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Recirculation time and liquid slug mass transfer in co-current upward and downward Taylor flow

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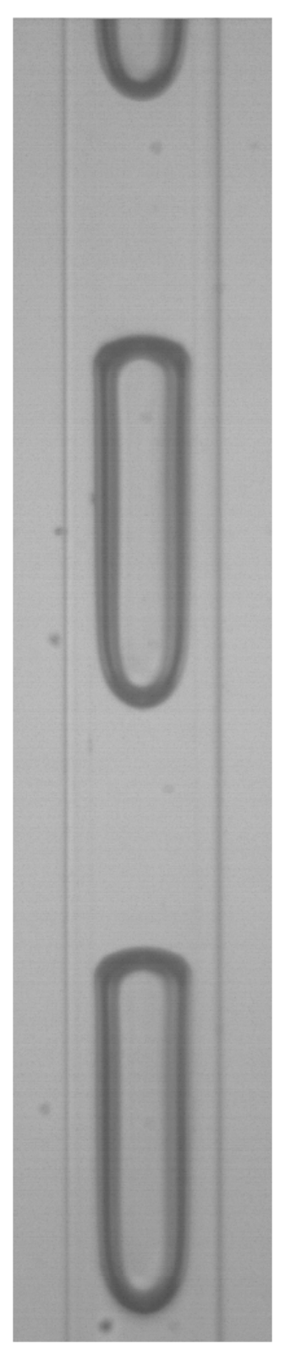
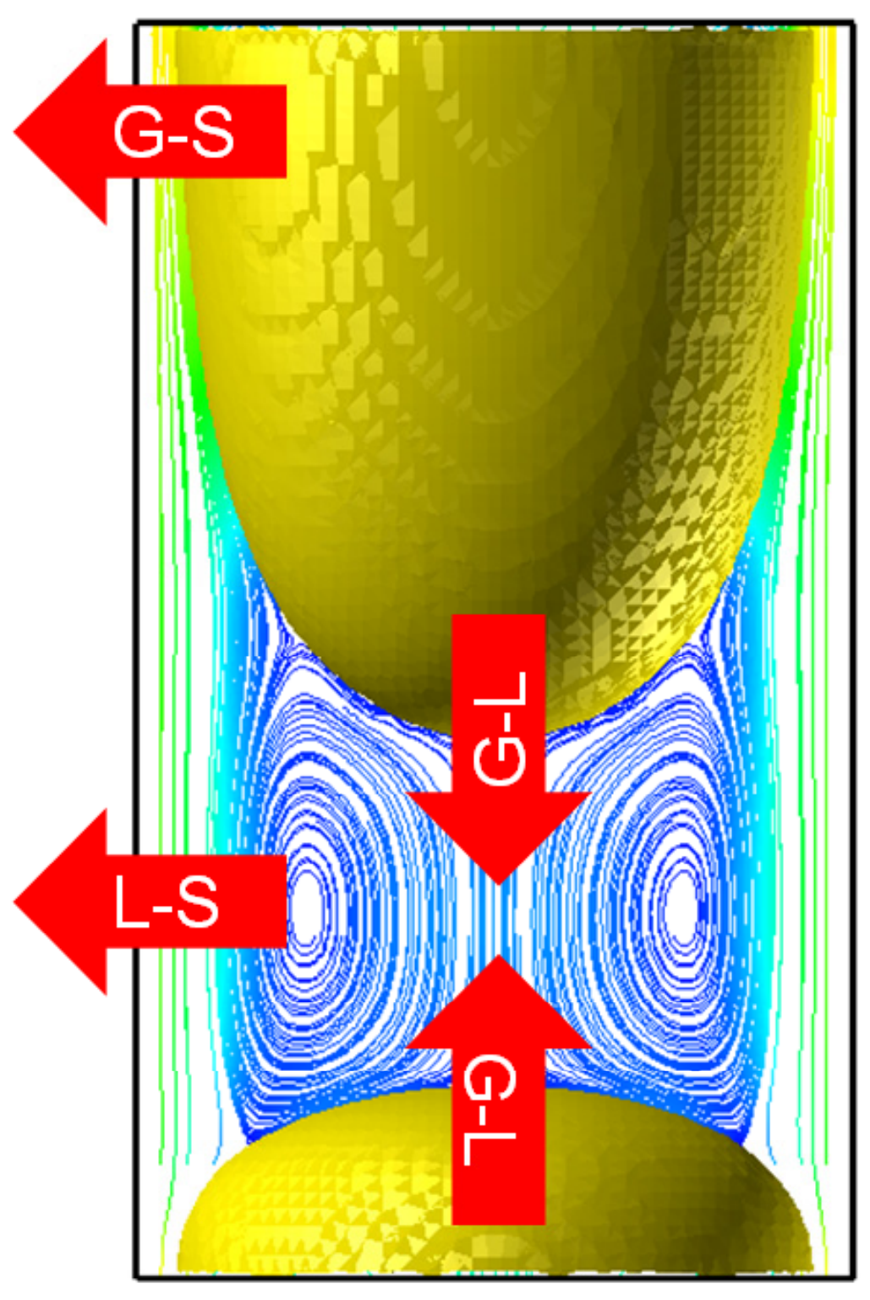
1. Introduction



