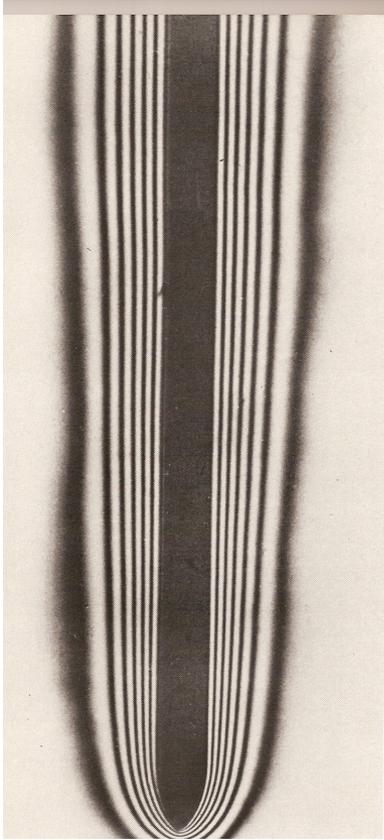


Mais que faire pour des écoulements avec deux échelles spatiales ?

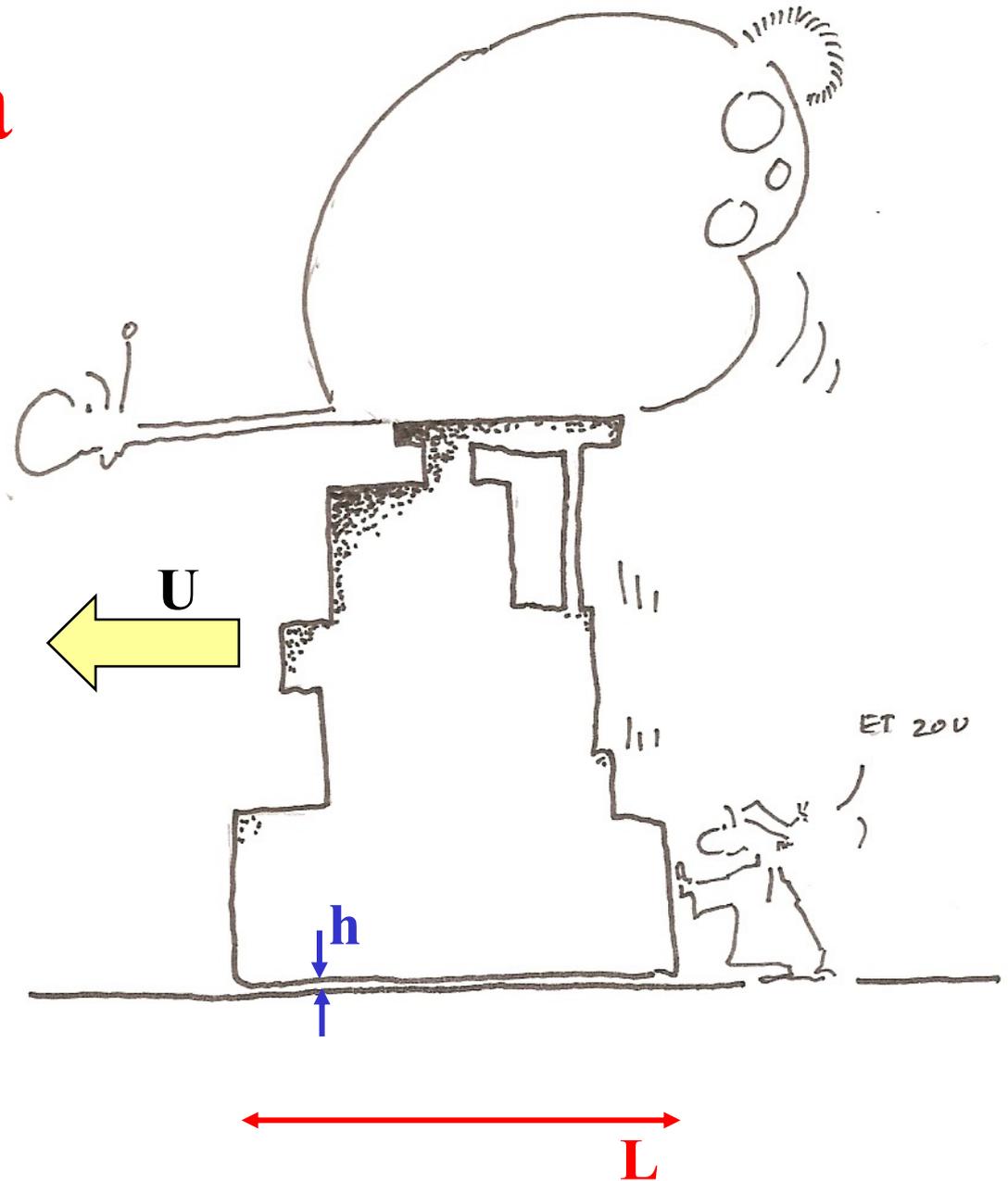


*Convection naturelle
le long d'une plaque
verticale : écoulement
laminaire permanent*



*Lubrification et convoyage
hydraulique : butée Michell*

Théorie de la lubrification

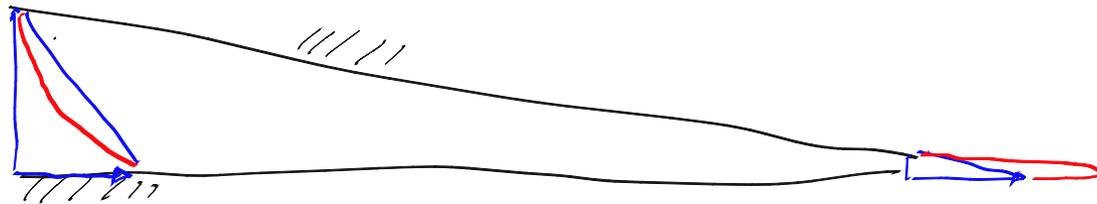
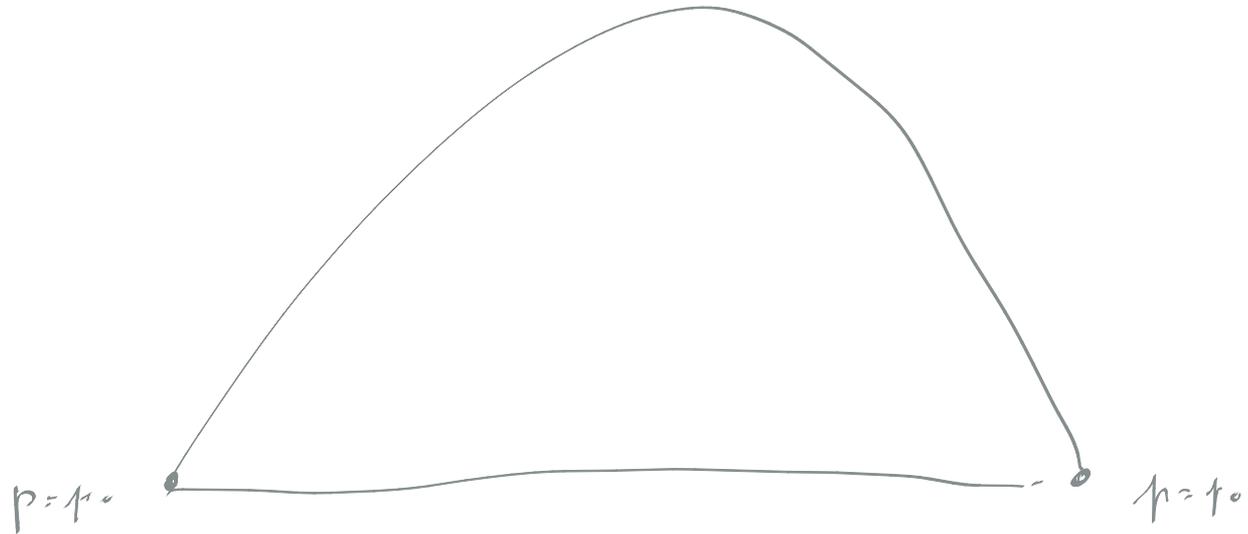


Convoyage hydraulique de charges très importantes :

- turbines hydroélectriques
- applications marines
- butées hydrauliques

Intuitivement...

