

ESCOAMENTO EM DUTOS: transientes fluidodinâmicos e perdas de carga

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MOTIVAÇÃO:

demanda energética no setor de transportes...

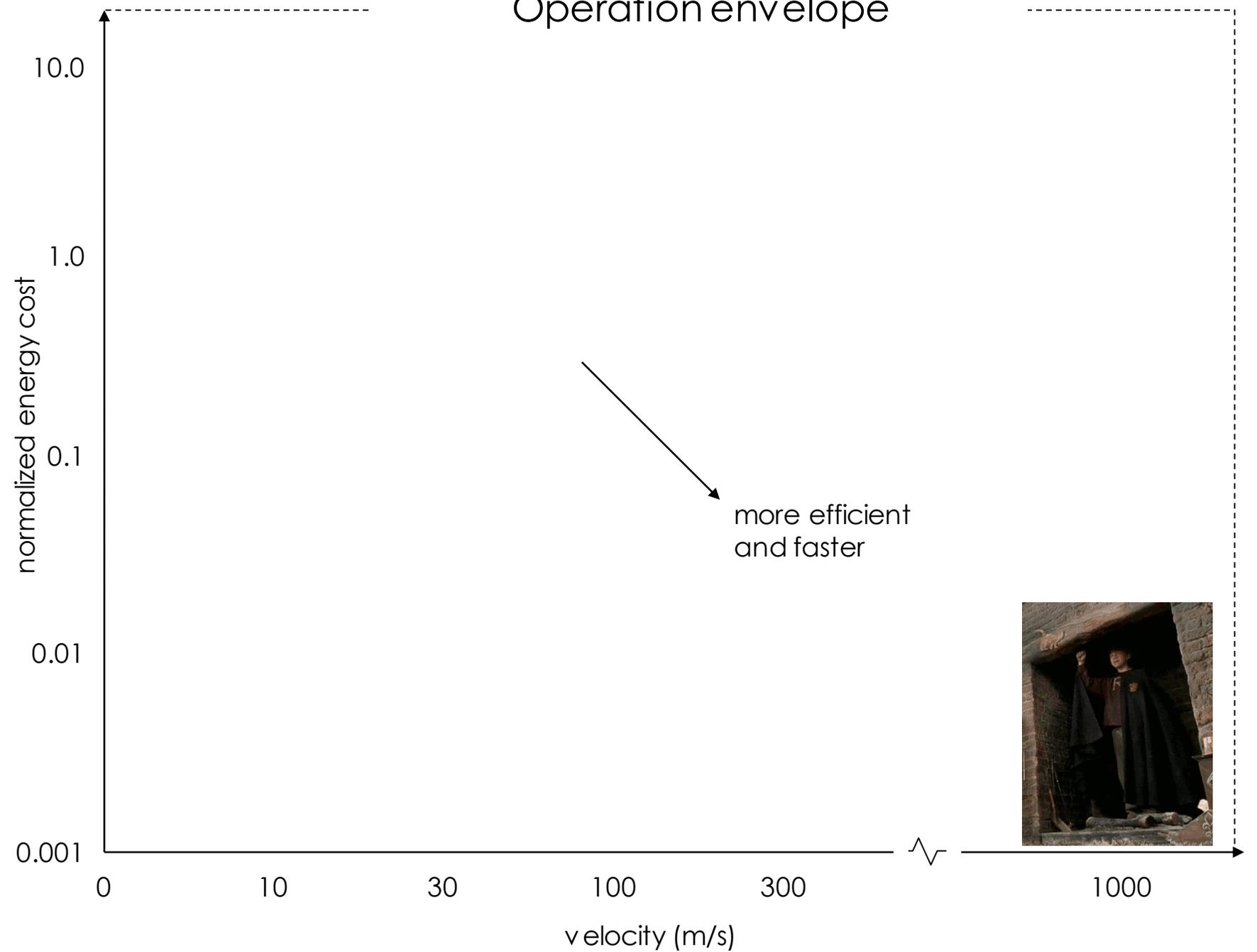
Demand / Modal

- freight
- passengers

<http://sia.planning.unc.edu/>

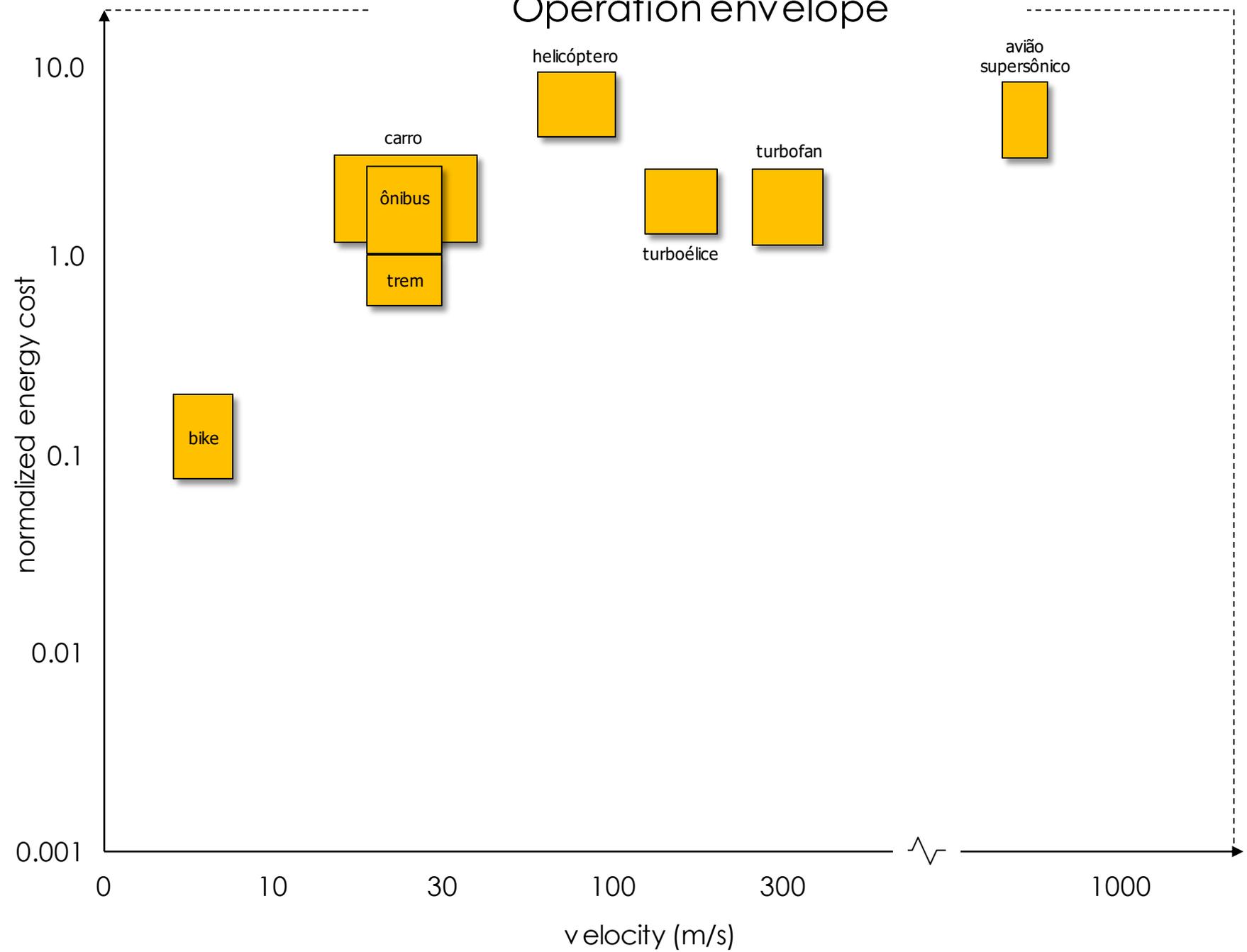
consumo ~ atrito ~ velocidade ~
área externa
capacidade de transporte ~
volume

Operation envelope



Demand / Modal

Operation envelope



freight
passengers

<http://sia.planning.unc.edu/>

consumo ~ atrito ~ velocidade ~
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volume

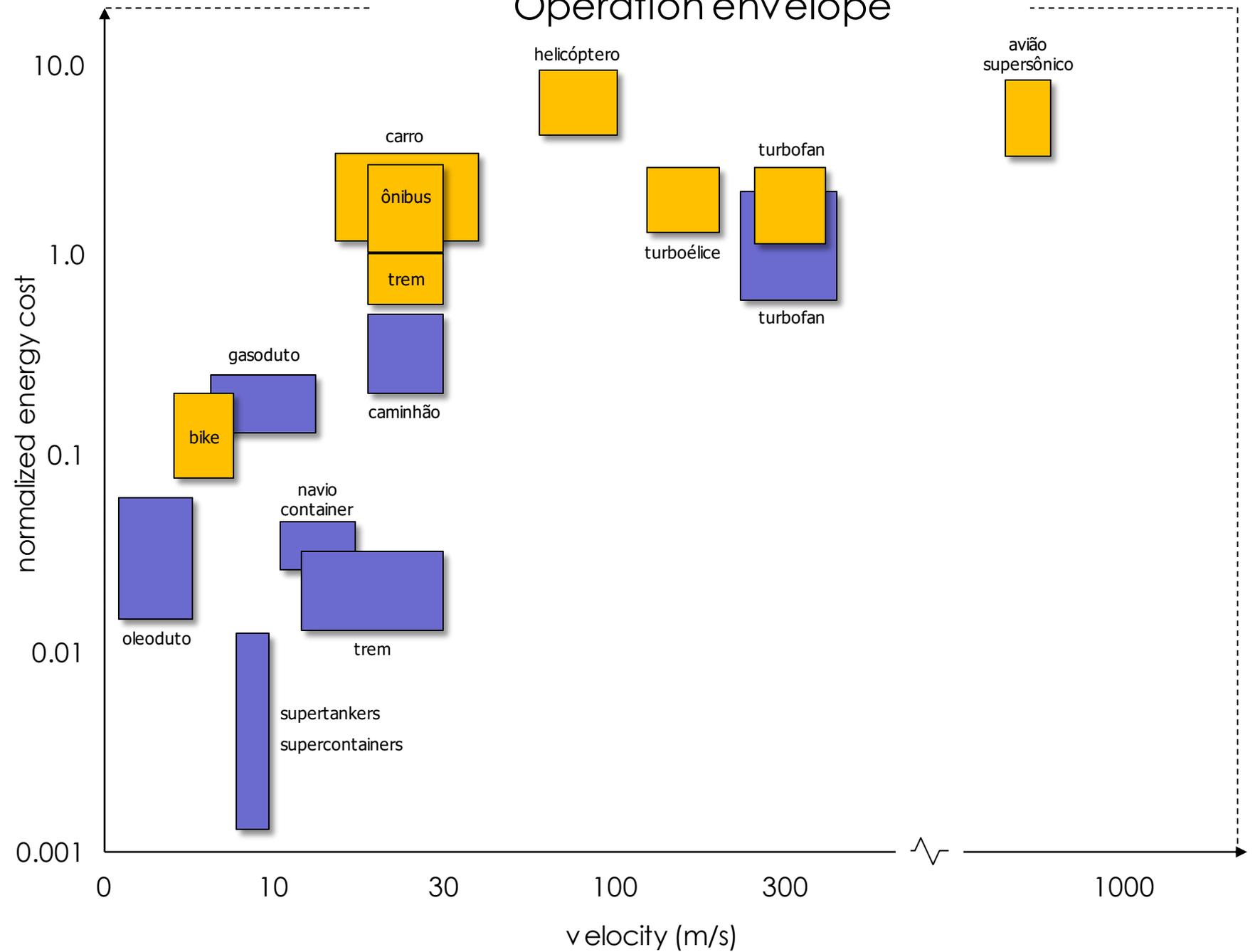
Demand / Modal

■ freight
■ passengers

<http://sia.planning.unc.edu/>

consumo ~ atrito ~ velocidade ~
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Operation envelope



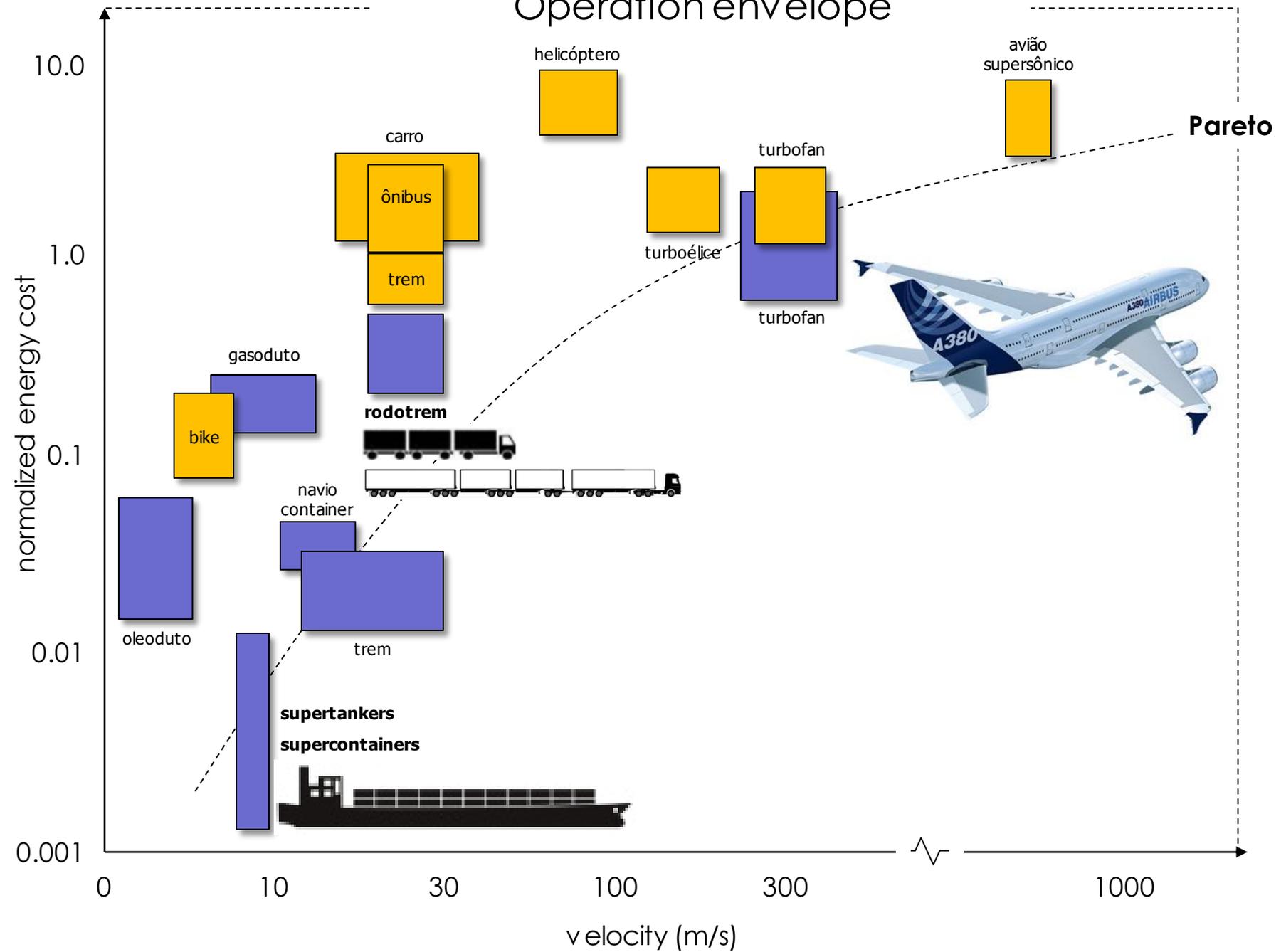
Demand / Modal

freight
 passengers

<http://sia.planning.unc.edu/>

consumo ~ atrito ~ velocidade ~
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volume

Operation envelope



Demand / Modal

Pipeline total length

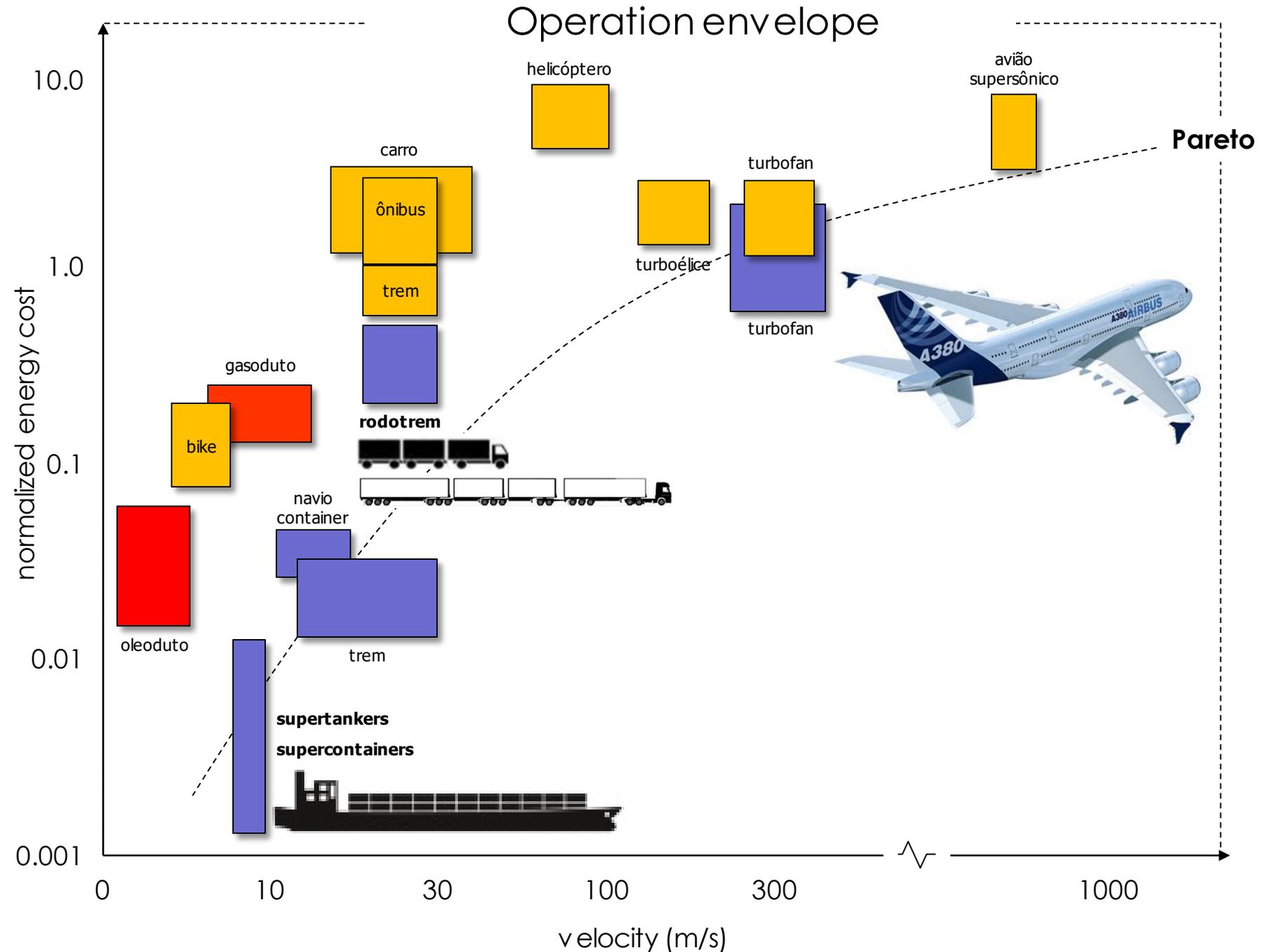
3.5 Mkm

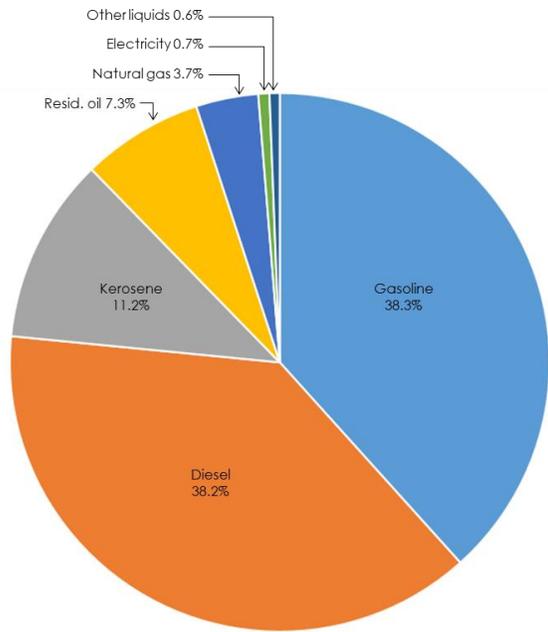
in 120 countries,
75% of which are in the
United States

 freight
 passengers

<http://sia.planning.unc.edu/>

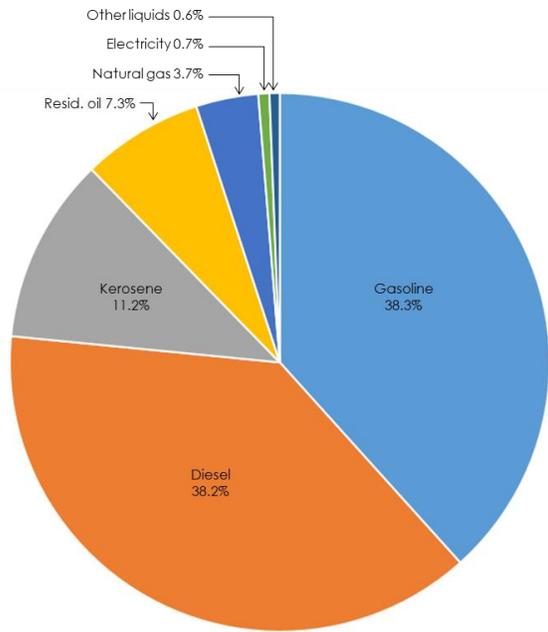
consumo ~ atrito ~ velocidade ~
área externa
capacidade de transporte ~
volume





