Newcastle University
School of Engineering

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pig MONTHLY

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In This Issue

New Funding & PDRA Position

"Scalable engineering approaches for exploiting a novel biocomposite material applied to light-driven CO_2 absorption and utilization"

PI:	Dr Kamelia Boodhoo
Co-I:	Dr Sharon Velasquez-Orta
	Prof Michael Flickinger (NCSU, US)
Awarding Body:	BBSRC NIBB C1Net
Amount:	£62,418
Duration:	1st Nov 2017—31st May 2018

Recruitment of a PDRA is currently open. Anyone interested in applying should contact Dr Kamelia Boodhoo.

IbD Meeting: TRIZ Workshop

As part of the Intensified by Design (IbD) project, a TRIZ workshop was recently hosted at Newcastle University (from 21-22 September), facilitated by Prof Pavel Livotov (PPI Lab, Offenburg University). TRIZ is a problem solving methodology that contains 40 basic principles that can be used during brainstorming sessions to identify alternative/more efficient processes. Examples of the principles include:

- Transformation of the physical/chemical properties (35)
- Prior useful action (10)
- Segmentation (1)

During the meeting, several researchers from Newcastle (Dr Kamelia Boodhoo, Prof David Reay, Dr Vlad Zivkovic, Dr Richard Law, Dr Anh Phan, Dr Ahmad Mustaffar and Jonathan McDonough) worked with IbD project partners to generate 17 ideas and three solution concepts to improve the separation of ceramic-metal powders produced from high energy ball milling, a Case Study hosted by one of the industrial partners, MBN Nanomaterialia S.p.A. (Treveso, Italy).

Upcoming Conferences

- **2017 *AIChE* Annual Meeting** (Oct 29-Nov 3 2017, Minneapolis, US). Late Registration Deadline: 25th October 2017
- **25th International Symposium on Chemical Reaction Engineering, ISCRE25** (20-23 May 2018, Florence, Italy). Early Registration Deadline: End of March 2018
- **16th International Heat Transfer Conference** (10-15 August 2018, Beijing, China). Registration Deadline: 25th July 2018
- **ChemEngDayUK2018** (27-28 March 2018, Leeds, UK). Abstract Submission Opening: September 2017
- **2018 *AIChE* Spring Meeting** (22-26 April 2018, Orlando, Florida). Abstract Submission Deadline: 13 November 2017
- **6th International Conference on Micro and Nano Flows, MNF2018** (9-12 Sep 2018, Atlanta, Georgia, US). Abstract Submission Deadline: 1st December 2017

A large proportion of the PI group will be attending WCCE10 in Barcelona from 1st-5th October. Details of the talks and posters that will be presented can be found below for each day of the conference. A map of the venue has also been included.

Presentations

Monday 2nd October

- J McDonough, R Law, A Harvey | *Intensification of Transport Phenomena using 3D Printed Fluidic Oscillators* | KN-61641 | IPIC: Batch to Continuous 1 | Room A5 | 16:00-17:30 (*see this issue's research spotlight article for more details*)
- J McDonough, S Ahmed, A Phan, A Harvey | *A study of the flow structures generated by oscillating flows in a helical baffled tube* | SOC-25471 | IPIC: Batch to Continuous 1 | Room A5 | 16:00-17:30
- H Wang, A Phan, V Zivkovic, K Boodhoo | *Particle classification via Taylor-Couette flow: Experimental and Simulation Studies* | SOC-66376 | IPIC: Batch to Continuous 1 | Room A5 | 16:00-17:30
- S, Al-Hengari, K Boodhoo | *Characterization of Micromixing Efficiency in T and Y Narrow Channel Reactors: Evaluation with Villermaux/Dushman Test Reaction* | SOC-27466 | IPIC: Teaching/Batch to Continuous 2 | Room A5 | 17:30-19:00