ÉCOULEMENT
INCOMPRESSIBLE
2D
STATIONNAIRE
PAS DE GRAVITE

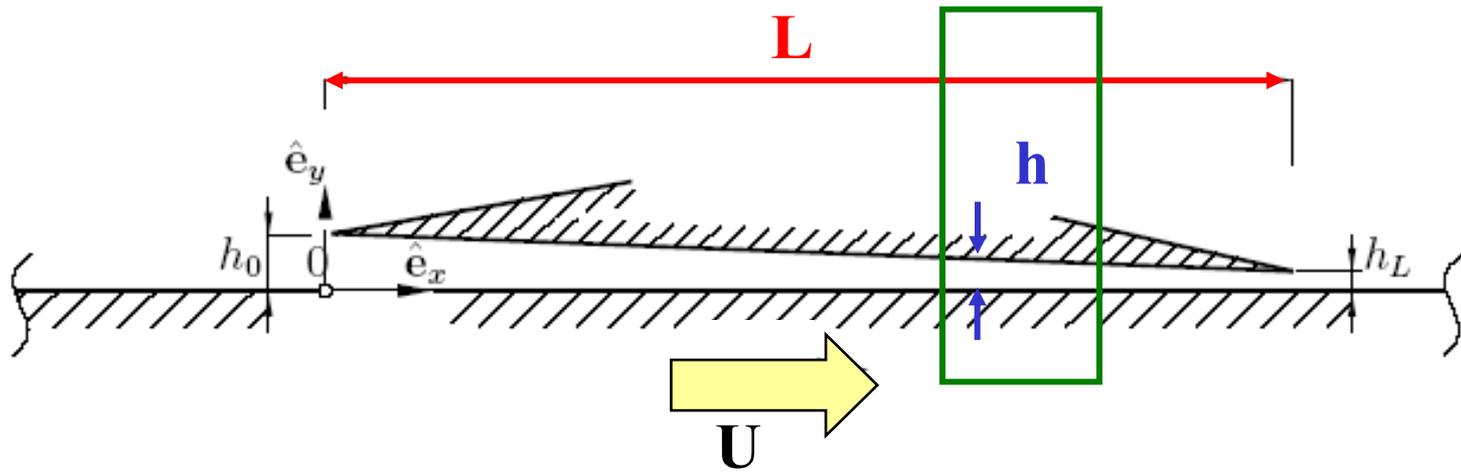
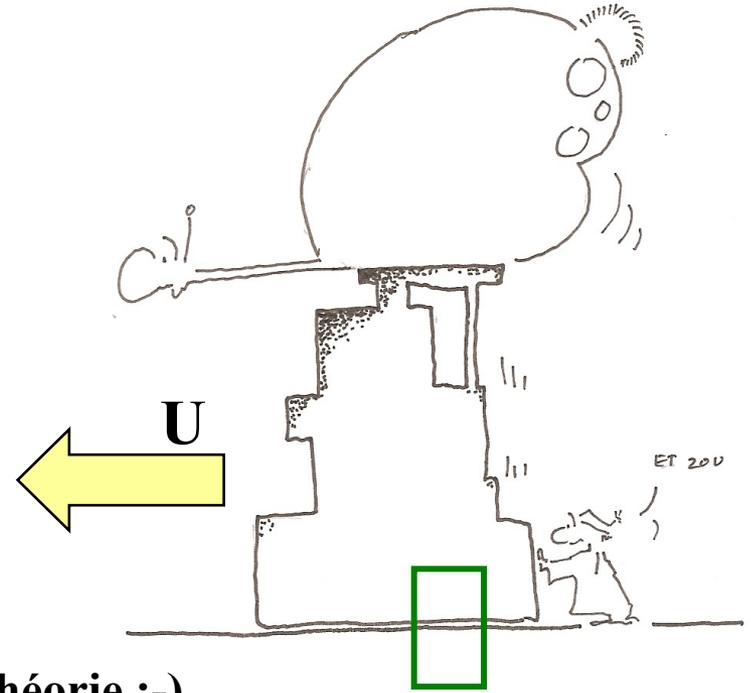


Théorie de la lubrification

$$h \ll L$$

Hypothèse géométrique de base

Valable dans la zone centrale uniquement en théorie :-)



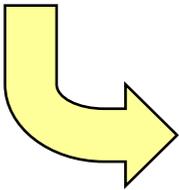
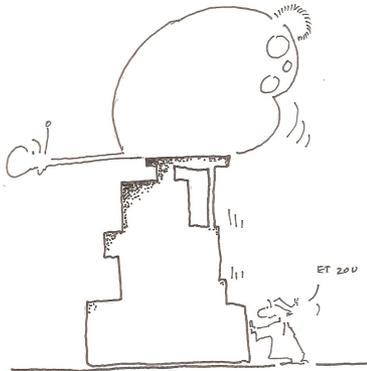
$$h \ll L$$

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0$$
$$\rho u \frac{\partial u}{\partial x} + \rho v \frac{\partial u}{\partial y} = -\frac{\partial p}{\partial x} + \mu \frac{\partial^2 u}{\partial x^2} + \mu \frac{\partial^2 u}{\partial y^2}$$
$$\rho u \frac{\partial v}{\partial x} + \rho v \frac{\partial v}{\partial y} = -\frac{\partial p}{\partial y} + \mu \frac{\partial^2 v}{\partial x^2} + \mu \frac{\partial^2 v}{\partial y^2}$$

Longueur horizontale caractéristique : L

Longueur verticale caractéristique : h

Vitesse horizontale caractéristique : U



**Comment choisir une
vitesse verticale
caractéristique ?**

Définir une vitesse
verticale caractéristique...

$$h \ll L$$

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

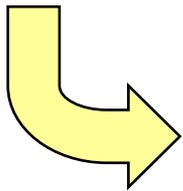


$$\frac{U}{L} = \frac{V}{h}$$

$$V \approx \frac{h}{L} U \ll U$$

$$\boxed{\mathcal{O}(U/L) \frac{\partial u}{\partial x}} + \boxed{\mathcal{O}(V/h) \frac{\partial v}{\partial y}} = 0$$

Il ne faut pas définir de vitesse caractéristique verticale !



$$V = \frac{Uh}{L} \ll U$$

Simplifications...

$$\begin{aligned}
 & \cancel{\rho U \frac{\partial U}{\partial x}} + \cancel{\rho \nu \frac{\partial U}{\partial y}} = - \frac{\partial p}{\partial x} + \cancel{\mu \frac{\partial^2 U}{\partial x^2}} + \mu \frac{\partial^2 U}{\partial y^2} \\
 & \underbrace{\cancel{\rho U^2/L}}_{\partial(\rho U^2/L)} + \underbrace{\cancel{\rho \nu U/h}}_{\partial(\rho \nu U/h)} = - \frac{\partial p}{\partial x} + \underbrace{\cancel{\mu \frac{\partial^2 U}{\partial x^2}}}_{\partial(\mu \frac{U}{L^2})} + \underbrace{\mu \frac{\partial^2 U}{\partial y^2}}_{\partial(\mu \frac{U}{h^2})} \\
 & \underbrace{\rho \frac{U h}{L} \frac{U}{h}}_{\partial(\rho U^2/L)} = - \frac{\partial p}{\partial x} + \mu \frac{\partial^2 U}{\partial y^2}
 \end{aligned}$$

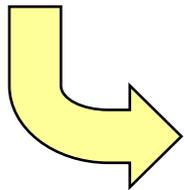
$$\frac{\text{INERTIE}}{\text{VISQUEUX}} = \frac{\rho U^2/L}{\mu U/h^2} = \underbrace{\frac{\rho U L}{\mu}}_{Re} \underbrace{\frac{h^2}{L^2}}_{\ll 1} \ll 1$$

$\{$ EN SUPPOSANT
 QUE Re RESTE
 ACCEPTABLE

Quand peut-on négliger les termes d'inertie ?

$$\begin{array}{c} \mathcal{O}(\rho U^2/L) \\ \boxed{\rho u \frac{\partial u}{\partial x}} \end{array} + \begin{array}{c} \mathcal{O}(\rho U^2/L) \\ \boxed{\rho v \frac{\partial u}{\partial y}} \end{array} = -\frac{\partial p}{\partial x} + \begin{array}{c} \boxed{\mu \frac{\partial^2 u}{\partial x^2}} \end{array} + \begin{array}{c} \boxed{\mu \frac{\partial^2 u}{\partial y^2}} \\ \mathcal{O}(\mu U/h^2) \end{array}$$

