CFD modelling of mass transfer with and without chemical reaction in liquid-liquid slug flow capillary microreactors

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Outline

- Introduction
- Motivation & objectives
- CFD model
- Model validation
- Closing remarks
Introduction - Micoreactor technology

Appeal of small scales to chemical engineers:

- Important technique for process intensification
- Improved performance due to high specific surface areas enhancing heat and mass transfer
- Enhanced mass transfer increases reaction rates & reduces process volumes
- Precise control of highly exothermic and hazardous reactions
- Numbering-up instead of scale-up
Introduction - slug flow reactor

An alternative to suspended drop or film contactor?

- Uniform, well-defined slug size
- High specific interfacial area
- Enhanced mass transfer

PIV Measurement
CFD simulations
Velocity vectors
CFD particle tracing
Taylor-like vortices - Internal circulations

Recirculation
Diffusion
Recirculation

Slug Flow

Stratified Flow
Facile temperature profiling along the reactor
Straightforward downstream phase separation
Motivation & Objectives

- Slug flow concept & mass transfer performance
  \(\text{(Burns and Ramshaw, 2001; Harries et al., 2003)}\)

- Elucidation & optimisation of nitration reactions
  \(\text{(Dummann et al. 2003; Loebbecke et al, 2003)}\)

- Fundamental hydrodynamic modelling
  \(\text{(Kashid et. al. 2005; Kashid et. al. 2006; Kashid and Agar, 2006)}\)

- Prediction of mass transfer rates and reaction
  \(\text{(ISCRE 2006)}\)

- Powerful experimental tool for analysing biphasic reactions

- Identification of asymptotic limits for technical processes
Incompressible Navier-Stokes equation

\[
\frac{\partial u}{\partial t} + \nabla \cdot (uu) = -\frac{1}{\rho} \left[ \nabla p - \nabla \cdot \mu (\nabla u + [\nabla u]^T) \right] + \frac{1}{\rho} F_{sf} \\
\nabla u = 0
\]

where \( \rho = \sum \alpha_k \rho_k \) and \( \mu = \frac{\sum \alpha_k \rho_k \mu_k}{\sum \alpha_k \rho_k} \)

The indicator function

\[
\frac{\partial \alpha_k}{\partial t} + u_k \cdot \nabla \alpha_k = 0
\]

Surface tension + wall adhesion

Assumption:
- No mass transfer between phases
- Isothermal conditions

Commercial CFD software package, Fluent 6.2

Experimental: (ID = 1 mm, Velocity = 20 mm/s)

CFD: (ID = 1 mm, Velocity = 20 mm/s)
CFD model

- **Schematic representation:**

- **Assumption:** $C_1' = C_1'' = C_1'''$, $C_2' = C_2''$

→ Reduces computational resources significantly
Governing Equations – fluid flow

Assumptions

- Slugs are Newtonian, viscous and incompressible
- Shape of the slug and volume invariant
- Flow is laminar and mass diffusivity constant
- Mass transfer and reaction does not affect the flow patterns within the slugs

Flow field

\[
\frac{\partial (\rho u)}{\partial t} + \rho u \cdot \nabla u = \nabla \cdot \left[ \mu \left( \nabla u + \nabla^T u \right) \right] - \nabla \rho \quad \Omega \in \mathbb{R}^2 \times [0, T]
\]

\[
\nabla u = 0
\]

Density and viscosity

\[
\rho = \rho_0 f(X)
\]

\[
\mu = \mu_0 f(X)
\]

Interface condition

\[
\frac{\partial u_1}{\partial n_1} = \frac{\mu_1}{\mu_2} \frac{\partial u_2}{\partial n_2}
\]
Governing Equations

– Mass transfer & reaction

- Species transport

\[ \frac{\partial C_1}{\partial t} + \nabla \cdot (uC_1 - D_1 \nabla C_1) = \pm r_{ik} \; ; \; \frac{\partial C_2}{\partial t} + \nabla \cdot (uC_2 - D_2 \nabla C_2) = \pm r_{ik} \]

- Interface condition

\[ D_1 \frac{\partial C_1}{\partial x} = D_2 \frac{\partial C_2}{\partial x} \]

\[ C_2 = mC_1 \]

