INTRODUCTION TO PROCESS INTENSIFICATION:

PHILOSOPHY AND BASIC PRINCIPLES
SOURCES OF OIL:
FORAMINIFERA
THE OMNIPRESENT CHEMISTRY: FROM THE CRADLE TO THE GRAVE ...AND BEYOND!
Consumption of chemical products is rapidly increasing

- new types of chemical and biochemical products brought to the market
- new markets open in different parts of the world for already existing products

Main reasons

- rapid growth in world’s population
- growth in consumers’ wealth
- growth in consumers’ needs
OIL PRODUCTION FORECAST
(U.S. Energy Information Administration)
THE NON-SUSTAINABLE MANKIND

SOME FORECASTS:

- WE WILL ESSENTIALLY USE UP ALL THE WORLD’S OIL RESOURCES BY 2050 (S. A. Nelson)

- WE WILL ESSENTIALLY USE UP ALL THE WORLD’S GAS RESOURCES BY 2070 (P.-R. Baquis)

- WE WILL ESSENTIALLY USE UP ALL THE WORLD’S COAL RESOURCES BY 2500 (S. A. Nelson)
Steam Cracker - Cathedral of the Chemical Industries of 20th Century

An extinct species in 50 years?
How to solve the resources problem?

**OPTION 1:**
- start exploitation of extraterrestrial resources
  - still in the S-F stage and may remain so

**OPTION 2:**
- develop technically and economically feasible processes based on the renewable feedstocks ("green", biomass-based processes)
Some open questions to **OPTION 2**:  

- do we have enough arable land to feed mankind **AND** to provide energy **AND** to supply raw materials simultaneously?  
- what will we do with by-products, such as CO$_2$?  
- how will this “new farming” influence environment?  
- what will be repercussions of genetic manipulations?  
- what about inorganic chemical products?  
- when will this all be feasible?
How to solve the resources problem?

OPTION 3:

- develop innovative methods and technologies that would DRASTICALLY increase the EFFICIENCY of chemical and biochemical processes

- FACTOR 4 (Von Weizsacker, 1998)
- FACTOR 10 (Schmidt-Bleek, 1993)
- FACTOR 20? (AllChemE – Alliance for Chemical Sciences and Technologies in Europe, 2001)
G. Agricola, *De Re Metallica*, 1556

Chemical Process Industry, 2012

- THIS IS NOT THE WAY TO BOOST EFFICIENCY
- PROCESS INNOVATION IS CLEARLY NEEDED
Innovation = Unproven Solutions

("Plant manager never wants to be the first")

"Don’t bother me with new ideas, I’ve got a battle to fight!"
Process industry is facing numerous challenges

- Raw materials
- Energy
- Labor
- Land
- Water

- Availability
- Prices
- Environmental demands: CO₂, safety, ...
- Cost competitiveness
- Higher added value
- Recycling

Current feedstock
Bio-based feedstock

Source: Roland Berger
Only 25 wt% of what goes into the pipe comes out as goods and services

(Source: World Resource Institute)
## ISSUES OF CONCERN FOR CHEMICAL INDUSTRY: ENVIRONMENT

<table>
<thead>
<tr>
<th>Industry Sector</th>
<th>Product tonnage</th>
<th>Tons by-product/ton product</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oil refining</td>
<td>$10^6 - 10^8$</td>
<td>&lt; 0.1</td>
</tr>
<tr>
<td>Bulk chemicals</td>
<td>$10^4 - 10^6$</td>
<td>1 - 5</td>
</tr>
<tr>
<td>Fine chemicals</td>
<td>$10^2 - 10^4$</td>
<td>5 – 50+</td>
</tr>
<tr>
<td>Pharmaceuticals</td>
<td>$10 - 10^3$</td>
<td>25 – 100+</td>
</tr>
</tbody>
</table>
Laws and regulations

Identified possible improvements versus expected developments in legislation

Shrink is inevitable

Our technology X

Legislative and regulatory constrains

Is our technology X able to sustain the compliance with future legislative and regulatory constrains?

