Energy Efficient Heat Exchange and Catalysis

The UNIHEAT Project

Dr. Francesco Coletti
Industry Engagement Manger

Credits

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Overview

- Energy efficiency in thermal and catalytic processes
- Overview of the UNIHEAT project
- UNIHEAT Research programme
  - Crude oil fouling
  - Other UNIHEAT research themes
- UNIHEAT Industry Engagement Programme

Energy demand & utilisation

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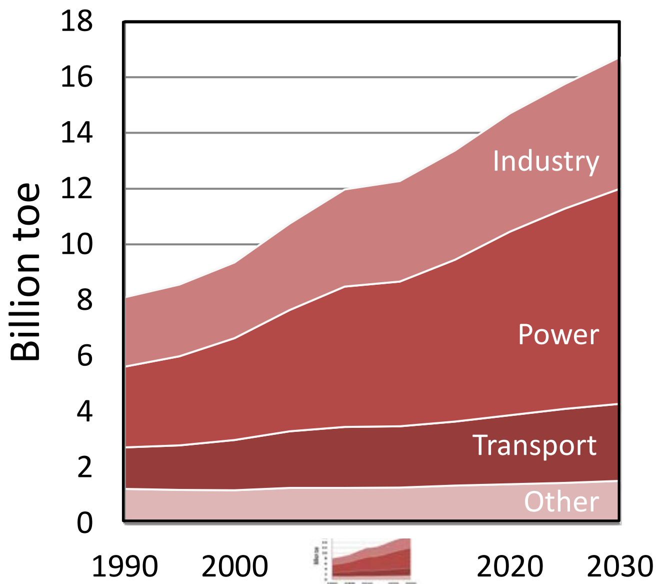
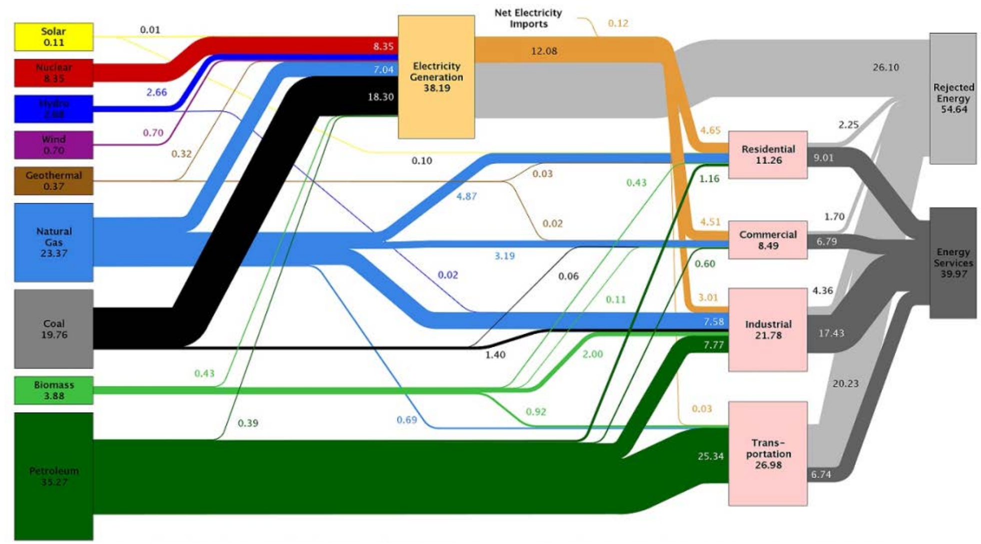
Growing global energy demand



Data source: BP

Energy utilisation



Source: LLNL

Energy efficiency plays a key role in meeting demand

Thermal energy efficiency

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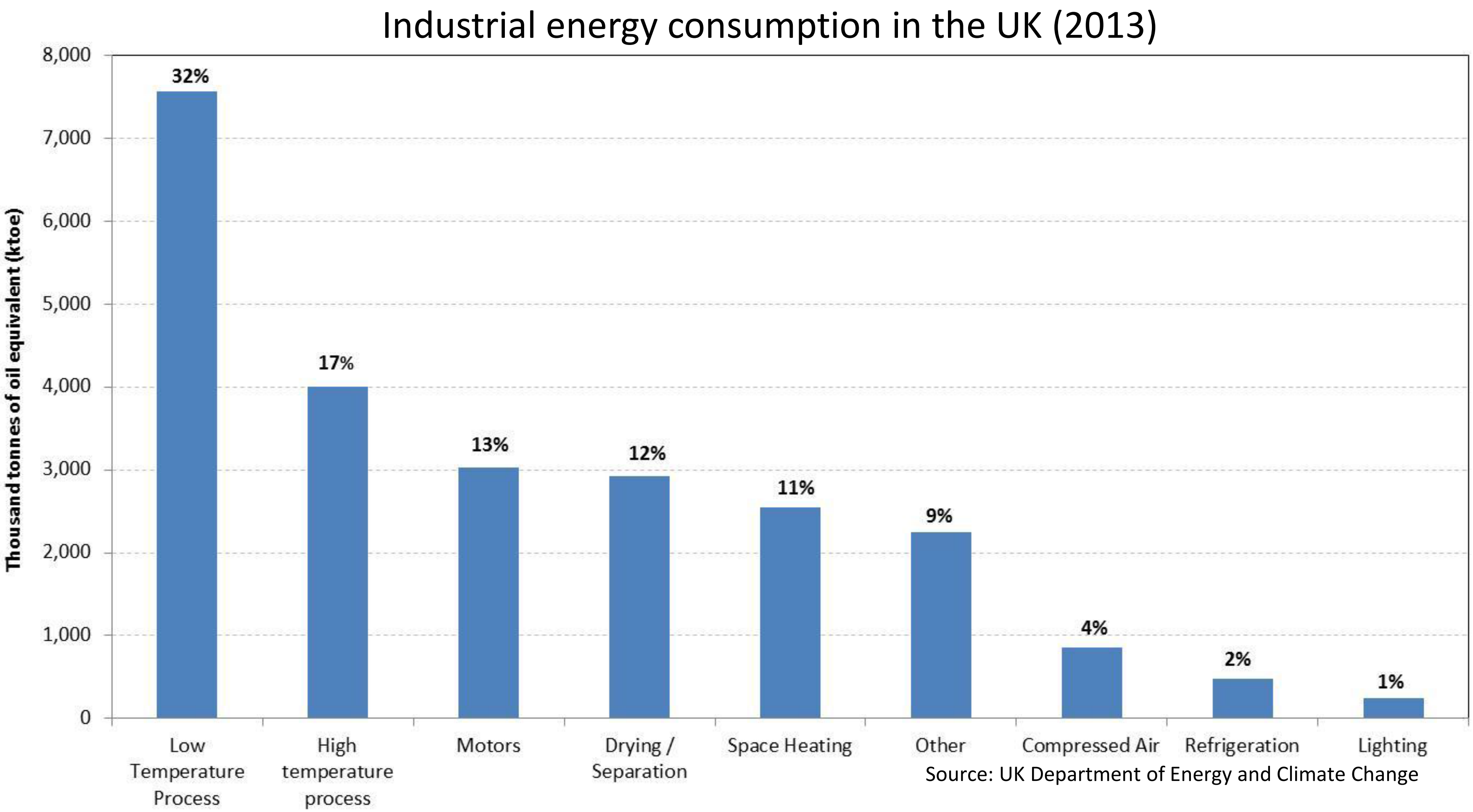

Source: UK Department of Energy and Climate Change

72% of energy is consumed in thermal processes

Thermal energy efficiency

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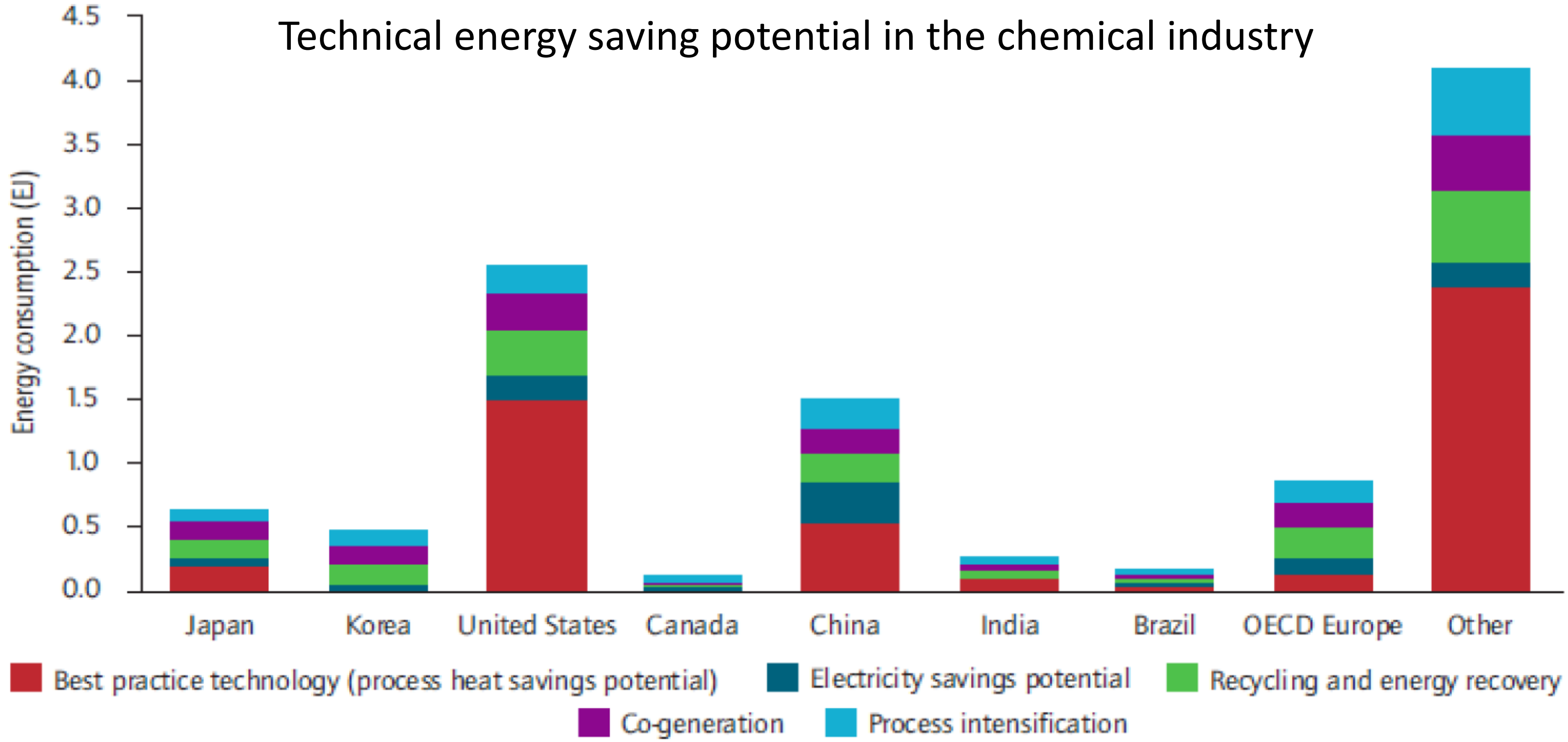
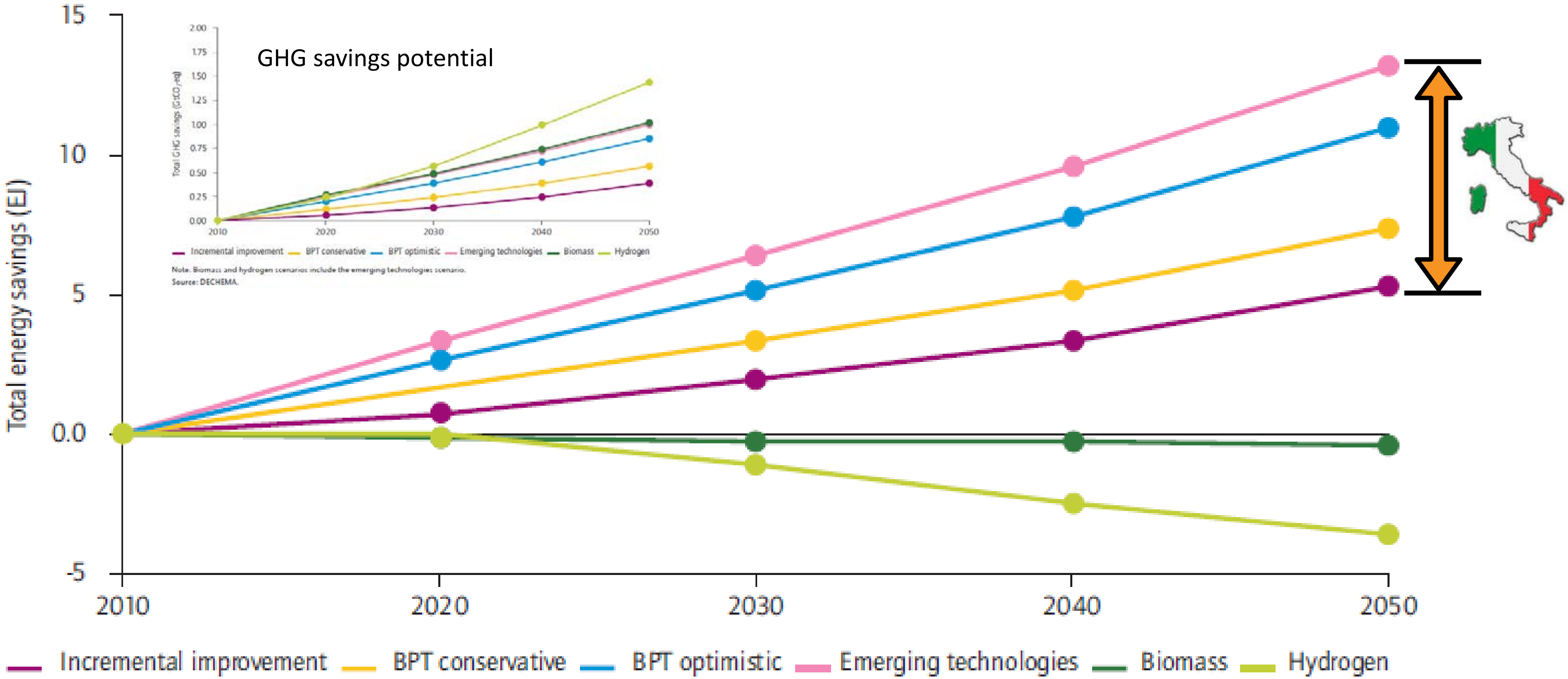


Note: Energy savings potential based on 2010 production levels.

Source: IEA.

Global thermal savings in chemical processes > UK total E consumption!

Savings potential via catalysis



Data for chemical industry
Source: DECHEMA

Large opportunities by improved catalysis and catalytic processes

Energy in oil refineries

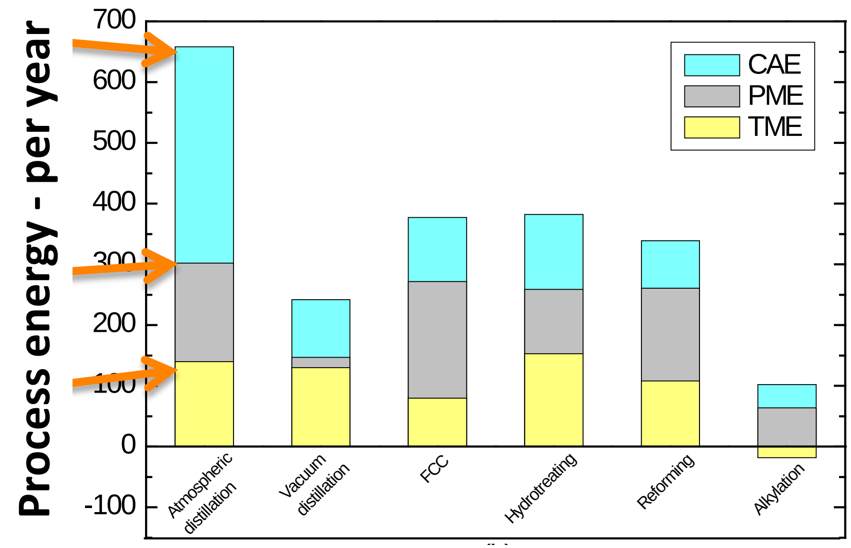
Oil Refineries ~ 5-7% of crude oil energy to operate

current average energy used

54%

practical minimum energy

theoretical minimum energy required



(Source: US DOE, 2006)

Over 25% of refinery energy losses could be practically recovered

UNIHEAT Project - Overview

The numbers

US$ **15** Million project funding

3 year progamme

71 research team members

A target of **8** patents

Largest research project ever assembled in this area

Project objectives

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Radical increase in industrial energy efficiency

Target industries: **oil and gas, in particular refining, petrochemicals and power**

- **Improving design** of heat exchange equipment, energy recovery networks
- Intensification of heat exchanging processes by **preventing fouling**
- **Reduction of hydraulic drag** in oil pipelines
- **Recovery** and efficient utilisation of **waste heat**
- Advanced modelling for efficient management of combined heat and reaction in oil and chemical processes utilising new catalysts
- Enhancing energy efficiency in **catalytic processes** for the petrochemical industry
- Improving industrial processes for **heavy oil upgrading**