- Species transport, if partition coefficient \((m) \neq 1\)

\[ \hat{C}_1 = C_1 \sqrt{m} \; ; \; \hat{C}_2 = \frac{C_2}{\sqrt{m}} \]

\[ \frac{\partial \hat{C}_1}{\partial \left( \sqrt{m} t \right)} + \frac{1}{\sqrt{m}} \nabla \cdot (u\hat{C}_1 - D_1 \nabla \hat{C}_1) = \pm \hat{r}_{ik} \; ; \; \frac{\partial \hat{C}_2}{\partial \left( \frac{1}{\sqrt{m}} t \right)} + \sqrt{m} \nabla \cdot (u\hat{C}_2 - D_2 \nabla \hat{C}_2) = \pm \hat{r}_{ik} \]

- Interface condition becomes

\[ D_1 \sqrt{m} \frac{\partial \hat{C}_1}{\partial x} = D_2 \sqrt{m} \frac{\partial \hat{C}_2}{\partial x} \]

\[ \hat{C}_2 = \hat{C}_1 \]
Boundary conditions

- No-slip at the moving walls
- Zero species flux at the moving walls
- Periodic boundary concept to connect the extremities of domain
- Moving boundary concept to set velocity of interface
- Interface and periodically connected interface satisfies:

  - Fluid flow
    \[ \mu_1 \frac{\partial u_1}{\partial x} = \mu_2 \frac{\partial u_2}{\partial x} \]

  - Species transport
    \[ \frac{D_1}{\sqrt{m}} \frac{\partial \hat{C}_1}{\partial x} = \frac{D_2}{\sqrt{m}} \frac{\partial \hat{C}_2}{\partial x} \]
    \[ \hat{C}_2 = \hat{C}_1 \]
Physical properties defined using Heaviside function

\[ H(x, y) = \begin{cases} 
1 & \text{when } x \leq X \\
0 & \text{when } x > X 
\end{cases} \]

Physical property, \( \phi = \phi_2 + (\phi_1 - \phi_2)H(x, y) \)

Terms in the Convection-diffusion equations for \( m \neq 1 \)

\[
\frac{\partial \hat{C}}{\partial t} = \frac{\partial \hat{C}_2}{\partial \left( \frac{1}{\sqrt{m}} t \right)} + \left( \frac{\partial \hat{C}_1}{\partial \left( \sqrt{mt} \right)} - \frac{\partial \hat{C}_2}{\partial \left( \frac{1}{\sqrt{m}} t \right)} \right) H(x, y)
\]

\[
u \cdot \nabla \hat{C} = \sqrt{m}u_2 \cdot \nabla \hat{C}_2 + \left( \frac{1}{\sqrt{m}} u_1 \cdot \nabla \hat{C}_1 - \sqrt{m}u_2 \cdot \nabla \hat{C}_2 \right) H(x, y)
\]

\[
\nabla \cdot \left( \hat{D} \nabla \hat{C} \right) = \sqrt{m} \nabla \cdot \left( \hat{D}_2 \nabla \hat{C}_2 \right) + \left( \frac{1}{\sqrt{m}} \nabla \cdot \left( \hat{D}_1 \nabla \hat{C}_1 \right) - \sqrt{m} \nabla \cdot \left( \hat{D}_2 \nabla \hat{C}_2 \right) \right) H(x, y)
\]
Solution (… continued)

- Reaction solution, straightforward operator splitting strategy, within each time step, $\Delta t = t_{n+1} - t_n$
  - Step 1: Solution of convection-diffusion equations, all in parallel
    \[
    \frac{\partial C_{ik}}{\partial t} + u \cdot \nabla C_{ik} - \nabla \left( D_{ik} \nabla C_{ik} \right) = 0
    \]
  - Step 2: Obtained concentration field used as initial data for reaction ODE
    \[
    \frac{dC_{ik}}{dt} = \pm r_{ik}
    \]

- Discretisation: time $\rightarrow$ implicit BE, space $\rightarrow$ FEM
- Flux correction $\rightarrow$ upwind
- Equations are implemented in FEATFLOW
- Transient simulations
Results - fluid flow

Test simulation

\[ v_1 = 0.3 \times 10^{-5} \text{ m/s} \quad v_2 = 0.3 \times 10^{-3} \text{ m/s} \]