2012

> 2020
ISSUES OF CONCERN FOR CHEMICAL INDUSTRY: SAFETY

Union Carbide, Bhopal, December 3, 1984

BASF, Oppau/Ludwigshafen, September 21, 1921

AZF, Toulouse, September 21, 2001

TERRORISM – THE PLAGUE OF THE 21ST CENTURY: IS CHEMICAL INDUSTRY SAFE ENOUGH?
License to Operate

Within 8 days from the accident ban on ALL chemical activities in the Toulouse area, Licence to Operate withdrawn permanently

AZF, Toulouse, September 21, 2001
ISSUES OF CONCERN FOR CHEMICAL INDUSTRY: PUBLIC IMAGE

ONLY TOBACCO AND NUCLEAR SECTORS HAVE WORSE PUBLIC IMAGE
sooner or later a critical limit will be reached
competitors will follow
the only way to go beyond that limit and gain significant long-term advantage over the competitors is via innovative technological development
One of PI definitions:

A set of often radically innovative principles ("paradigm shift") in process and equipment design, which can bring significant (more than a factor of 2) benefits in terms of process and chain efficiency, capital, energy, inventory, quality, wastes, process safety, etc.

(European Roadmap of Process Intensification, 2007)
PI - fundamental benefits

- Energy savings (20 – 80%)
- CapEx and OpEx savings (20 – 80%)
- Selectivity and yield increase (up to >10 times)
- Significant process safety increase (reactor volume & inventory of chemicals decreased 10-1000 times + better reaction control)

(2006 study by SenterNovem, Dutch Energy and Environmental Agency)
Lower costs due to PI

- **land costs** (much higher production capacity and/or number of products (plants) per unit of manufacturing area);

- **other investment costs** (cheaper, compact equipment, reduced piping etc.);

- **costs of raw materials** (higher yields/selectivities);

- **costs of utilities** (energy in particular);

- **costs of waste-stream processing** (less waste in general).
Lower costs due to PI

COST OF PRESENT PROCESS = 100%
Shorter time to the market = lower cost

Example: How to shorten time to the market in pharmaceutical technologies?

Possible solution: a continuous lab-scale plant as a commercial-scale production unit

Advantages:

- FDA approval procedures of drug technology take place only once: the lab-scale is the commercial-scale.
- Process development takes place only once, with no scale-up via a pilot plant to the industrial scale.

Result:

- Start of the commercial production speeded up, in some cases even by several years.
- Time to the market shortened - patent time better utilized.

Do not forget: in continuous operation 1 ml/s = 30 t/year!
LESSON LEARNED:
Process could have been intensified to contain a total inventory of less than 10 kg of MIC, instead of 41 tons!

Intensified means: SAFER!

Union Carbide, Bhopal, December 3, 1984
SHORT HISTORY OF PI
Origins of Process Intensification

FROM NASA's SPACE PROGRAM TO INNOVATIVE CHEMICAL PLANTS
History of process intensification

• Term “Process Intensification” appeared in early 1960’s
  • Mostly East-European publications on METALLURGY
  • “Process Intensification” = “Process Improvement”

• Comes to chemical engineering literature in 1970’s
  (Leszczynski, 1973, Romankov, 1977, Kleemann and Hartmann, 1978)
  • still East-European domain
  • still “Process Intensification” = “Process Improvement”
History of process intensification

• 1983 - Colin Ramshaw from ICI New Science Group describes studies on application of centrifugal fields (so-called “HiGee”) in distillation processes
  • PI = “devising exceedingly compact plant which reduces both the “main plant item” and the installations costs”

• 1983 - Annual Research Meeting of IChemE entitled Process Intensification held at UMIST, Manchester
  • first paper presented at that meeting concerned PROCESSING OF GOLD ORE using intensive methods
  • PI = “order-of-magnitude reductions in process plant and equipment” (Heggs)
History of process intensification

• 1980’s and early 1990’s – mainly British discipline
  • primarily focused on four areas: the use of centrifugal forces, compact heat transfer, intensive mixing and combined technologies
  • 1995 - 1st Conference on Process Intensification
  • Process Intensification Network – PIN-UK