International Energy Outlook 2017





International Energy Outlook 2017

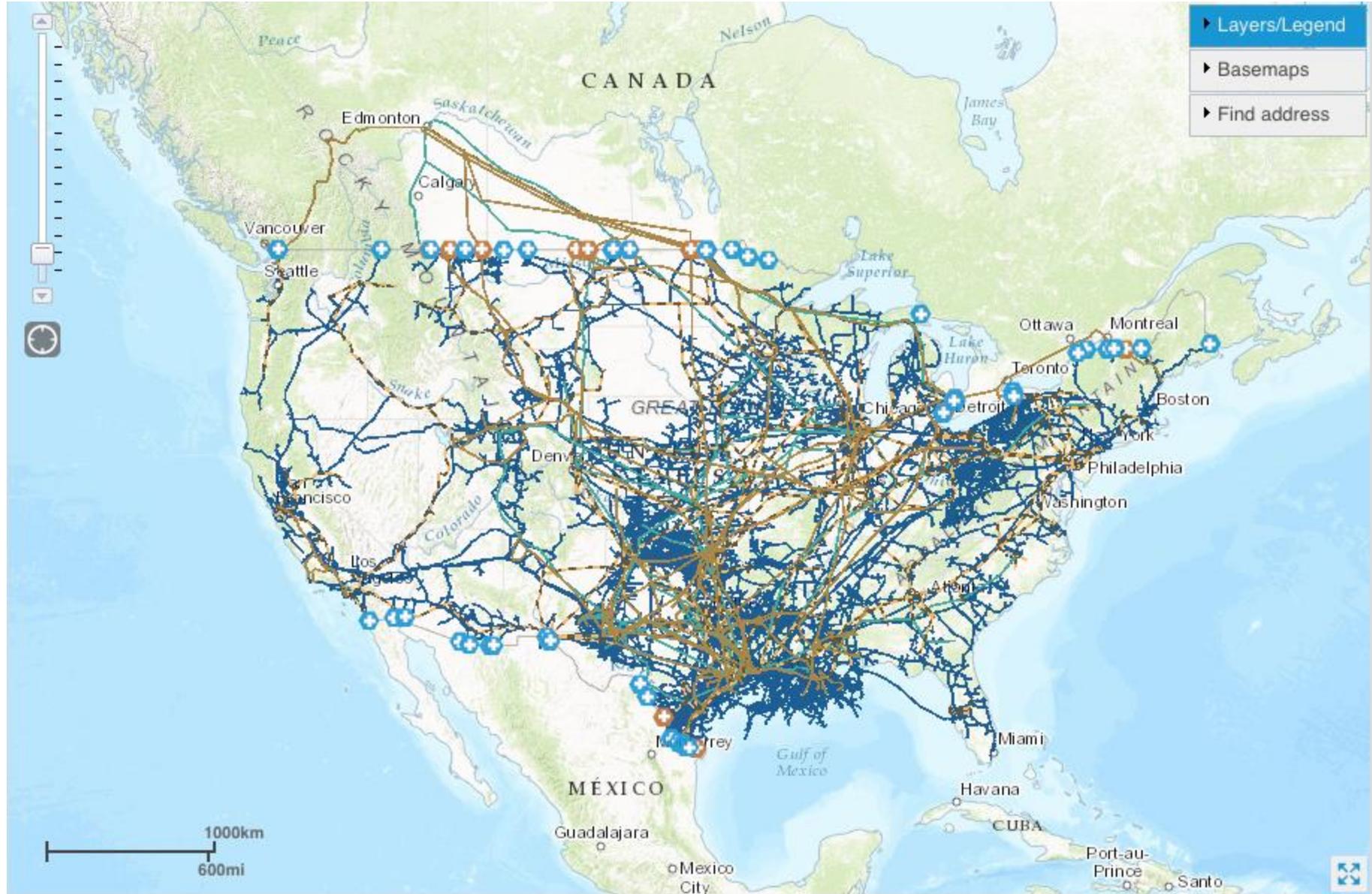


Blast at Azerbaijan's capital Baku
January 03, 2017

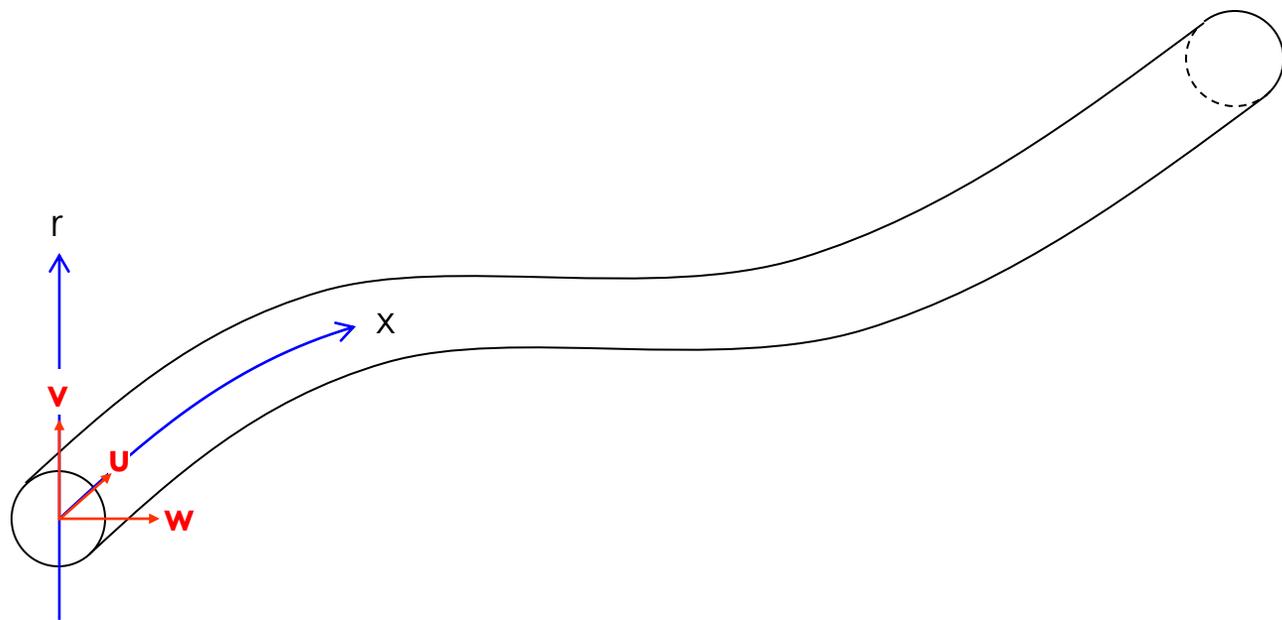
PHMSA Pipeline Incidents: (1996-2015)

Incident Type: All Reported System Type: ALL State: ALL

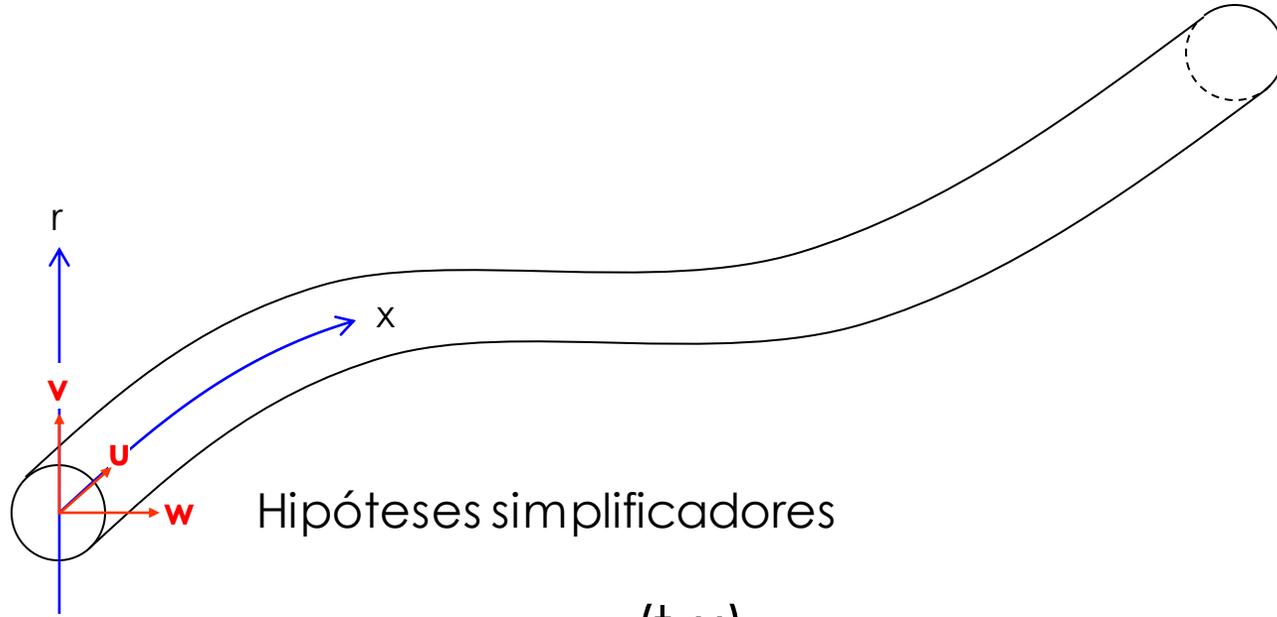
Calendar Year	Number	Fatalities	Injuries	Total Cost As Reported
1996	381	53	127	\$114,467,631
1997	346	10	77	\$79,757,922
1998	389	21	81	\$126,851,351
1999	339	22	108	\$130,110,339
2000	380	38	81	\$191,822,840
2001	341	7	61	\$63,092,462
2002	642	12	49	\$102,167,588
2003	672	12	71	\$139,057,814
2004	671	23	60	\$267,836,502
2005	719	17	47	\$1,245,463,189
2006	639	21	36	\$151,983,767
2007	611	15	49	\$153,903,544
2008	659	8	56	\$565,519,340
2009	627	13	64	\$179,070,183
2010	586	22	108	\$1,692,500,877
2011	592	14	56	\$426,551,870
2012	573	12	57	\$229,613,337
2013	619	9	44	\$349,961,947
2014	707	19	95	\$310,257,400
2015	715	12	49	\$342,202,062
Grand Total	11,208	360	1,376	\$6,862,191,965



Escoamento em dutos: obtenção das equações governantes...



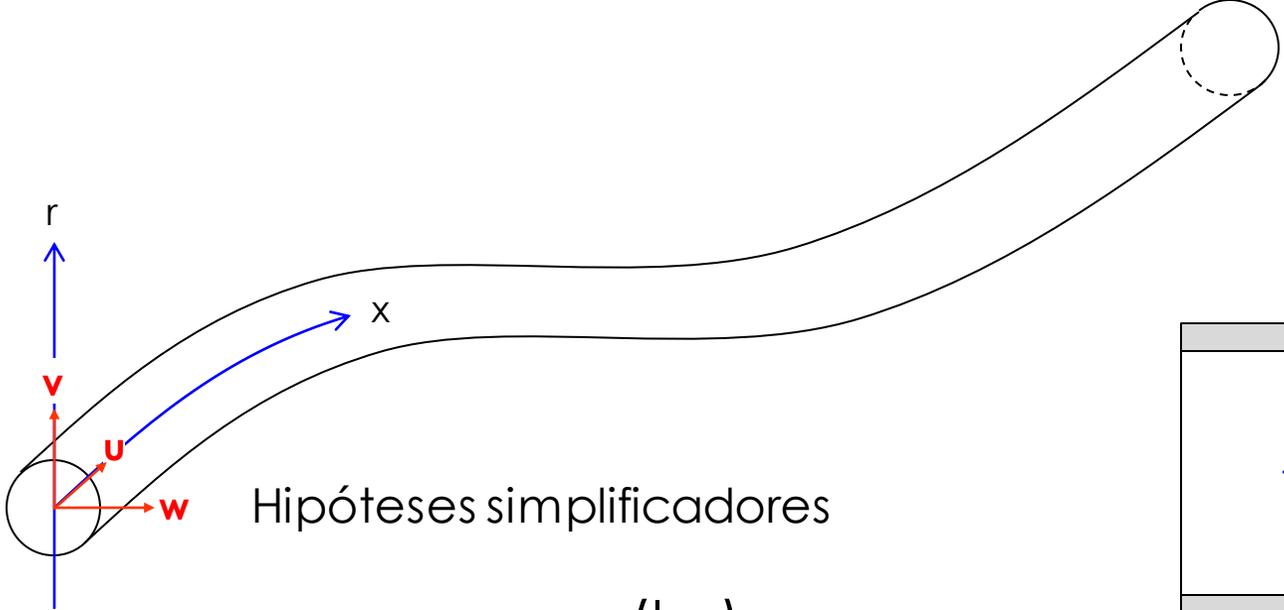
Escoamento em dutos: obtenção das equações governantes...



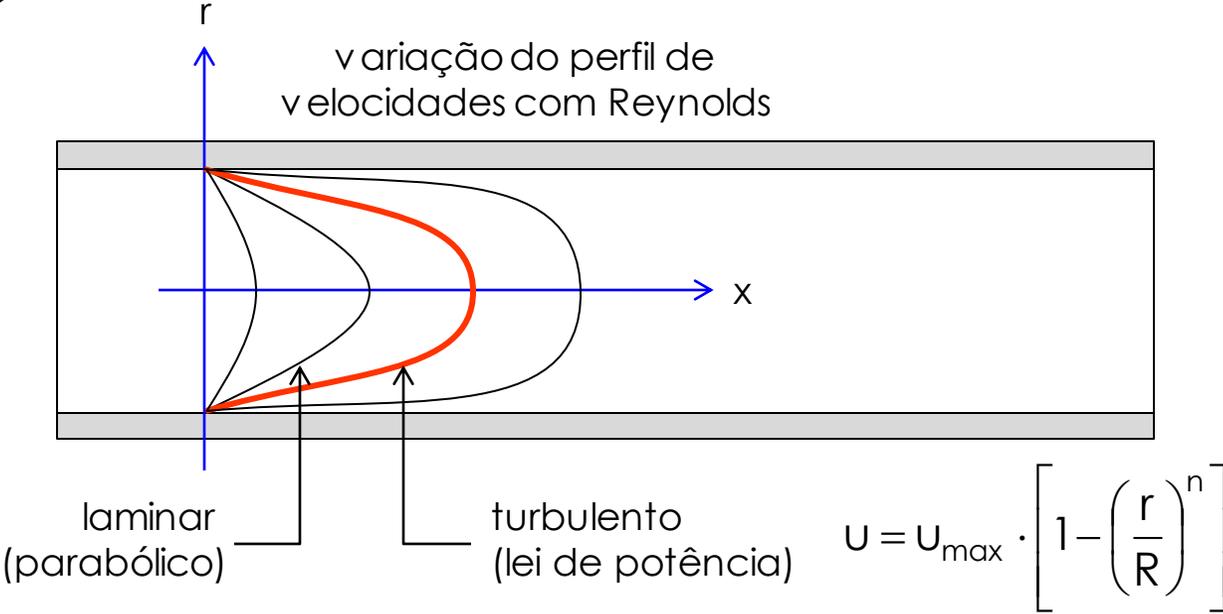
Hipóteses simplificadores

$$v \equiv w \equiv 0 \quad \rho = \rho(t, x)$$
$$u = u(t, x)$$

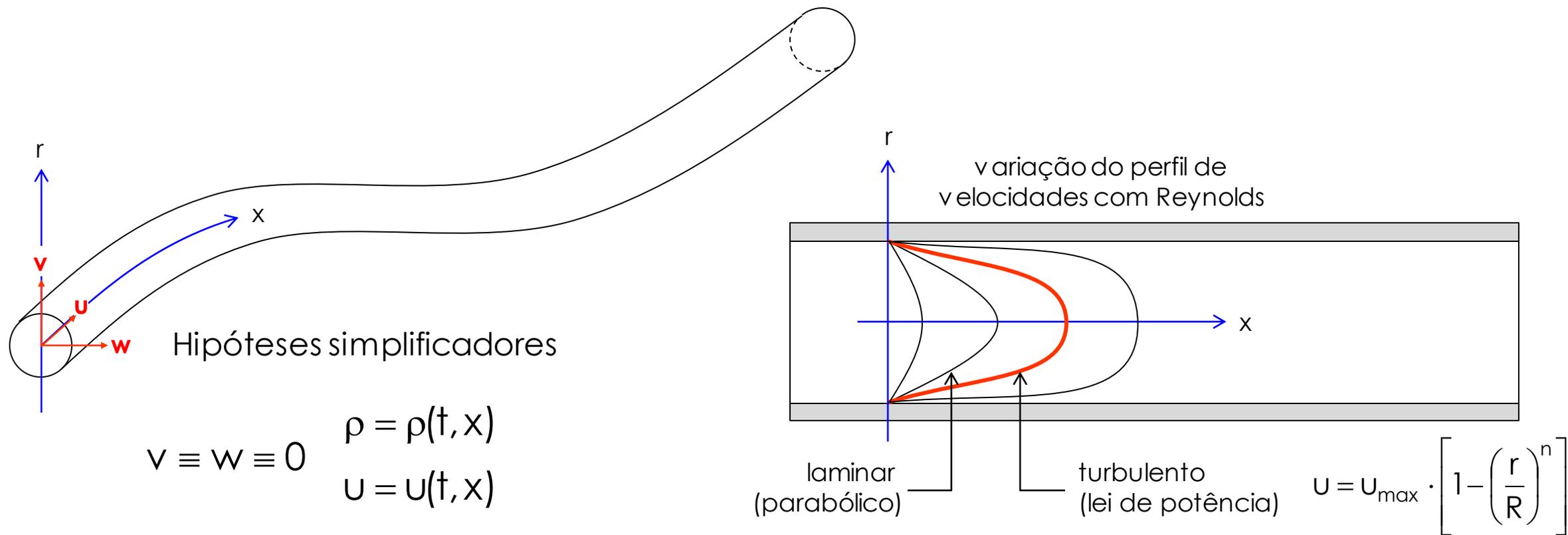
Escoamento em dutos: obtenção das equações governantes...