Monolithic reactors offer potential benefits for **heterogeneously catalyzed multiphase reactions** such as in Fischer-Tropsch synthesis. Reaction studies show that **Taylor flow** is superior as compared to other gas-liquid flow patterns. This is attributed to the advantageous mass transfer characteristics of Taylor flow due to large specific interfacial area, thin liquid films, and good mixing in the liquid slug by recirculation.

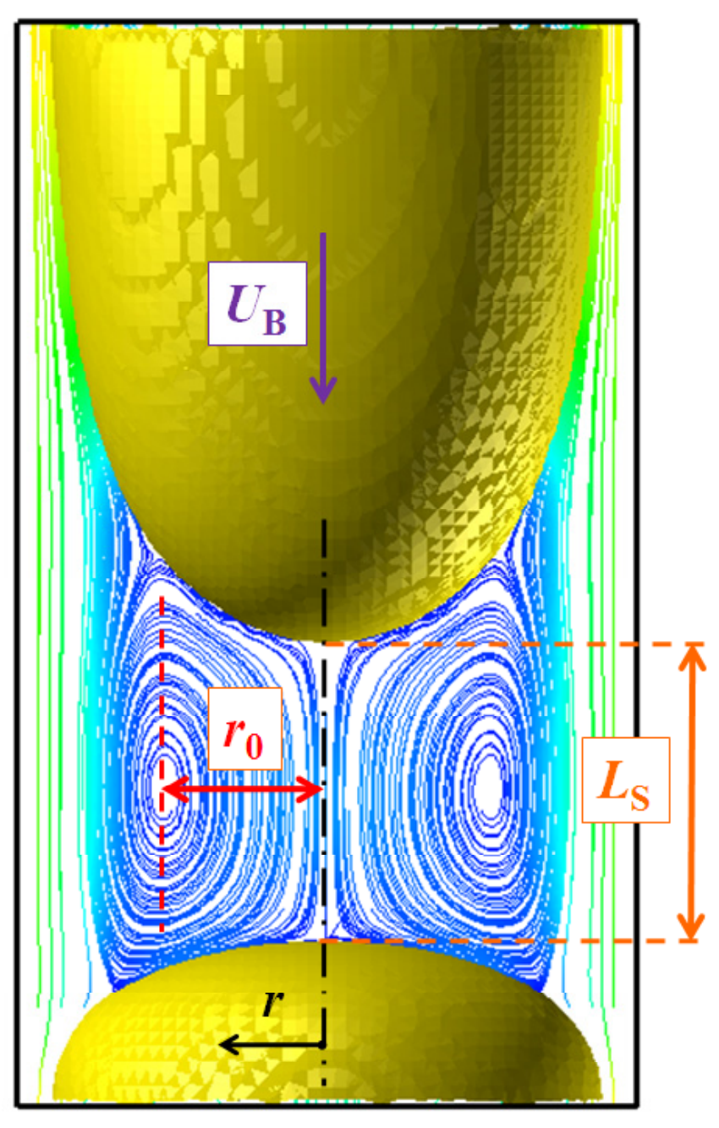
2. Problem formulation

The **mass transfer of a gaseous species to the catalytic wall** is partly through the liquid film (G-S) and partly through the liquid slug (G-L and L-S in series). **An open question is if mass transfer is more efficient in upward or in downward Taylor flow.** In [1] it is found that the volumetric mass transfer coefficient for the liquid slug is higher in upward than in downward Taylor flow; in [2] this is attributed to the smaller **liquid slug recirculation time** (τ) in upward flow. τ is defined as the time needed by the liquid to move from one end of the slug to the other end divided by the time needed by the liquid slug to travel a distance of its own length. **Here, we investigate the recirculation time in a rectangular channel theoretically and the mass transfer in a square channel numerically.**