• late 1990’s – growing interest and activities in different parts of the world
  • research centers in US (PNNL, MIT), France (Greth CEN), Germany (IMM), UK (BHR), China (HighGravitec) and many more…
  • industry enters the scene – first applications at Eastman, Dow, DSM, Sulzer and many more…
Awareness of the importance of PI has grown strongly in last 10 years

- PI placed clearly in sustainability context
- First university courses, books, international conferences, journal
- National networks in UK, NL and DE
- Numerous industrial initiatives
- EFCE establishes of the Working Party on Process Intensification
- PI in FP7
- European Roadmap for PI
POSITION OF PI
After W. Marquardt (2000)
## Process Intensification versus Process Systems Engineering and Process Optimization

<table>
<thead>
<tr>
<th></th>
<th>Process Optimization</th>
<th>Process Systems Engineering</th>
<th>Process Intensification</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Aim</strong></td>
<td>Performance improvement of existing concepts</td>
<td>Multi-scale integration of existing and new concepts</td>
<td>Development of new concepts of process steps and equipment</td>
</tr>
<tr>
<td><strong>Focus</strong></td>
<td>Model, numerical method</td>
<td>Model, software</td>
<td>Experiment, phenomenon, interphase</td>
</tr>
<tr>
<td><strong>Interdisciplinarity</strong></td>
<td>Weak (interface with applied mathematics)</td>
<td>Modest (mostly applied mathematics and informatics, chemistry)</td>
<td>Strong (chemistry &amp; catalysis, applied physics, mechanical engineering, materials science, electronics, etc.)</td>
</tr>
</tbody>
</table>
PI as a technology toolbox

- spinning disk reactor
- static mixer reactor
- monolithic reactor
- microreactor
- static mixer
- compact heat exchanger
- rotating packed bed
- centrifugal adsorber
- heat-integrated reactors
- reactive separations
- reactive comminution
- reactive extrusion
- fuel cells
- membrane absorption
- membrane distillation
- adsorptive distillation
- centrifugal fields
- ultrasounds
- solar energy
- microwaves
- electric fields
- plasma technology
- supercritical fluids
- dynamic (periodic) reactor operation
PI technologies on maturity S-curve

Different stages of technical development

- Embryonic
- Growth
- Mature
- Aging

Performance of technology

Natural limit of technology

Conventional

- Stirred vessel
- Shell&tube Hex
- Mixer settler
- Filter
- Centrifuge
- One stage dest
- Conical dryer

Micro distillation
- Micro extraction
- Micro wave dryer
- Micro reactor
- Micro Hex
- Micro mixer
- RPB
- Flash dryer
- Centrifugal extractor
- Static mixer
- Loop reactor

(R. Reintjens)

Tom Van Gerven and Andrzej Stankiewicz

Process & Energy Department, Delft University of Technology, Leeghwaterstraat 44, 2628 CA Delft, The Netherlands
Fundamentals of Process Intensification

maximizing the effectiveness of intra- and intermolecular events

- each molecule getting the same processing experience
- optimizing the driving forces and maximizing the specific surface areas to which these forces apply
- maximizing synergistic effects from partial processes
What’s wrong with current reactors?
- Limited control upon molecules

Energizing molecules via conductive heating, or turning snooker into pinball
- non-selective
- amplifies random motions and collisions
- produces temperature gradients
A snooker game with molecules: how to hit the right one, with right energy, at right orientation?

CHALLENGE: control of the geometry of approach and mutual orientation of molecules at the moment of collision

CHALLENGE: the most efficient way of supplying energy (amount, form, position and moment) to let reactants molecules selectively overcome activation energy barrier

(www.drmackay.org)
Where are the limits of reaction rate?

