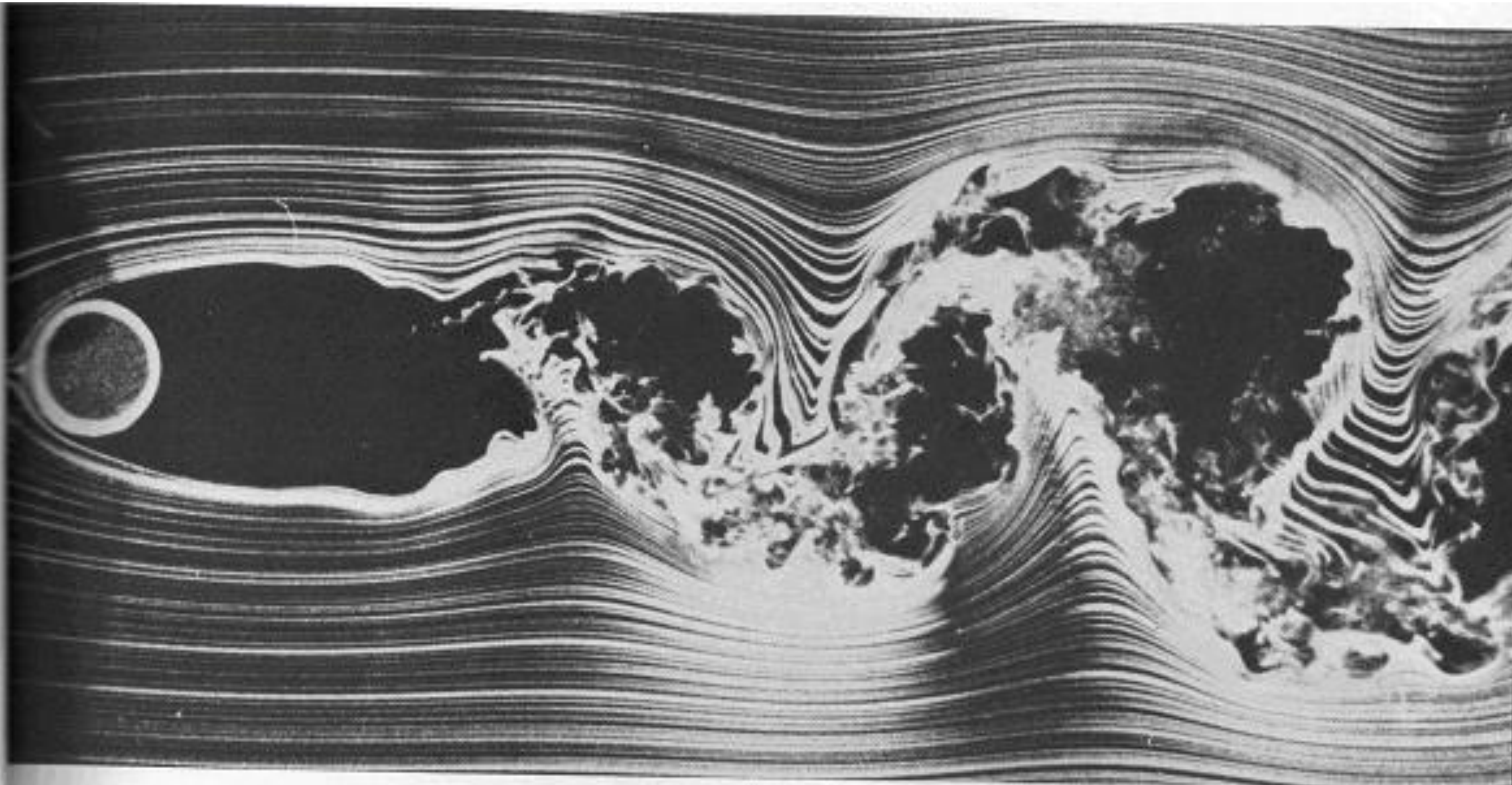




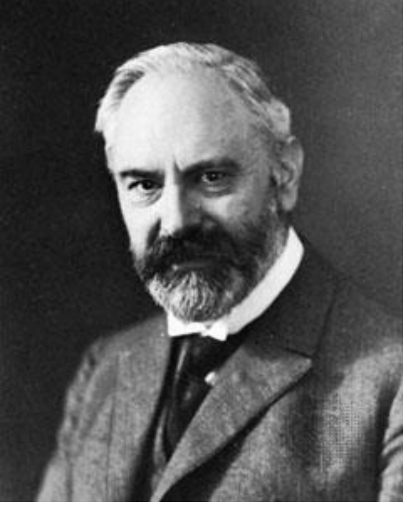
cilindro
Re = 105

Von Karman
vortex

cilindro Re = 10.000

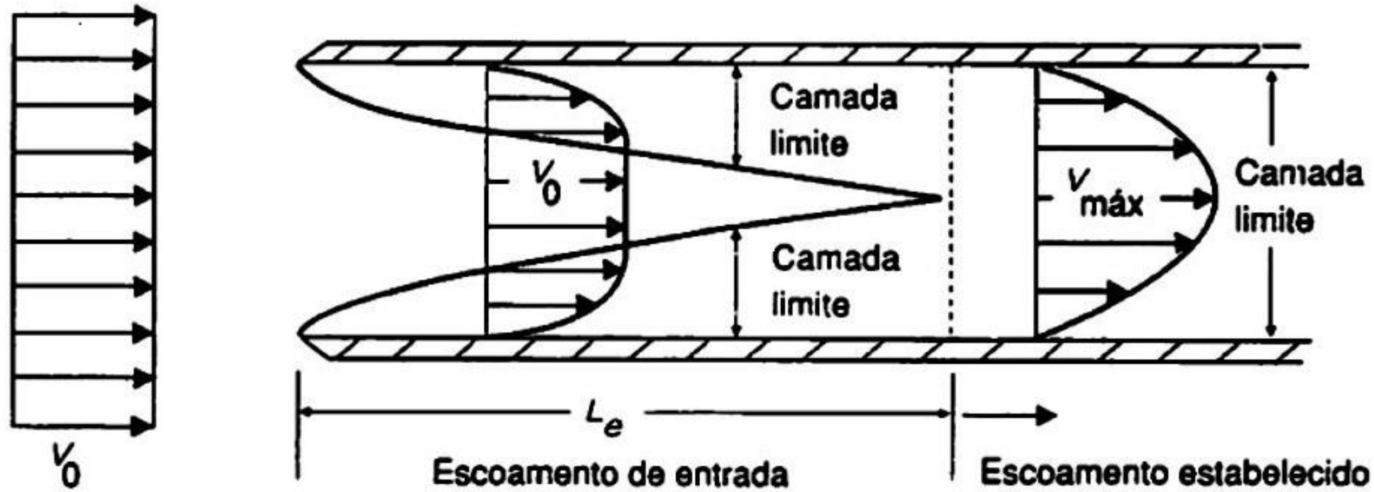


48. Circular cylinder at R**=10,000.** At five times the speed of the photograph at the top of the page, the flow pattern is scarcely changed. The drag coefficient consequently remains almost constant in the range of Reynolds number spanned by these two photographs. It drops later when, as in figure 57, the boundary layer becomes turbulent at separation. *Photograph by Thomas Corke and Hassan Nagib*



Prandtl
1875 –1953

$$\frac{\partial \overline{\vec{v}}}{\partial t} + \mathrm{div}\,\overline{\vec{v}}\,\overline{\vec{v}} = \mathrm{div}\left[\mu + \mu_T\right]\mathrm{gr\vec{a}d}\,\overline{\vec{v}} + \overline{\vec{g}}$$



$$\mu_T = \ell\,\mathrm{gr\vec{a}d}\,\overline{\vec{v}}$$

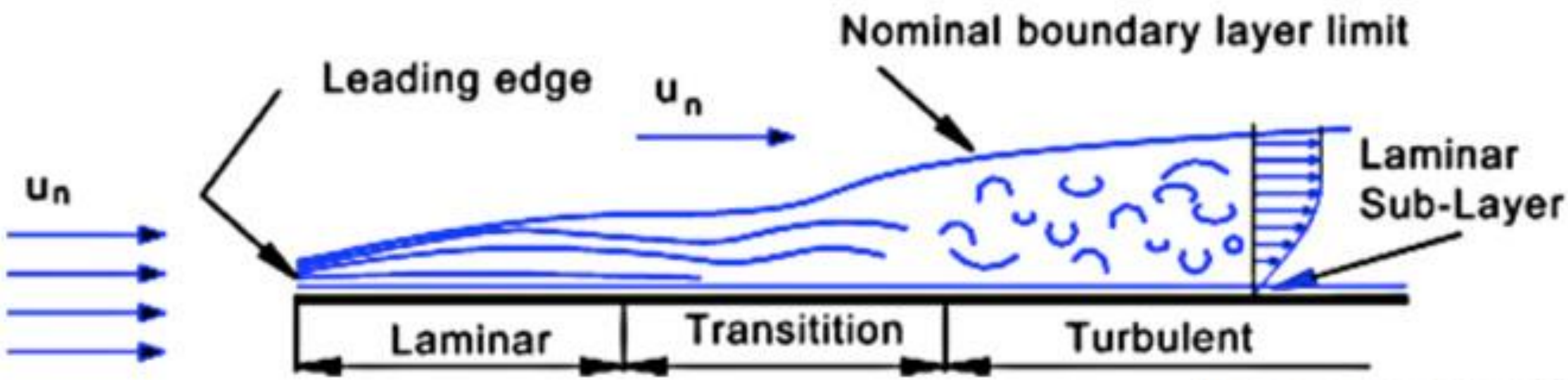
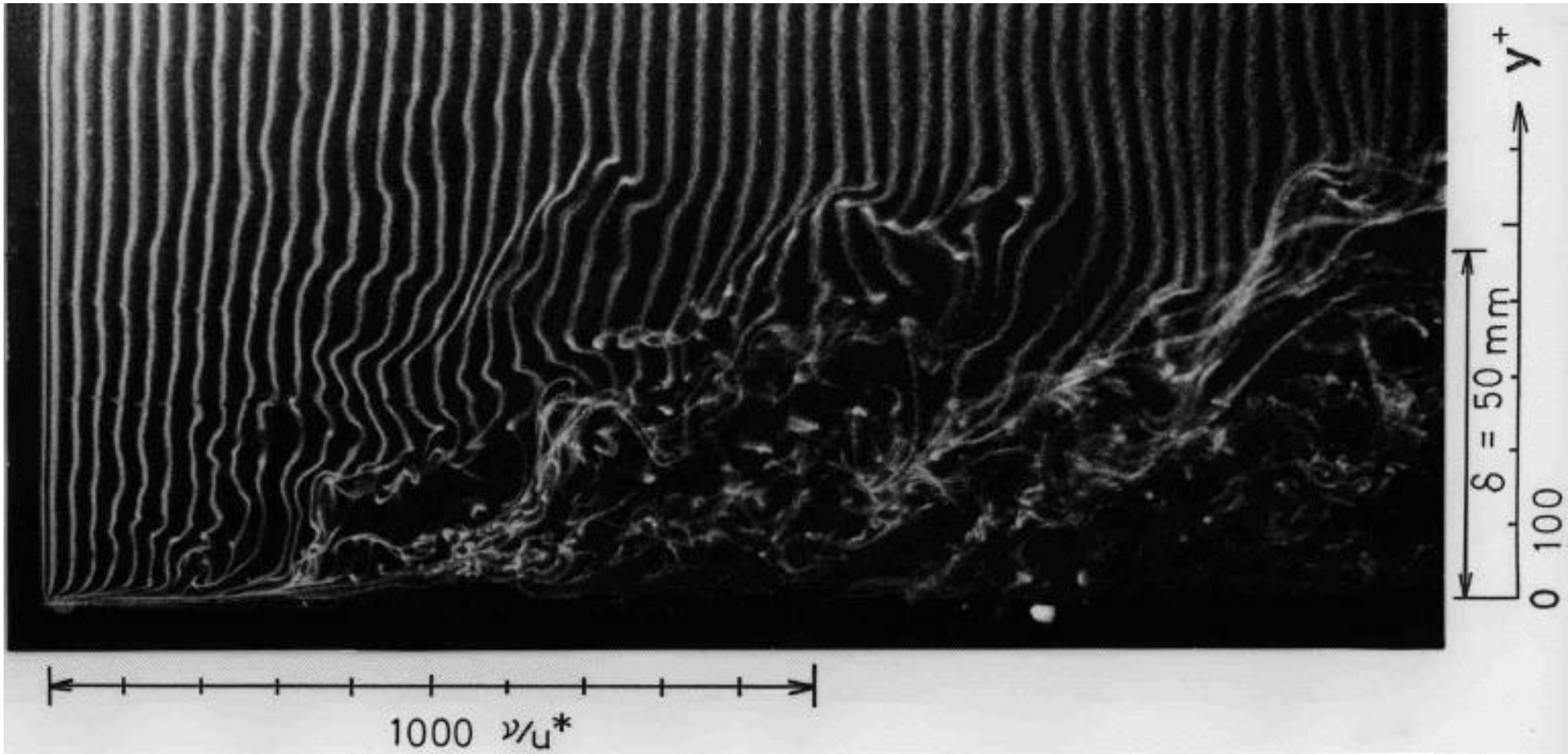


Image: www.roymech.co.uk/



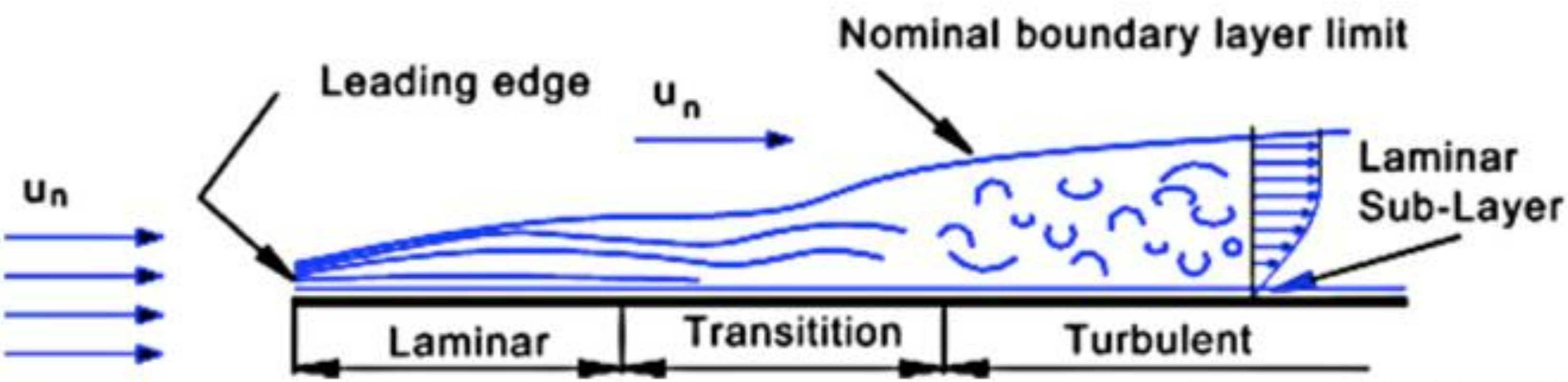
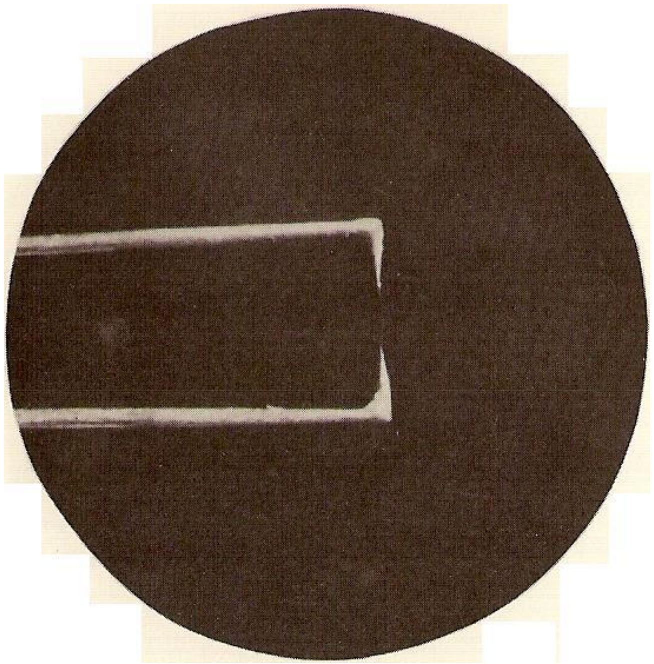


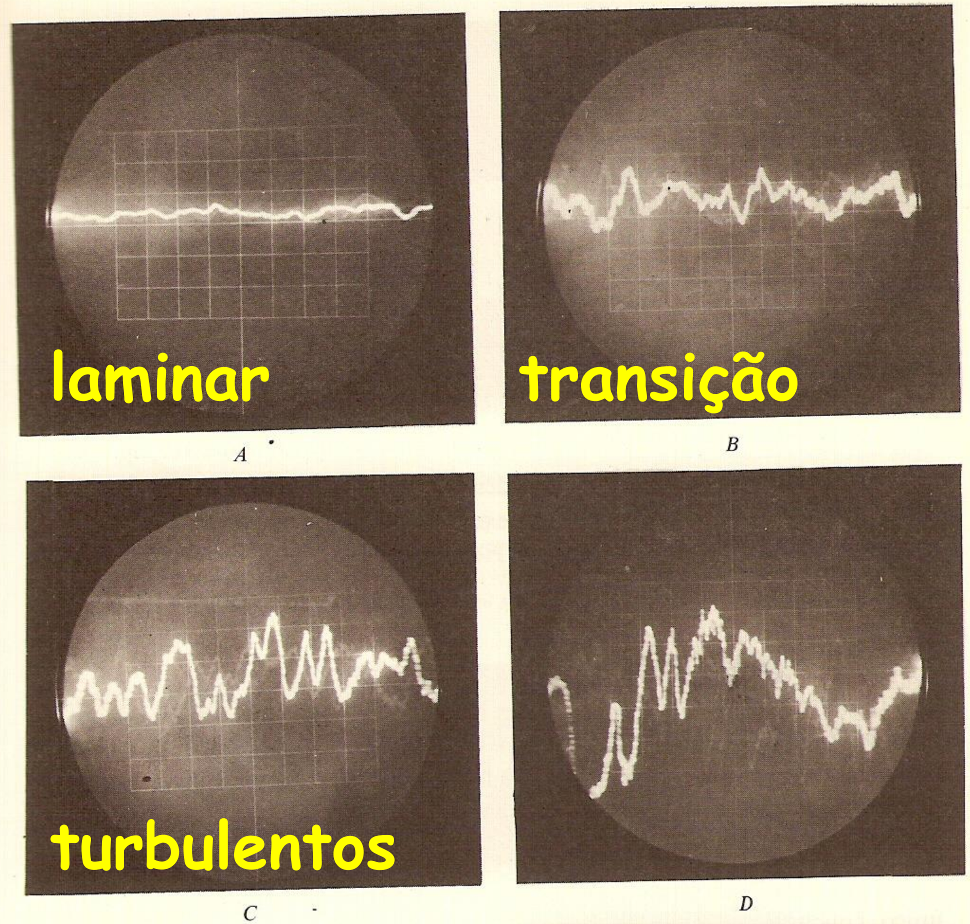
Image: www.roymech.co.uk/

$$\pi = \pi' + \overline{\pi}$$



anemômetro de fio quente

$$\vec{v} = \vec{v}' + \overline{\vec{v}}$$



osciloscópio

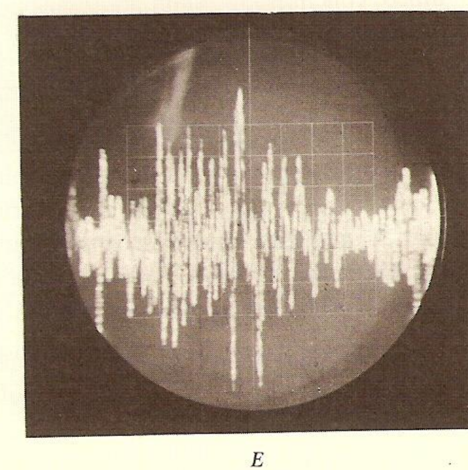
Fig. 34. Fotografias de flutuações da velocidade de perturbação v' visualizadas na tela de um osciloscópio através da técnica da anemometria de fio quente.

