It is the study of the movement of real fluids (viscous fluids).

The viscosity of liquids decreases as the temperature increases. Unlike that of liquids, the viscosity of gases increases with temperature.

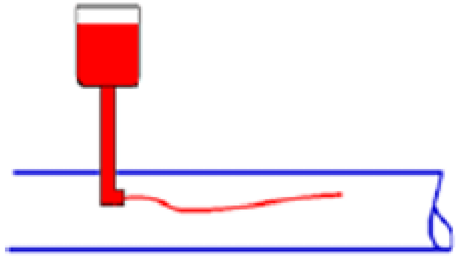
**Flow definitions**

**Real fluid :** A fluid is said to be real if, during its movement, the contact forces are not perpendicular to the surface elements on which they are exerted (they therefore have tangential components which oppose the sliding of the fluid layers over each other). This resistance is characterized by the viscosity.

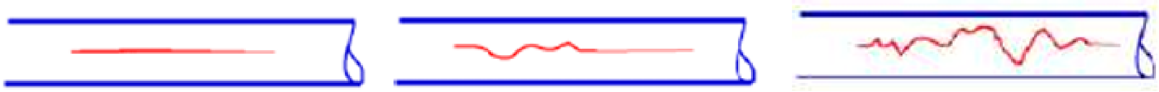
- Steady or stationary flows: A flow is steady or permanent if all the variables of the flow at each point are independent of time, otherwise the flow is unsteady or non-steady..
- Two-dimensional flows: This is a flow that depends on two variables such as plane flows or revolution flows..
- Source or sink: A source is a point in space from which the fluid exits with a constant flow rate. A sink is a point in which the fluid enters with a constant flow rate (negative source).

**Flow regimes, Reynolds experiment**

Knowledge of the flow regime of a fluid is a key point in process engineering, because it has an influence on most phenomena, in particular heat transfer, material transfer, pressure losses, etc. In **1883**, Osborne Reynolds **(1842-1912)**, professor of engineering at the University of Manchester, carried out experiments during the flow of a fluid in a straight cylindrical pipe. By injecting a dye into the axis of the pipe, he noticed that at low speed, the dye remains concentrated very close to the axis (the colored line is perfectly clear and well defined) characteristic of a stable laminar flow **(a)**, then at higher speed/flow, vortex structures are formed, more and more energetic, causing rapid diffusion due to turbulence **(b and c)** which largely takes over the molecular diffusion barely observable at low speed. The particles have disordered transverse movements and the fluid is uniformly colored.



Injection of the dye



a) Laminar regime b) Transient regime c) Turbulent regime

**Laminar regime** : a laminar flow is when the fluid has only translational and deformational movements, the trajectories and flow lines of the different particles of the fluid are arranged in parallel

**Turbulent regime** : Turbulent flow occurs when particles in a fluid undergo translational, rotational, and deformational motions. The flow is chaotic and the current lines are intersecting.

**Transient regime** : between these two regimes where the colored net oscillates without dividing.

Using different fluids (different viscosities), varying the flow rate and the diameter of the pipe, Reynolds showed that the parameter that allowed to determine whether the flow is laminar or turbulent is a dimensionless number called Reynolds number . It expresses the ratio between the inertial force $(\rho.u^2)$.. And the viscous force $\left(\mu.\frac{u}{d}\right)$.

It is given by the following relation:

$$Re = \frac{Inertial\ force}{Viscous\ force} = \frac{\rho.u.d}{\mu} = \frac{u.d}{\vartheta}$$

**u**: average flow velocity m/s

**d**: Pipe diameter in m

**μ**: dynamic viscosity of the fluid $N/m^2.s$

**ϑ**: kinematic viscosity of the fluid $m^2/s$

As Re increases, the inertial force becomes relatively larger and the flow destabilizes and becomes fully turbulent.

- **Si** $\boldsymbol{Re < 2000}$ : the flow is laminar
- **Si** $\boldsymbol{2000 < Re < 4000}$: the flow is transient
- **Si** $\boldsymbol{Re > 4000}$: the flow is turbulent

These values may vary slightly from one work to another, but in practice, the values leave no ambiguity. They will be clearly higher or lower than these limits. In turbulent flows, the value of is very important and can reach $\mathbf{10^5}$ up to $\mathbf{10^8}$.