Phase 1

Phase 2

Slug flow velocity = 10 m/s
Slug diameter = 0.5 mm
Slug length = 2 mm
Water – succinic acid – n-butanol
Capillary ID = 0.5 mm
Initial conc. in aqueous solution = 10 Kg/m³
Volumetric mass transfer coefficient

\[ k_L a = \frac{1}{T} \ln \left( \frac{C_{2,\text{sat}} - C_{2,\text{in}}}{C_{2,\text{sat}} - C_{2,\text{out}}} \right) \]

Fig: Mass transfer coefficients
Neutralisation reaction (Harries et al. 2003)

\[ \text{CH}_3\text{COOH} + \text{NaOH} \rightarrow \text{CH}_3\text{COONa} + \text{H}_2\text{O} \]

- Rapid, second order (k= 1.35 x 10^{11} L mol^{-1} s^{-1}) → implicit treatment for reaction ODEs
- Reaction medium: aqueous phase
- Partitioning of Acetic Acid in favour of aqueous phase: 85:1
- Governing equations – for species transport in water slug

\[
\frac{\partial C_{12}}{\partial t} + u_2 \cdot \nabla C_{12} - \nabla(D_{12} \nabla C_{12}) = -kC_{12}C_{22}
\]

\[
\frac{\partial C_{22}}{\partial t} + u_2 \cdot \nabla C_{22} - \nabla(D_{22} \nabla C_{22}) = -kC_{12}C_{22}
\]

\[
\frac{\partial C_{32}}{\partial t} + u_2 \cdot \nabla C_{32} - \nabla(D_{32} \nabla C_{32}) = kC_{12}C_{22}
\]

\[
\frac{\partial C_{42}}{\partial t} + u_2 \cdot \nabla C_{42} - \nabla(D_{42} \nabla C_{42}) = kC_{12}C_{22}
\]
Data used for chemical reaction simulation

Flow ratio (aqueous/organic): 1
Slug lengths: 1.5-3.8 mm
Slug diameter: 0.38 mm
Slug flow velocities: 0.6-16.6 mm/s

Density ratio (kerosene/water): 0.8
Viscosity ratio (kerosene/water): 1.82
Initial conc. of $CH_3COOH$ in kerosene: 0.5 mol/L
Initial conc. of $CH_3COOH$ in water: 0 mol/L
Initial conc. of NaOH in water: 0.25 mol/L
Initial conc. of $CH_3COONa$ in water: 0 mol/L
Partition coefficient for $CH_3COOH$ (m): 85

Smallest cell size: 0.008D mm
Smallest time step for u and p: $1 \times 10^{-4}$ s
Time step for mass transfer & reaction: $1 \times 10^{-5}$ s

Average concentrations in aqueous phase

Mesh independent solution
Results

Simulated snapshots for neutralisation reaction (Titration time = 5.24s)

Fig: Velocity vectors
End point of the titration was taken at 95% base neutralisation.
Closing remarks

Conclusions

- The model developed for mass transfer with/without reaction shows good agreement with experimental data of neutralisation reaction
- Very fine meshes required to discern true behaviour

Future work

- Incorporate interface curvature (level set method)
- Integrate wall film in model
- Detailed experimentation on mass transfer and chemical reaction
- DFG grant as of Oct. 2006
Thank you for your attention
References

- Kashid et al., *Industrial & Engineering Chemistry Research*, 44(14), 5003-5010, 2005
- Vandu et al., *Chemical Engineering Science*, 60(22), 6430-6437, 2005
Slug Flow Generation

- Y-Junction Flow
  - Experimental
    (Y-junction ID = 1 mm, Capillary ID = 1 mm, Slug Flow Velocity = 20 mm/s)

- Y-Junction Flow
  - CFD Simulation (Fluent(R))
    (Y-junction ID = 1 mm, Capillary ID = 1 mm, Slug Flow Velocity = 2 mm/s)
Hydrodynamics - Experimentation

**Operating Conditions:**

<table>
<thead>
<tr>
<th>System</th>
<th>Water - Cyclohexane</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow rate, ml/hr</td>
<td>0 – 100 (each phase)</td>
</tr>
<tr>
<td>Capillary ID, mm</td>
<td>0.5, 0.75 and 1</td>
</tr>
<tr>
<td>Y-junction ID, mm</td>
<td>0.5, 0.75 and 1</td>
</tr>
<tr>
<td>Pressure Sensor, bar</td>
<td>0-1</td>
</tr>
</tbody>
</table>

