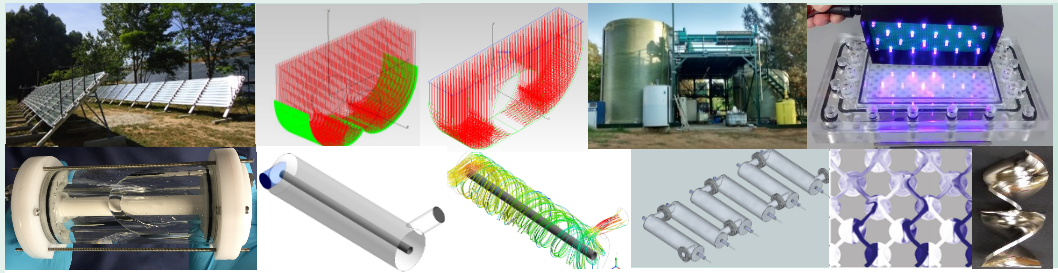

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AOPs PhD School

NOVEL PHOTOREACTORS FOR PHOTOCHEMICAL/ PHOTOCATALYTIC PROCESSES: TOWARDS PROCESS INTENSIFICATION

nereus COST ACTION ES1403

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SRE CM

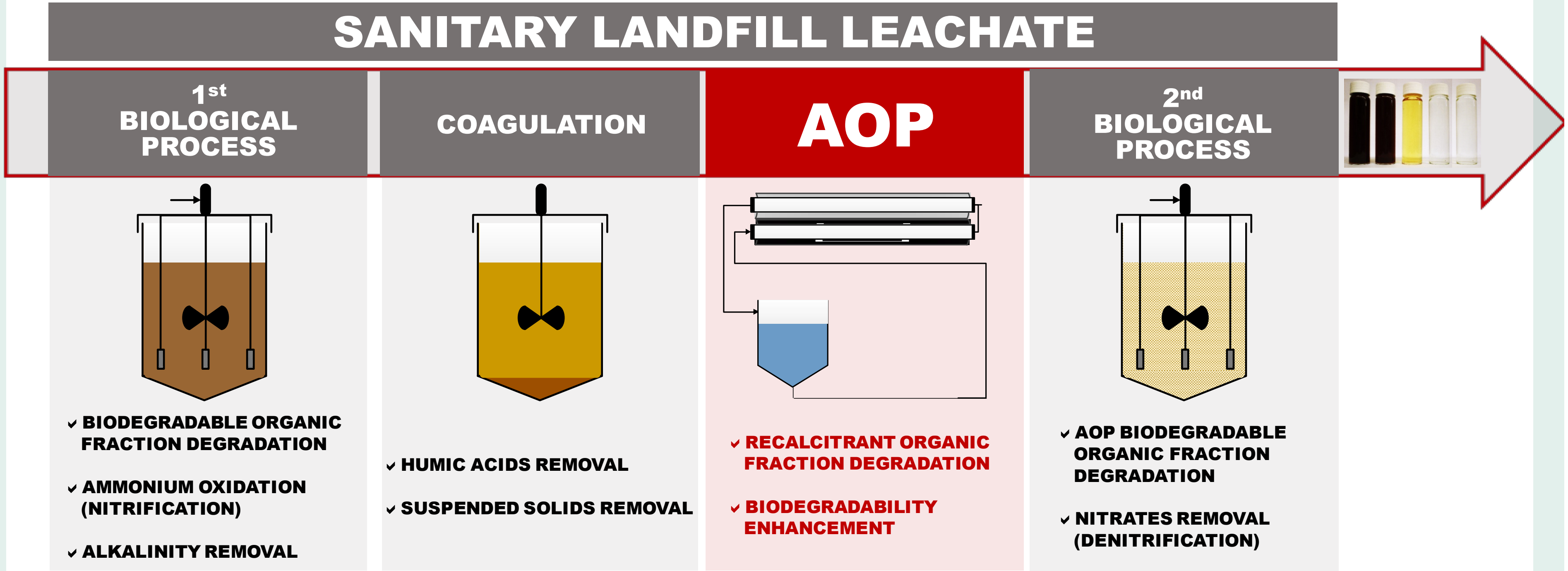
13/07/2017

INTRODUCTION

- Light induced AOPs/EAOPs are attractive technologies with potential application in the area of water, wastewater and air treatment;
- Industrial application remains limited due to low reactivity of photocatalyts in combination with photoreactors, high costs and scale up problems:
  - **Integration of AOPs/EAOPs with other technologies** such as coagulation/flocculation, biological oxidation, adsorption and membrane filtration to reduce substantially the costs associated with the AOPs/EAOPs step;
  - **Intensification of AOPs/EAOPs** through the use of innovative photoreactors (solar collectors, microreactors, photocatalytic membrane reactors) to minimize photon and mass transfer limitations.

PROCESS INTEGRATION

MULTISTAGE TREATMENT SYSTEM FOR LEACHATES



Most Expensive Step

Universidade do Porto
Faculdade de Engenharia
FEUP

efacec

European Patent nr. 14161588.0

Title: Method of Treating Leachate, Phototreatment Reactors and Respective Use

Applicant: EFACEC ENGENHARIA E SISTEMAS, S.A.