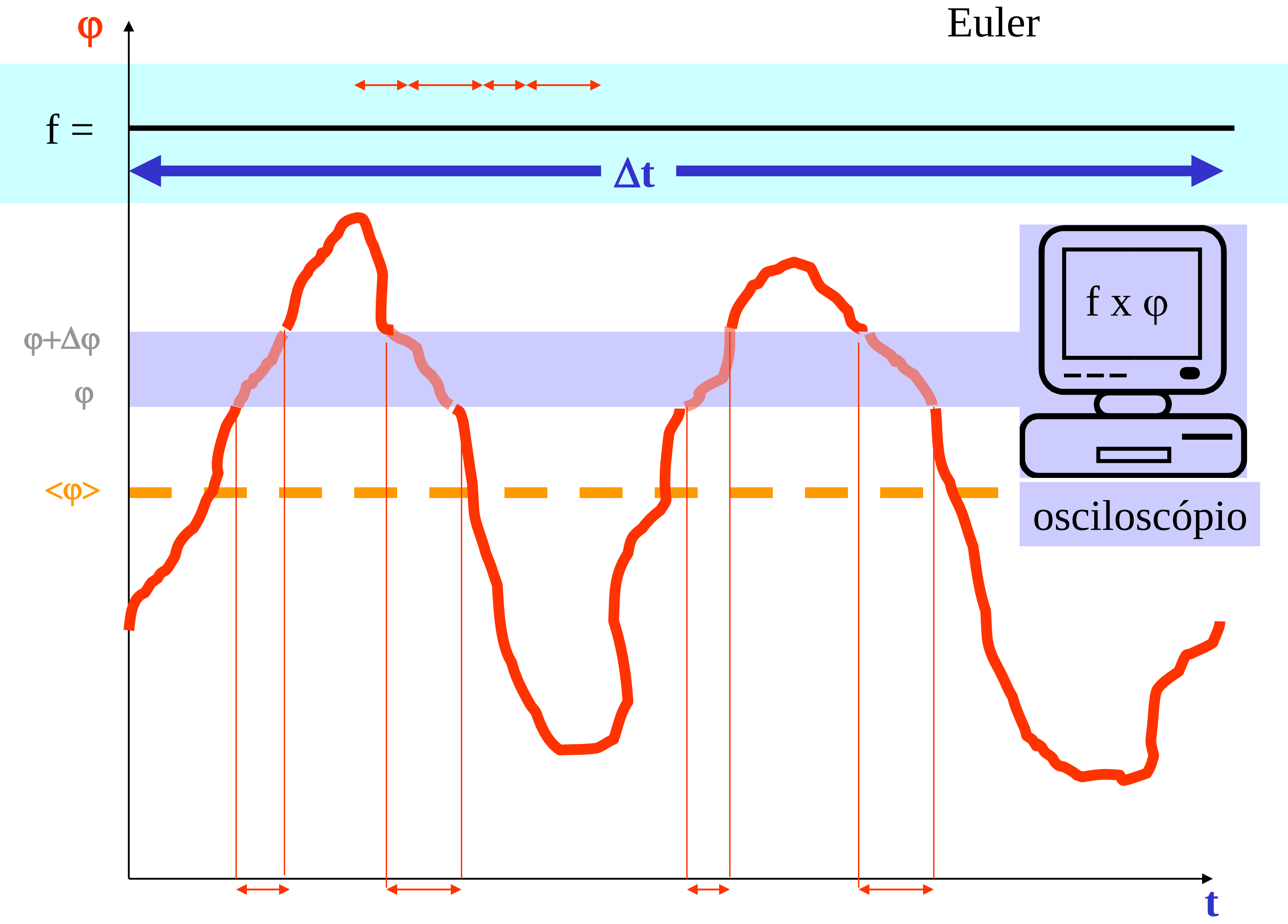
A – regime laminar

B – transição

C, D e E – regime turbulento, com diversas intensidades de turbulência.

A ordem de grandeza da intensidade de turbulência usual em escoamentos nas aplicações da Engenharia é de 0,05.

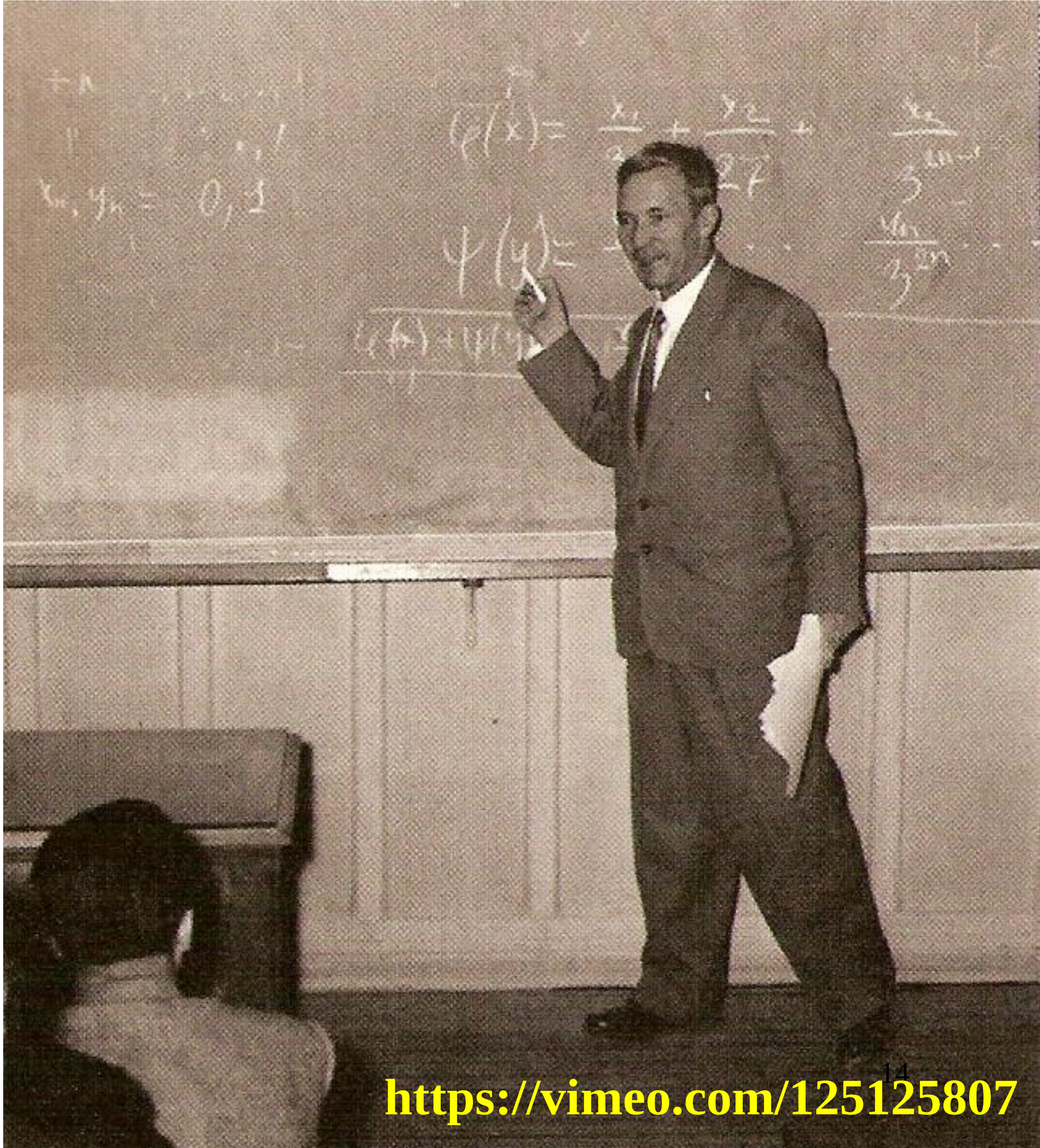




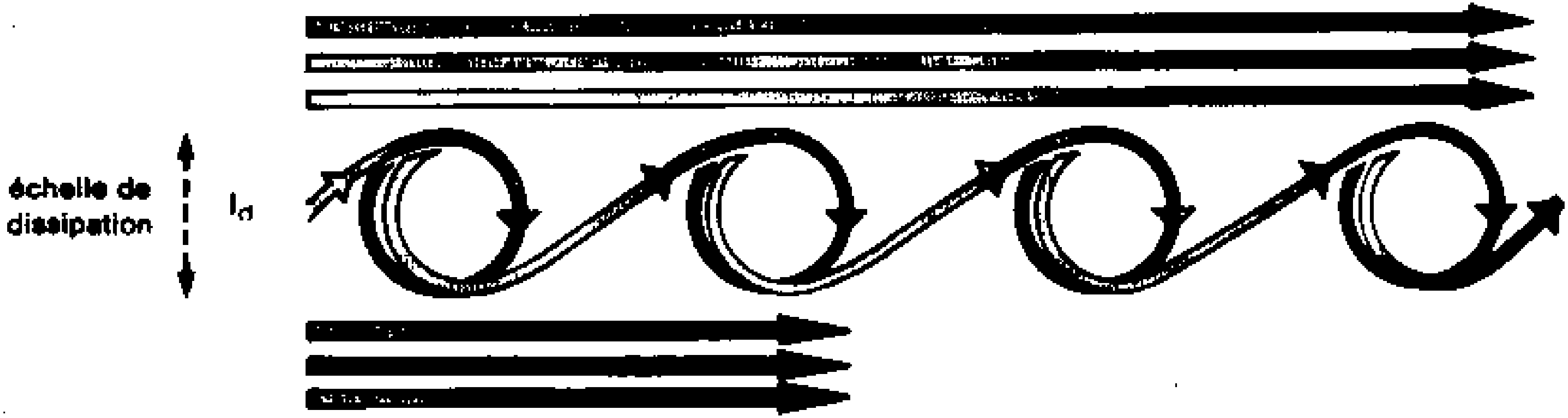
medidas

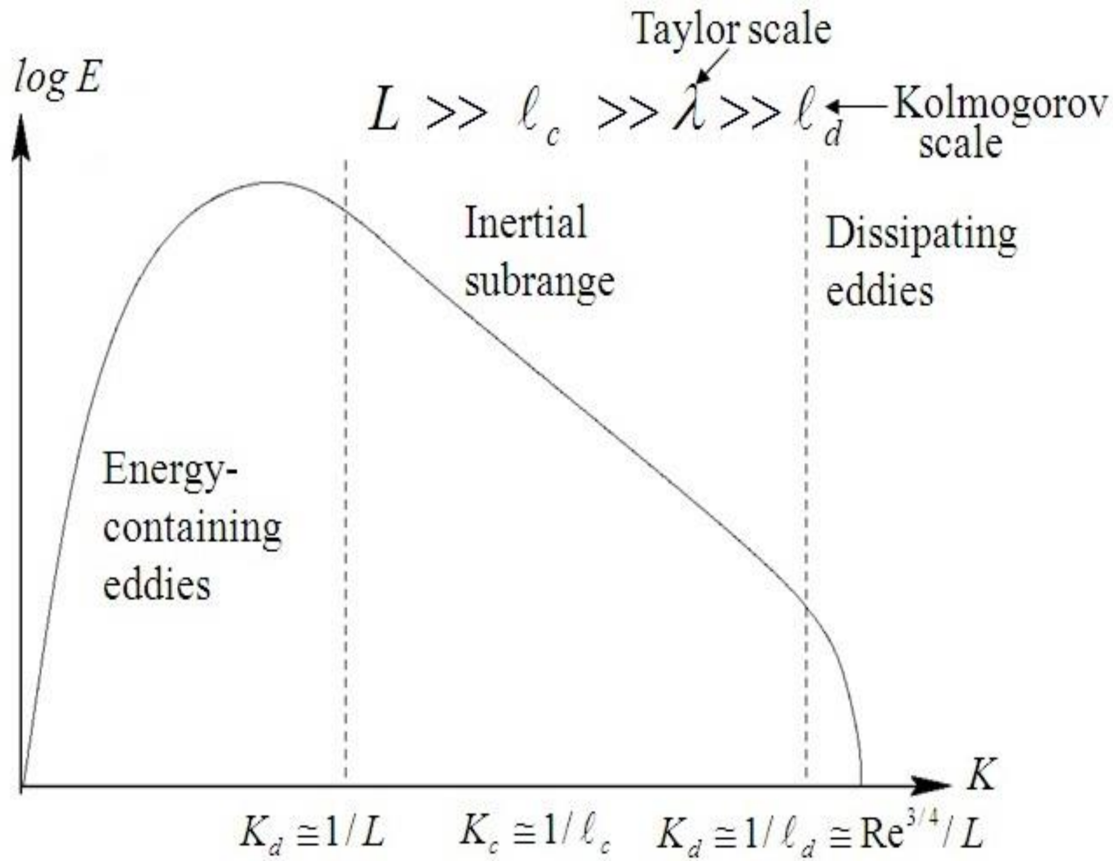
Kolmogorov
1903 -1987

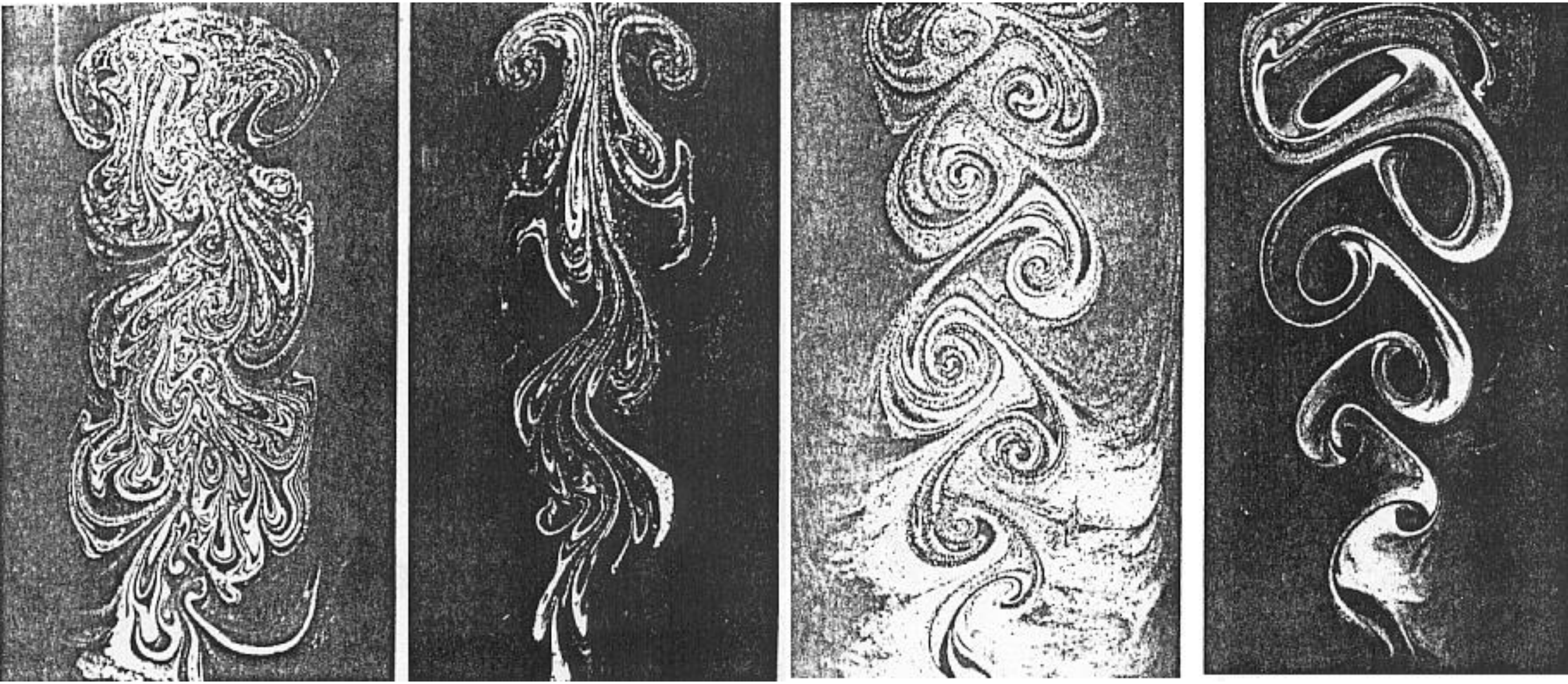
“meu interesse pelo estudo dos escoamentos turbulentos surgiu no fim dos anos 30. Pareceu-me evidente que a técnica matemática principal deveria ser a teoria das **funções aleatórias de diversas variáveis**, que estava então nascendo.”

