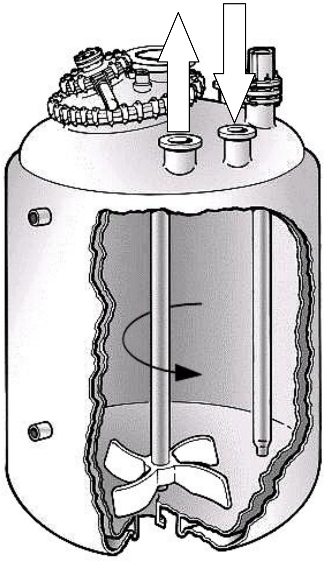
Heat transfer intensification in multifunctionlal heat exchangers

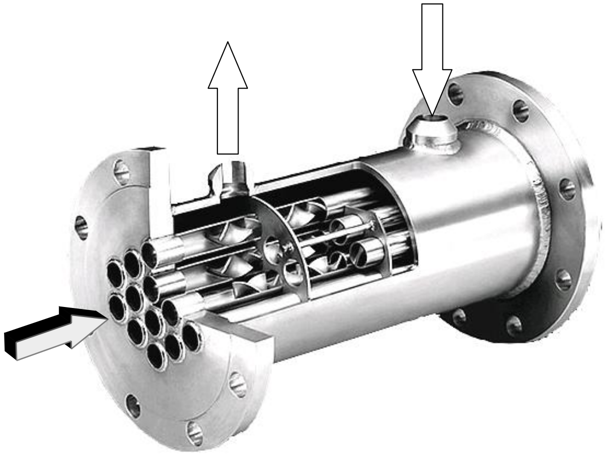
Multifunctional heat exchanger/reactor

- Integrating one or several unit operations in one single device
- Continuous versus batch operation
  - Lower product direct cost
  - Lower investment
  - Lower hold up
  - Lower utility consumption
  - Lower instrumentaion & control cost
  - Better safety

Batch vs Continuos

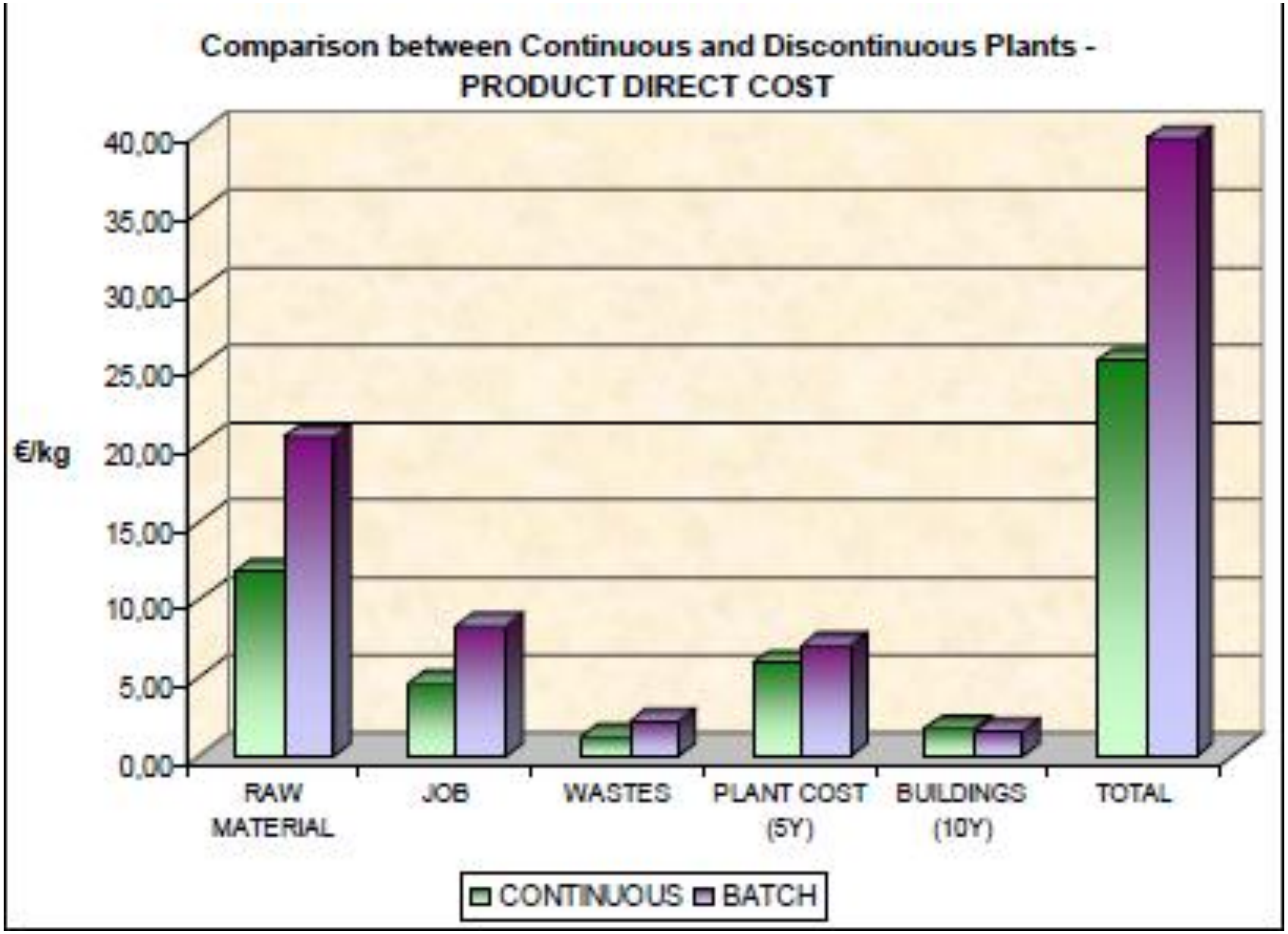


Batch



Continuos

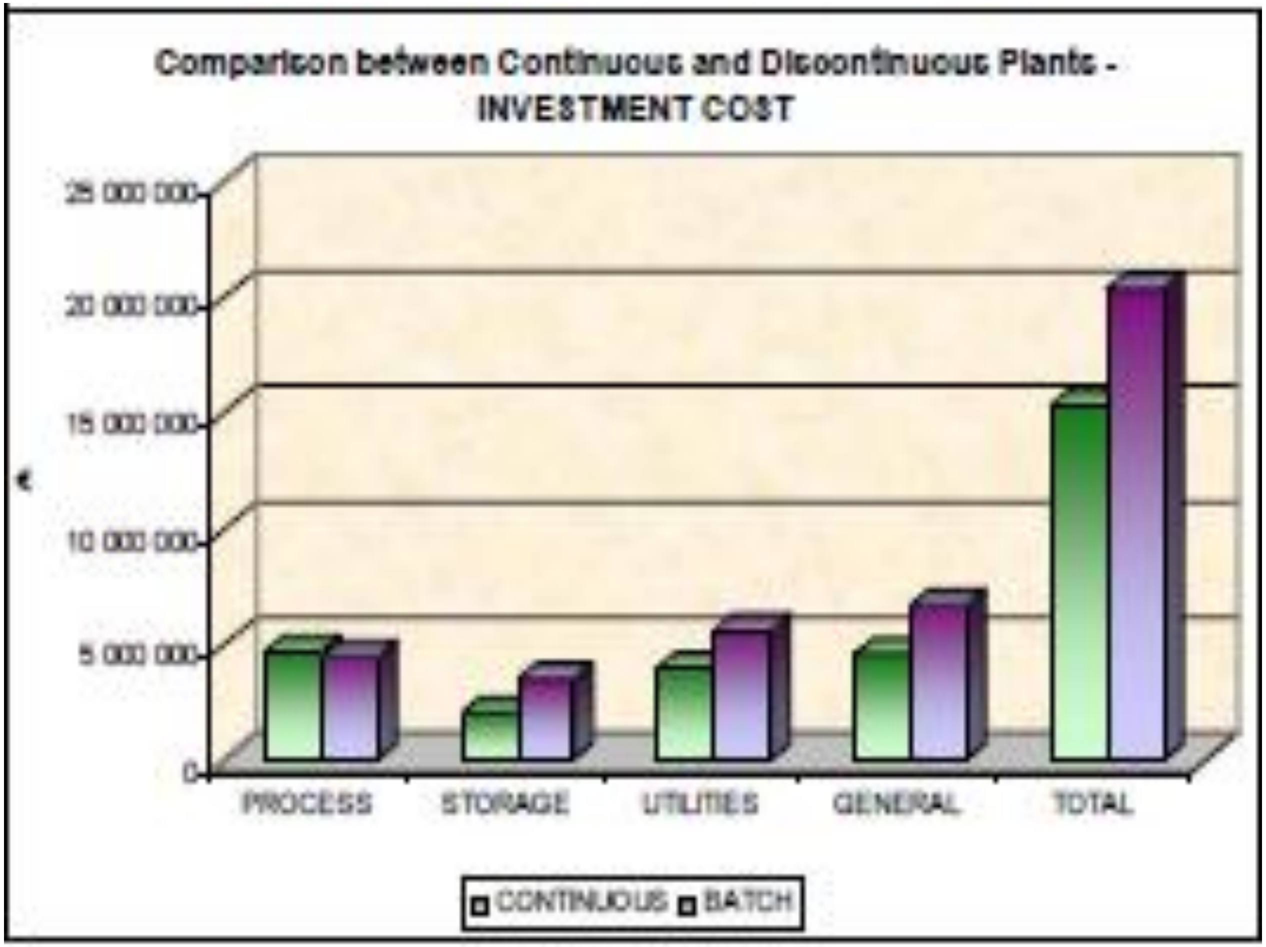
Continuos vs Batch - Selective Nitration



Comparison between Continuous and Discontinuous Plants -
PRODUCT DIRECT COST

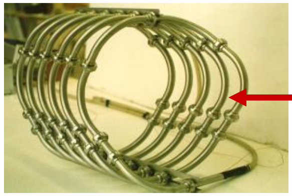
Pissavini - Corning

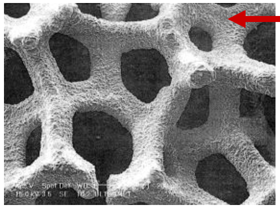
Continuos vs Batch - Selective Nitration

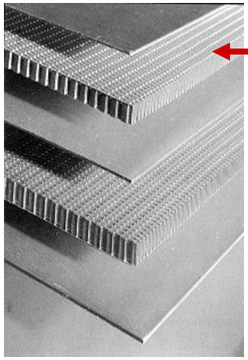


Passavini - Corning

Examples of MFHE

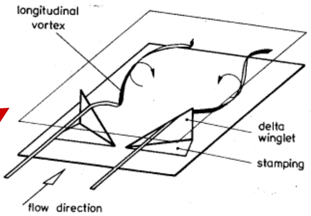


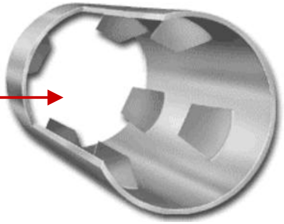




- Chaotic heat exchanger → **laminar**
- Metalic foams
- Turbulence promoters
- OSF fins
- HEV (High Efficiency Vortex)

turbulent





Economic consequencies

- Chemical industry consumes 41% of the energy consumption of French industry (stable since 2004)

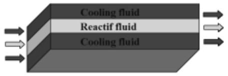
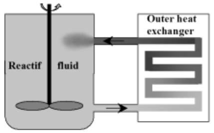
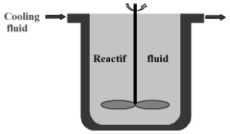
- Gas and oil constitute 71% of raw materials

- In 2005, French chemical industry has consumed 17. 8 Mt of petroleum =5.7 €B (54.5€/Br)

- 25% is used for energy purposes

- A 10 $/Br of increase in price = 2 €B
for French chemical industry

Heat exchange capability for different reactors

Process	Compact heat exchanger reactor (HEX)(1)	Tubular exchanger reactor (2)	Batch reactor with outer heat exchanger (2)	Batch reactor with double envelope (2)
Scheme				
Specific area (m^2/m^3)	800	400	10	2,5
Heat exchange ($W/m^2.K$)	5000	500	1000	400
Duty / volume ($kW/m^3.K$)	4000	200	10	1

S.Ferrouillat et al., Int J.Heat MassaTransfer, 2006

Heat transfer intensification

- Virtually every heat exchanger is a potential candidate for heat transfer intensification.

- Each application must be tested to see if it « makes sense ».