Imperial College London

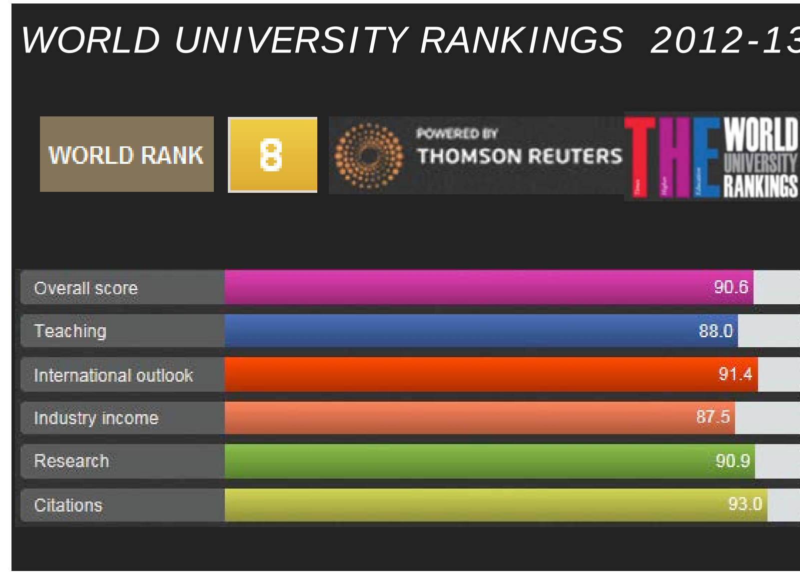
- 3,000 academic and research staff
- 15,600 students
  - (>1/3 postgraduate)
  - 126 countries
  - 49% Full time students non-UK nationals
- £765M turnover (£314M Research)
- Technology transfer:

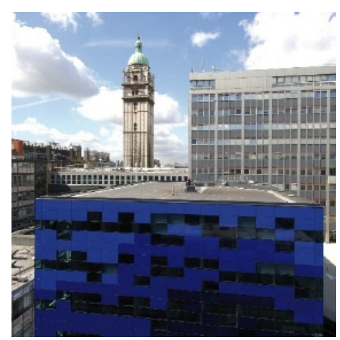
Imperial Innovations

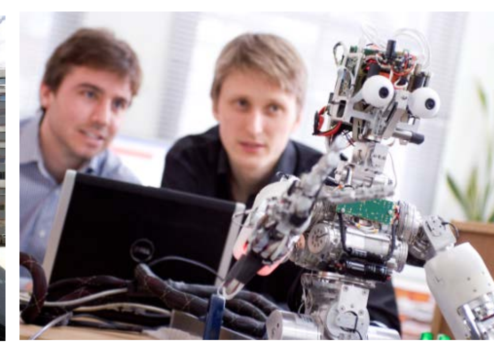
- 555 Patents filed
- 150 Licences under management
- £120 million Invested in spinouts since 2006
- £370 million Raised by spinouts since 2006

Imperial Consultants

- Leading UK academic consultancy provider
- 500+ Imperial staff involved
- Annual turnover >£20m
- Wholly-owned subsidiary of Imperial College







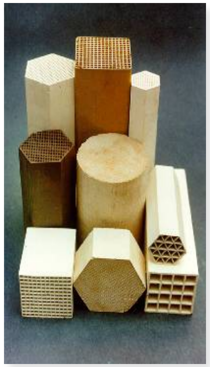
Imperial College London

Boreskov Institute of Catalysis - BIC

Founded by
G.K. Boreskov (1958-1984)

Boreskov Institute of Catalysis - BIC

- One of the largest R&D centres in catalysis
- Developed > 75 catalysts and catalytic tech.
- Highly-skilled personnel:
  - 1300 staff
  - 400 researchers
  - 5 members of the Russian Academy of Sciences
- Advanced catalysts and nanomaterials preparation
- Pilot plant facilities



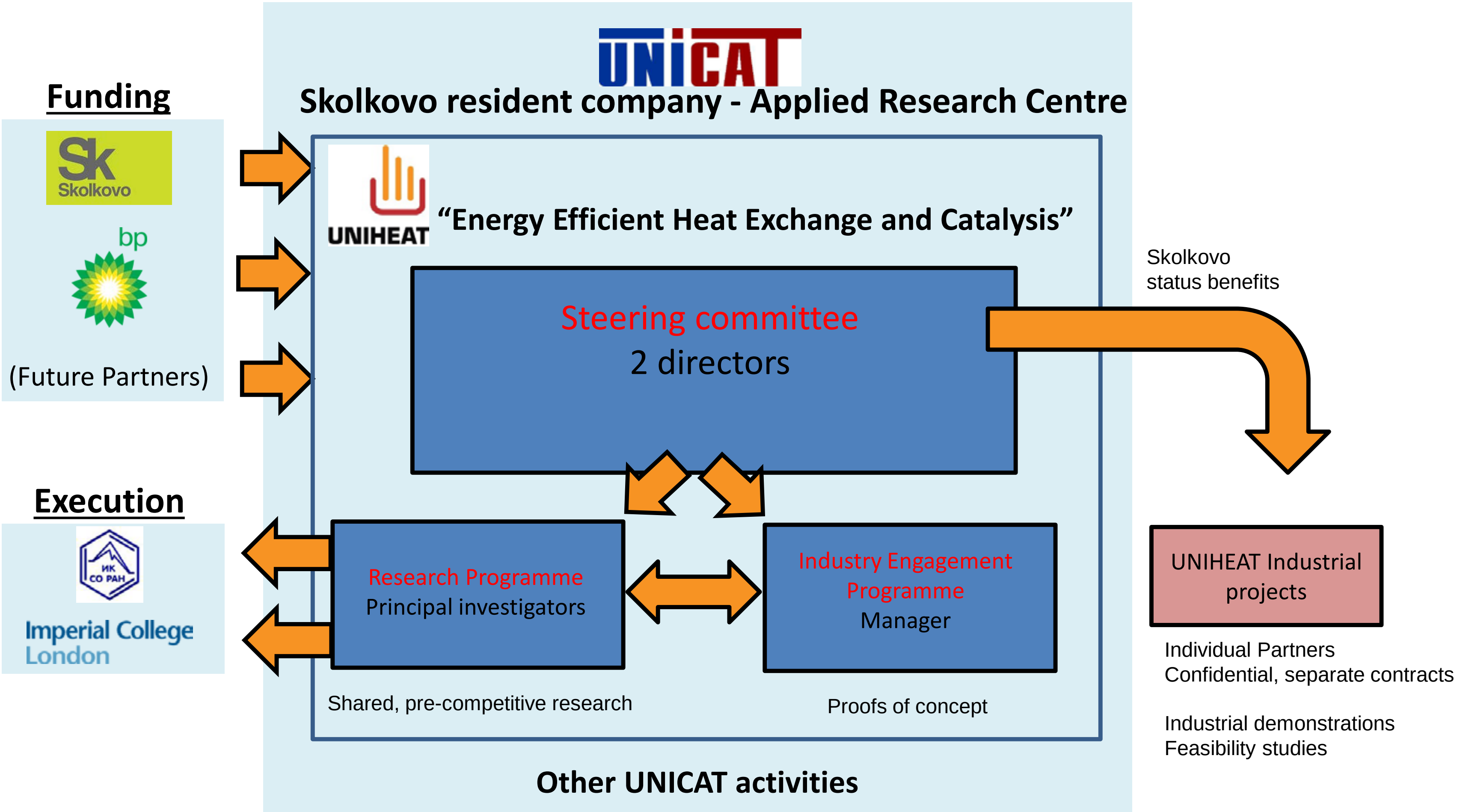
Catalysts & catalytic processes

- Conversion of light hydrocarbons & natural gas
- Oil refinery, heavy oil
- Key processes of chemical industry
- Natural gas treatment (desulfurization, etc.)
- Pharmaceutics
- Agricultural chemistry
- Polymerization of olefins
- Porous oxides
- Zeolites
- Environmental protection
- Non-traditional energetics, utilization and conversion of renewable feedstocks and coal

Adsorbents and composite materials with adjustable properties

- Selective sorbents of H_2O, CO_2 etc.
- Carbonaceous materials and technical carbon
- Fillers on the base of disperse materials

Structure



Agreement open for more Partners to join

Credits: Prof. S. Macchietto

UNIHEAT Project - Research programme

- Crude oil fouling
- Other UNIHEAT research themes

The UNIHEAT research team

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Name	Affiliation	Area of Expertise/Role
Prof. G.F. Hewitt	Imperial College London	Heat transfer, multiphase flow, nuclear power
Prof. G. Jackson	Imperial College London	Thermodynamics
Prof. S. Kazarian	Imperial College London	Advanced spectroscopic imaging, supercritical fluids processing
Prof. V.A. Kirillov	Boreskov Institute of Catalysis	Chemical engineering, heat and mass transfer, catalytic combustion
Prof. O.K. Matar	Imperial College London	Interfacial fluid mechanics, multiphase flow, first principle modelling
Prof. S. Macchietto	Imperial College London	Process Systems Engineering, UNIHEAT project co-director
Dr. C.N. Markides	Imperial College London	Heat transfer, thermodynamic cycles, energy conversion
Prof. O.N. Martyanov	Boreskov Institute of Catalysis	Catalysts and nanostructured materials physicochemical characterization, supercritical fluids , UNIHEAT project co-director
Dr. M. Millan-Agorio	Imperial College London	Catalytic upgrading of heavy oil, analytic characterization techniques
Prof. E. Müller	Boreskov Institute of Catalysis	Thermodynamics, Molecular simulation
Dr. A.V. Porsin	Boreskov Institute of Catalysis	Catalysts for air purification and fuel combustion, design of catalytic reactors, development of methods for testing catalysts and reactors
Dr. V.N. Snytnikov	Boreskov Institute of Catalysis	Catalysis, mathematical modelling, parallel algorithms, spectroscopy, chemical evolution, computational mathematics
Dr. V.A. Yakovlev	Boreskov Institute of Catalysis	Biofuels, hydrotreatment catalyst, combustion in FCB

+ 28 Students, 22 Research associates, 2 technicians

From molecular to plant scale

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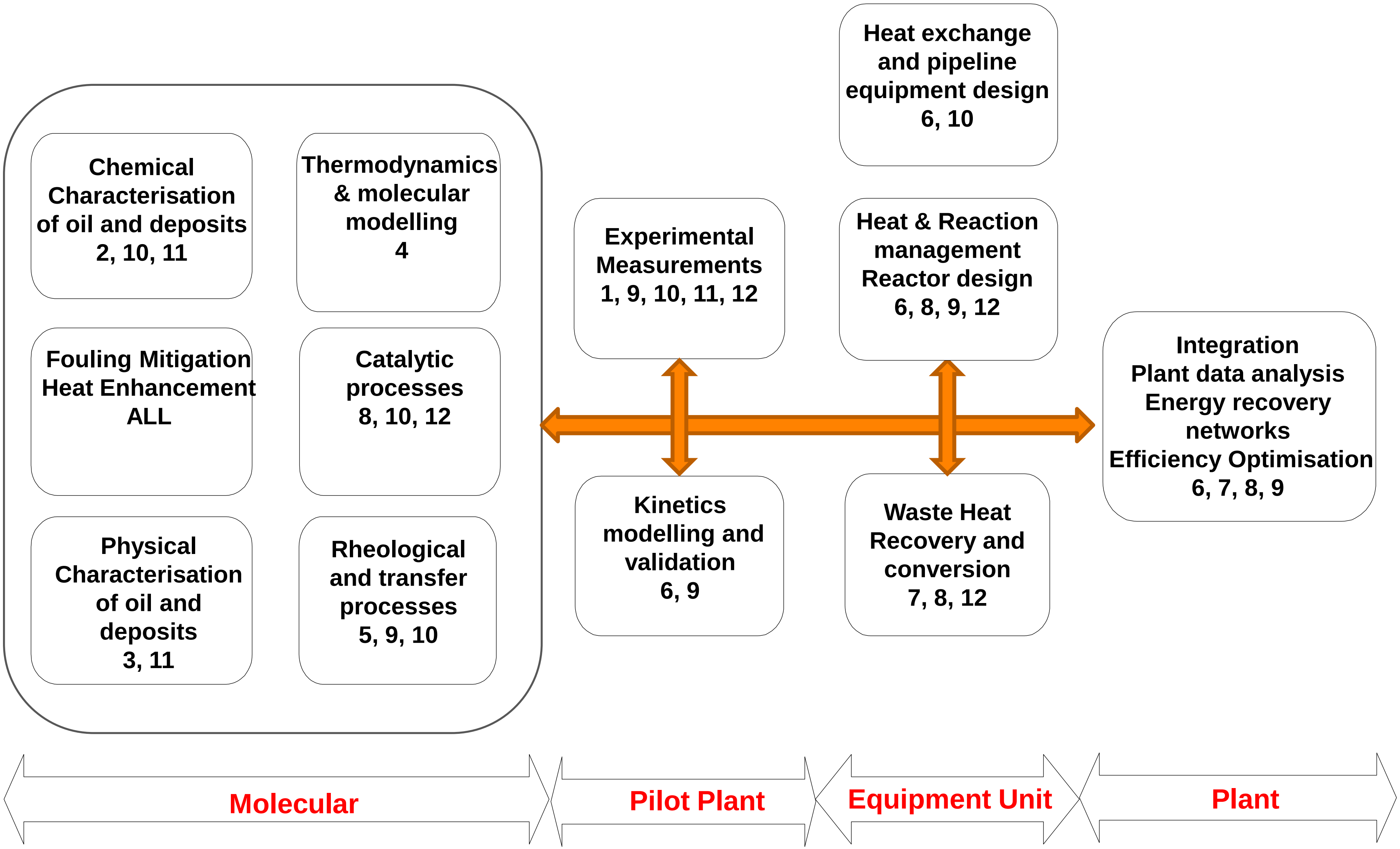

The UNIHEAT themes

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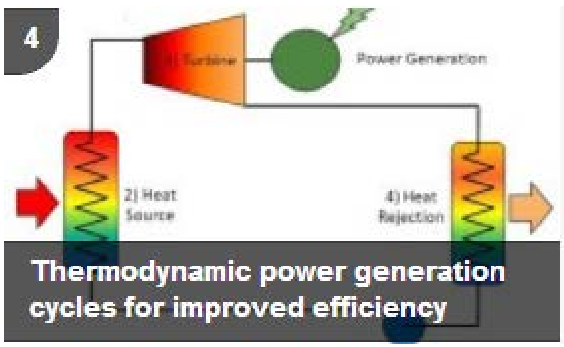
1 Multi-scale modelling of crude oil fouling: from molecular to plant scale

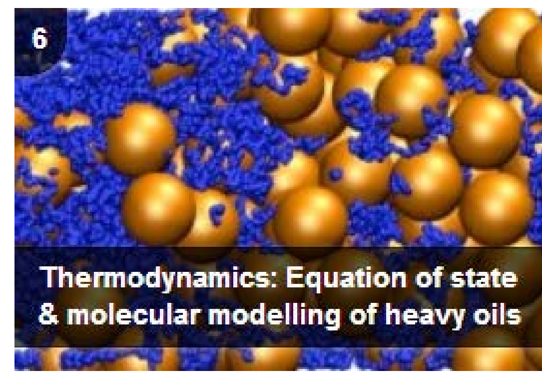
2 Physico-chemical properties of oil and deposits

3 Heavy Oil Catalytic Upgrading



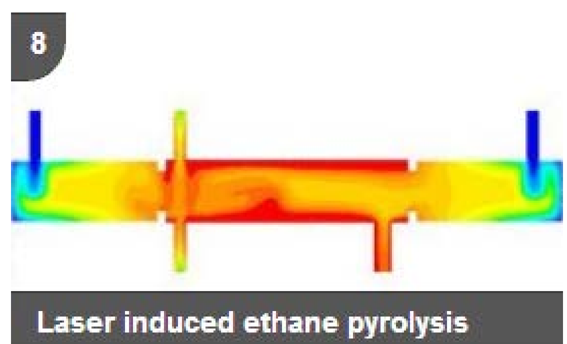
4 Thermodynamic power generation cycles for improved efficiency

5 Drag reduction in pipelines



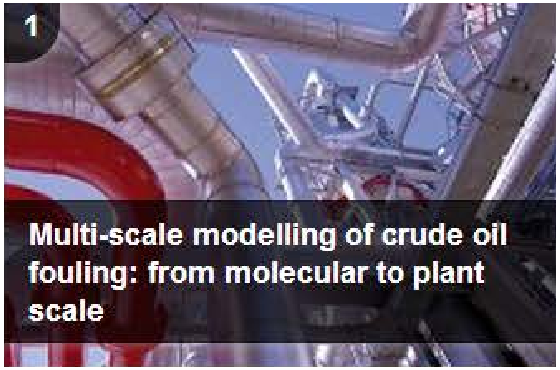
6 Thermodynamics: Equation of state & molecular modelling of heavy oils