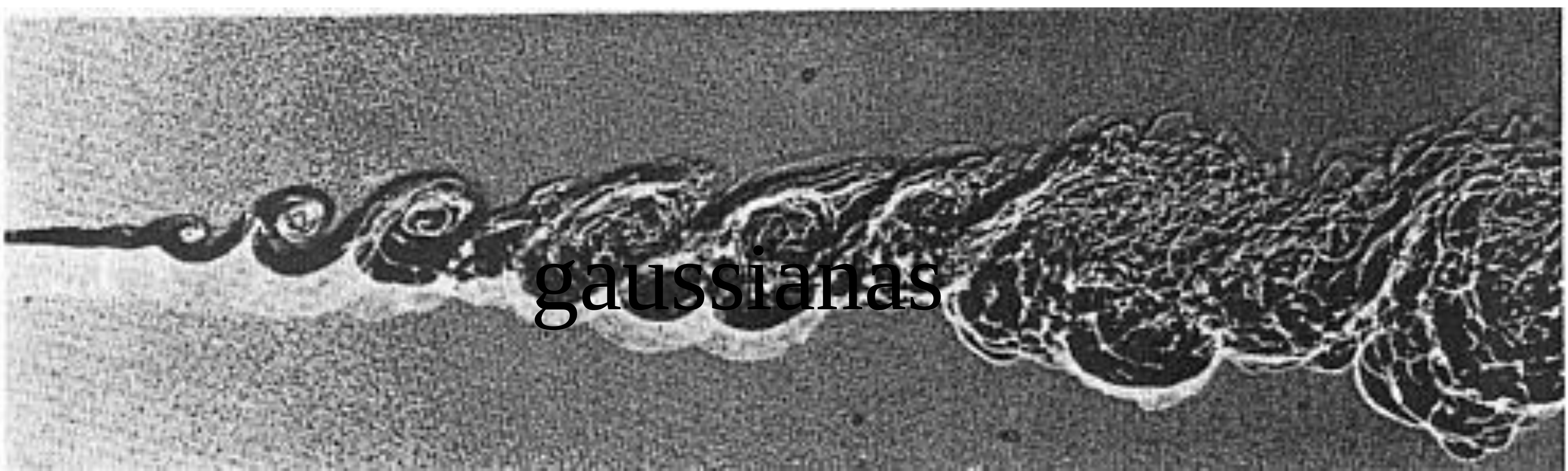


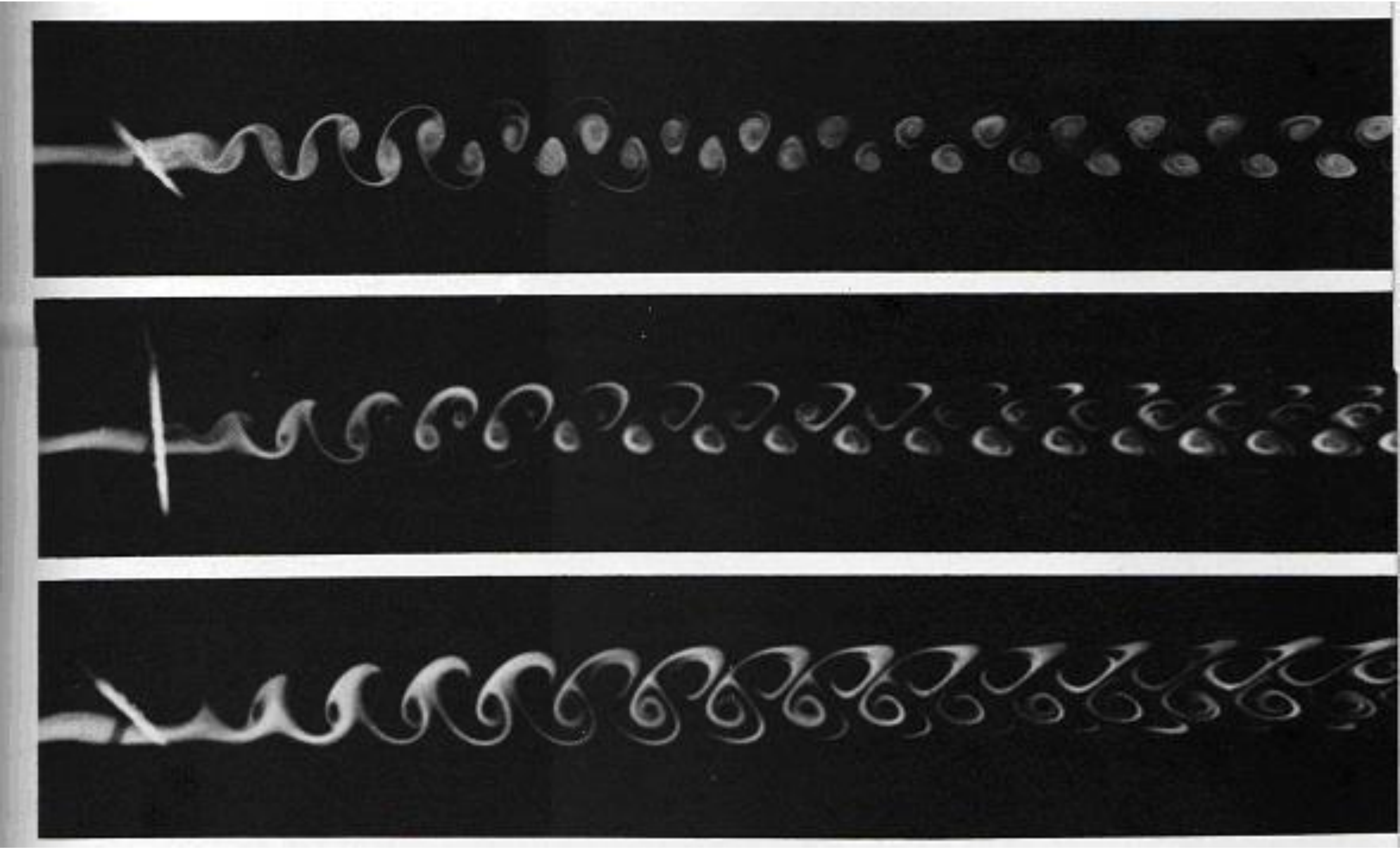
https://vimeo.com/125125807


échelle de dissipation
l_d

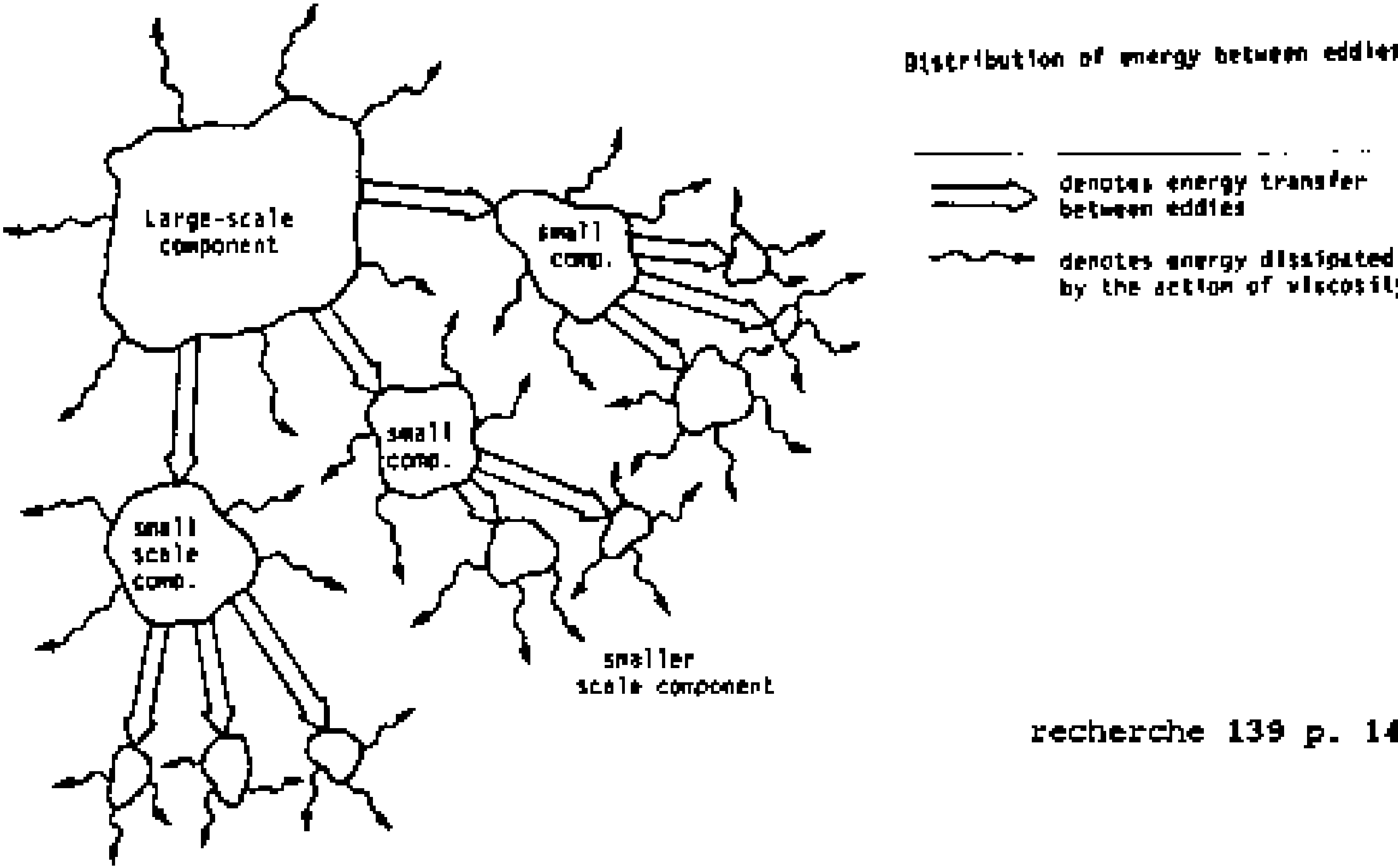

Taylor scale
$\log E$
$L >> \ell_c >> \lambda >> \ell_d$
Kolmogorov scale
Inertial subrange
Dissipating eddies
Energy-containing eddies
K
$K_d \cong 1/L$
$K_c \cong 1/\ell_c$
$K_d \cong 1/\ell_d \cong \mathrm{Re}^{3/4}/L$




gaussianas

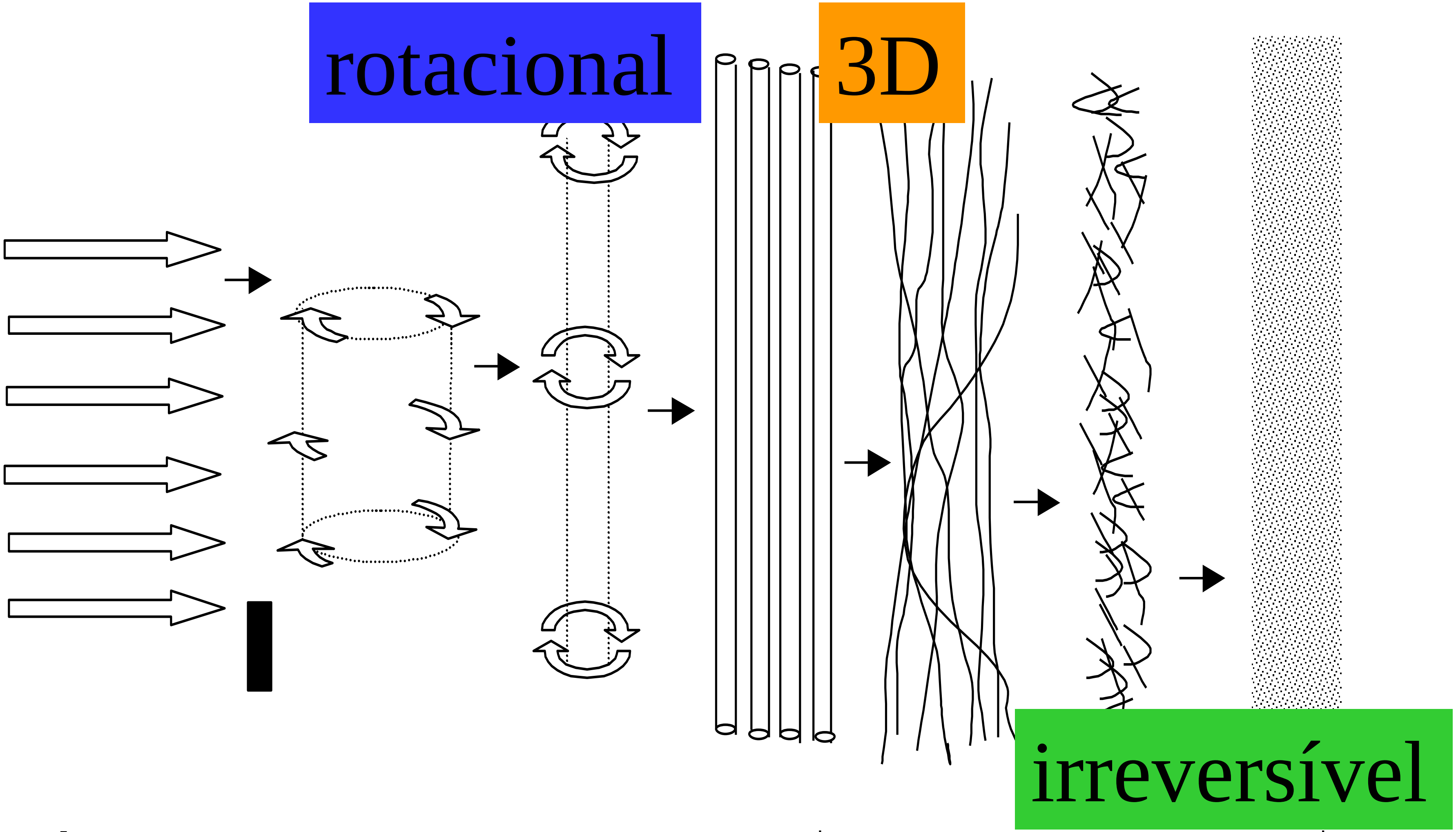


vortex Re = 100



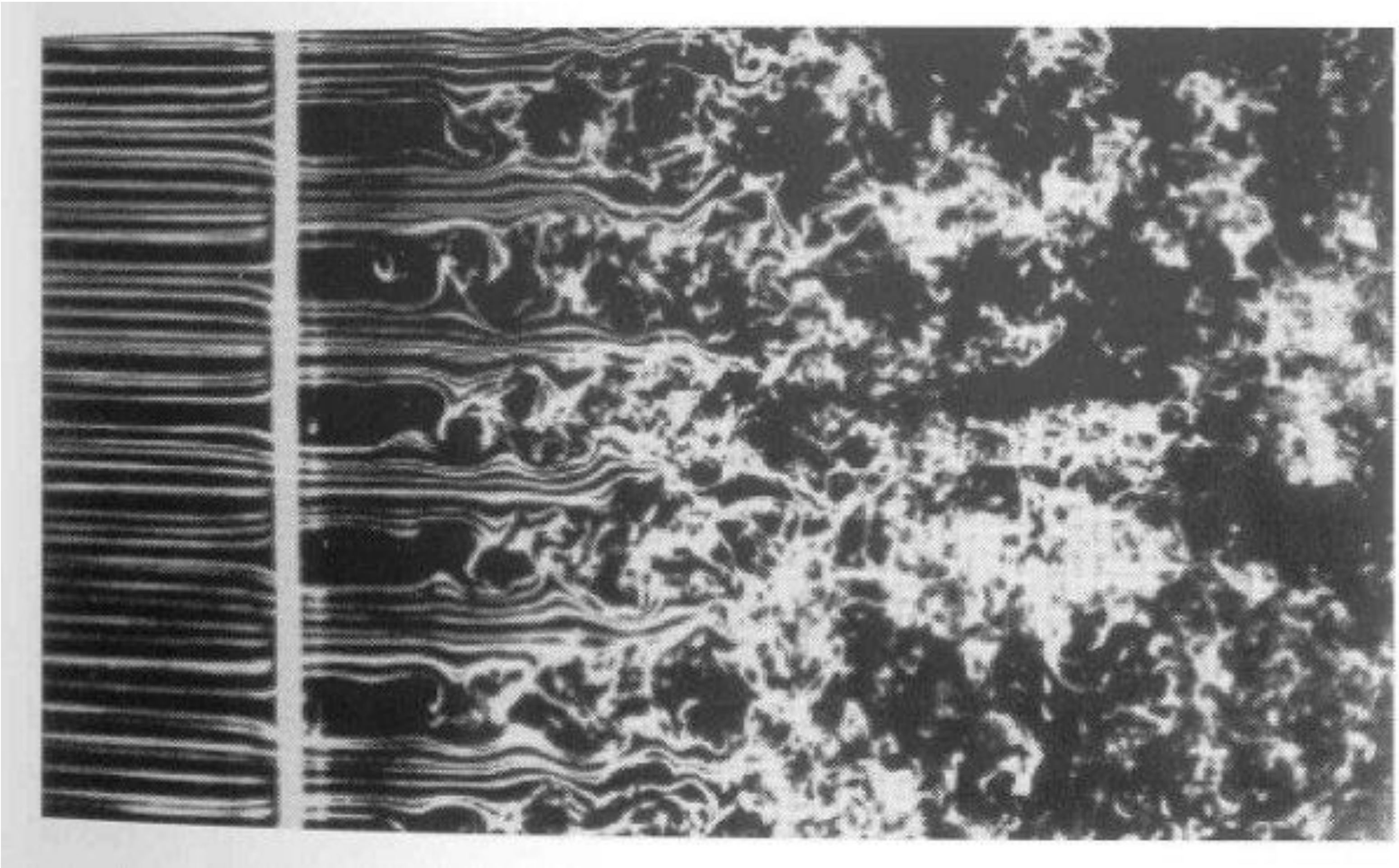
recherche 139 p. 1422

Kolmogorov



escala:	macro	transição	micro
energia cinética	macro	turbulenta	micro
proporcional:	**v**	←--------------- k -----------------→	T

escalas de turbulências



Escalas de Kolmogorov – menores escalas de turbulência

- Comprimento $\eta = \left(\dfrac{\nu^3}{\varepsilon}\right)^{1/4}$ $\qquad \dfrac{\eta}{l_0} = \mathrm{Re}^{-3/4}$

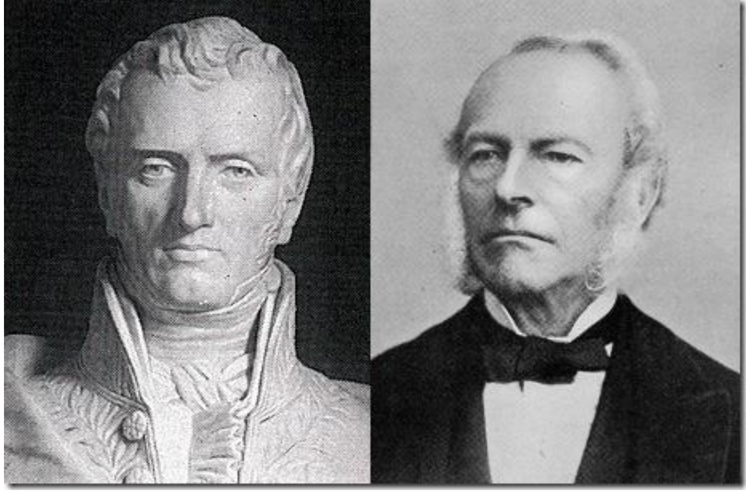
- Velocidade $u_\eta = (\nu\varepsilon)^{1/4}$ $\qquad \dfrac{u_\eta}{u_0} = \mathrm{Re}^{-1/4}$

- Tempo $\tau_\eta = \left(\dfrac{\nu}{\varepsilon}\right)^{1/2}$ $\qquad \dfrac{\tau_\eta}{\tau_0} = \mathrm{Re}^{-1/2}$