**Case of non-circular pipes**

In the case where the pipe is not circular, we define what is called the hydraulic diameter $d_H$ : $d_H = 4.\frac{straight\ section\ of\ the\ pipe}{wet\ perimeter}$

The hydraulic radius $r_H$ can also be defined in correspondence with the radius of the pipe : $r_H = \frac{cross\ section\ occupied\ by\ the\ fluid}{wet\ perimeter}$

- in the case of a circular pipe of diameter, we find $d_H = d$
- in the case of a square pipe, the hydraulic diameter is none other than the side of the square.
- for a fluid flowing in an annular space, we can show that $\boldsymbol{d_H = 2.e = d_{ext} - d_{int}}$ **;** where **e** is the thickness of the annular space.

## Pressure loss

In fluid mechanics, pressure loss corresponds to the dissipation of mechanical energy of a fluid in motion1 between two points of a pipeline, or through equipment (valve, elbow, etc.), due to friction of the fluid on the walls and on itself. This mechanical energy is transformed into heat by friction. This dissipation of energy leads to a total pressure loss along the network.

We denote ΔP the total pressure loss between two points. For liquids, it is common to express this total pressure loss by a total height loss ΔH, then expressed in meters of fluid column. These two notations are strictly equivalent with the relation :

$$\boldsymbol{\Delta P = \rho g \Delta H}$$

- $\Delta P$ : Total pressure loss (in pascal).
- **ΔH**: Total height loss (in meters).
- $\boldsymbol{\rho}$ : is the density of the fluid in kg $m^{-3}$.

- g is the acceleration of gravity in m $s^{-2}$.

When friction is present, Bernoulli's theorem no longer applies and the charge is no longer constant in the circuit. We then speak of charge loss.

For incompressible fluids, we then use the generalized Bernoulli theorem, including a pressure loss term, which is written as:

$$\frac{v_1^2}{2g} + z_1 + \frac{p_1}{\rho g} = \frac{v_2^2}{2g} + z_2 + \frac{p_2}{\rho g} + \Delta H$$

- $v$ : fluid velocity [m $s^{-1}$]
- g : acceleration of gravity [m $s^{-2}$]
- $z$ : altitude [m]
- P : pressure [Pa]
- $\rho$ : density of the fluid [kg $m^{-3}$]
- $\boldsymbol{\Delta H}$ : Pressure loss expressed in meters of fluid column [m]

For an incompressible fluid, with a constant tube section, the speed is also constant, the altitudes "z" being imposed. The pressure loss results in a decrease in pressure. The more general relationship is written as :

with : $\boldsymbol{\Delta P = \rho g \Delta H}$

$$\frac{v_1^2}{2g} + z_1 + \frac{p_1}{\rho g} = \frac{v_2^2}{2g} + z_2 + \frac{p_2}{\rho g} + \frac{\Delta \mathrm{P}}{\rho g}$$

We distinguish between linear and singular pressure losses

**Linear pressure losses**

Regular pressure losses which quantify the energy lost along a straight pipeline of constant section; Regular pressure losses are generated by the friction of the fluid on the internal wall of the pipe throughout its passage, they depend on :

- the length and diameter of the pipe (L in meters)

• the viscosity of the fluid

• the relative roughness of the pipe

• the speed of the fluid in circulation (therefore the flow rate) (V in m/s).

Between two points separated by a length L, in a pipe of diameter D there appears a pressure loss ΔHL, expressed in the following form :

$$\Delta H_L = \frac{L}{D_h}\frac{V^2}{2g}\ \lambda$$

with :

L: length of the pipe

$D_h$: hydraulic diameter "m" defined by $D_h = \frac{4S}{P_m}$

S being the section of the pipe and Pm the wetted perimeter

V: fluid flow speed (m/s$^2$)

λ: pressure loss coefficient which depends on the flow regime (unitless).

g: gravitational acceleration

Hence the general formula:

$$\rho \cdot g \cdot \Delta H = \Delta \mathrm{P} = \Lambda \cdot \frac{\mathrm{L}}{\mathrm{D_h}} \cdot \frac{\rho \cdot v^2}{2}$$

The value of the coefficient λ is found in specific charts, called the Moody diagram or the Nikuradze Harp, for each pipeline configuration. These are most often graphs expressing the value of λ as a function of the Reynolds number of the flow, for different values of relative roughness.

