Powering process intensification in an oscillatory flow meso-reactor

N. Reis, A. [1]P. Harvey, A. A. Vicente and J. A. Teixeira
Institute for Biotechnology and Bioengineering, Centro de Engenharia Biológica, Universidade do Minho, 4710-057 Braga, Portugal, tel. +351 253 604400, e-mail: jateixeira@deb.uminho.pt; [1]School of Chemical Engineering and Advanced Materials, University of Newcastle upon Tyne, NE1 7RU, UK, tel. +44 (0) 191 222 7268, e-mail: a.p.harvey@newcastle.ac.uk.

In the last few years chemical and biochemical engineers have started acknowledging the advantages of carrying out reactions at the small scale. Although plant design is traditionally based in scaled-up equipment the recent developments in scaled-down platforms is motivating the Process Intensification of industrial processes following some of the key advantages presented by such technologies. PI offers the possibility to develop and carry out chemical, pharmaceutical and biochemical reactions/separations in a sustainable way through higher selectivities, and is now regarded as a major driving force for the development of "meso-technologies" (Pieters et al., 2007). The size of the plant is adapted to the reaction/separation and the increase in plant capacity is achieved through a scale-out rather than a scale-up approach, representing additional savings in plant capital and operational costs (especially those related with the cleaning of batches).

The work herein presented is concentrated in the development of a continuous, tubular meso-reactor with potential applications in fine chemicals and pharmaceuticals industries. The internal diameter of the tube is about 4.4 mm and a controllable mixing is achieved by pushing the fluid through a series of periodic, smoothed-wall constrictions in a sinusoidal way (Figure 1). The flow patterns are dominated by vortex rings generated from the flow separation at the surface of each constriction (Reis et al., 2005), resulting in large enhancements in heat and mass transfer rates. In the limit case, the oscillatory meso-reactor (OMR) can be regarded as a series of several hundreds or even thousands of small ideal stirred tanks, depending on the total length of the reactor.

Particle Image Velocimetry (PIV) was used to experimentally visualise the flow patterns in the OMR (Figure 2a) for a wide range of fluid oscillation frequencies (f) and centre-to-peak amplitudes (x_0). The macroscopic flow patterns were studied as a function of the oscillatory displacement, and average values of velocities and standard deviation for both radial and axial coordinates were calculated from each individual instantaneous velocity vector maps and then averaged for some consecutive oscillation cycles. Two dimensionless parameters R_V and R_S were determined representing the ratio of cycle-average radial velocity to axial velocity and the ratio of standard deviation in the radial velocity to axial velocity (a direct measurement of the relative mixing power), respectively, and correlated with the mixing and flow behaviour as given by the residence time distribution (RTD) functions.

It is demonstrated that both R_V and R_S can be fined-tuned by changing the value of f or for x_0 = 1 mm, and both correlated well with the experimental axial dispersion in the macroscopic flow patterns. A high selectivity given by a minimum axial dispersion coefficient is assured when both R_V and R_S approach the ratio of mean internal tube diameter to the constrictions spacing (i.e. 0.294), which could be obtained using a value of f around 10 s^{-1}. Lower values of R_V and R_S would represent extended backmixing and lower mixing states, respectively, resulting from the imposed axial oscillations in the fluid as illustrated in Figure 2b. Additionally, the product $R_S \cdot f$ exponentially increased with the product $R_V \cdot f$, according to the equation:

$$R_S \cdot f = 0.7175 \exp(0.4693 R_V \cdot f), \text{ with } r^2 = 0.99 \quad (1)$$

This represents a positive correlation between the intensity of the mixing and the backflow, which is in agreement with a long time-scale model for real batch stirred tanks (Levenspiel, 1972).

Experiments at higher x_0 suggested that the oscillation amplitude governs the length of vortex rings propagation through the fluid in the cavities of the OMR, thus promoting the axial motion of fluid while assuring a good radial homogeneity (i.e. high R_V ratios).

The flexibility demonstrated in terms of control of mixing intensities and flow behaviour makes the OMR an outstanding platform for PI and especially for the processing of heterogeneous systems.