PROCESS INTEGRATION




PROCESS INTEGRATION

PROCESS INTEGRATION

PROCESS INTEGRATION

PROCESS INTENSIFICATION

Stankiewicz and Moulijn (2000) and **Stankiewicz and Drinkenburg** (2004) provide a definition of PI, comprising *novel equipment, processing techniques, and process development methods that, compared to conventional ones, offer substantial improvements in (bio)chemical manufacturing and processing.*

Stankiewicz, A., & Moulijn, J. A. (2000) Process intensification: Transforming chemical engineering. *CEP*, *96*, 22.

Stankiewicz, A., & Drinkenburg, A. H. (2004). Process intensification: History, philosophy, principles. In A. Stankiewicz & J. A. Moulijn (Eds.) *Re-engineering the chemical processing plant* (pp. 1–32). NewYork: Dekker.

Jacob A. Moulijn

- *Producing much more with much less* is the clue to process intensification.

Computers and Chemical Engineering 32 (2008) 3–11

PROCESS INTENSIFICATION:
Photocatalytic Processes

1. Overcoming mass transfer limitations: promoting fast adsorption-desorption, increasing catalyst surface area (hydrodynamics; external mass transfer; internal mass transfer)
2. Optimizing photon transfer limitations: optimum lighting strategy and reactor geometry to maximize irradiance;
3. Equipment: smaller, lighter, cheaper, excellent operation.

- Illumination Efficiency:

$$\eta_{ill} = k \underbrace{\left(\frac{P_{cat}}{P_{lamp}}\right)}_{\text{Average power efficiency}} \underbrace{\left(\frac{A_{min,E}}{A_{cat}}\right)}_{\text{Incidence light uniformity}}$$

k – illuminated catalyst coated surface per reaction liquid volume (m_{ill}^2/m^3);
P_{cat} – *radiant power incident on the catalyst surface (W);*
P_{lamp} – *radiant power emitted from the lamp (W);*
$A_{min,\,E}$ – *catalyst surface that receives at least the band-gap energy (m^2)*
A_{cat} – *total catalyst surface (m^2)*

Tom Van Gerven et al 2007, Chemical Engineering and Processing: Process Intensification 46, pp 781-789
Tom Van Gerven et al 2015, Chemical Engineering and Processing: Process Intensification 97, pp 106-111

PROCESS INTENSIFICATION: Photocatalytic Processes

1. Overcoming mass transfer limitations: promoting fast adsorption-desorption, increasing catalyst surface area (hydrodynamics; external mass transfer; internal mass transfer)
2. Optimizing photon transfer limitations: optimum lighting strategy and reactor geometry to maximize irradiance;
3. Equipment: smaller, lighter, cheaper, excellent operation.

- Reactivity of photocatalyst in combination with the photoreactor (mol of pollutants converted per m^3 of reactor per second (or accumulated energy));
- Photocatalytic space-time yield – m^3 water treated per m^3 of reactor per day per kW.

Tom Van Gerven et al 2007, Chemical Engineering and Processing: Process Intensification 46, pp 781-789

Tom Van Gerven et al 2015, Chemical Engineering and Processing: Process Intensification 97, pp 106-111

PROCESS INTENSIFICATION:
SOLAR COLLECTOR OPTICS

Solar Hardware for Photocatalytic Processes are Based on TiO_2 Application

- Optics
- Geometry
- Reactor Materials

TiO_2

UV Radiation

Reflective surface material with high UV reflectance (electropolished anodized aluminum)

Double truncated parabola geometry to maximize light reflection into the absorber tube

New Solar Hardware for Photo-Fenton Applications

Opportunities for New Photoreactor Design

Photo-Fenton

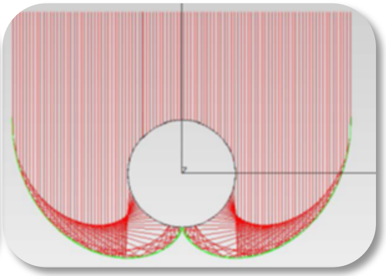
UV-Vis Radiation

Reflective surfaces with different materials and geometries must be tested

- ⇨ Low-cost
- ⇨ More resistant to outdoor conditions
- ⇨ Higher volumetric capacity (nº tubes/m^2)

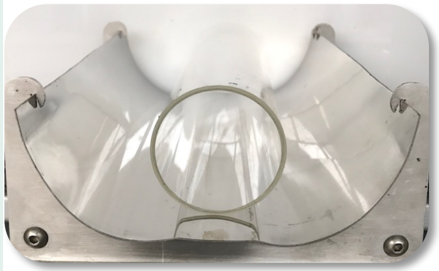
PROCESS INTENSIFICATION:
SOLAR COLLECTOR OPTICS

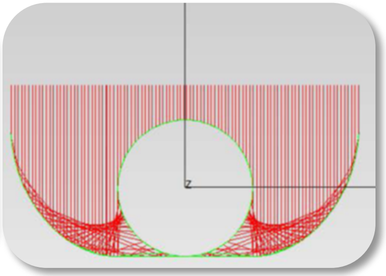
2 Pieces Double Parabola (DP)



Advantages	Disadvantages
- Geometric Concentration Ratio of 1.00	- Higher area of reflector aperture - Higher manufacturing cost - Fix no. of absorber tubes/m^2 (~29 tubes per 6 m^2)

