Spinning Disc Reactor: Basic Principles and Applications

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Outline

- Operating Principles of SDR
  - Characteristic features of thin film flow
- Exploiting SDR characteristics: case studies of SDR application

Spinning Disc Reactors

Feed pipes

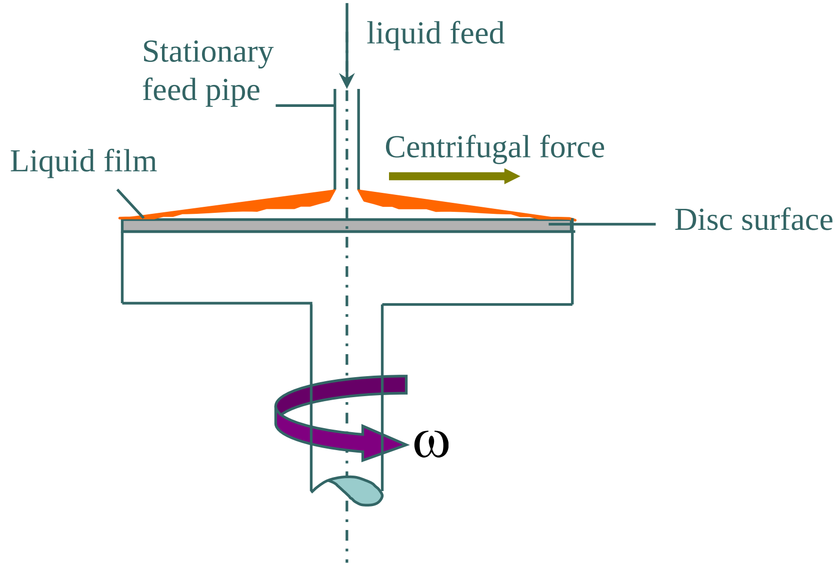
200 mm diam. smooth stainless steel disc

100 mm disc surface

Water cooled jacket

Characteristics features of SDR

- Rotation of disc surface creates high centrifugal fields which promote thin film flow
  - Centrifugal acceleration (=$\omega^2 r$) as high as 1000g
  - Film thickness typically 50-500 μm
- Films are highly sheared and have numerous unstable surface ripples
- Various disc configurations may be used for enhanced performance
  - Smooth
  - Metal sprayed
  - Grooved



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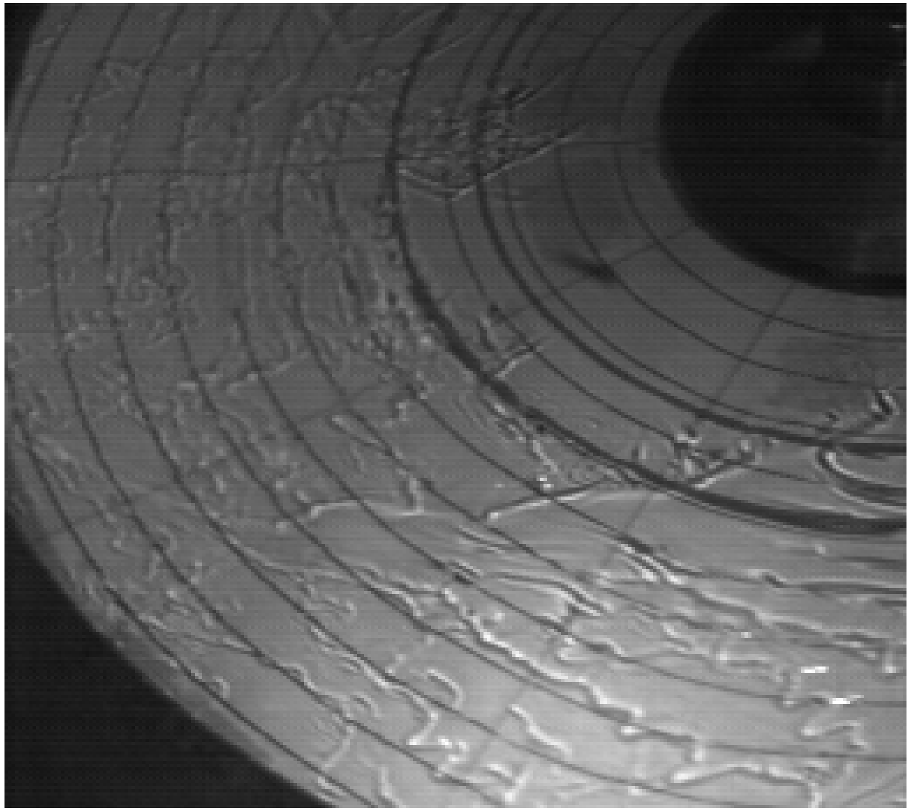
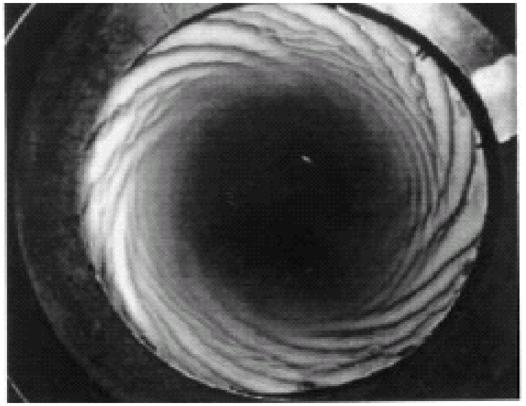
Thin film flow on a spinning disc

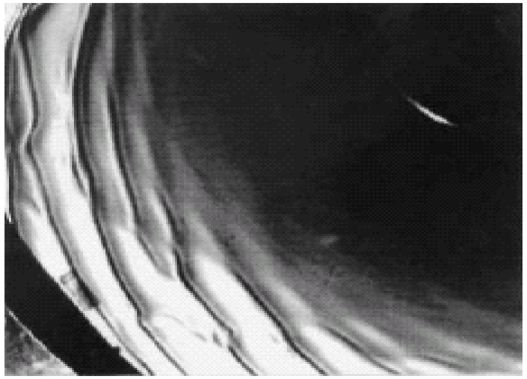


- Water like liquid on disc rotating at 400 rpm

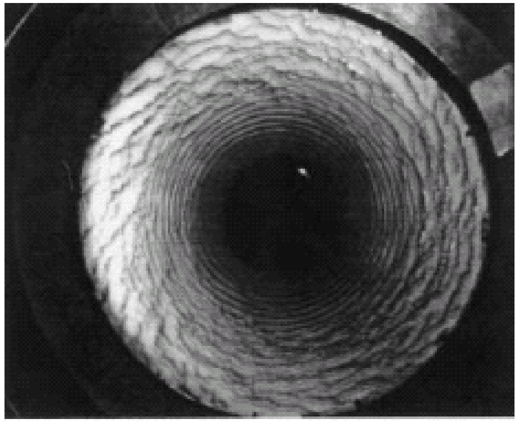
Wave formation in water-like fluid on rotating disc