- Reynolds $\mathrm{Re}_\eta = \dfrac{u_\eta \eta}{\nu} = 1$

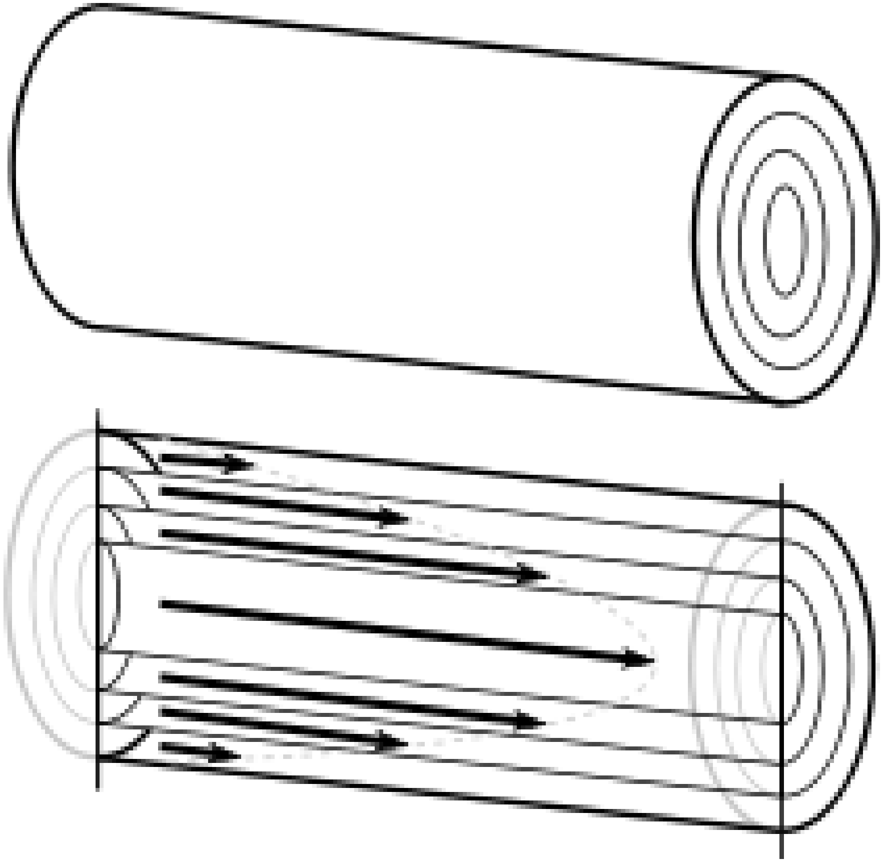
$$\underbrace{\frac{\partial(\rho\vec{v})}{\partial t}}_{\text{transiente}} = \underbrace{-\mathrm{div}(\rho\vec{v}\vec{v})}_{\text{convecção}} - \underbrace{\mathrm{div}\vec{\vec{\tau}}}_{\substack{\text{força}\\ \text{contato}\\ \text{irreversível}}} \underbrace{-\mathrm{gr}\vec{\mathrm{a}}\mathrm{dp}}_{\substack{\text{força}\\ \text{contato}\\ \text{reversivel}}} + \underbrace{\rho\vec{g}}_{\substack{\text{força}\\ \text{campo}}}$$

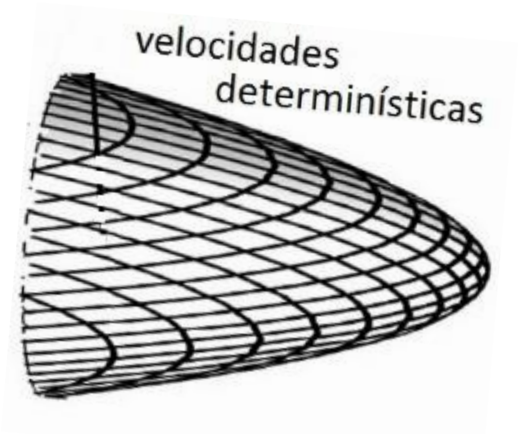
$$\vec{\vec{\tau}} = -\mu\frac{\partial v_z}{\partial r}$$



Navier
1785-1836

Stokes
1819 -1903





$$\boxed{v_z = \frac{\Delta p R^2}{2\mu L}\left[1 - \left(\frac{r}{R}\right)^2\right]}$$

$$\boxed{\frac{v_z}{v_o} = 1 - \left(\frac{r}{R}\right)^2}$$

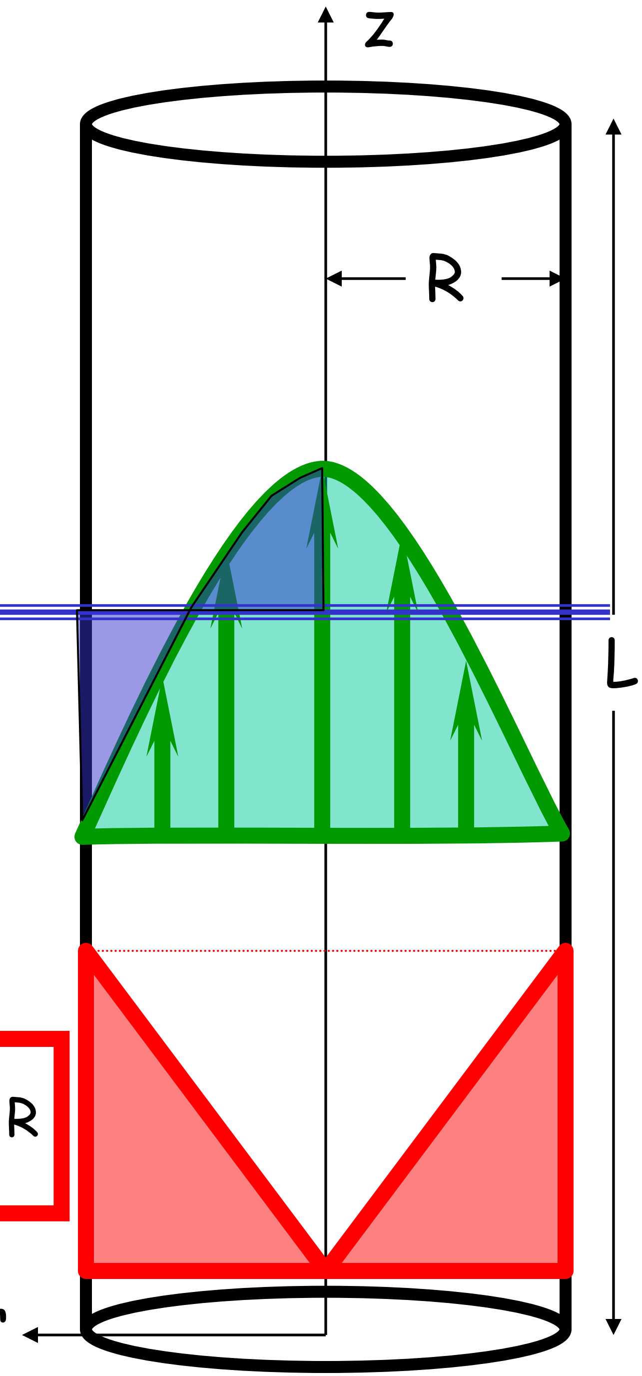
v_{bulk} = $\dot{m} v_b = \rho\, v_b\, \pi R^2 = \int_0^R \rho\, v_z\, 2\pi r\, dr$

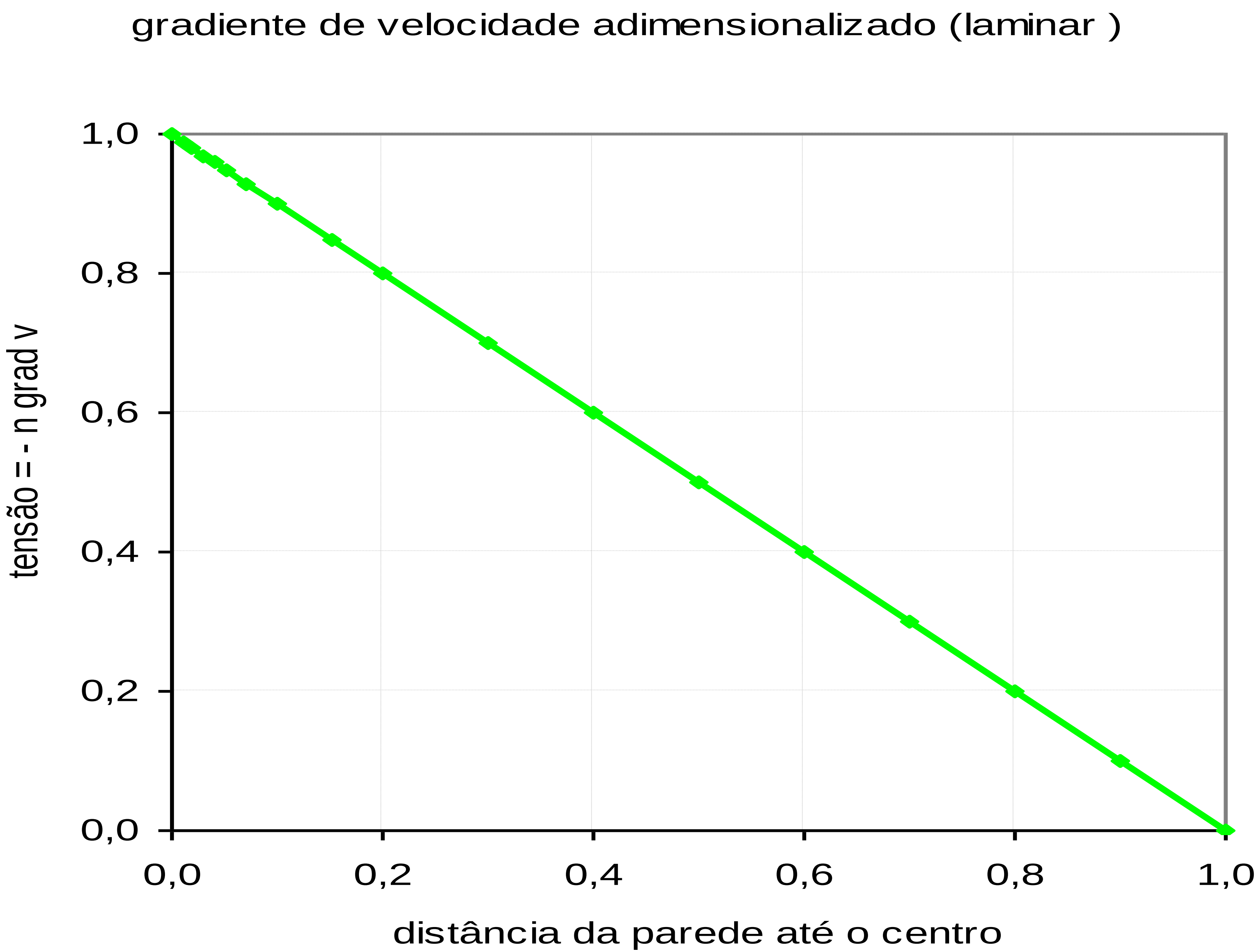
$$v_b = \frac{\rho\, 2\pi}{\rho\, \pi R^2}\int_0^R v_z\, r\, dr = \frac{2}{R^2}\,\frac{\Delta p\, R^2}{2\,\mu\, L}\int_0^R \left(1 - \left(\frac{r}{R}\right)^2\right) r\, dr$$

$$\boxed{v_b = \frac{R^2\, \Delta p}{4\,\mu\, L}}$$

tensão $\quad \zeta_{rz} = -\mu\frac{\partial v_z}{\partial r} = -\mu\frac{\partial}{\partial r}\left[\frac{\Delta p}{2\,\mu\, L}\left(R^2 - r^2\right)\right]$

$$\boxed{\zeta_{rz} = \frac{\Delta p}{L} r} \qquad \boxed{\zeta_w = \frac{\Delta p}{L} R}$$




gradiente de velocidade adimensionalizado (laminar)
tensão = - n grad v
1,0
0,8
0,6
0,4
0,2
0,0
0,0
0,2
0,4
0,6
0,8
1,0
distância da parede até o centro

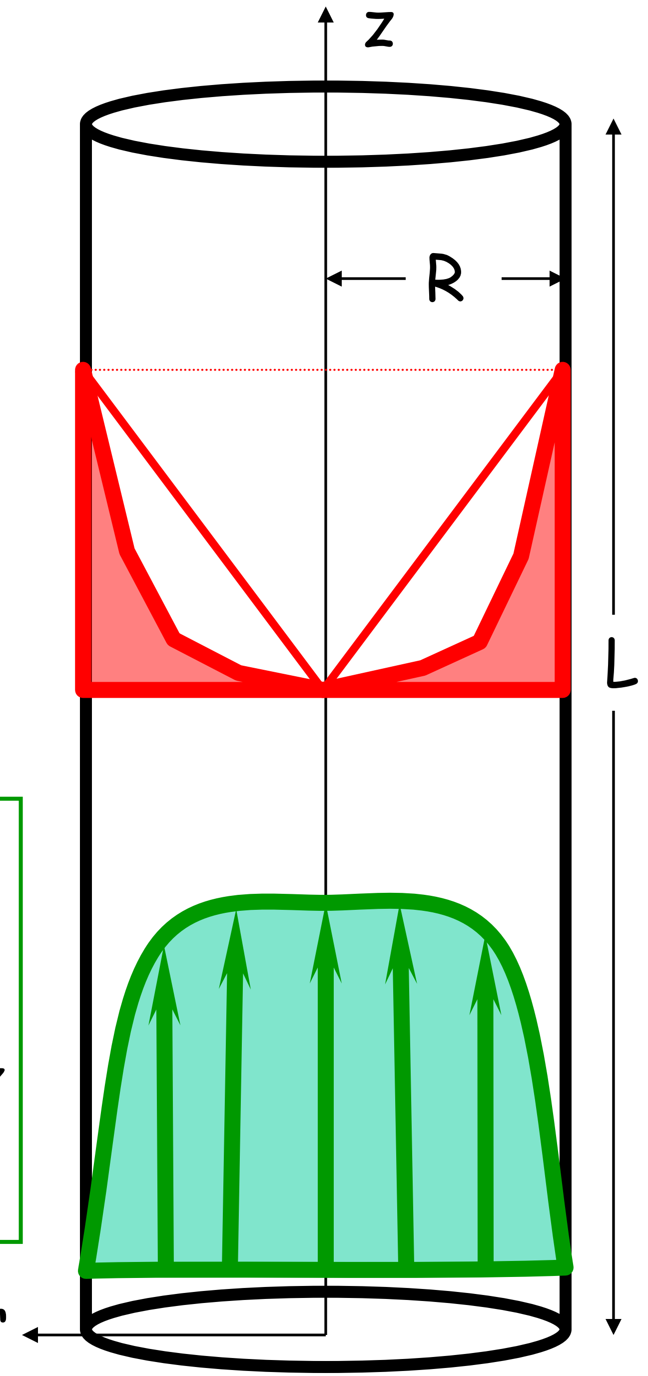
Turbulento

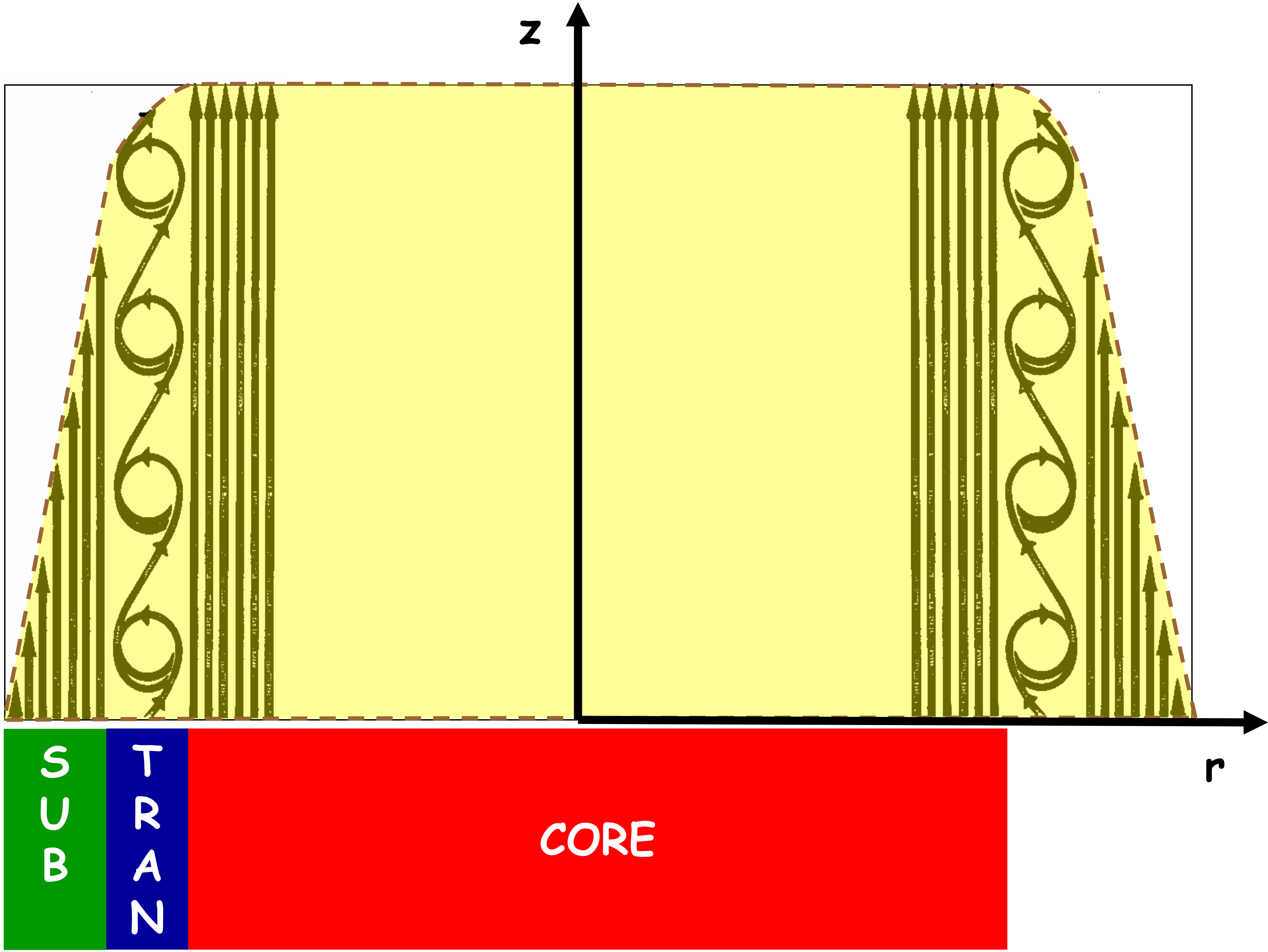
$$\vec{\vec{\zeta}} = \nu\, \vec{\mathrm{grad}}\, \overline{\vec{v}} - \overline{\vec{v}'\vec{v}'} = \nu_T\, \vec{\mathrm{grad}}\, \overline{\vec{v}}$$

$0 > y^+ > 5$ $\quad$ $\overline{v}^+ = y^+\left[1 - \frac{1}{4}\left(\frac{y^+}{14{,}5}\right)^3\right]$