Tuesday 3rd October

- A Lopez Fernandez, M Gunam Resul, A Harvey | *Sustainable Epoxidation of Terpenes using Continuous Mesoscale Oscillatory Baffled Reactor under Microwave Irradiation* | SOC-47596 | IPC: Hybrid Process & Multifunctional Process | Room A5 | 11:30-13:00
- A Mustaffar, K Boodhoo, A Phan | *Heat Pipe Screw Dryer: a novel, energy-efficient drying technology* | SOC-26506 | IPIC: Hybrid Process and Multifunctional Process 2 | Room A5 | 16:00-17:30

Wednesday 4th October

- A Rehman, A Lopez Fernandez, A Harvey | *Intensification of cyclic carbonate synthesis from epoxides and CO2 using tube-in-tube gas/liquid microreactor* | OC-48541 | IPIC: Batch to Continuous 3 | Room C6 | 11:30-13:00
- S Ahmed, A Phan, A Harvey | *A study of gas-liquid flow regimes and mass transfer enhancement in various designs of oscillatory baffled reactors* | OC-21891 | TOPIC 3: Multiphase Flow & reactors 3 | Room C7 | 16:00-17:30

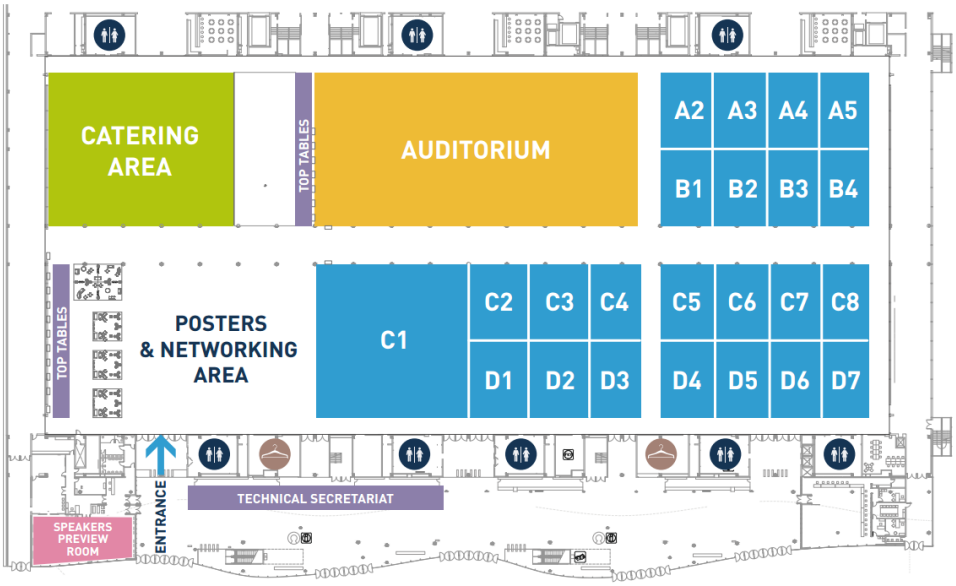
Thursday 5th October

- S Musa, M Al-Karawi, G Caldwell, J Lee | *Combined Harvesting and Oil Extraction of Microalgae for Biodiesel Production using a Foam Column* | OC-56661 | Topic 6.6: Microalgae Biotech. 2 | Room B1 | 08:30-10:00
- M Al-Karawi, O Gordon, S Musa, G Caldwell, J Lee | *Drainage enhancement in the continuous foam flotation column used for algae biomass recovery* | OC-46701 | Topic 6.6: Microalgae Biotech. 1 | Room B1 | 08:30-10:00
- S Ahmed, A Phan, A Harvey | *Developing a scale-up correlation for oscillatory baffled reactors* | OC-21931 | IPIC: Scale-up & Industrial Implementation of Intensified Technologies 1 | Room C6 | 08:30-10:00