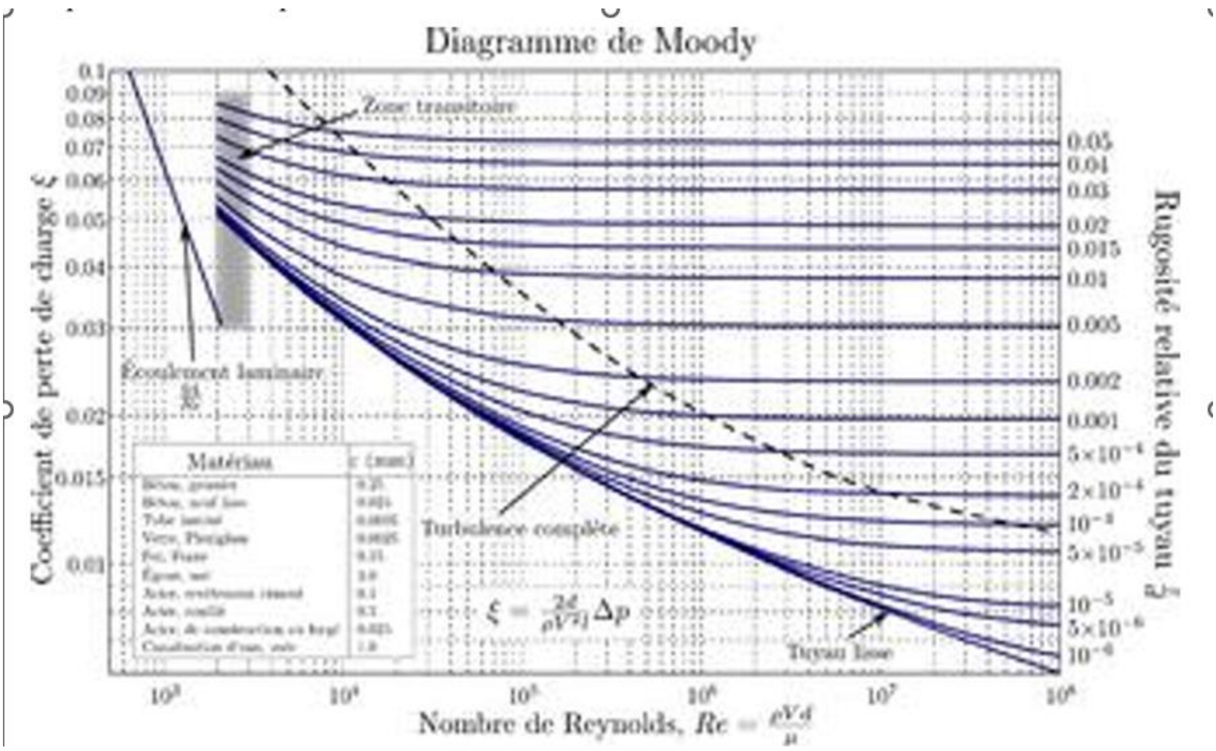



**Figure Moody – Stanton diagram**

For **laminar flow**, the value of f is: $\lambda = \frac{64}{Re}$

**Smooth turbulent flow**: The expression for λ is provided: Either by the experimental law of BLASIUS, valid in smooth turbulent regime for $\lambda = \frac{0.316}{Re^{0.25}}$

**Rough turbulent flow**

In this case, λ is independent of the Reynolds number, and therefore of the viscosity, and depends only on the relative roughness $\frac{\varepsilon}{D}$, ε being the average thickness of the wall roughness. For industrial work, an approximate expression of λ is given by the BLENCH formula, in which ε takes conventional values depending on the material.

$$\lambda = 0.8\sqrt{\frac{\varepsilon}{D}}$$

To limit pressure losses, laminar flow is sought in low-pressure pipes and in high-pressure pipes of industrial power installations where efficiency must be good. Turbulent flow is sought when the weight and size of installations are to be limited, to the detriment of efficiency.

***Application***

Oil with absolute viscosity 0.101 Pa.s and specific gravity $\delta = 0.85$ circulates in 3000mm of cast iron pipe 300 mm in diameter at a rate of 44.4 l/s. What is the pressure loss in the pipe?

$V = \frac{Q}{S} = \frac{0,0444}{\frac{1}{4}\pi\,(0,3)^2} = 0,628 m/s$ and $\mathrm{Re} = \frac{VD\rho}{\mu} = \frac{0,628 \times 0,3 \times 0,85 \times 1000}{0,101} = 1585$

Which means that the flow is laminar. So:

$$f = \frac{64}{\mathrm{Re}} = 0,0404$$

and load loss :

$\Delta p = \rho \frac{V^2 L}{2D} \times f = 0,0404 \times \frac{3000}{0,3} \times \frac{(0,628)^2}{2 \times 9,81} = 8,14 m$ *( in the case of a circular pipe with a diameter, we find* $d_H = d$ *)*

**Singular load losses**

Singular pressure losses which quantify the energy lost at the passage of singularity (narrowings, widening, confluence, bends….etc.)