3. Theoretical analysis of liquid slug recirculation time τ

Circular channel cross section (see [3])



$$\tau = U_B r_0^2 \Big/ 2\int_0^{r_0} V(r)r\,dr \qquad V(r) = 2J\left(1-\frac{r^2}{R^2}\right) - U_B$$

$V \equiv u - U_B$ = velocity in moving frame of reference

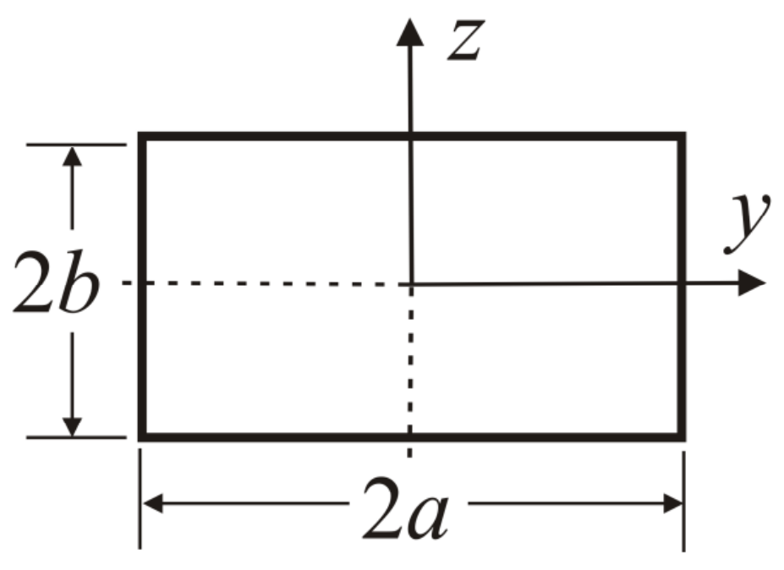
$J = (Q_G+Q_L)/A_{ch}$ = total superficial velocity

$$V(r_0) = 0 \quad \Rightarrow \quad \frac{r_0}{R} = \sqrt{1-\frac{U_B}{2J}} \quad \Rightarrow \quad \tau_{\text{circular}} = \left(\frac{J}{U_B} - \frac{1}{2}\right)^{-1}$$

$$\frac{U_B}{J} \equiv \psi = \psi(Ca) \quad \text{where} \quad Ca \equiv \frac{\mu_L U_B}{\sigma} \quad \text{and} \quad 1 \le \psi \le 2$$

Rectangular channel cross section

$$u(y,z) = \frac{64}{\pi^3} J \frac{\sum\limits_{n=1,3,5}^{\infty} \frac{(-1)^{\frac{n-1}{2}}}{n^3}\left[1-\frac{\cosh\left(\frac{n\pi}{2a}z\right)}{\cosh\left(\frac{n\pi b}{2a}\right)}\right]\cos\left(\frac{n\pi}{2a}y\right)}{1-\frac{192a}{\pi^5 b}\sum\limits_{n=1,3,5}^{\infty}\frac{1}{n^5}\tanh\left(\frac{n\pi b}{2a}\right)}$$



Approximation of Natarajan & Lakshmanan [4]:

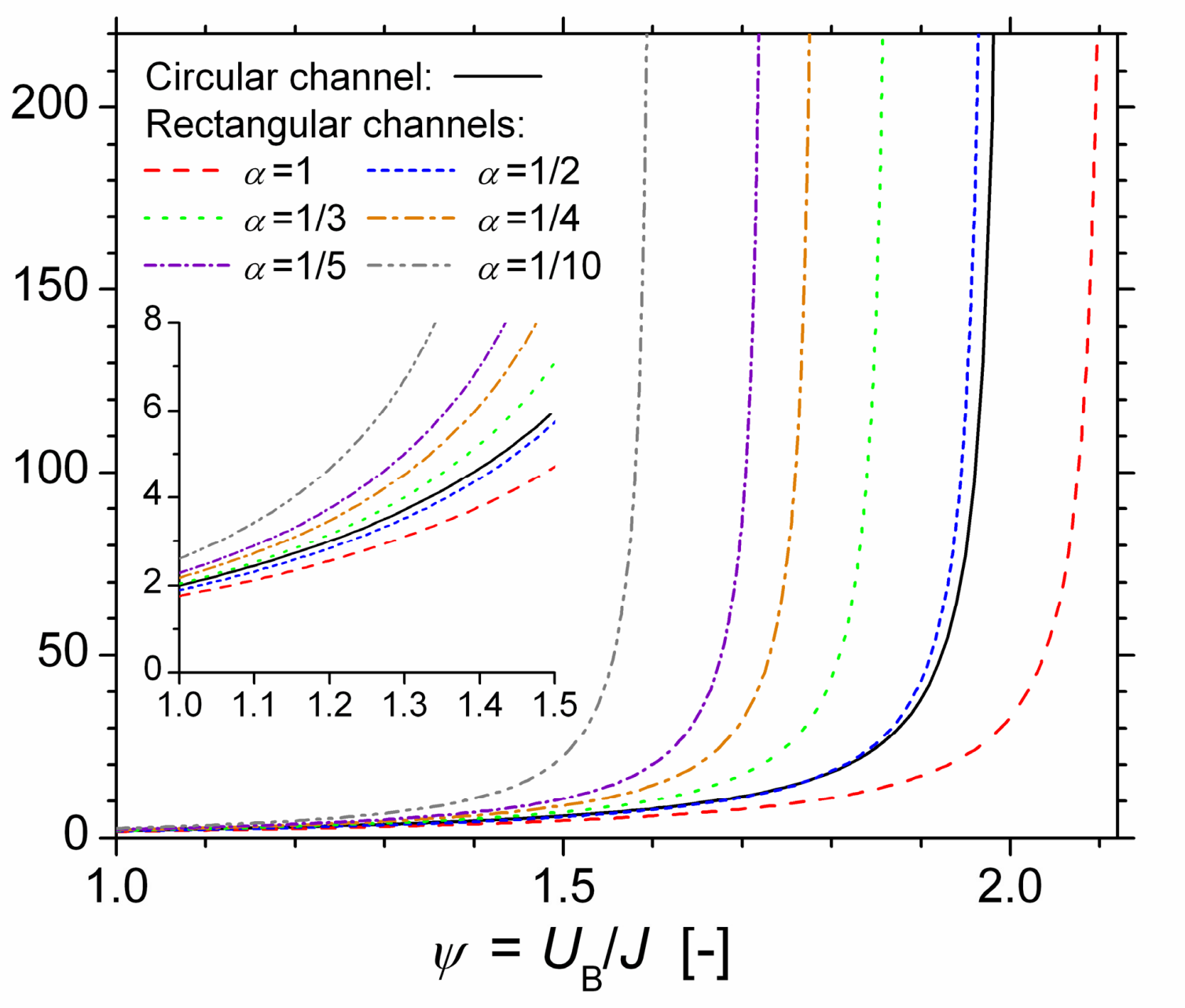
$$u(y,z) \approx U_{\max}(1-Y^n)(1-Z^m) \qquad Y \equiv y/b,\ Z \equiv z/a,\ \alpha \equiv b/a$$

$$U_{\max} = \frac{m+1}{m}\frac{n+1}{n}J, \quad \phi \equiv \frac{U_B}{U_{\max}} = \psi\frac{J}{U_{\max}} \qquad 1 \le \psi \le \frac{m+1}{m}\frac{n+1}{n}$$