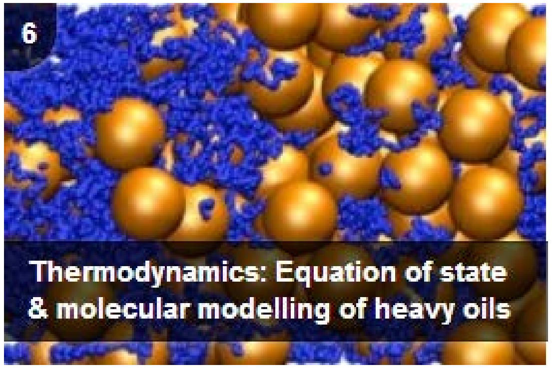
7 Oil fouling tests in HIPOR facility



8 Laser induced ethane pyrolysis

Crude oil fouling

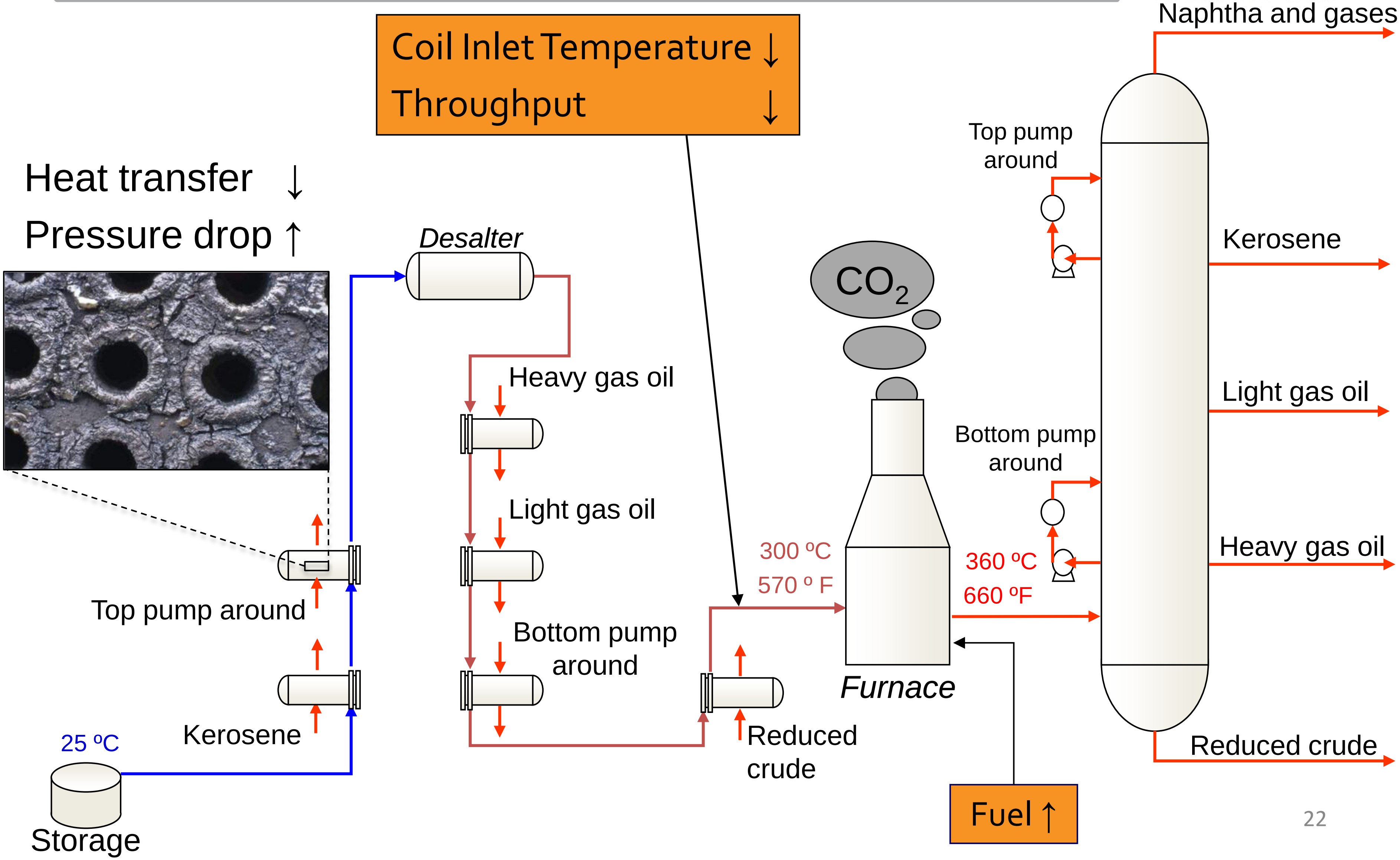




UNIHEAT Project - Research programme

- Crude oil fouling
- Other UNIHEAT research themes

Crude Distillation Unit



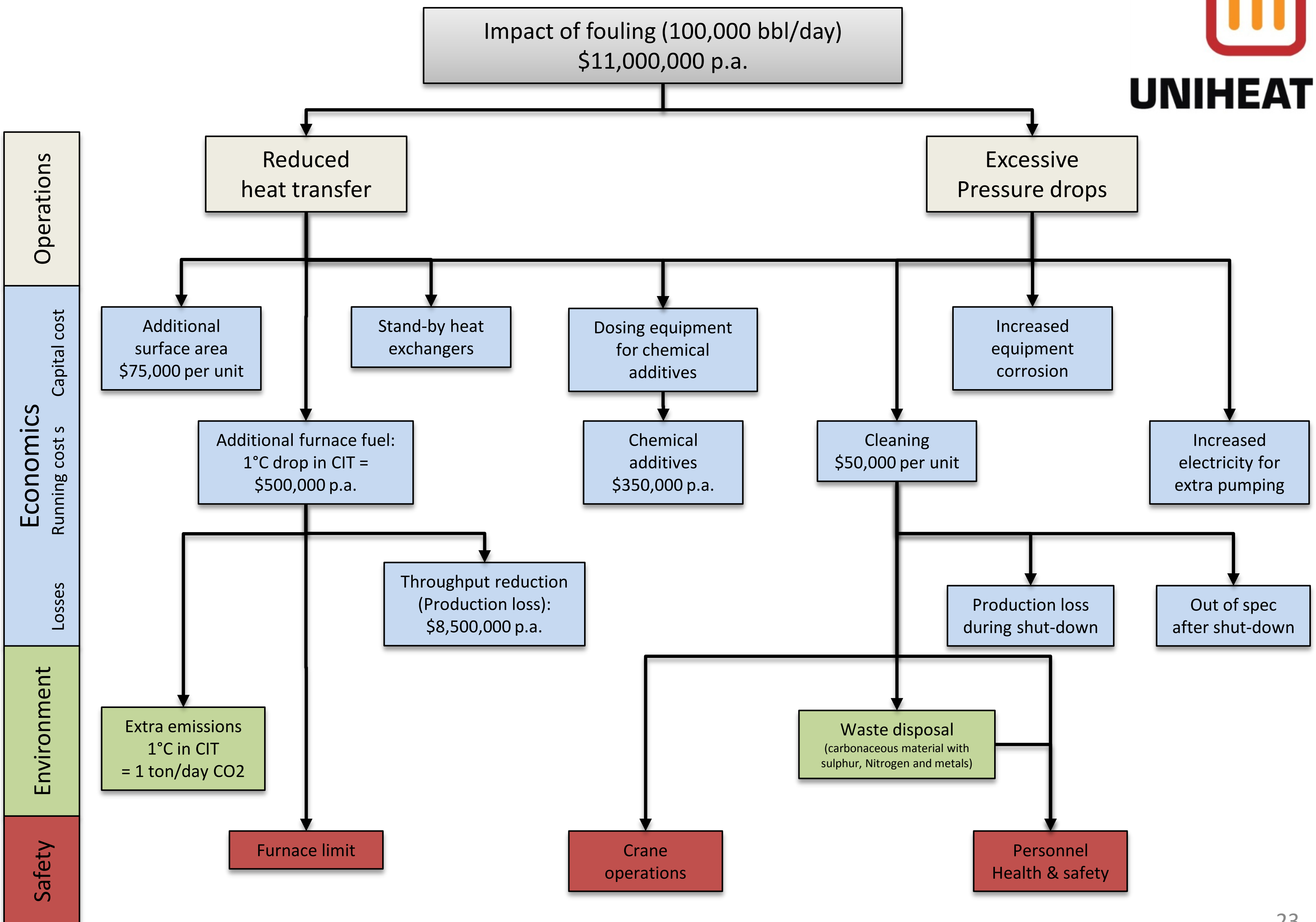


Image courtesy of Hexxcell Ltd.

Fouling in pictures

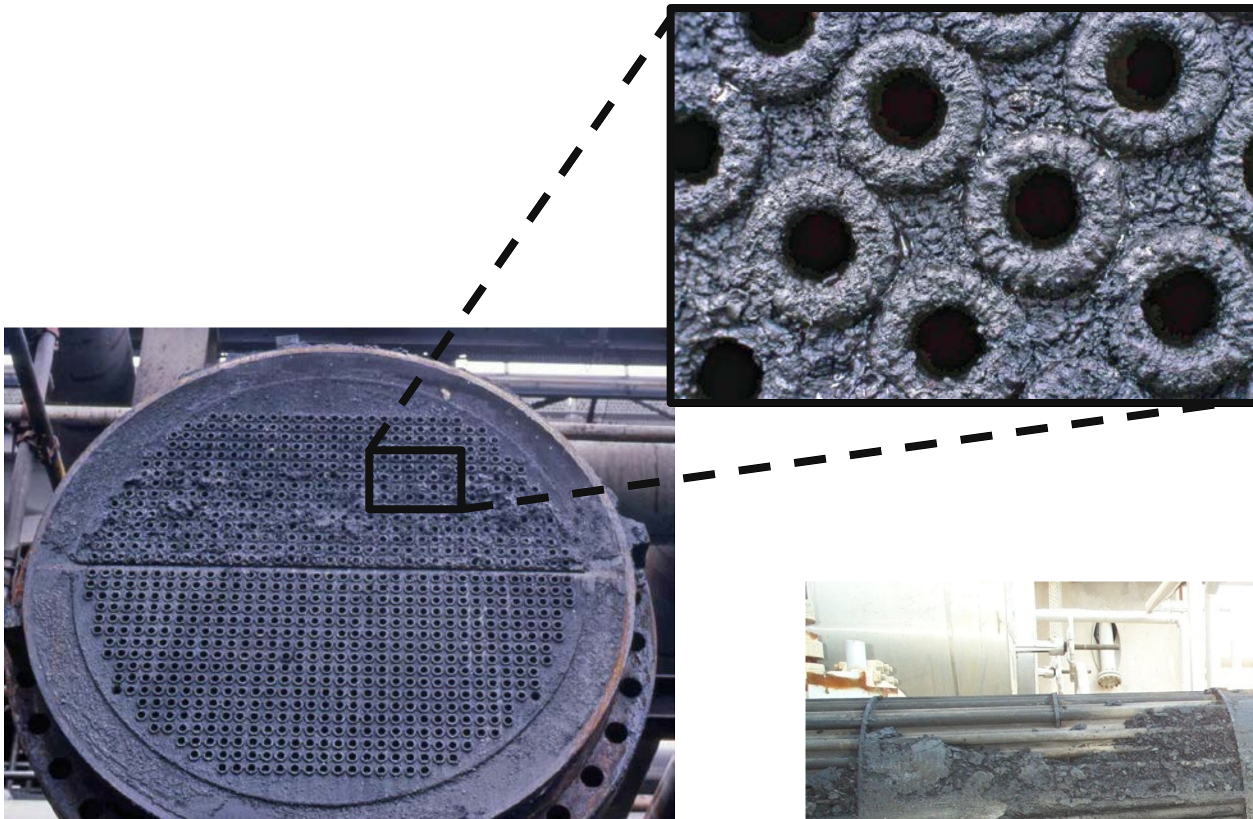
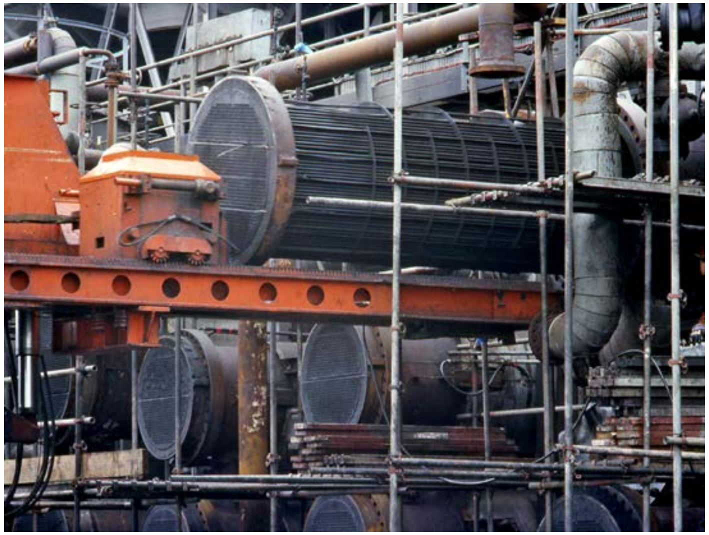
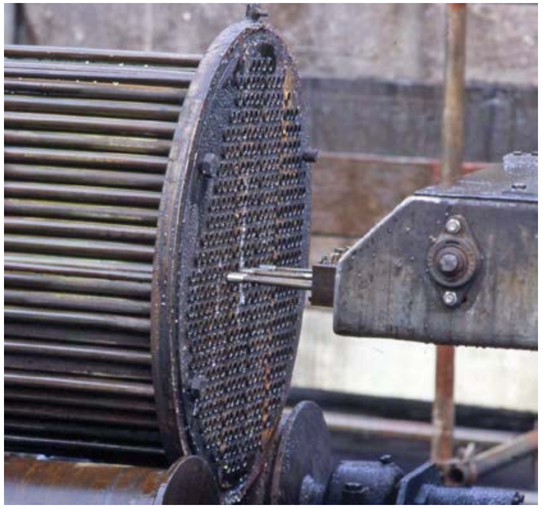


Photo courtesy Prof. Crittenden

Cleaning





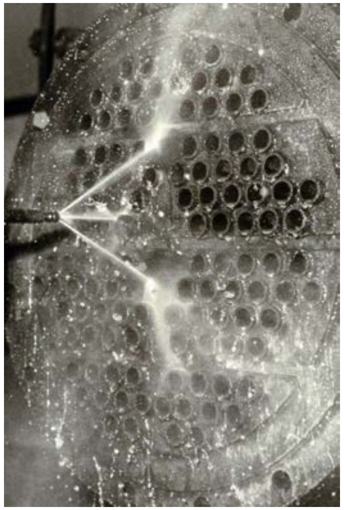


Photo courtesy Prof. Crittenden

Ask this guy!

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Photo courtesy Prof. Crittenden

Crude oil fouling - challenges

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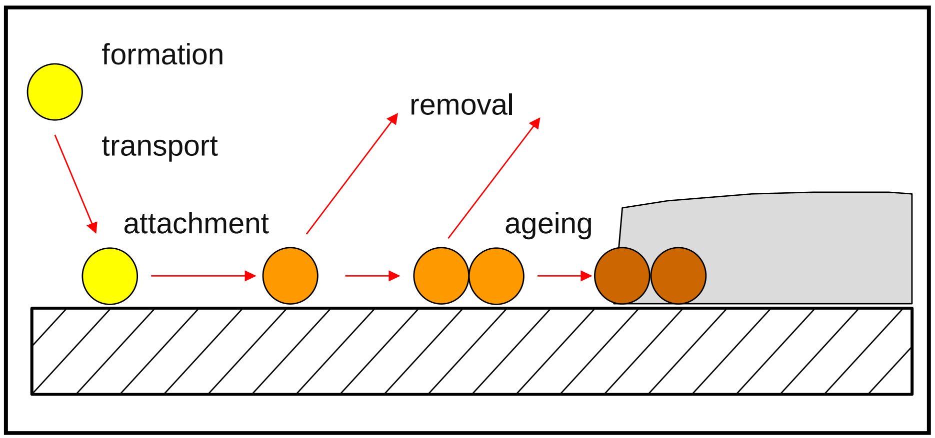
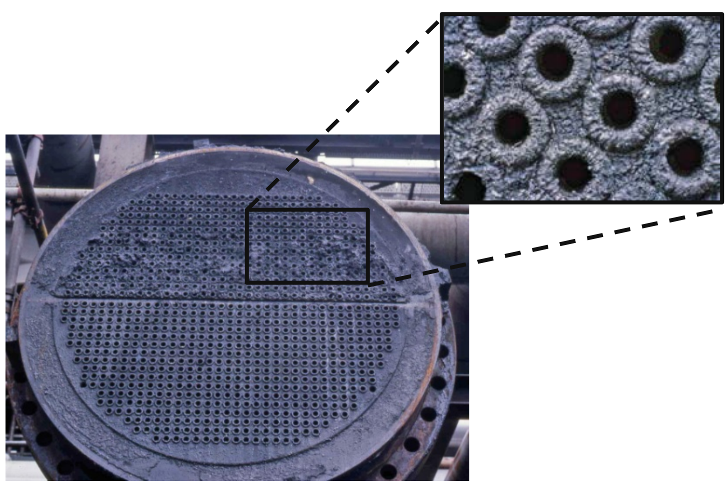
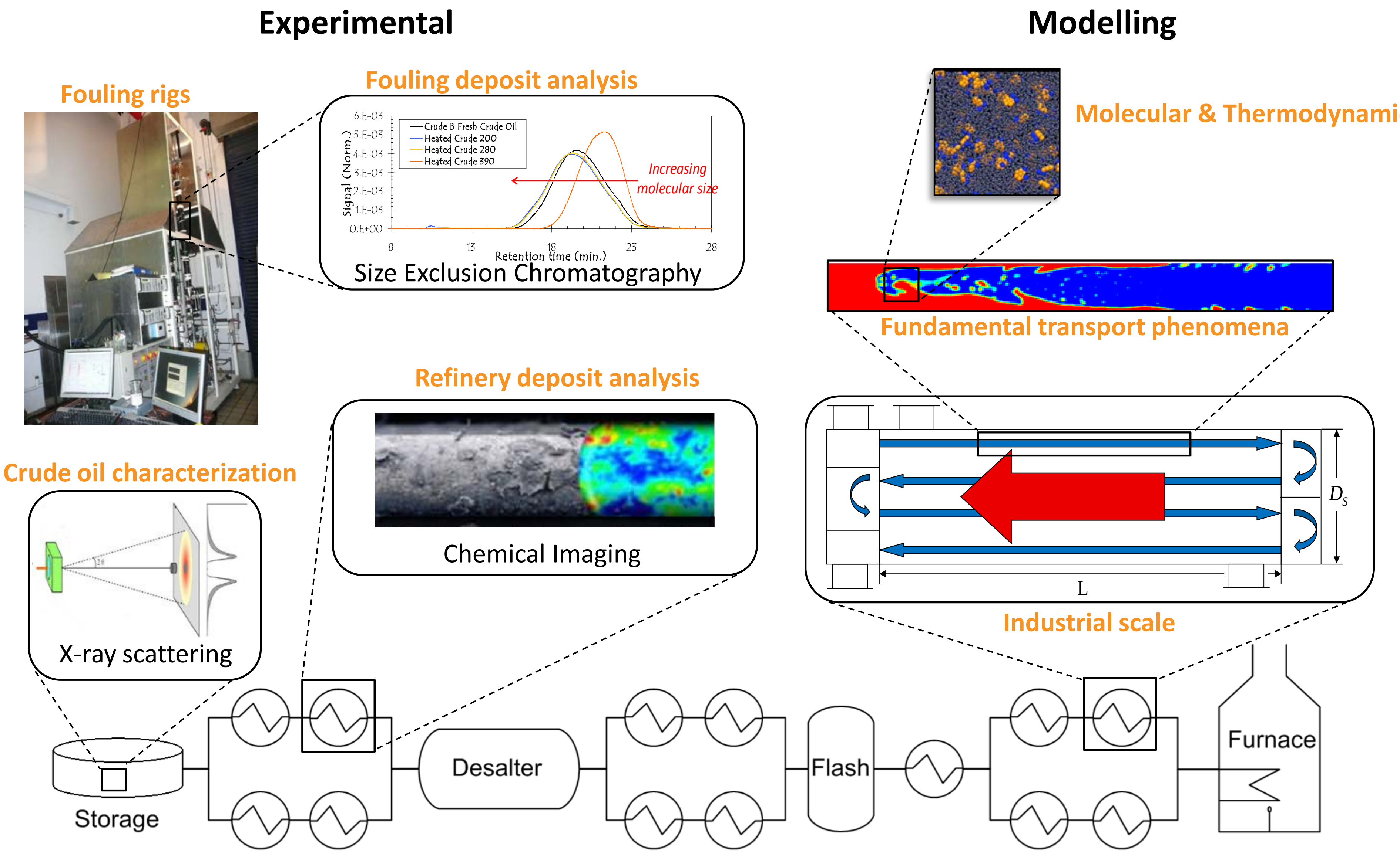


Coletti *et al.* (2010). *AIChE J.* **56**(12): 3257-3273.