$\mathcal{O}(\rho VU/h) \qquad \mathcal{O}(\mu U/L^2) \ll \mathcal{O}(\mu U/h^2)$

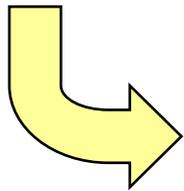


*Hypothèse de lubrification :
Écoulements rampants*

$$\frac{\boxed{\text{Forces d'inertie}}}{\boxed{\text{Forces visqueuses}}} = \frac{\rho U^2/L}{\mu U/h^2} = \underbrace{\frac{\rho U L}{\mu}}_{Re_L} \frac{h^2}{L^2} \ll 1$$

Et l'autre équation ?

$$\begin{array}{c}
 \mathcal{O}(\rho U^2 h/L^2) \quad \mathcal{O}(\rho U^2 h/L^2) \\
 \boxed{\cancel{\rho u \frac{\partial v}{\partial x}}} + \boxed{\cancel{\rho v \frac{\partial v}{\partial y}}} = -\frac{\partial p}{\partial y} + \boxed{\cancel{\mu \frac{\partial^2 v}{\partial x^2}}} + \boxed{\mu \frac{\partial^2 v}{\partial y^2}} \\
 \mathcal{O}(\mu U h/L^3) \ll \mathcal{O}(\mu U/Lh)
 \end{array}$$



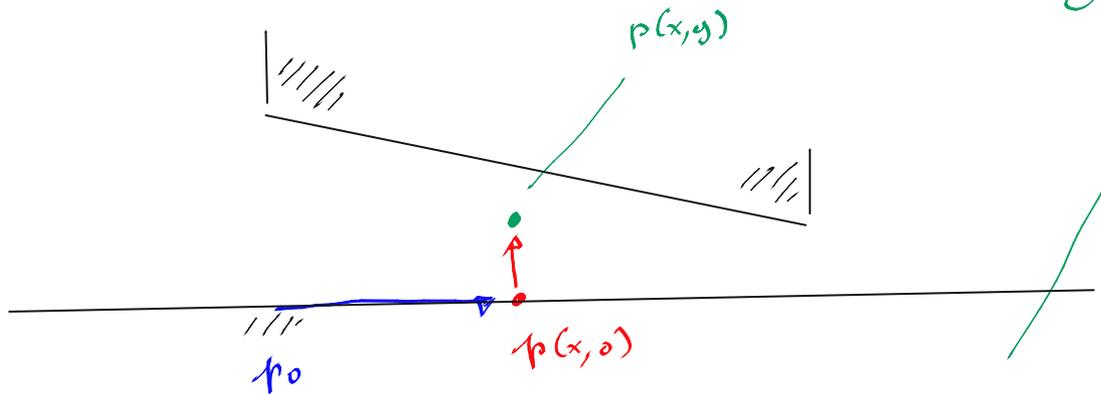
*On obtient la
même condition...*

$$\frac{\boxed{\text{Forces d'inertie}}}{\boxed{\text{Forces visqueuses}}} = \frac{\rho U^2 h/L^2}{\mu U/Lh} = \underbrace{\frac{\rho U L}{\mu}}_{Re_L} \frac{h^2}{L^2} \ll 1$$

Et la pression...

$$\cancel{h} \mu \frac{U \cancel{h}}{L} \cancel{h^2}$$

$$\partial \left(h \frac{\mu U}{h^2} \right) = \partial \left(\frac{\mu U}{L} \right)$$



$$p(x,y) - p_0 = \boxed{p(x,0) - p_0} + y \frac{\partial p}{\partial y} \Big|_{(x,0)} + y^2 \dots$$

C'EST PETIT
CAR $y^2 \ll y \ll 1$

$$\partial(L) \sim \frac{\partial p}{\partial x} \sim \partial \left(\frac{\mu U}{L} \right) \sim \partial \left(\frac{\mu U L}{h^2} \right)$$

$$p(x, y) - p_0 = \boxed{p(x, 0) - p_0} + \cancel{y \frac{\partial p}{\partial y} \Big|_{(x, 0)}} + y^2 \dots$$

$\partial(\frac{\mu U}{L})$

C'EST PETIT
CAR $y^2 \ll y \ll 1$

$\partial(L) \sim x \frac{\partial p}{\partial x}$

$\partial(\frac{\mu U}{h^2})$

$\partial(\frac{\mu U}{h^2})$

$$\frac{\mu U}{L} \frac{h^2}{L} \ll \frac{\mu U L}{h^2} \frac{h^2}{L}$$

$$\frac{h^2}{L^2} \mu U \ll \mu U$$

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

$$0 = -\frac{dp}{dx} + \mu \frac{\partial^2 u}{\partial y^2}$$

Théorie de la lubrification

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

$\mathcal{O}(\mu U/Lh)$

Et la pression ?

$$p(x, y) - p_0 = \boxed{p(x, 0) - p_0} + \boxed{y \cancel{\frac{\partial p}{\partial y}} \Big|_{y=0}}$$

$\mathcal{O}(\mu UL/h^2) \gg \mathcal{O}(\mu UL/L^2)$

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

$\mathcal{O}(\mu U/h^2)$

Equations de Reynolds (1889)

Théorie de la
lubrification

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

$$0 = -\frac{dp}{dx} + \mu \frac{\partial^2 u}{\partial y^2}$$

Film fluide mince

$$h \ll L$$

*Hypothèse de lubrification :
Écoulements rampants*

$$\underbrace{\frac{\rho U L}{\mu}}_{Re_L} \frac{h^2}{L^2} \ll 1$$

Est-ce que l'hypothèse de lubrification est réaliste ?

$$\begin{aligned}L &= 10 \text{ cm} \\h &= 0.5 \text{ mm} \\U &= 1 \text{ m/s}\end{aligned}$$

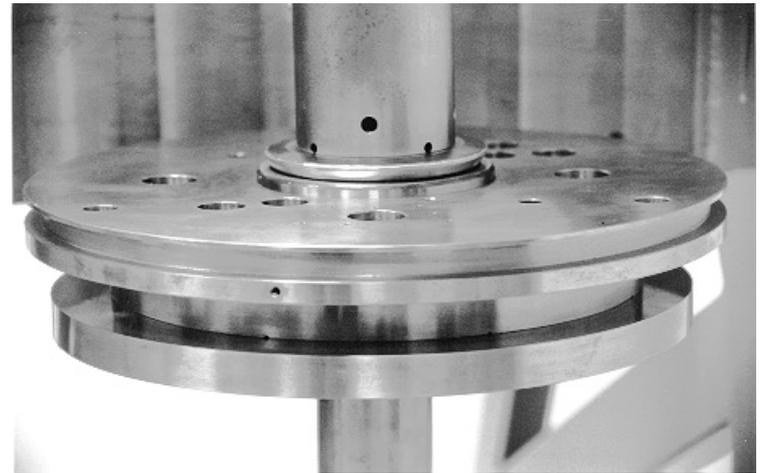
$$\begin{aligned}\rho &= 900 \text{ kg/m}^3 \\ \mu &= 60 \cdot 10^{-3} \text{ Ns/m}^2\end{aligned}$$

Huile SAE50 à 60 degrés

$$\frac{\rho U L}{\mu} \frac{h^2}{L^2} \ll 1$$

0.0375

Re_L



Huile SAE 50

C'est quoi ?

Transport maritime



Marine LCX

Une huile formulée spécialement pour la lubrification des gros moteurs diesel marins à crosse. Elle lubrifie les cylindres grâce à un indice de basicité très élevé de 70 et un grade SAE* 50.