$$v \equiv w \equiv 0$$
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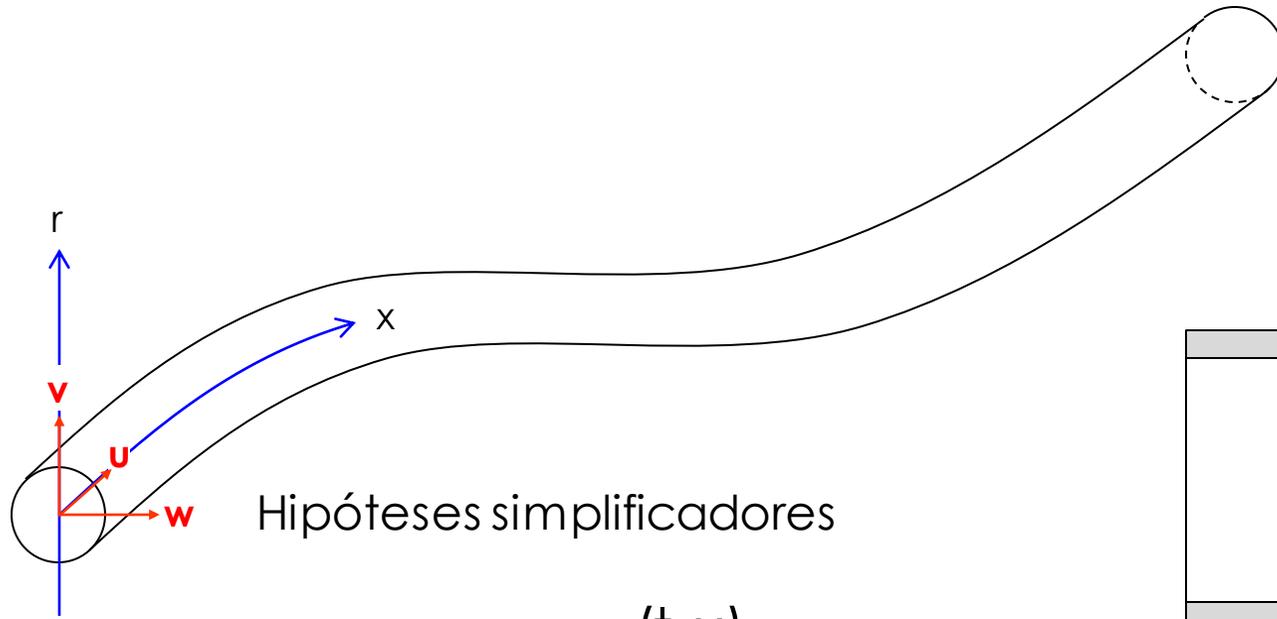


Escoamento em dutos: obtenção das equações governantes...



$$\dot{m} = \rho \int_A u \cdot dA = \rho \frac{A}{A} \int_A u \cdot dA = \rho A U_{\text{med}}$$

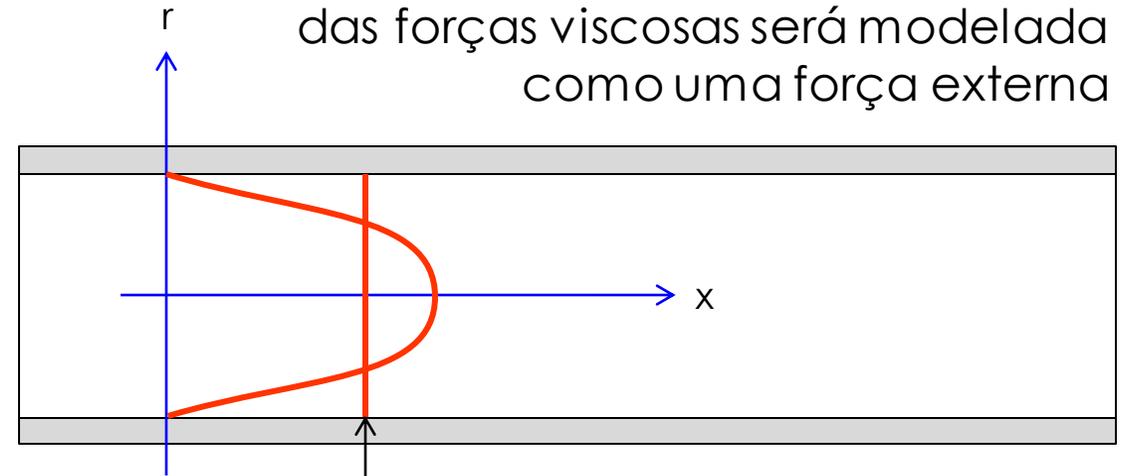
Escoamento em dutos: obtenção das equações governantes...



Hipóteses simplificadores

$$v \equiv w \equiv 0 \quad \rho = \rho(t, x)$$
$$u = u(t, x)$$

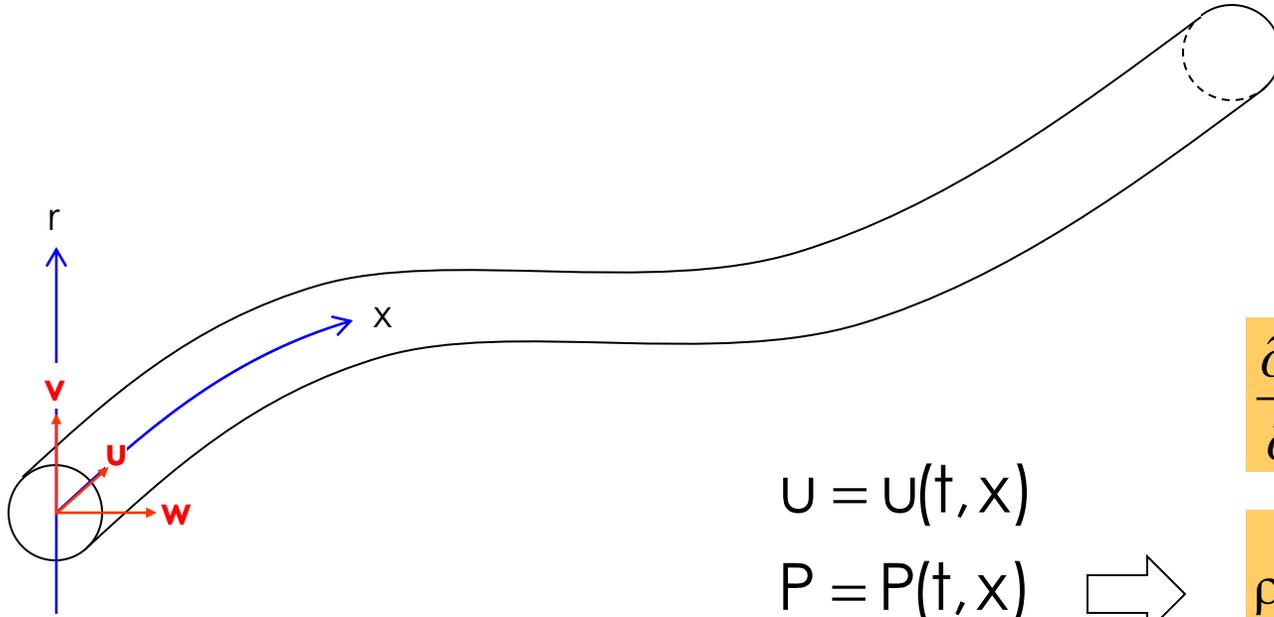
Obs.: não havendo escorregamento entre as camadas de fluido, a ação das forças viscosas será modelada como uma força externa



perfil uniforme resultando na mesma vazão mássica

$$U_{\text{med}} = \frac{1}{A} \int_A u \cdot dA \rightarrow U_{\text{med}}(t, x) = u(t, x)$$

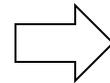
Escoamento em dutos: obtenção das equações governantes...



$$U = U(t, x)$$

$$P = P(t, x)$$

$$\rho = \rho(t, x)$$



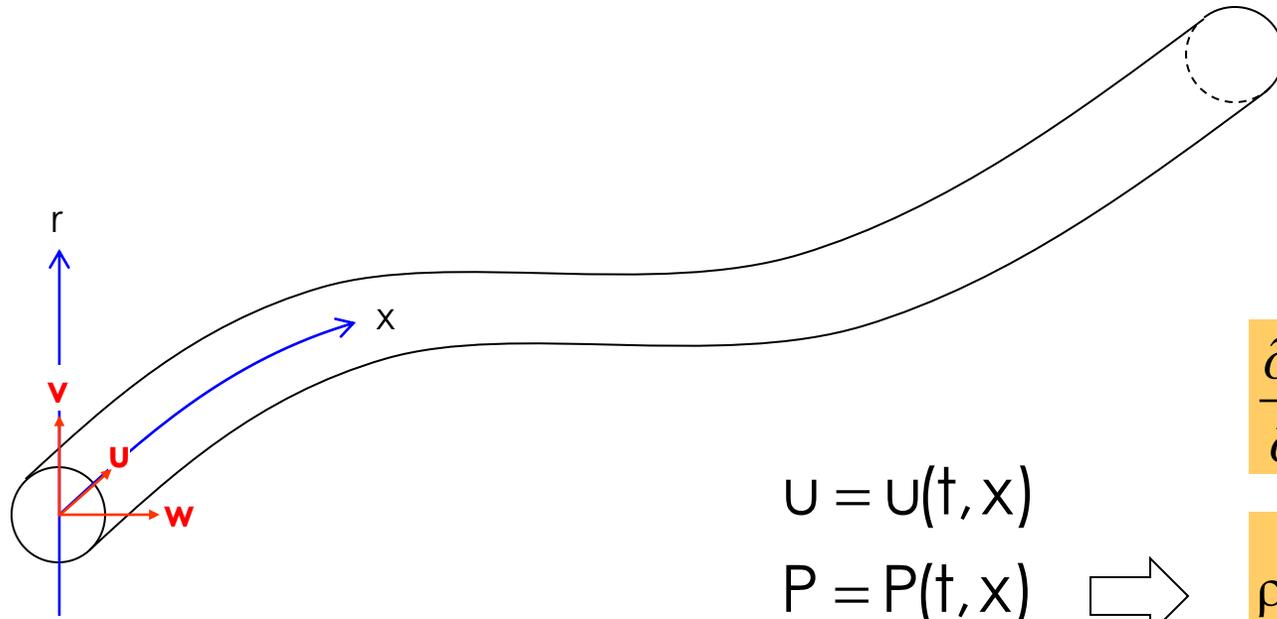
$$\frac{\partial \rho}{\partial t} + \vec{\nabla} \cdot (\rho \vec{U}) = 0$$

$$\rho \cdot \left(\frac{\partial \vec{U}}{\partial t} + \vec{U} \cdot \vec{\nabla} \vec{U} \right) = -\vec{\nabla} P + \mu \nabla^2 \vec{U} + \sum \vec{F}_{3D}$$

$$\rho C_p \left(\frac{\partial T}{\partial t} + \vec{U} \cdot \vec{\nabla} T \right) = \vec{\nabla} \cdot (k \vec{\nabla} T) + \tilde{T} : \tilde{D}$$

Obs.: a densidade pode ser calculada em função da pressão e temperatura

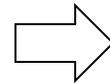
Escoamento em dutos: obtenção das equações governantes...



$$U = U(t, x)$$

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$$\frac{\partial \rho}{\partial t} + \vec{\nabla} \cdot (\rho \vec{U}) = 0$$

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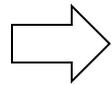
Obs.: a densidade pode ser calculada em função da pressão e temperatura

Escoamento em dutos: obtenção das equações governantes...

$$u = u(t, x)$$

$$P = P(t, x)$$

$$\rho = \rho(t, x)$$



$$\frac{\partial \rho}{\partial t} + \vec{\nabla} \cdot (\rho \vec{U}) = 0$$

$$\rightarrow \frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x} (\rho u) = \frac{\partial \rho}{\partial t} + u \frac{\partial \rho}{\partial x} + \rho \frac{\partial u}{\partial x} = 0$$

Derivada material: derivada tomada ao longo de um caminho movendo-se com velocidade u

$$\frac{D\odot}{Dt} = \frac{\partial \odot}{\partial t} + u \frac{\partial \odot}{\partial x}$$

Módulo de elasticidade volumétrica de um fluido (compressibilidade)

$$K = \frac{\Delta P}{\Delta V / V} = \frac{\Delta P}{\Delta \rho / \rho}$$

Velocidade de propagação de pequenas perturbações acústicas (isentrópica)

$$a^2 = \frac{K}{\rho}$$

$$\rightarrow \frac{1}{\rho} \frac{D\rho}{Dt} + \frac{\partial u}{\partial x} = \frac{1}{K} \frac{DP}{Dt} + \frac{\partial u}{\partial x} = 0 \rightarrow$$

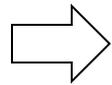
$$\frac{\partial P}{\partial t} + \rho a^2 \frac{\partial u}{\partial x} = 0$$

Escoamento em dutos: obtenção das equações governantes...

$$u = u(t, x)$$

$$P = P(t, x)$$

$$\rho = \rho(t, x)$$



$$\rho \cdot \left(\frac{\partial \vec{u}}{\partial t} + \vec{u} \cdot \vec{\nabla} \vec{u} \right) = -\vec{\nabla} P + \mu \nabla^2 \vec{u} + \sum \vec{F}_{3D}$$

$$\rightarrow \rho \cdot \left(\frac{\partial u}{\partial t} + u \cdot \frac{\partial u}{\partial x} \right) = -\frac{\partial P}{\partial x} + \mu \frac{\partial^2 u}{\partial x^2} + \sum \vec{F}_{3D}$$

Força gravitacional exercida sobre o fluido em função da inclinação da tubulação em relação à horizontal

$$F_g = \rho g \sin \theta$$

Como não há deslizamento entre as camadas de fluido a ação das forças viscosas pode ser modelada pela equação de Darcy-Weisbach

$$F_\mu = \pm f \cdot \frac{\rho}{D} \cdot \frac{u^2}{2} \rightarrow F_\mu = f \cdot \frac{\rho}{D} \cdot \frac{u \cdot |u|}{2}$$



$$\rightarrow \frac{\partial u}{\partial t} + u \cdot \frac{\partial u}{\partial x} + \frac{1}{\rho} \frac{\partial P}{\partial x} + g \sin \theta + f \cdot \frac{u |u|}{2D} = 0$$

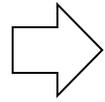
$$u \ll a \rightarrow$$

$$\frac{\partial u}{\partial t} + \frac{1}{\rho} \frac{\partial P}{\partial x} + g \sin \theta + f \cdot \frac{u |u|}{2D} = 0$$

Solução das equações pelo método das características...

$$\frac{\partial P}{\partial t} + \rho a^2 \frac{\partial u}{\partial x} = 0$$

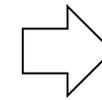
$$\frac{\partial u}{\partial t} + \frac{1}{\rho} \frac{\partial P}{\partial x} + g \sin \theta + f \cdot \frac{u |u|}{2D} = 0$$



Busca de direções especiais de integração (C+ e C-), ao invés das direções canônicas x e t, nas quais as EDPs se tornam EDOs nas variáveis de descrição do problema (pressão e velocidade). Por sua vez, estas EDOs podem ser resolvidas numericamente sobre uma partição do suporte.

$$P(t = t_0, x) \rightarrow \{P_k\}_{t_0}$$

$$u(t = t_0, x) \rightarrow \{u_k\}_{t_0}$$



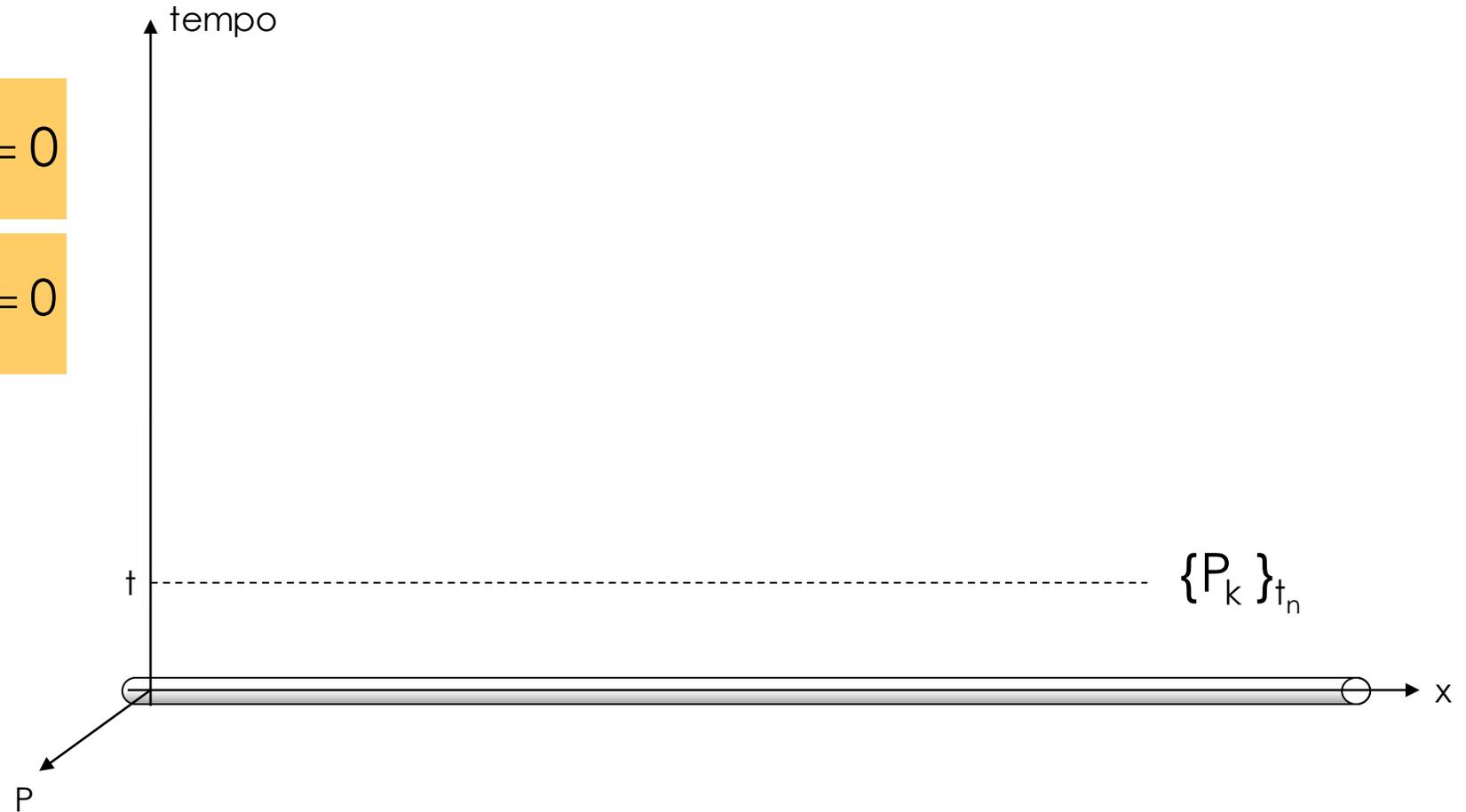
$$\{P_k\}_{t_n} \rightarrow \{P_k\}_{t_{n+1}}$$

$$\{u_k\}_{t_n} \rightarrow \{u_k\}_{t_{n+1}}$$

Solução das equações pelo método das características...

$$\frac{\partial P}{\partial t} + \rho a^2 \frac{\partial u}{\partial x} = 0$$

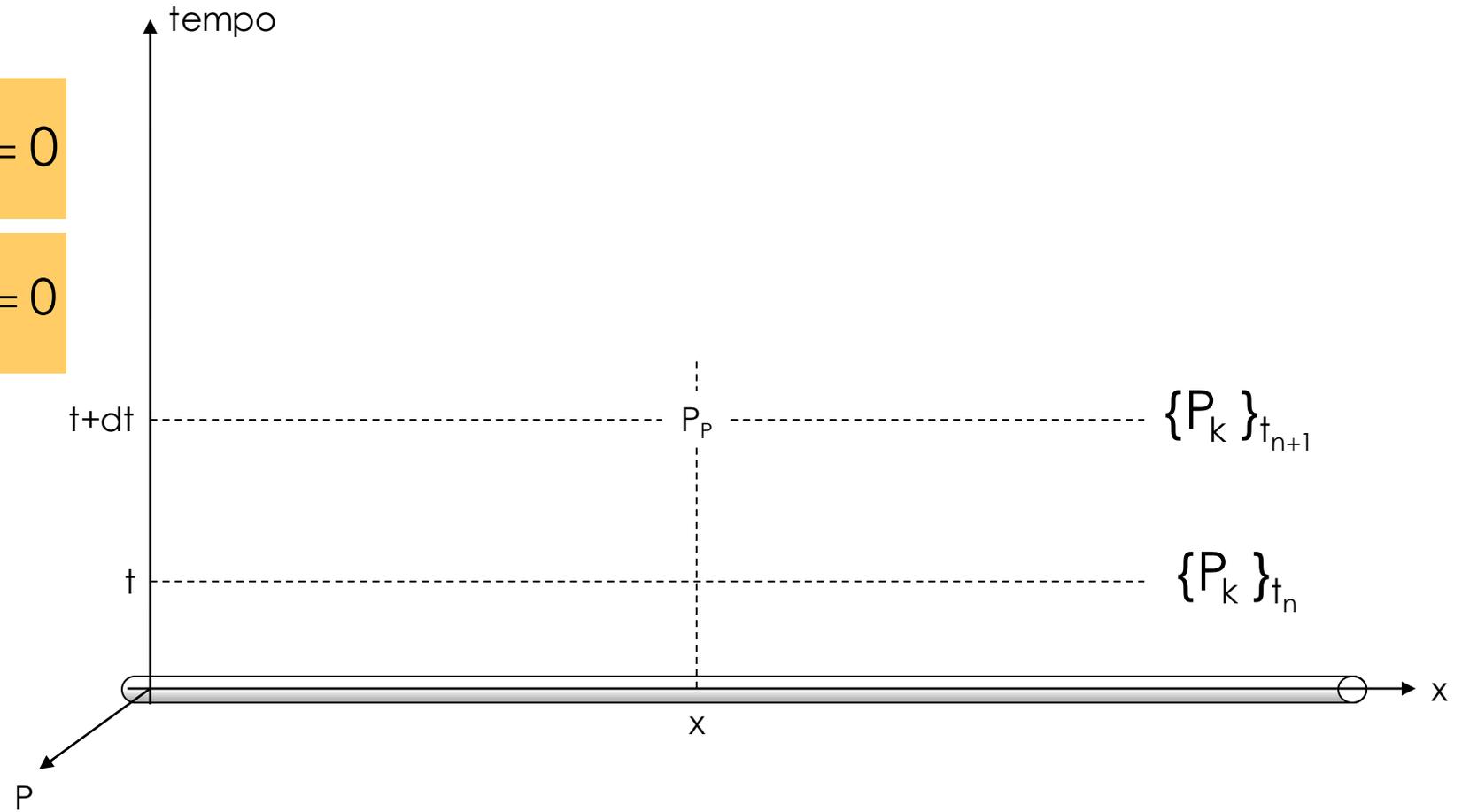
$$\frac{\partial u}{\partial t} + \frac{1}{\rho} \frac{\partial P}{\partial x} + g \sin \theta + f \cdot \frac{u |u|}{2D} = 0$$



Solução das equações pelo método das características...