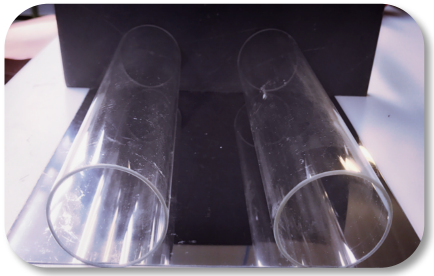
Single Piece Double Parabola (SP)

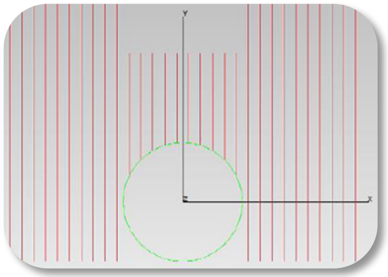




Advantages	Disadvantages
- Smaller area of reflector aperture - Higher no. of absorber tubes/m^2 (32 tubes per 6 m^2) - Lower manufacturing cost	- Geometric Concentration Ratio of 0.82

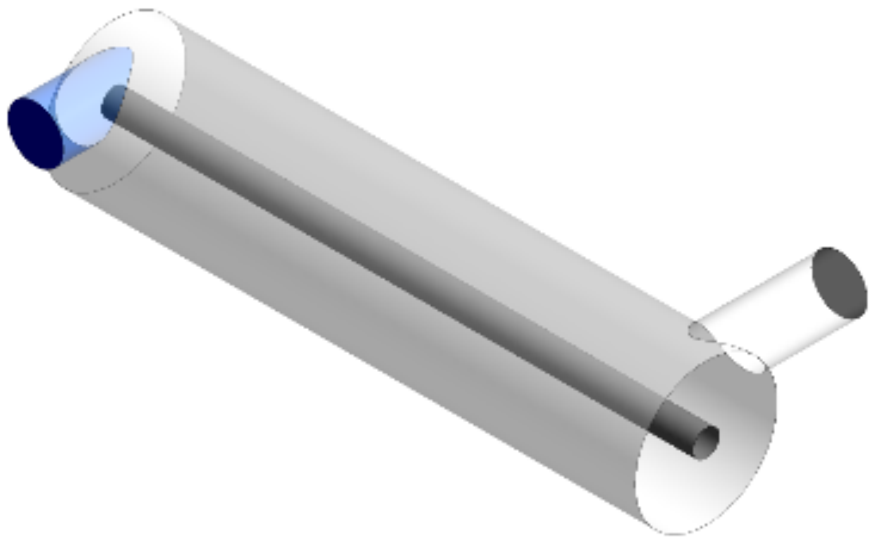
Flat (F)

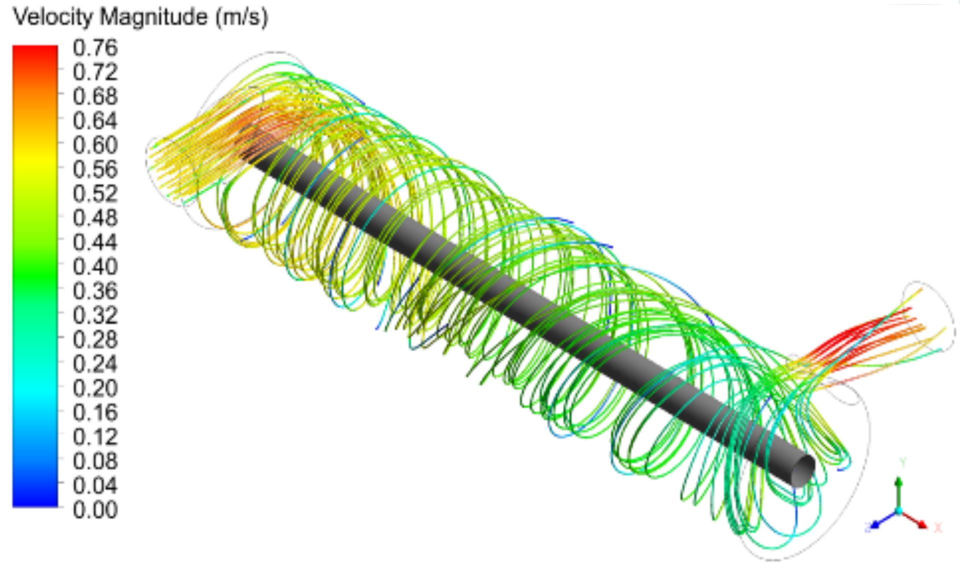




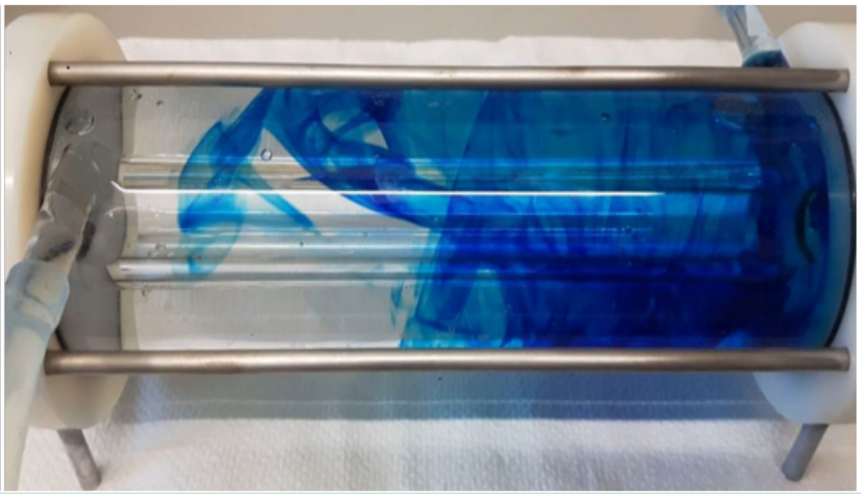
Advantages	Disadvantages
- Higher no. of absorber tubes/m^2 (40 tubes per 6 m^2) - Lower manufacturing cost	- Low reflection of diffuse radiation - Geometric Concentration Ratio of 0.64