Grades offerts :

SAE 50

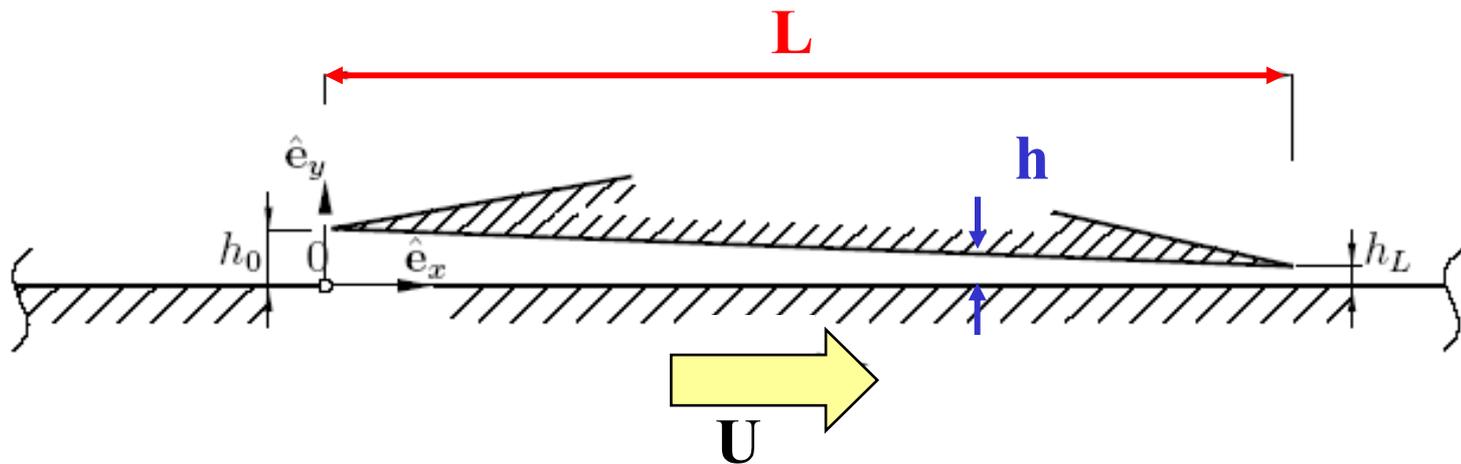
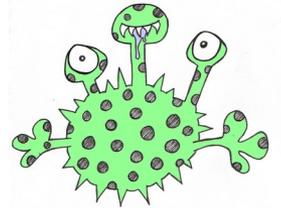
[Fiche technique](#)

[Fiche signalétique](#)

$$\left\{ \begin{array}{l} \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \\ -\frac{dp}{dx} + \mu \frac{\partial^2 u}{\partial y^2} = 0 \end{array} \right.$$

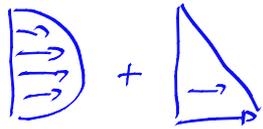
-i- calcul
de $u(x,y)$

$$u(x,y) = -\frac{dp}{dx} \frac{h^2}{2\mu} \frac{y}{h} \left(1 - \frac{y}{h}\right) + U \left(1 - \frac{y}{h}\right)$$



Calcul du profil de vitesse...

$$\frac{dp}{dx} = \mu \frac{\partial^2 u}{\partial y^2}$$



$$u(x, y) = - \underbrace{\frac{dp}{dx}}_{\text{red bracket}} \underbrace{\frac{h^2}{2\mu}}_{\text{red bracket}} \left(1 - \frac{y}{h}\right) \frac{y}{h} + U \left(1 - \frac{y}{h}\right)$$


The equation is enclosed in a blue rectangular box. A red line connects the underbraced terms to the dimensional analysis below.

$$\left[\frac{\cancel{N}}{m^3} \right] \left[\frac{\cancel{m^2}}{\cancel{N_s}} m^2 \right]$$

$$\underbrace{\hspace{10em}}_{\left[\frac{m}{s} \right]}$$

$$\frac{\tau}{\mu} = 2 \frac{du}{dy}$$

$$\left[\frac{N}{m^2} \right] \quad \left[\frac{1}{s} \right]$$

Calcul du profil de pression...

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

$$0 = \int_0^h \frac{\partial u}{\partial x} dy + \int_0^h \frac{\partial v}{\partial y} dy$$

$$= \frac{d}{dx} \underbrace{\int_0^h u dy}_{Q(x)} + \underbrace{\left[v \right]_0^h}_{=0}$$

$$u(x, y) = - \frac{dp}{dx} \frac{h^2}{2\mu} \left(1 - \frac{y}{h}\right) \frac{y}{h} + U \left(1 - \frac{y}{h}\right)$$



$$0 = \frac{d}{dx} \left[- \frac{dp}{dx}(x) \frac{h^2(x)}{2\mu} \int_0^{h(x)} \underbrace{\left(1 - \frac{y}{h}\right) \frac{y}{h}}_{\frac{h(x)}{6}} dy + U \frac{h}{2} \right]$$

$$0 = \frac{d}{dx} \left[-\frac{dp}{dx}(x) \frac{h^2(x)}{2\mu} \int_0^{h(x)} \underbrace{\left(1 - \frac{y}{h}\right) \frac{y}{h}}_{\frac{h(x)}{6}} dy + U \frac{h}{2} \right]$$

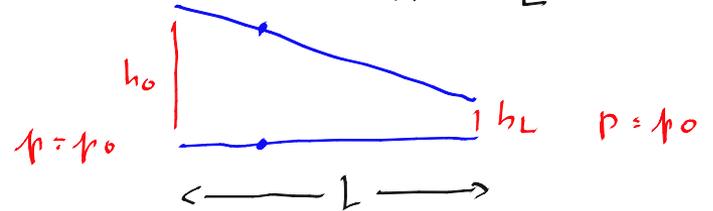
$$0 = \frac{d}{dx} \left[-\frac{dp}{dx} \frac{h^3}{12\mu} + \frac{Uh}{2} \right]$$

$$\frac{d}{dx} \left[\frac{dp}{dx}(x) h^3(x) \right] = 6\mu U \frac{dh}{dx}$$

$$\left(\frac{dh}{dx}\right)^2 \frac{d}{dh} \left[\frac{dp}{dh} h^3 \right] = 6\mu U \frac{dh}{dx}$$

$$-\frac{d}{dh} \left[\frac{dp}{dh} h^3 \right] = \underbrace{\frac{6\mu U L}{h_0 - h_L}}_C$$

$$\frac{dh}{dx} = \frac{h_L - h_0}{L}$$



$$-\frac{dp}{dh} h^3 = C [h + A]$$

$$-\frac{dp}{dh} = C \left[\frac{1}{h^2} + \frac{A}{h^3} \right]$$

$$p(h) = C \left[\frac{1}{h} + \frac{A}{2h^2} + B \right]$$

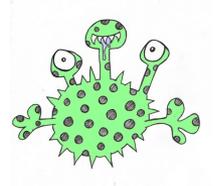
$$\begin{cases} -\frac{dp}{dx} + \mu \frac{\partial^2 u}{\partial y^2} = 0 \\ \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \end{cases}$$

-ii- calcul
de $p(x)$

$$0 = \int_0^h \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} dy$$

$$0 = \frac{d}{dx} \overbrace{\int_0^h u(x, y) dy}^{Q(x)} + \cancel{\left[v(x, y) \right]_0^h}$$

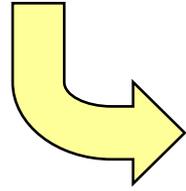
En utilisant l'expression de $u(x, y)$



Equation classique de
Reynolds (1889)

$$0 = \frac{d}{dx} \left(-\frac{dp}{dx} \frac{h^3}{12\mu} + \frac{Uh}{2} \right)$$

$$0 = \frac{d}{dx} \left(-\frac{dp}{dx} \frac{h^3}{12\mu} + \frac{Uh}{2} \right)$$



$$\frac{d}{dx} \left(h^3(x) \frac{dp}{dx}(x) \right) = 6\mu U \frac{dh}{dx}$$

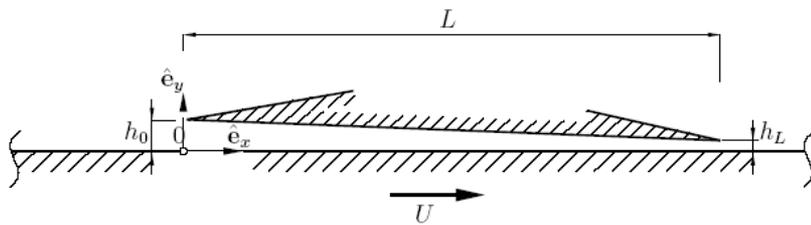
$$-\frac{d}{dh} \left(h^3 \frac{dp}{dh}(h) \right) = \frac{6\mu UL}{h_0 - h_L}$$

$$-h^3 \frac{dp}{dh}(h) = \frac{6\mu UL}{h_0 - h_L} (h + A)$$

$$-\frac{dp}{dh}(h) = \frac{6\mu UL}{h_0 - h_L} \left(\frac{1}{h^2} + \frac{A}{h^3} \right)$$