...or is our thinking about reactions and reactors not limited by the traditional, macroscopic temperature-based approach to reaction kinetics?

\[ k = k_0 e^{-\frac{E_a}{R \cdot T}} \]

Laser-induced vibration: C-H bond stretching, making the target molecule “bigger” for collisions + introducing stripping collisions: reaction rate increase >100x

(Simpson et al. 1996; Kandel & Zare, 1998; Hoffman, 2000)
Control of spatial orientation of molecules and geometry of collisions

Methods for controlling molecular alignment and orientation

Orientation control via nano-structural confinement
- Shape-selective catalysts
- Imprinted catalysts
- Molecular reactors (cyclodextrins)
- Liquid crystals

Alignment and orientation control via external fields
- Molecular beam
- Stark’s effect methods (electric field)
- Brute force methods
  - Magnetic
  - Electric
  - Adiabatic
  - Femtosecond

- Non-resonant laser

• Molecules get immobilized
• Structures confining the access
• “Take it or leave it”

• Molecules move
Control of spatial orientation of molecules and geometry of collisions

(A)- Orientation of a molecular beam of carbonyl sulphide molecules moving along the $z$-axis by a hexapole electric field (left) followed by their dissociation by a laser beam acting along the $x$-axis (from Rakitzis, et al, 2004); (B) - Probability plot of the molecular orientation of the OCS molecule; dotted arrows are proportional to the orientation probability of the OCS dipole moment along each direction.
Control of spatial orientation of molecules and geometry of collisions

A “multitubular reactor” of the future?

Multi-beam hexapole honeycomb device for orienting molecules in static electric field

(Shimizu, 2003)
Fundamentals of Process Intensification

- Maximizing the effectiveness of intra- and intermolecular events
- Giving each molecule the same processing experience
- Optimizing the driving forces and maximizing the specific surface areas to which these forces apply
- Maximizing synergistic effects from partial processes

**PRINCIPLES (GOALS)**

**APPROACHES**

**SCALES**

**ENERGY** (thermodynamic domain)

**STRUCTURE** (spatial domain)

**SYNERGY** (functional domain)

**TIME** (temporal domain)
What’s wrong with current reactors?
- Limited control upon molecules

Illustration of the energy distribution problem in molecules, in relation to the yield of simple parallel reactions. A stirred-tank reactor with conductive heating generates energy distribution due to temperature gradients, which translate to both material and energy losses.
Giving each molecule the same processing history

Stirred-tank reactor with a heating jacket (a) contradicts the 2nd principle of Process Intensification. The residence time of molecules is widely distributed and both concentration and temperature non-uniformities are present. On the other hand, a plug-flow reactor with a gradientless, volumetric (e.g. microwave) heating (b) enables a close realization of that principle.
Fundamentals of Process Intensification

- Maximizing the effectiveness of intra- and intermolecular events
- Giving each molecule the same processing experience
- Maximizing synergistic effects from partial processes

- Optimizing the driving forces and maximizing the specific surface areas to which these forces apply
Optimizing the driving forces and maximizing the specific surface areas to which those force apply

Surface to volume ratio depends on diameter

\[
\frac{A}{V} = \frac{\pi \cdot D \cdot L}{\left(\frac{\pi \cdot D^2 \cdot L}{4}\right)} = \frac{4}{D}
\]

Enhance mass and heat transfer by increasing the transfer area

<table>
<thead>
<tr>
<th>D (m)</th>
<th>1</th>
<th>0.1</th>
<th>0.001</th>
</tr>
</thead>
<tbody>
<tr>
<td>A / V (m²/m³)</td>
<td>4</td>
<td>40</td>
<td>4000</td>
</tr>
</tbody>
</table>
Optimizing the driving forces and maximizing the specific surface areas to which those force apply

How to catch up with the Nature and generate ultra-high-interface systems?

<table>
<thead>
<tr>
<th>D (m)</th>
<th>0.0001</th>
</tr>
</thead>
<tbody>
<tr>
<td>A/V (m²/m³)</td>
<td>40000</td>
</tr>
</tbody>
</table>

Capillary blood vessels

<table>
<thead>
<tr>
<th>D (m)</th>
<th>0.00001</th>
</tr>
</thead>
<tbody>
<tr>
<td>A/V (m²/m³)</td>
<td>400,000</td>
</tr>
</tbody>
</table>
Fundamentals of Process Intensification

- **PRINCIPLES (GOALS)**
  - Maximizing the effectiveness of intra- and intermolecular events
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  - Maximizing synergistic effects from partial processes