Intensification ratio: $I = \frac{hA}{(hA)p}$

In a two fluid counter flow HEX: $Q = UA\Delta T_m$

Or : $Q = \frac{UA}{L} L\Delta T_m$

Overall thermal resistance: $\frac{L}{UA} = \frac{L}{h_1 A_1} + \frac{L t_w}{k_w A_w} + \frac{L}{h_2 A_2}$

Three objectives

Intensification: reduction of thermal resistance per unite length L/UA for 3 objectives:

1.HEX size reduction if Q kept constant

2.Increased UA exploited two ways:

- Reduced ΔT_m if Q and L kept constant
- Increadse heat transfer if L kept constant

3.Reduced pumping power for fixed heat duty

Intensification techniques

I. Passive techniques (surface geometry or fluid additives)

II. Active techniques (external power)

Intensification techniques

I. Passive techniques

1. **Coated surfaces** (Teflon; drop condensation)
2. **Rough surfaces** (mixing in BL)
3. **Extendes surfaces** (fins=A, special=h, micro-channels)
4. **Displaced inserts**
5. **Swirl flow** (twisted inserts, VG, Kenics)
6. **Coiled tubes**
7. **Surface tension** (capilary wicking drain liquid film)
8. **Additives for liquids** (solid particles or gas bubbles)
9. **Additives for gases** (solid particles or liquid drops)

Intensification techniques

II. Active techniques

1. **Mechanical aids** (stirring, rotating, scraping)
2. **Surface vibration** (piezoelectric « spray cooling »)
3. **Fluid vibration** (from pulsation to ultrasound)
4. **Electrostatic fields** (ac or dc current, greater bulk mixing)
5. **Injection** (porous surfaces, surface degasing)
6. **Suction** (vapor removal in boling)
7. **Jet impingement**

R.L. Webb

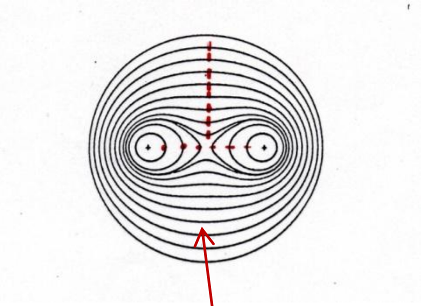
Physics of heat transfer intensification

- **At low and moderate temperatures heat transfer intensification is intimately ralated to mixing in the bulk, flow renewal close to the wall and better fluid-wall contact.**
- **Novel solutions should be devised based on the flow physics and chemistry , adapted to the flow regime.**
- **Using extra fluid-solid conact surface should be avoided as much as possible.**

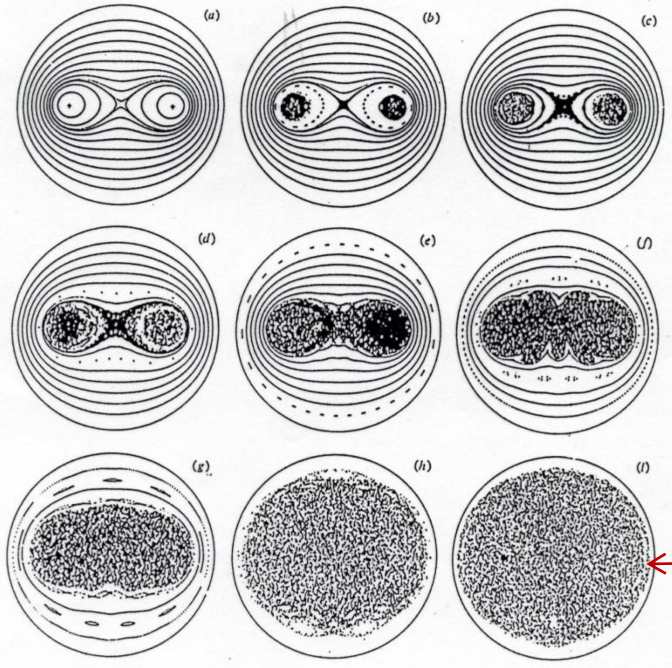
Two examples: laminar flow and turbulent flow

Heat transfer intensification in laminar flow

Better mixing using less energy



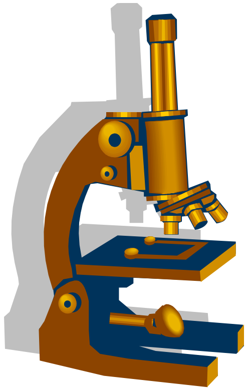
Non chaotic



Résultats des itérations décrites en φ 2.2. Les paramètres sont β = 0,5 et (a) μ = 0,005 ; (b) 0,1 ; (c) 0,125 ; (d) 0,15 ; (e) 0,20 ; (f) 0,35 ; (g) 0,50 ; (h) 1,0 ; (i) 1,5. Les croix indiquent la position de chaque agitateur [1]

$\mu = \frac{\Gamma T}{2\pi a^2}$ $\beta = \frac{b}{a}$ $\because \Gamma = 2\pi,\ a = 1 \therefore \mu = T;\ \beta = b$

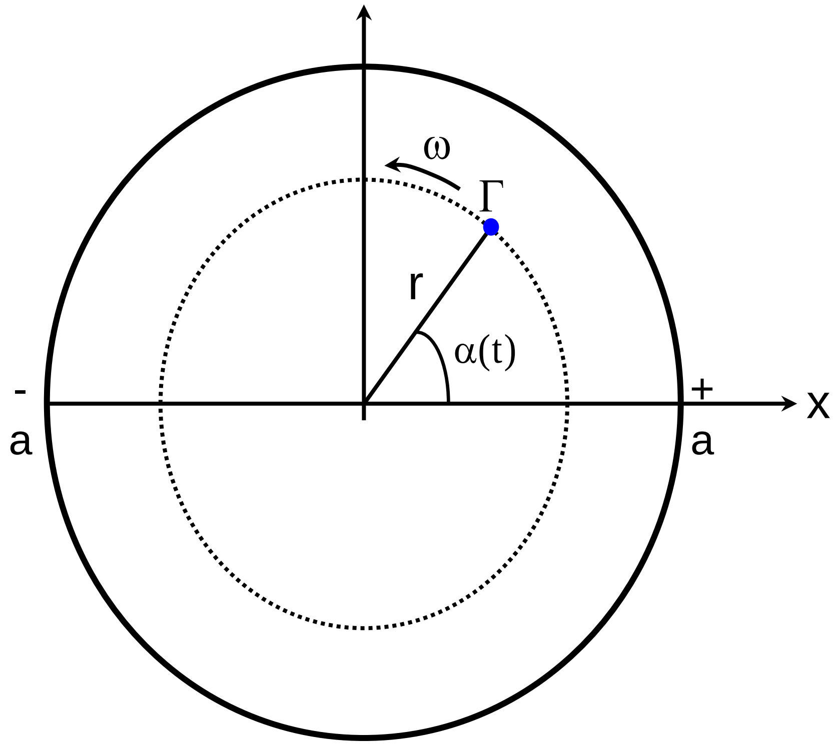
Chaotic



Mixing by chaotic advectio

$$\Omega = \frac{\omega \pi a^2}{\Gamma}$$

$$R = \frac{r}{a}$$



Agitateur en rotation dans un récipient circulaire

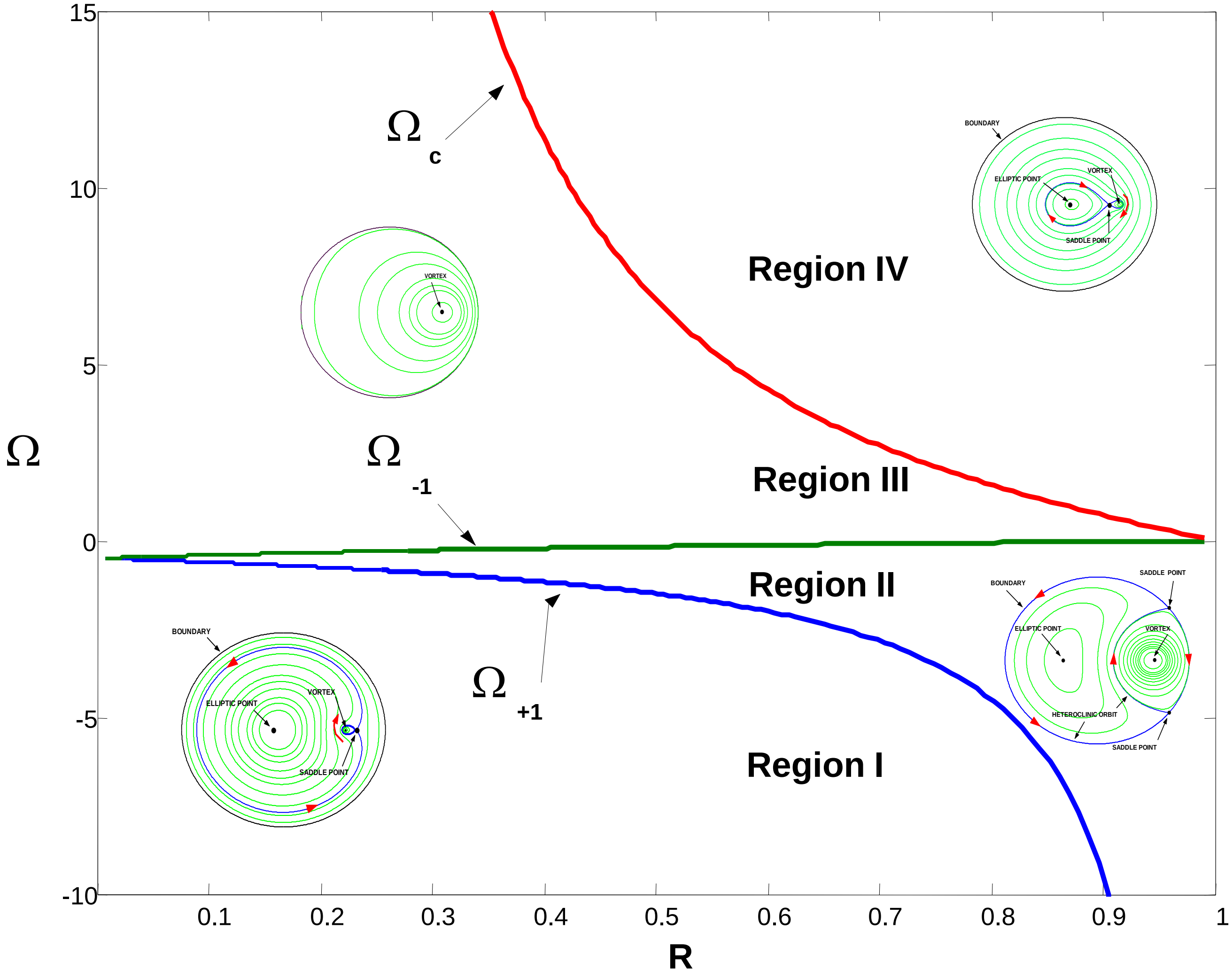
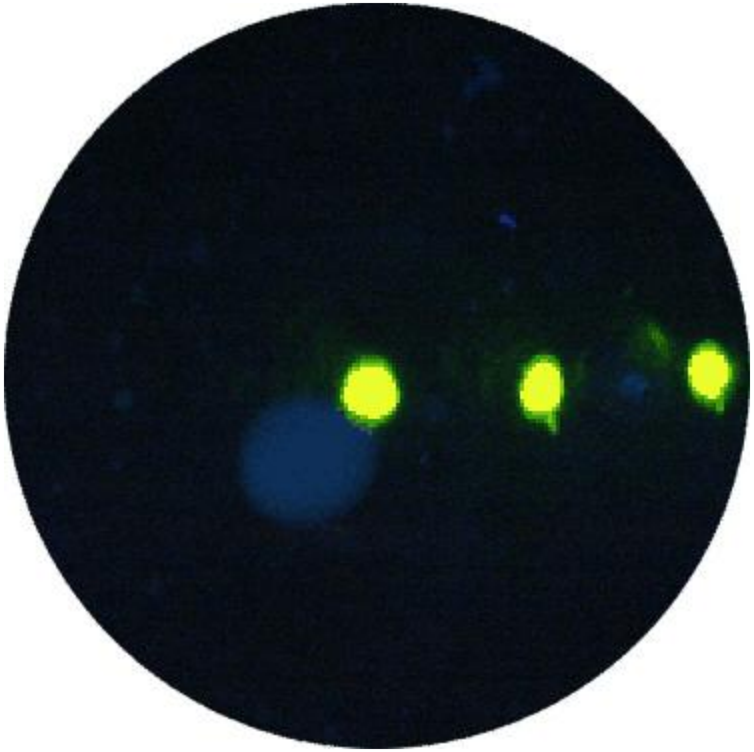


Diagramme de bifurcation avec différentes régions dans l’espace des ph

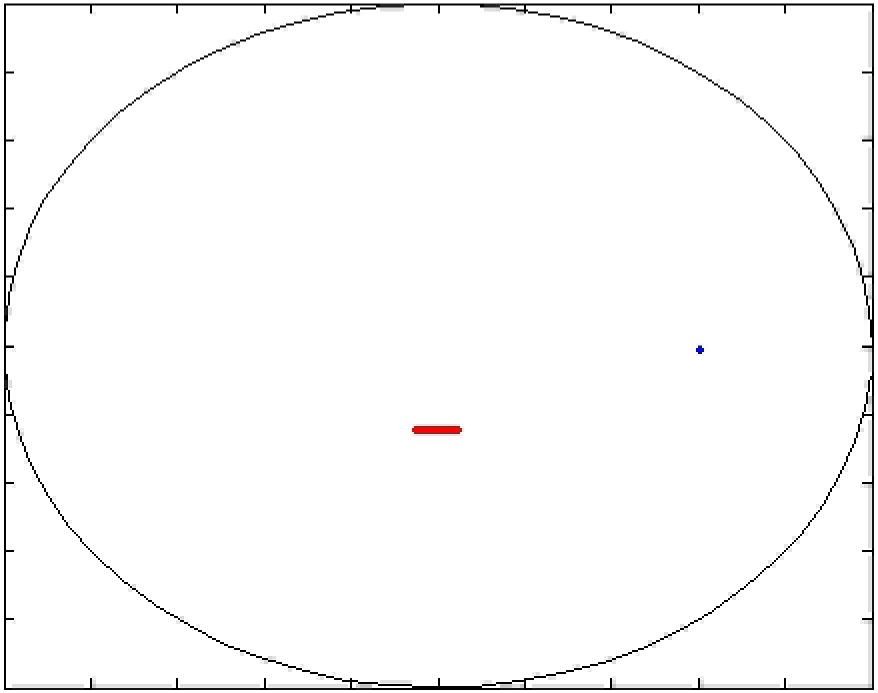
A. Ould El Moctar (LTN), France, A.Goullet & N. Aubry(NJIT), USA