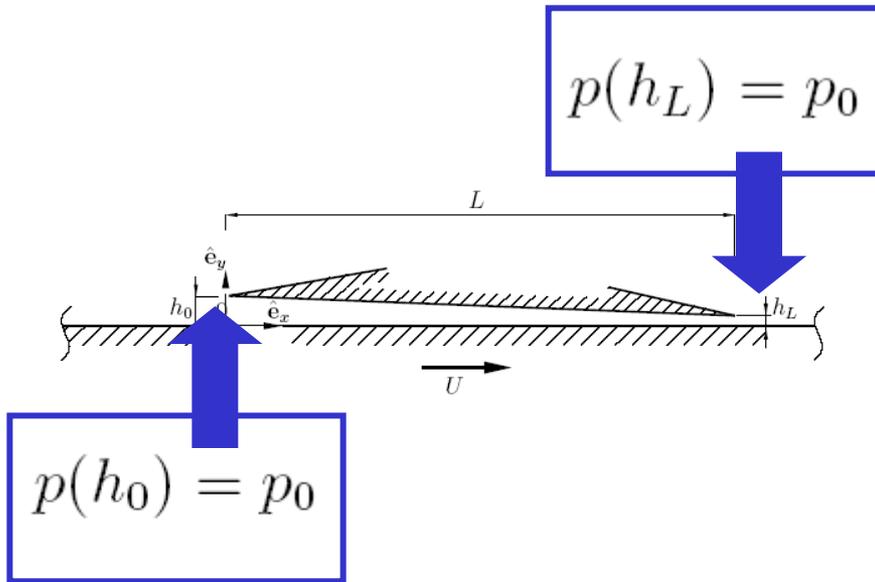
$$p(h) = \frac{6\mu UL}{h_0 - h_L} \left(B + \frac{1}{h} + \frac{A}{2h^2} \right)$$

Palier plat



$$\frac{x}{L} = \frac{h_0 - h(x)}{h_0 - h_L}$$

$$\frac{dh}{dx} = -\frac{h_0 - h_L}{L}$$



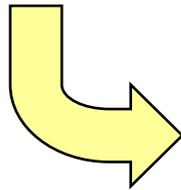
Deux conditions
aux limites

Deux
constantes

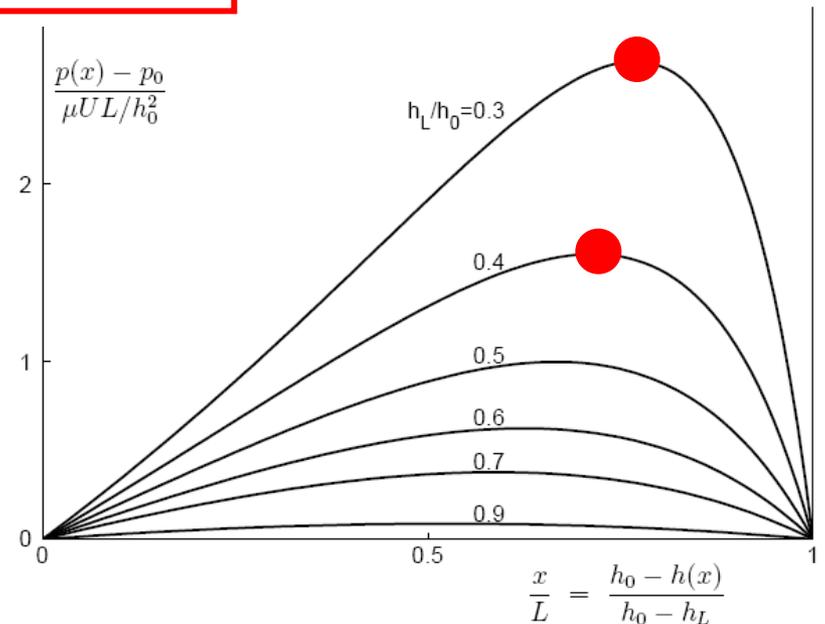
$$p(h) = \frac{6\mu UL}{h_0 - h_L} \left(\boxed{B} + \frac{1}{h} + \frac{\boxed{A}}{2h^2} \right)$$

$$p(h) - p_0 = \frac{6\mu UL(h_0 - h)(h - h_L)}{(h_0^2 - h_L^2)h^2}$$

Où la
pression
est-elle
maximale ?



$$h = \frac{2 h_0 h_L}{(h_0 + h_L)}$$

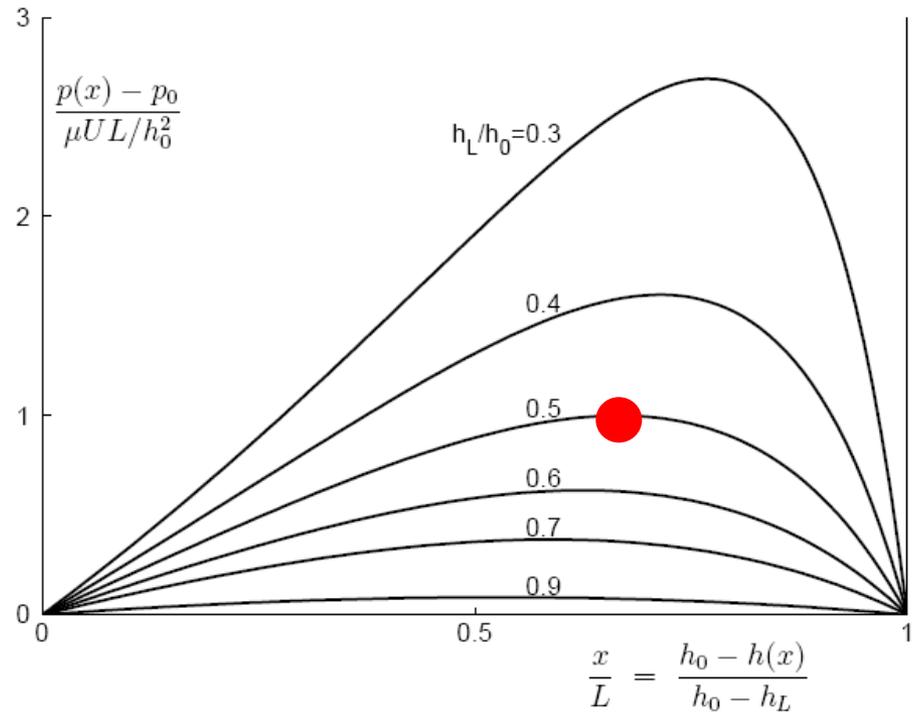


Cette pression
peut être
énorme !

$$\begin{aligned}L &= 10 \text{ cm} \\h_0 &= 0.1 \text{ mm} \\h_L &= 0.05 \text{ mm} \\U &= 10 \text{ m/s}\end{aligned}$$

$$\begin{aligned}\rho &= 900 \text{ kg/m}^3 \\ \mu &= 0.1 \text{ Ns/m}^2\end{aligned}$$

Huile SAE50 à 50 degrés

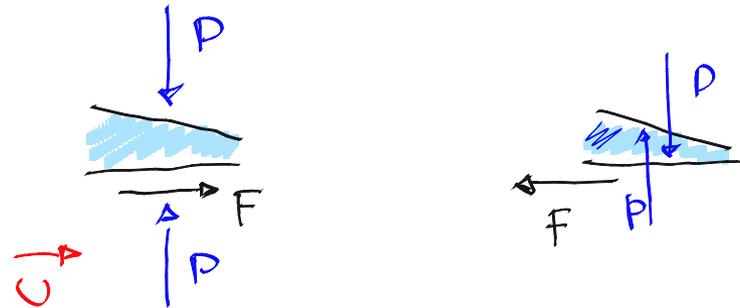
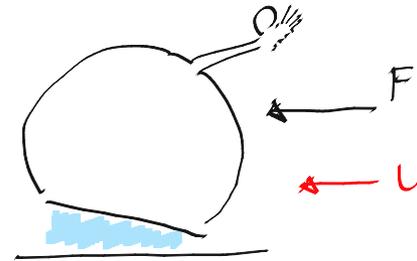