$$m = 1.7 + 0.5\alpha^{-1.4}$$

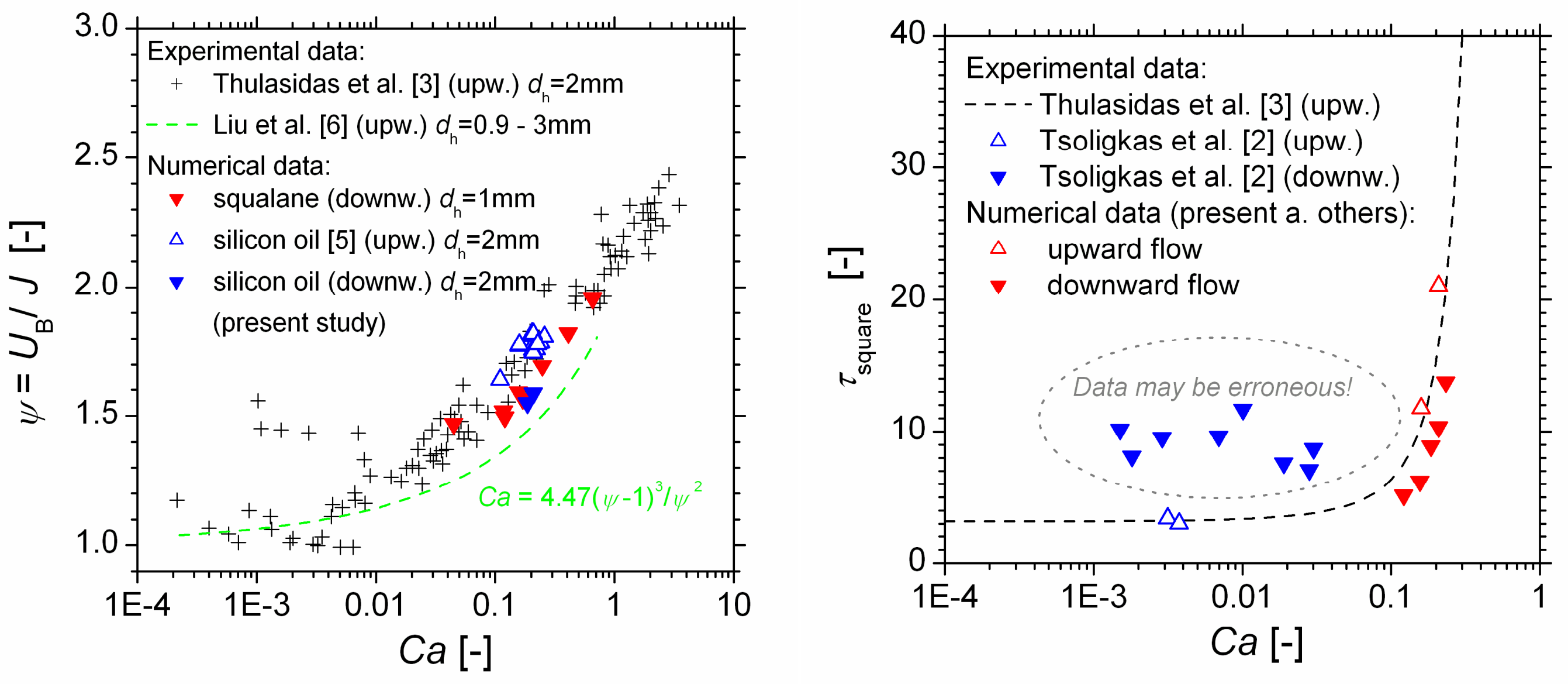
$$n = \begin{cases} 2 & \text{for } 0 \le \alpha \le 1/3 \\ 2 + 0.3(\alpha - 1/3) & \text{for } 1/3 < \alpha \le 1 \end{cases}$$

$$\tau = \frac{1}{\phi^{-1}-1}\frac{m+1}{m}\frac{\int_0^1\left(\frac{1-u^n}{(1-\phi)^{-1}-u^n}\right)^{\frac{1}{m}}du}{\int_0^1\left(\frac{(1-u^n)^{m+1}}{(1-\phi)^{-1}-u^n}\right)^{\frac{1}{m}}du}$$