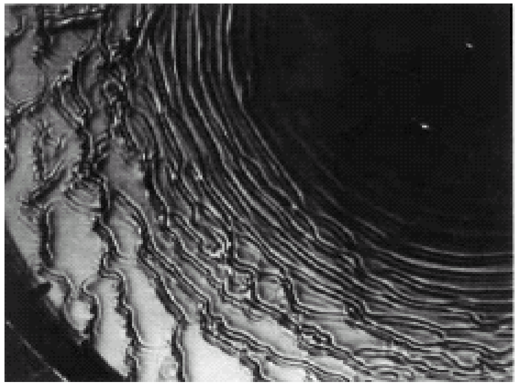
Mass flowrate of liquid= 0.013-0.019 kg/s



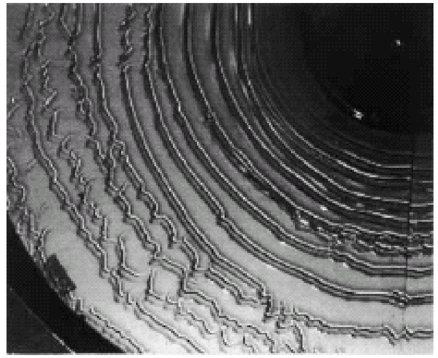


$\omega = 10\ s^{-1}$

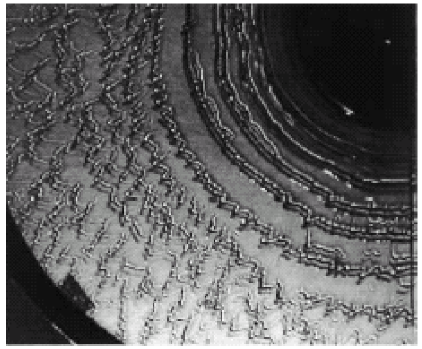




$\omega = 20\ s^{-1}$



$\omega = 40\ s^{-1}$



$\omega = 60\ s^{-1}$

Spiral waves

Irregular surface ripples

(Source: Aoune & Ramshaw, Int. J. Heat & Mass Transfer, 42, 2543-2556 (1999))

Parameters of interest in SDR based on centrifugal model

Residence time: $$t_{res} = \left(\frac{81\,\pi^2\,\nu}{16\,\omega^2\,Q^2} \right)^{1/3} \left(r_o^{4/3} - r_i^{4/3} \right)$$

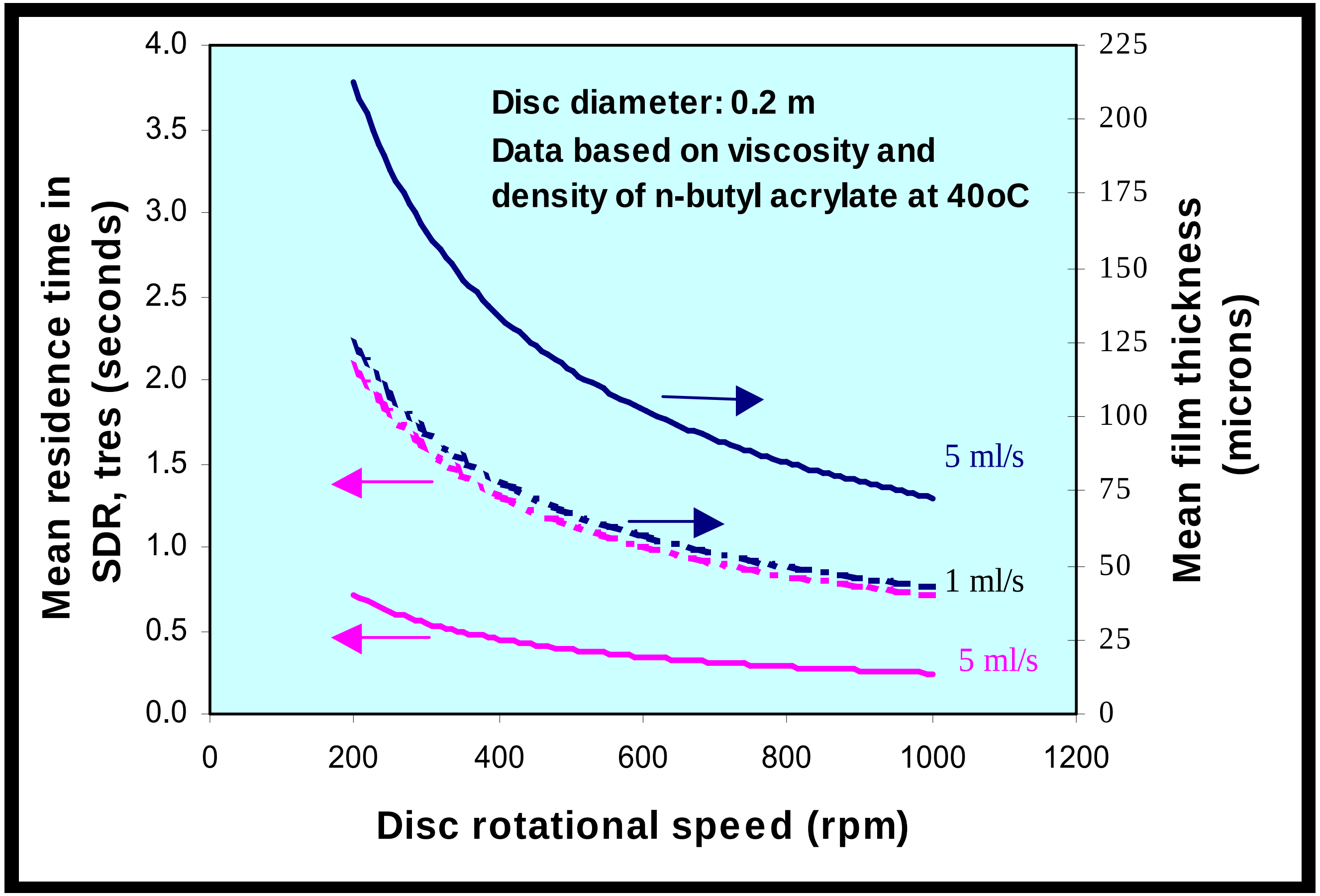
Film thickness: $$\delta = \left(\frac{3}{2\,\pi} \frac{\nu\,Q}{\omega^2\,r^2} \right)^{1/3}$$

Shear rate: $$\dot{\gamma}_{ave.} = \left. \frac{dv_r}{dz} \right|_{z=0} = \frac{\omega^2 r \delta}{2\nu} = 1.5 \left(\frac{Q\omega^4 r}{18\pi\nu^2} \right)^{1/3}$$

where

Q: feed flowrate
ν: kinematic viscosity ($=\eta/\rho$)
ω: rotational speed ($= 2\pi N/60$)
r: radial distance across disc surface