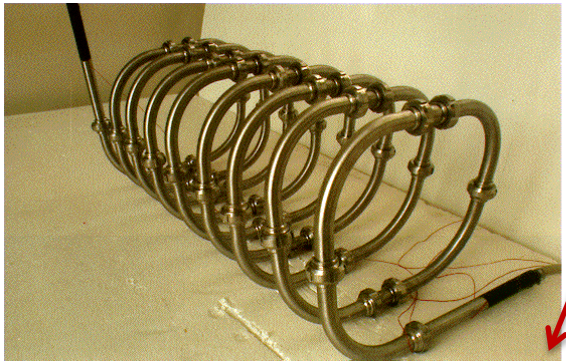
Mixing quality for 2 different protocols(R=0.6 et Ω=±1.5)

π/2+π/4



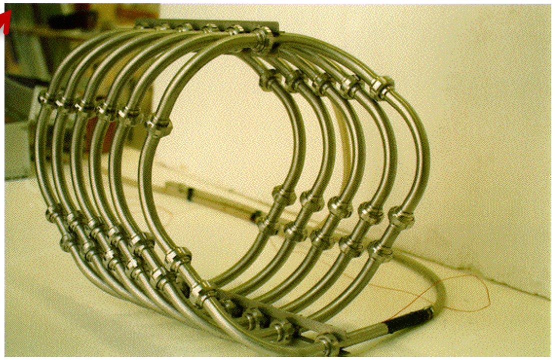
π/4+π/2

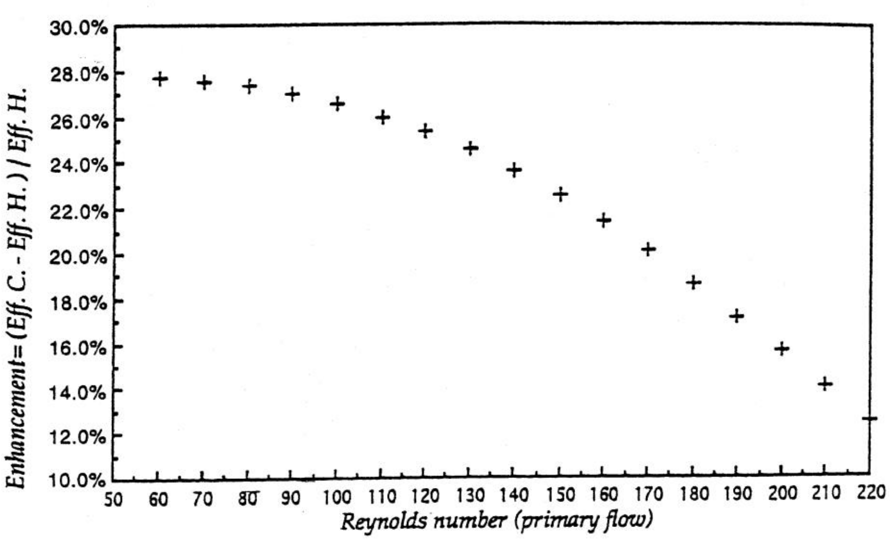




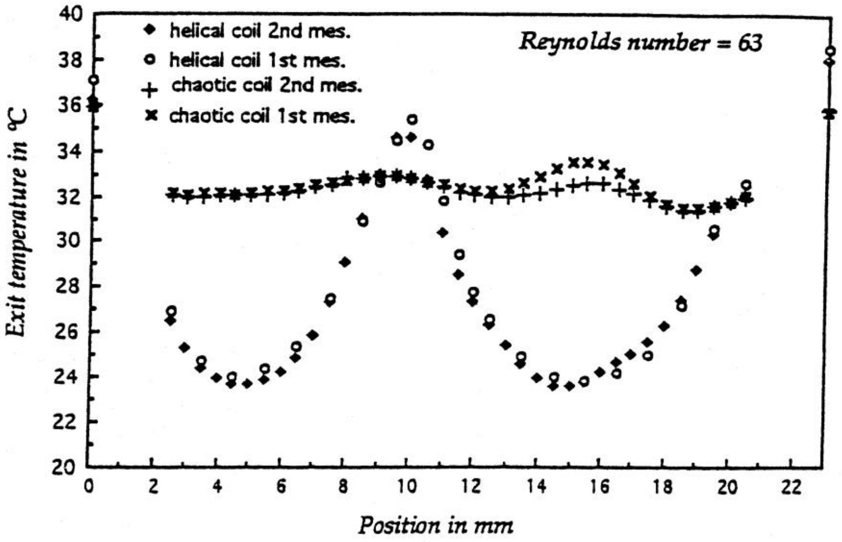
Chaotic heat exchanger

Helical heat exchanger



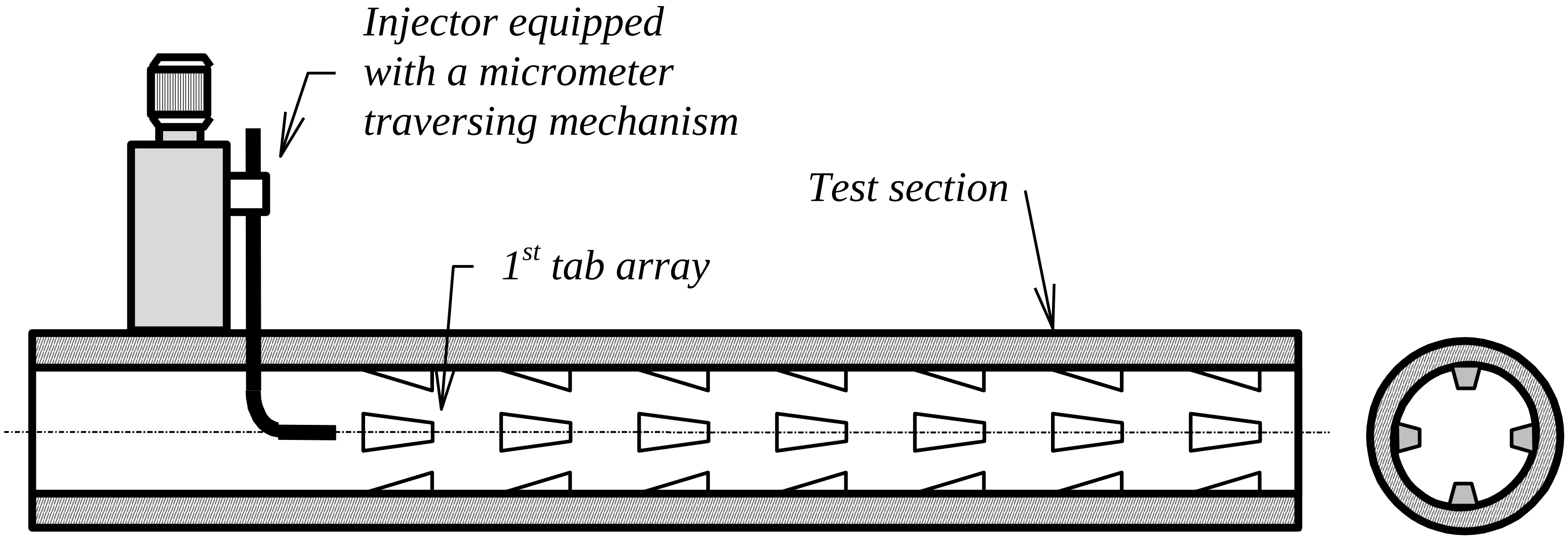


Energy efficiency



Temperature uniformity

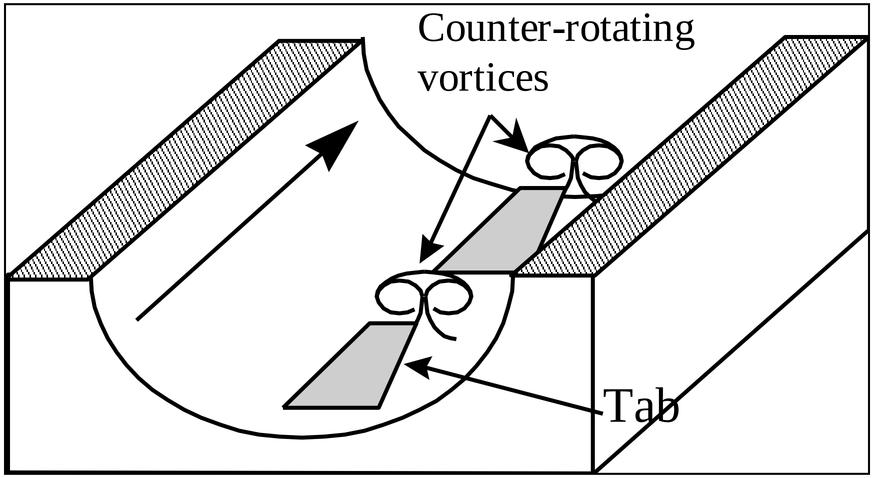
Heat transfer intensification in turbulent flow



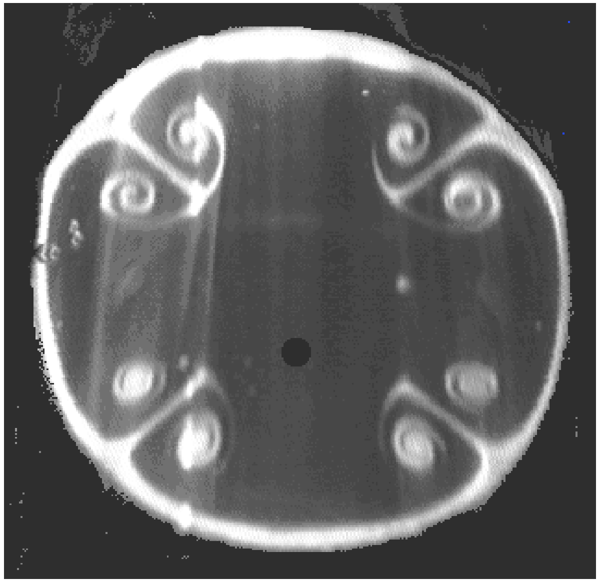
Longitudinal view of the static mixer HEV.