- **Measure**
  - **New experimental techniques**
    - **Small & large scale**
- **Understand**
  - **Oil & deposit characterisation**
  - **Deposition kinetics**
  - **Interfacial/rheological properties**
  - **Thermodynamics and molecular properties**
- **Model**
  - **At all scales, dynamics**
  - **Integrate**
  - **Validate**
  - **Scale up**
- **Mitigate/Improve/ Optimise**
  - **Process**
  - **Exchanger design/retrofit**
  - **Energy integration networks**
  - **Control and operations**

Crude oil fouling – UNIHEAT



Crude oil fouling – modelling

UNIHEAT Theme 1

Thermo & Molecular modelling

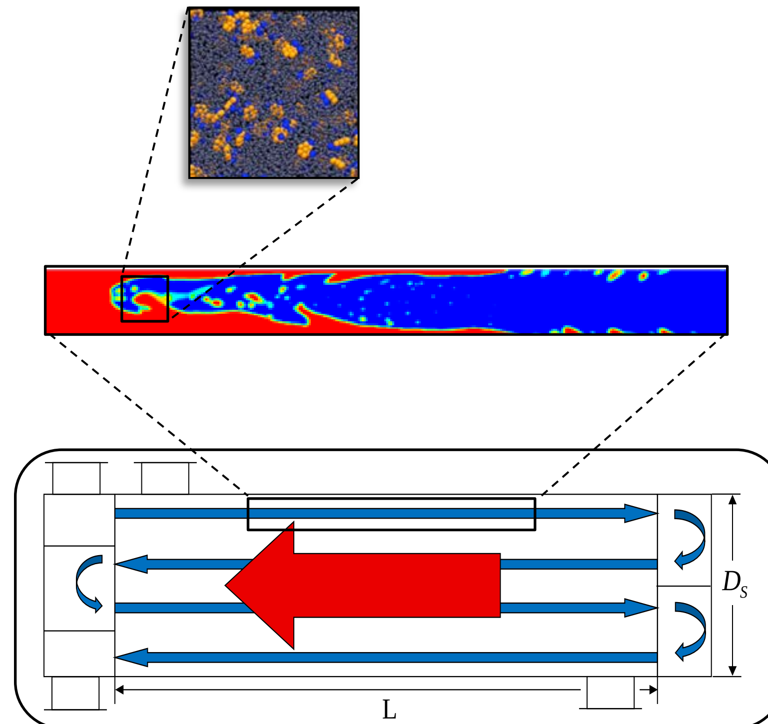
Prof. E. Müller and Prof. G. Jackson

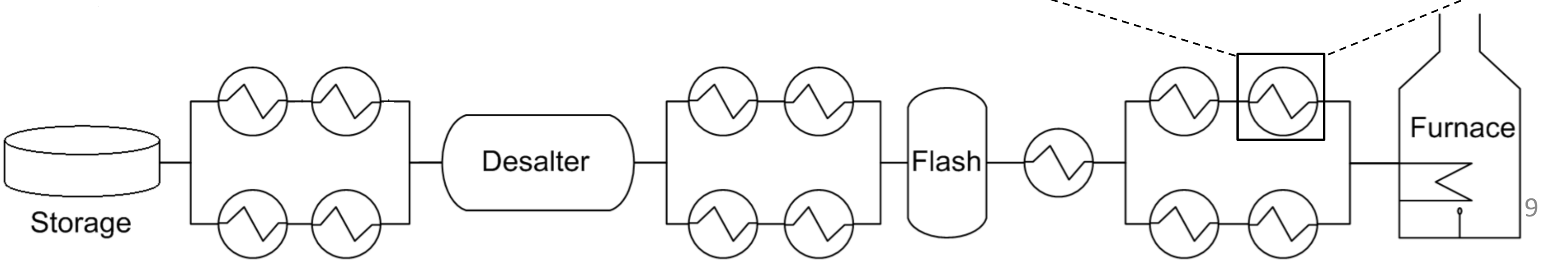
Fundamental transport phenomena

Prof. O.K. Matar

Industrial scale modelling

Prof. S. Macchietto





OBJECTIVES

- Research:
  - To produce a fully predictive model for fouling in refinery heat exchangers
- Technology transfer:
  - To utilise predictive models to improve monitoring, desing and operations of refinery pre-heat trains

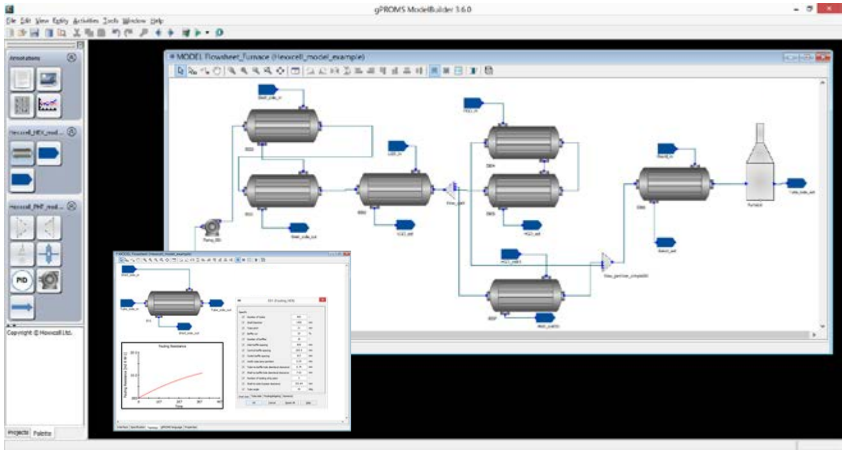


Image courtesy of Hexxcell ltd.

Thermo & Molecular modelling

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Experimental (bulk phase) data

↓

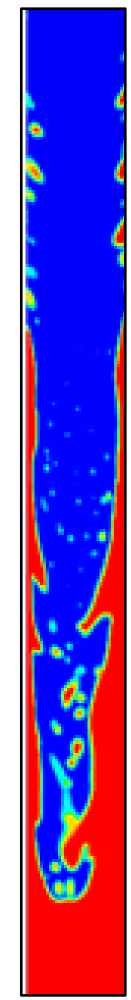
Analytical Equation of state → Properties of bulk fluids →

↓

Parameters for the intermolecular potential

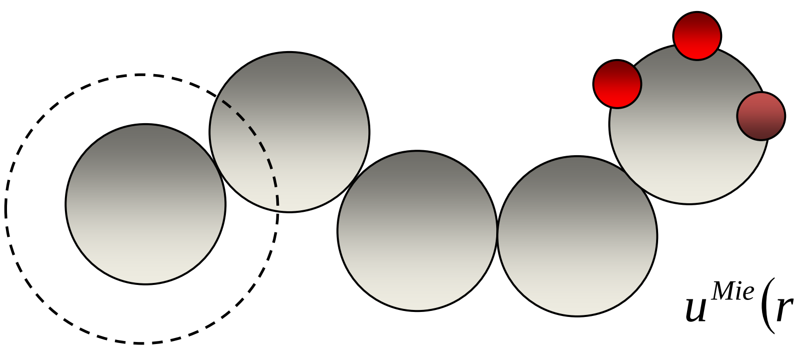
↓

Molecular simulation → Interfacial & transport properties; mesophases →



Equation of Sate

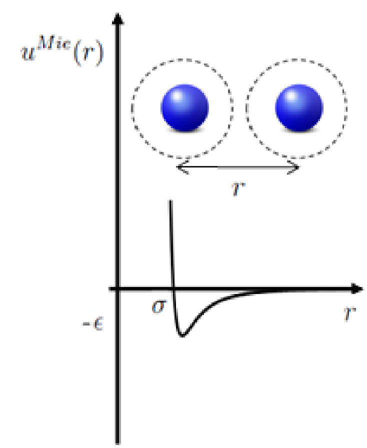
- Statistical Associating Fluid Theory (SAFT)
- Monomeric segments (repulsion/attraction)
- Non-spherical molecules (chains)
- Association (hydrogen bonding, chem. equil.)



New segment-segment Mie potential

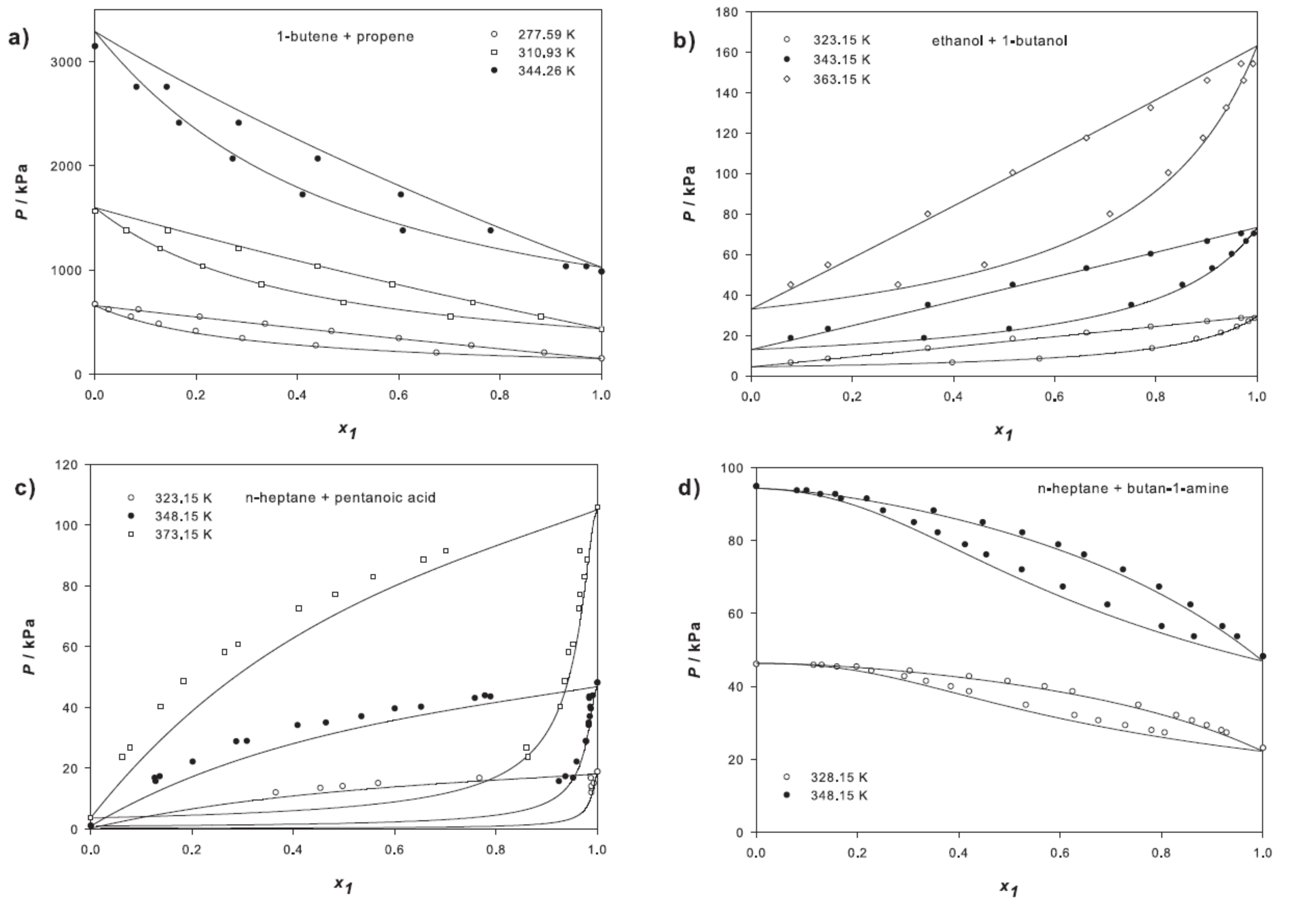
$$u^{Mie}(r) = C(\lambda_r, \lambda_a)\varepsilon\left\{\left(\frac{\sigma}{r}\right)^{\lambda_r} - \left(\frac{\sigma}{r}\right)^{\lambda_a}\right\}$$

$$C(\lambda_a, \lambda_b) = \frac{\lambda_r}{\lambda_r - \lambda_a}\left(\frac{\lambda_r}{\lambda_a}\right)^{\frac{\lambda_a}{\lambda_r - \lambda_a}}$$



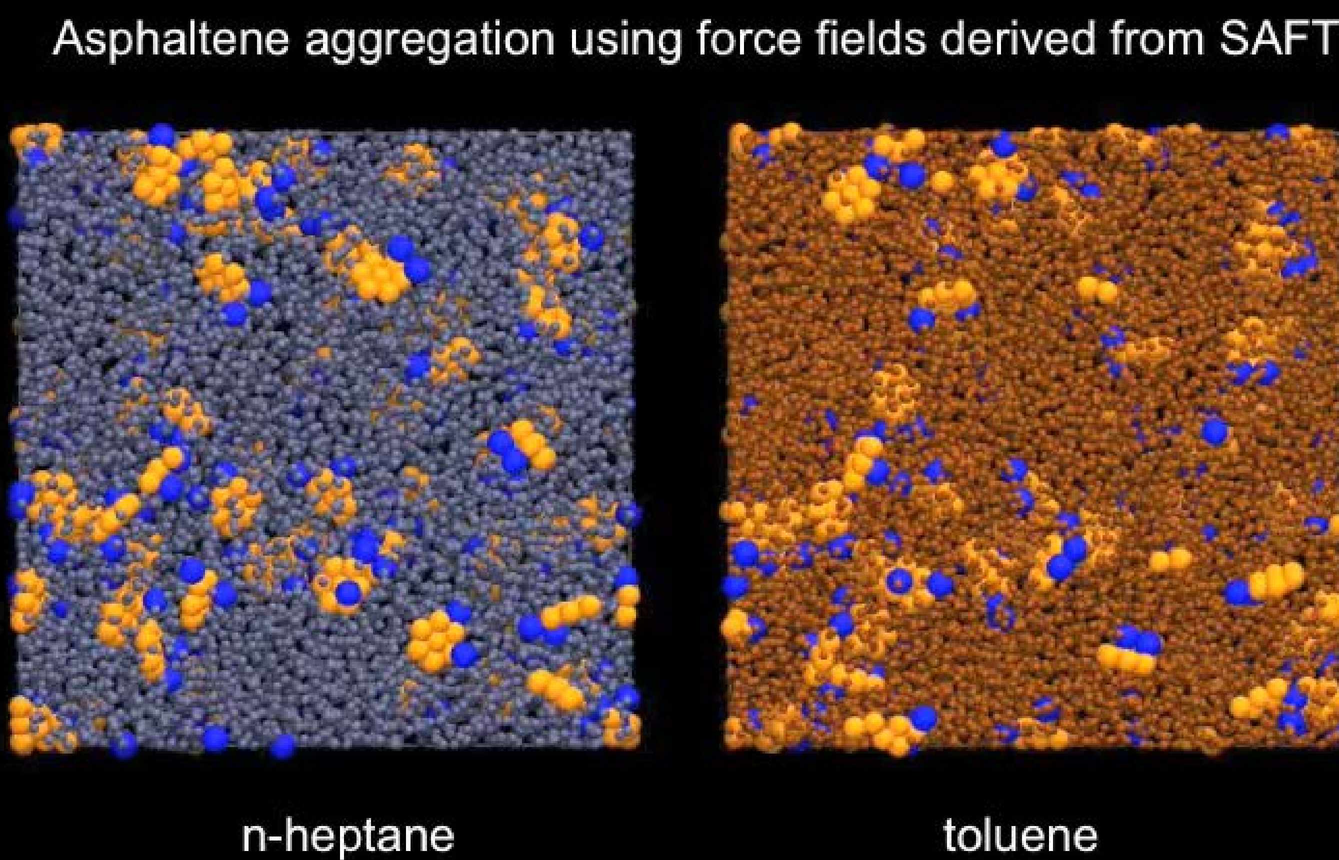
Lafitte, T., Apostolakou, A., Avendaño, C., Galindo, A., Adjiman, C. S., Müller, E. A., & Jackson, G. (2013). Accurate statistical associating fluid theory for chain molecules formed from Mie segments. The Journal of Chemical Physics, 139(15), 154504. doi:10.1063/1.4819786

Example: VLE Predictions in Mixtures



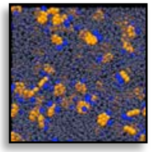
Lymperiadis et al., J. Chem. Phys. 127, 234903 (2007); Lymperiadis et al., Fluid Phase Equil. 274, 85 (2008)

Molecular modelling



Key reference: Avendaño, C., Lafitte, T., Adjiman, C. S., Galindo, A., Müller, E. A., & Jackson, G. (2013). SAFT-γ Force Field for the Simulation of Molecular Fluids: 2. Coarse-Grained Models of Greenhouse Gases, Refrigerants, and Long Alkanes. J. Phys. Chem. B, 117(9), 2717–2733.