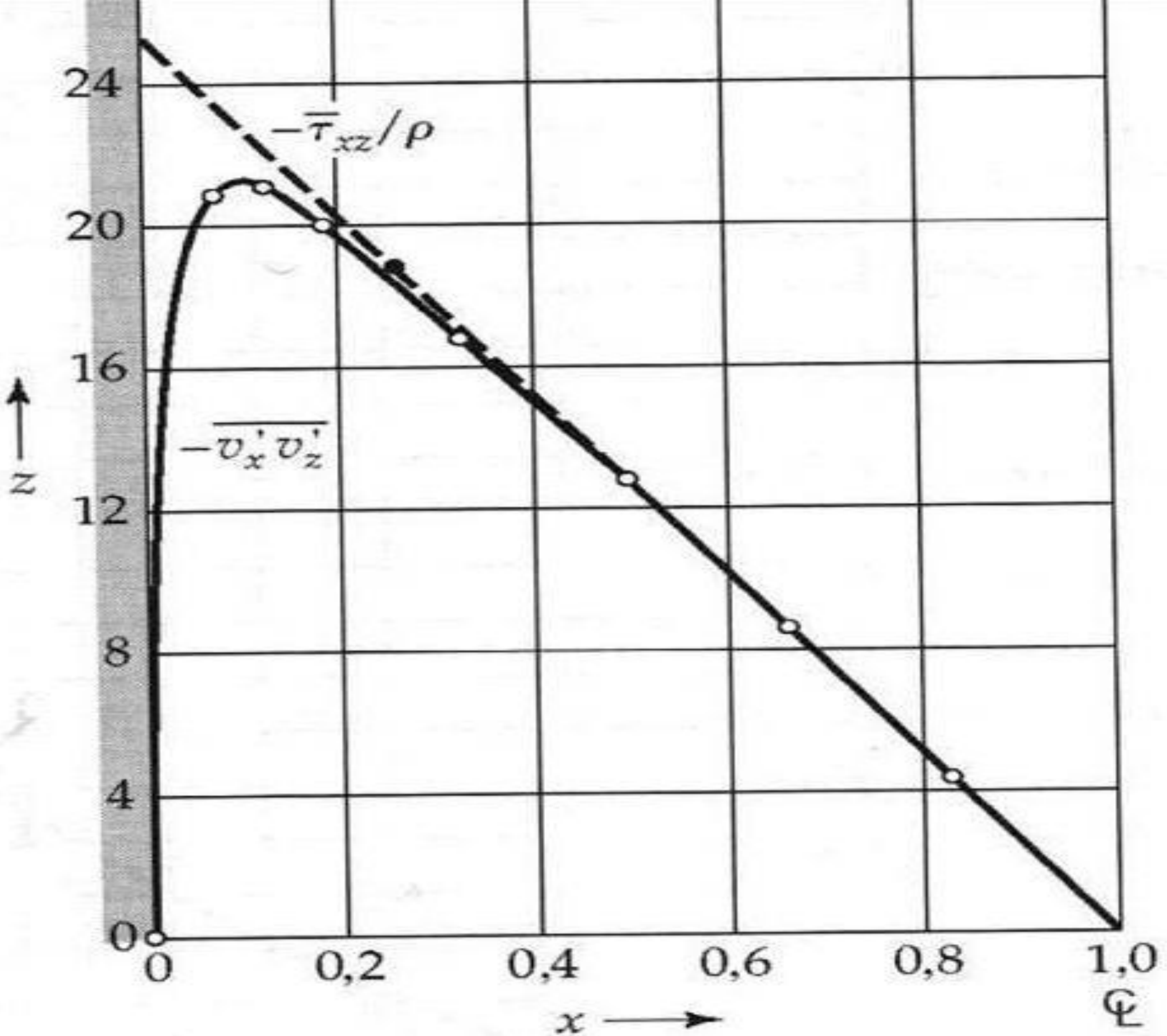
$5 > y^+ > 30$ $\quad$ $\overline{v}^+ = 5\ln\left(y^+ + 0{,}205\right) - 3{,}27$

$y^+ > 30$ $\quad$ $\overline{v}^+ = 2{,}5\ln y^+ + 5{,}5$




z
r
SUB
TRAN
CORE

Tensão



Escoamento turbulento

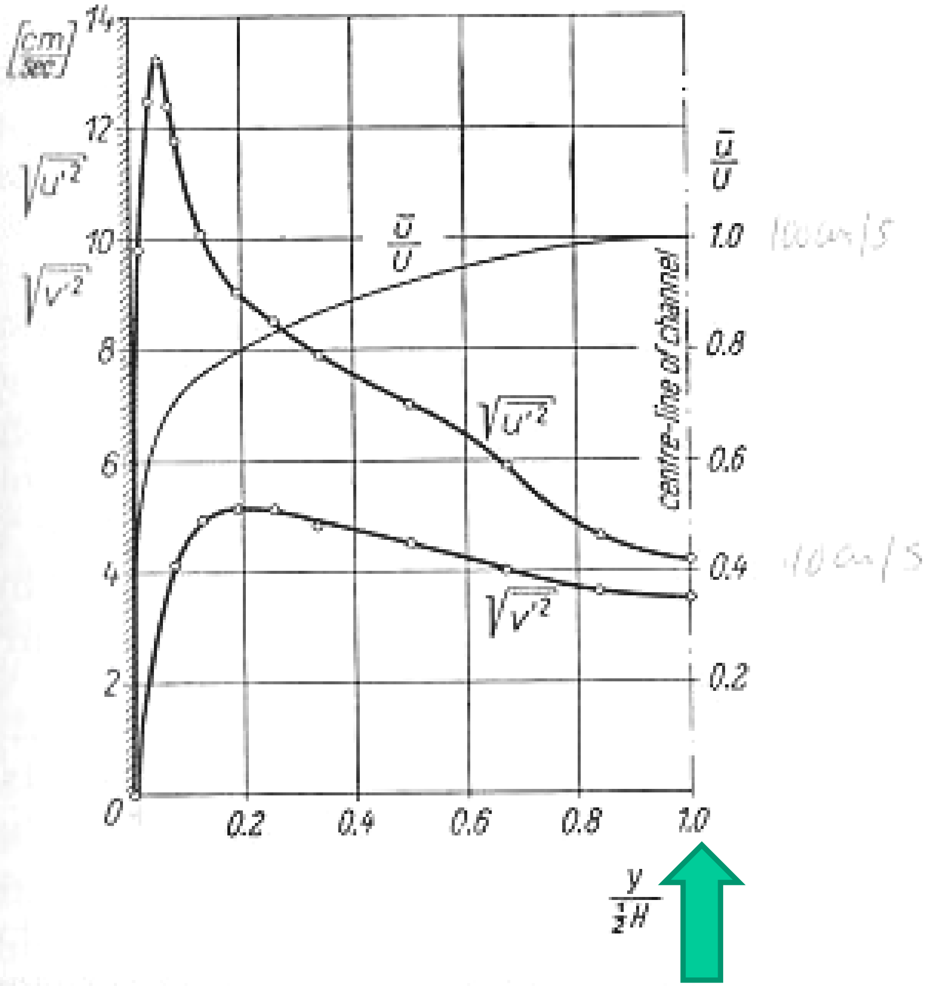


Fig. 18.3. Measurement of fluctuating turbulent components in a wind tunnel, at maximum velocity U = 100 cm/sec after Reichardt [41]

Root-mean-square of longitudinal fluctuation $\sqrt{\overline{u'^2}}$, transverse fluctuation $\sqrt{\overline{v'^2}}$, mean velocity $\overline{u}$

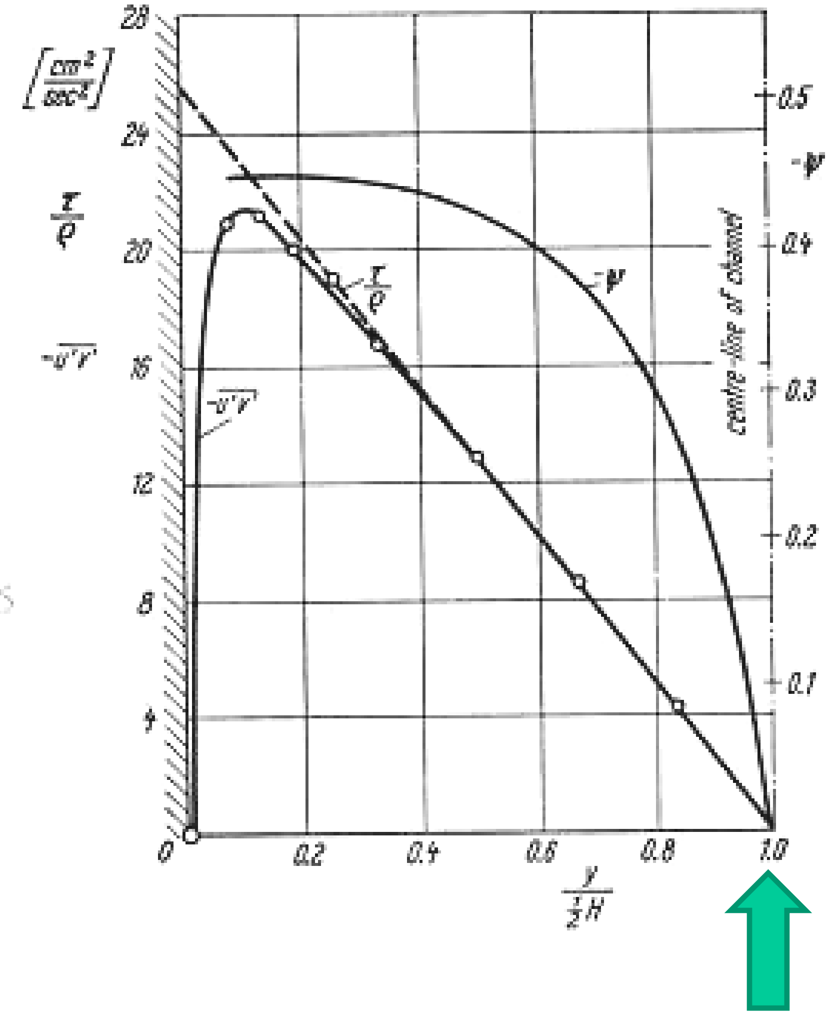


Fig. 18.4. Measurement of fluctuating components in a channel, after Reichardt [41]

The product $\overline{u'\,v'}$, the shearing stress τ/ϱ, and the correlation coefficient ψ

Intensidade de Turbulência

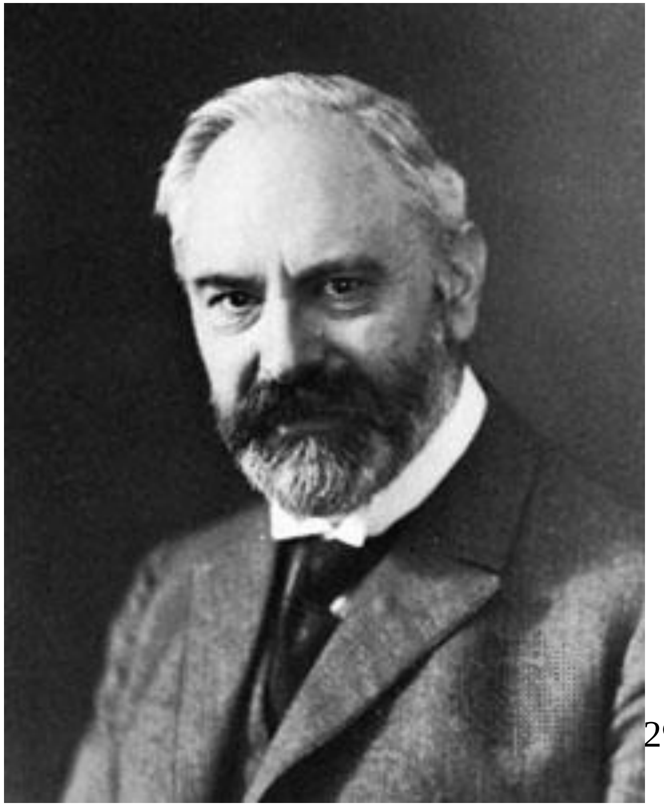
sendo a difusividade turbulenta >> laminar:

$$\left\lfloor \lambda_\phi + \lambda_{\phi T} \right\rfloor \approx \lambda_{\phi T}$$

$$\frac{\partial \overline{\varphi}}{\partial t} + \mathrm{div}\,\overline{\vec{v}}\;\overline{\varphi} = \mathrm{div}\,\lambda_{\phi T}\,\vec{\mathrm{grad}}\,\overline{\varphi} + \overline{\dot{\sigma}_{M_\phi}}$$

voltou à poderosa

agora super-poderosa



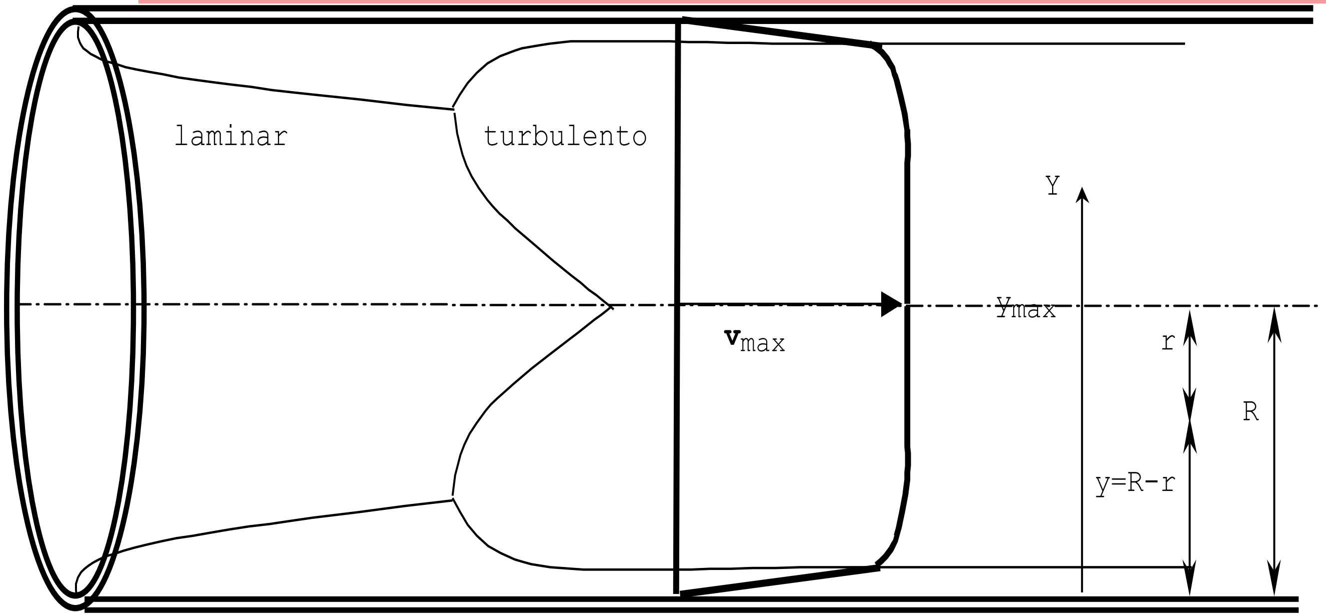
$$\lambda_{\vec{v}T} = \ell_m^2 \left| \vec{\vec{\mathrm{grad}}}\,\overline{\vec{v}} \right|$$

Prandtl mixing lenght

hipótese

Turbulento

Escoamento unidimensional em estado estacionário sobre uma superfície (parede plana, tubo escoamento desenvolvido)



$$\cancel{\frac{\partial \overline{\varphi}}{\partial t}} + \operatorname{div} \overline{\vec{v}}\, \overline{\varphi} = \operatorname{div}\left[\lambda_{\phi} + \lambda_{\phi T}\right] \operatorname{gr\vec{a}d} \overline{\varphi} + \cancel{\overline{\dot{\sigma}_{M_\phi}}}$$

$$\lambda_{\vec{v}T} = \nu_T = \ell_m^2 \left|\operatorname{gr\vec{a}d} \overline{\vec{v}}\right| >> \lambda_{\vec{v}} = \nu$$

lm = comprimento de mistura de Prandtl

$$\operatorname{div} \overline{\vec{v}}\, \overline{\vec{v}} = \operatorname{div}\left\{\ell_m^2 \left|\operatorname{gr\vec{a}d} \overline{\vec{v}}\right| \operatorname{gr\vec{a}d} \overline{\vec{v}}\right\}$$

$$\operatorname{div}\overline{\vec{v}}\,\overline{\vec{v}} = \operatorname{div}\left\{\ell_m^2 \left|\operatorname{gr\vec{a}d}\overline{\vec{v}}\right| \operatorname{gr\vec{a}d}\overline{\vec{v}}\right\}$$

Próximo à parede (w)

$$\ell_m = \alpha\ y$$

$$\left\{\operatorname{d\vec{i}v}\ \overline{\vec{v}}\ \overline{\vec{v}}\right\}_w = \operatorname{d\vec{i}v}\left\{\alpha^2\ y^2\ \left(\frac{\partial \overline{v_z}}{\partial y}\right)^2\right\} = \frac{1}{\rho}\operatorname{d\vec{i}v}\ \vec{\vec{\tau}}_w$$

$$\alpha^2\ y^2\left(\frac{\partial \overline{v_z}}{\partial y}\right)^2 = \frac{\tau_w}{\rho} \qquad \rightarrow \qquad y\ \frac{\partial \overline{v_z}}{\partial y} = \frac{1}{\alpha}\sqrt{\frac{\tau_w}{\rho}}$$

$$d\ \overline{v}_z = \frac{1}{\alpha}\sqrt{\frac{\tau_w}{\rho}}\ \frac{dy}{y} \qquad \overline{v}_z = \frac{\sqrt{\tau_w/\rho}}{\alpha}\ln y + cte'$$

$$\overline{v}_z^+ = \frac{\overline{v}_z}{\sqrt{\tau_w/\rho}}$$

$$y^+ = \frac{y}{\nu}\sqrt{\frac{\tau_w}{\rho}} = \frac{y}{\mu}\sqrt{\rho\ \tau_w}$$

$$u_t = \sqrt{\tau_w/\rho}$$

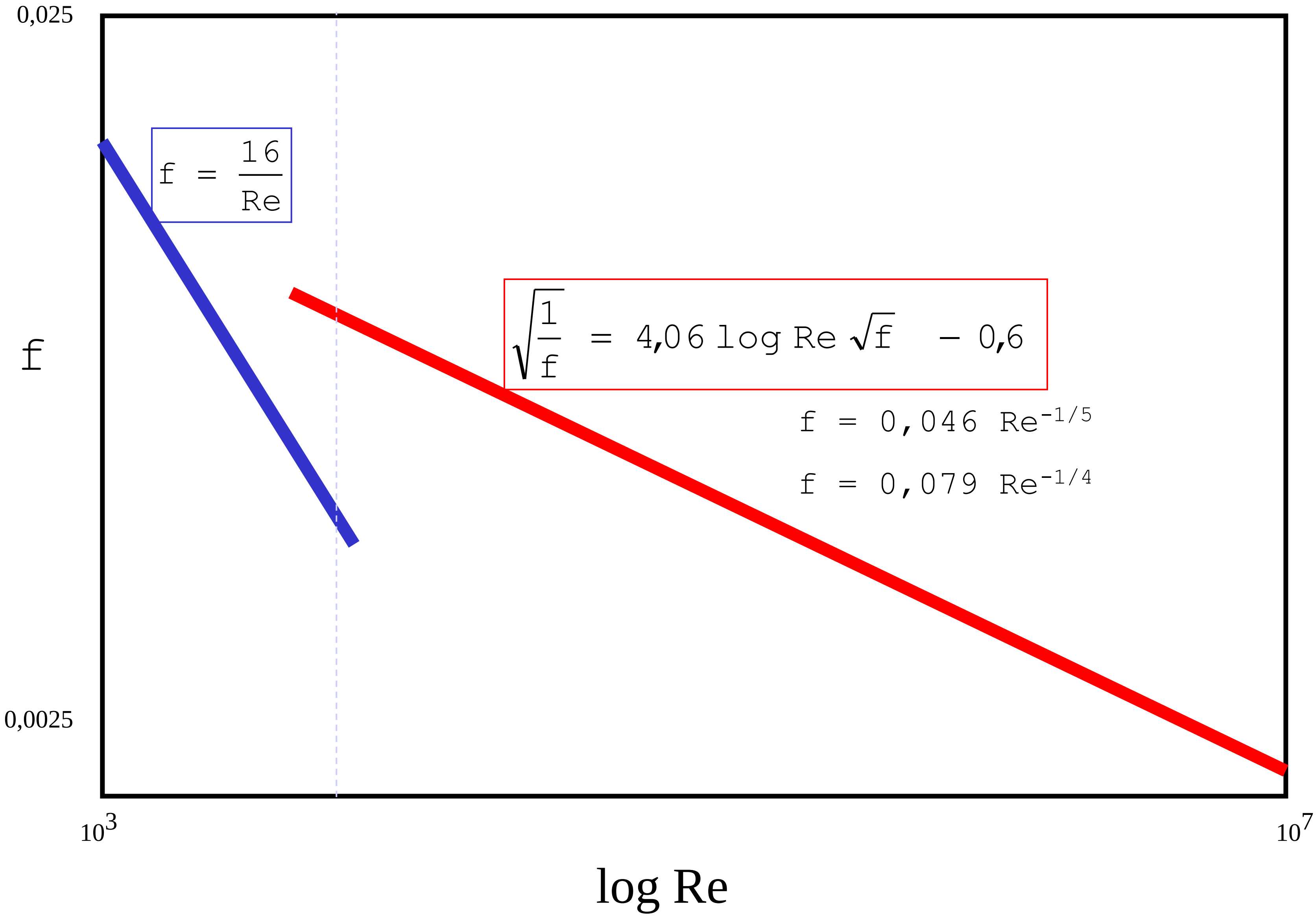
“drift velocity”