$$p_{\max} - p_0 = \frac{3 \mu U L (h_0 - h_L)}{2 h_0 h_L (h_0 + h_L)}$$

10^7 Pascal

Charge utile

$$P_z = \int_0^L p(x) - p_0 \, dy$$



$$F = -\mu \int_0^L \frac{\partial v}{\partial y} \, dx$$

Force de poussée

Puissance
dissipée

FU

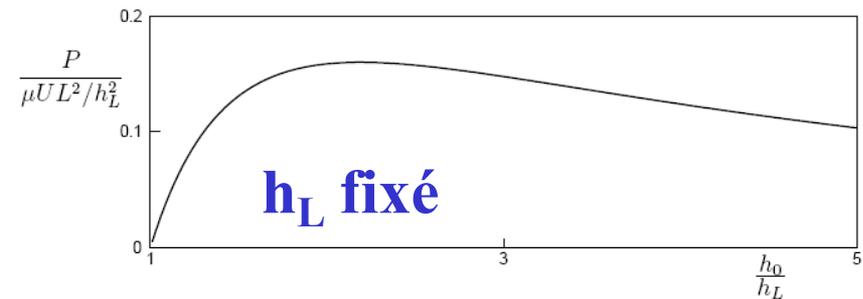
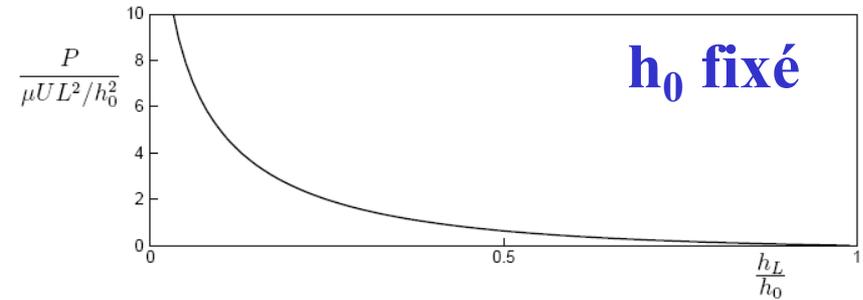
Charge utile

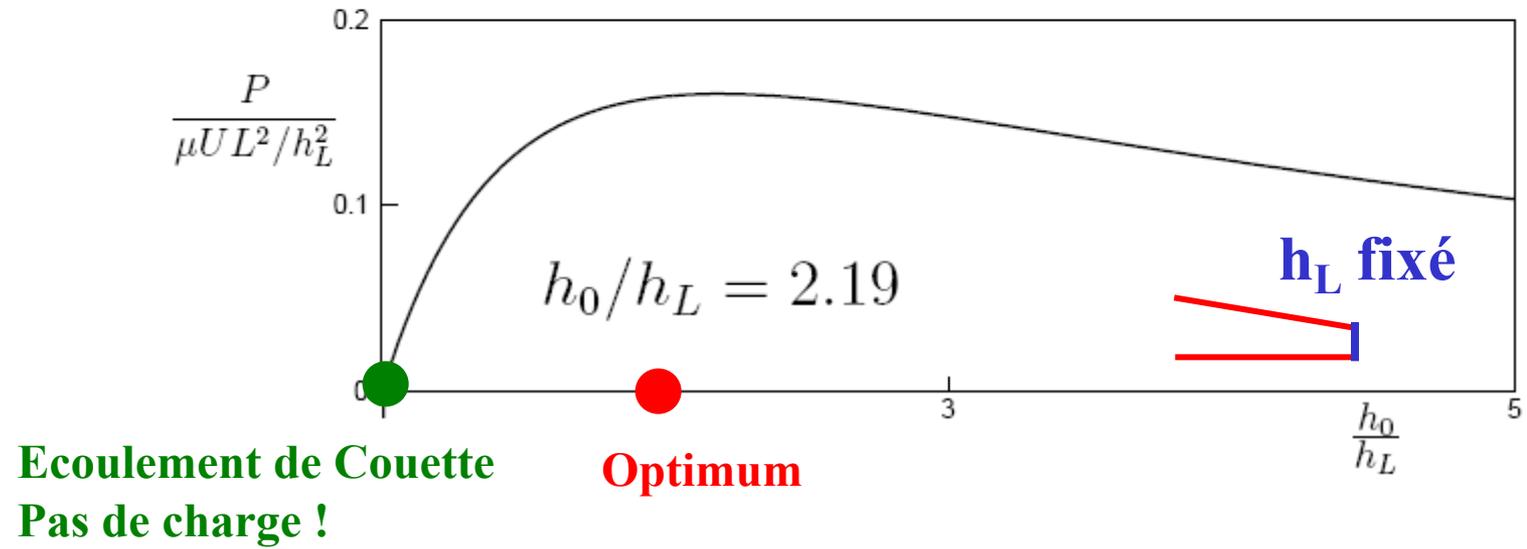
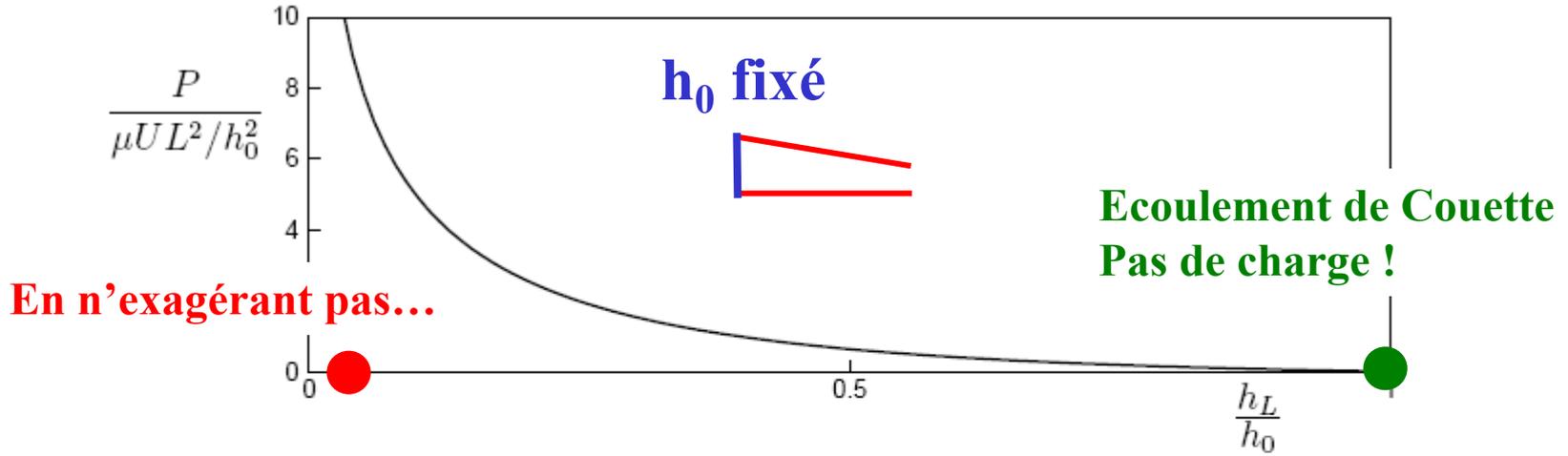
$$P = \int_0^L (p(x) - p_0) dx$$

$$= -\frac{L}{(h_0 - h_L)} \int_{h_0}^{h_L} (p(h) - p_0) dh$$

$$= -\frac{L}{(h_0 - h_L)} \frac{6 \mu U L}{(h_0^2 - h_L^2)} \int_{h_0}^{h_L} \left[(h_0 + h_L) \frac{1}{h} - \frac{h_0 h_L}{h^2} - 1 \right] dh$$