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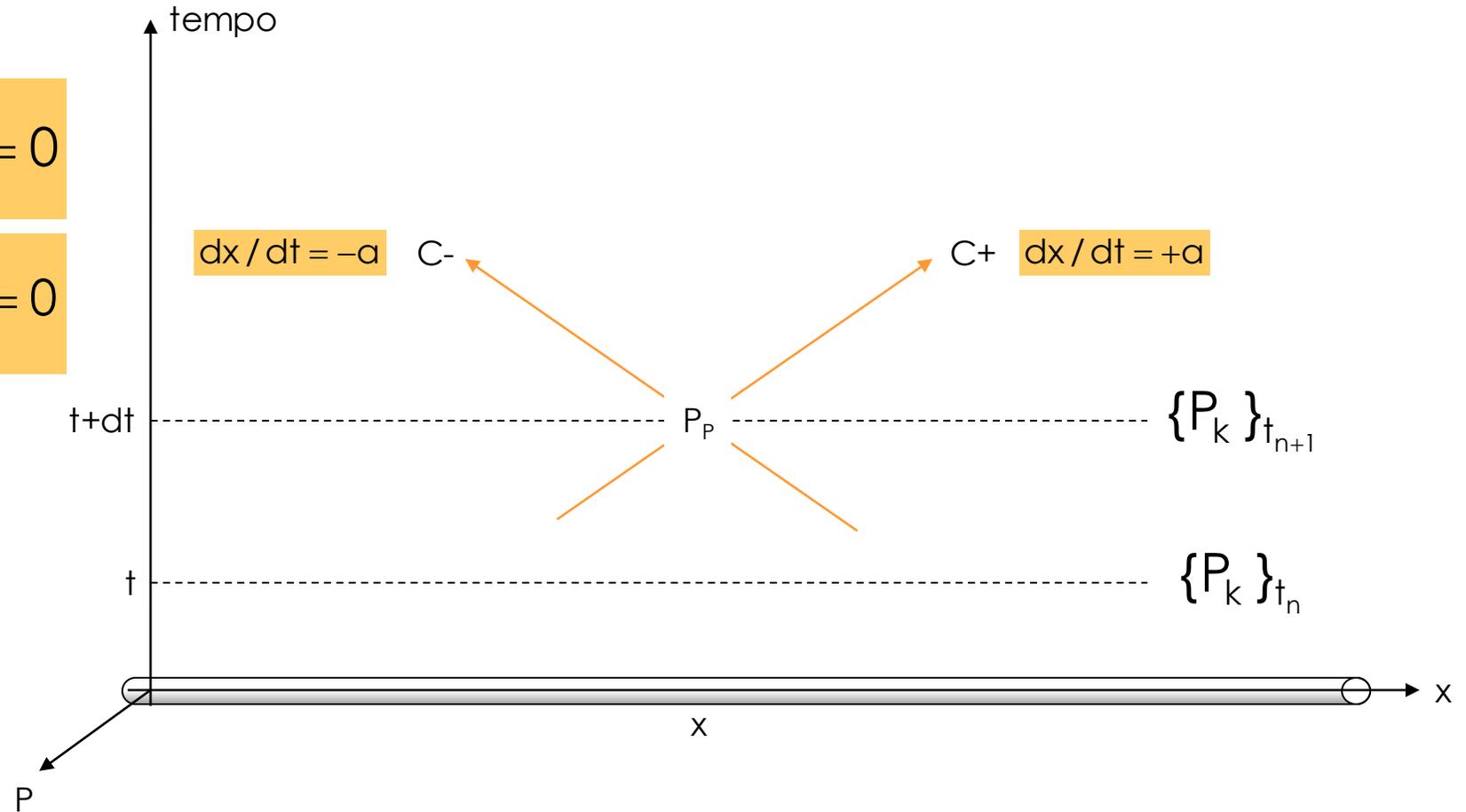
$$\frac{\partial u}{\partial t} + \frac{1}{\rho} \frac{\partial P}{\partial x} + g \sin \theta + f \cdot \frac{u|u|}{2D} = 0$$



Solução das equações pelo método das características...

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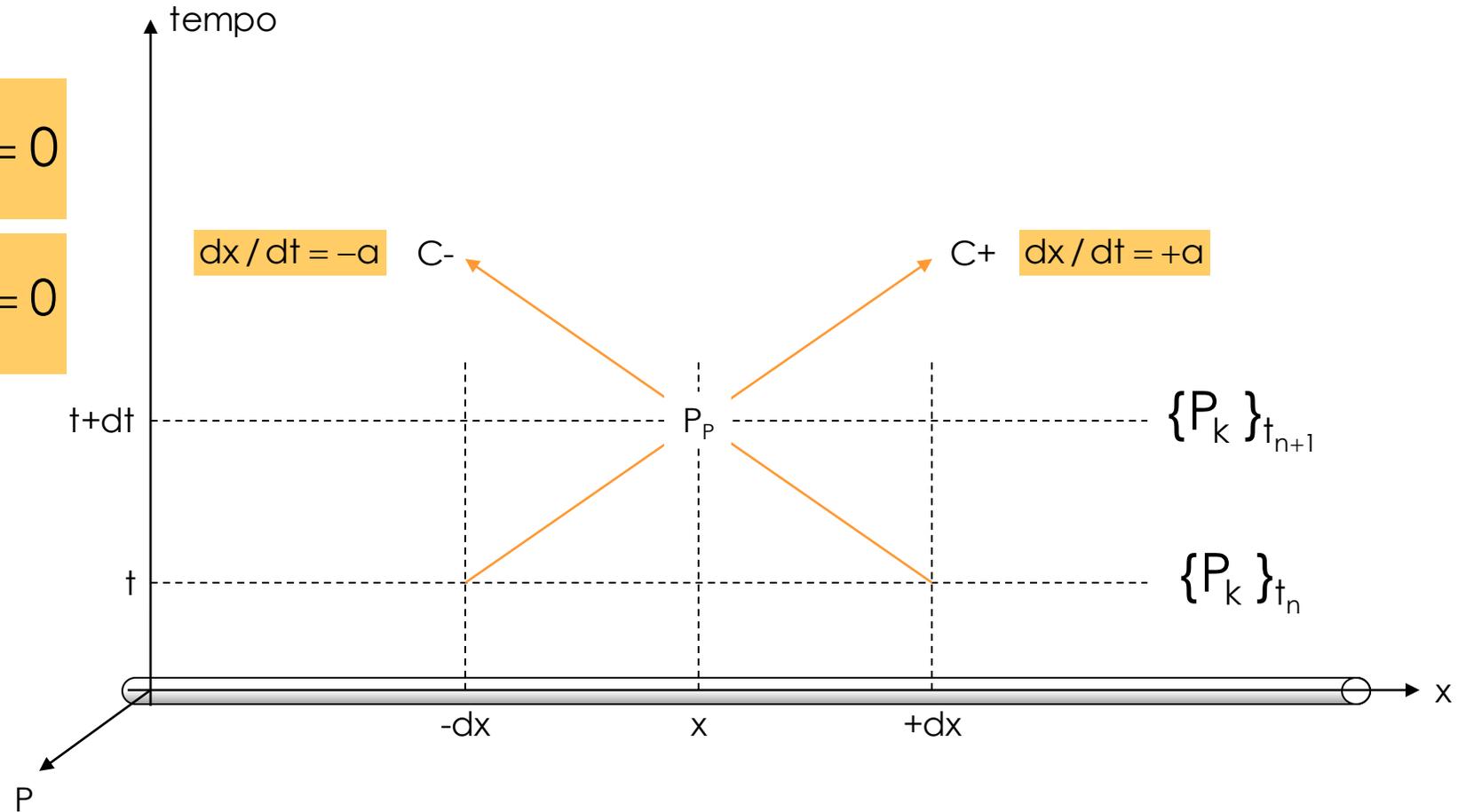
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Solução das equações pelo método das características...

$$\frac{\partial P}{\partial t} + \rho a^2 \frac{\partial u}{\partial x} = 0$$

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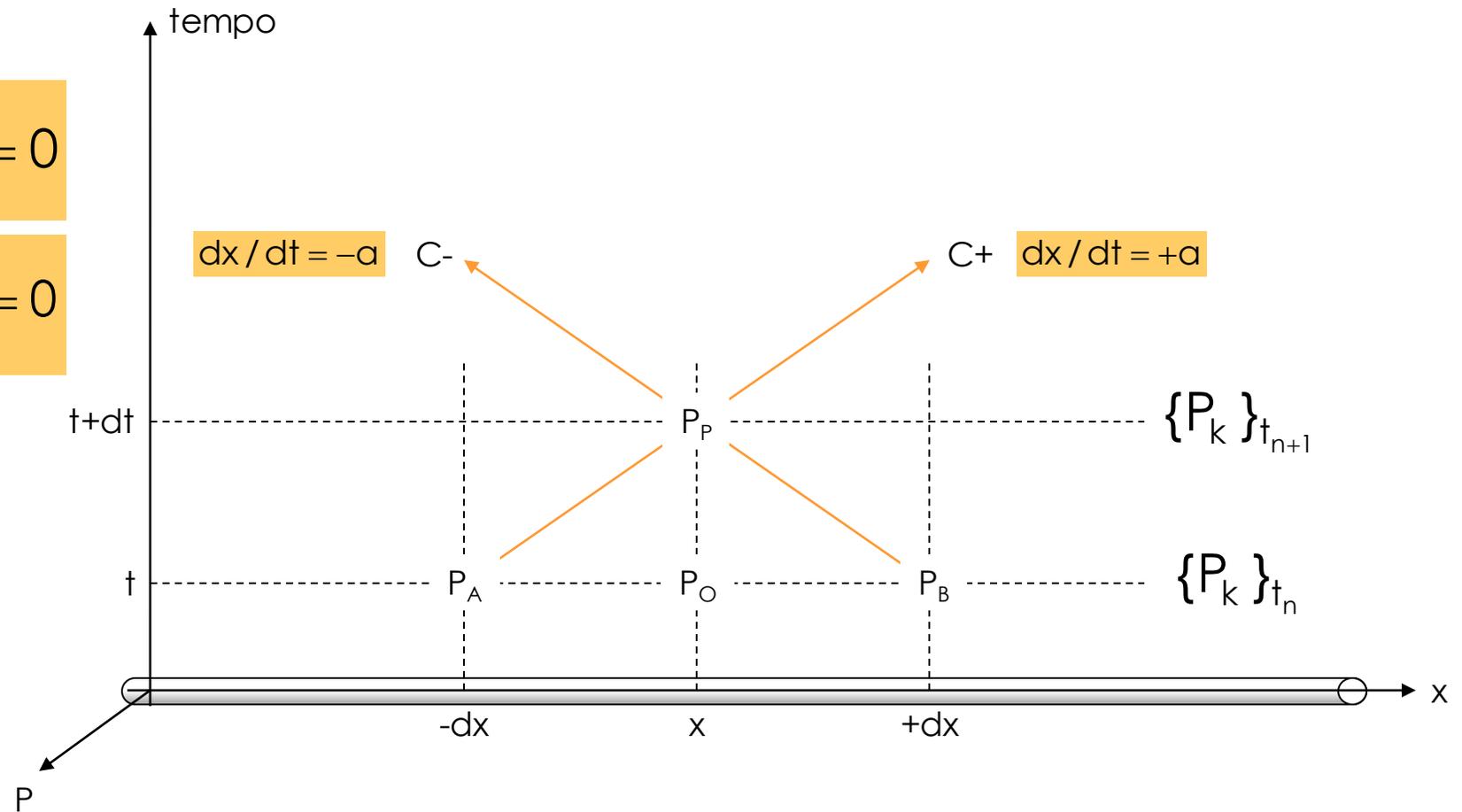


Solução das equações pelo método das características...

$$\frac{\partial P}{\partial t} + \rho a^2 \frac{\partial u}{\partial x} = 0$$

$$\frac{\partial u}{\partial t} + \frac{1}{\rho} \frac{\partial P}{\partial x} + g \sin \theta + f \cdot \frac{u|u|}{2D} = 0$$

$$\operatorname{tg} \theta = \frac{Z_B - Z_A}{2dx}$$



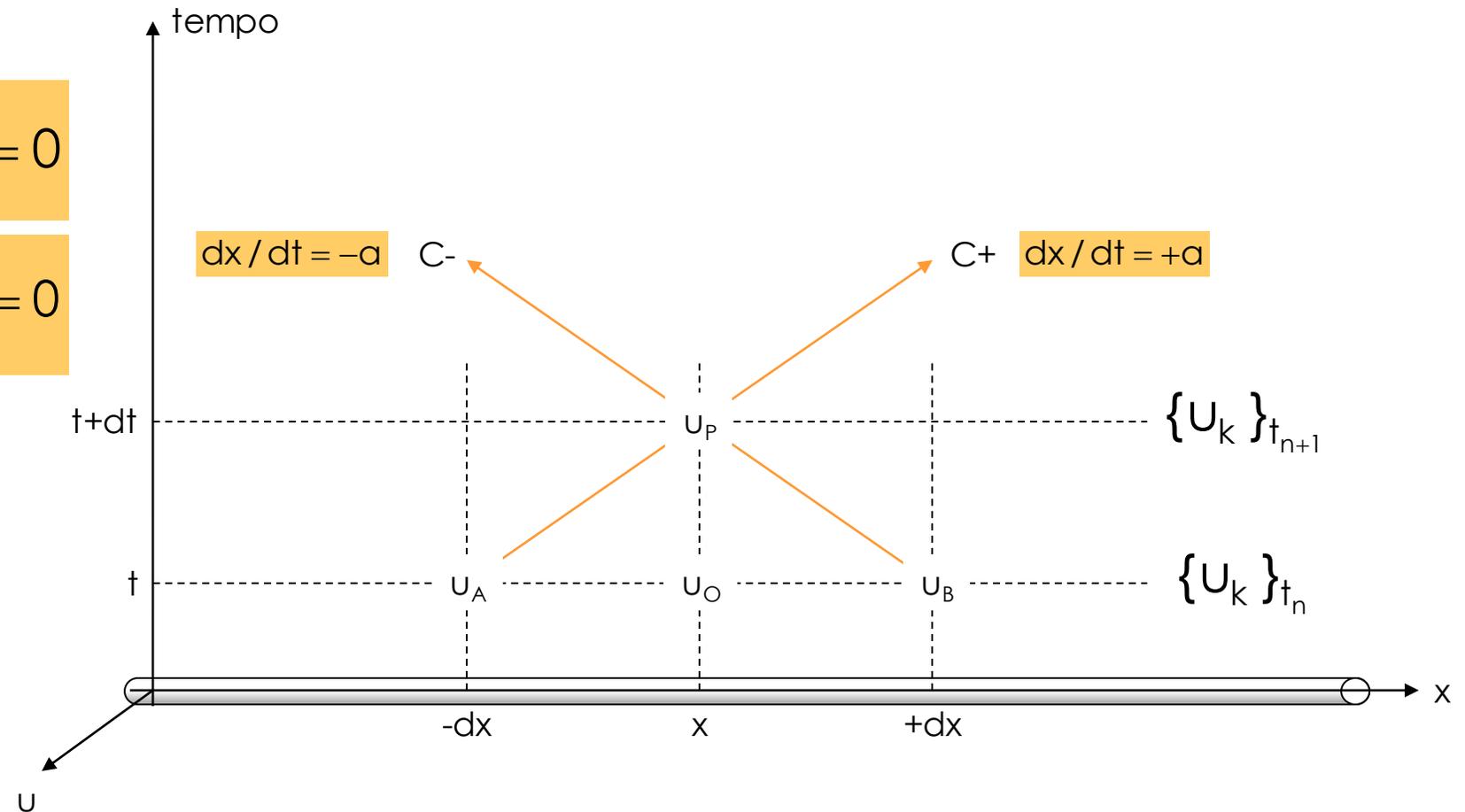
$$P_P = \frac{(P_A + \rho g Z_A + \rho a V_A)(\rho a + R|V_B|) + (P_B + \rho g Z_B - \rho a V_B)(\rho a + R|V_A|)}{2\rho a + R(|V_A| + |V_B|)} - \rho g Z_P$$

Solução das equações pelo método das características...

$$\frac{\partial P}{\partial t} + \rho a^2 \frac{\partial u}{\partial x} = 0$$

$$\frac{\partial u}{\partial t} + \frac{1}{\rho} \frac{\partial P}{\partial x} + g \sin \theta + f \cdot \frac{u|u|}{2D} = 0$$

$$\operatorname{tg} \theta = \frac{Z_B - Z_A}{2dx}$$

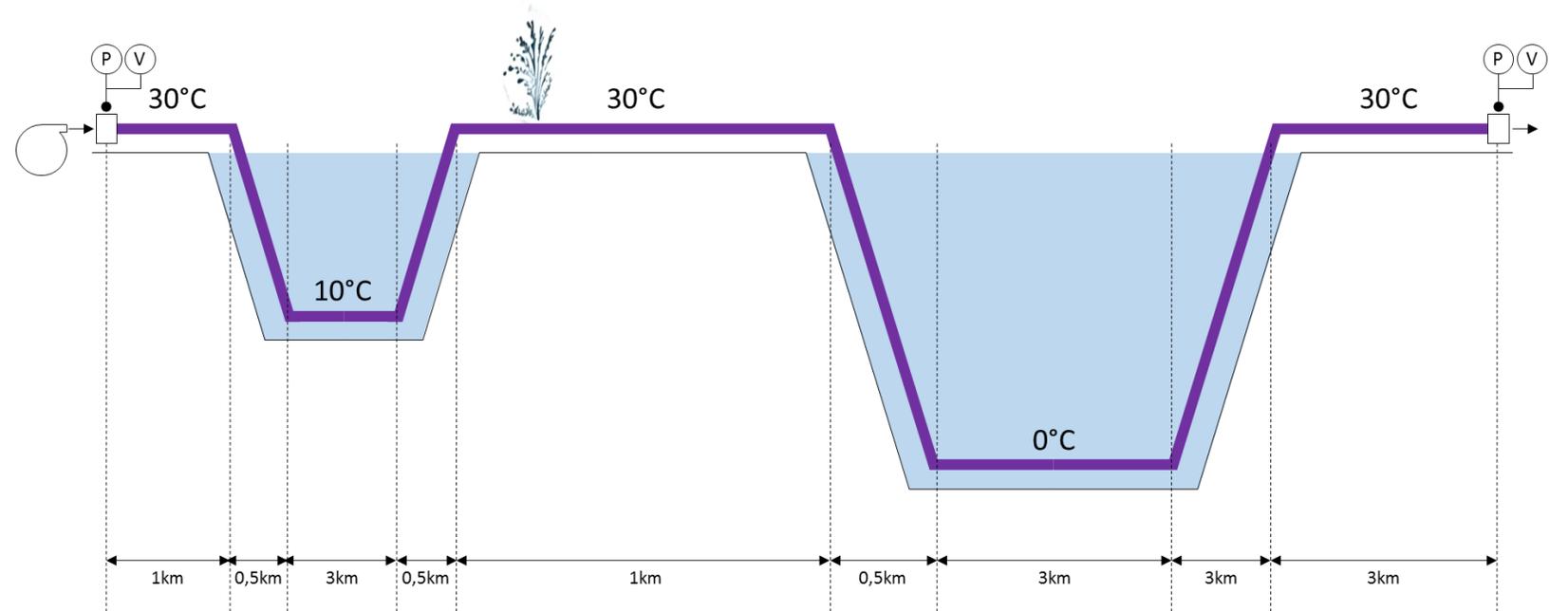


$$V_P = \frac{P_A + \rho g Z_A - P_B - \rho g Z_B + \rho a (V_A + V_B)}{2 \rho a + R (|V_A| + |V_B|)}$$

O cálculo de cada nó (P ou u) em $t+dt$ depende apenas dos valores nodais anteriores nas posições $x-dx$, x e $x+dx$...