**Flow Regime:**

- Slug Flow
- Drop Flow
- Deformed Interface Flow

**Experimental Set-up:**

- P1, P2 - Piston Pumps
- PT - Pressure Transducer
- Y-jn - Y-junction
- CM - Capillary Microreactor
- L - Light
- CC - Commercial Camera
- W - Water
- CH - Cyclohexane

**Inlet flow velocity of cyclohexane [mm/s]**

**Inlet flow velocity of water [ml/hr]**
Slug Size

Photographic measurements

a) Equal inlet flow rates
(Y-junction ID = 0.5 mm)

b) Unequal inlet flow rates
(Water Flow Rate = 10 ml/hr, Y-junction ID = 0.5 mm,
Capillary ID = 0.5 mm)
Pressure Drop

Simplest Model:
Pressure Drop = Hydrodynamic Pressure Drop of Individual Phase + Capillary Pressure

\[ \Delta P_U = \Delta P_H + P_C \]
\[ = \Delta P_W + \Delta P_{CH} + P_C \]

Where,

\[ \Delta P_W = \frac{8 \mu_W V W}{r^2} \]
\[ \Delta P_{CH} = \frac{8 \mu_{CH} V_{CH}}{r^2} \]
\[ P_C = \frac{2 \gamma}{r} \cos \theta \]
Wall Film

- Wall material: PTFE
- System: Nitration acid (HNO₃ + H₂SO₄) + aromatic
- Film not visible under microscope (<10μm)
- High aromatic wettability

Experimentation

1. Nitration acid
2. Aromatics on Wall material: PTFE
3. SS flow
4. No aromatics

Initial droplets shrink & disappear
Residual aromatic found in acid

⇐ Step 2: Initial droplets shrink & disappear

- Dynamic experiments confirm presence of an organic wall film
Assumptions:
- One dimensional laminar flow
- Internal circulations within the slugs are neglected i.e. hard slug
- Pressure drop due to film region only

SS equation for velocity profile in the film:
\[
\frac{\partial^2 V}{\partial r^2} + \frac{1}{r} \frac{\partial V}{\partial r} = \frac{g_c}{\mu} \frac{\Delta P}{L}
\]
Upon integration:
\[
\left( \frac{\Delta P}{L} \right)_f = \left( \frac{1}{1-k^4} \right) \left( \frac{\Delta P}{L} \right)_{CH}
\]
where,
\[
k = \frac{R-h}{R}
\]
In terms of inlet flow ratio, \( \alpha \):
\[
\frac{\Delta P}{L} = \left( \frac{\alpha}{1-k^4} \right) \left( \frac{\Delta P}{L} \right)_{CH}
\]
Pressure Gradient vs Slug Flow Velocity at equal flow rate of both phases (Y-junction ID = 0.5 mm)
### Interfacial area:

<table>
<thead>
<tr>
<th>ID mm</th>
<th>Equal Flow Rate</th>
<th>Unequal Flow Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$Q_w = Q_{CH}$</td>
<td>$Q_w = 5 - 100$ ml/hr</td>
</tr>
<tr>
<td>w/o Film</td>
<td>W/o Film</td>
<td>W/o Film</td>
</tr>
<tr>
<td>m²/m³</td>
<td>m²/m³</td>
<td>m²/m³</td>
</tr>
<tr>
<td>0.5</td>
<td>1080 - 1970</td>
<td>1085 - 1770</td>
</tr>
<tr>
<td></td>
<td>4500 – 4800</td>
<td></td>
</tr>
<tr>
<td>0.75</td>
<td>880 - 1330</td>
<td>960 – 1330</td>
</tr>
<tr>
<td></td>
<td>3200 – 3330</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>620 - 870</td>
<td>730 – 1025</td>
</tr>
<tr>
<td></td>
<td>2400 – 2510</td>
<td></td>
</tr>
</tbody>
</table>

- Mechanically agitated stirred tank reactors: ~ 500 m²/m³
- Presence of wall film offers ~ x 3-4 higher interfacial area

### Power input:

<table>
<thead>
<tr>
<th>Contactor Type</th>
<th>Power Input kJ/m³ of liquid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agitated extraction column</td>
<td>0.5 – 190</td>
</tr>
<tr>
<td>Mixer-settler</td>
<td>150 – 250</td>
</tr>
<tr>
<td>Rotating disk Impinging Streams contactor</td>
<td>175 – 250</td>
</tr>
<tr>
<td>Impinging Streams</td>
<td>280</td>
</tr>
<tr>
<td>Impinging Stream Extractor</td>
<td>35 - 1500</td>
</tr>
<tr>
<td>Centrifugal Extractor</td>
<td>850 - 2600</td>
</tr>
<tr>
<td>Liquid-liquid slug flow (Present Work)</td>
<td>0.2 - 20</td>
</tr>
</tbody>
</table>
Internal Circulations – PIV Experimentation