PROCESS INTENSIFICATION:
PHOTOREACTOR USING ARTIFICIAL LIGHT - FluHelik

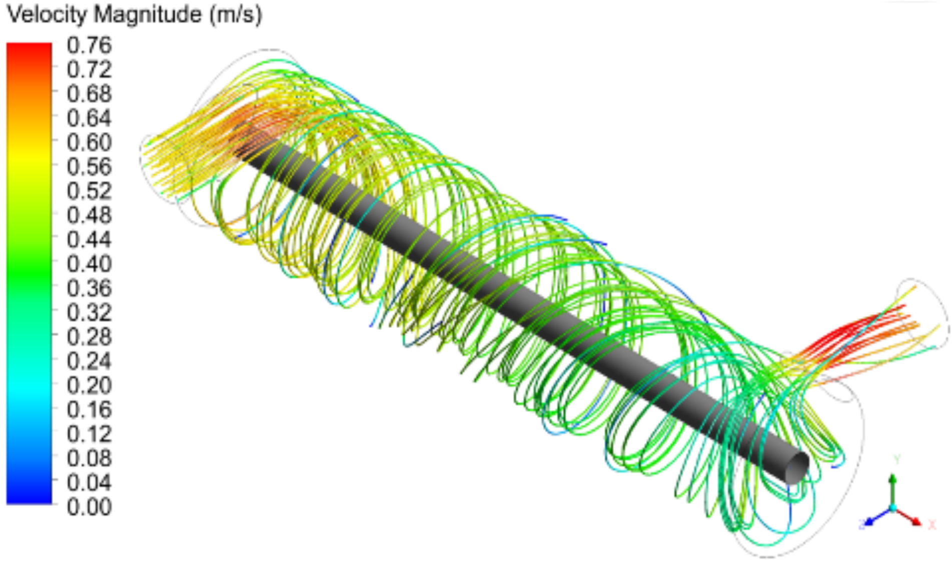


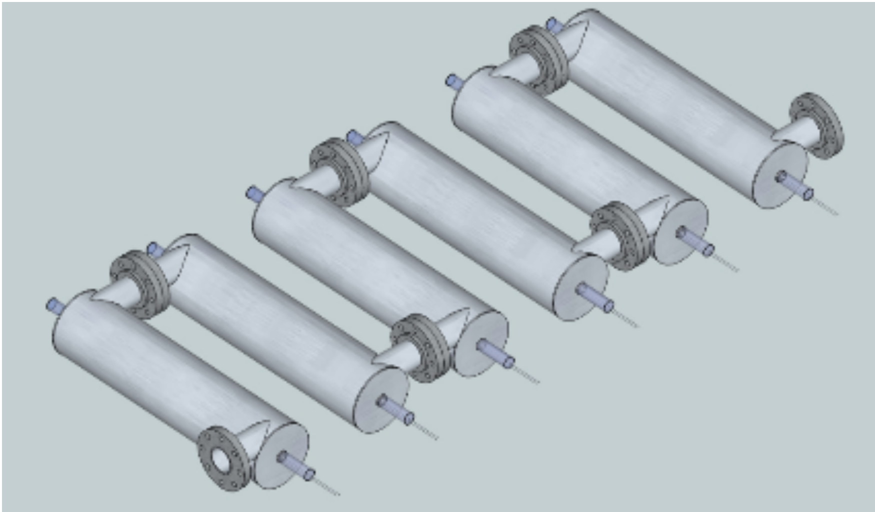


Helical Motion of Fluid Around the UVC Lamp, Inducing Unique Fluid Dynamics and Irradiation Properties



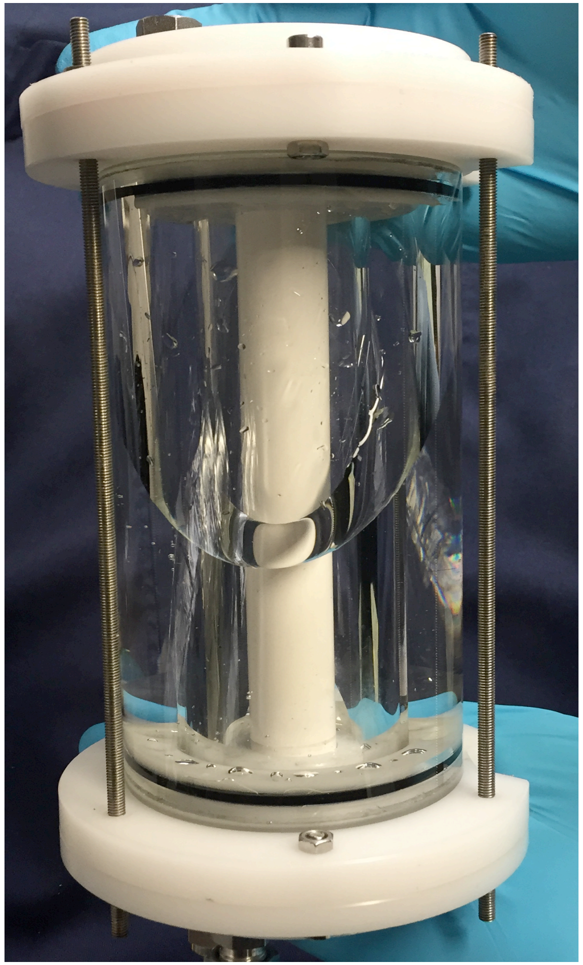
PROCESS INTENSIFICATION:
PHOTOREACTOR USING ARTIFICIAL LIGHT - FluHelik