Mean residence time and film thickness profiles in SDR



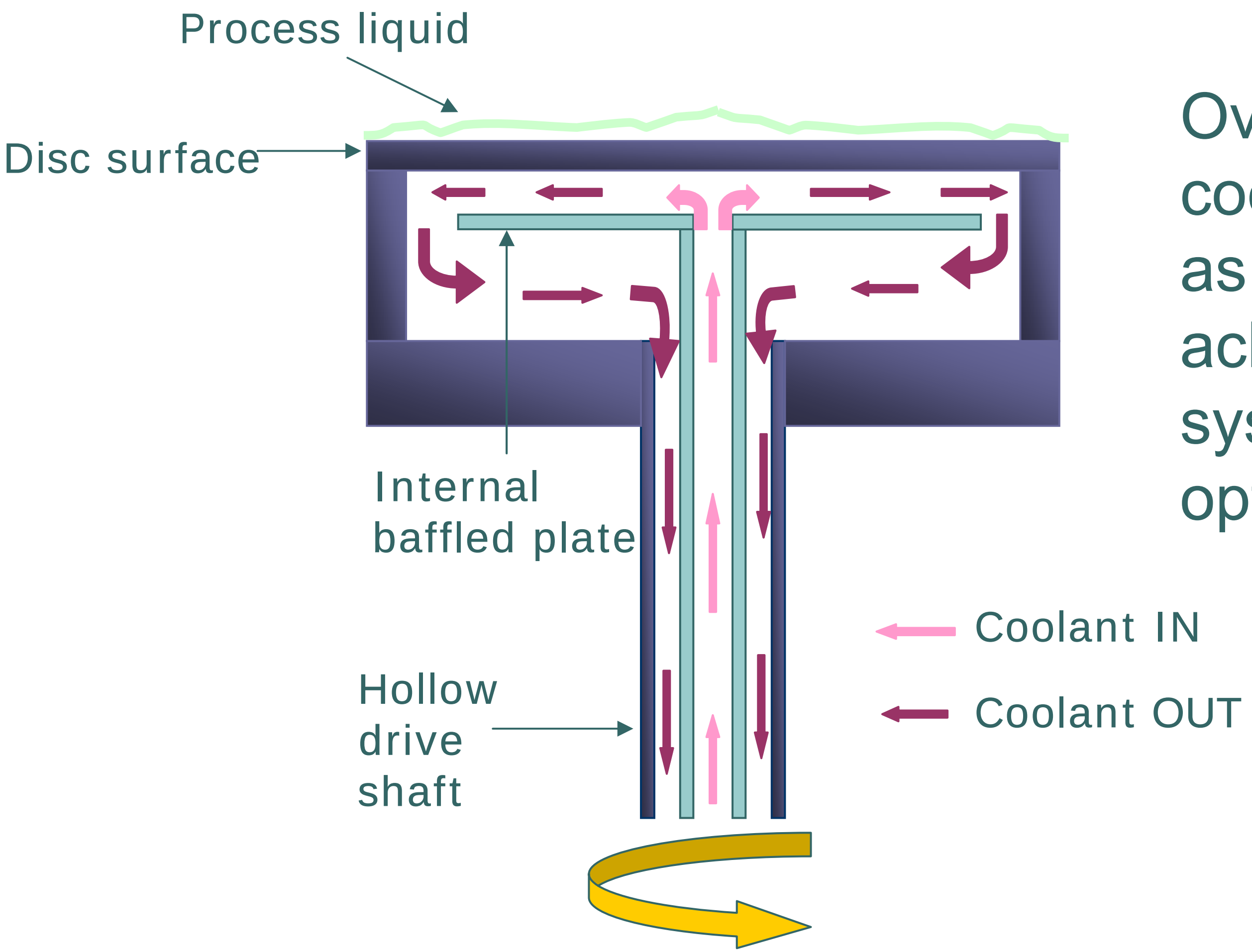
Thin film flow regime in SDR

- Reynolds number:

$$\mathrm{Re} = \frac{4Q}{\pi \nu D}$$

- Various flow regimes observed:
  - Re<16: smooth laminar flow
  - 16≤ Re< 40: Small amplitude waves
  - 40≤ Re< 80: Sinusoidal and regular waves
  - Re>80: Random surface waves
- Waves greatly influenced by disc speed

Heat transfer characteristics of thin film



Internal cooling/heating system in SDR

Overall heat transfer coefficient U as high as 4 kW/m^{2}K can be achieved using this system under optimised conditions