Posters

Wednesday 4th–Thursday 5th October

- K Boodhoo, M von Sosch, M Beard, E Richmond, M Flickinger | *Enhancement of CO_2 gas-liquid mass transfer in thin wavy film flow on a spinning disk* | JE-IPIC-011 | Hybrid/Multifunctional Process
- T Horie, N Numata, S Wang, A Harvey, N Ohmura | *Evaluation of Mixing Characteristics in a Micro Oscillatory Baffled Reactor* | JE-IPIC-054 | Process Intensification for New Product Development
- O do Nascimento, V Zivkovic, D Reay | *Effect of Circulating Fluidised Bed geometry on the hydrodynamics of liquid-solid flow micro channel* | JE-IPIC-026 | Modular Process
- M Resul, A Rehman, A Lopez, A Harvey | *Intensification of terpenes epoxidation using continuous meso-scale Oscillatory Baffled Reactor* | JE-IPIC-005 | Batch to Continuous
- S Sana, K Boodhoo | *Exploiting the spinning disc technology for solvent-antisolvent precipitation of starch nanoparticles* | JE-IPIC-007 | Batch to Continuous
- A Umar, P In-na, G Caldwell, J Lee | *Growth and Maintenance of Microalgae on a Filter Paper Strip and its Potential for Biological CO2 Mitigation* | T6.6.261 | Marin Biotechnology & Engineering
- K Zhang, F Saleem, AP Harvey | *Intensification of Gasifier Effluent Treatment Using Non-Thermal Plasmas* | JE-IPIC-064 | Scale-up & Industrial Implementation of Intensified Technologies



Materials Substitution Meeting

Prof Adam Harvey, Dr Ana Lopez, Mohamad (Faiz) Gunam Resul and Abdul Rehman attended the Materials Substitution meeting at the Chemistry Research Laboratory, Oxford from 14-15 September. Collaborators from the University of York, Imperial College London and University of Oxford were also in attendance. The Agendas for both days of the meeting are summarized below.

Day 1: Management Meeting & Updates from the PI Group

- Ana Lopez | *Limonene epoxidation in microwave vs conventional heating. Continuous limonene epoxidation using novel microwave irradiated meso-OBR*
- Mohamad Gunam Resul | *Continued optimization of the epoxidation of terpenes in Oscillatory Baffled Reactors (OBRs) and batch reactor*
- Abdul Rehman | *Kinetic study of limonene cyclic carbonate synthesis in batch reactor*

Day 2

- PI Teleconference with IAB: Christoph Gürtler (*Covestro*), Rowena Sellens (*Econic*), and James Clark (*University of York*)
- PDRA Meetings

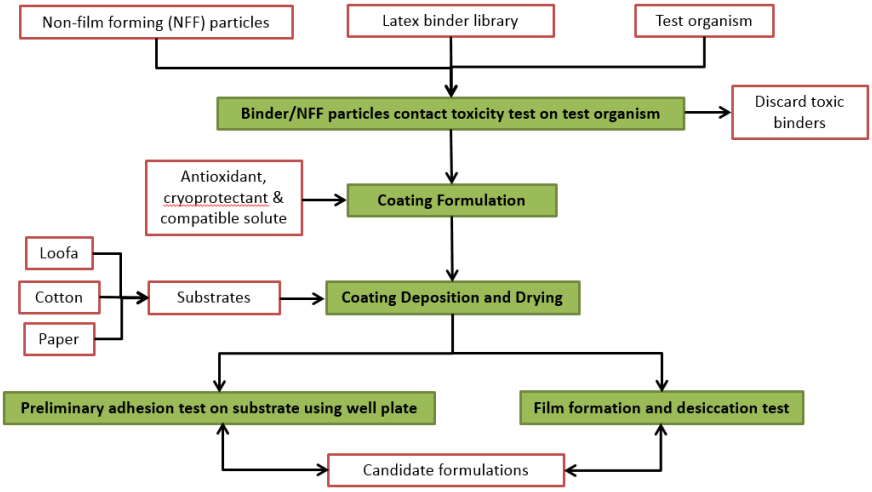
Faiz, Adam, Abdul & Ana stood in front of the Bodleian Library

Other Information

- Full contact details and research profiles for the PI group members can be found at the website: www.pig.ncl.ac.uk
- For enquires about collaborations or PhD study, see the website: www.pig.ncl.ac.uk
- If anyone would like to contribute any articles, or if anyone has any ideas regarding the newsletter please contact Jonathan McDonough: jonathan.mcdonough@ncl.ac.uk

Collaboration with NC State

Abbas Umar and Pichaya In-na recently returned to Newcastle after an research visit during the summer to NC State University. The title of this research project was: "*A screening method for materials to produce photosynthetic bio-composites for CO_2 sequestration*". The screening scheme is visualized below.