$$\overline{v}_z^+ = \frac{1}{\alpha}\ln y^+ + cte$$

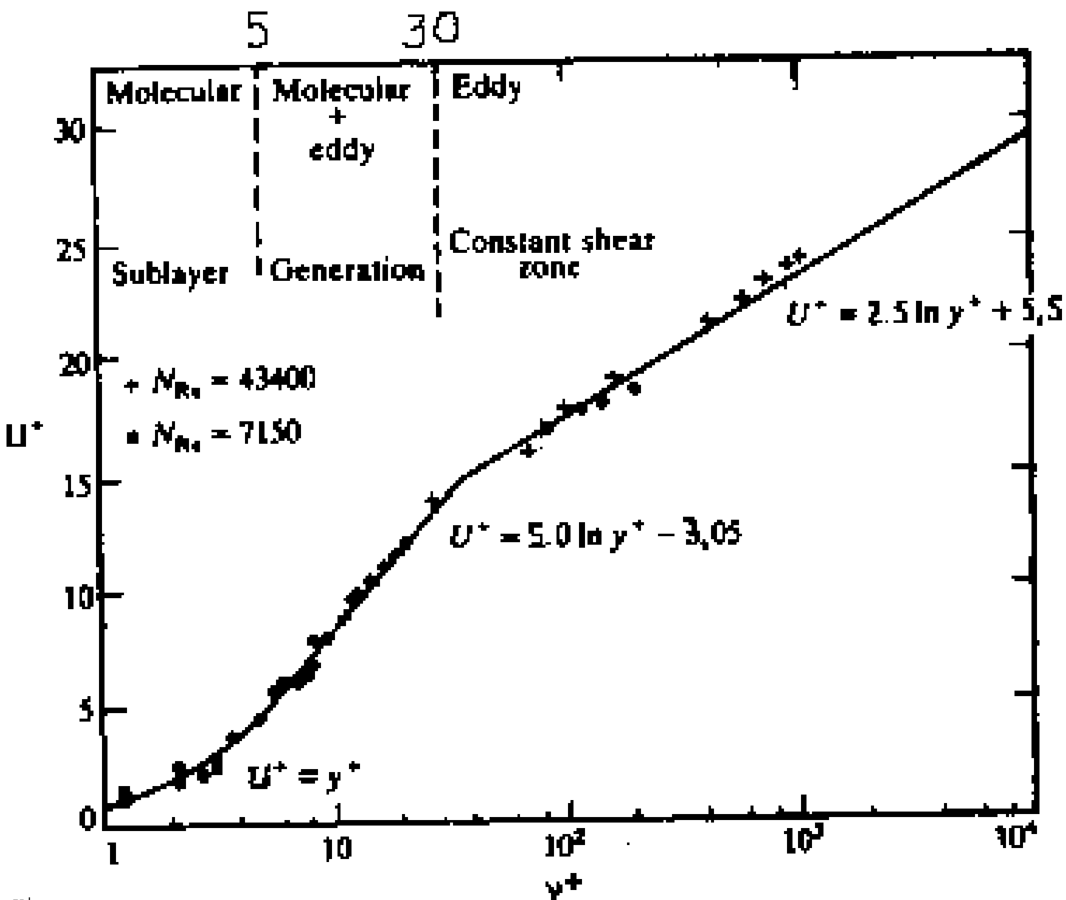
v+

fator de atrito

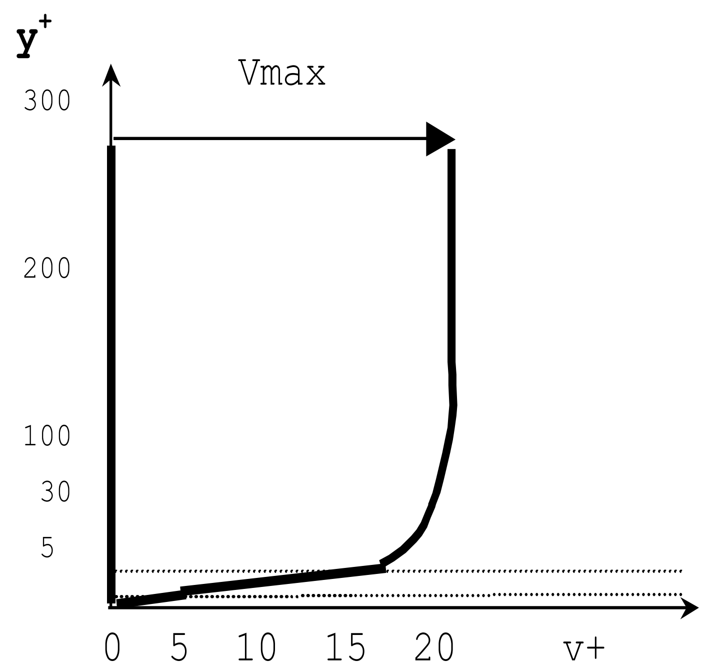
$$\tau_w = \frac{f}{2} \rho v_b^2$$



Região	subcamada	transição	“Core” turbulento
Mecanismo	molecular	molecular + eddy	eddy
propriedade	λ_{Φ}	$\lambda_{\Phi} + \lambda_{\Phi T}$	$\lambda_{\Phi T}$
V^+	y^+	$5 \ln y^+ - 3{,}05$	$2{,}5 \ln y^+ + 5{,}5$
y^+ min	0	5	30
y^+ max	5	30	∞



y+



Perfil Universal de Velocidades

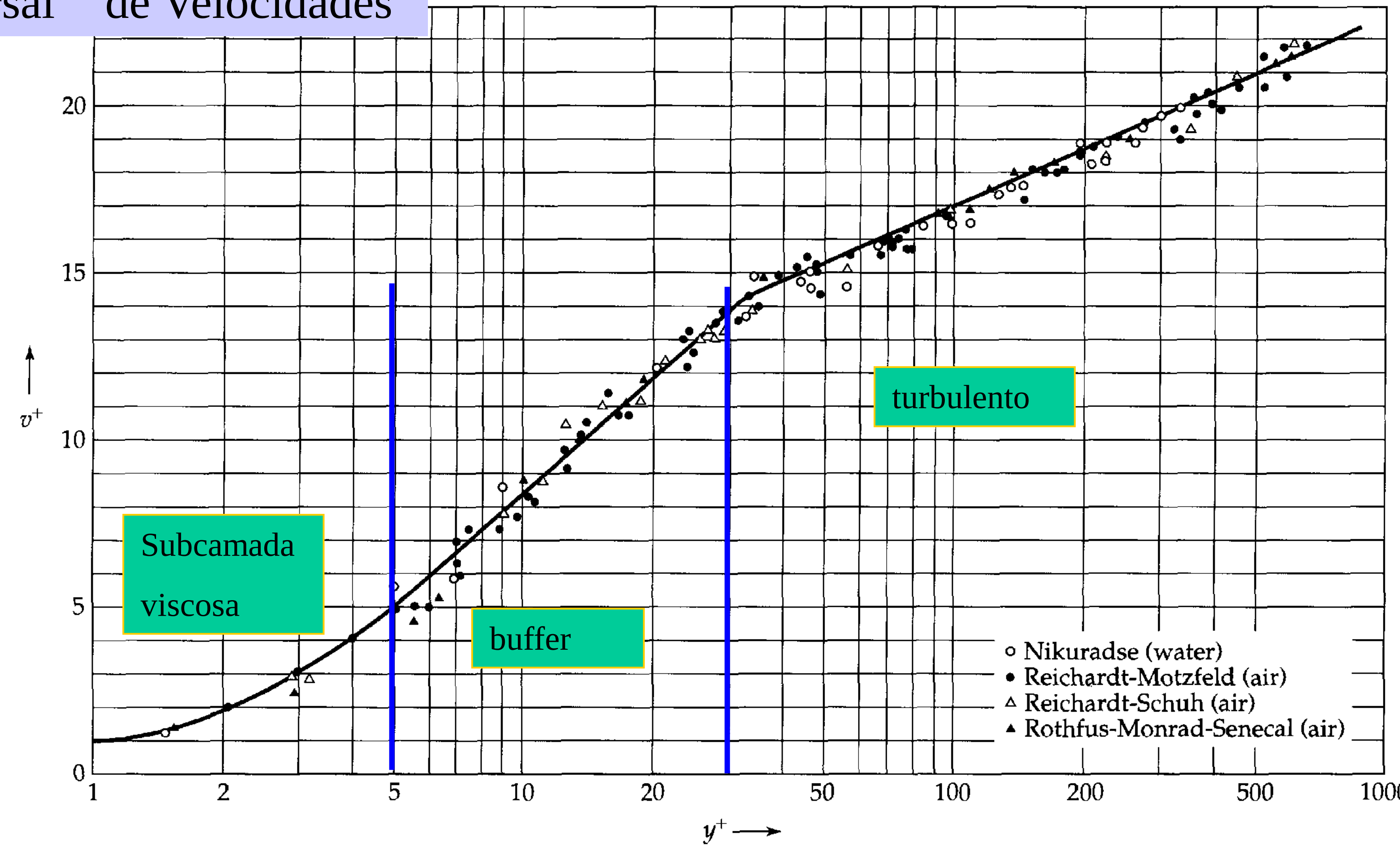


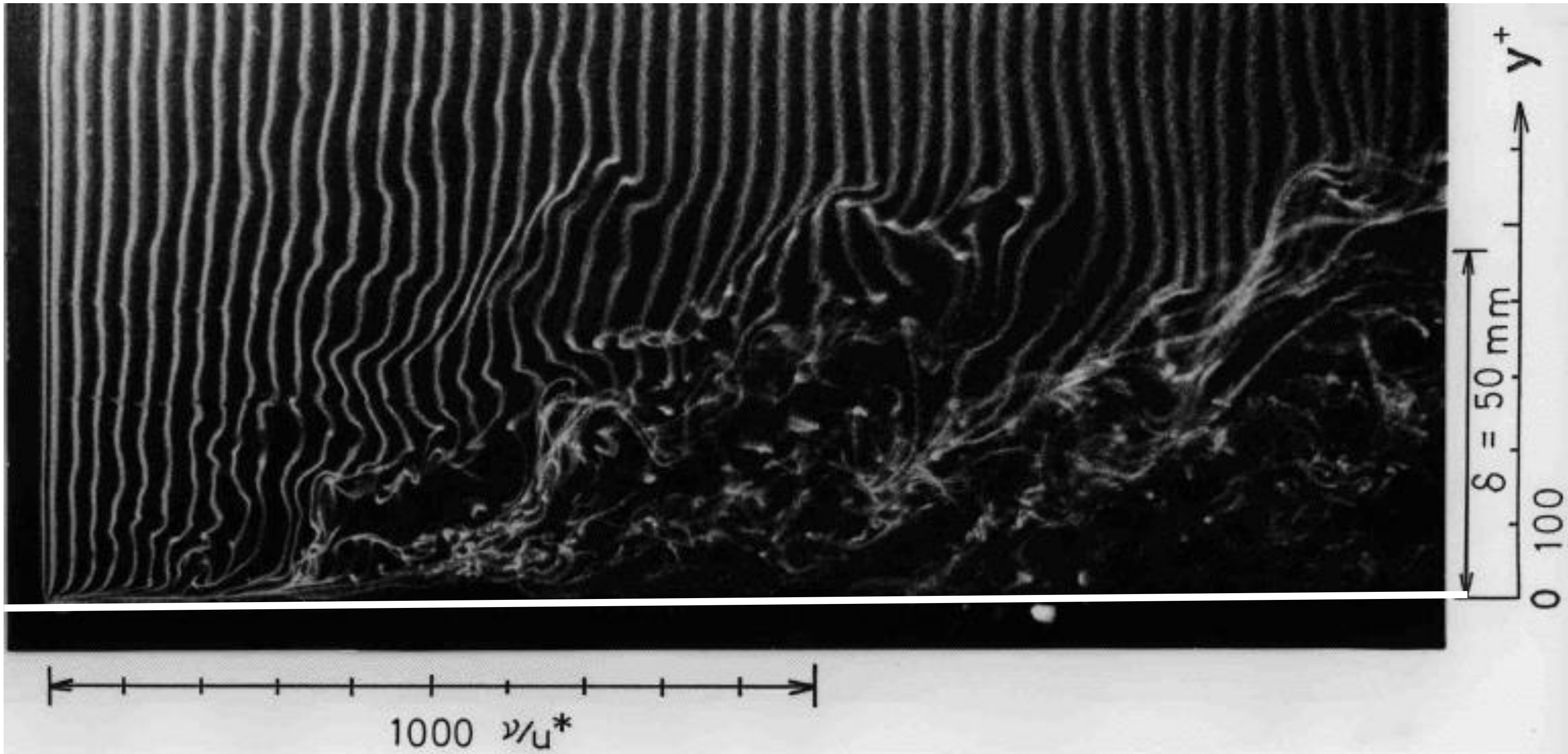
Fig. 5.5-3. Dimensionless velocity distribution for turbulent flow in circular tubes, presented as $v^+ = \bar{v}_z/v_*$ vs. $y^+ = yv_*\rho/\mu$, where $v_* = \sqrt{\tau_0/\rho}$ and τ_0 is the wall shear stress. The solid curves are those suggested by Lin, Moulton, and Putnam [*Ind. Eng. Chem.*, **45**, 636–640 (1953)]:

$$0 < y^+ < 5: \qquad v^+ = y^+[1 - \tfrac{1}{4}(y^+/14.5)^3]$$

$$5 < y^+ < 30: \qquad v^+ = 5 \ln(y^+ + 0.205) - 3.27$$

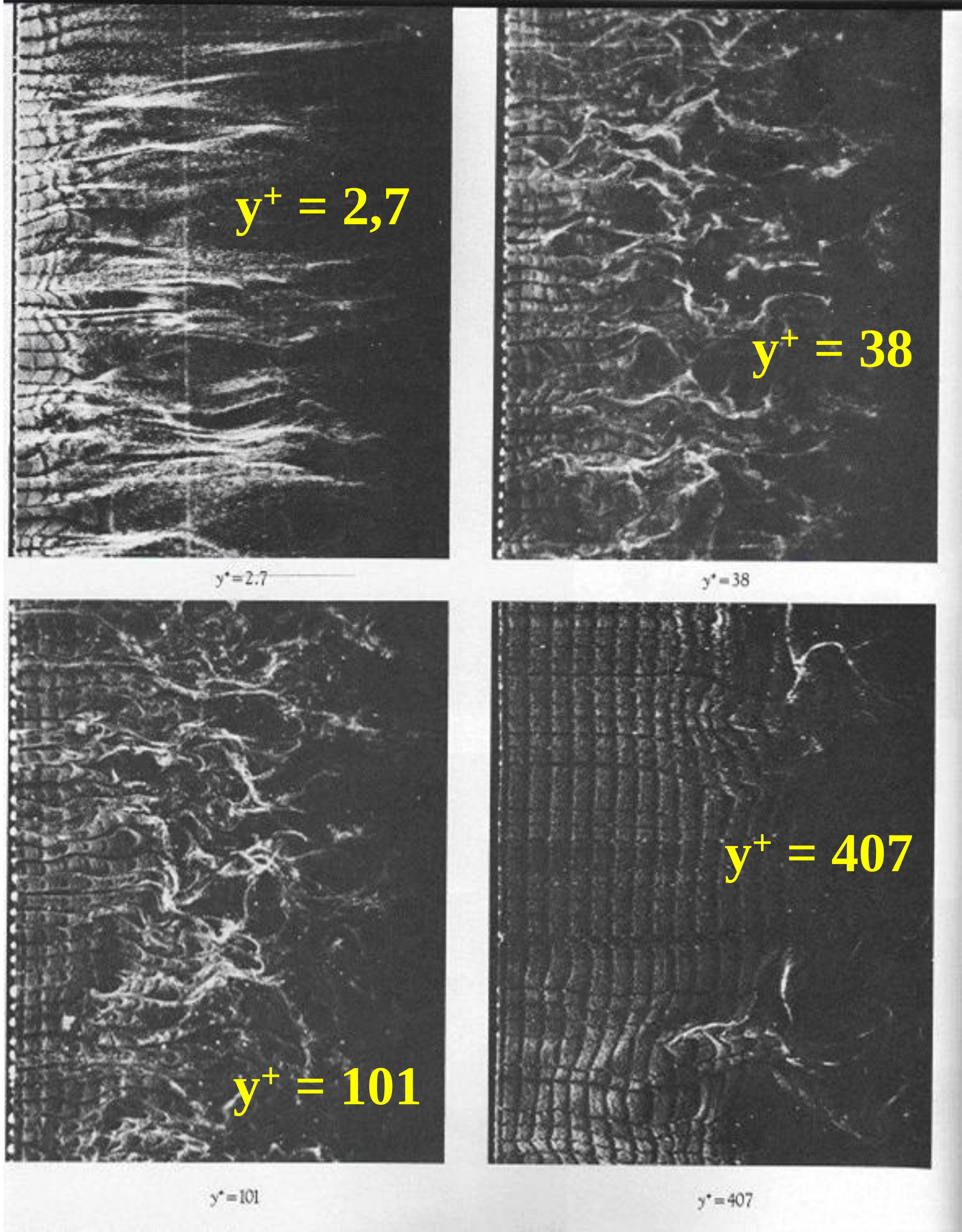
$$30 < y^+: \qquad v^+ = 2.5 \ln y^+ + 5.5$$