Vortex generation

Mechanism of vortex generation

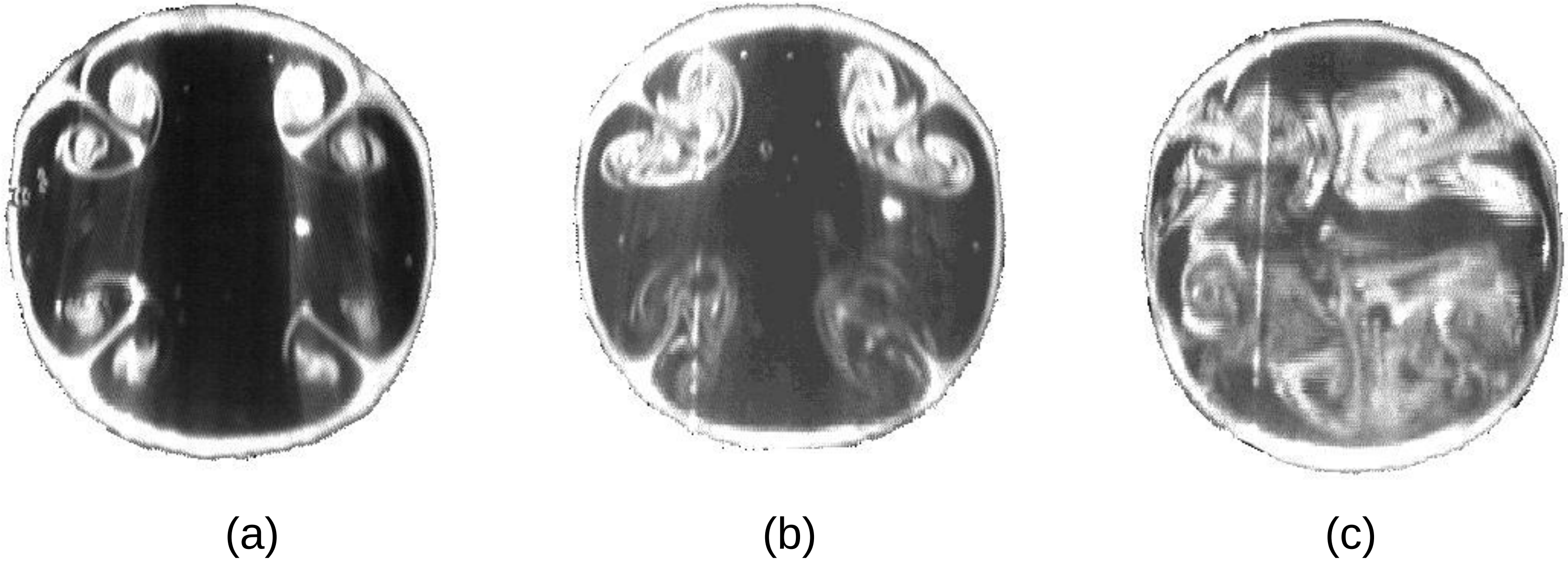


LIF flow visualization



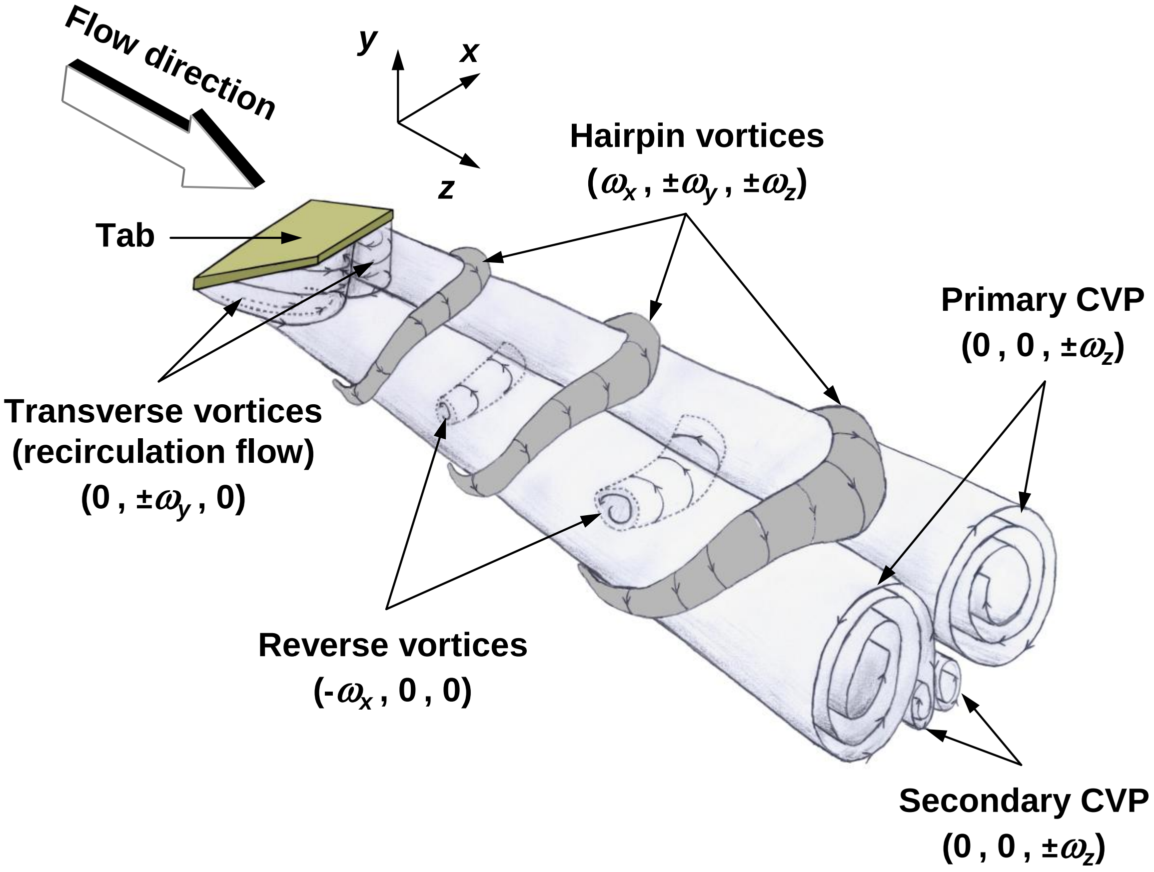
Downstream of the 1st row

Vortex evolution



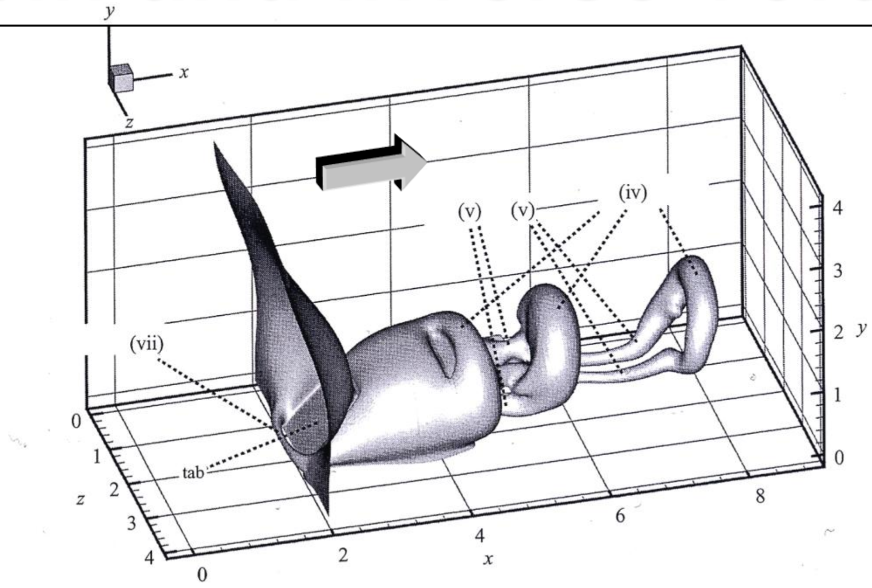
Photographs of the flow structures downstream from each line of vortex generators for *Re* = 1500; (a) downstream of the 1st baffle; (b) 2nd baffle; (c) 4th baffle.

Behind a tab

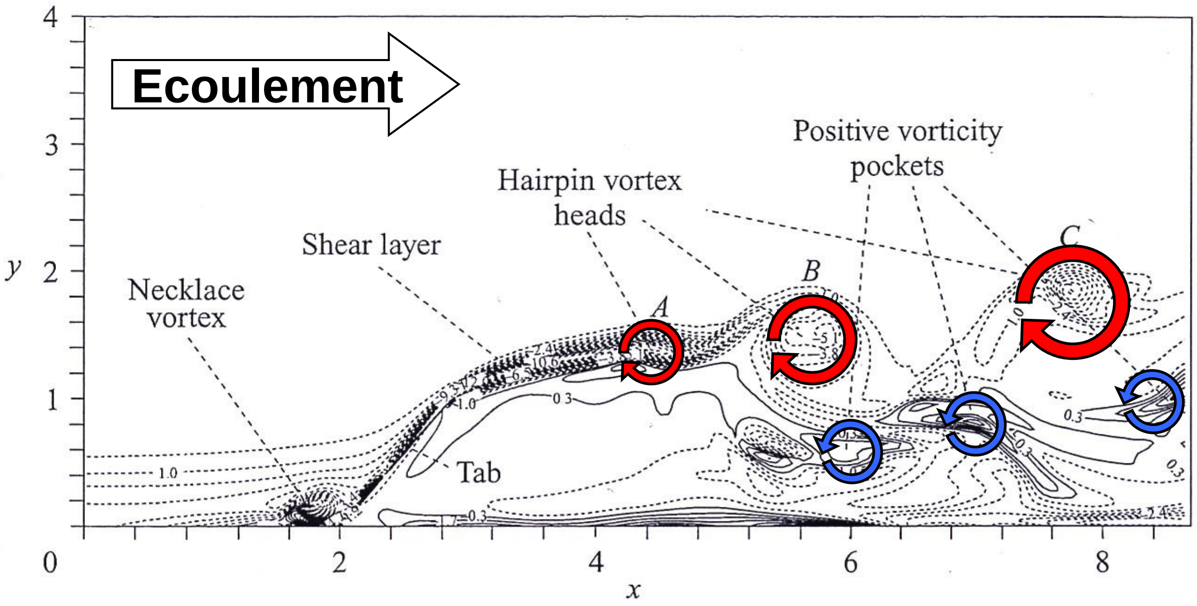


Flow direction
y
x
z
Tab
Hairpin vortices
(ω_x , ±ω_y , ±ω_z)
Primary CVP
(0 , 0 , ±ω_z)
Transverse vortices
(recirculation flow)
(0 , ±ω_y , 0)
Reverse vortices
(-ω_x , 0 , 0)
Secondary CVP
(0 , 0 , ±ω_z)

Hairpin and inverse vortices



Dong et Meng, JFM (2004)
Yang *et al.*, EF (2001)