Fundamental transport modelling



Fluid, interfacial & transport properties

Chemical reaction and equilibrium

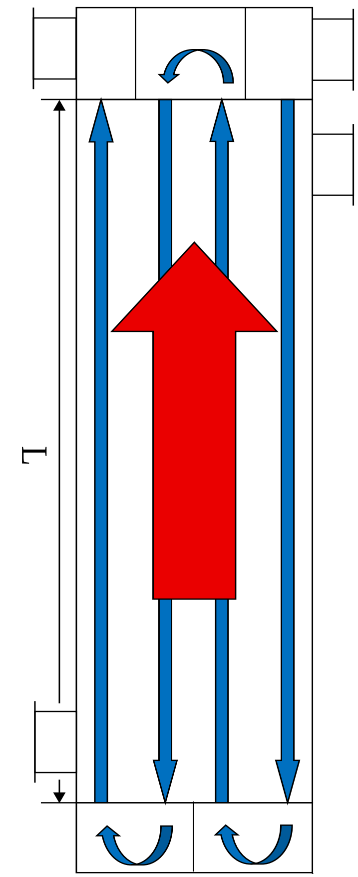
Momentum balance

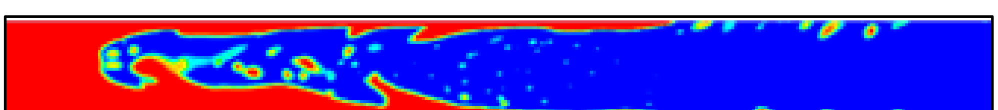
Heat balance

Fouling deposition & removal rate

Shear stress and pressure drops

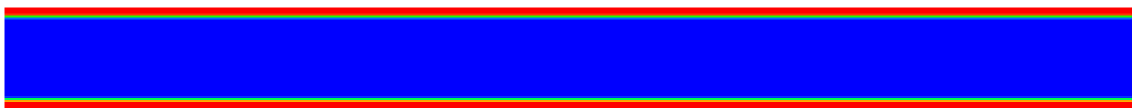
Heat transfer coefficient





Laminar flow - DNS

Re= 500; 2D Modelling



VOLUME FRACTION

TEMPERATURE

Viscosity

Video credits: Prof. O.K. Matar

Turbulent flow - LES

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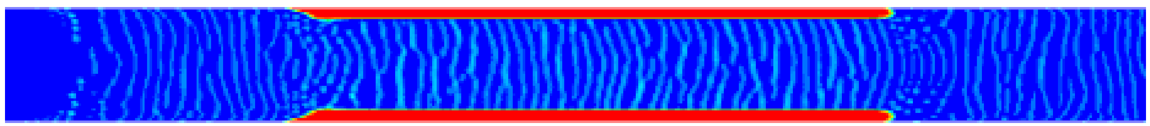
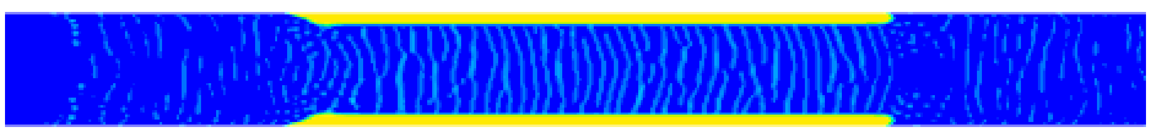
Re= 34 000; 3D Modelling



VOLUME FRACTION

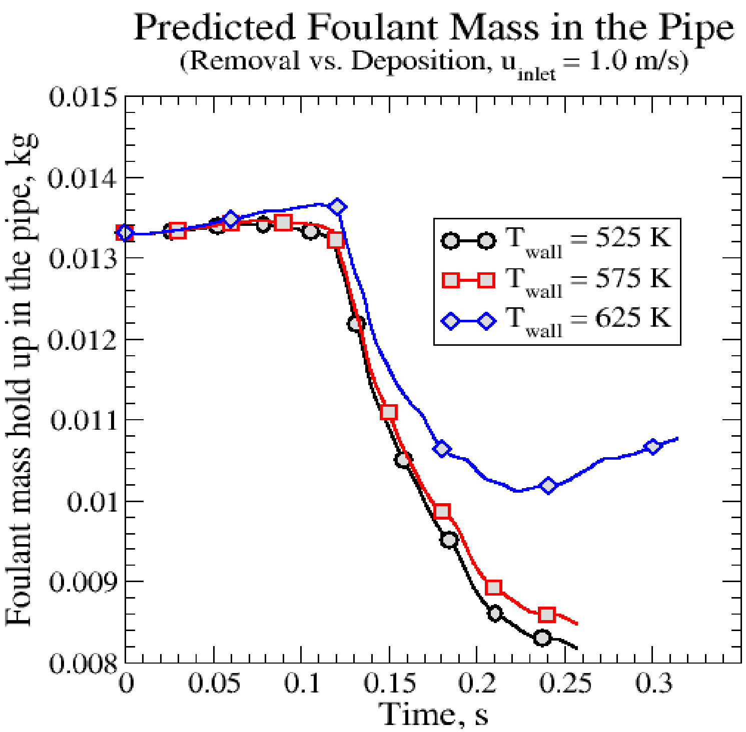
TEMPERATURE



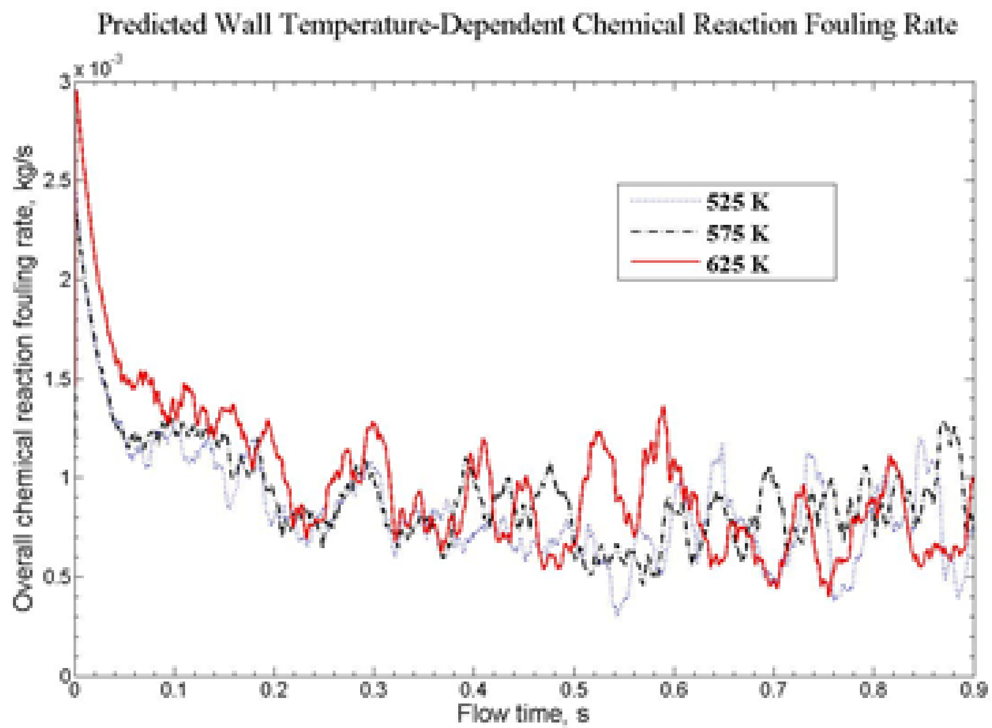
Viscosity

Video credits: Dr. J. Yang and Prof. O.K. Matar

Impact of Surface T on Fouling Formation



The history of total mass of fouling in the pipe

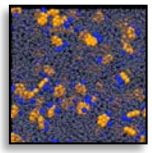


The overall fouling rate in the pipe

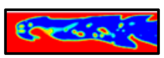
Fouling formation rate increases with surface temperature

Credits: Dr. J. Yang and Prof. O.K. Matar

Industrial scale modelling



Fluid, interfacial & transport properties



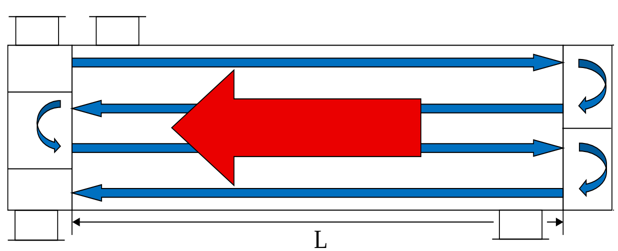
Deposition & removal rates

Shell-side coupled to multi-pass tube-side model

Costing and impact model

Design, retrofit

Operations



Industrial scale models

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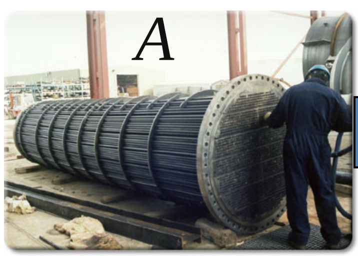
$$Q = UAf_t \Delta T_{ln}$$

$$\frac{1}{U} = \frac{1}{U_c} + R_f$$

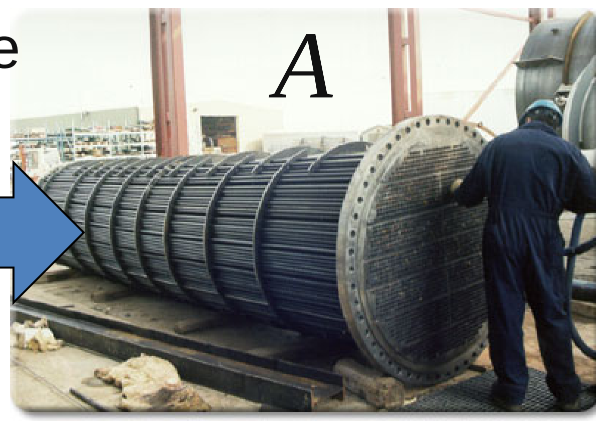
TEMA fouling factors

Bad performance

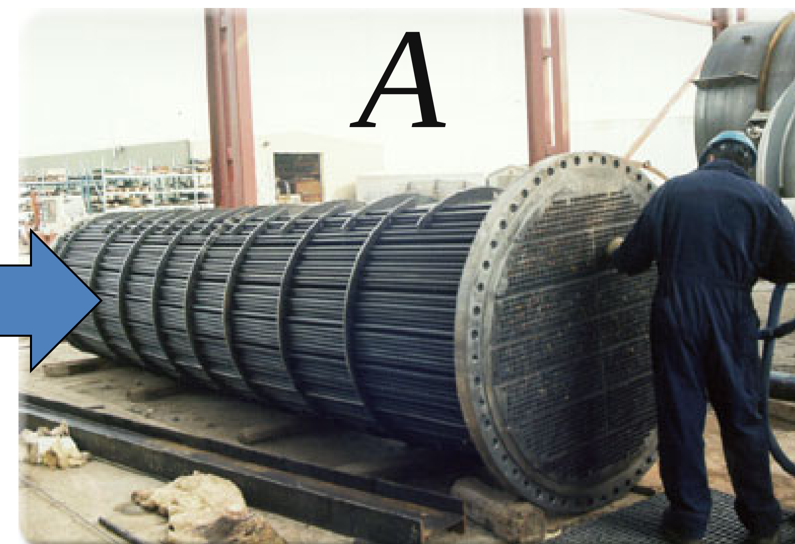


It fouls!

Higher T, Lower v



It fouls more!



It fouls like mad!

The “self-fulfilling prophecy”

Courtesy of Hexxcell Ltd

High fidelity thermo-hydraulic model

Validated: Exxon, Shell (Hexxcell Ltd)

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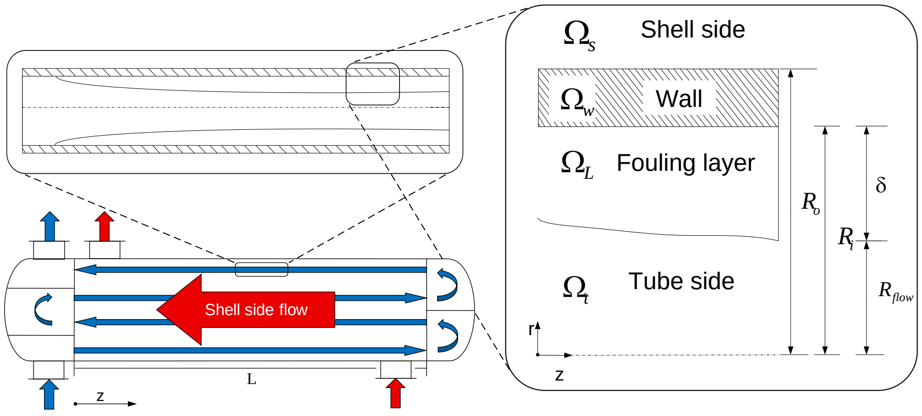
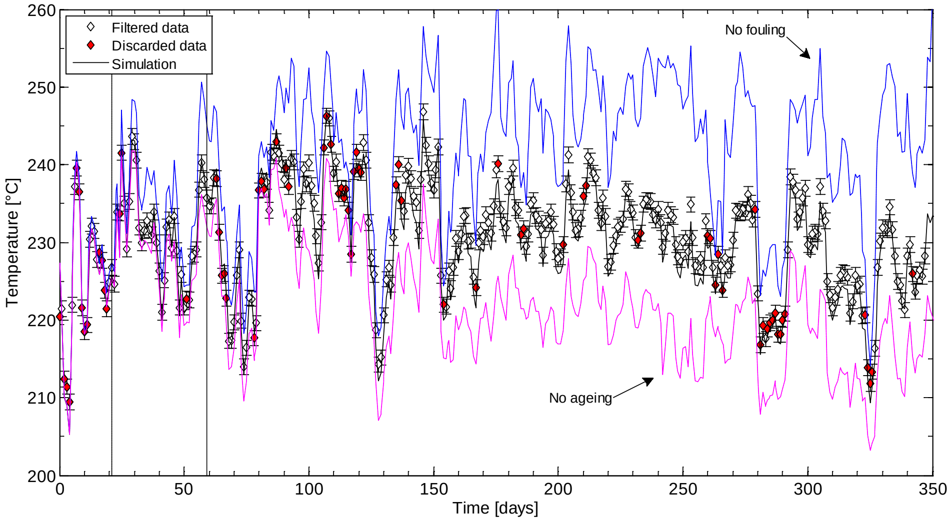
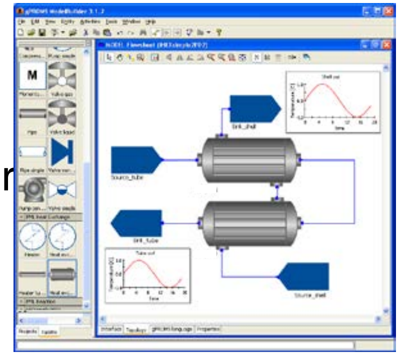




Main features:

- Multi-scale (single tube to network)
- Dynamic and distributed (geometry + local T, v, h, phys props ...)
- Fouling function of local conditions (EP + other models)
- Interacting thermal/fouling/fluid-dynamics (growing deposit layer
- Thermal ageing model
- Exchanger geometry, configuration

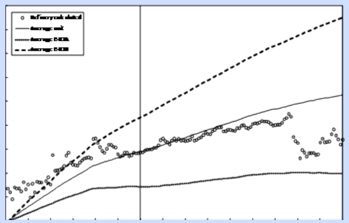


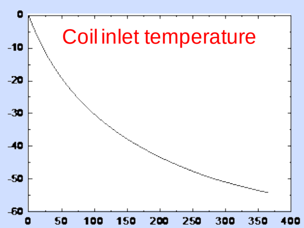
F. Coletti and S. Macchietto (2011). A dynamic, distributed model of shell–and–tube heat exchangers undergoing crude oil fouling. *Ind. Eng. Chem. Res.* **50** (8): 4515–4533.

Applications

Operations

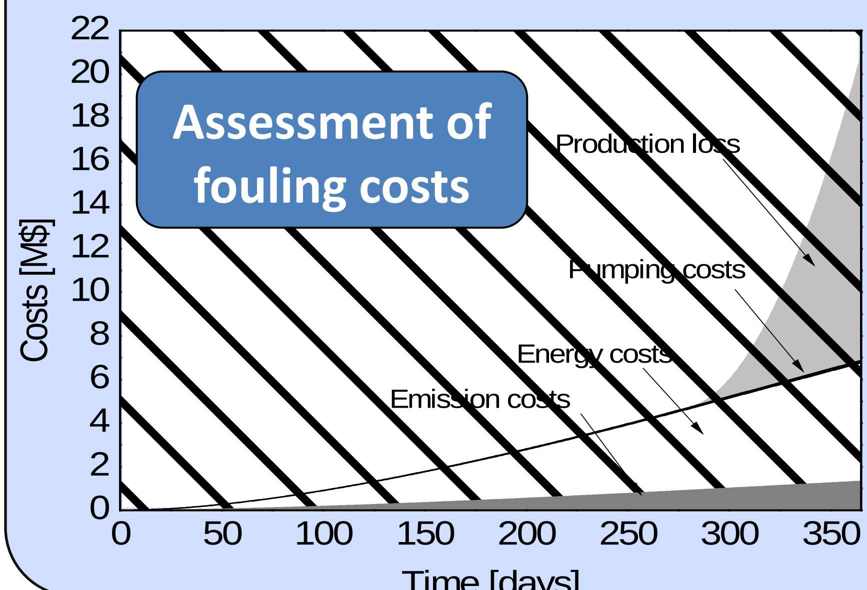
Enhanced fouling monitoring



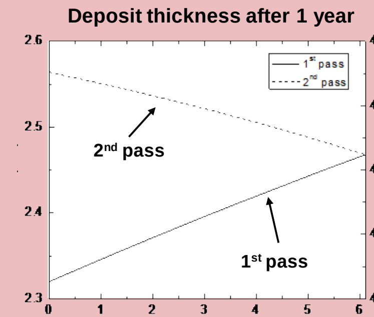


Control (bypass, flow split, ...)