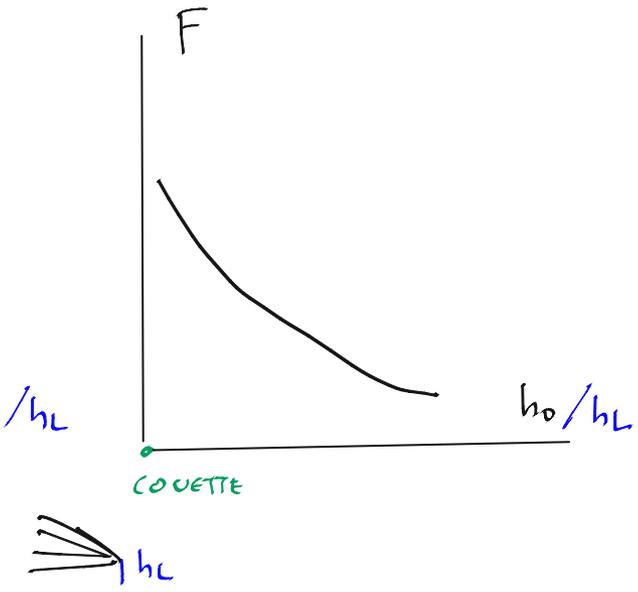
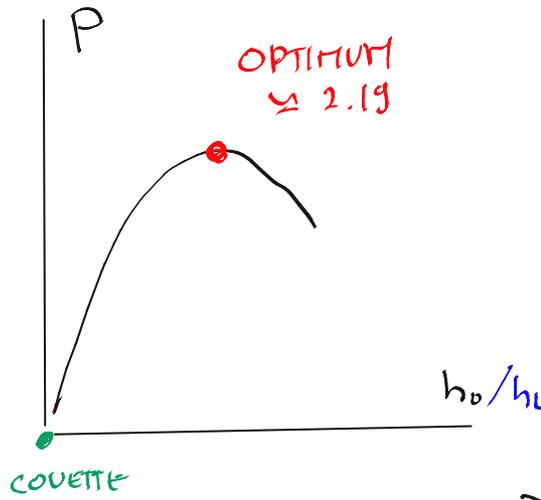
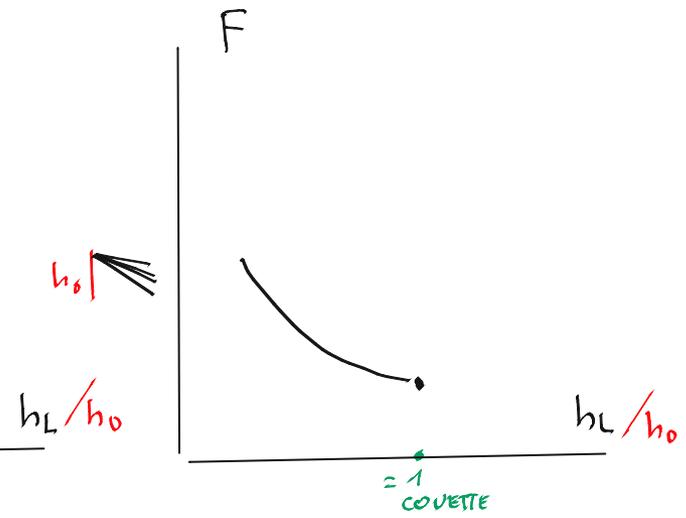
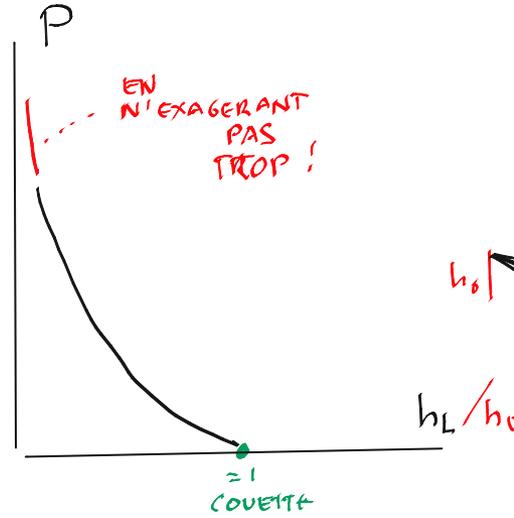
$$= -6 \mu U L^2 \left[\frac{1}{(h_0 - h_L)^2} \log \left(\frac{h_L}{h_0} \right) + \frac{2}{(h_0^2 - h_L^2)} \right]$$



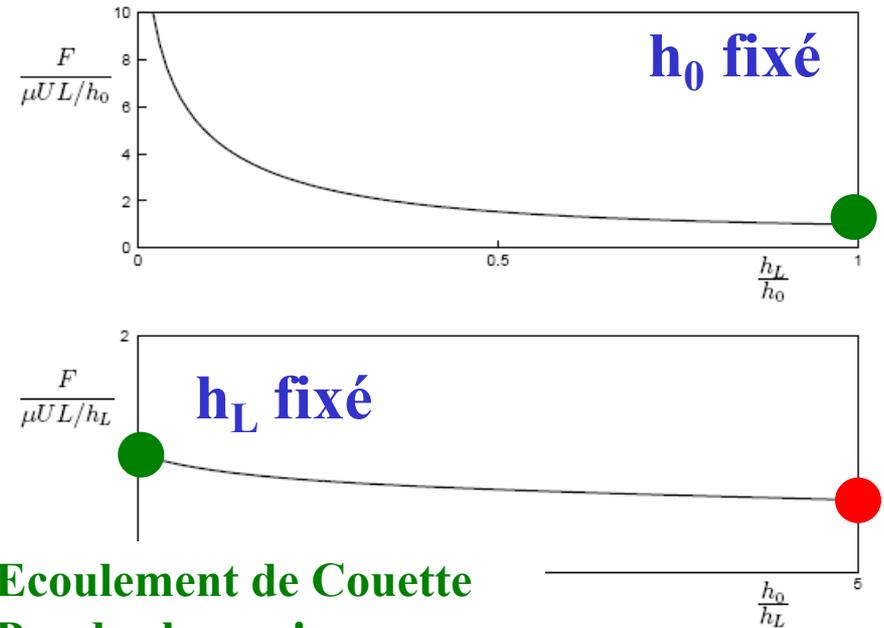


Rapport optimal...

Quatre petits graphes !



Force exercée par le fluide sur la partie mobile



**La force diminue de
façon monotone lorsque
le rapport augmente...**

$$\begin{aligned}
 F &= - \int_0^L \mu \left. \frac{\partial u}{\partial y} \right|_{y=0} dx \\
 &= \frac{\mu U L}{(h_0 - h_L)} \int_{h_0}^{h_L} \left[\frac{6}{h^2} \frac{h_0 h_L}{(h_0 + h_L)} - \frac{4}{h} \right] dh \\
 &= -\mu U L \left[\frac{6}{(h_0 + h_L)} + \frac{4}{(h_0 - h_L)} \log \left(\frac{h_L}{h_0} \right) \right]
 \end{aligned}$$

La puissance consommée est dissipée...

$$F U = -\frac{\mu U^2 L}{h_0} \left[\frac{6}{(1 + h_L/h_0)} + \frac{4}{(1 - h_L/h_0)} \log \left(\frac{h_L}{h_0} \right) \right]$$

Embêtant...

S'assurer que l'huile est bien refroidie car la viscosité (et donc la charge utile) décroît rapidement avec la température...

...en chaleur !

A propos de la viscosité de notre huile SAE 50

Transport maritime



Marine LCX

Une huile formulée spécialement pour la lubrification des gros moteurs diesel marins à crosse. Elle lubrifie les cylindres grâce à un indice de basicité très élevé de 70 et un grade SAE* 50.

Grades offerts :
SAE 50

[Fiche technique](#)
[Fiche signalét](#)