Ecoulement

Pair of counter-rotating vortices

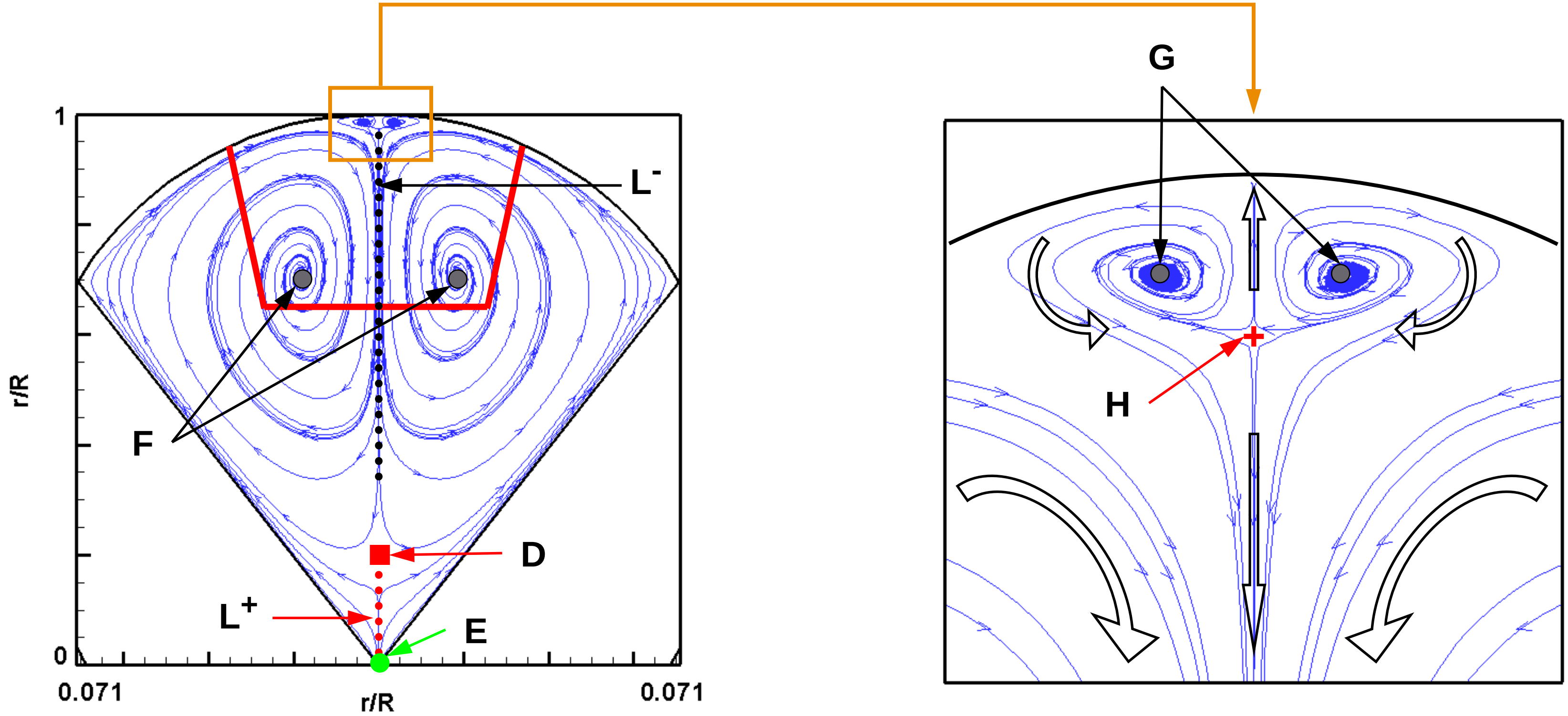
F: Elliptic stable points

L^+: Negative bifurcation line

E: Stable point

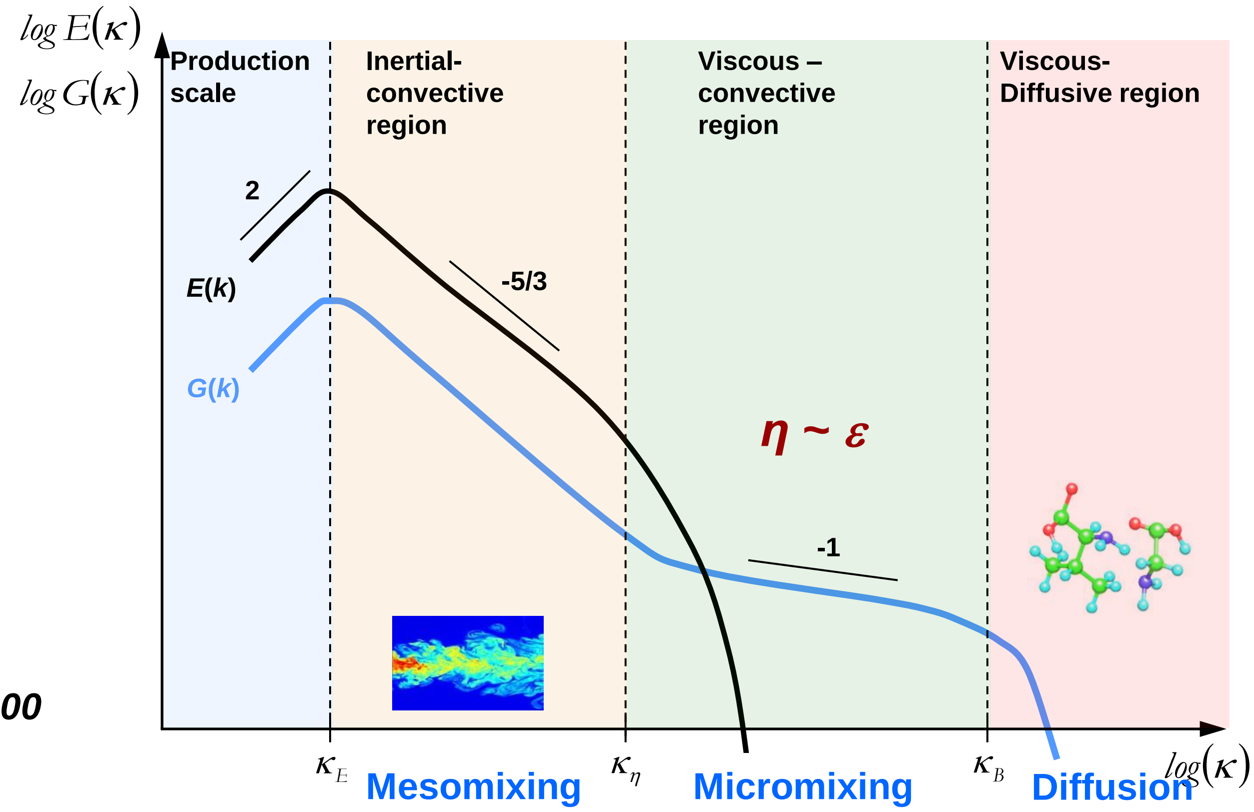
L^-: Negative bifurcation line

D&H: Hyperbolic point



Mixing scales

- **Macromixing:** Advection by the mean field
- **Mesomixing:** Advection by velocity fluctuations
- **Micromixing:** Up to molecular scale, decisive for reaction selectivity

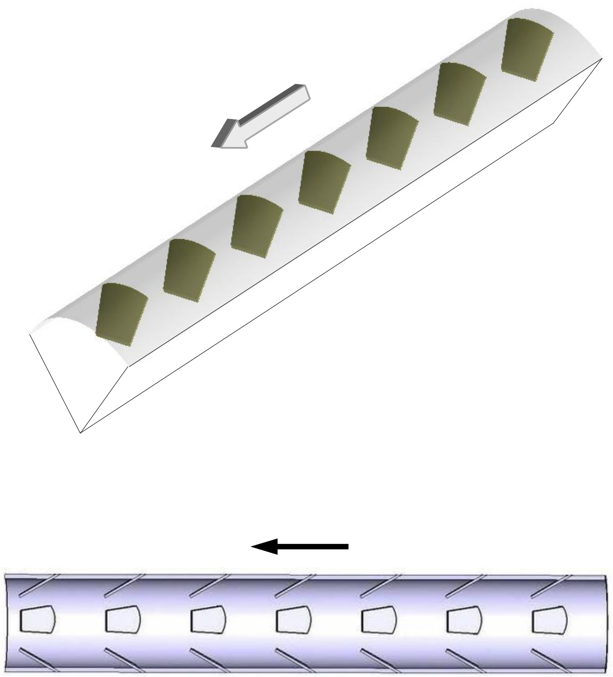


Schmidt No>1000

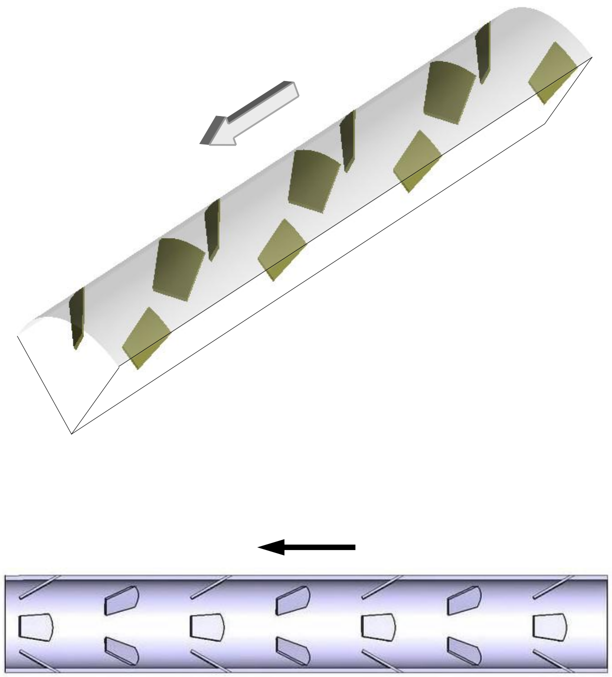
Wavenumber (m^{-1})

Three tab arrangements

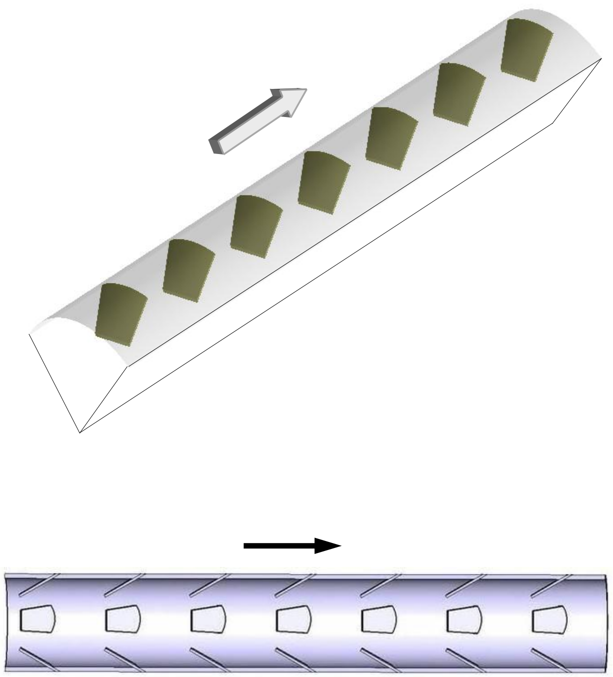
Rangées alignées sens direct



Rangées décalées sens direct

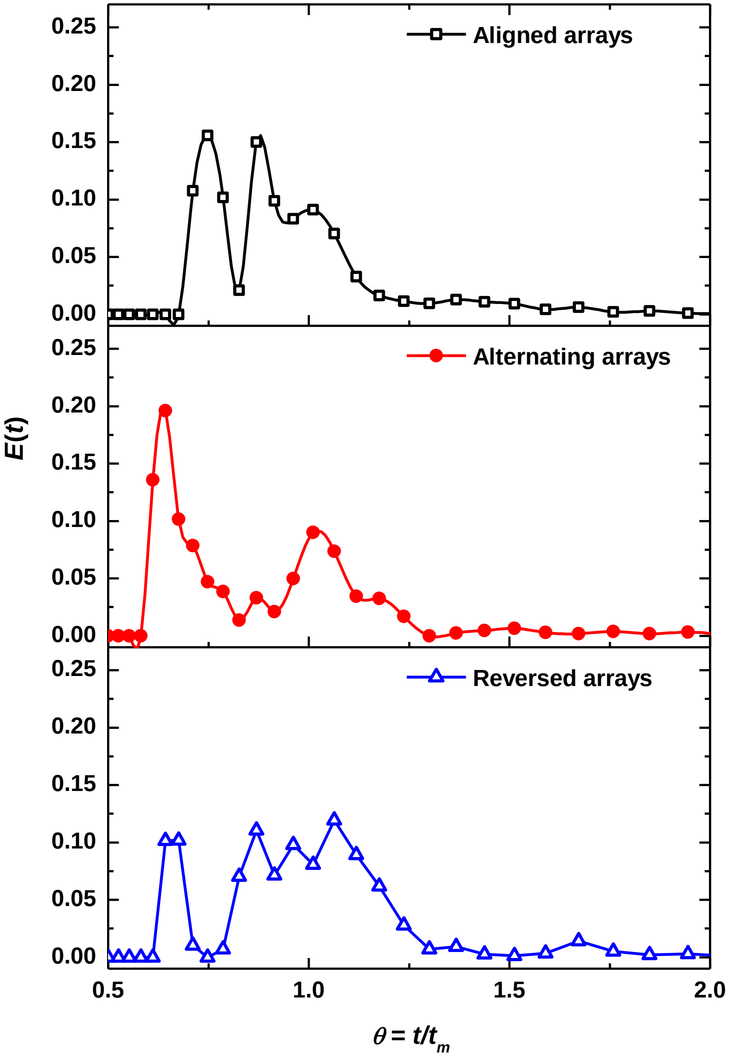


Rangées alignées sens inverse

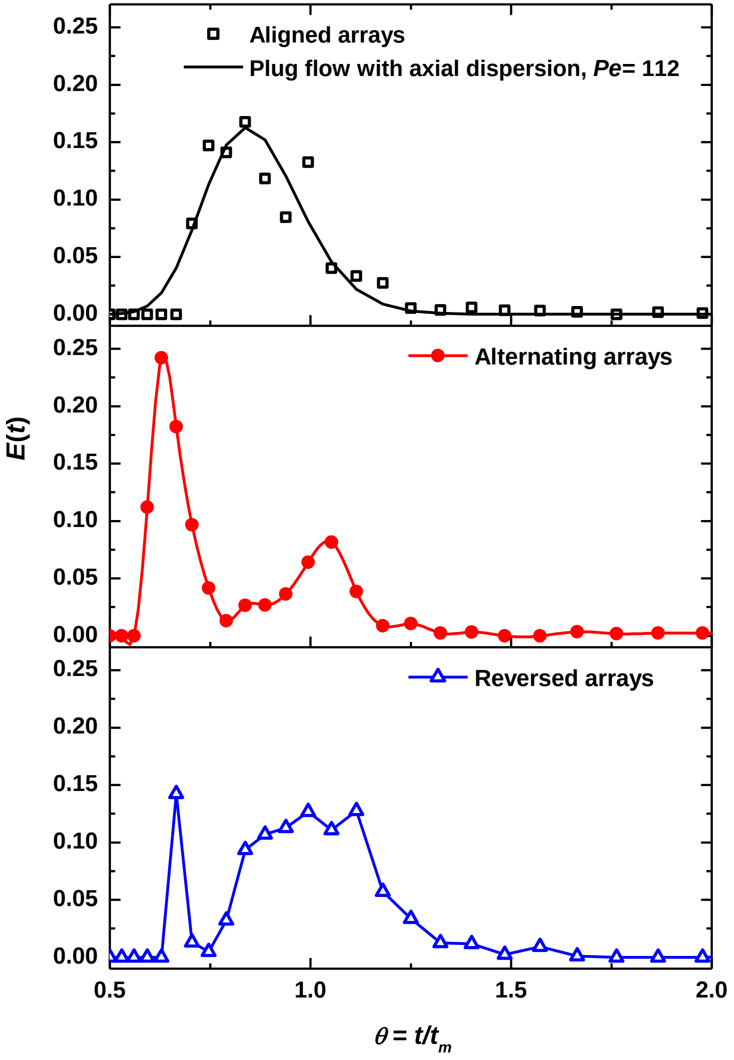


Macromixing (DTS)