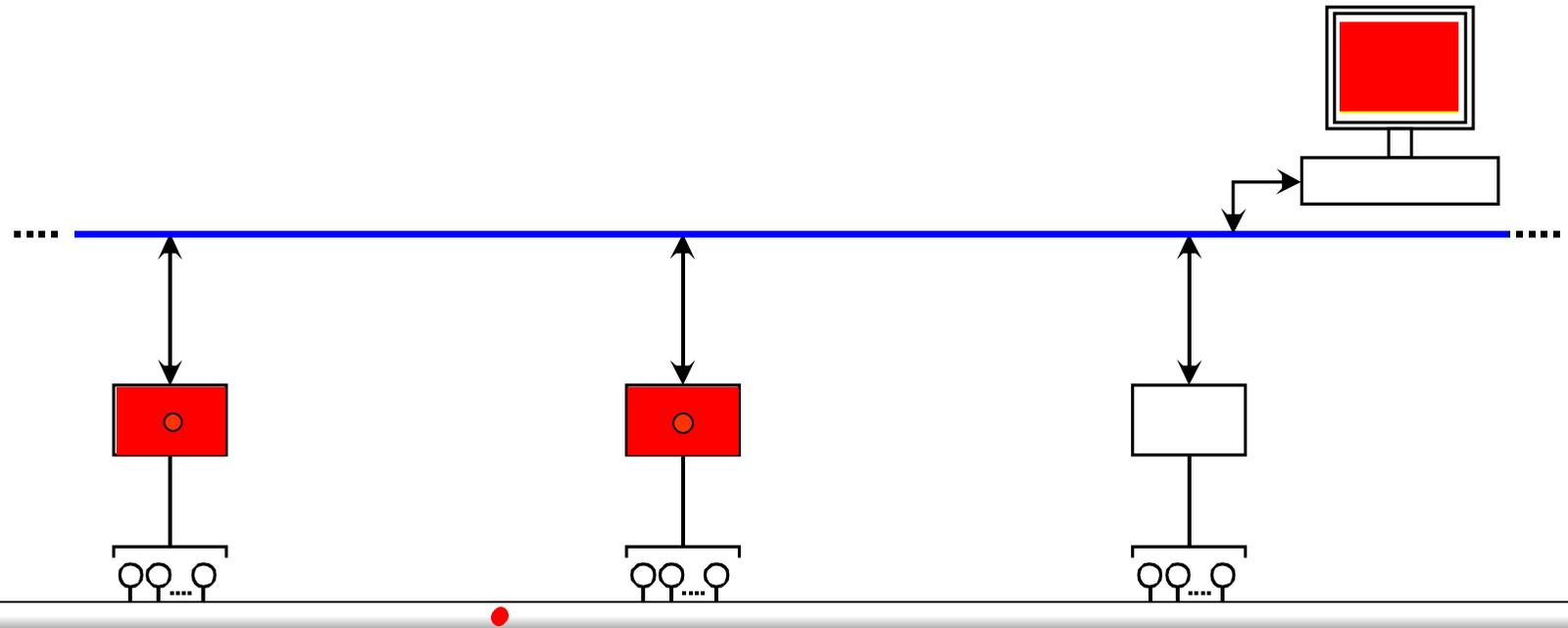
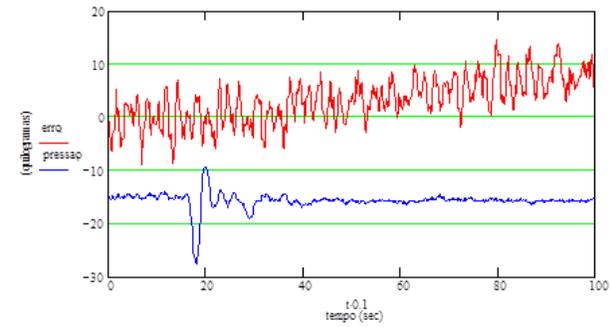
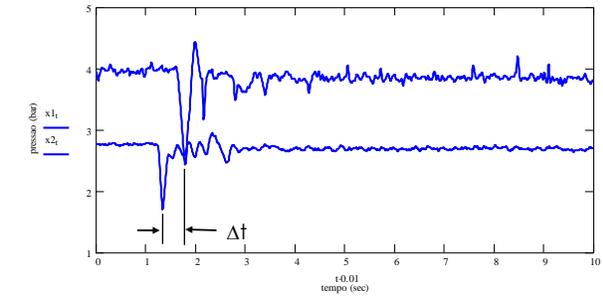
... PARALELIZAÇÃO MASSIVA !

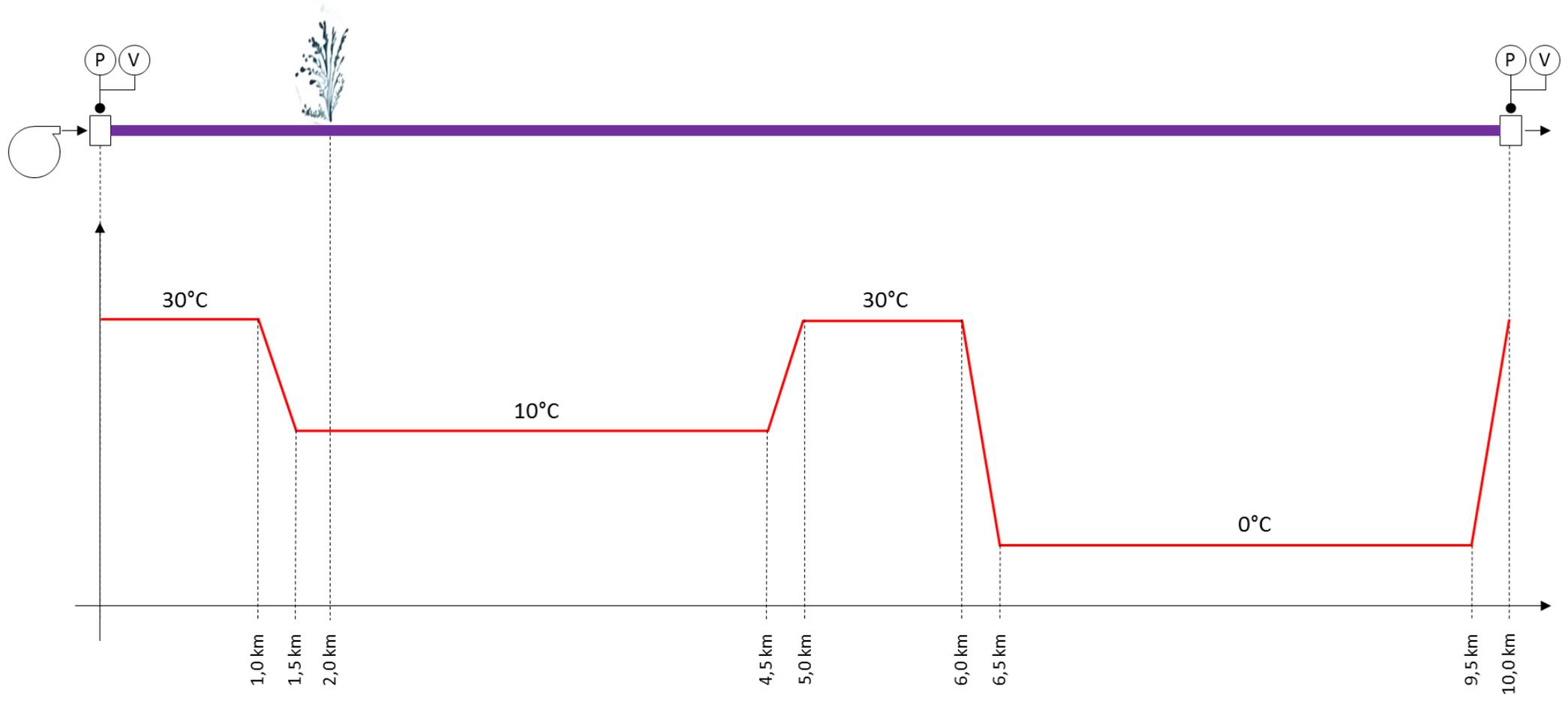
CPU+FPGA, CPU+GPU



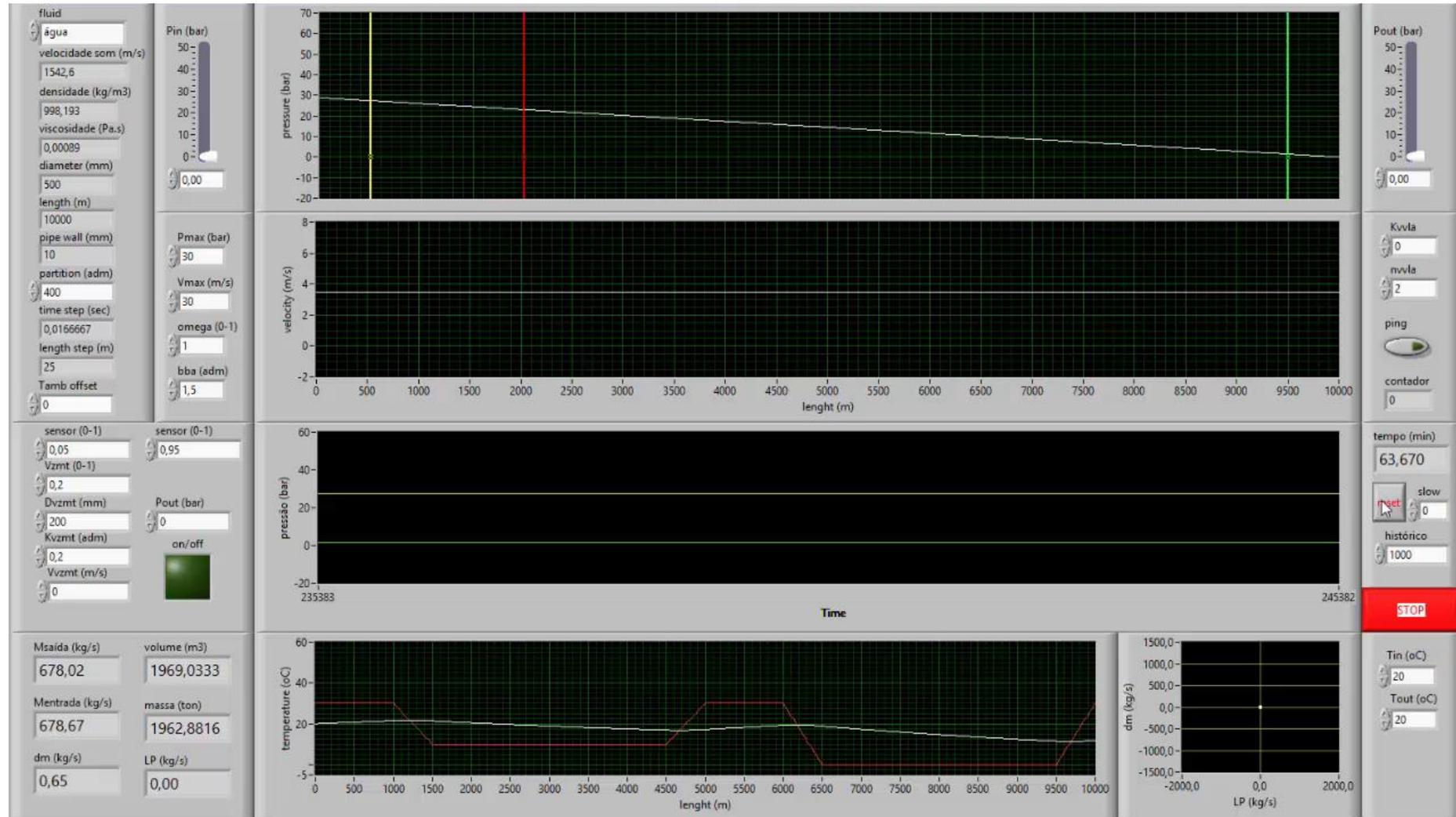


Arquitetura de um sistema de detecção passiva de vazamentos...





Simulador "faster than real time"...

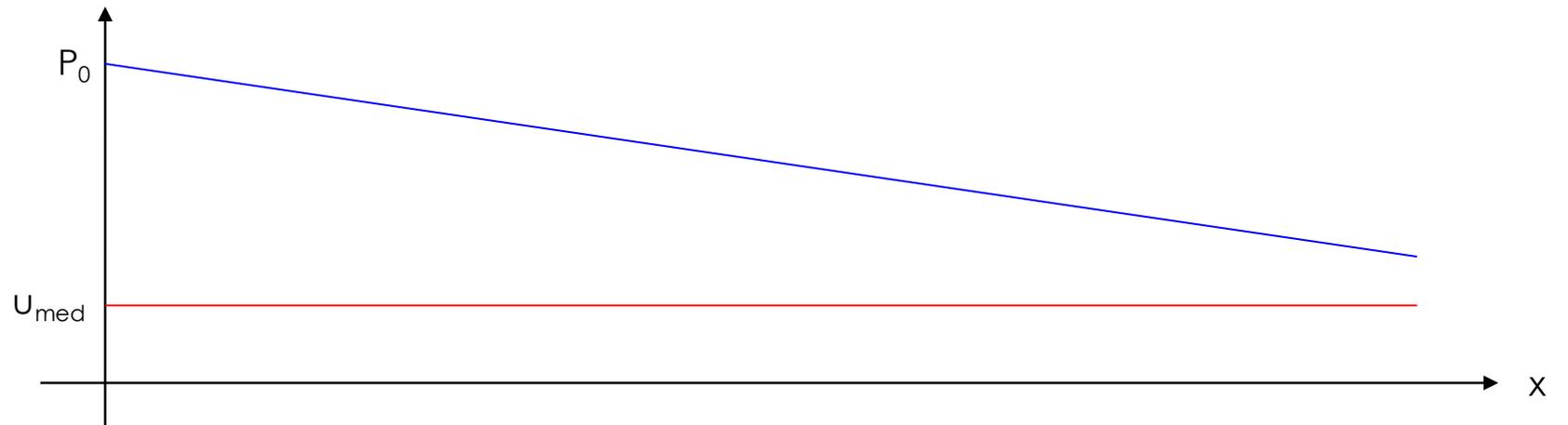


Solução das equações em regime permanente...

$$\cancel{\frac{\partial P}{\partial t}} + \rho a^2 \frac{\partial u}{\partial x} = 0 \quad \rightarrow a = \text{cte} \Rightarrow u = \text{cte}$$

$$\cancel{\frac{\partial u}{\partial t}} + \frac{1}{\rho} \frac{\partial P}{\partial x} + g \sin \theta + f \cdot \frac{u|u|}{2D} = 0 \quad \rightarrow \theta = \text{cte} \Rightarrow P = a_0 + a_1 \cdot x$$

$$a_0 = P_0 \quad a_1 = -f \cdot \frac{\rho u |u|}{2D}$$



A equação de Darcy e cálculo do fator de atrito...



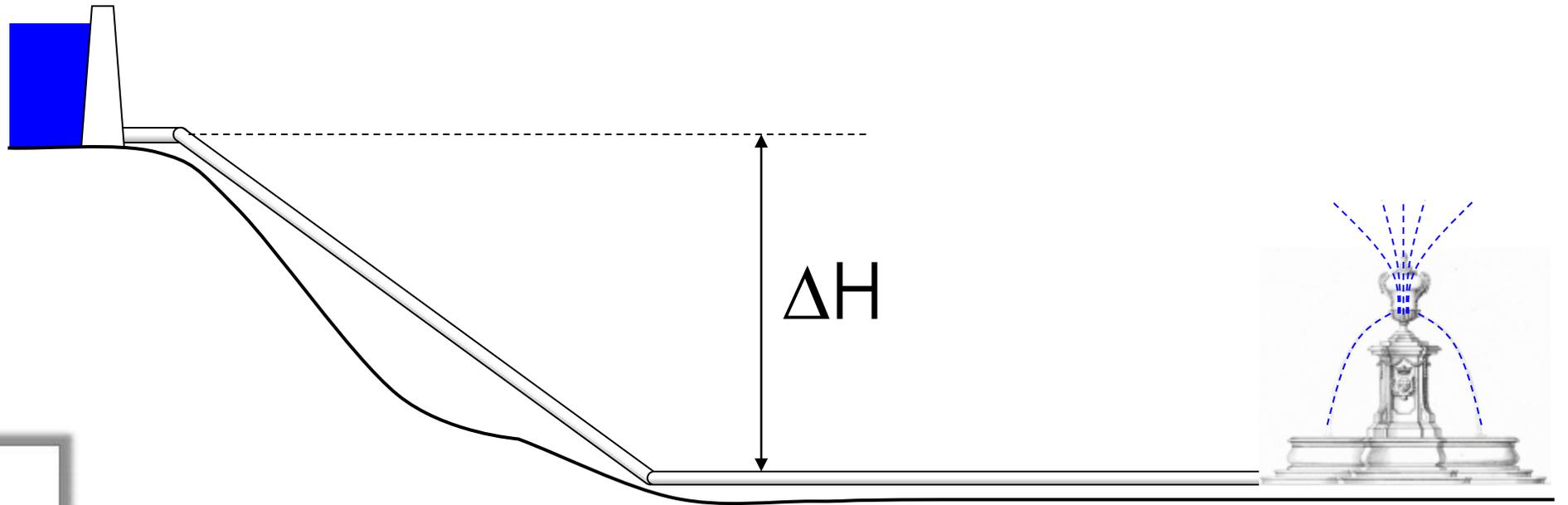
Henry Darcy



A equação de Darcy e cálculo do fator de atrito...