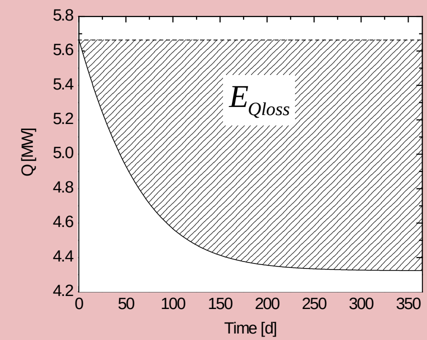
Assessment of fouling costs



Design /retrofit

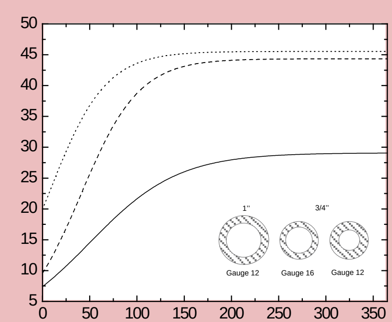


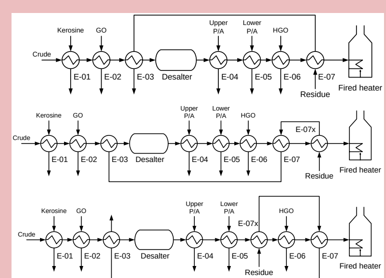
Fouling analysis



Impact on energy/CO2

Single HEX design/retrofit





HEN structure design / retrofit

Crude oil fouling - Experimental

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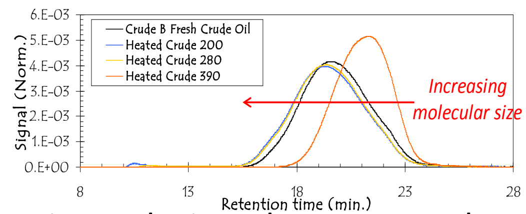
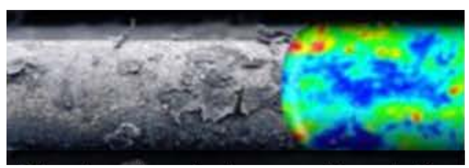
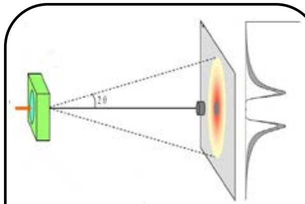
UNIHEAT Themes 2&7



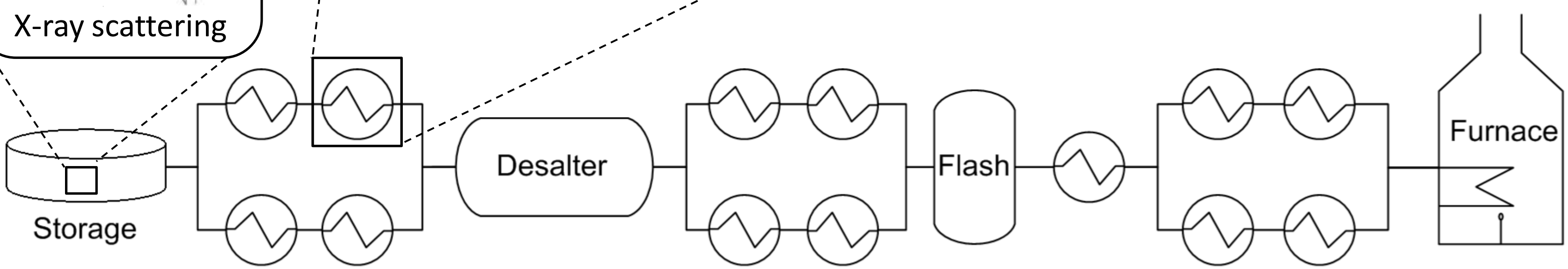
Size Exclusion Chromatography



Chemical Imaging



X-ray scattering



Fouling rigs

Pilot plant scale – Prof. G. F. Hewitt

Lab scale – Dr. Marcos Millan

Chemical structure and molecular weight characterization

Dr. Marcos Millan

Chemical Imaging

Prof. S. Kazarian

X-ray scattering

Prof. O. N. Martyanov

High Pressure Oil Rig (HiPOR)

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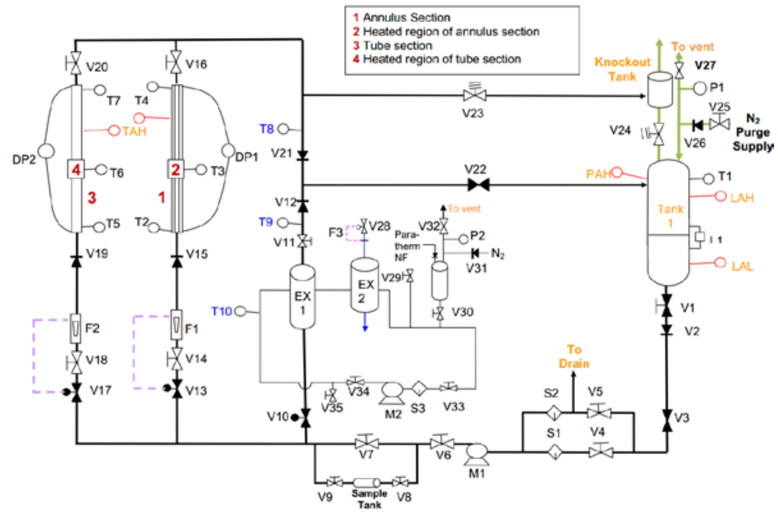
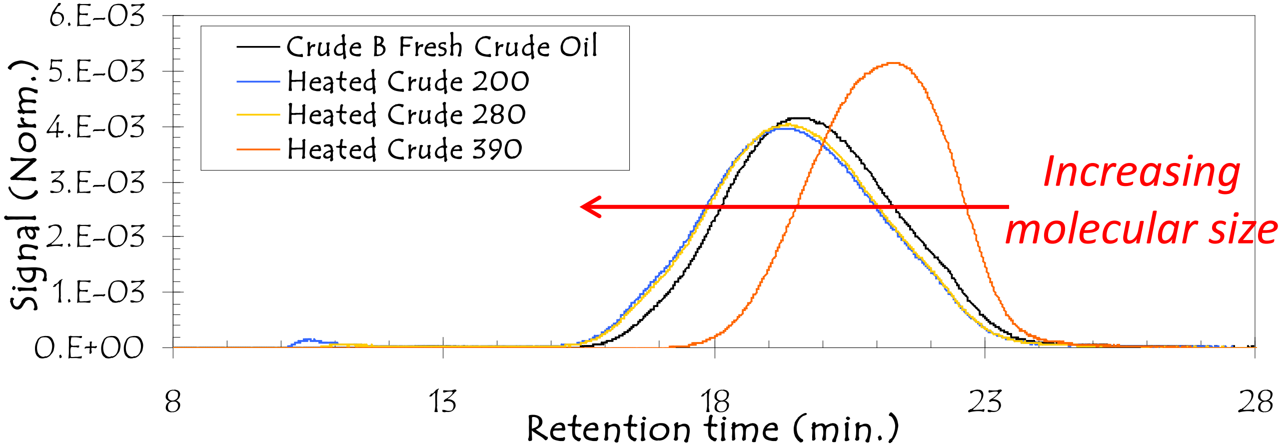


Fouling deposits at controlled, industrial conditions

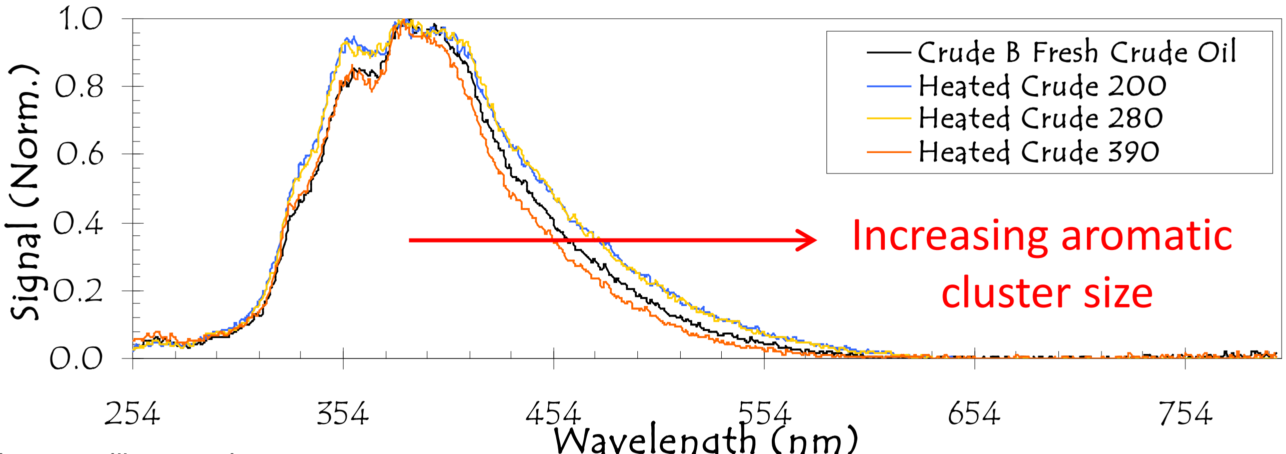
Credits: Prof. G.F. Hewitt

Chemical Characterisation

Changes in the oil preceding/accompanying formation of deposits on surfaces or catalysts can be tracked as a function of operating conditions (temperature, pressure, crude oil blend, etc.)



Size Exclusion Chromatography



Synchronous UV-F Spectroscopy

Credits: Dr. Millan-Agorio

Small angle X-ray scattering

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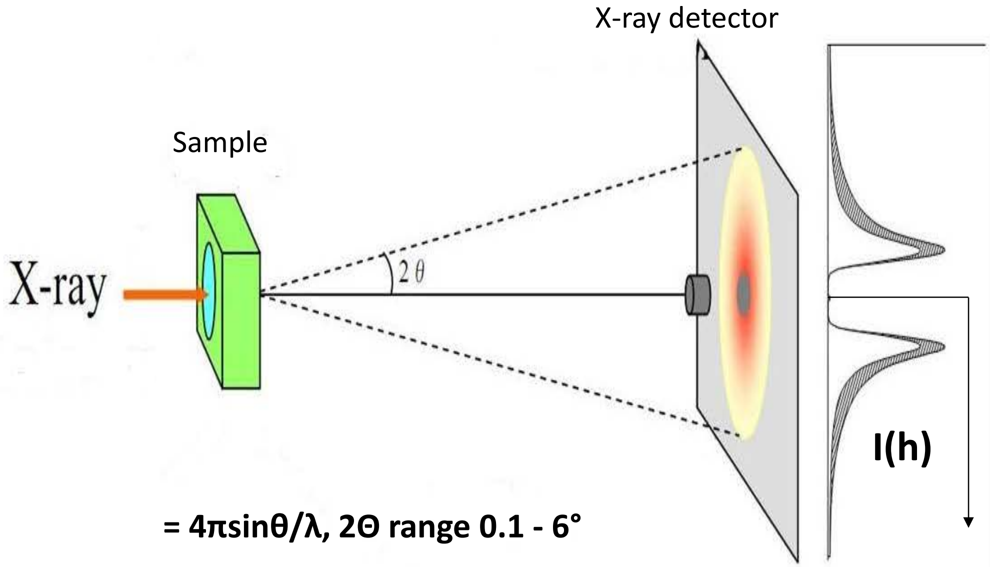
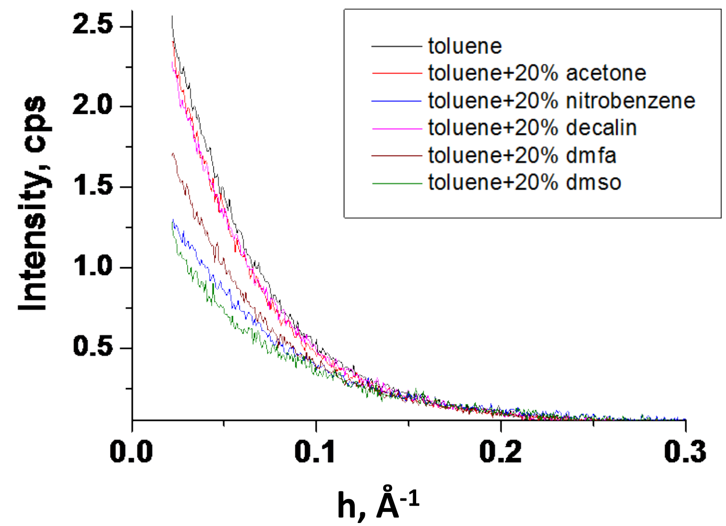
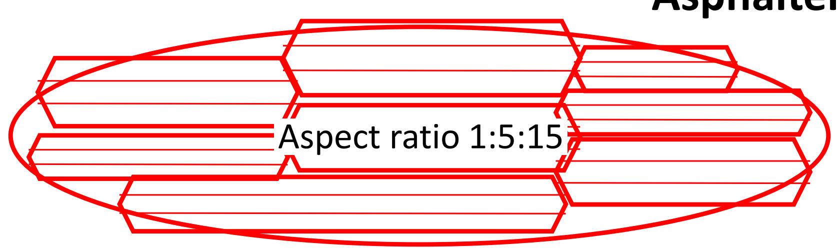


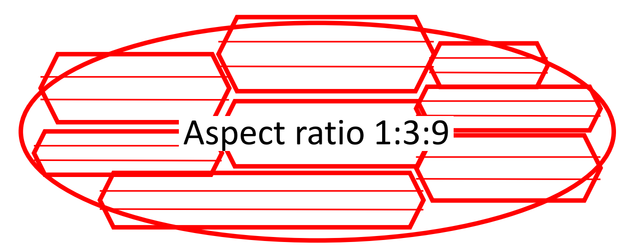
Additives for asphaltene solutions in toluene



Asphaltene aggregate



in toluene



in Tatar oil

Asphatene aggregation depends on solvent and additive type

Credits: Prof. O.N. Martyanov and Dr. Y.V. Larichev

Analysis of key features of the Deposits by a combination of multiple techniques

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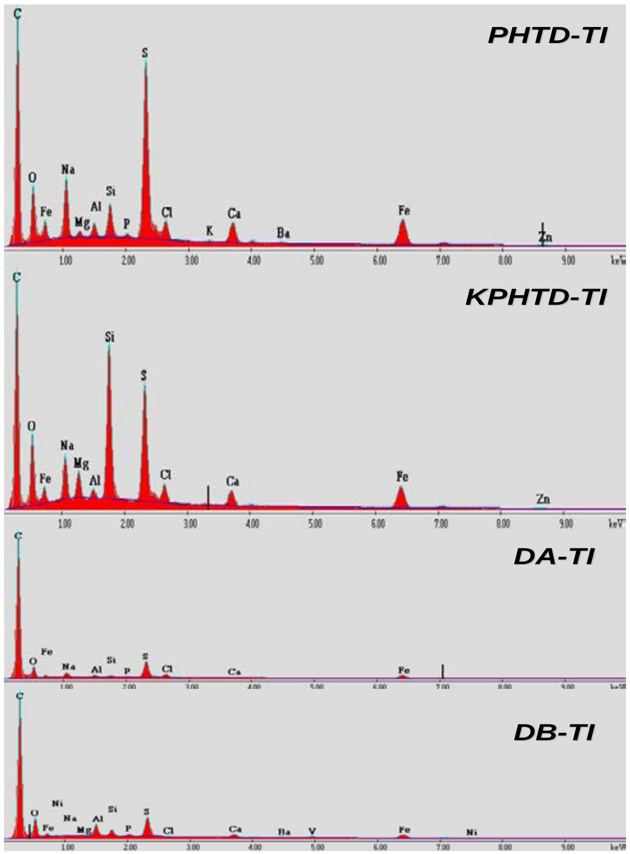
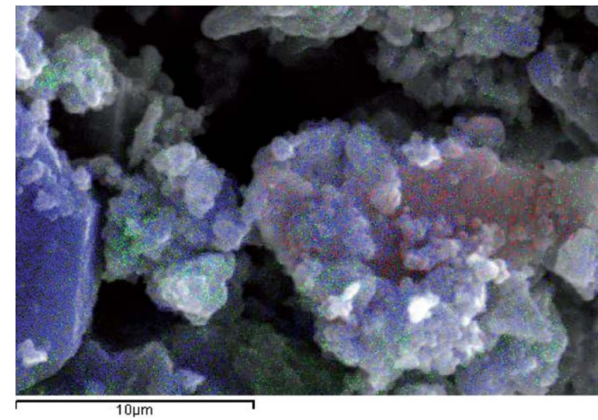
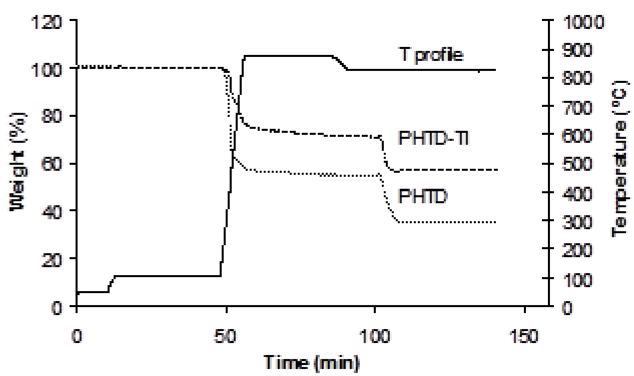


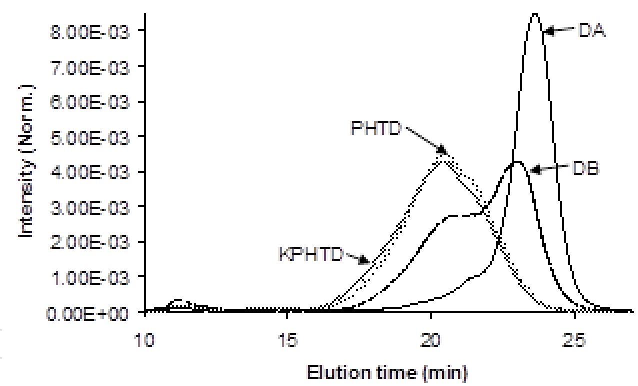
EDX analysis of the insoluble fraction of industrial heat exchanger deposits to determine the likely origins of deposit formation

Scanning Electron Microscopy of a catalyst surface showing regions of preferential formation of carbon deposits.