***Re* = 7500**

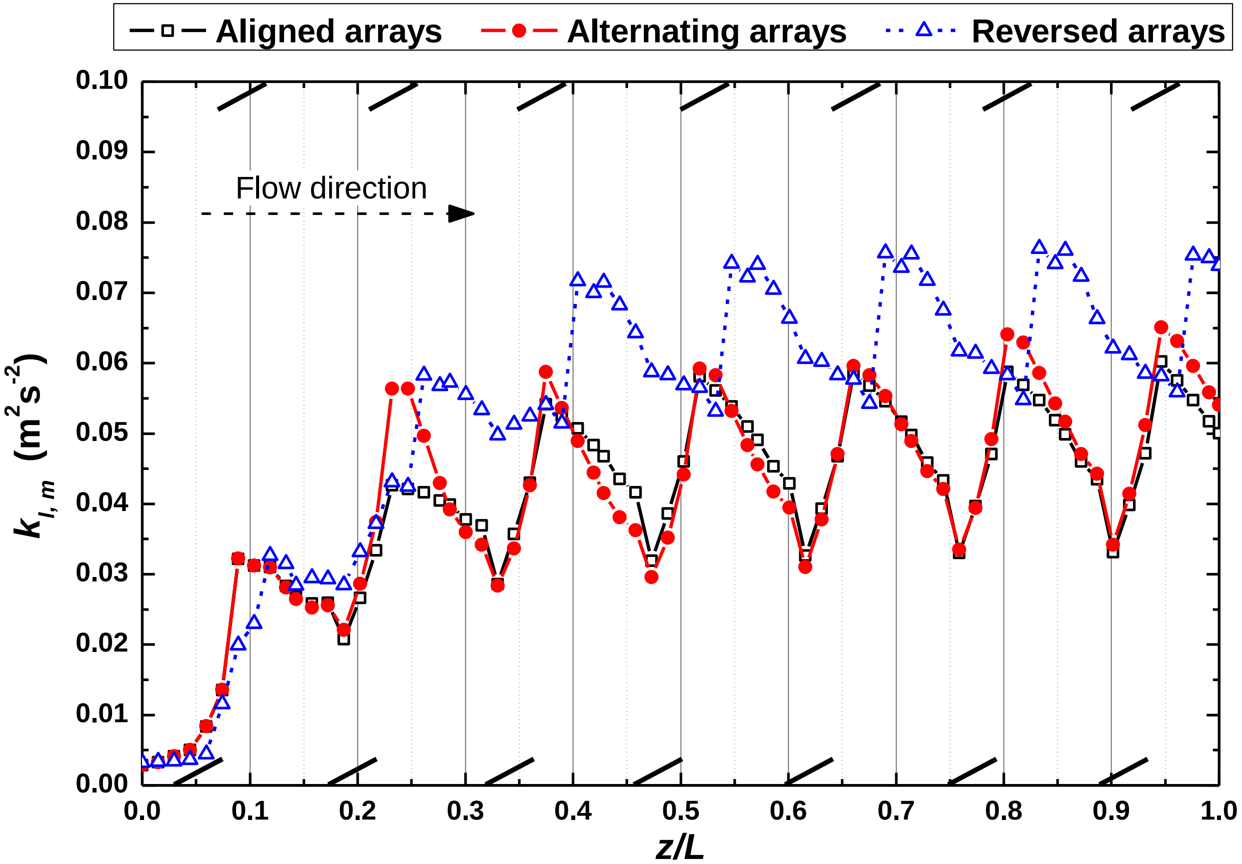


***Re* = 15000**



Mesomixing (TKE)

k **: TKE moyennée sur la section**



Intensification compared to linear arrangement

+ 8%   for alternated

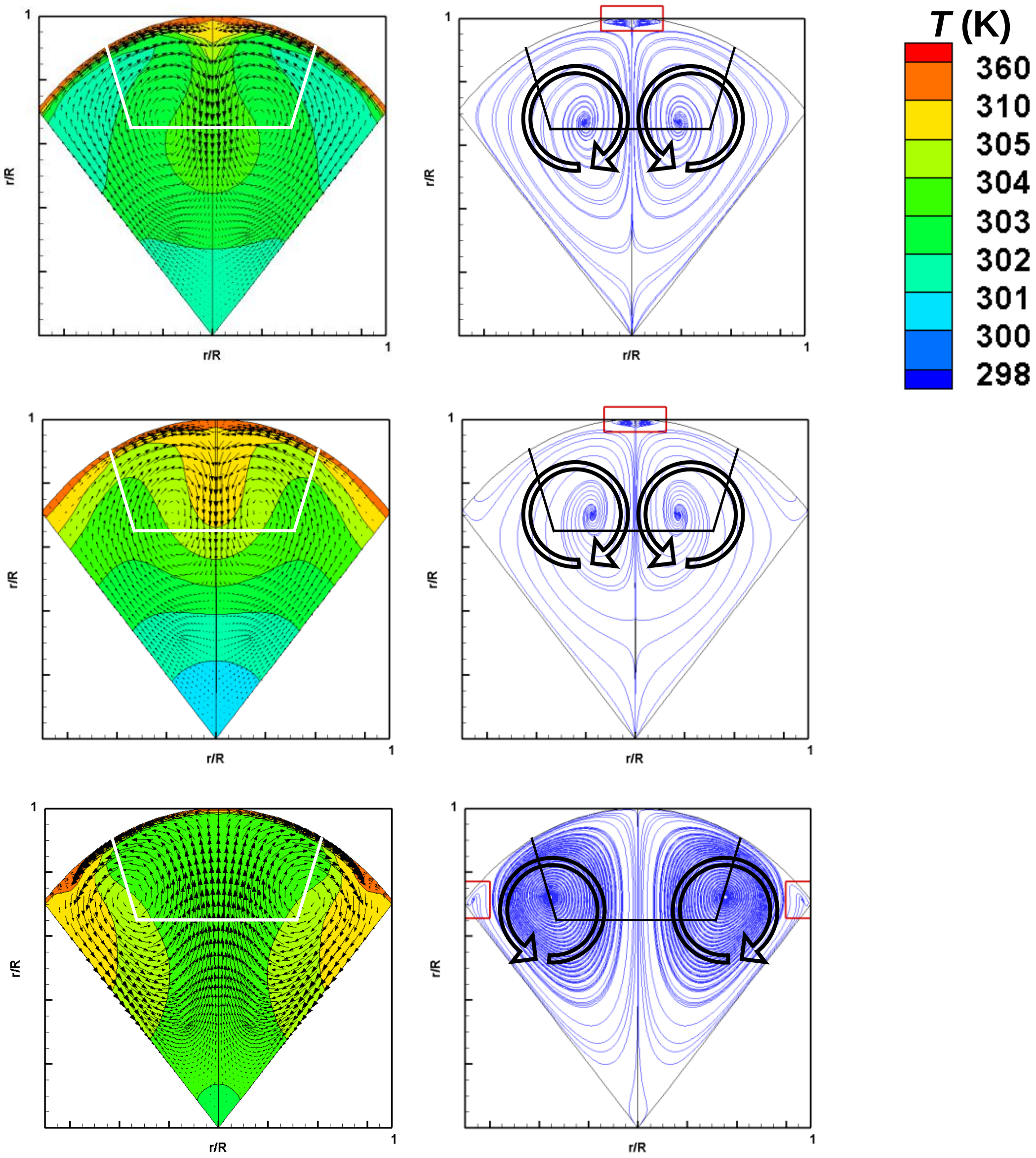
+ 27% for inverse

Temperature field

Allined arrays

Alternated arrays

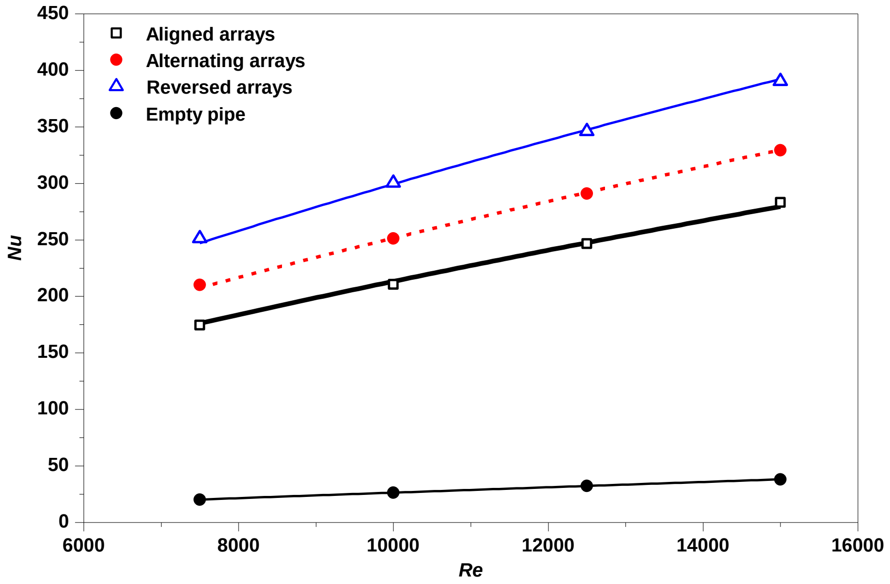
Inverse arrays



Global thermal performance

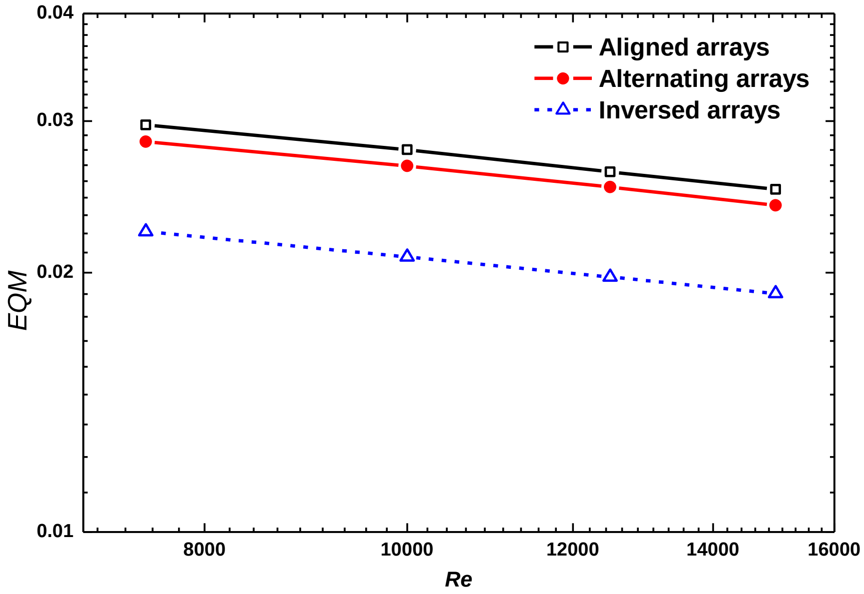
Nusselt number

$$Nu = \frac{\dot{m}\, c_p}{\pi\, L\, \lambda} \frac{T_{b,outlet} - T_{b,inlet}}{T_w - T_{mean}}$$



Écart Quadratique Moyen

$$EQM = \frac{\sigma(T)}{\overline{T}}$$

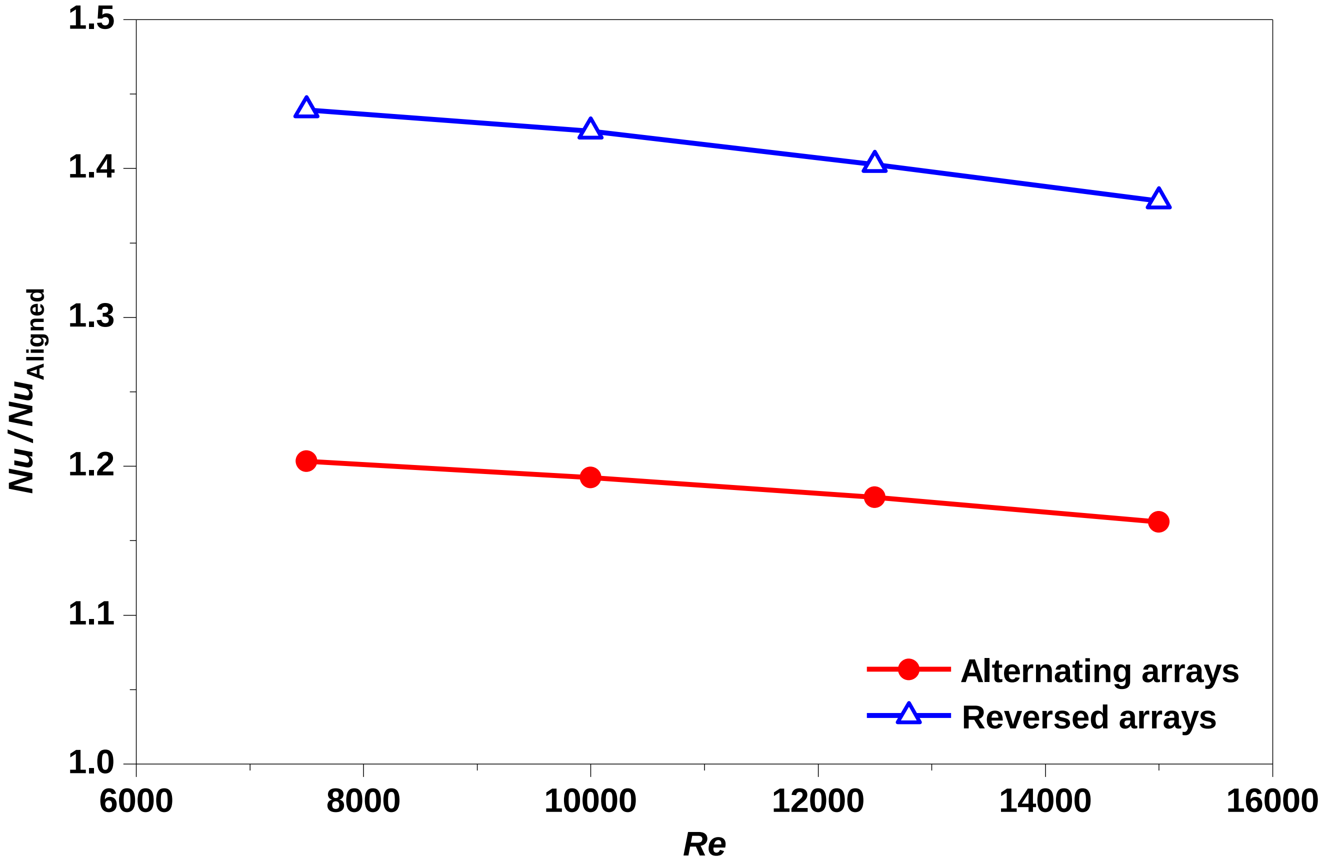


Gnielinski, ICE (1976)