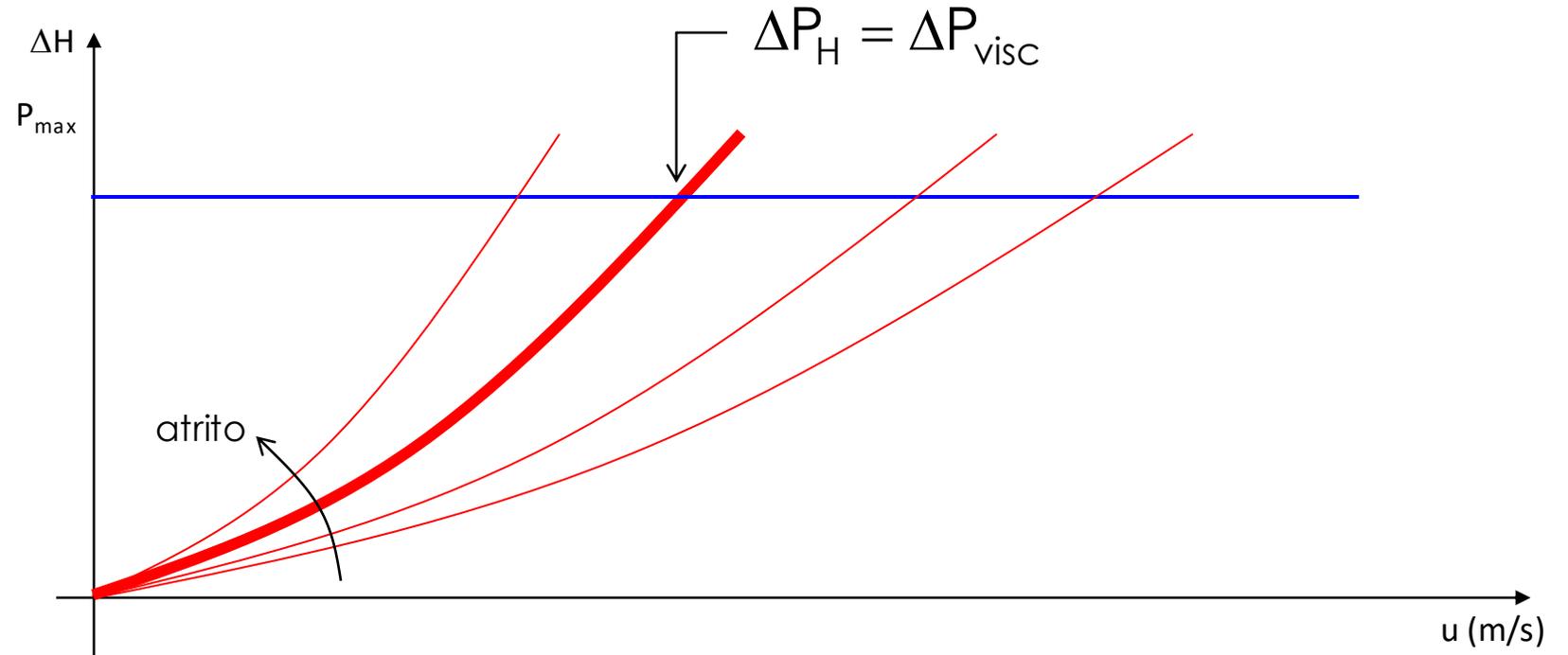
Henry Darcy



A equação de Darcy e cálculo do fator de atrito...



Henry Darcy



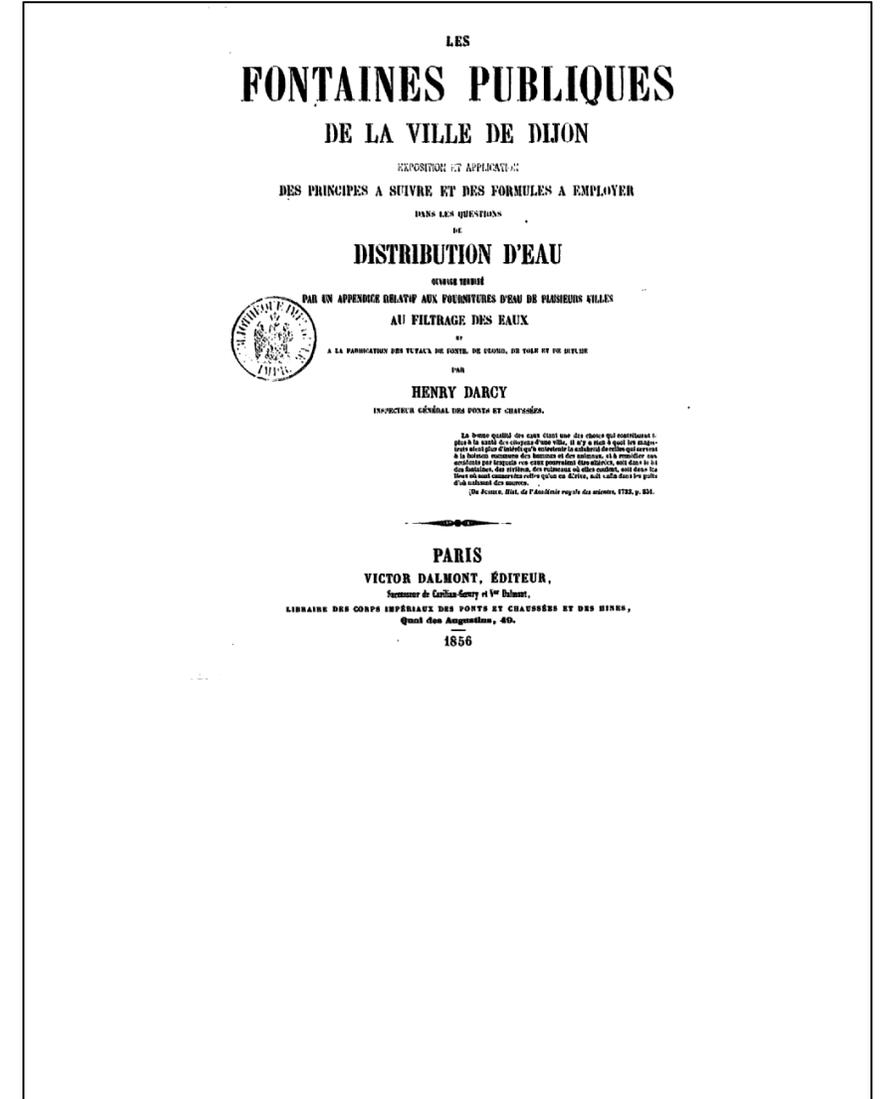
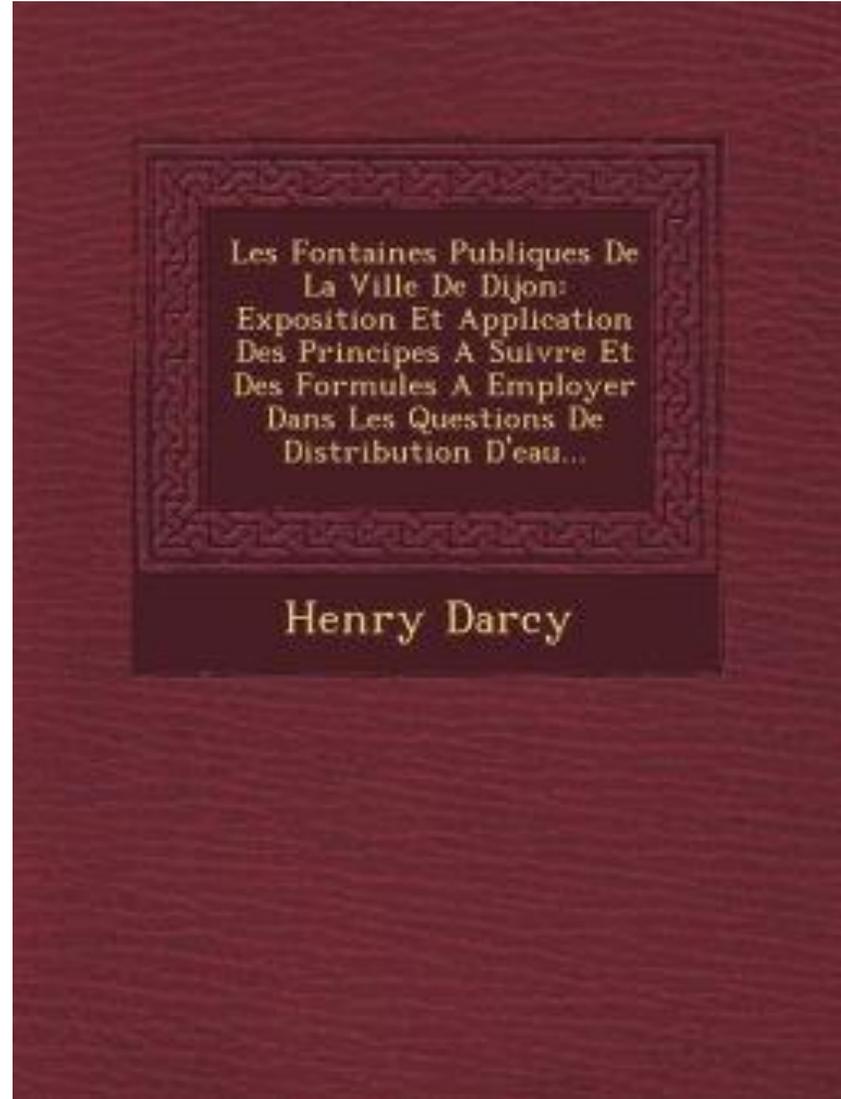
$$\Delta P_{visc} = f \cdot \frac{L}{D} \cdot \rho \frac{V^2}{2}$$

$$f = f(Re, e/D) \quad \text{fator de atrito}$$

A equação de Darcy e cálculo do fator de atrito...

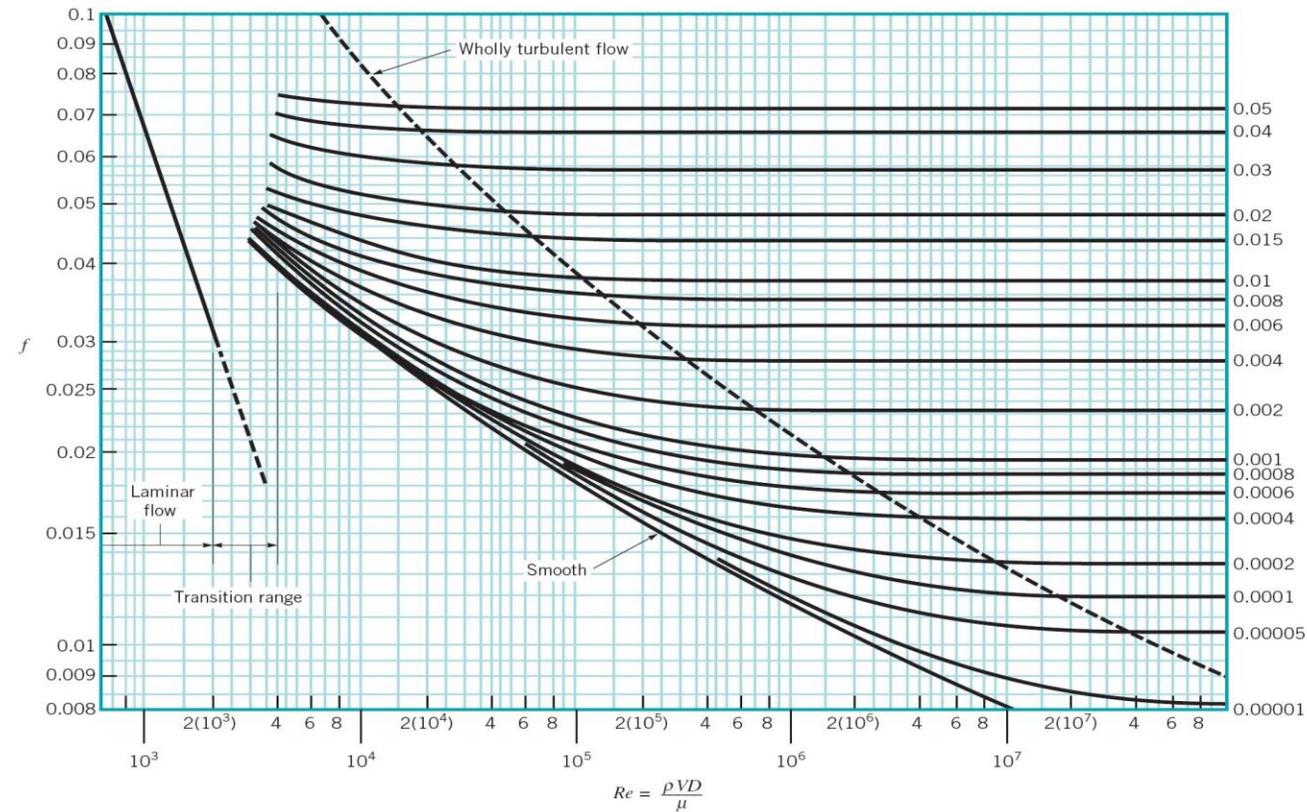


Henry Darcy



A equação de Darcy e cálculo do fator de atrito...

Diagrama de Moody



Laminar ($Re < 2500$)

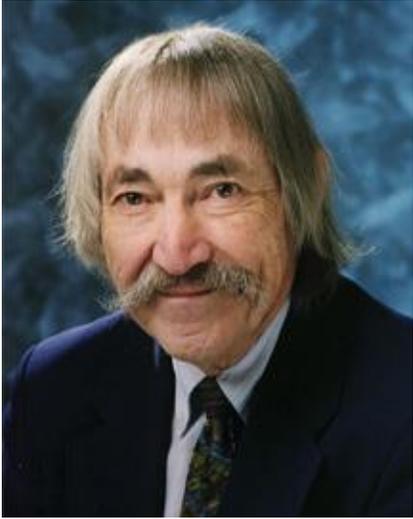
$$f = \frac{64}{Re}$$

Turbulento ($Re > 4000$)

$$\frac{1}{\sqrt{f}} = -2 \log \left(3.7 \frac{e}{D} + \frac{2.51}{Re \sqrt{f}} \right)$$

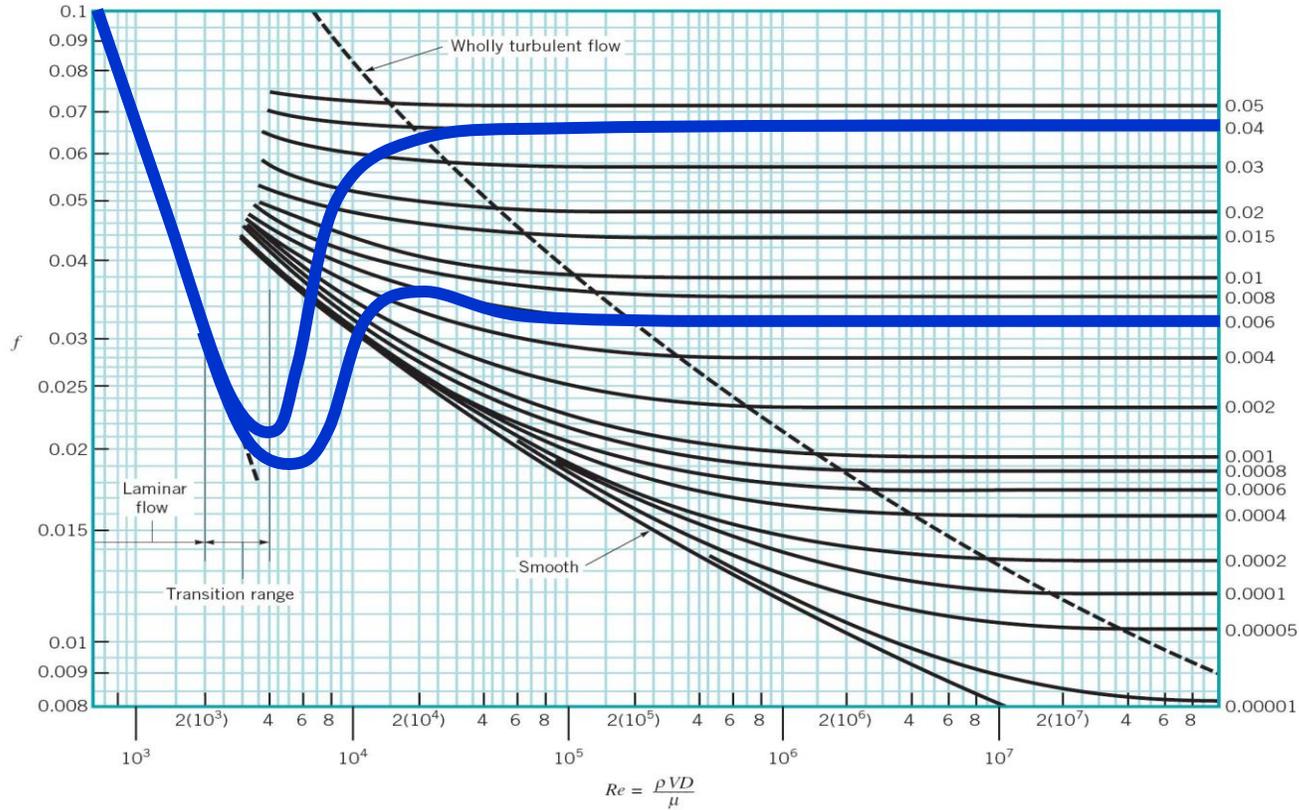
Colebrook-White

A equação de Darcy e cálculo do fator de atrito...



Stuart W. Churchill

Diagrama de Moody



Laminar ($Re < 2500$)

$$f = \frac{64}{Re}$$

Turbulento ($Re > 4000$)

$$\frac{1}{\sqrt{f}} = -2 \log \left(3.7 \frac{e}{D} + \frac{2.51}{Re \sqrt{f}} \right)$$

Colebrook-White

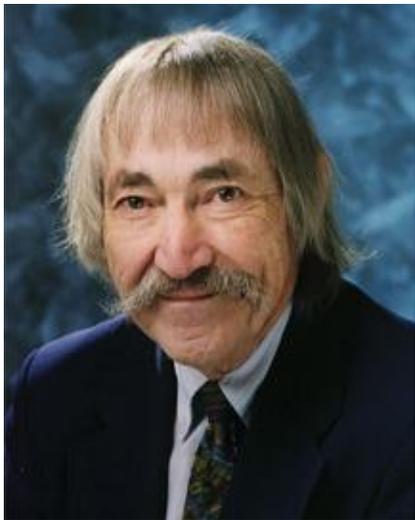
$$f = 8 \cdot \left[\left(\frac{8}{Re} \right)^{12} + (A + B)^{-1,5} \right]^{1/12}$$

$$A = \left\{ 2,457 \ln \left(\left(\left(\frac{7}{Re} \right)^{0,9} + 0,27 \cdot \frac{\varepsilon}{D} \right)^{-1} \right) \right\}^{16}$$

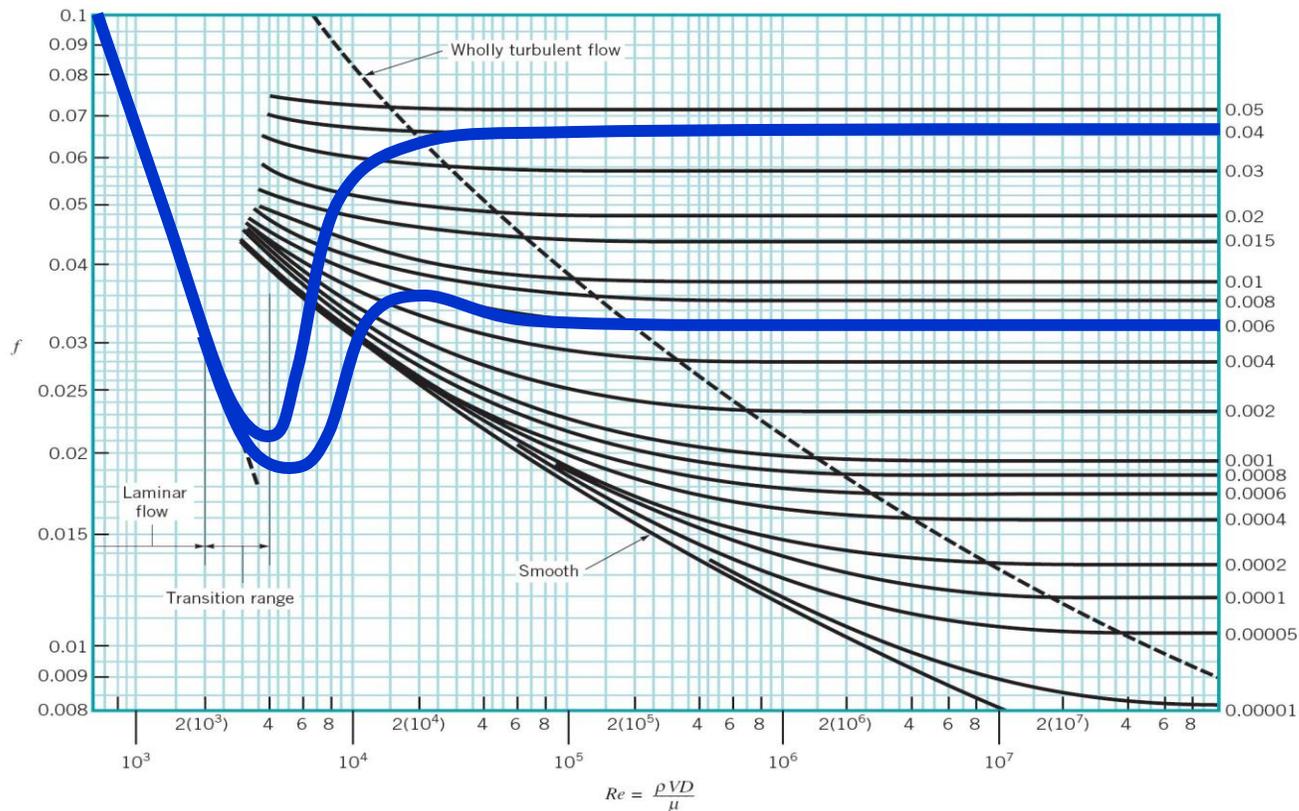
$$B = \left(\frac{37530}{Re} \right)^{16} \quad Re = \frac{4 \cdot m}{\mu \pi D}$$

A equação de Darcy e cálculo do fator de atrito...