$$T = 20^{\circ}C$$

$$T = 40^{\circ}C$$

$$T = 50^{\circ}C$$

$$T = 60^{\circ}C$$

$$T = 80^{\circ}C$$

$$T = 100^{\circ}C$$

$$\mu = 1.100 \text{ Ns/m}^2$$

$$\mu = 0.210 \text{ Ns/m}^2$$

$$\mu = 0.100 \text{ Ns/m}^2$$

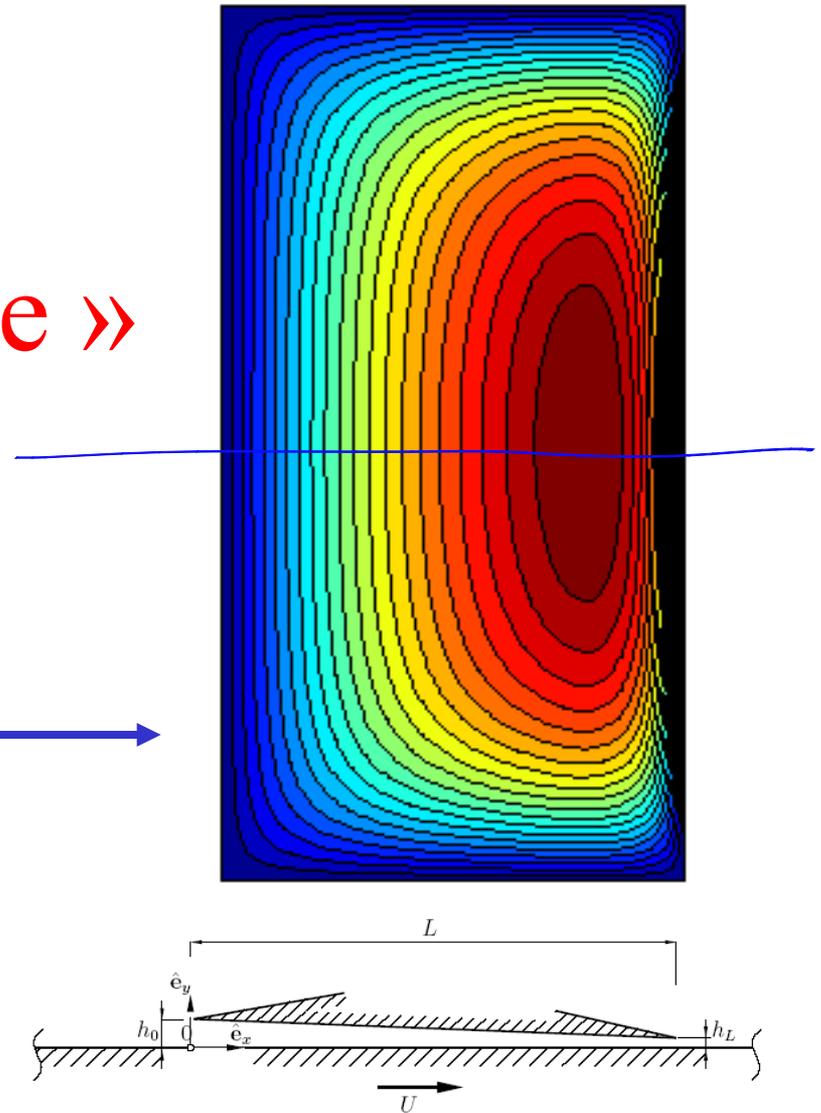
$$\mu = 0.060 \text{ Ns/m}^2$$

$$\mu = 0.025 \text{ Ns/m}^2$$

$$\mu = 0.013 \text{ Ns/m}^2$$

Analyse « tridimensionnelle » du palier plat

pression sous un palier
dont la largeur vaut le
double de la longueur



Lubrification 2D $\frac{1}{2}$

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

$$\frac{\partial p}{\partial x} = \mu \frac{\partial^2 u}{\partial z^2}$$

$$\frac{\partial p}{\partial y} = \mu \frac{\partial^2 v}{\partial z^2}$$

$$\frac{\partial p}{\partial z} = 0$$

Film fluide mince

$$h \ll L$$

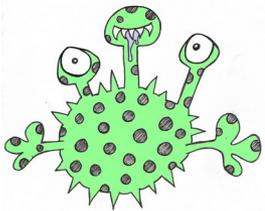
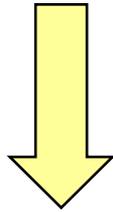
*Hypothèse de lubrification :
Écoulements rampants*

$$\underbrace{\frac{\rho U L}{\mu}}_{Re_L} \frac{h^2}{L^2} \ll 1$$

**Théorie de la
lubrification**

$$\left\{ \begin{array}{l} \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \\ -\frac{\partial p}{\partial x} + \mu \frac{\partial^2 u}{\partial z^2} = 0 \\ -\frac{\partial p}{\partial y} + \mu \frac{\partial^2 v}{\partial z^2} = 0 \end{array} \right.$$

-i- calcul
de $u(x,y,z)$
et de $v(x,y,z)$



$$u(x, y, z) = -\frac{\partial p}{\partial x} \frac{h^2}{2\mu} \frac{z}{h} \left(1 - \frac{z}{h}\right) + U \left(1 - \frac{z}{h}\right)$$

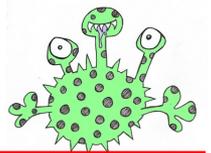
$$v(x, y, z) = -\frac{\partial p}{\partial y} \frac{h^2}{2\mu} \frac{z}{h} \left(1 - \frac{z}{h}\right)$$

-ii- calcul
de $p(x,y)$

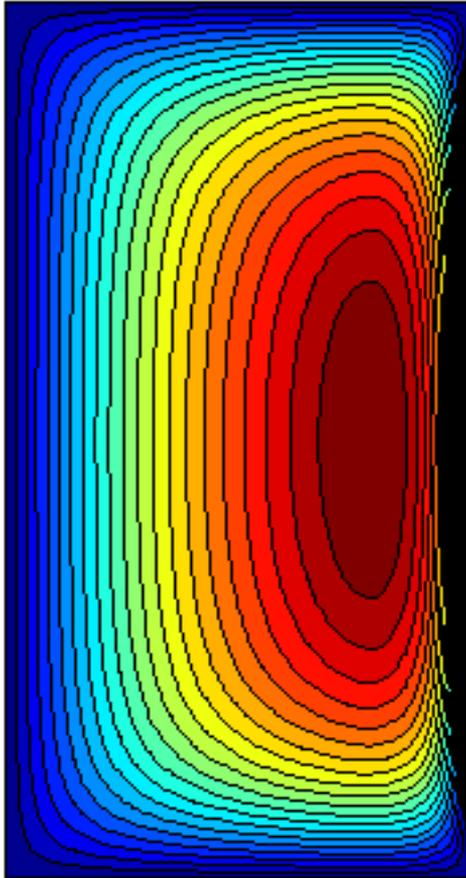
$$\begin{cases} -\frac{\partial p}{\partial x} + \mu \frac{\partial^2 u}{\partial z^2} = 0 \\ -\frac{\partial p}{\partial y} + \mu \frac{\partial^2 v}{\partial z^2} = 0 \\ \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0 \end{cases}$$

$$\int_0^h \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} dz = 0$$

$$\frac{\partial}{\partial x} \int_0^h u(x,y,z) dz + \frac{\partial}{\partial y} \int_0^h v(x,y,z) dz + \left[\cancel{w(x,y,z)} \right]_0^h = 0$$



$$\frac{\partial}{\partial x} \left(h^3 \frac{\partial p}{\partial x} \right) + \frac{\partial}{\partial y} \left(h^3 \frac{\partial p}{\partial y} \right) = 6\mu U \frac{dh}{dx}$$



-iiii- calcul
numérique par
différences finies
de $p(x,y)$

$$h^3 \left(\frac{\partial^2 p}{\partial x^2} + \frac{\partial^2 p}{\partial y^2} \right) + 3h^2 \left(\frac{h_L - h_0}{L} \right) \frac{\partial p}{\partial x} = 6\mu U \left(\frac{h_L - h_0}{L} \right)$$

Un triple diplôme belgo-germano-français ?

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Vincent Legat
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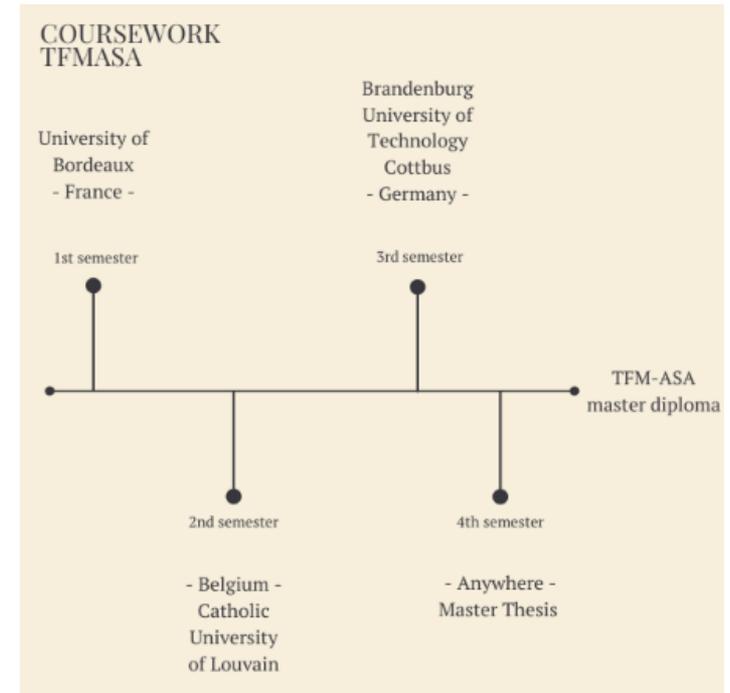
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TFM-ASA Master Program

The TFM-ASA Master Program is a two-year Master of Science Program taught in English by 3 Universities in 3 different countries (Catholic University of Louvain (Belgium) , Brandenburg University of Technology (Germany) and University of Bordeaux (France)).

The students will benefit from top quality training in Mechanical and Aerospace Engineering. They will spend an entire semester in each university. Many industrial partners are directly involved through internships for students, conferences and even courses.



Et tout cela
en deux années !



Master in Transferts, Fluids and Materials for Aeronautical and Space Applications

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