Latex binder & non-film forming particle screening scheme

The Flickinger group (and Abbas & Pichaya), NC State, 2017

3D Printed Fluidic Oscillators

Jonathan McDonough, Dr Richard Law, Prof Adam Harvey

Introduction

Bistable fluidic oscillators (Fig. 2) are devices that produce autonomous oscillations via the use of fluid dynamic phenomena (such as the Coandă effect) and feedback. Originally developed for computing operations, these devices have found new interest in a range of intensified applications (including microbubble enhancement in gas spargers, flow separation control in aeronautics, and enhanced combustion). Fluidic oscillators provide an active-type mixing enhancement (pulsatile flows), but require no moving parts, making them an appealing option for realising robust mixing. In this research, a potential new application of liquid-based fluidic oscillators is being explored: the development of a new flow chemistry platform that requires no moving parts. This idea extends from the Oscillatory Baffled Reactor (OBR), which uses actively generated oscillations in the presence of baffles to produce high-quality plug flow at low flow rates. Although the OBR can enable the conversion of long residence time batch processes to continuous processes, the use of moving parts may have hindered the uptake of this technology to industry applications.

The ultimate goal of this research is to develop a new flow chemistry platform that can achieve active-type mixing enhancements (using pulsatile flows) with no moving parts.

Rapid Prototyping using 3D Printing

All fluidic oscillators (and reactor geometries) in this work were fabricated using two stereolithographic 3D printers: MiiCraft+ and Form1+, shown in Fig. 1. Stereolithography involves the layer-by-layer construction of prototypes through the photopolymerisation of a resin. The MiiCraft+ used digital light projection (DLP) technology, where each resin layer was cured simultaneously through the projection of a UV image into the resin tank. In contrast, the Form1+ used a single UV laser point (155 μm) that scanned through the resin tank to quickly trace out the shape of the current layer. Both printers used proprietary methyl acrylate based resins containing additives and photoinitiators,

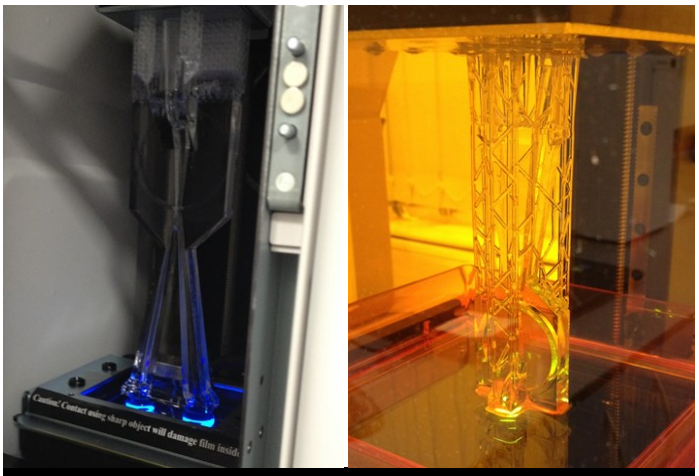


Fig. 1—3D Printers; (L) MiiCraft+, (R) Form1+

resulting in semi-transparent parts (the opaqueness was controlled by the roughness of the surface). The Form1+ could deliver an XY (horizontal) resolution of ~155 µm and a Z axis (vertical) resolution of 25–200 µm. The MiiCraft+ could achieve similar Z-axis resolution of 50–100 µm, and a superior X/Y-axis resolution of 56 µm. The Form1+ build times ranged from 4–12 hours depending on the number and orientation of the parts and vertical resolution selected. The MiiCraft+ was slower, requiring around 14–20 hours per single oscillator.