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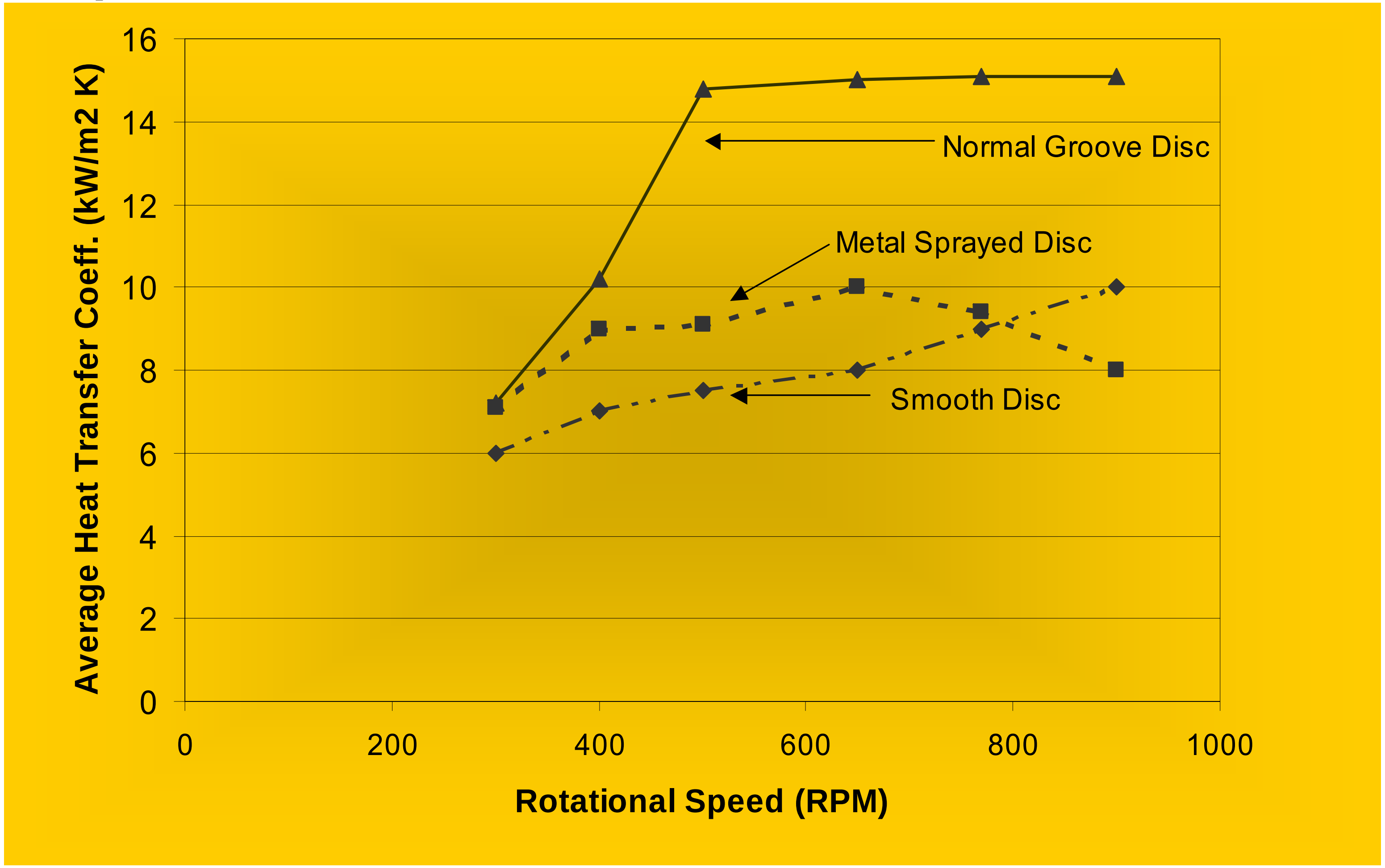
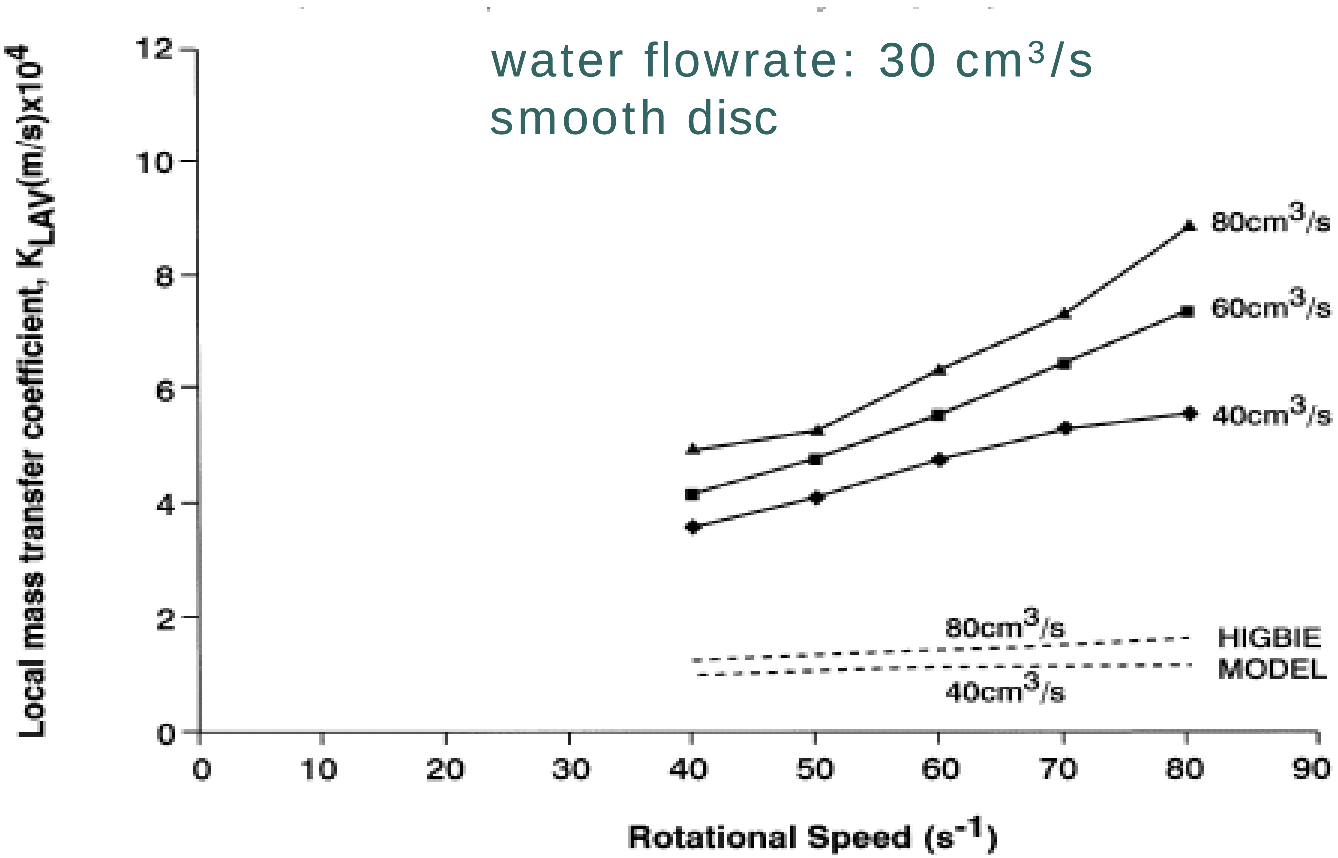
Convective heat transfer characteristics of films on rotating disc surfaces



Effect of rotational speed on local mass transfer coefficients in SDR film



(Source: Aoune & Ramshaw, Int. J. Heat & Mass Transfer, 42, 2543-2556 (1999))

Summary of characteristics of thin film flow in SDR

- Vigorous mixing characteristics at film surface (waves) and within film (high shear)
- High heat and mass transfer rates
- Short and easily controllable residence times

  These characteristics make the SDR particularly suitable for reactions that are:

  - **Highly exothermic**
  - **Inherently fast**

- Extremely short path lengths for efficient UV penetration in photo-reactions

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Reactions/processes for potential SDR application (1)

- Inherently fast, highly exothermic reactions
  - Acid-base neutralisation
  - Sulphonation
  - Polymerisations
    - Free-radical polymerisations
      - Chemical initiated
      - UV-initiated (photopolymerisation)
    - Cationic polymerisation
    - Step-growth polymerisations
      - Polyesterifications

Reactions/processes for potential SDR application (2)

- Reactions requiring rapid mixing
  - Crystallisations for narrow distribution of particle size
  - Organic, competitive reactions for high selectivity or high yield of desired product

- Processes involving heat sensitive materials
  - Polymer processing at high temperatures
  - Food processing
    - Short residence times in SDR gives minimal risk of degradation of product

Case study 1

SDR applications to mixing/mass transfer limited processes in pharmaceutical industry

Example 1: Phase transfer catalysed reaction- Darzen process

Rate limiting step: mass transfer across immiscible phases

	Batch Process	SDR process (4500 rpm)
Conversion	100%	90%
Reaction time	1 hr	<1 s
Reaction temp.	0^oC	20^oC
Impurity level	1.5%	0.1%
Reactor volume	100 (arbitrary units)	1
Production capacity	8 tonnes/yr	8 tonnes/yr