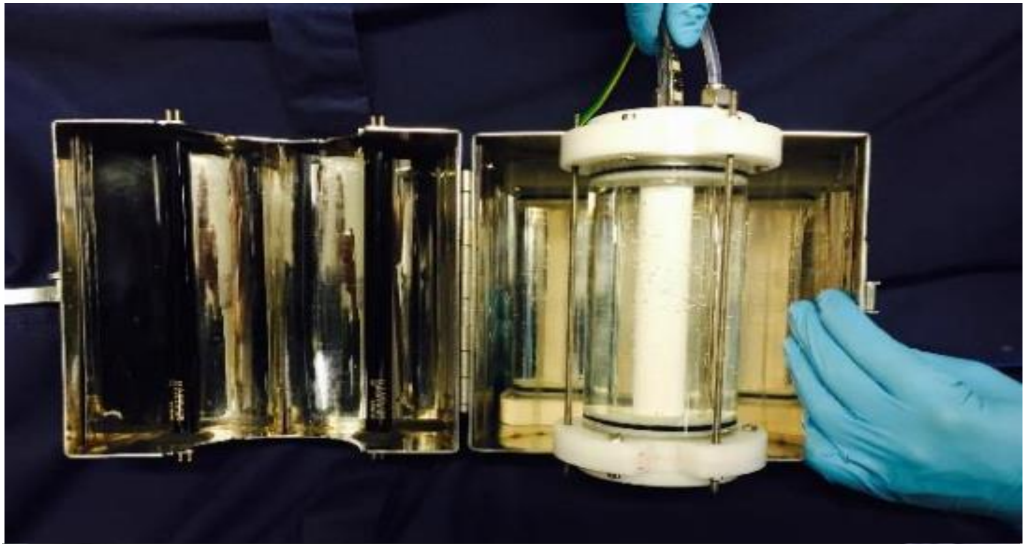




i. higher velocities in almost the entire domain of the reactor but with low velocities near the UVC lamp, promoting high contact between fluid and radiation;
ii. higher turbulent intensity and subsequent higher degree of mixing;
iii. longer residence time of fluid particles inside the reactor and lower fraction of short-circuiting zones;
iv. more uniform UV fluence;
v. very simple and compact arrangement in series for full scale applications.