Experimental set up:
- X-Y Translation Platform
- LabChip
- Exciter Blue Filter
- Object Condenser
- Chromatic Beam Splitter
- 540 nm
- CCD camera

Experimental Snapshot:
- PIV velocity distribution
- Water (+ fluorescence) – paraffin oil, V = 0.031 mm/s

ISCRE Presentation – 6th September, 2006
CFD Simulations

- Incompressible Navier-Stokes equation
  \[
  \frac{\partial u}{\partial t} + u \cdot \nabla u - \nu \Delta u + \nabla p = f; \nabla u = 0
  \]

- Boundary conditions
  - Moving Wall, \( V_{\text{wall}} = V_{\text{av}} \)
  - Stationary Interface, \( V_{\text{int}} = 0 \)

- Numerical mesh

- Solver
  - 2D, Projected solver, FEATFLOW

Fig: snapshot of CFD simulation

Fig: Parabolic profiles in a slug

(ISCRE Presentation – 6th September, 2006)
CFD - Recirculation Time

- Important parameter for Mass Transfer and Mixing
- Time required for liquid particles to move from one end of the slug to the other end

\[
\tau_{\text{nofilm}} = \frac{L \left( r^0 \right)^2}{2 \int_0^L U(r) r \, dr}
\]

Fig: Recirculation time without film
Fig: Recirculation time with film
Method of visualization

Converts Eulerian description of a flow into Langragian description with selected particle

In-house developed algorithm, GMVPT

<table>
<thead>
<tr>
<th>Phase 1</th>
<th>Phase 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>L = 2.379 mm</td>
<td>L = 1.12 mm</td>
</tr>
<tr>
<td>D = 0.75 mm</td>
<td>D = 0.75 mm</td>
</tr>
<tr>
<td>$V_{av} = 5.64 \text{ mm/s}$</td>
<td>$V_{av} = 11.28 \text{ mm/s}$</td>
</tr>
</tbody>
</table>
Mass Transfer - Experimentation

Fig.: Volumetric mass transfer coefficient

Operating Conditions:

<table>
<thead>
<tr>
<th>System</th>
<th>Chemical system</th>
<th>$k_L a \times 10^4$, s$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contactor</td>
<td>Water (c) – iodine-CCl$_4$ (d)</td>
<td>0.16-16.6</td>
</tr>
<tr>
<td>Agitated vessel</td>
<td>Water (c) – succinic acid – n-butanol (d)</td>
<td>57</td>
</tr>
<tr>
<td>Rotated disk</td>
<td>n-hexane(c) – acetone – water (d)</td>
<td>0.15</td>
</tr>
<tr>
<td>Rotated agitated</td>
<td>Water (c) – iodine – kerosene (d)</td>
<td>16.6</td>
</tr>
<tr>
<td>Impinging streams</td>
<td>Water (c) – iodine – kerosene (d)</td>
<td>1187 - 3975</td>
</tr>
<tr>
<td>Kerosene (d) – acetic acid – water (c)</td>
<td>500 – 3000</td>
<td></td>
</tr>
<tr>
<td>Water (c) – acetaldehyde – vinyl acetate (d)</td>
<td>375 - 1120</td>
<td></td>
</tr>
<tr>
<td>Perforated plate</td>
<td>Water (c) – iodine – kerosene (d)</td>
<td>560 – 2000</td>
</tr>
<tr>
<td>Packed column</td>
<td>CCl$_4$ (c) – acetone – water (d)</td>
<td>28.5</td>
</tr>
<tr>
<td>Spray column</td>
<td>Water (c) – acetone – benzene (d)</td>
<td>8 - 60</td>
</tr>
<tr>
<td>Impinging streams</td>
<td>Water (c) – iodine – kerosene (d)</td>
<td>15 - 2100</td>
</tr>
<tr>
<td>Kerosene (d) – acetic acid – water (c)</td>
<td>500 – 3000</td>
<td></td>
</tr>
<tr>
<td>Water (c) – iodine – kerosene (d)</td>
<td>1187 - 3975</td>
<td></td>
</tr>
<tr>
<td>Sprayed column</td>
<td>Water (c) – iodine – kerosene (d)</td>
<td>775 - 2500</td>
</tr>
<tr>
<td>Impinging streams</td>
<td>Water (c) – iodine – kerosene (d)</td>
<td>1187 - 3975</td>
</tr>
<tr>
<td>Kerosene – acetic acid – water (c)</td>
<td>1364 - 4456</td>
<td></td>
</tr>
<tr>
<td>Water (c) – succinic acid – n-butanol (d)</td>
<td>375 - 1120</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Capillary ID, mm</th>
<th>Slug flow regime</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Y-junction ID, mm</td>
<td>0.5, 0.75 and 1</td>
<td></td>
</tr>
</tbody>
</table>