- **APPROACHES**
  - **SCALES**
    - Molecular processes
    - Catalyst/reaction processes, particles, thin films
  - Processing units
  - Processing plant/site
  - Hydrodynamics and transport processes, single- and multiphase systems

- **STRUCTURE** (spatial domain)
  - **ENERGY** (thermodynamic domain)
  - **SYNERGY** (functional domain)
  - **TIME** (temporal domain)
Maximizing synergistic effects from partial processes

Example: catalytic function + separation function

methanol + ammonia → monomethylamine + dimethylamine + trimethylamine

(MMA) (DMA) (TMA)

ordinary Si-Al catalyst

Carbon molecular sieve layer (∼ 0.5 nm pores)

Selectivity
(MMA+DMA)/TMA

catalyst
2

catalyst + membrane
5

Agar, 1999
**STRUCTURE** (spatial domain)

- Maximizing the effectiveness of intra- and intermolecular events

**ENERGY** (thermodynamic domain)

- Giving each molecule the same processing experience

**SYNERGY** (functional domain)

- Optimizing the driving forces and maximizing the specific surface areas to which these forces apply

**TIME** (temporal domain)

- Maximizing synergistic effects from partial processes

**APPROACHES**

**PRINCIPLES (GOALS)**

- Maximizing the effectiveness of intra- and intermolecular events
- Giving each molecule the same processing experience
- Optimizing the driving forces and maximizing the specific surface areas to which these forces apply
- Maximizing synergistic effects from partial processes
STRUCTURE: examples
Example: Microreactor for manufacturing of a specialty product (DSM)

Traditional technology

Stirred Tank Reactor: the reactants are mixed in a large vessel, and the heat is removed through the jacket or a heat transfer coil.

PI technology

Microreactor: the reactants are mixed, and the heat is removed through thousands of micro channels, fabricated by micromachining or lithography.

Benefits

- Equipment content 3 litres vs 10 m³
- 20% higher selectivity → 20% higher material yield
- Process more reliable because continuous instead of batch
- Same capacity (1700 kg/h)

Photos courtesy of DSM and Forschungszentrum Karlsruhe
Fundamentals of Process Intensification

**PRINCIPLES** (GOALS)

- **Maximizing the effectiveness of intra- and intermolecular events**
- ** Giving each molecule the same processing experience**
- **Optimizing the driving forces and maximizing the specific surface areas to which these forces apply**
- **Maximizing synergistic effects from partial processes**

**APPROACHES**

- **STRUCTURE** (spatial domain)
- **ENERGY** (thermodynamic domain)
- **SYNERGY** (functional domain)
- **TIME** (temporal domain)
ENERGY: examples

- X-Rays
- Ultraviolet
- Visible
- Infrared
- Microwaves
- Radio waves

**Wave Length (meters)**

- $10^{-10}$
- $10^{-8}$
- $10^{-6}$
- $10^{-5}$
- $10^{-4}$
- $10^{-3}$
- $10^{-2}$
- $10^{-1}$
- $1$

**Frequency (MHz)**

- $3 \times 10^{12}$
- $3 \times 10^{10}$
- $3 \times 10^8$
- $3 \times 10^6$
- $3 \times 10^4$
- $3 \times 10^2$

**Molecular vibrations**

**Molecular rotations**

**ACOUSTIC CAVITATION**

- Bubble forms
- Bubble grows in successive cycles
- Reaches unstable size
- Undergoes violent collapse

- Laser Radiation

**ENERGY**

MSc Course on Process Intensification
Example: High-Gravity Rotating Packed Bed for the production of hypochlorous acid (Dow Chemical)

**Traditional technology**

A system of absorption-stripping columns: the main product (HClO) has to be removed as quickly as possible from the reaction environment to prevent its decomposition.

**PI technology**

Reactive stripping in High-Gravity (HiGee) Rotating Packed Beds: the reactants are subjected to intensive contact and the product is immediately removed via stripping using high-gravity forces in a rotating apparatus with a specially designed packing.