PROCESS INTENSIFICATION:
PHOTOCATALYTIC MEMBRANE REACTORS

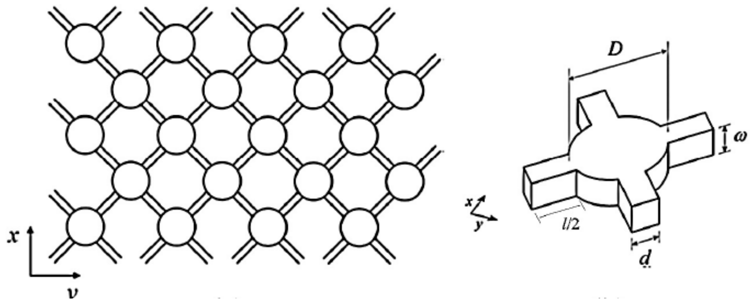


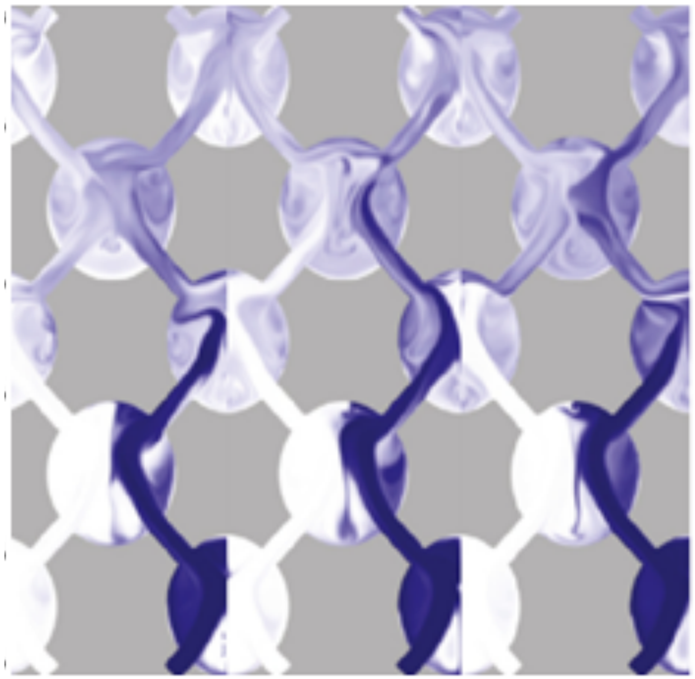


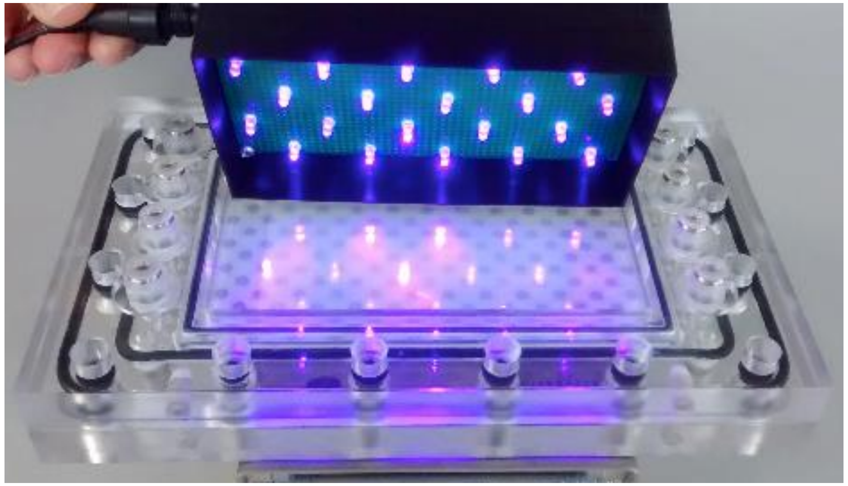
Separation Function/Photocatalytic Activity

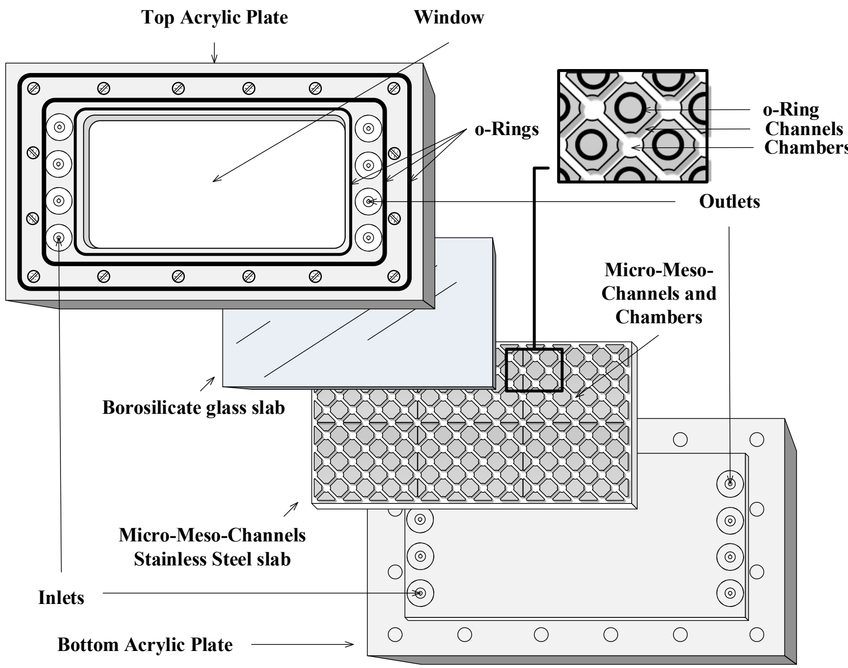
- Enhancement of its antifouling properties (in situ regeneration)
- Negligible mass transfer limitations; Negligible photons transfer limitation