Singular pressure losses are due to geometric variations of the pipe section, accidental or not. We therefore count changes of direction (elbows, T-connectors), section reductions, valves or taps…….

Singular pressure losses occur when there is disruption of the normal flow by separation of the fluid from the walls or by the formation of vortices.

The formula used is: $\Delta P = \rho.g.\Delta H = K\frac{\rho v^2}{2}$ or $\Delta H = k.\frac{v^2}{2g}$

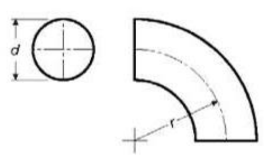
**ΔP**: singular pressure loss in pascal (Pa)

$K$ : singular pressure loss coefficient; depending on the shape of the passage zone.

**ρ** : density of the fluid [kg/m$^3$]

**v** : fluid speed [m/s]

The value of K is given by the manufacturers in their catalogs. Some average values are given in the following table:

<table>
<tr><td>Coude à 90°</td><td>
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<tr><th>r/d</th><th>K</th></tr>
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<tr><td>0,75</td><td>0,5</td></tr>
<tr><td>1,00</td><td>0,4</td></tr>
<tr><td>1,50</td><td>0,3</td></tr>
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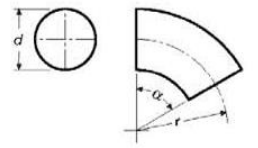
<tr><td>Coude à 30°, 45° et 60°</td><td>
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<tr><th rowspan="2">r/d</th><th colspan="3">K</th></tr>
<tr><th>α = 30°</th><th>α = 45°</th><th>α = 60°</th></tr>
<tr><td>0,50</td><td>0,3</td><td>0,5</td><td>0,7</td></tr>
<tr><td>0,75</td><td>0,2</td><td>0,3</td><td>0,3</td></tr>
<tr><td>1,00</td><td>0,1</td><td>0,2</td><td>0,3</td></tr>
<tr><td>1,50</td><td>0,1</td><td>0,2</td><td>0,2</td></tr>
<tr><td>2,00</td><td>0,1</td><td>0,1</td><td>0,1</td></tr>
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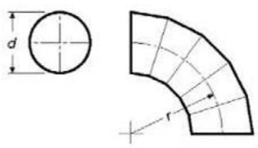
<tr><td>Coude 90° à secteurs</td><td>
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<tr><td>1,00</td><td>0,4</td></tr>
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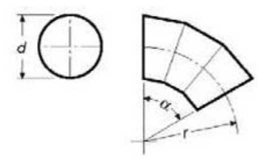
<tr><td>Coude 30°, 45° et 60° à secteurs</td><td>
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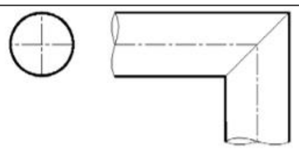
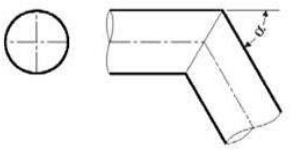
<tr><td>Coude 90° à angle vif</td><td></td><td>K = 1,4</td></tr>
<tr><td>Coude 30°, 45° et 60° à angle vif</td><td>
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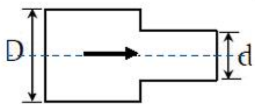
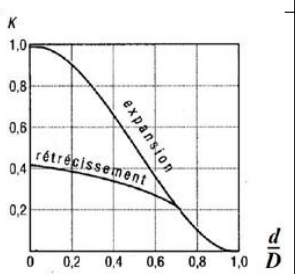
<tr><td>Rétrécissement brusque</td><td>
</td><td rowspan="2">
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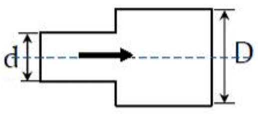
<tr><td>Elargissement brusque</td><td>
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To calculate the overall load loss of a circuit, it is therefore necessary to add the regular load losses and the singular load losses:

$$\Delta \boldsymbol{P}_{globale} = \Delta \boldsymbol{P}_{\underset{(\boldsymbol{lin\acute{e}aire})}{\boldsymbol{reguliere}}} + \Delta \boldsymbol{P}_{singuliere} \Rightarrow \Delta \boldsymbol{P}_{\boldsymbol{T}} = \Delta \boldsymbol{P}_{\boldsymbol{L}} + \Delta \boldsymbol{P}_{\boldsymbol{s}}$$