Pieters, B., Andrieux, G., Eloy, J.-C., 2007. The impact of microtechnologies on chemical and pharmaceutical production processes. Chemical Engineering & Technology 30 (3), 407–409

Reis, N., et al., 2005. Fluid mechanics and design aspects of a novel oscillatory flow meso-reactor. Chemical Engineering Research & Design 83 (A4), 357–371.

Levenspiel, O. (1972). Chemical reaction engineering (1st edition ed.). New York: John Wiley & Sons, Inc.

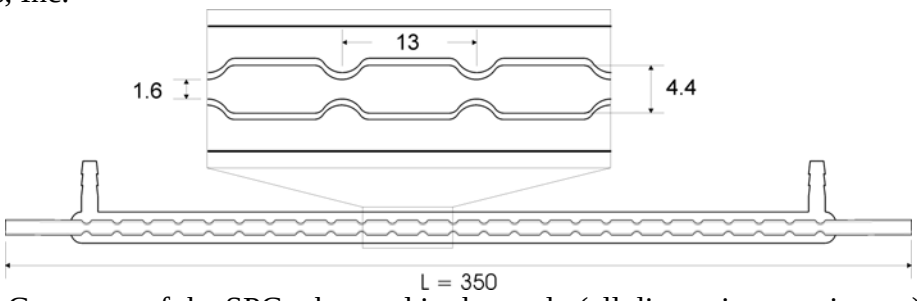
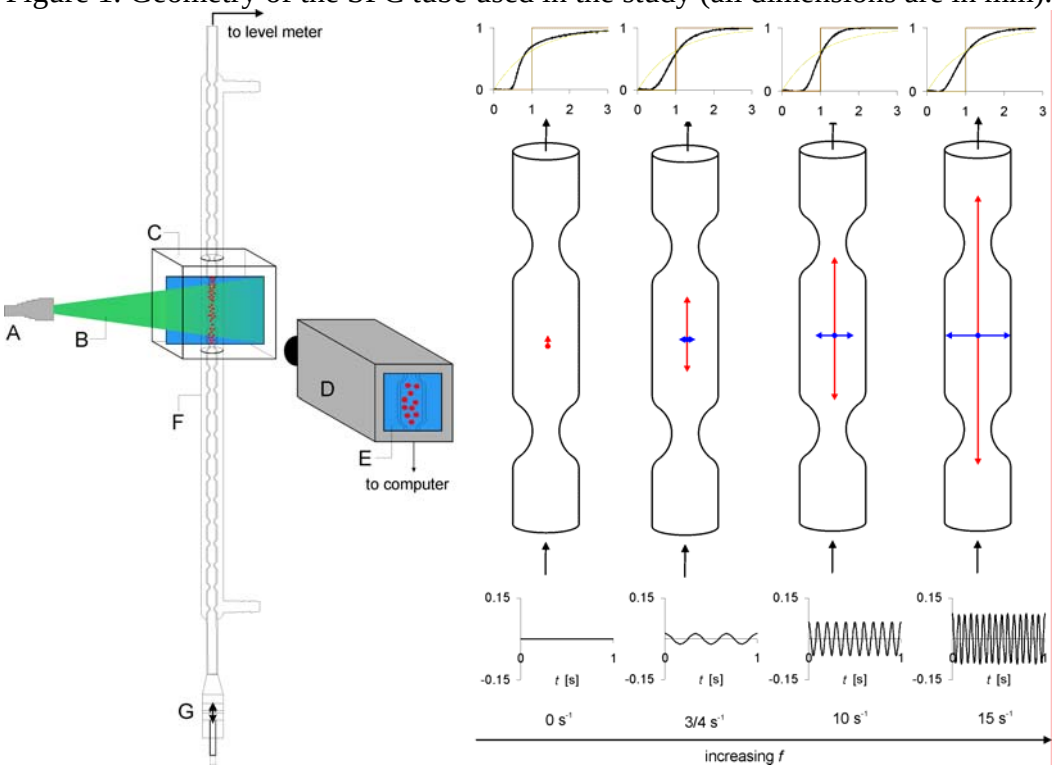


Figure 1. Geometry of the SPC tube used in the study (all dimensions are in mm).



(a) (b)

Figure 2. (a) Experimental PIV setup. (b) Schematics of the effect of R_V on the RTD at increasing values of f (0 to 15 s^{-1}), for x_0 = 1 mm.