Thermogravimetric analysis to determine the deposit degree of graphitisation



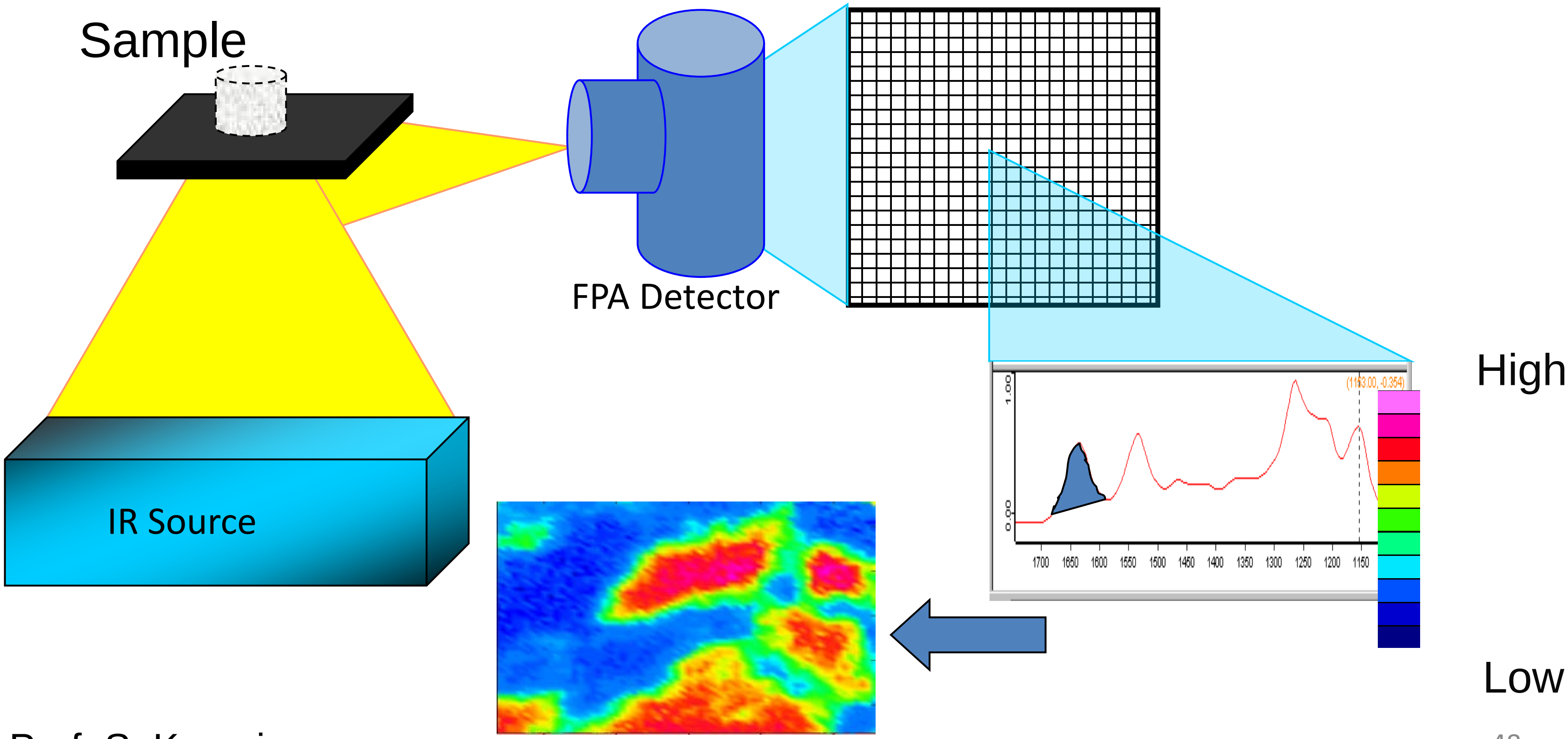


Analysis of the soluble fraction of industrial heat exchanger deposits

Credits: Dr. Millan-Agorio

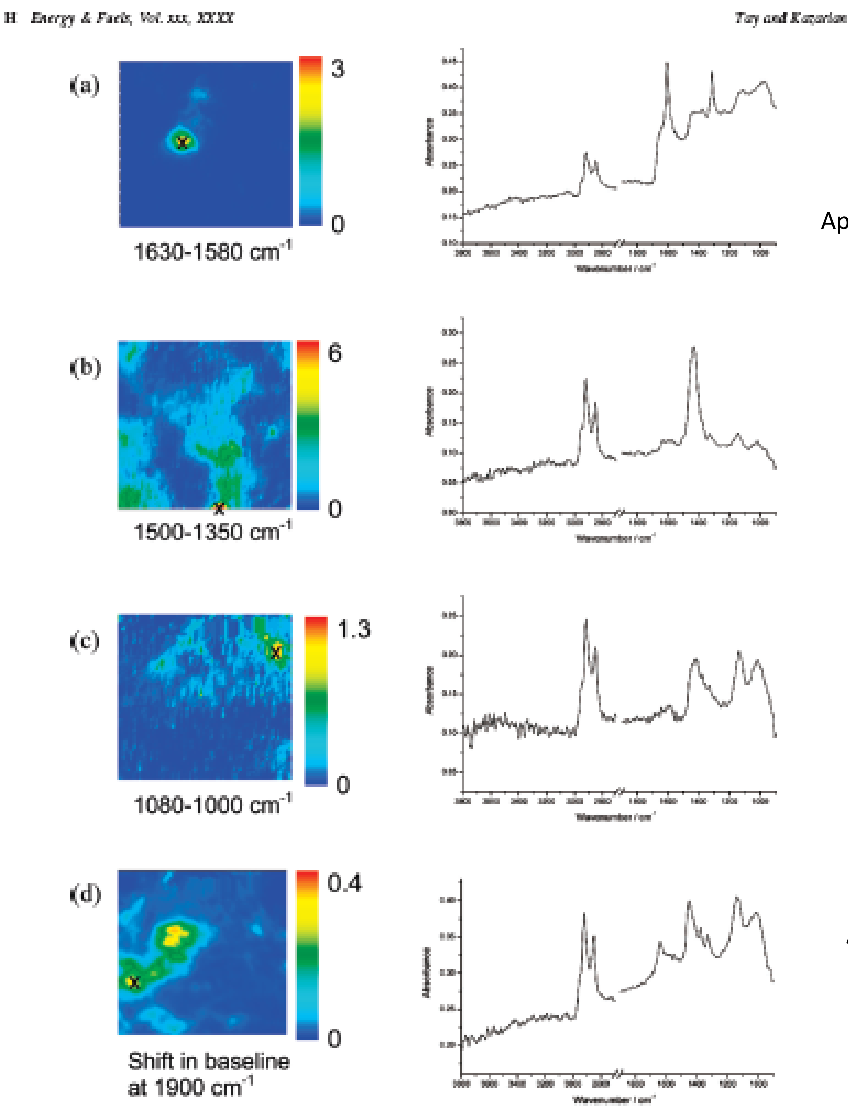
Chemical imaging with IR spectroscopy

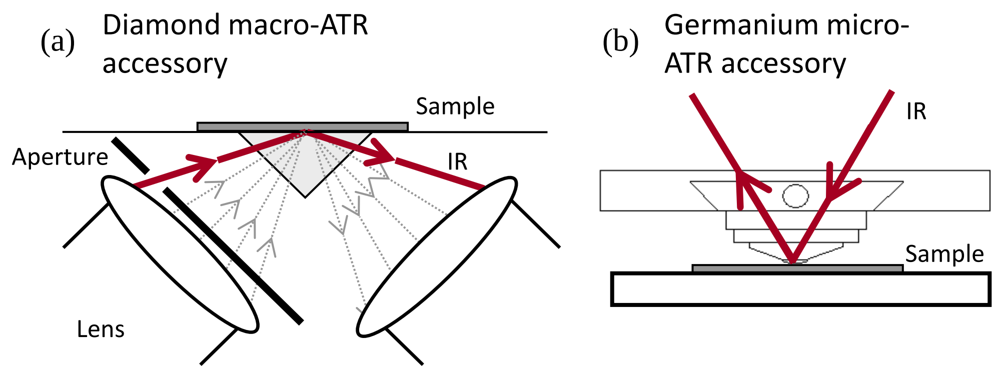
Imaging techniques based on ATR-FTIR: non-destructive; combine chemical and spatial information; small amounts of sample required.

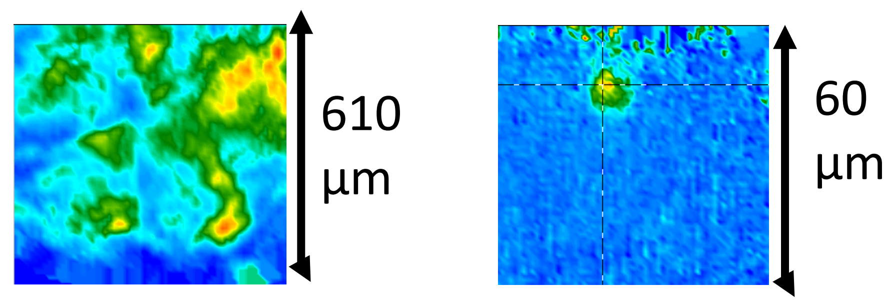


Credits: Prof. S. Kazarian

ATR imaging of crude deposits







Energy & Fuels 2009, 23, 4059

Asphaltenes, carbonates, sulphates, sulfoxides, oxalates and possibly coke in refinery deposits

Credits: Prof. S. Kazarian

UNIHEAT Project - Research programme

- Crude oil fouling
- Other UNIHEAT research themes

Thermodynamic power generation cycles

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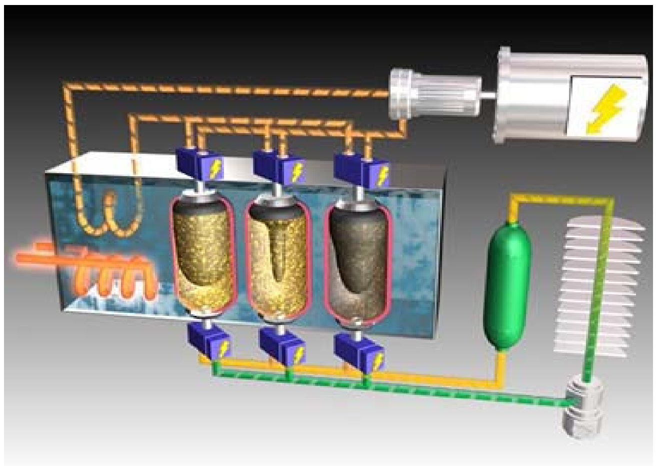
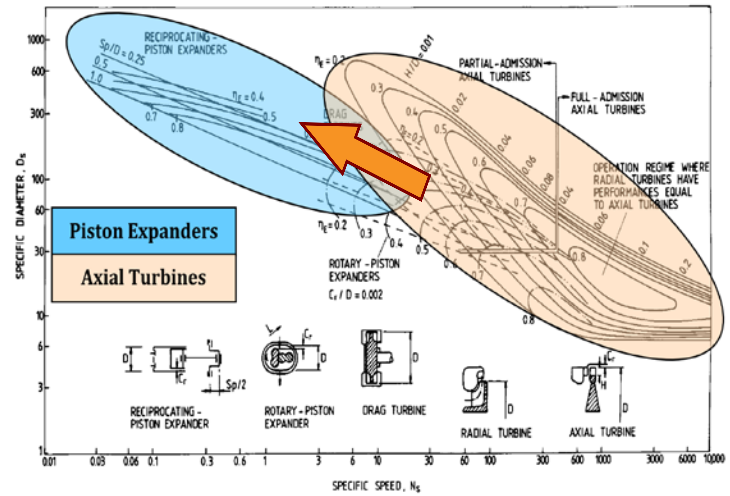
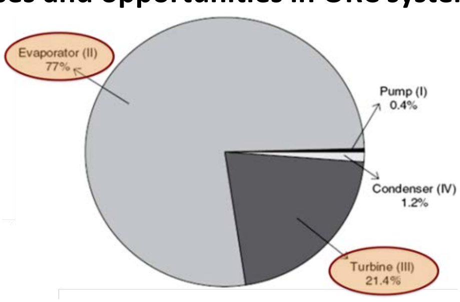
Thermohydraulic Generator-ORC (THG-ORCs)



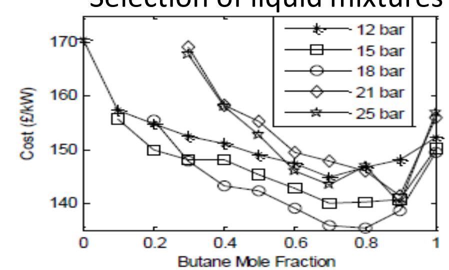
Expander selection



Losses and opportunities in ORC systems



Selection of liquid mixtures



Conversion of waste heat to useful power

Credits: Dr. CN. Markides

Liquid Stirling Engine + Catalytic Heater (LSE-CH)

UNIHEAT

- **Simpler and cheaper** than a Stirling engine, turbine and multiple expansion steam engine
- **Low emissions**
- **Working fluid** in liquid state can serve as lubricant for all rubbing parts
- Incompressible liquid working fluid decreases **remarkably** dead volume
- **Catalyst heat generation**: 100 – 1,000 ^{o}C
- **Easily scalable**: 1 W to 1 MW per cylinder
- **Thermochemical heat recuperation** is possible

Credits: Prof. V. Kirillov, patent pending

Heavy oils upgrade

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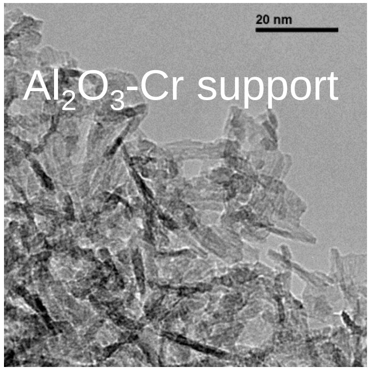
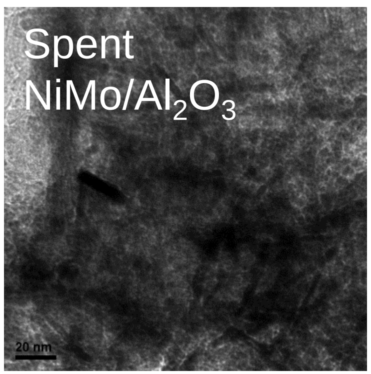
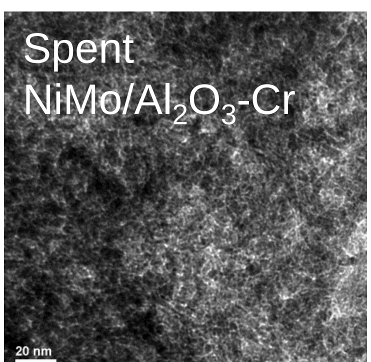
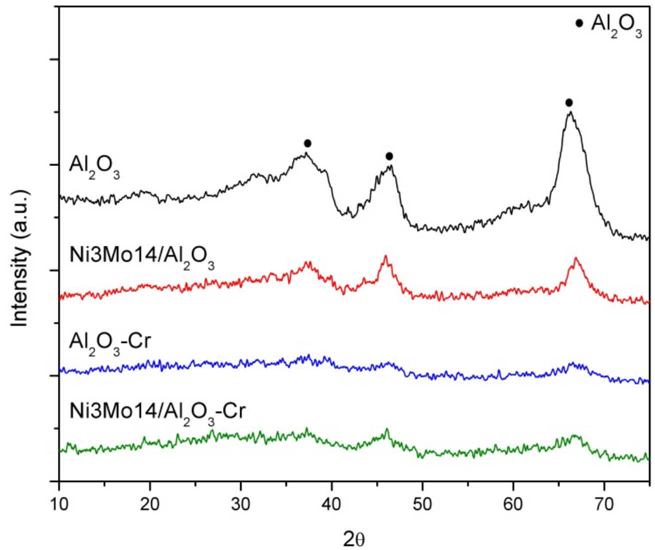
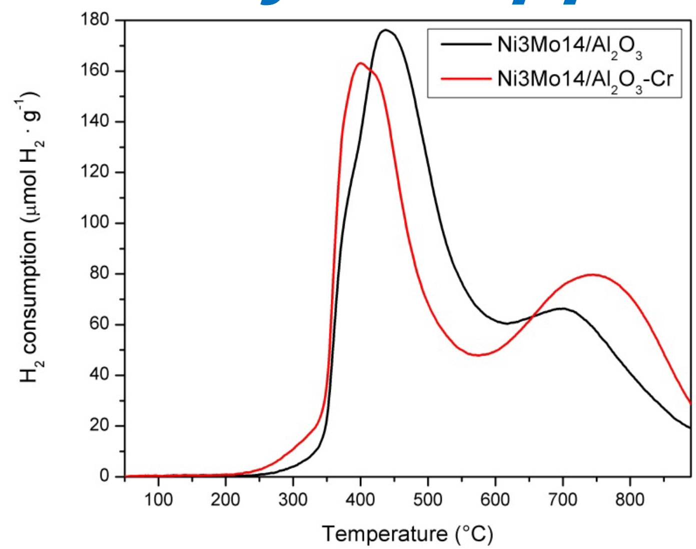






Cr-doped Al_2O_3 as catalytic support





- Al_2O_3-Cr allows NiO & MoO_3 to reduce at lower temperatures
- Different distribution of coke on catalyst
- NiMo/Al_2O_3-Cr achieves better asphaltene upgrading

Catalyst	Reaction T	g coke/ g catalyst	Conversion fraction>450°C	Conversion Asphaltenes
NiMo/Al_2O_3	425°C	0.31	46%	76%
NiMo/Al_2O_3-Cr	425°C	0.45	52%	82%