The experimental data are those of J. Nikuradse for water (○) [*VDI Forschungsheft*, **H356** (1932)]; Reichardt and Motzfeld for air (●); Reichardt and Schuh (△) for air [H. Reichardt, NACA Tech. Mem. 1047 (1943)]; and R. R. Rothfus, C. C. Monrad, and V. E. Senecal for air (■) [*Ind. Eng. Chem.*, **42**, 2511–2520 (1950)].



y+
δ = 50 mm
0 100
1000 ν/u*

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+

Comprimento

Comprimento de Mistura - Prandtl

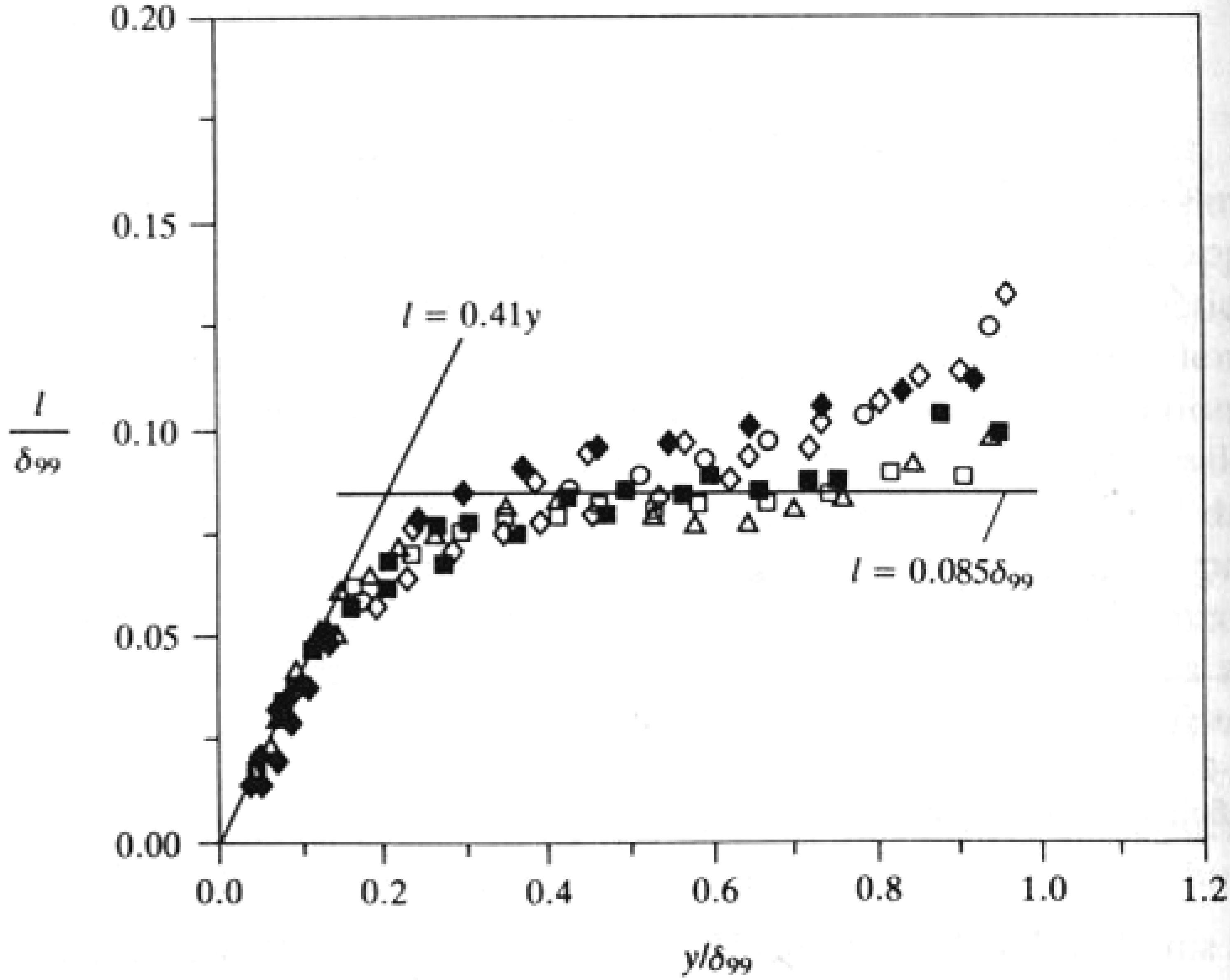


FIGURE 11-2
Mixing-length measurements of Andersen[1] for no pressure gradient, advers
gradient, blowing, and suction.

Comprimento de Mistura - Prandtl

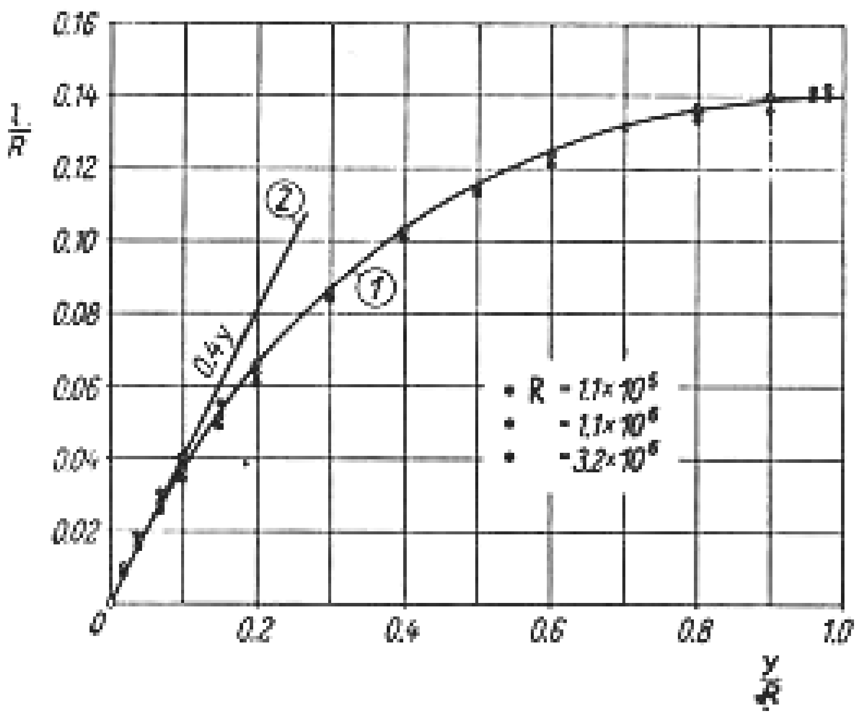


Fig. 20.5. Variation of mixing length over pipe diameter for smooth pipes at different Reynolds numbers

Curve (1) from eqn. (20.18)

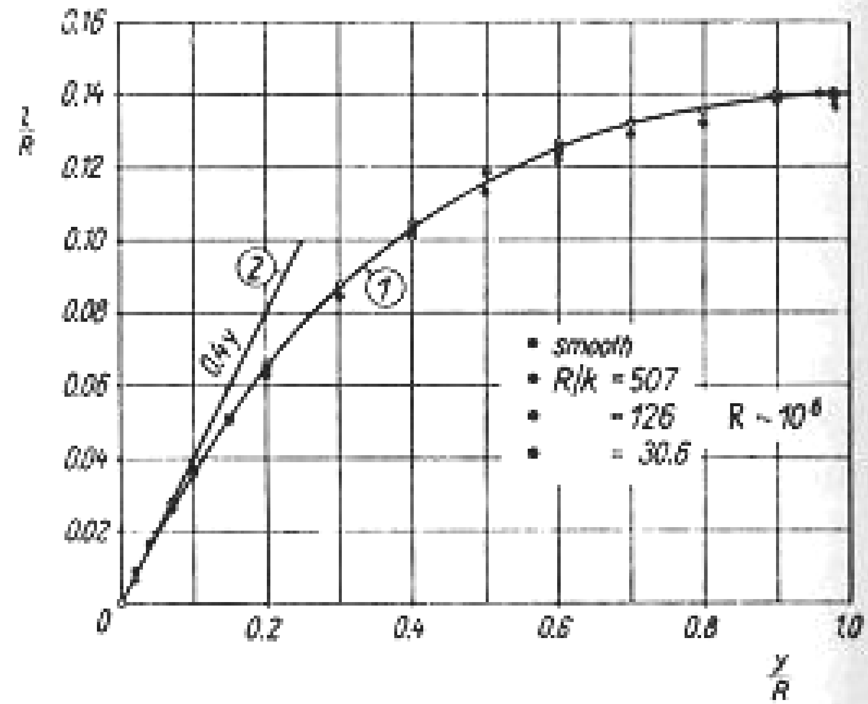


Fig. 20.6. Variation of mixing length over pipe diameter for rough pipes

Curve (1) from eqn. (20.18)

sendo $\varphi = v$:

$$\frac{\partial \bar{\vec{v}}}{\partial t} + d\vec{i}v\, \bar{\vec{v}}\; \bar{\vec{v}} = d\vec{i}v\; \nu_T\, gr\vec{a}d\, \bar{\vec{v}} - \frac{gr\vec{a}d\, \bar{p}}{\bar{\rho}} + \bar{\vec{g}}$$

Prandtl mixing lenght	$\lambda_{\vec{v}T} = \nu_T = \dfrac{\mu_T}{\rho} = \ell_m^2 \left\lvert gr\vec{\vec{a}}d\; \bar{\vec{v}} \right\rvert$
similaridade Prandtl	$\nu_T = c_\mu \ell \sqrt{K}$
k	$\boxed{K} \Rightarrow$ $k = \overline{e_{cT}} = \dfrac{\overline{\vec{v}' . \vec{v}'}}{2}$ $\dfrac{D\,k}{Dt} = div\left(\dfrac{\nu_T}{\sigma_k}\, gr\vec{a}d\; k\right) + \nu_T \left\lvert gr\vec{a}d\; \vec{v} \right\rvert^2 - c_D \dfrac{k^{3/2}}{\ell}$
k ε	$\nu_T = C_\mu\, K^2/\varepsilon$

Modelos de Turbulência

Reynolds Stress

$$\vec{\vec{R}} = \overline{\vec{v}'.\vec{v}'}$$

sete equações diferenciais	$\frac{D\vec{\vec{R}}}{Dt} = -\,\mathrm{d}\vec{\mathrm{i}}\mathrm{v}\left[\vec{\vec{\vec{\vec{j}}}}_{\vec{\vec{R}}} + \vec{\vec{\vec{\pi}}}_{\vec{\vec{R}}} + \vec{\vec{\vec{\Omega}}}_{\vec{\vec{R}}}\right] + \overline{\dot{\vec{\vec{\sigma}}}_{M_{\vec{\vec{R}}}}} - \overline{\dot{\vec{\vec{\varepsilon}}}_{M_{\vec{\vec{R}}}}}$
algébrico	$\vec{\vec{R}} = \frac{2}{3} K\,\vec{\vec{\delta}} + \left[\frac{C_D}{C_1 - 1 + {}^{p}/_{\varepsilon}}\right]\left(\overline{\dot{\vec{\vec{\sigma}}}_{M_{\vec{\vec{R}}}}} - \frac{2}{3}\,p\,\vec{\vec{\delta}}\right)\frac{K}{\varepsilon}$
2 eq. K ε	$\nu_T = C_\mu\, {}^{K^2}/_{\varepsilon}$
0 eq. Prandtl mixing lenght	$\nu_T = \ell_m^2\left\lvert\, \mathrm{gr}\vec{\mathrm{a}}\mathrm{d}\ \vec{\vec{v}}\right\rvert$
large eddy simulation LES	por hora apenas fornecem parâmetros

tabela

Rayleight

$$\Phi_v = 2\left[\left(\frac{\partial v_x}{\partial x}\right)^2 + \left(\frac{\partial v_y}{\partial y}\right)^2 + \left(\frac{\partial v_z}{\partial z}\right)^2\right] + \left[\frac{\partial v_y}{\partial x} + \frac{\partial v_x}{\partial y}\right]^2 + \left[\frac{\partial v_z}{\partial y} + \frac{\partial v_y}{\partial z}\right]^2 + \left[\frac{\partial v_x}{\partial z} + \frac{\partial v_z}{\partial x}\right]^2 - \frac{2}{3}\left[\frac{\partial v_x}{\partial x} + \frac{\partial v_y}{\partial y} + \frac{\partial v_z}{\partial z}\right]^2$$

Dissipação da energia cinética de turbulência - ε

$$\varepsilon = \nu\left[2\left\langle\left(\frac{\partial v'_x}{\partial x}\right)^2\right\rangle + 2\left\langle\left(\frac{\partial v'_y}{\partial y}\right)^2\right\rangle + 2\left\langle\left(\frac{\partial v'_z}{\partial z}\right)^2\right\rangle + \left\langle\left(\frac{\partial v'_y}{\partial x} + \frac{\partial v'_x}{\partial y}\right)^2\right\rangle + \left\langle\left(\frac{\partial v'_z}{\partial y} + \frac{\partial v'_y}{\partial z}\right)^2\right\rangle + \left\langle\left(\frac{\partial v'_z}{\partial x} + \frac{\partial v'_x}{\partial z}\right)^2\right\rangle\right]$$

Energia cinética de turbulência - k

$$k = \frac{1}{2}\left(v_x'^2 + v_y'^2 + v_z'^2\right)$$

$$\frac{\partial \bar{k}}{\partial t} + div\,\bar{\vec{v}}\,\bar{k} = div\,\frac{\nu_T}{\sigma_k}\,gr\vec{a}d\,\bar{k} + P_k - \varepsilon$$

$$\frac{\partial \varepsilon}{\partial t} + div\,\bar{\vec{v}}\,\varepsilon = div\,\frac{\nu_T}{\sigma_\varepsilon}\,gr\vec{a}d\,\varepsilon + C_{\varepsilon 1}\frac{\varepsilon}{\bar{k}}P_k - C_{\varepsilon 2}\frac{\varepsilon^2}{\bar{k}}$$

$$P_k = -\bar{\rho}\,\nu_T\left(gr\vec{a}d\,\bar{\vec{v}} : gr\vec{a}d\,\bar{\vec{v}}\right)$$

$$\nu_T = C_\mu \frac{\bar{k}^2}{\varepsilon}$$

$\sigma_k = 1,0$; $\sigma_\varepsilon = 1,217$;
$C_{\varepsilon 1} = 1,44$; $C_{\varepsilon 2} = 1,92$; $C_\mu = 0.09$

constantes experimentais

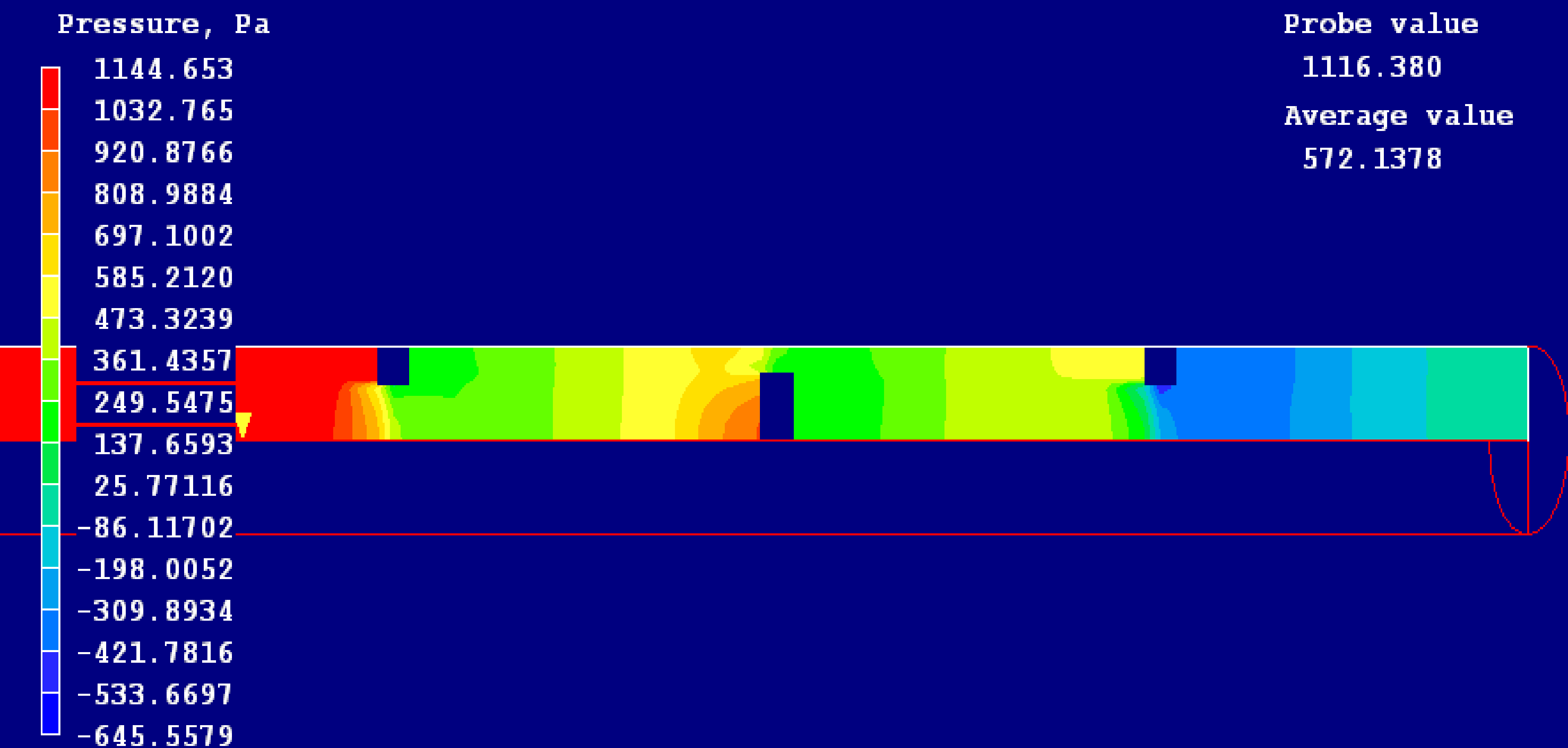
Rayleight $P = \mu \Phi_v = \rho \nu \left(\mathrm{gr\vec{\vec{a}}d}\,\vec{v} : \mathrm{gr\vec{\vec{a}}d}\,\vec{v} \right)$

turbulento $\vec{\vec{\zeta}}_T = -\rho\ \nu_T\ \ \mathrm{gr\vec{\vec{a}}d}\,\overline{\vec{v}}$

comprimento de mistura de Prandtl $\nu_T = \ell_m^2 \left| \mathrm{gr\vec{\vec{a}}d}\,\overline{\vec{v}} \right|$