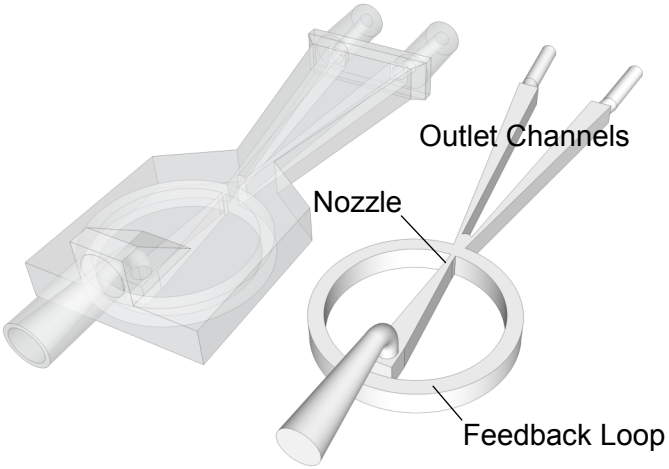


Fig. 2—Bistable fluidic oscillator example

Geometric Characterization

The effects of seven geometric parameters on the flow-switching frequencies were first studied for water and a variety of glycerol water mixtures. The most consequential design parameter was found to be the splitter distance (Fig. 3), which could be reliably used to tune the frequency at a particular flow rate. The angle between the outlet channels also had a slight effect on the frequencies, with larger angles producing higher frequencies. Changing the orientation of the feedback loop from horizontal to vertical, and reducing the length of the inlet zone both suppressed the flow-switching response. Parameters that did not influence the switching frequencies (in the ranges studied) were the feedback loop width/length and convergence length of the nozzle. Overall, frequencies of 2–22 Hz were produced for kinematic viscosities of 1.00–4.37 mm^2/s, in the range of Re = 600–12,000 (400–1200 mL/min).

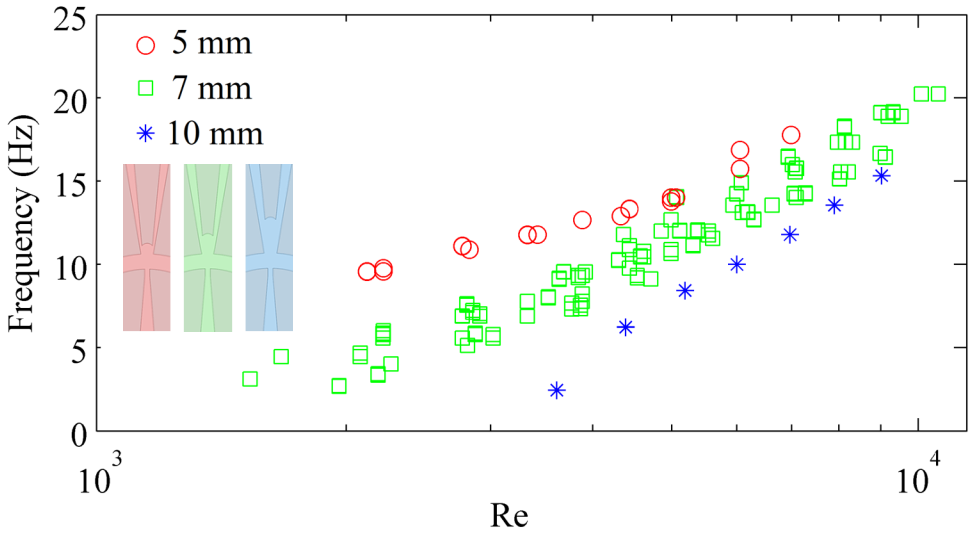


Fig. 3—Effect of splitter distance on flow-switching frequencies

Lowering the Volumetric Flow Rate Requirement

The main drawback found in the geometric characterization study was a minimum flow rate requirement of 400 mL/min before the flow-switching response initiated. From a flow chemistry perspective, this is sub-optimal because it limits the residence times that are compatible with the pulsatile mixing. To reduce the volumetric flow rate requirement, several new oscillator designs were printed that varied the cross-sectional area of the nozzle (Fig. 2), by either

changing the channel height or changing the overall scale of the device. Fig. 4 shows the results of reducing the channel height. It can be seen that this approach does enable lower flow rates to be compatible with the pulsatile flows, by decoupling the volumetric flow rate from the jet velocity emerging from the nozzle. The lowest volumetric flow rate produced corresponds to a flow of 100 mL/min in each outlet channel. Another method currently being considered to reduce the flow rate requirement is to split the flow amongst more outlet channels. The benefit of this approach is integrated flow distribution could be realised, which may be beneficial for scale up.