PROCESS INTENSIFICATION: PHOTOCATALYTIC MICRO-MESO-REACTORS (NETmix) USING MICROSCALE ILLUMINATION

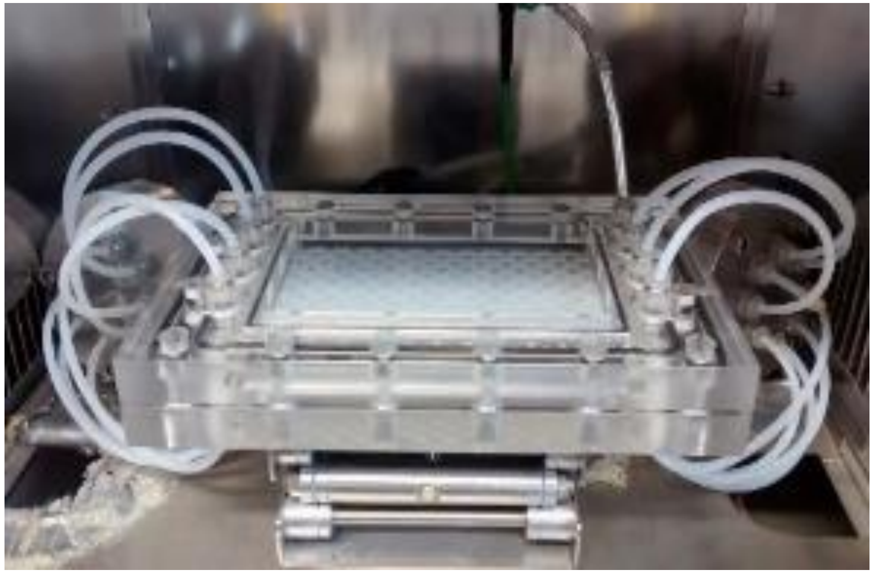








PROCESS INTENSIFICATION: PHOTOCATALYTIC MICRO-MESO-REACTORS (NETmix) USING MICROSCALE ILLUMINATION



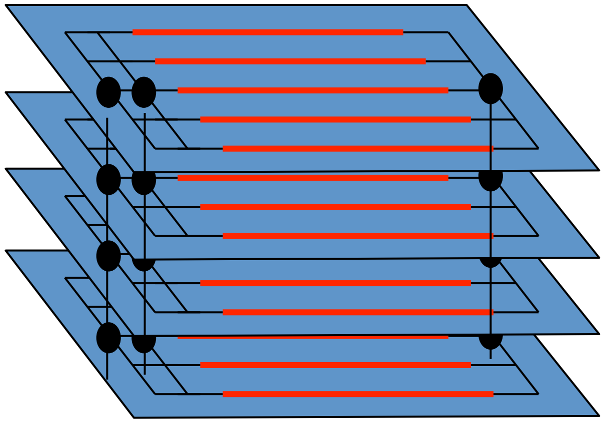
- high illuminated catalyst surface area per reactor volume;

- due to the small size of the channels, microreactors present short molecular diffusion distances;

- uniform irradiance of the entire catalyst surface and through the entire reactor depth;

- self-cleaning effect (fast removal of adsorbed byproducts, renewing the catalytic sites);

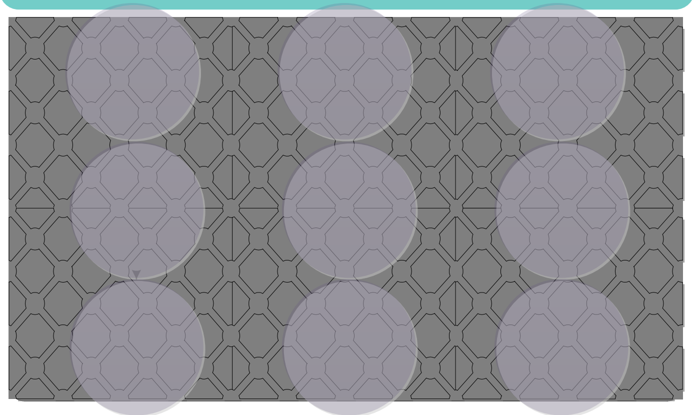
- "scaling-out" or "numbering-up" instead of scaling-up.