Table: Operating Conditions

- Contactor: Chemical system: Water (c) – iodine-CCl$_4$ (d), k$_L a \times 10^4$, s$^{-1}$: 0.16-16.6
- Agitated vessel: Chemical system: Water (c) – succinic acid – n-butanol (d), k$_L a \times 10^4$, s$^{-1}$: 57
- Rotated disk: Chemical system: n-hexane(c) – acetone – water (d), k$_L a \times 10^4$, s$^{-1}$: 0.15
- Rotated agitated column: Chemical system: Water (c) – iodine – kerosene (d), k$_L a \times 10^4$, s$^{-1}$: 16.6
- Spray column: Chemical system: Water (c) – acetone – benzene (d), k$_L a \times 10^4$, s$^{-1}$: 8 - 60
- Packed column: Chemical system: CCl$_4$ (c) – acetone – water (d), k$_L a \times 10^4$, s$^{-1}$: 7.4 -24
- Perforated plate column: Chemical system: Water (c) – acetaldehyde – vinyl acetate (d), k$_L a \times 10^4$, s$^{-1}$: 28.5
- Impinging streams: Chemical system: Water (c) – iodine – kerosene (d), k$_L a \times 10^4$, s$^{-1}$: 15 - 2100
- Kerosene (d) – acetic acid – water (c), k$_L a \times 10^4$, s$^{-1}$: 500 – 3000
- Water (c) – iodine – kerosene (d), k$_L a \times 10^4$, s$^{-1}$: 560 – 2000
- Rotating disks impinging streams: Chemical system: Water (c) – iodine – kerosene (d), k$_L a \times 10^4$, s$^{-1}$: 1187 - 3975
- Kerosene – acetic acid – water (c), k$_L a \times 10^4$, s$^{-1}$: 1364 - 4456
- Water (c) – succinic acid – n-butanol (d), k$_L a \times 10^4$, s$^{-1}$: 775 - 2500
- Present work: Chemical system: Water – succinic acid – n-butanol, k$_L a \times 10^4$, s$^{-1}$: 375 - 1120

- System: Water – succinic acid – n-butanol
- Regime: Slug flow regime
- Capillary ID, mm: 0.5, 0.75 and 1
- Y-junction ID, mm: 0.5, 0.75 and 1
Key Issues and Design Parameters

Key Issues:
- Internal Circulations
- Hydrodynamics
- Slug Flow Stability
- Presence of Wall Film

Design Parameters:
- Flow Regimes
- Flow Patterns within the Slugs
- Circulation Time
- Slug Dimension
- Pressure Drop
- Mass Transfer Coefficient
- Film Thickness
Wall Film

- Hydrophobic wall preferentially wetted by organic phase
- Experimentally observed transition behaviour ~ 10 mm
- Film thickness (Bretherton Law):
  \[ h = 1.34RCa^{2/3} \]
- Enhanced interfacial area:
  Without Film: \( a \approx 2\pi r^2 \)
  With Film: \( a = 2\pi \left[ (r - h)^2 + rl \right] \) Where, \( r \) = Radius of capillary
- Slug & average flow velocity:
  \[ V_s = \frac{2}{1 + (R_s/R)^2} V_{av} \]
- Film not stagnant: \( Q_{av} = Q_{film} + Q_{slug} \)
Introduction - Liquid-liquid contacting

➢ Suspended drop contactors
  – Difficult to control drop size conditioning
  – Scale-up is difficult
  – Efficiency diminishes at low solvent/feed ratio

➢ Film contactors
  – Ability to optimise solvent/feed ratio