Nusselt number in a plain straight tube

Intensification criteria

Nusselt number ratio: $Nu/Nu_{référence}$



Reference: classical HEV

Intensification criteria

Synergie field

Guo *et al.*, IJHMT (1998, 2005)

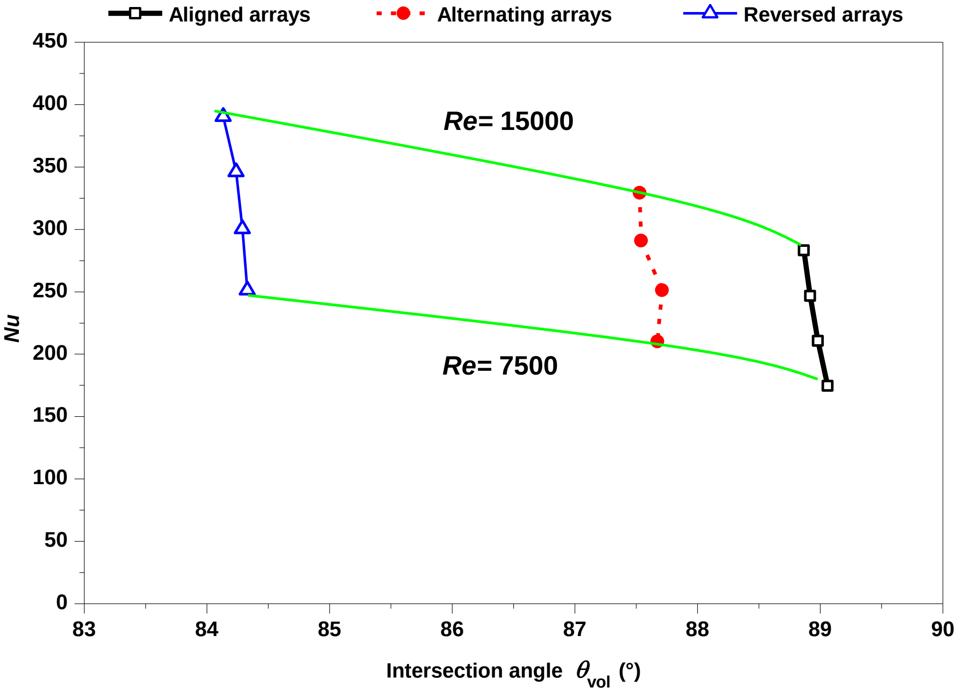
$$\rho c_p \vec{U}\cdot\vec{\nabla}T = \lambda \nabla^2 T$$

$$\rho c_p \iiint_{Vol} \left(\vec{U}\cdot\vec{\nabla}T\right) dx\,dy\,dz = \Phi \propto Nu$$

$$\sim$$

$$\vec{U}\cdot\vec{\nabla}T = \left|\vec{U}\right|\left|\vec{\nabla}T\right|\cos(\theta)$$

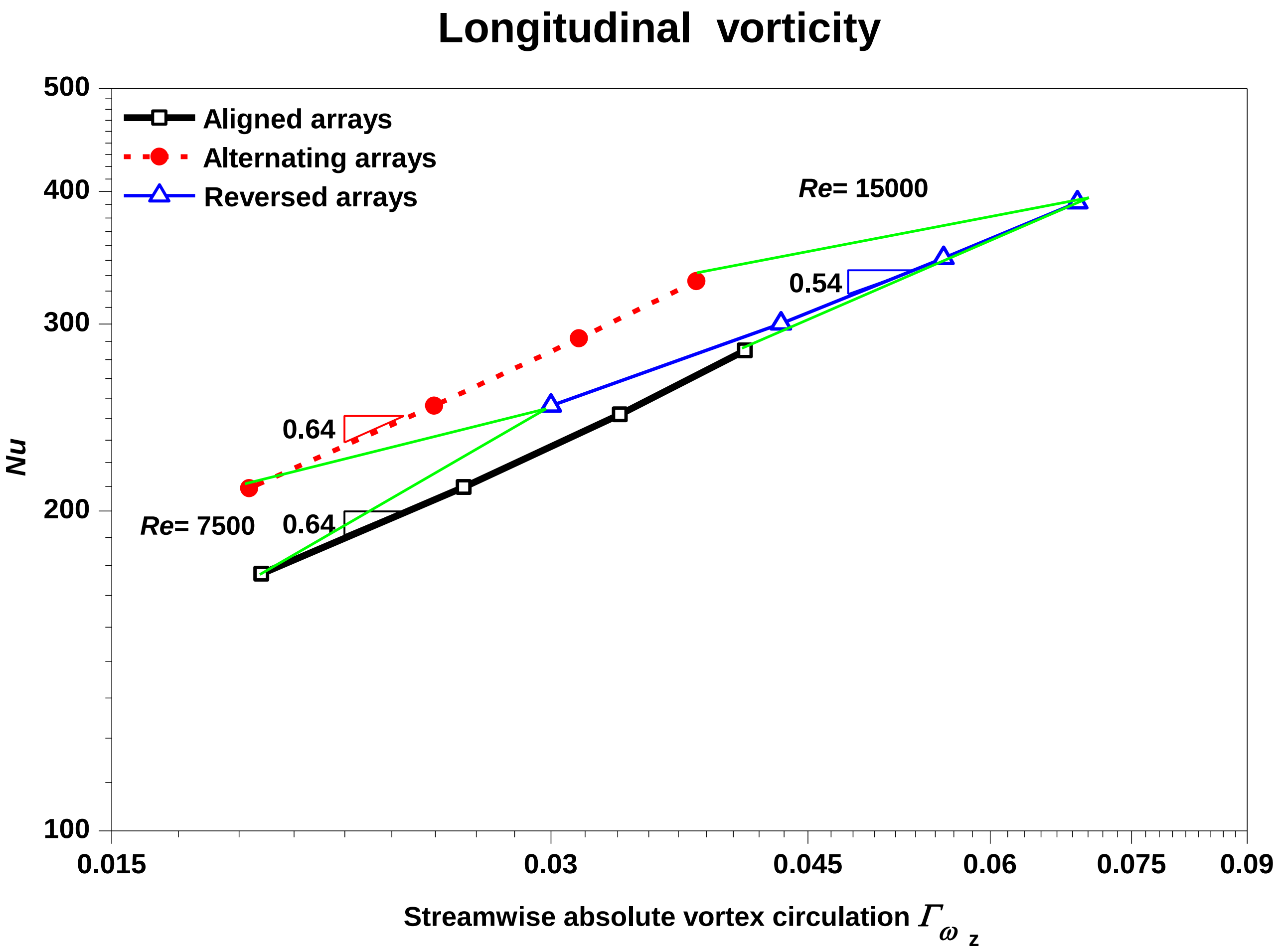
$$\theta = \arccos\left(\frac{U\dfrac{\partial T}{\partial x}+V\dfrac{\partial T}{\partial y}+W\dfrac{\partial T}{\partial z}}{\sqrt{U^2+V^2+W^2}\sqrt{\left(\dfrac{\partial T}{\partial x}\right)^2+\left(\dfrac{\partial T}{\partial y}\right)^2+\left(\dfrac{\partial T}{\partial z}\right)^2}}\right)$$



Relation between the mean angle and and Nusselt number

Not a universal relation but the same order

Intensification criteria



Nusselt number as a function of longitudinal vorticity

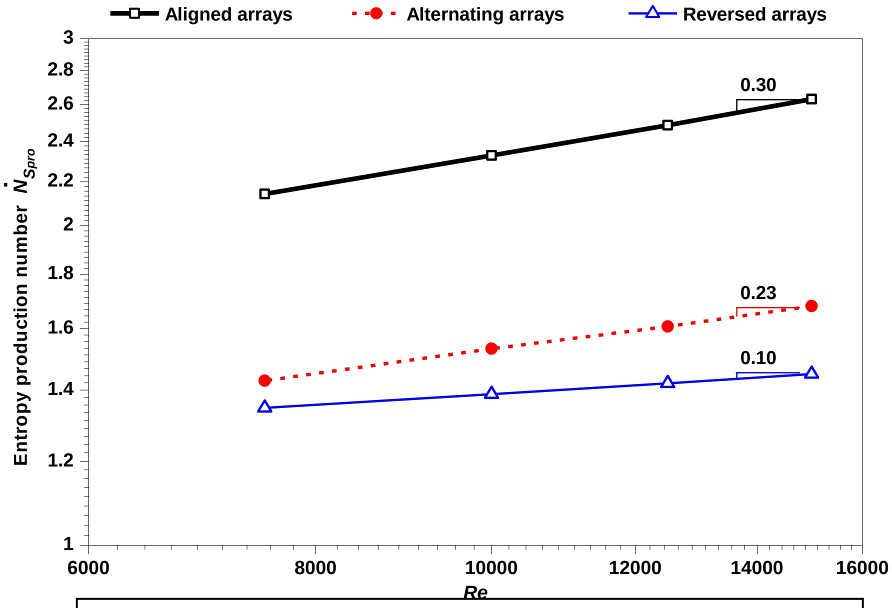
Criteria for energy efficiency

Entropy productionc: caraterizes tmransformation of mechanical eng. to heat

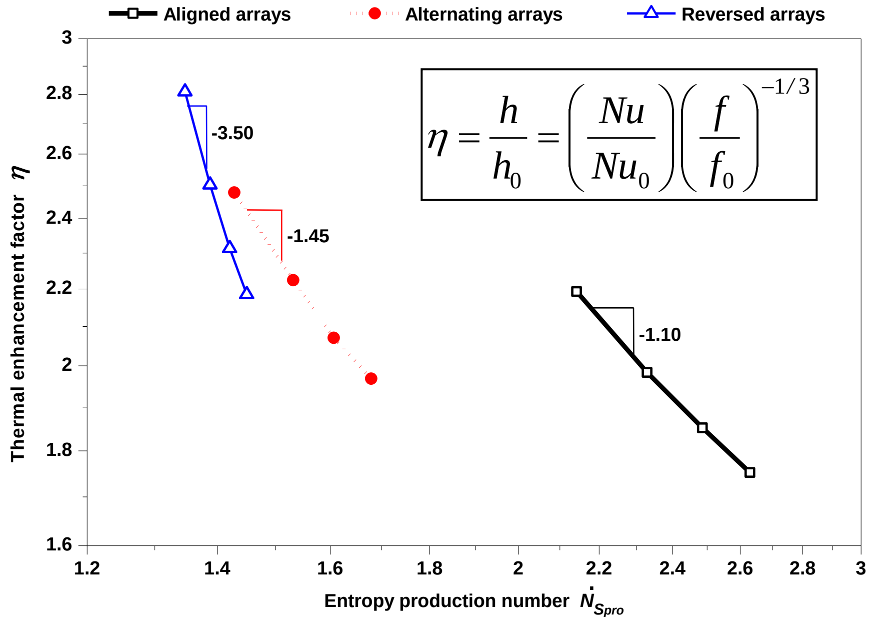
Kock et Herwing, IJHMT (2004), IJHFF (2005)

Hesselgreaves, IJHMT (2000)

$$\dot S = \underbrace{\dot S_{\bar V} + \dot S_{V'}}_{\dot S_{viscous}} + \underbrace{\dot S_{\bar T} + \dot S_{T'}}_{\dot S_{thermal}} \Longrightarrow \dot S_{pro} = \iiint_V \dot S \, dx\, dy\, dz \Longrightarrow N_{\dot S_{pro}} = \frac{\dot S_{pro} T_w}{Q_w}$$