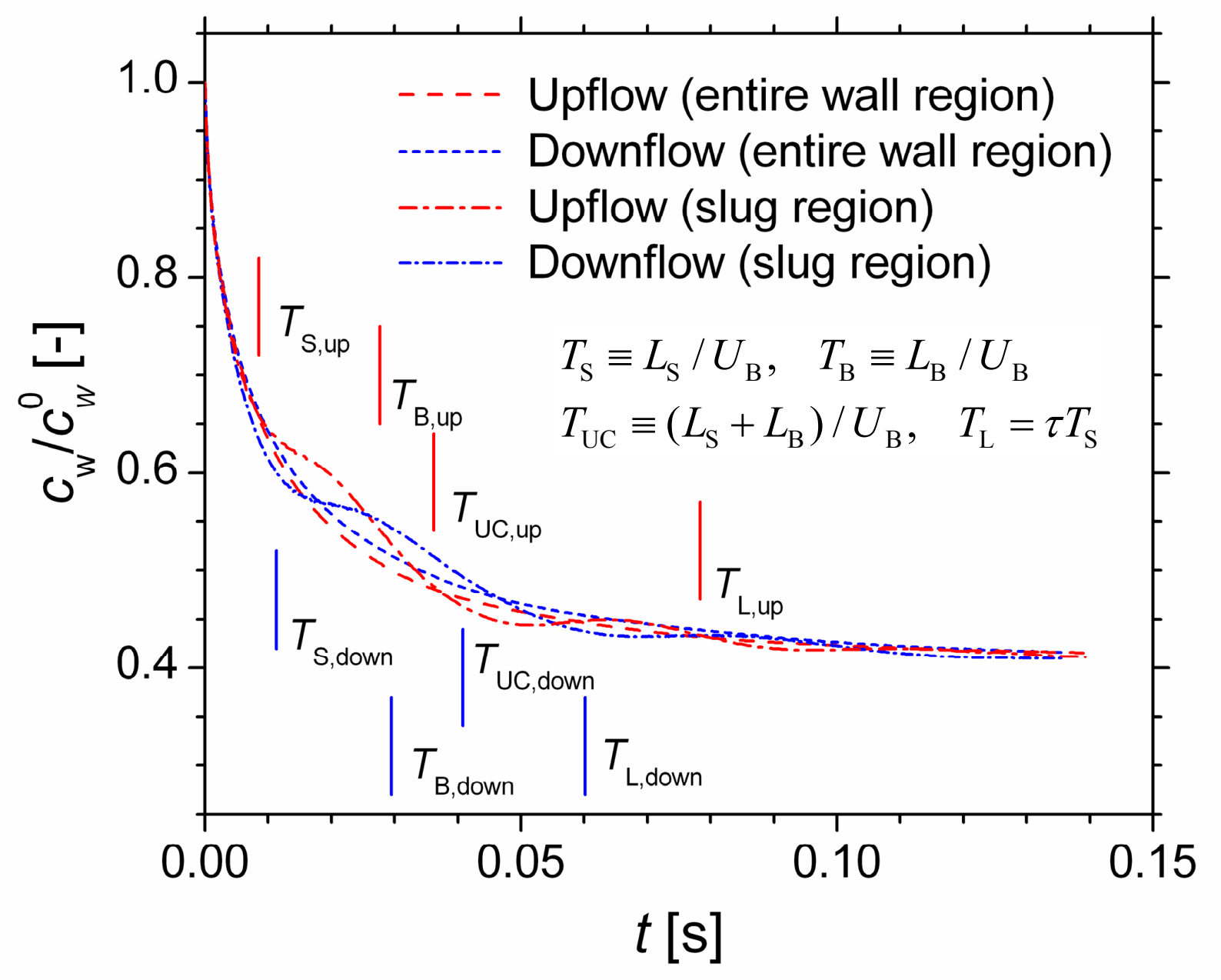
4. Numerical simulations of Taylor flow in a square mini-channel