Diagrama de Moody



Stuart W. Churchill

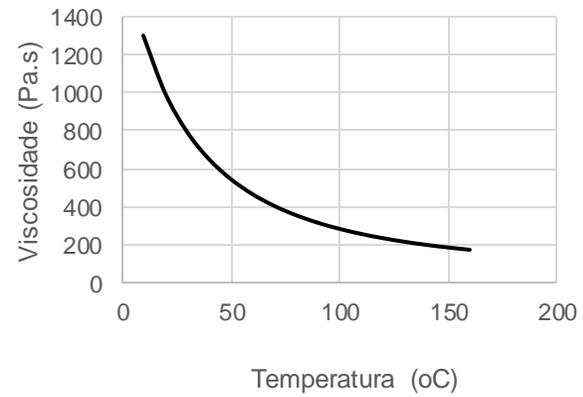
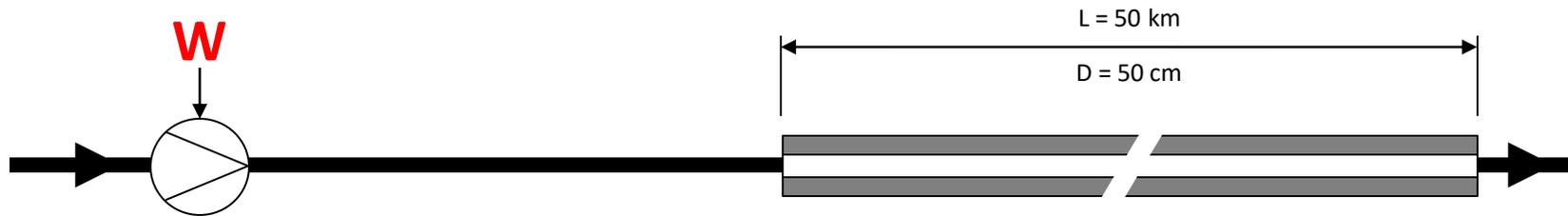


$$f = 8 \cdot \left[\left(\frac{8}{Re} \right)^{12} + (A + B)^{-1,5} \right]^{1/12}$$

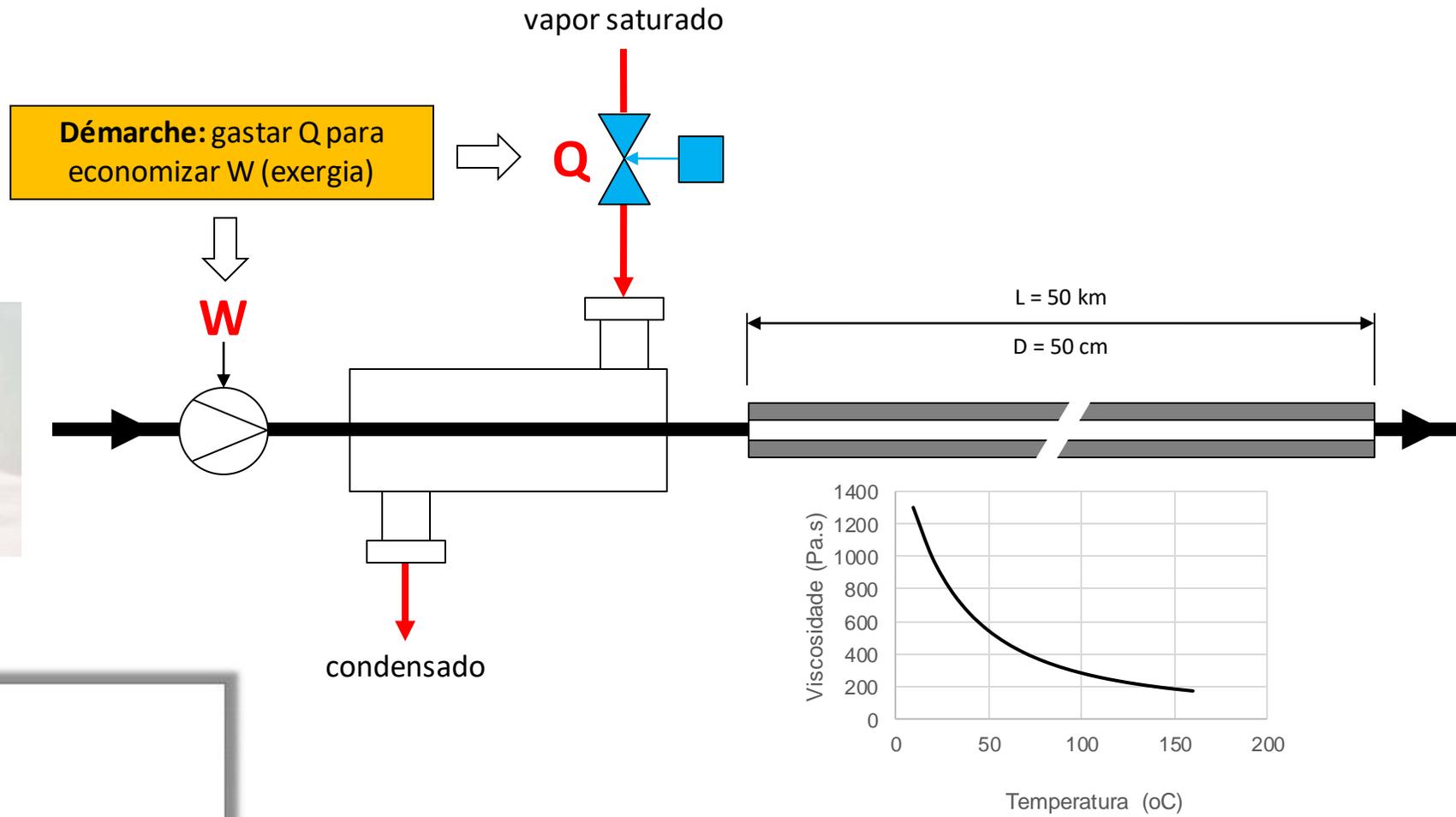
$$A = \left\{ 2,457 \ln \left(\left(\left(\frac{7}{Re} \right)^{0,9} + 0,27 \cdot \frac{\varepsilon}{D} \right)^{-1} \right) \right\}^{16}$$

$$B = \left(\frac{37530}{Re} \right)^{16} \quad Re = \frac{4 \cdot m}{\mu \pi D}$$

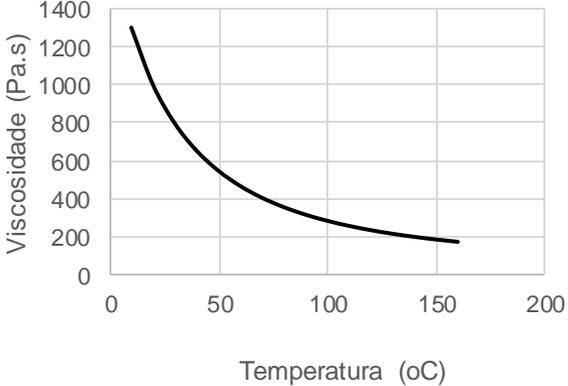
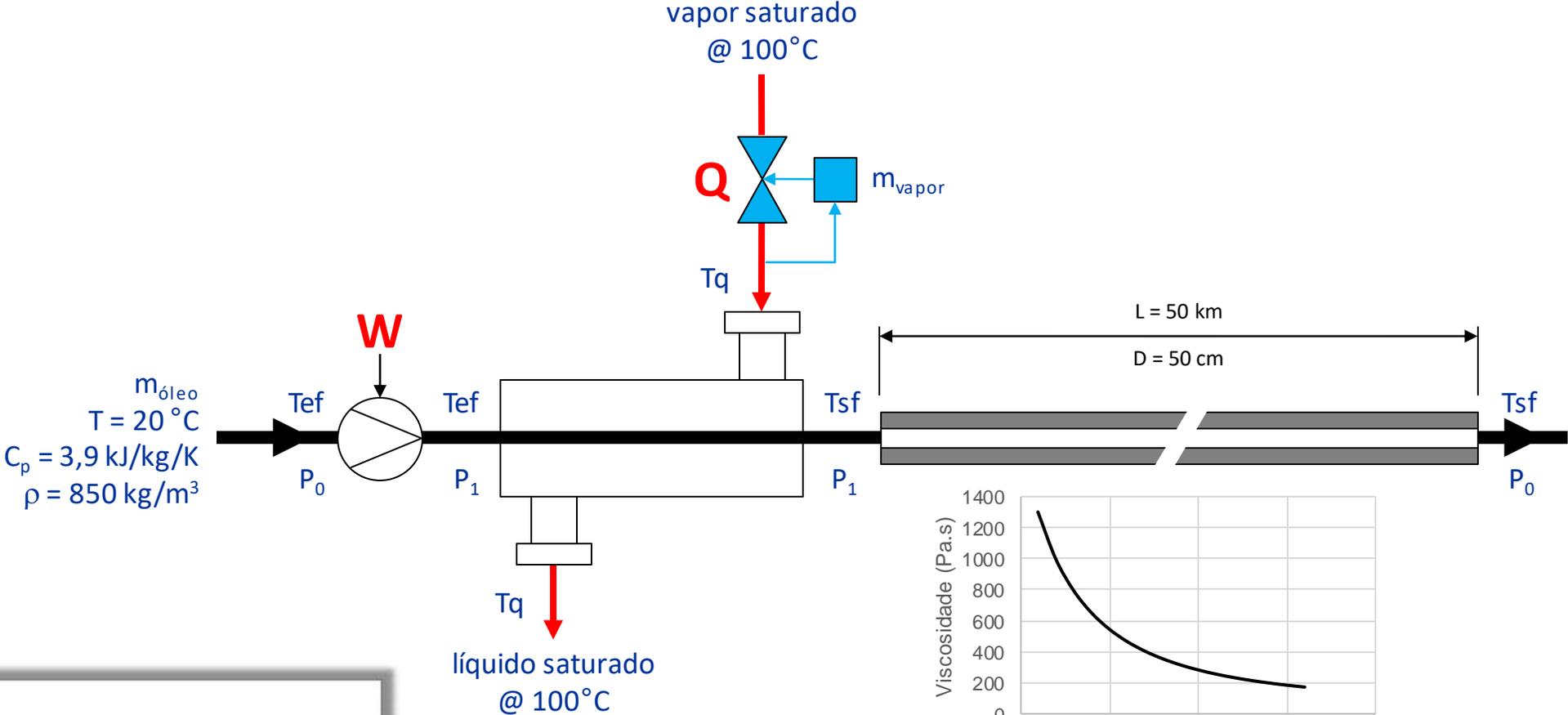
Exemplo: bombeio de óleo ultra viscoso...



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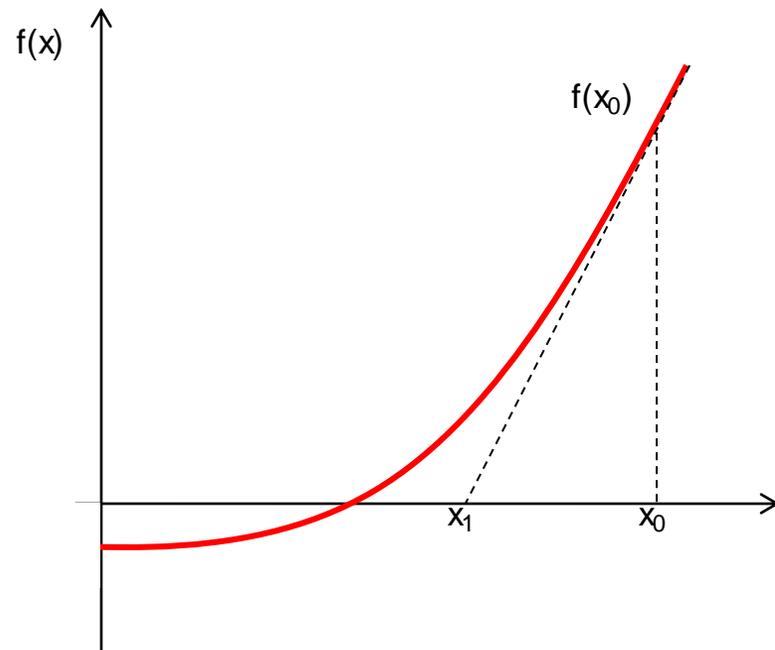
$$\mu(T) = 6.7109 \cdot 10^{-6} \cdot T^4 - 2.9844 \cdot 10^{-3} \cdot T^3 + \dots$$

$$\dots + 5.0341 \cdot 10^{-1} \cdot T^2 - 4.0864 \cdot 10^{+1} \cdot T + 1.6546 \cdot 10^{+3} \quad [\mu] = \text{Pa} \cdot \text{s}, [T] = ^\circ\text{C}$$

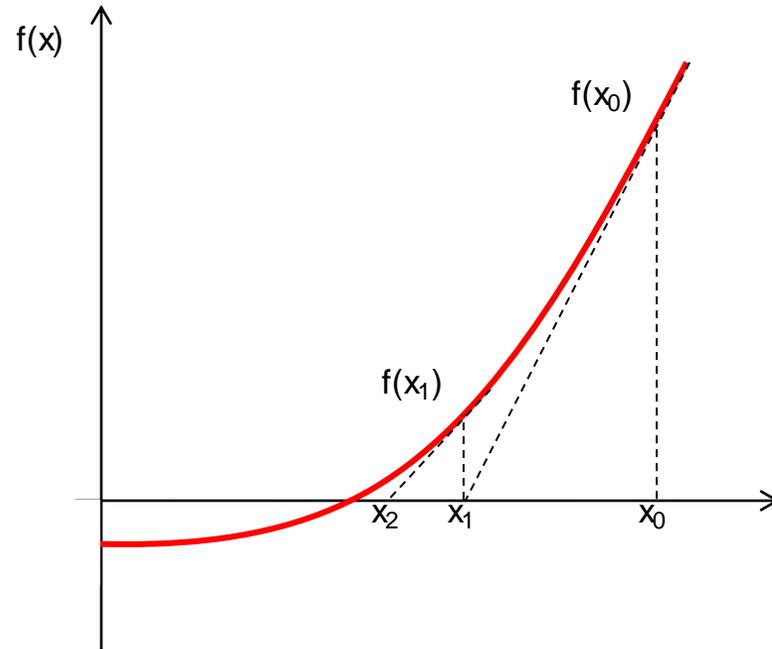
Solução de Equações Não Lineares

NEWTON – RAPHSON

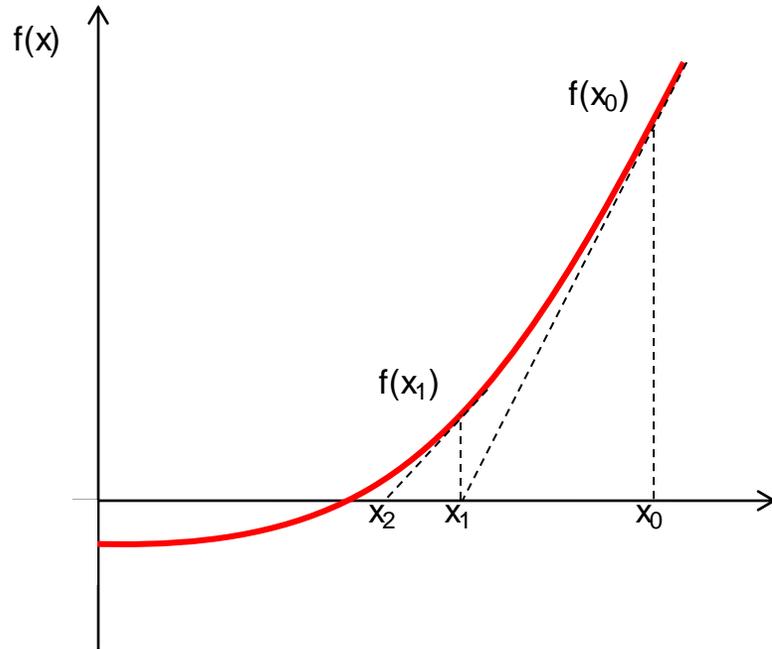
Solução pelo método de Newton-Raphson: 1D



Solução pelo método de Newton-Raphson: 1D



Solução pelo método de Newton-Raphson: 1D



Equação da reta tangente:

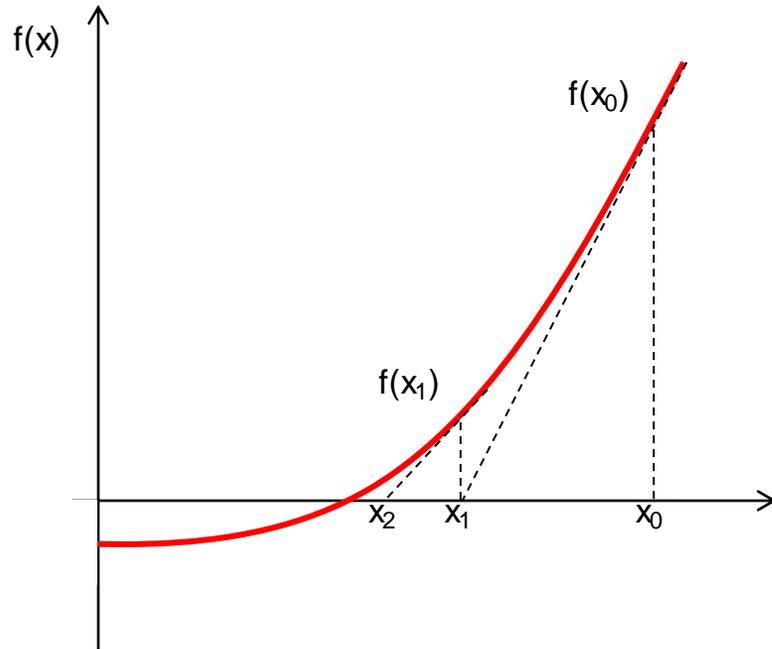
$$y = a \cdot x + b$$

$$a = f'(x_0)$$

$$f(x_0) = f'(x_0) \cdot x_0 + b$$

$$b = f(x_0) - f'(x_0) \cdot x_0$$

Solução pelo método de Newton-Raphson: 1D



Equação da reta tangente:

$$y = a \cdot x + b$$

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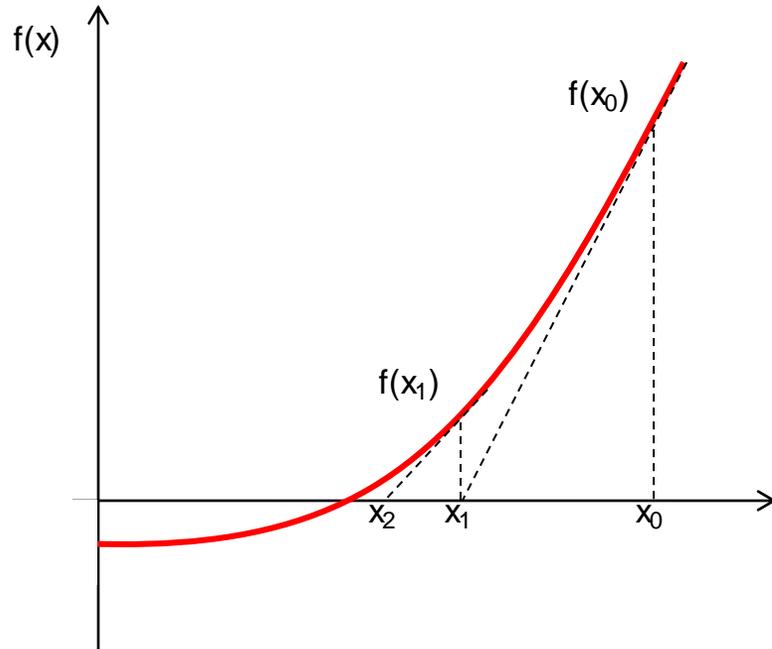
$$b = f(x_0) - f'(x_0) \cdot x_0$$