**Benefits**

- Equipment size decreased by a factor of ca. 40
- Ca. 15% higher product yield
- 50% reduction of the stripping gas
- 1/3 reduction in waste water & chlorinated byproducts
- Same processing capacity

Photos courtesy of Dow Chemical Company;
# Fundamentals of Process Intensification

<table>
<thead>
<tr>
<th>PRINCIPLES (GOALS)</th>
<th>STRUCTURE (spatial domain)</th>
<th>ENERGY (thermodynamic domain)</th>
<th>SYNERGY (functional domain)</th>
<th>TIME (temporal domain)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>maximizing the effectiveness of intra- and intermolecular events</td>
<td>giving each molecule the same processing experience</td>
<td>optimizing the driving forces and maximizing the specific surface areas to which these forces apply</td>
<td>maximizing synergistic effects from partial processes</td>
</tr>
</tbody>
</table>

**APPROACHES**

- **Structure**
  - Catalyst/reaction processes, particles, thin films
  - Processing units

- **Energy**
  - Hydrodynamics and transport processes, single- and multiphase systems

- **Synergy**
  - Fundamentals of Process Intensification

- **Time**
  - (temporal domain)
SYNERGY: examples

- Silicalite-1 coating
- Pt catalyst
- TiO$_2$ support

Conventional Process  Membrane Process
Example: Methyl acetate in multifunctional reactor (Eastman Chemical)

**Traditional technology**

28 pieces of equipment: separation problem - two azeotropes

**PI technology**

Multifunctional reactor column including reactive and extractive distillation steps

**Benefits**

- Equipment from 28 reduced to 3
- Reduced energy consumption by ca. 85%
- Reduced investment by ca. 80%
Fundamentals of Process Intensification

**Principles (Goals)**
- Maximizing the effectiveness of intra- and intermolecular events
- Giving each molecule the same processing experience
- Optimizing the driving forces and maximizing the specific surface areas to which these forces apply
- Maximizing synergistic effects from partial processes

**Approaches**
- **Structure** (spatial domain)
- **Energy** (thermodynamic domain)
- **Synergy** (functional domain)
- **Time** (temporal domain)

**Molecular Processes**
- Catalyst/reaction processes, particles, thin films
- Processing units
- Hydrodynamics and transport processes, single- and multiphase systems
TIME: examples
Example: Oscillatory Baffle Flow Reactor

James Bond at James Robinson, or SHAKEN, NOT STIRRED...

Reduction in:
- Space (20x)
- Process time (20x)
- Capital cost (2x)
- Energy and waste (many times)
- Quality defects
**Fundamentals of Process Intensification**

**PRINCIPLES (GOALS)**
- Maximizing the effectiveness of intra- and intermolecular events
- Giving each molecule the same processing experience
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**APPROACHES**
- **STRUCTURE** (spatial domain)
- **ENERGY** (thermodynamic domain)
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**SCALES**
- **Molecular processes**
- **Catalyst/reaction processes, particles, thin films**
- **Hydrodynamics and transport processes, single- and multiphase systems**
- **Processing units**
- **Processing plant/site**
SUMMARIZING…

Fundamental principles and approaches of Process Intensification are applicable to any chemical process or operation. Intensification needs simultaneous addressing the four domains, as given below:

<table>
<thead>
<tr>
<th>Domain</th>
<th>Main focus</th>
<th>Process Intensification concepts applied</th>
<th>Motivation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spatial</td>
<td>Structured environment</td>
<td>Milli- and microchannels; structured (catalyst) surfaces</td>
<td>• well-defined geometry&lt;br&gt;• creating maximum specific surface area at minimum energy expenses&lt;br&gt;• creating high mass and heat transfer rates&lt;br&gt;• precise mathematical description&lt;br&gt;• easy understanding, simple scale-up</td>
</tr>
<tr>
<td>Thermodynamic</td>
<td>Alternative forms and transfer mechanisms of energy</td>
<td>Electric and electromagnetic fields</td>
<td>• manipulation of molecular orientation&lt;br&gt;• excitation of targeted molecules&lt;br&gt;• selective, gradientless and local energy supply</td>
</tr>
<tr>
<td>Functional</td>
<td>Integration of functions/steps</td>
<td>Combination of alternative energy forms (e.g. electric and laser fields), combination of catalyst and energy source or energy-absorbing material.</td>
<td>• synergistic effects&lt;br&gt;• better heat management&lt;br&gt;• increase of overall efficiency&lt;br&gt;• more compact equipment</td>
</tr>
<tr>
<td>Temporal</td>
<td>Timing of the events, introducing dynamics</td>
<td>Dynamic (pulsed) energy supply, millisecond contacting</td>
<td>• controlled energy input&lt;br&gt;• utilizing resonance&lt;br&gt;• increased energy efficiency&lt;br&gt;• side reactions minimized</td>
</tr>
</tbody>
</table>
SUMMARIZING: about multidisciplinarity