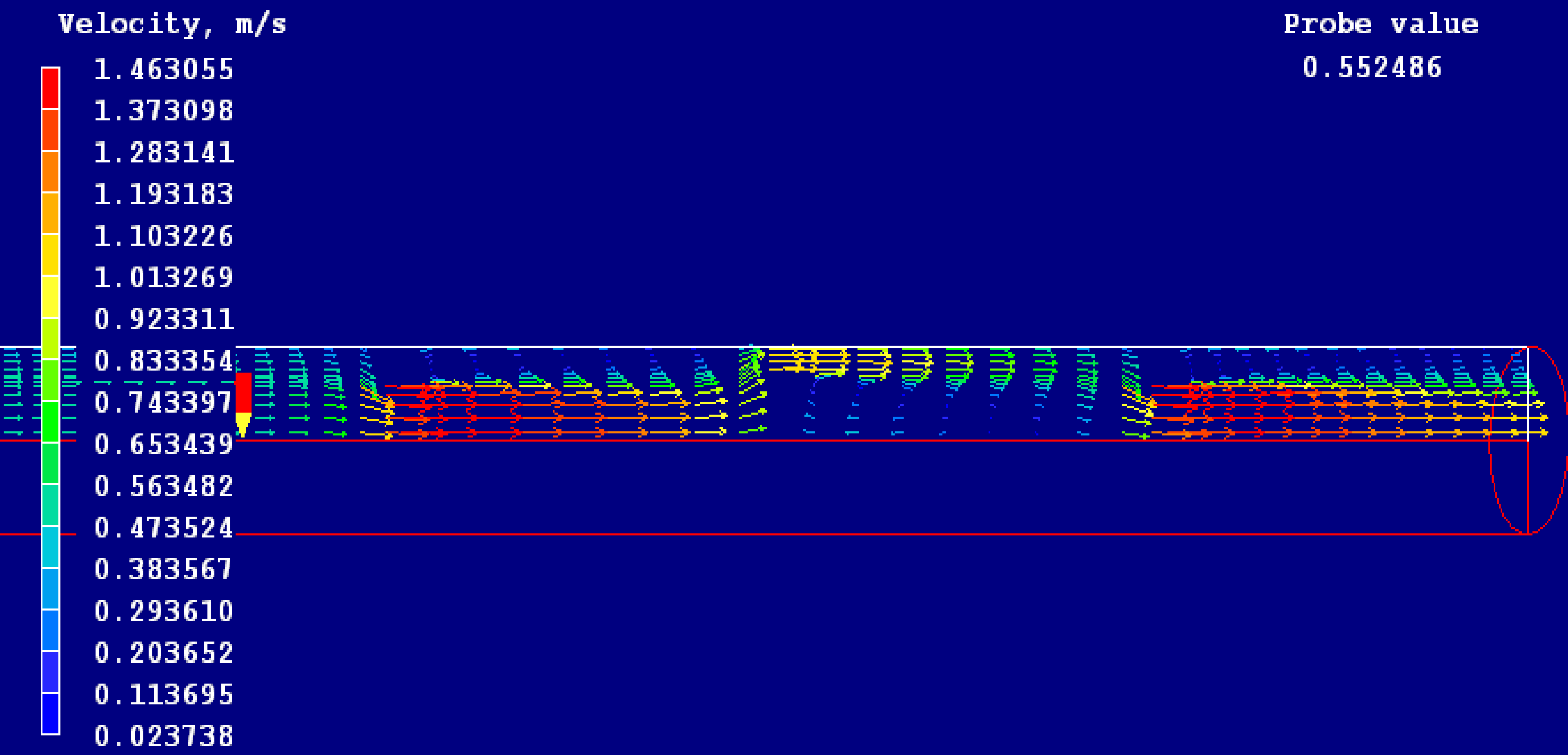
dissipação de energia cinética de turbulência

$$\boxed{P_k = -\overline{\rho}\,\ell_m^2 \left(\mathrm{gr\vec{\vec{a}}d}\,\overline{\vec{v}} : \mathrm{gr\vec{\vec{a}}d}\,\overline{\vec{v}} \right)}$$

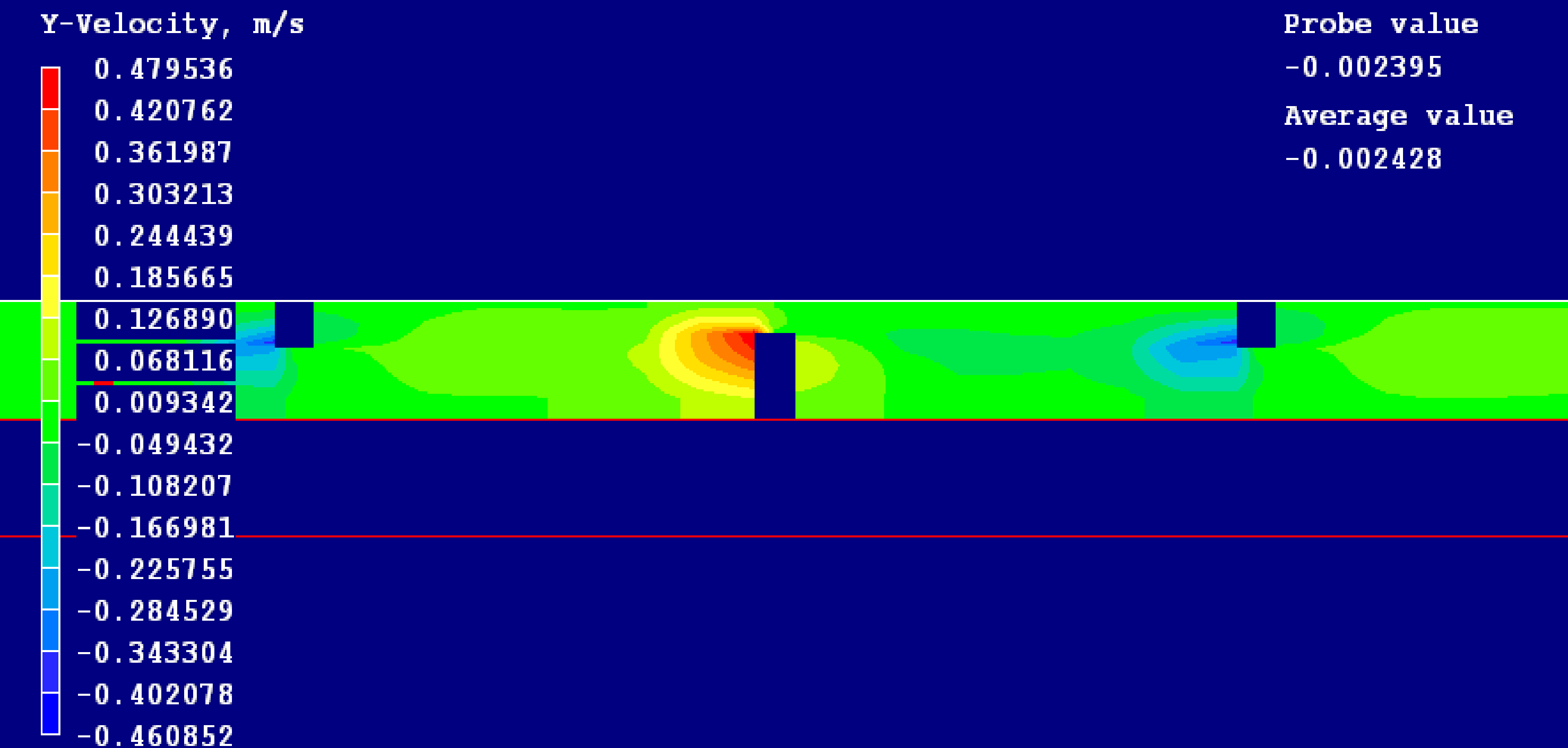


Pressure, Pa
1144.653
1032.765
920.8766
808.9884
697.1002
585.2120
473.3239
361.4357
249.5475
137.6593
25.77116
-86.11702
-198.0052
-309.8934
-421.7816
-533.6697
-645.5579
Probe value
1116.380
Average value
572.1378

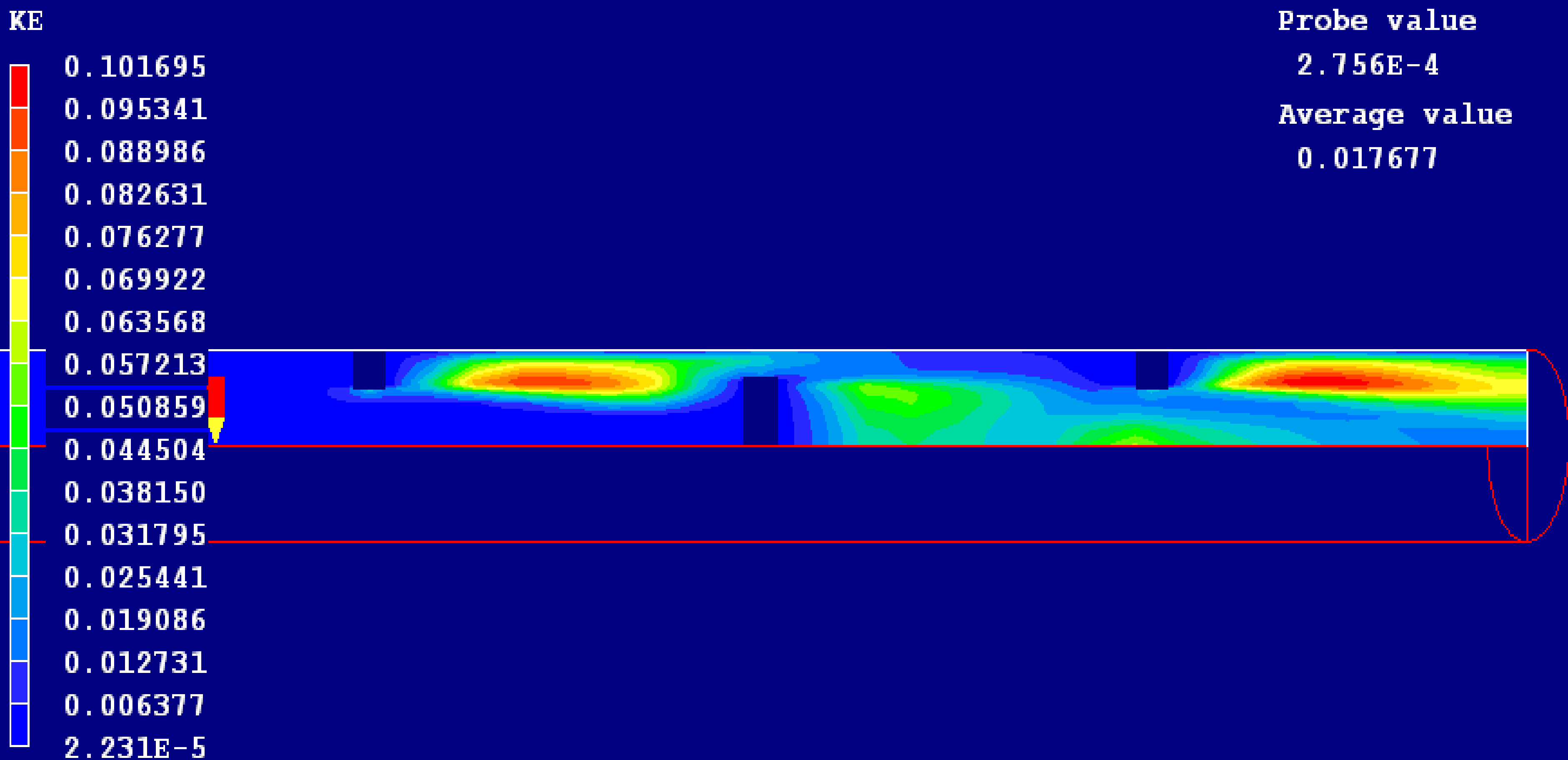
pressão



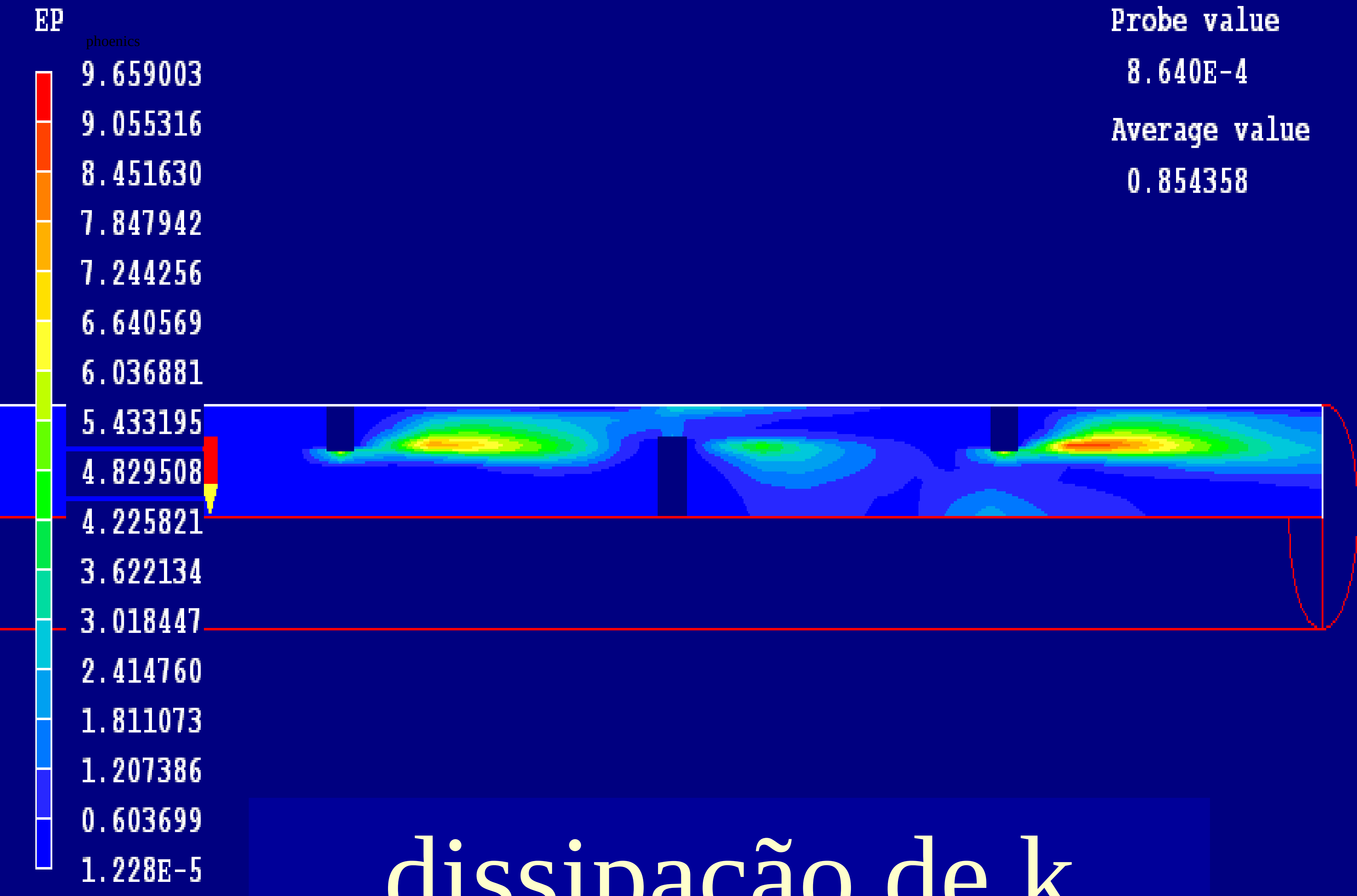
velocidades



velocidade radial

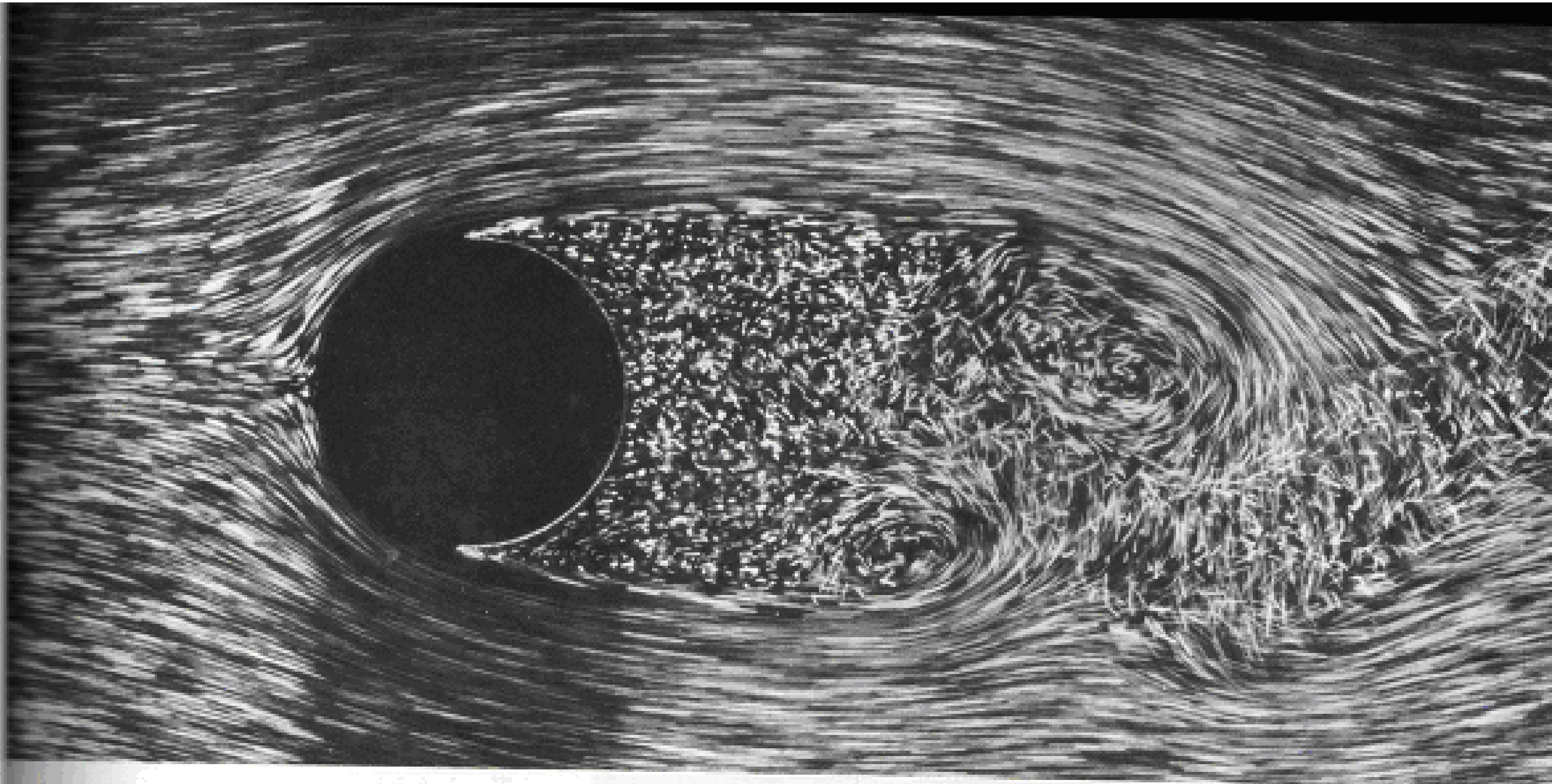


energia cinética de turbulência k



dissipação de k

cilindro Re = 2000



47. Circular cylinder at R=2000. At this Reynolds number one may properly speak of a boundary layer. It is laminar over the front, separates, and breaks up into a turbulent wake. The separation points, moving forward as the Reynolds number is increased, have now attained their upstream limit, ahead of maximum thickness. Visualization is by air bubbles in water. *ONERA photograph, Werlé & Gallon 1972*

Re 2000