Credits: Dr. M. Millan

Drag reduction in oil pipelines

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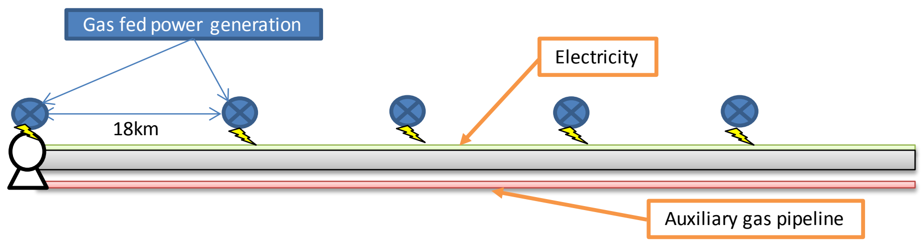
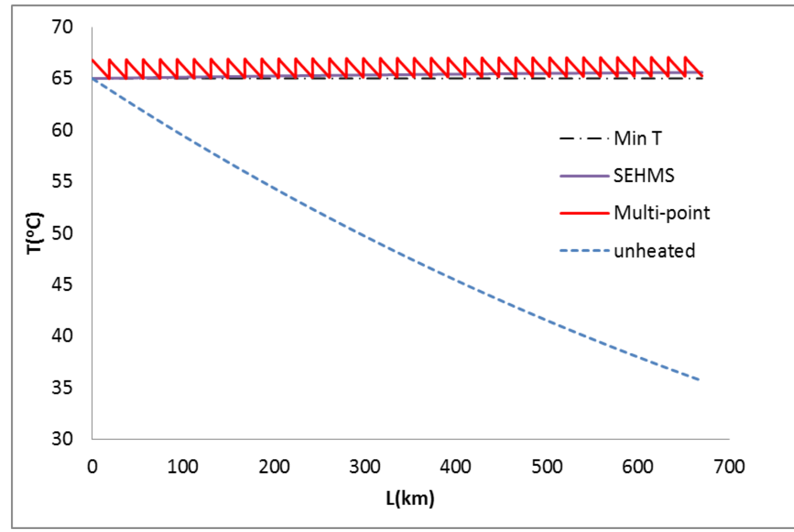
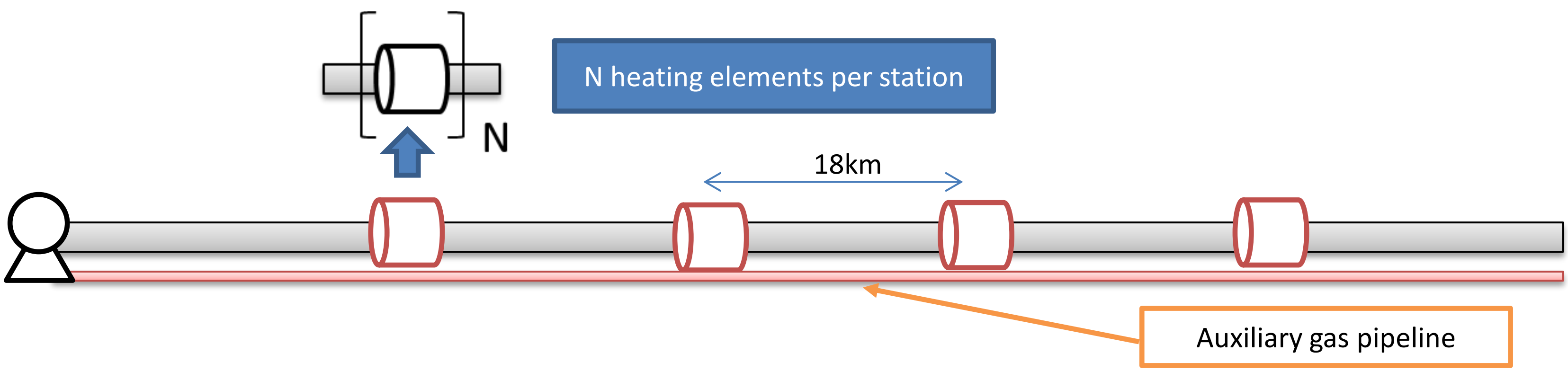
(a) Existing continuous electrical heating



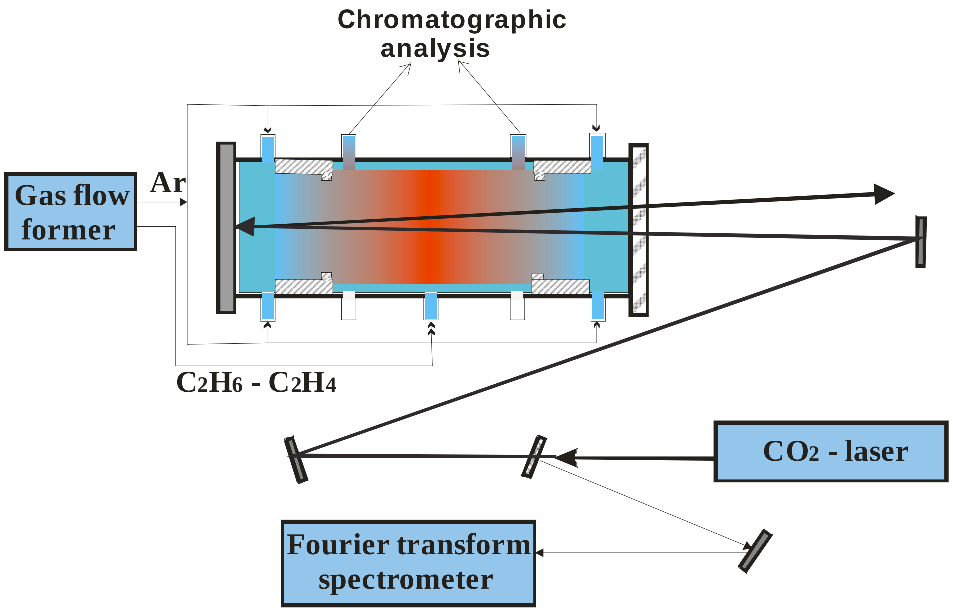


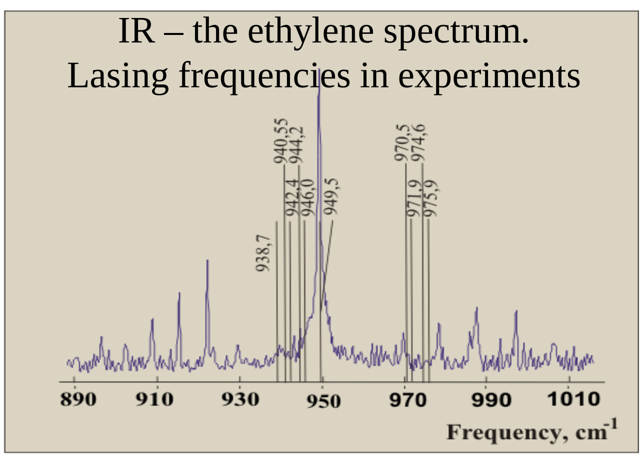
(b) Multi-point heating system using <u>alternative gas heaters</u>

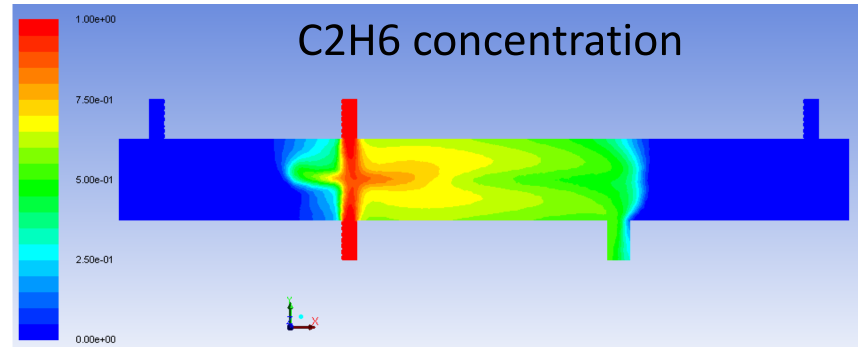


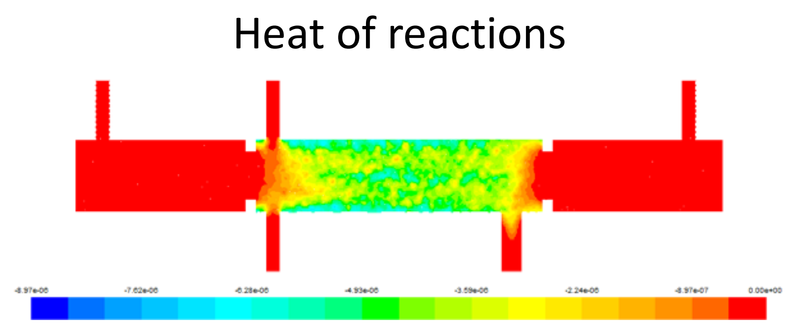
Credits: Prof. S. Macchietto and Prof. A. Porsin

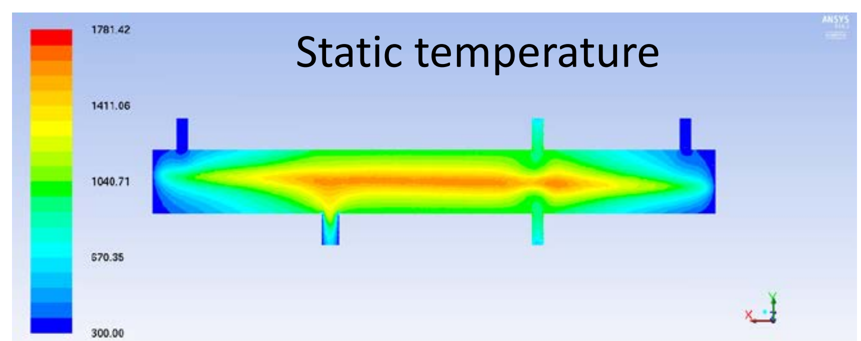
Laser Induced Pyrolysis of Light Hydrocarbons











Credits: Prof. V.N. Snytnikov

UNIHEAT Project - Industry engagement

Mr. Paul Docx
Managing Director

Dr. Francesco Coletti
Industry Engagement Manager

Ms. Tatiana Schofield
Business Development Manager

Ms. Ivette Trinidad
Assist. Project Manager

Technology transfer is difficult !

UNIHEAT

Traditional, linear approach

Science

↓

Engineering

↓

Applications

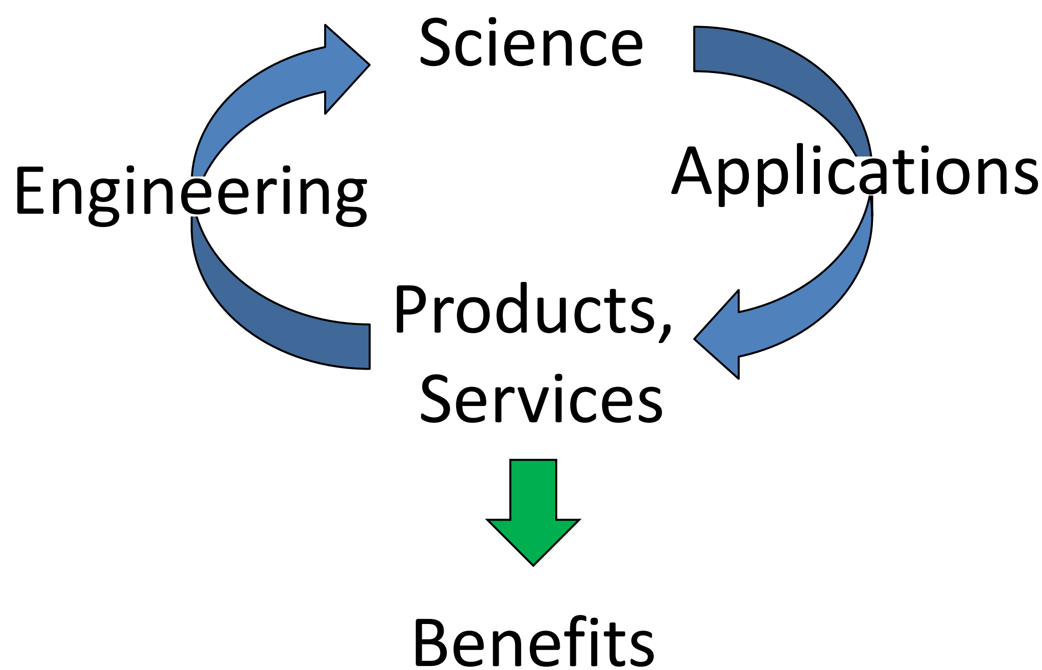
↓

Products/Services

↓

Benefits

Structured Approach + Experience



Innovation by design

3 Steps to Innovation

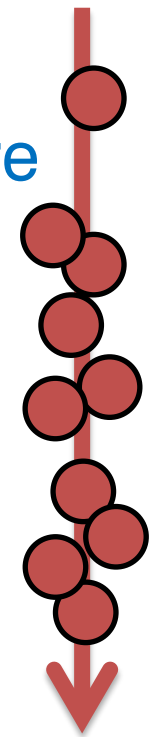
UNIHEAT

- Advanced Research
  methods, data, software
- Lab Demonstration
  small/medium scale
- Industrial feasibility
  full scale, real

3 Steps to Innovation – with industry

UNIHEAT

- Advanced Research
  methods, data, software
- Lab Demonstration
  small/medium scale
- Industrial feasibility
  full scale, real



Industry partners

Engagement
focus, trust, relevance

Data, materials
proof of concept

Plant, people
performance, benefit,
... steps for use

Greater probability of Technology Transfer success

IEP events

UNIHEAT

UNIHEAT at Total Energy USA, 19-21 November 2013, Houston, Texas.

UNIHEAT Brainstorming event

VIP breakfast – UK embassy, Moscow

UK Heat transfer conference sponsorship

UNIHEAT hosts inaugural Annual Conference

UNIHEAT Office

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Office phone: +7 495 2582169

Working with industry

UNIHEAT

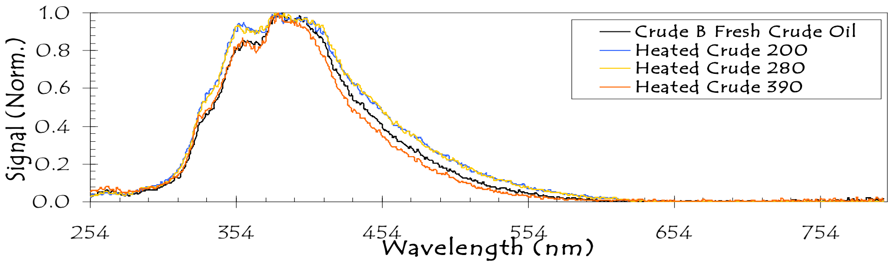
Collaboration opportunities:

- Major Partnerships (co-sponsoring the whole project)
- Bespoke projects (tailored to specific needs)
- Feasibility & Case studies
- R&D or Consultancy

“We are pleased to be involved with this very important research programme. Improving heat exchange technology remains important for the environmental efficiency of the oil processing industry. We are very pleased to team up with Skolkovo to fund Boreskov and Imperial, two of the world’s leading research institutes in this key research programme”

Scott Sloan, President of BP Russia, December 2013

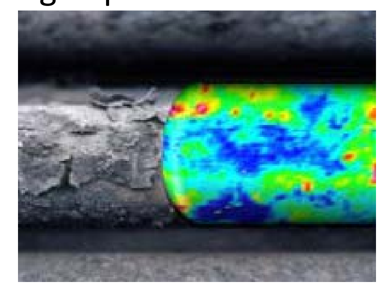
What can we offer?



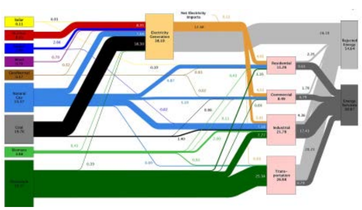
Advanced oil characterization techniques

Catalytic technology expertise

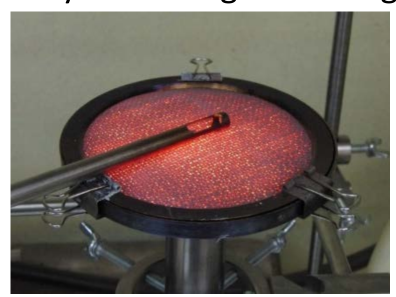
Fouling deposit characterization



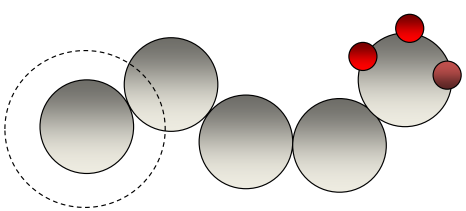
Energy efficiency analysis



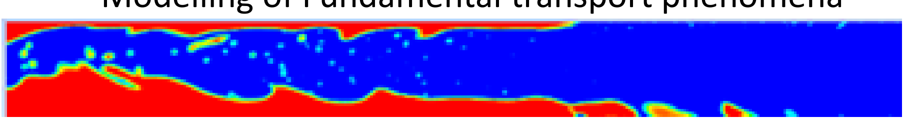
Catalytic heating technology

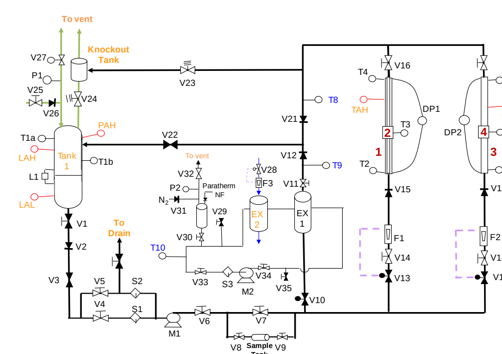


Advanced thermodynamics modelling



Modelling of Fundamental transport phenomena





Test runs on oil rig facilities

Acknowledgments

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Sk
Сколково

bp

Imperial College London

Novosibirsk State University

НГУ

UNICAT

bp

Skolkovo

UNIHEAT

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