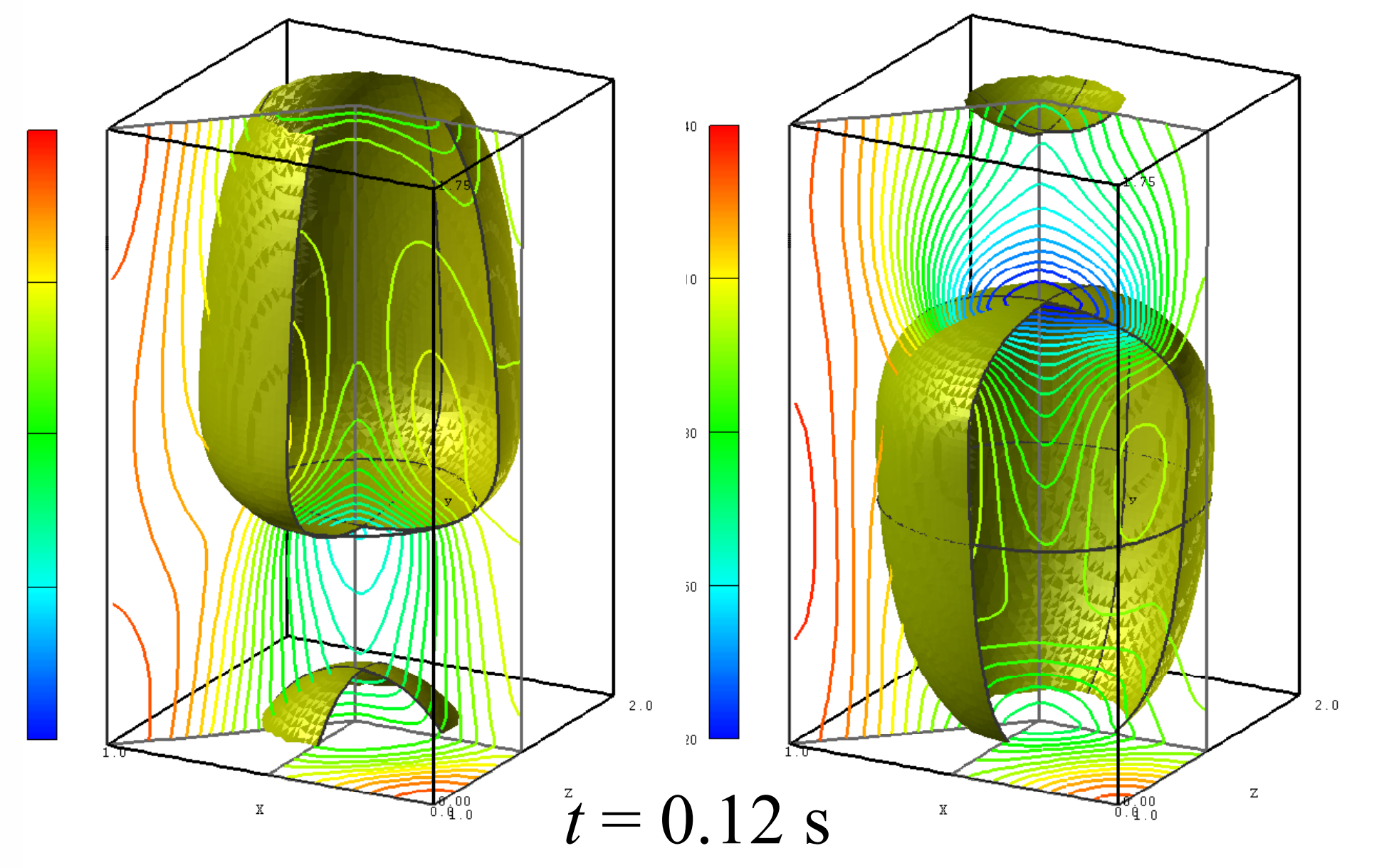
Evaluation of recirculation time as function of capillary number *Ca*:



For given J, $\psi = U_B/J$ is larger in upward than in downward flow because of buoyancy. Therefore, it is $\psi_{up} > \psi_{down}$ and $\tau_{up} > \tau_{down}$.

Simulation of mass transfer from a 4 mesh cell thick wall layer into the center:





upward flow downward flow

5. Conclusions

- The recirculation time is a unique function of the aspect ratio α and $\psi = U_B/J$.
- For equal J, ψ is larger in upward than in downward flow (due to buoyancy).
- For the same capillary number *Ca*, the theoretically and numerically evaluated recirculation time is larger in upward than in downward flow (in contrast to the experimental results in [2]). This suggests that the liquid slug mass transfer (G-L and L-S) is more efficient in downward flow.
- The overall mass transfer rate (including the contribution through the liquid film) is, however, very similar in upward and in downward Taylor flow.

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