Raiz da reta tangente:

$$x = -b/a$$

$$x_1 = x_0 - \frac{f(x_0)}{f'(x_0)}$$

Solução pelo método de Newton-Raphson: 1D



Equação da reta tangente:

$$y = a \cdot x + b$$

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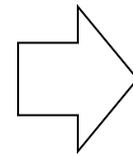
$$f(x_0) = f'(x_0) \cdot x_0 + b$$

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Raiz da reta tangente:

$$x = -b/a$$

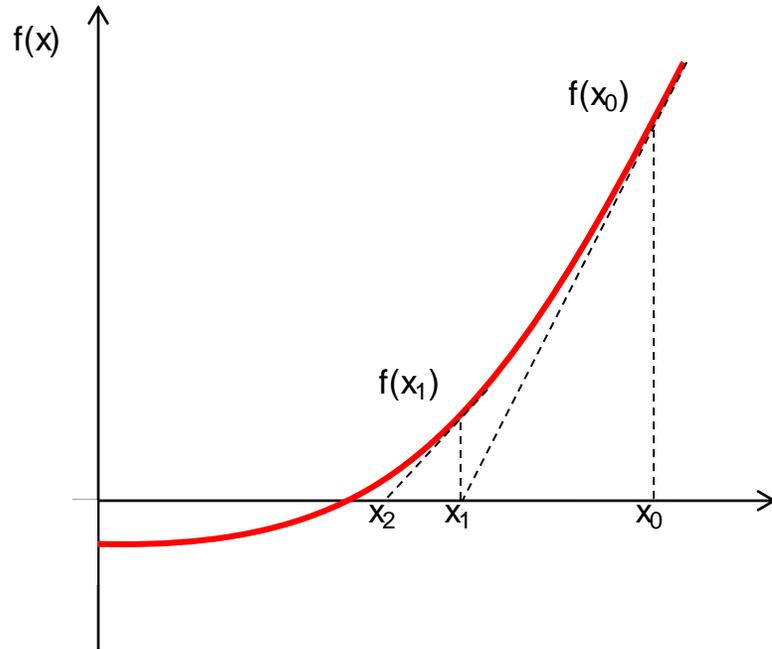
$$x_1 = x_0 - \frac{f(x_0)}{f'(x_0)}$$



Fórmula de recorrência

$$x_{k+1} = x_k - \frac{1}{f'(x_k)} \times f(x_k)$$

Solução pelo método de Newton-Raphson: 1D



Equação da reta tangente:

$$y = a \cdot x + b$$

$$a = f'(x_0)$$

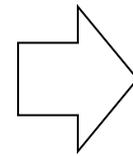
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Raiz da reta tangente:

$$x = -b/a$$

$$x_1 = x_0 - \frac{f(x_0)}{f'(x_0)}$$



Fórmula de recorrência $N \times N$

$$\vec{x}_{k+1} = \vec{x}_k - \text{Jac}_k^{-1} \times \vec{f}(\vec{x}_k)$$

Exemplo de aplicação...

$$f(x) = \cos(x) - x = 0$$

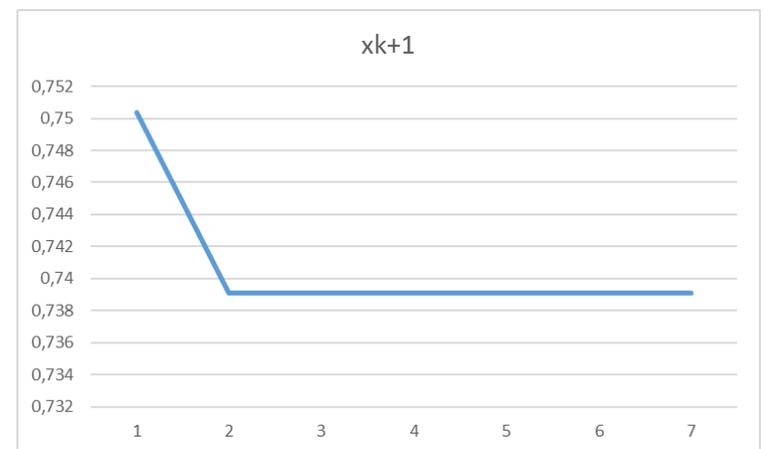
$$f'(x) = -\sin(x) - 1$$

Fórmula de recorrência

$$x_{k+1} = x_k - \frac{1}{f'(x_k)} \times f(x_k)$$

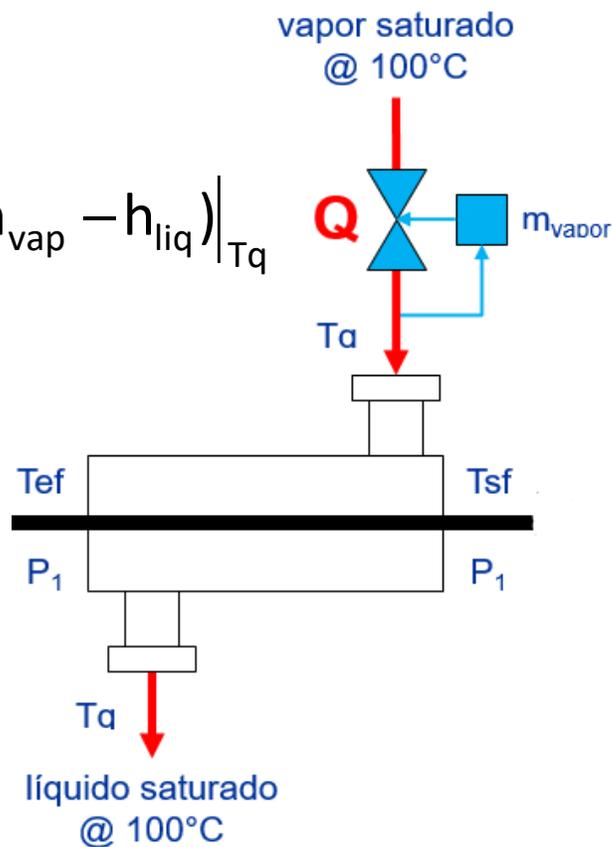
$$x_{k+1} = x_k - \frac{\cos(x_k) - x_k}{-\sin(x_k) - 1}$$

xk	f(xk)	f'(xk)	xk+1	
1	-0,4597	-1,84147	0,750364	
0,750364	-0,01892	-1,6819	0,739113	
0,739113	-4,6E-05	-1,67363	0,739085	
0,739085	-2,8E-10	-1,67361	0,739085	
0,739085		0	-1,67361	0,739085
0,739085		0	-1,67361	0,739085
0,739085		0	-1,67361	0,739085



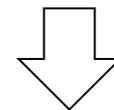
Exemplo: bombeio de óleo ultra viscoso...

$$Q = m_{\text{vapor}} \cdot (h_{\text{vap}} - h_{\text{liq}}) \Big|_{Tq}$$



$$Q = m_{\text{óleo}} C_{p_{\text{óleo}}} \cdot (T_{\text{sf}} - T_{\text{ef}})$$

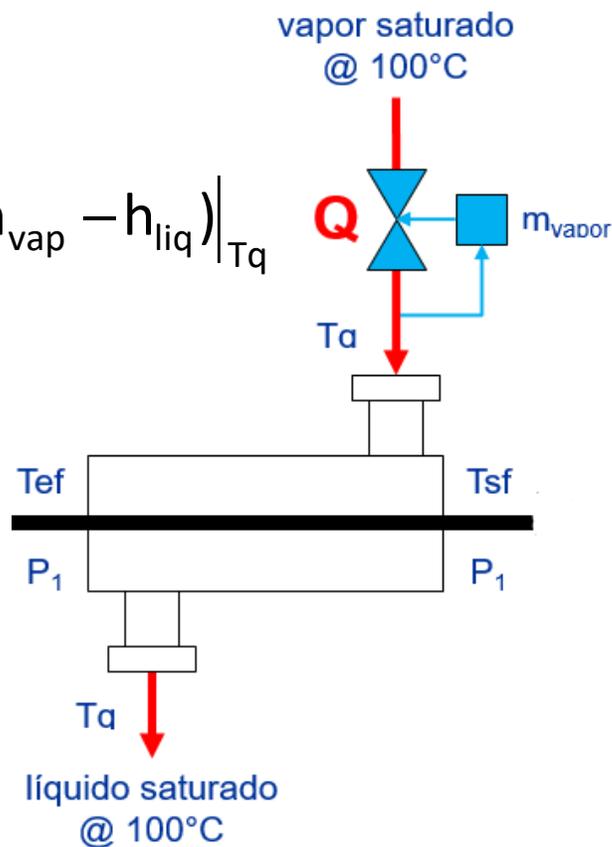
$$Q = UA \cdot \frac{[(Tq - T_{\text{sf}}) - (Tq - T_{\text{ef}})]}{\ln\left(\frac{Tq - T_{\text{sf}}}{Tq - T_{\text{ef}}}\right)}$$



$$(Tq - T_{\text{sf}}) = (Tq - T_{\text{ef}}) \cdot \exp\left(\frac{-UA}{m_{\text{óleo}} C_{p_{\text{óleo}}}}\right)$$

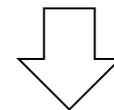
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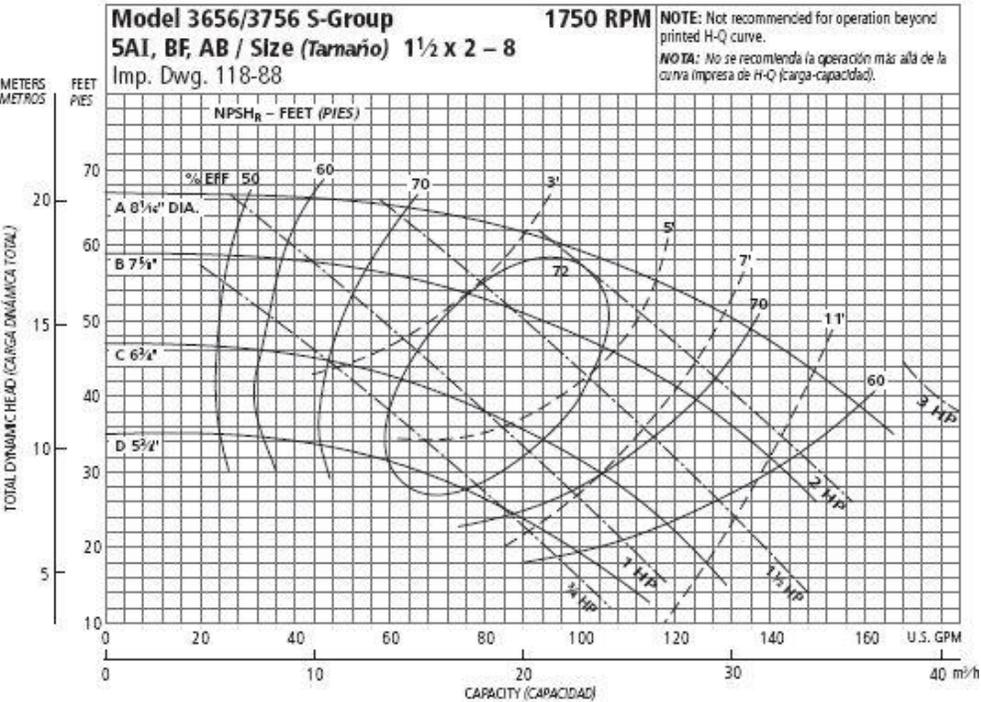
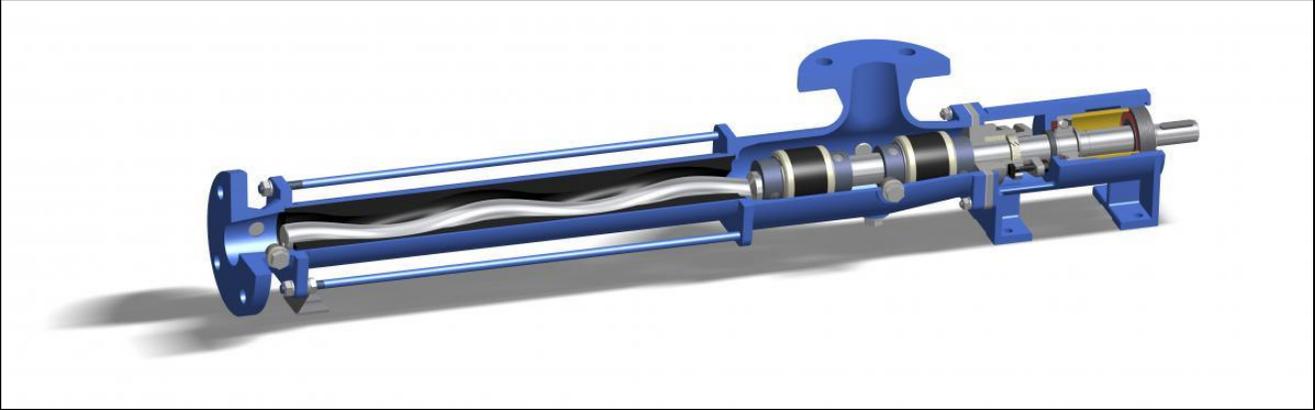
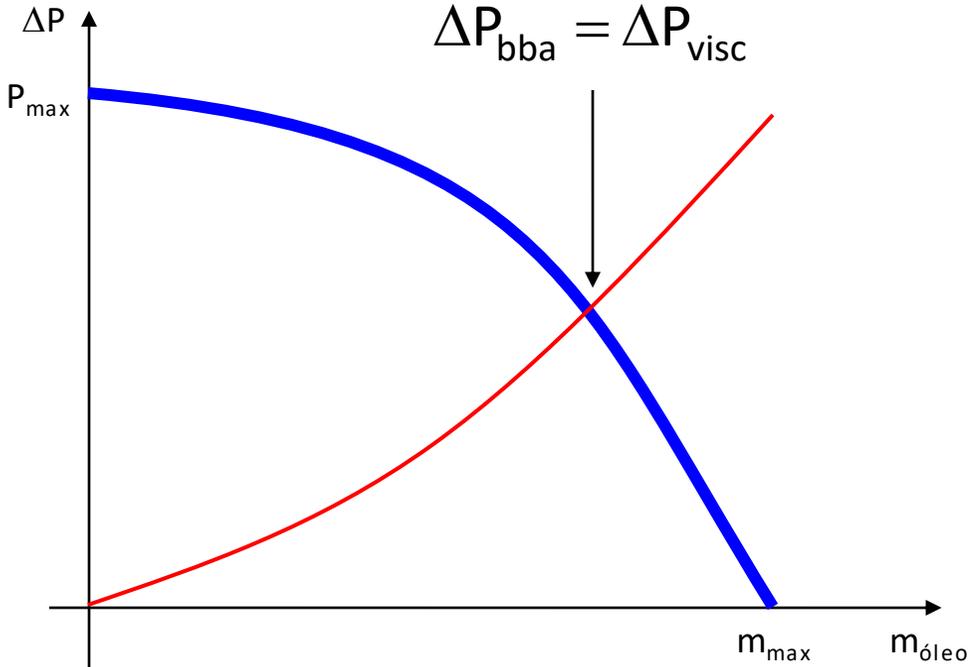
$$Q = UA \cdot \frac{[(Tq - T_{\text{sf}}) - (Tq - T_{\text{ef}})]}{\ln\left(\frac{Tq - T_{\text{sf}}}{Tq - T_{\text{ef}}}\right)}$$



$$(Tq - T_{\text{sf}}) = (Tq - T_{\text{ef}}) \cdot \exp\left(\frac{-UA}{m_{\text{óleo}} C_{p_{\text{óleo}}}}\right)$$

$$f_1 = (Tq - T_{\text{sf}}) - (Tq - T_{\text{ef}}) \cdot \exp\left(\frac{-UA}{m_{\text{óleo}} C_{p_{\text{óleo}}}}\right)$$

Exemplo: bombeio de óleo ultra viscoso...



Os parâmetros P_{max} , m_{max} e n podem ser obtidos das curvas fornecidas pelo fabricante...

$$\Delta P_{bba} = P_{max} \cdot \left[1 - \left(\frac{m_{\text{óleo}}}{m_{max}} \right)^n \right]$$

Exemplo: bombeio de óleo ultra viscoso...

$$f_2 = P_{\max} \cdot \left[1 - \left(\frac{m_{\text{óleo}}}{m_{\max}} \right)^n \right] - f(\text{Re}) \cdot 0,8106 \frac{L}{\rho D^5} \cdot m^2$$

$$\text{Re} = \frac{4 \cdot m_{\text{óleo}}}{\mu \pi D}$$

$$T = T_{\text{sf}}$$

$$\mu(T) = 6.7109 \cdot 10^{-6} \cdot T^4 - 2.9844 \cdot 10^{-3} \cdot T^3 + \dots$$

$$\dots + 5.0341 \cdot 10^{-1} \cdot T^2 - 4.0864 \cdot 10^{+1} \cdot T + 1.6546 \cdot 10^{+3}$$

$$f_1(m_{\text{óleo}}, T_{\text{sf}}) = (T_q - T_{\text{sf}}) - (T_q - T_{\text{ef}}) \cdot \exp\left(\frac{-UA}{m_{\text{óleo}} C_{p_{\text{óleo}}}}\right)$$

$$f_2(m_{\text{óleo}}, T_{\text{sf}}) = P_{\text{max}} \cdot \left[1 - \left(\frac{m_{\text{óleo}}}{m_{\text{max}}} \right)^n \right] - f(\text{Re}) \cdot 0,8106 \frac{L}{\rho D^5} \cdot m_{\text{óleo}}^2$$

$$\begin{bmatrix} m_{\text{óleo}} \\ T_{\text{sf}} \end{bmatrix}_{k+1} = \begin{bmatrix} m_{\text{óleo}} \\ T_{\text{sf}} \end{bmatrix}_k - [\text{Jac}]_k^{-1} \cdot \begin{bmatrix} f_1 \\ f_2 \end{bmatrix}_k$$

T1 Aquecimento de óleo para reduzir a potência de bombeio.xlsm - Excel

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Nova Janela Organizar Tudo Congelar Painéis Ocultar Reexibir

Dividir Exibir Lado a Lado Rolagem Sincronizada Redefinir Posição da Janela

Alterar Janelas Macros

A1 parâmetros

	A	B	C	D	E	F	G	H	I	J	K	L	M	N
1	parâmetros					xk			fk			móleo	Tsf	
2	Cp	4,19	kJ/kg/K		móleo	0,64796256	kg/s	f1	0	oC	f1	-36,0056364	-1	
3	ρ	998	kg/m3		Tsf	87,3154972	oC	f2	0,00E+00	Bar	f2	-235,518819	1,39722013	
4														
5	Tef	20	oC			xk			fk			1	2	
6	Tq	100	oC		móleo	0,64796256	kg/s	dmóleo	0	kg/s	1	-0,00488835	-0,003498624	
7	UA	5	kW/k		Tsf	87,3154972	oC	dTsf	0	oC	2	-0,8239919	0,1259702	
8														
9	Pmax	150	bar											
10	mmax	5	kg/s		Desempenho									
11	n	1,2	nd		μ	3,27914E-01	Pa.s							
12					Re	33,546	nd							
13	D	7,50E-02	m		f	1,908	nd	= 64/Re						
14	L	50000	m		P	137,082	bar							
15	e	1	mm		V	8,818	m/min							
16					Wbba	534,013	kW							
17	eps	0,01	any		TT	94,506	horas							
18														
19														

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Pronto

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Tutorial: Bombeio de Óleo

https://www.youtube.com/watch?v=6SIqQKqvMzs&list=PLmho8Rrd60c_duh02aThHOAHp-x7fmA-&tt=1002s

Sistema de pré-aquecimento de óleo "baiano"...

Démarche: gastar Q para economizar W (exergia)

vapor saturado

condensado

$L = 50 \text{ km}$
 $D = 50 \text{ cm}$

Viscosidade (Pa.s)

Temperatura (°C)

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