Source: Oxley, P. et al. "Evaluation of spinning disc reactor technology for the manufacture of pharmaceuticals", *Ind. Eng. Chem. Res.*, 39, 2175-2182 (2000)

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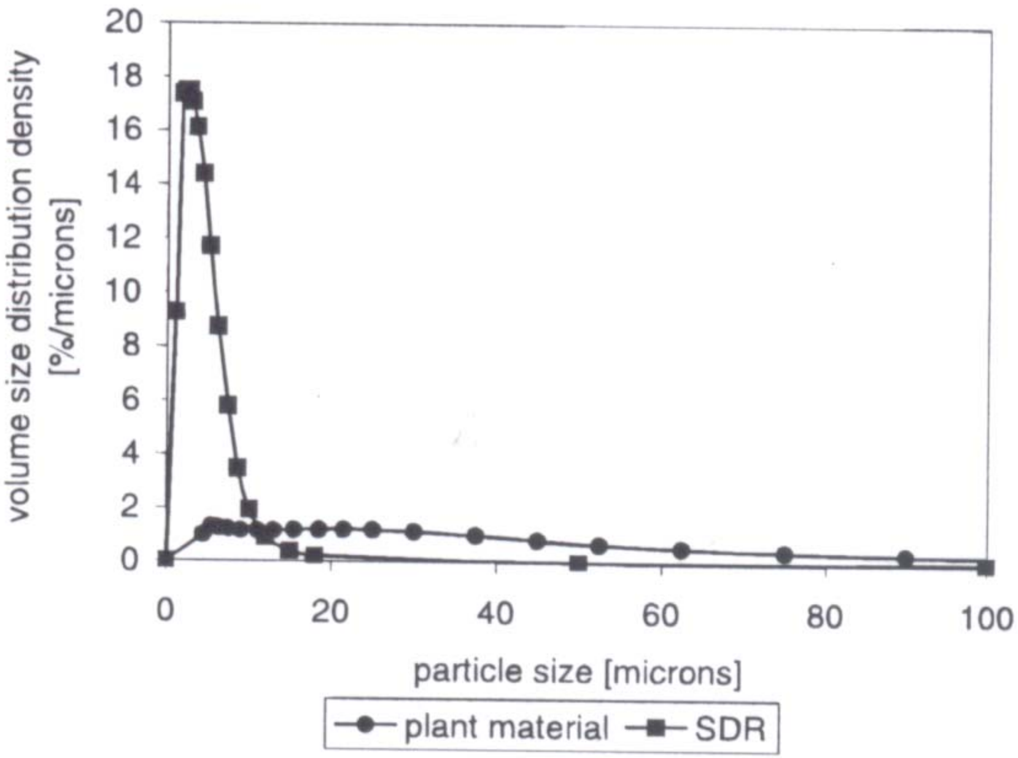
Crystallisation in SDR

- Rapid micromixing in the SDR film at high supersaturation
- Homogeneous nucleation
- Smaller crystal sizes with tighter distribution

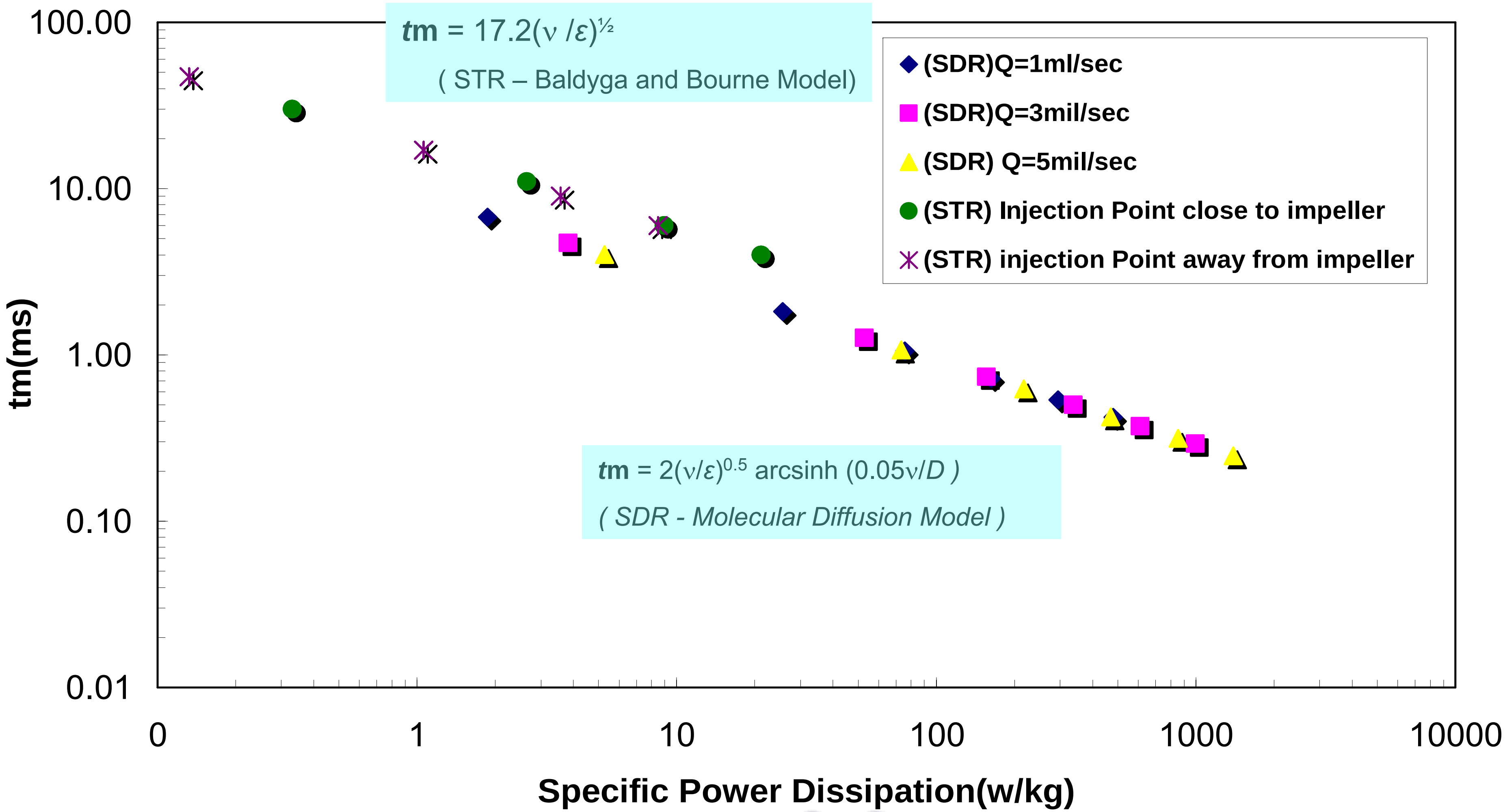
Example 2: Recrystallisation of an API

Rate limiting step: mixing (hence mass transfer)