MULTI-CHANNEL DESIGN
SCALE-UP IN PARALLEL

PROCESS INTENSIFICATION: PHOTOCATALYTIC MICRO-MESO-REACTORS (NETmix) USING MICROSCALE ILLUMINATION

9 LEDs - 75° viewing angle

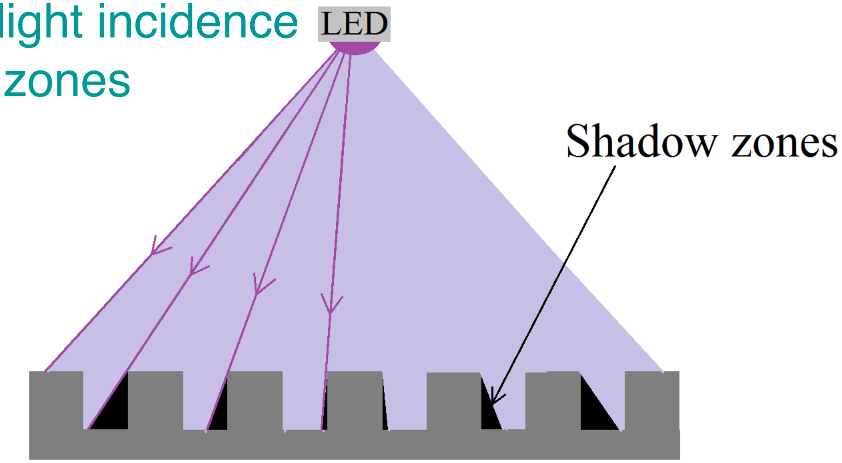


Front view

LED illumination

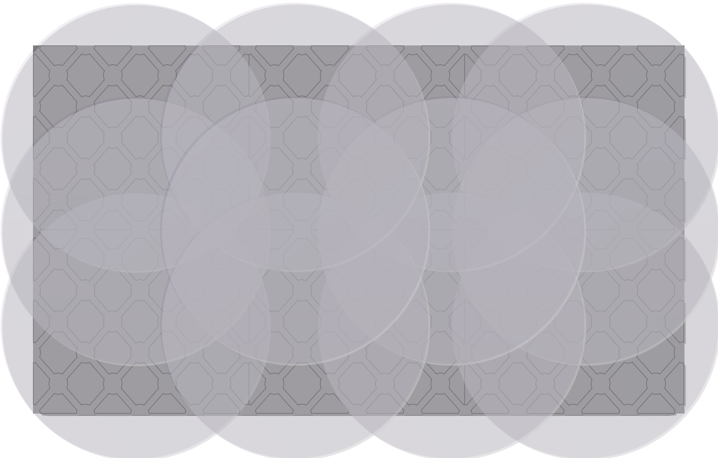
Oblique light incidence

Shadow zones

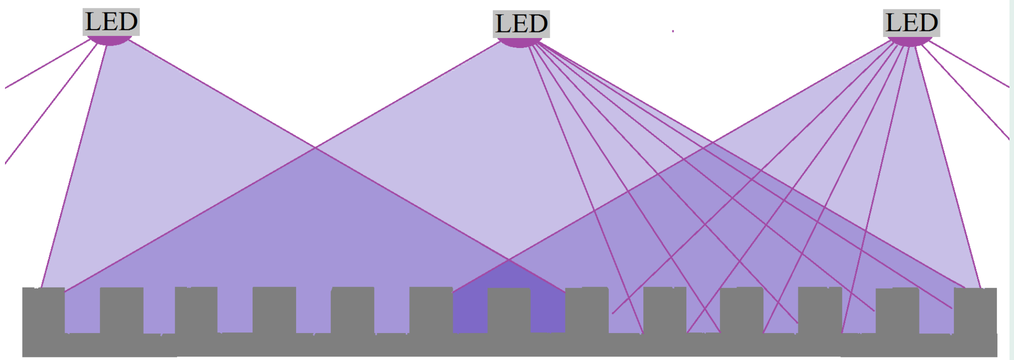


Side view

12 LEDs - 120° viewing angle

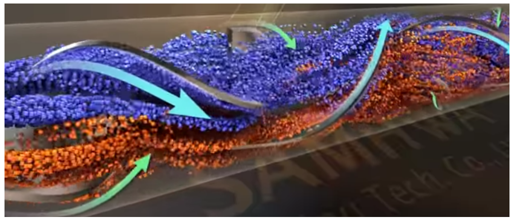


Front view

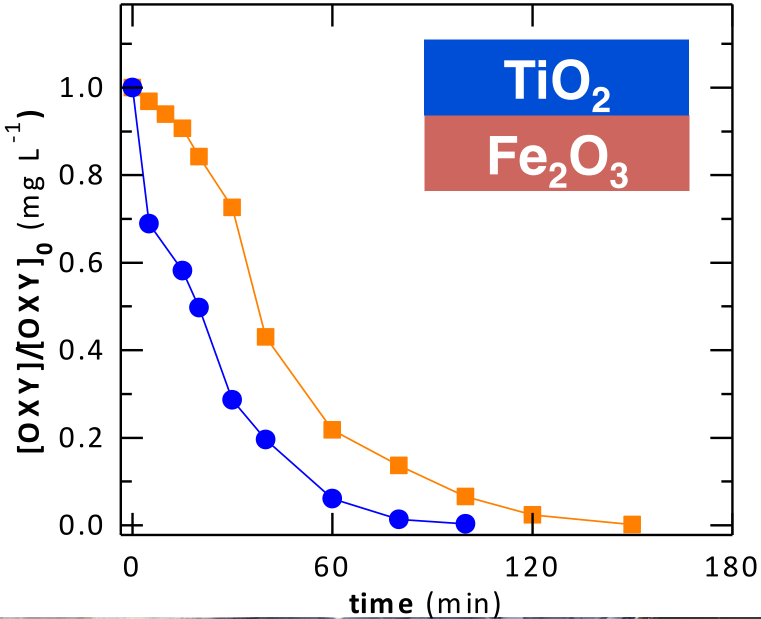


Side view

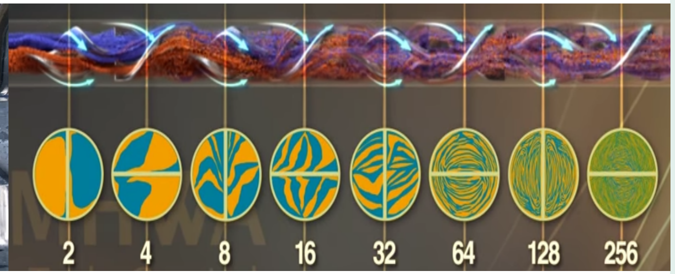
PROCESS INTENSIFICATION: TUBULAR PHOTOCATALYTIC REACTOR WITH STATIC MIXER



MAIN ADVANTAGES:
- Higher degree of mixing
- Overall area is illuminated when using a reflector at the bottom



≈ 80 m_{ill}^2 m^{-3}



EXPERIMENTAL CONDITIONS	1 g TiO_2 77 mg L^{-1} H_2O_2	Fe_2O_3 using 1.5 g catalyst and 154 mg L^{-1} H_2O_2	pH = 4-6	T = 24-30 °C	Natural solar radiation

FINAL REMARKS/CHALLENGES

Integration of AOPs/EAOPs with other Technologies

Development of Breakthrough Designs for Photoreactors Towards Process Intensification

MAIN CHALLENGES TO BE ADDRESSED IN THE FUTURE

ACKNOWLEDGEMENTS

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LABORATORY OF SEPARATION AND REACTION ENGINEERING
LABORATORY OF CATALYSIS AND MATERIALS

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III CIPOA

Medellin (Guatapé), Colombia
November 14 – 17, 2017

3rd IBEROAMERICAN CONFERENCE ON ADVANCED OXIDATION TECHNOLOGIES (III CIPOA)
2nd COLOMBIAN CONFERENCE ON ADVANCED OXIDATION PROCESSES (II CCPAOX)

Abstract submission deadline 15/07/2017
http://cipoa2017.com

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