Multidisciplinarity of R&D approach is essential to Process Intensification. Collaboration between chemical engineering and other disciplines such as chemistry & catalysis, material science, applied physics or electronics is of crucial importance.

(O. Levenspiel: Chemical Reactor Omnibook)
<table>
<thead>
<tr>
<th>Date</th>
<th>Block</th>
<th>Subject</th>
<th>Lecturer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thurs 8 Nov</td>
<td></td>
<td>Designing a Sustainable Chemical Plant (including elements of Inherently Safer Process Design) – presentation of PI project assignments</td>
<td>Stefanidis/Sturm</td>
</tr>
<tr>
<td>Mon 12 Nov</td>
<td>PI in Temporal Domain</td>
<td>TIME</td>
<td>Stefanidis</td>
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<tr>
<td>Thurs 15 Nov</td>
<td>PI in Spatial Domain</td>
<td>STRUCTURE</td>
<td>Stankiewicz</td>
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<td>Mon 19 Nov</td>
<td>PI in Thermodynamic Domain</td>
<td>ENERGY – Part 1</td>
<td>Stefanidis</td>
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<tr>
<td>Thurs 22 Nov</td>
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<td>ENERGY – Part 2</td>
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<tr>
<td>Mon 26 Nov</td>
<td>PI in Functional Domain</td>
<td>SYNERGY – Part 1</td>
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<tr>
<td>Thurs 29 Nov</td>
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<td>SYNERGY – Part 2</td>
<td>Stankiewicz</td>
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<tr>
<td>Mon 3 Dec</td>
<td></td>
<td>Reactive Distillation and Heat Integrated Distillation</td>
<td>Kiss (Akzo Nobel)</td>
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<tr>
<td>Thurs 6 Dec</td>
<td>“FOCUS ON” lectures by guest experts:</td>
<td>Photocatalytic and Ultrasonic Reactors</td>
<td>Van Gerven (Katholieke Universiteit Leuven)</td>
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<tr>
<td>Mon 10 Dec</td>
<td></td>
<td>Rotating Fluidized Beds</td>
<td>De Wilde (Université Catholique de Leuven)</td>
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<tr>
<td>Thurs 13 Dec</td>
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<td>PI project assignments – mid-term reporting/discussion</td>
<td>Students</td>
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<tr>
<td>Mon 17 Dec</td>
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<td>PI project assignments – mid-term reporting/discussion</td>
<td>Students</td>
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<tr>
<td>Wed 23 Jan</td>
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<td>EXAMINATION</td>
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<td>EXTRA EXAMINATION</td>
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Present course

- 22 hours of lectures
- case study project (inc. 4 hrs mid-term review)
- 6 credit points:
  - written examination (50%)
  - case study project (50%)

Required minimum: grade 6 on written examination AND grade 6 in total

- Daily help-desk/project supervision:
  Guido Sturm, George Krintiras, Maryam Khodadadian
Present course - materials

Lecture notes

(Auxiliary) Re-Engineering the Chemical Processing Plant Process Intensification

Edited by: Andrzej Stankiewicz Jacob A. Moulijn

Book
Hard Cover | Illustrated
Print ISBN: 0-8247-4302-4
www.dekker.com

(Auxiliary) Process Intensification Info Sheets (aid for the case study project)

Free on-line reading via TUD Library
QUESTIONS?