Source: Oxley, P. et al. "Evaluation of spinning disc reactor technology for the manufacture of pharmaceuticals", *Ind. Eng. Chem. Res.*, 39, 2175-2182 (2000)

Micromixing: SDR vs STR



Case study 2

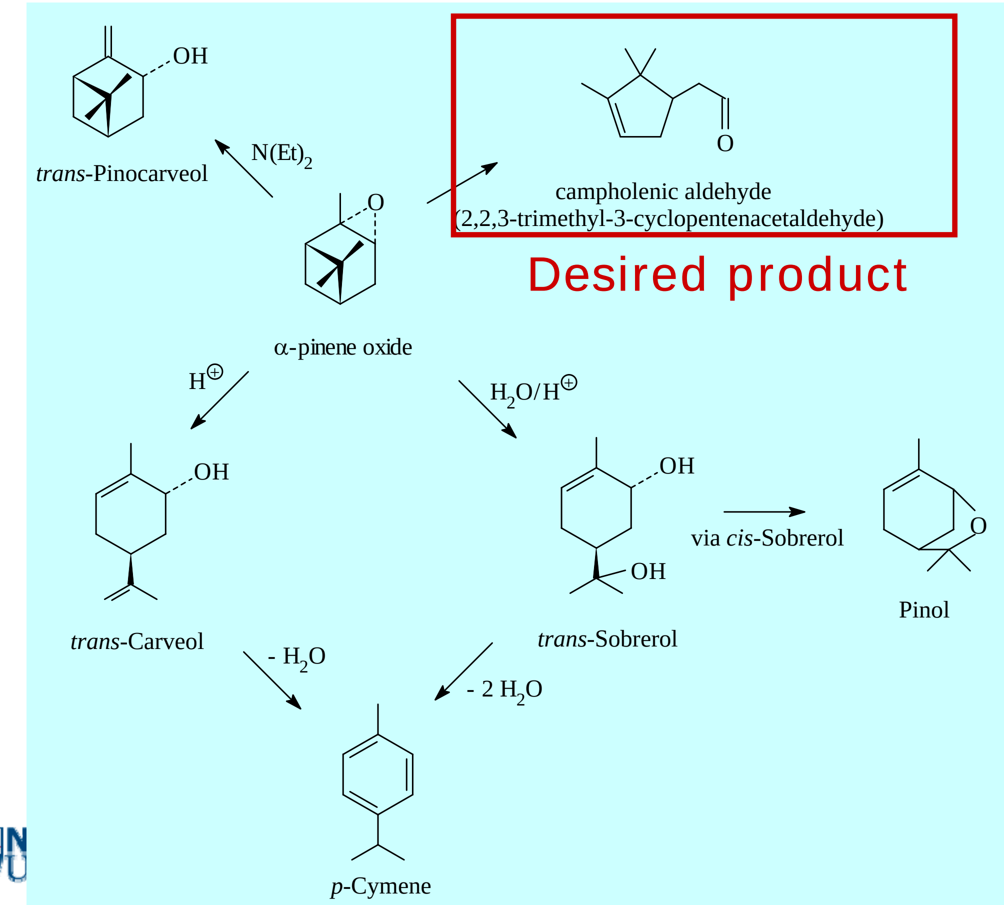
Application of SDR to organic catalytic reaction using immobilised catalyst

Process chemistry

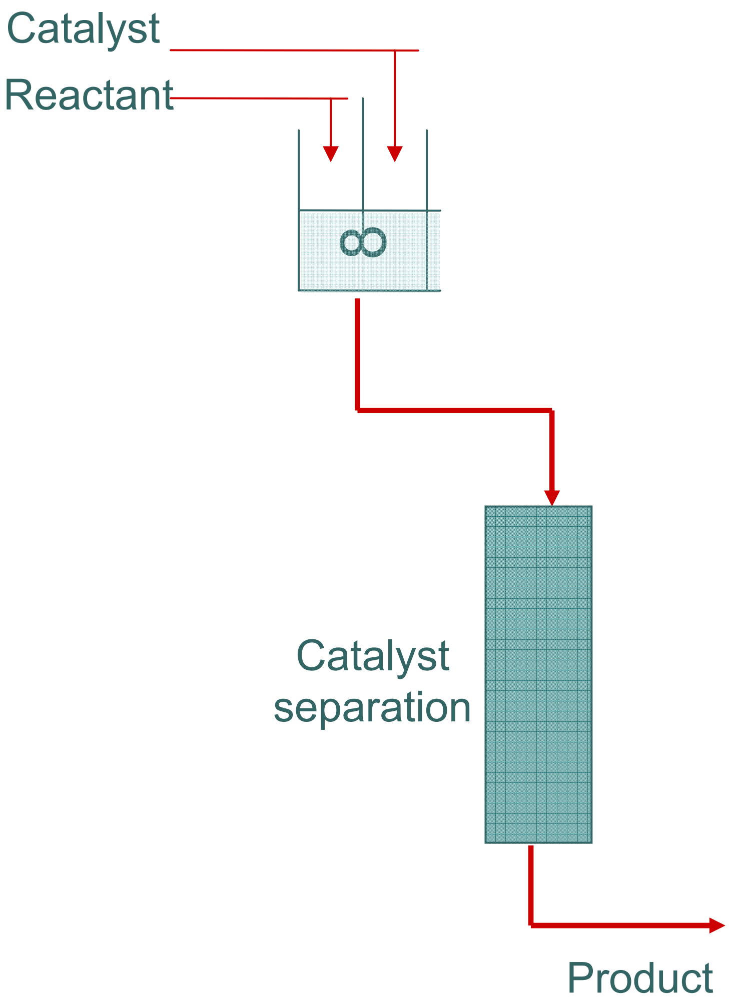
$$A \xrightarrow{\text{Catalyst}} B$$

A – α-pinene oxide, B – campholenic aldehyde

- Homogeneous catalyst used in current industrial process
- Low selectivity due to many side reactions



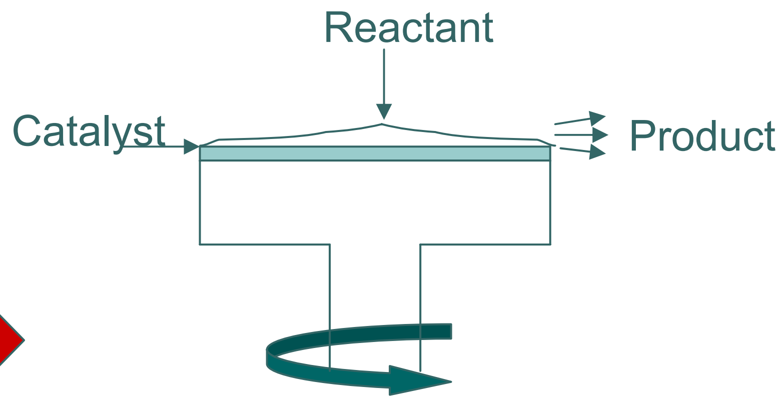
Current industrial process



- Batch process where processing time is typically very high (order of hours)
- Need to separate catalyst from product using large amounts of solvent in downstream separation process
- Environmental considerations of waste disposal