Classification of geometries according to entropy numberd

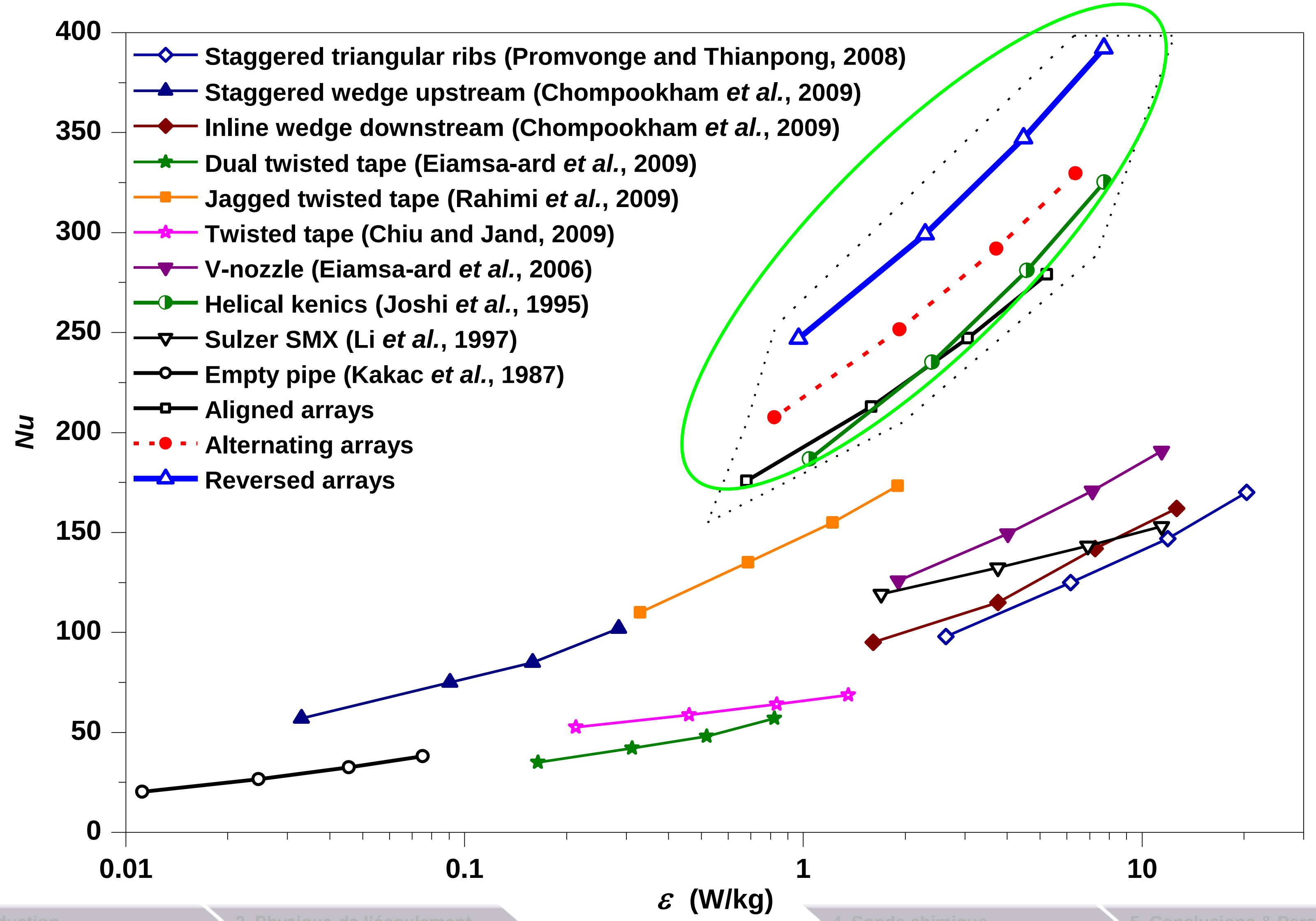


$$\eta = \frac{h}{h_0} = \left(\frac{Nu}{Nu_0}\right)\left(\frac{f}{f_0}\right)^{-1/3}$$

Colburn factor

Energy efficiency

Efficiency Diagram



Energy Challenges and the Role of Interdisciplinary Research

H. Peerhossaini, J. Szarka, and L. Valentin

Paris Interdisciplinary Energy Research Institute (PIERI),
Université Paris Diderot,
5 rue Thomas Mann, 75013 Paris, France

THE NEED FOR AN INTEGRATED APPROACH TO SOLVE COMPLEX PROBLEMS

It is both unrealistic and counterproductive to separate the scientific and technical aspects of energy from its surrounding politics.

Scientific and technical issues

- what alternative energy sources can be explored?
- how can energy be produced from these sources?
- what research projects?
- what innovations to increase energy efficiency?

THE NEED FOR AN INTEGRATED APPROACH TO SOLVE COMPLEX PROBLEMS

The aim is to devise applied solutions in social and economic contexts.

Economic issues often prevail

-what will be the costs of new energy sources?

-what will be the best energy mix in economic terms?

Social questions open out into political issues

-what imbalances between countries can be predicted?

THE NEED FOR AN INTEGRATED APPROACH TO SOLVE COMPLEX PROBLEMS

-what will be the impact of new modes of production and consumption of energy?
-what can history teach us about technology and energy transitions?

The environmental dimension will be crucial
-what are the least polluting sources?
-how do we reconcile "least polluting sourcing" with "most economical sourcing"?
-what energy mix will be the friendliest to the environment?

PARIS INTERDISCIPLINARY ENERGY RESEARCH INSTITUTE (PIERI)

PIERI is an interdisciplinary research centre, based in France at the Université Paris Diderot, which specializes in the themes outlined above.

Its mission: to bring together researchers in both the physical sciences (biology, chemistry, information technology, mathematics, physics, earth sciences, engineering) and the social sciences (anthropology, economics, geography, history, philosophy, political science, sociology).

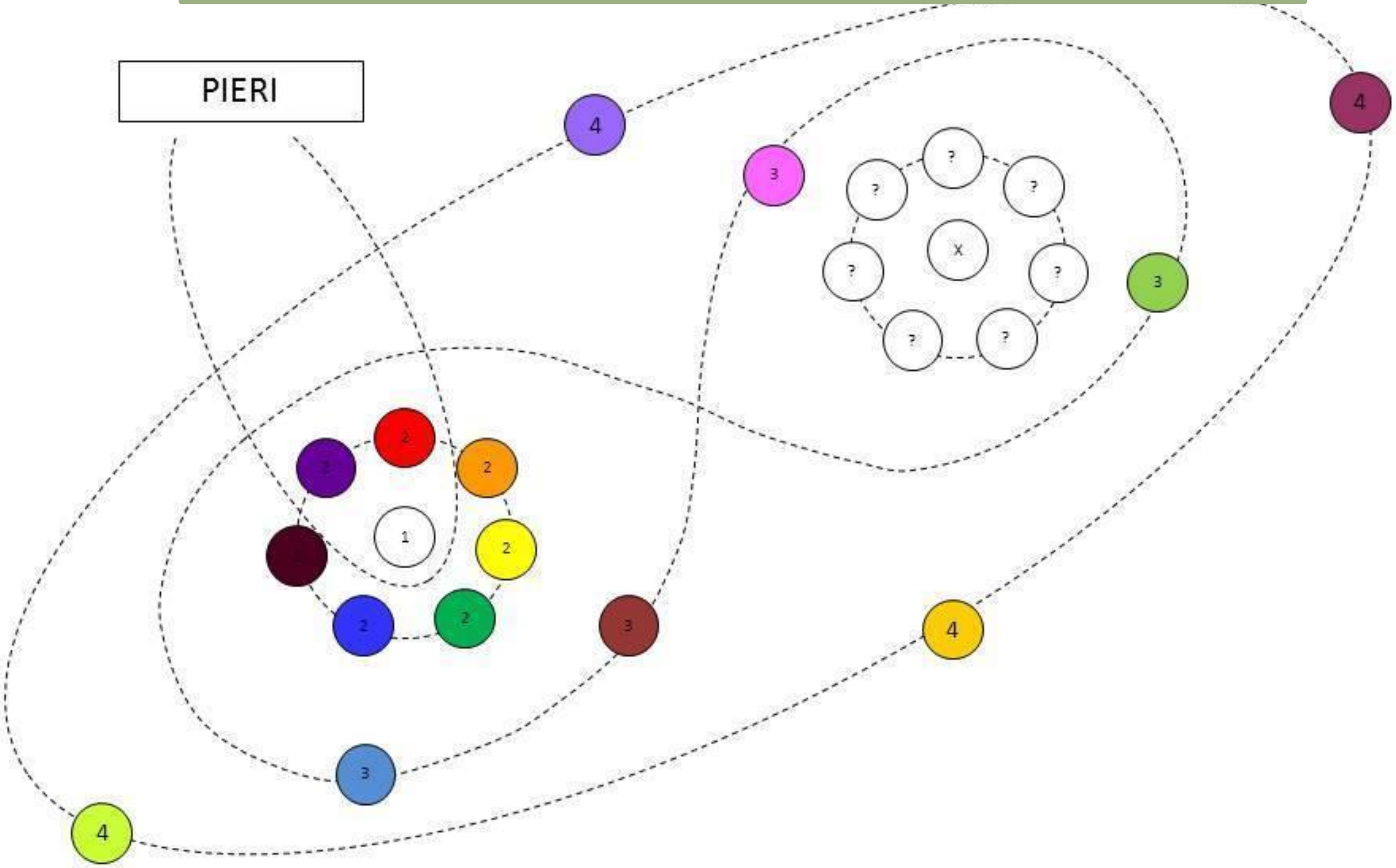
RESEARCH ORIENTATIONS: BALANCING FUNDAMENTAL AND APPLIED RESEARCH

Organized around four axes

- Basic science and low-carbon energy sources;
- The science and technology of energy efficiency;
- Forecasting, social and economic analysis, and public policy studies;
- Interdisciplinary epistemology.

PIERI AS AN INTERNATIONAL RESEARCH NETWORK

Five categories of membership



SCIENCE PARK AND START-UPS

- A science park is planned to operate in conjunction with the many companies who support PIERI.

- Given the transversal activities of the PIERI, numerous start-up ventures and hence significant employment creation are expected.

THE NINE INTERDISCIPLINARY RESEARCH GROUPS FORMING THE LIED/PIERI

1. Innovative materials and biomaterials
2. Transport, instabilities and fluctuations
3. The geography of energy sourcing;
4. The multilevel governance of energy;
5. Social representation and innovation: hydrogen and other energy pathways;

THE NINE INTERDISCIPLINARY RESEARCH GROUPS FORMING THE LIED/PIERI

6. Energy efficiency and modes of consumption;

7. Forecasting models and interdisciplinary convergence;

8. Smart grids.

9. The interdisciplinary methodology of energy studies

EXEMPLES OF PROJETS

1. Innovative materials and biomaterials

- biomimetic catalysis and genetic engineering,
- biologically assisted energy production,
- thermoelectric & photovoltaic generation of electricity,
- nanostructured materials for thermoelectricity
- hierarchical architecture of energy conversion

EXEMPLES OF PROJETS

2. Transport, instabilities and fluctuations

- turbulence control for energy efficiency in transport,
- tidal-wave energy,
- micro-mixing by turbulence for heat transfer intensification,
- materials for energy,
- thermo-acoustics.
- modeling of complexity also extend to economic, sociological and geographic systems.
- forecasting models and interdisciplinary convergence,
- physical modeling of geomatics,
- smart grids

EXAMPLES OF PROJECTS

Bottom-up ('micro') analyses are particularly relevant when addressing energy efficiency. Spatial dimensions of energy sourcing and constructing large data banks

3. The geography of energy sourcing

- energy and cities,
- territorial governance of energy transitions,
- energy integration and inequalities,
- spatial energy indicators,
- the energy landscape,
- spatial analysis and modeling of commercial energy flows

EXAMPLES OF PROJECTS

Aims: To integrate macro- and micro-level analyses.
To investigate the economic and political dimensions of issues such as international trade in energy and access to energy supplies in developing countries.

4. The multilevel governance of energy

- wind power and landscape issues,
- emergence of transnational solar energy projects,
- carbon capture and storage policy,
- developing a fiscal incentive policy for businesses,
- possible successors to the Kyoto Protocol,
- comparative analysis of carbon taxing,
- intra-European political issues of electricity generation and carbon emission regulations,
- geopolitical issues related to the coordination of European energy policy

EXAMPLES OF PROJECTS

Hydrogen as an energy **source** and **carrier** raises a large range of questions: the assessment of technological and geological needs for better assessment of the role of hydrogen in the energy mix; appraisal of the social dimension.

5. Social representation and innovation: hydrogen and other energy pathways

- This potential new energy carrier was chosen because of real challenges it poses.

A range of possible sources of natural hydrogen are already being discussed (ultrabasic rocks, in situ coal gasification, biological processes), as well as industrial processes to manufacture hydrogen, opposition has emerged, both from energy companies and society.

EXAMPLES OF PROJECTS

Linkages between energy efficiency, which is typically treated as a technical issue, and energy consumption, which is often considered in social or behavioral terms.

6. Energy efficiency and modes of consumption

- man-machine-system interface in energy efficiency in industry,
- energy sobriety and efficiency,
- indicators of energy sobriety and energy efficiency,
- national economic impact of environmental constraints on construction activities,
- behavioral and techno-social analysis of renewable energies

EXEMPLES OF PROJETS

This research group consolidates expertise in modeling complex systems drawn from both the physical and the social sciences.

7. Forecasting models and interdisciplinary convergence

- the role of energy efficiency in the energy transition,
- renewable energy in the energy mix,
- urban modeling and territorial science,
- energy exchange in world trade.

EXAMPLES OF PROJECTS

This highly pragmatic theme illustrates the need for close partnership between the ‘hard’ sciences, the social sciences, engineering and industry.

8. Smart grids

- ‘bottom-up’ analyses promoting the secure operation of smart grids
- future intelligent energy clusters
- smart grids versus smart metering.

EXEMPLES OF PROJETS

Reflexion on interdisciplinary methodology While historians of science and technology play a leading role here, linguists also have their place.

9.The interdisciplinary methodology of energy studies

This inclusive group will look into interdisciplinary problems arising within the thematic groups and illuminate methodological questions.

EDUCATION: PREPARING FUTURE GENERATIONS FOR ENERGY CHALLENGES

Master's programs

- Physics of energy
- Energy, ecology and society
- Environmental sciences
- Biology for bioenergies (under process)
- Chemistry for energy (under process)

ASSOCIATING TECHNICAL EXPERTISE WITH PHILOSOPHICAL REFLECTION

These programs give invaluable opportunities to students, who increasingly seek to associate technical expertise with philosophical reflection, responsible citizenship with greater participation in the political life of the society in which they live, in order to address multiple energy challenges.

CONCLUSIONS

- In the energy domain, interdisciplinary research is a necessity.

- Any serious investigation into energy soon reveals the impracticality of separating scientific and technical issues from the surrounding political and social contexts.

- It is crucial to devise innovative research organizations capable of rising to these challenges.

- The PIERI-LIED is an example of a research institute working in this direction