Objectives of study

- Easier catalyst separation
  - Development of heterogeneous catalysts
  - Immobilisation on reactor surface
  - Re-usable

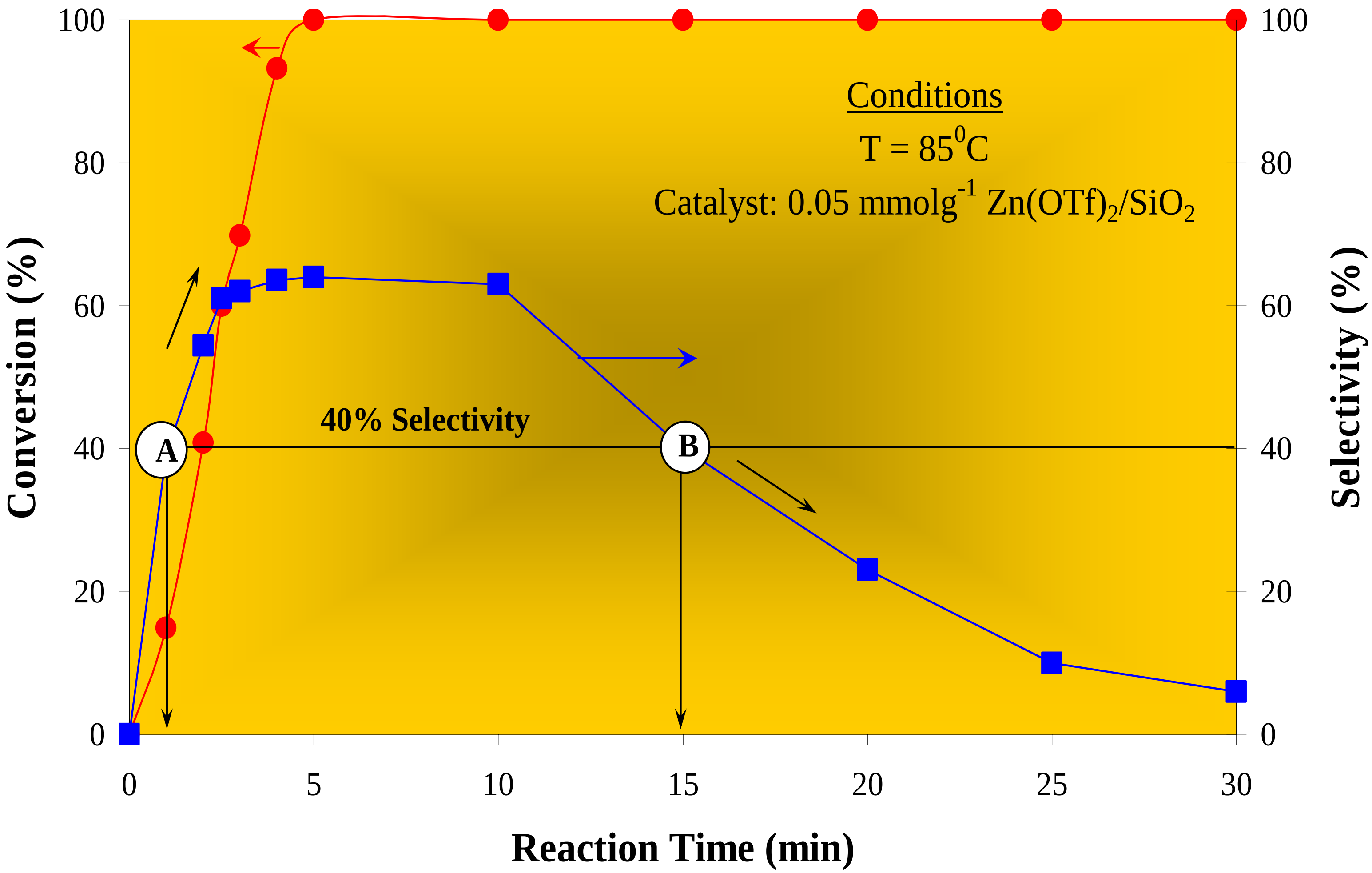


- Improve selectivity towards campholenic aldehyde using heterogeneous catalysis and intensified continuous processing

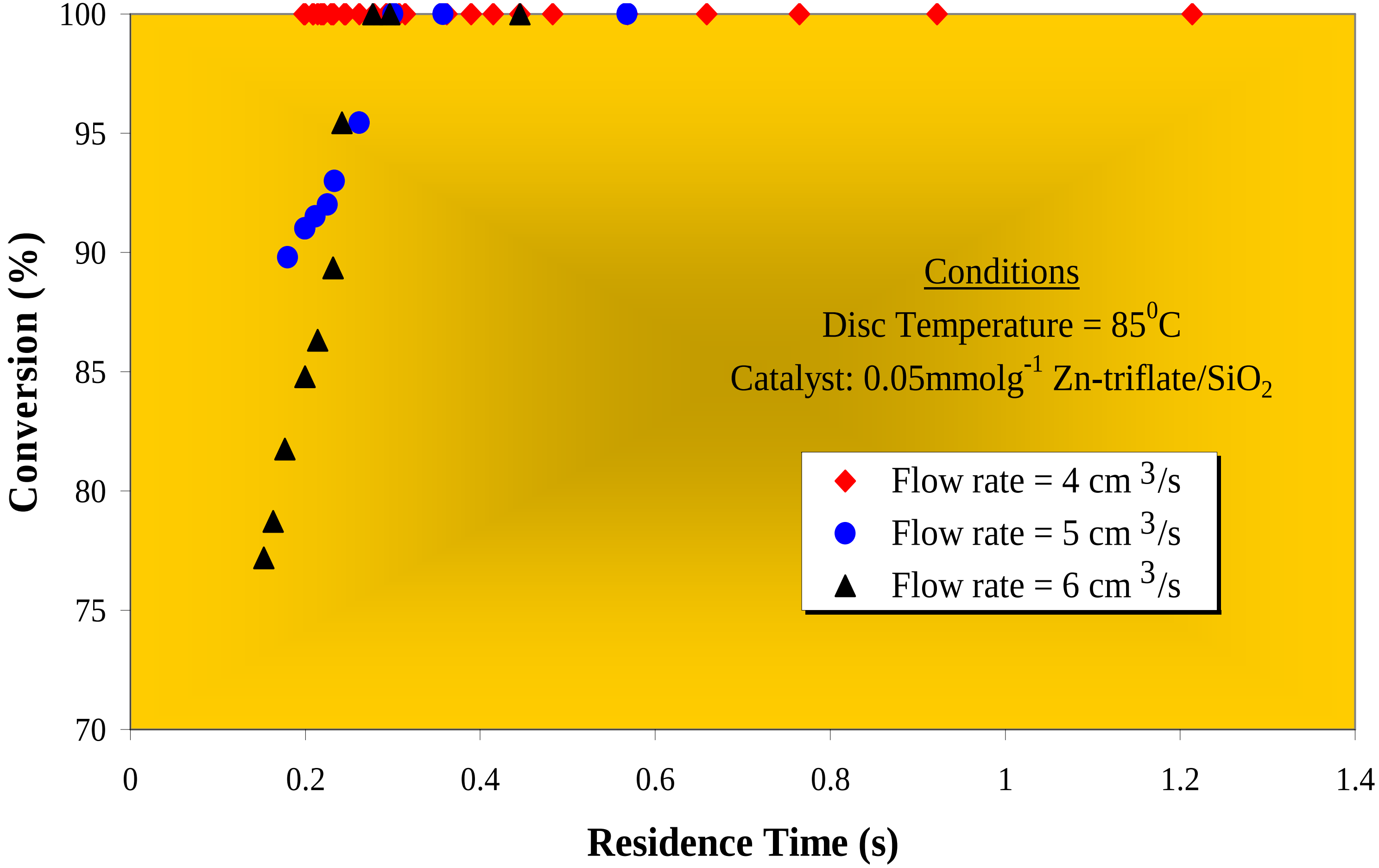
SDR processing:

- Continuous process
- Processing time of the order of seconds
- Catalyst fixed to rotating surface

STR data for benchmarking

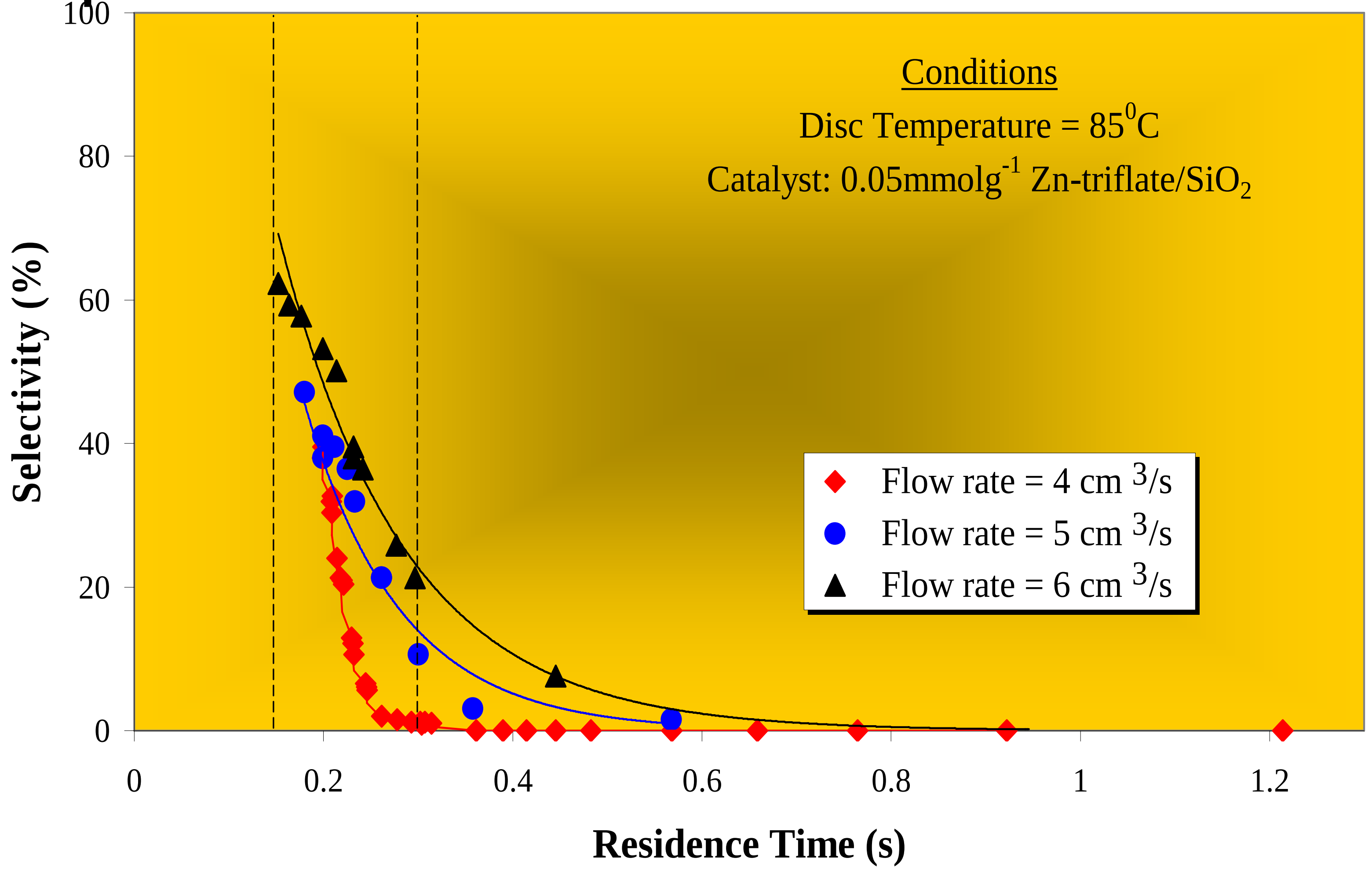


Effect of SDR residence time on conversion



M. Vicevic, K.V.K. Boodhoo and K. Scott, Catalytic Isomerisation of alpha-pinene oxide to campholenic aldehyde using silica supported zinc triflate catalysts: II. Performance of immobilised catalysts in a continuous Spinning Disc Reactor. *Chem. Eng. J.* **133**(1-3), 43-57 (2007).

Effect of SDR residence time on selectivity



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Summary of results

- Reaction completed within 0.5 s in one SDR pass compared to a timescale of at least 5 min in the batch process
  - Improved mixing and mass transfer rates in the thin film formed on the rotating disc surface allows the catalytic reaction to proceed at its inherent rate in SDR
  - Reaction slower in batch due to mixing limitations

- High selectivity in the SDR is encouraged by the short and controllable residence times achieved on the disc

- High catalyst activity can be maintained in SDR over long periods of time as shown by re-use studies

Demonstrated benefits of SDR

- Faster reaction rates
  - Reduced processing time
- Improved product quality
  - Better control of molecular weight properties in polymerisations
  - Tighter particle size distribution in crystallisations
- Improved selectivity
  - Less unwanted by-products
  - Greener/cleaner technology since reduced downstream processing required
- Improved intrinsic safety
  - Low volumes of materials processed