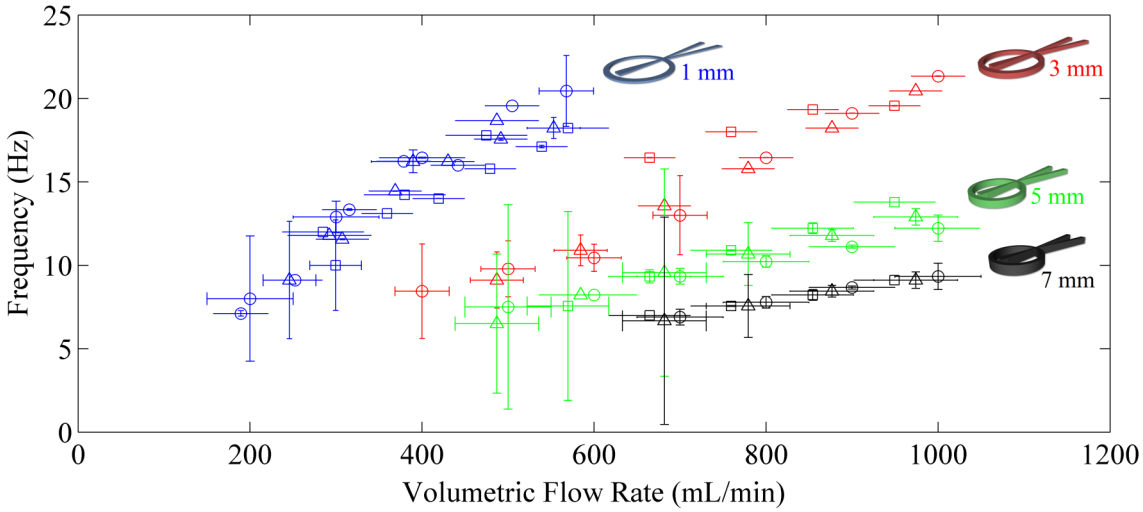


Fig. 4—Effect of channel height on the flow-switching frequency

Plug Flow

The ability of these pulsatile flows to improve the plug flow quality of standard reactor geometries was assessed using tracer pulse experiments and the tanks-in-series model. Based on the preliminary data (Fig. 5) it has been shown for the first time that the pulsatile flows generated by fluidic oscillators do improve the plug flow performance of straight channels containing helical coil inserts and helically coiled channels. It is believed that the pulsatile flows decouple the effects of axial dispersion from secondary flows in a similar manner to the OBR. With the reactor geometries, only a 30% drop in pulsation frequency was observed, compared to the unrestricted oscillators. Future work in this area will focus on improving the experimental methodology, and performing more detailed reactor geometry optimization (using the rapid turnaround times afforded by the 3D printers).

Other Research Areas and Future Work

Computational fluid dynamics simulations and particle image velocimetry experiments are currently being performed in order to gain insight into the flow structures and how they can be exploited for enhanced mixing. The simulations currently reveal that vortices are shed from the inlets of each outlet channel by the sweeping fluid jet produced from the nozzle. In addition, experiments are being conducted in order to assess the potential tube-side heat transfer enhancements in shell-and-tube heat exchangers that can be achieved with these pulsatile flows. The current results suggest there is scope to optimize the tube insert geometry in a manner that is compatible with the pulsatile flow. For example, orifice baffles dampen the pulsing flows while helical baffles provide additional swirling. Finally, experiments are being designed to investigate the micro-mixing times achievable with these fluidic oscillators.

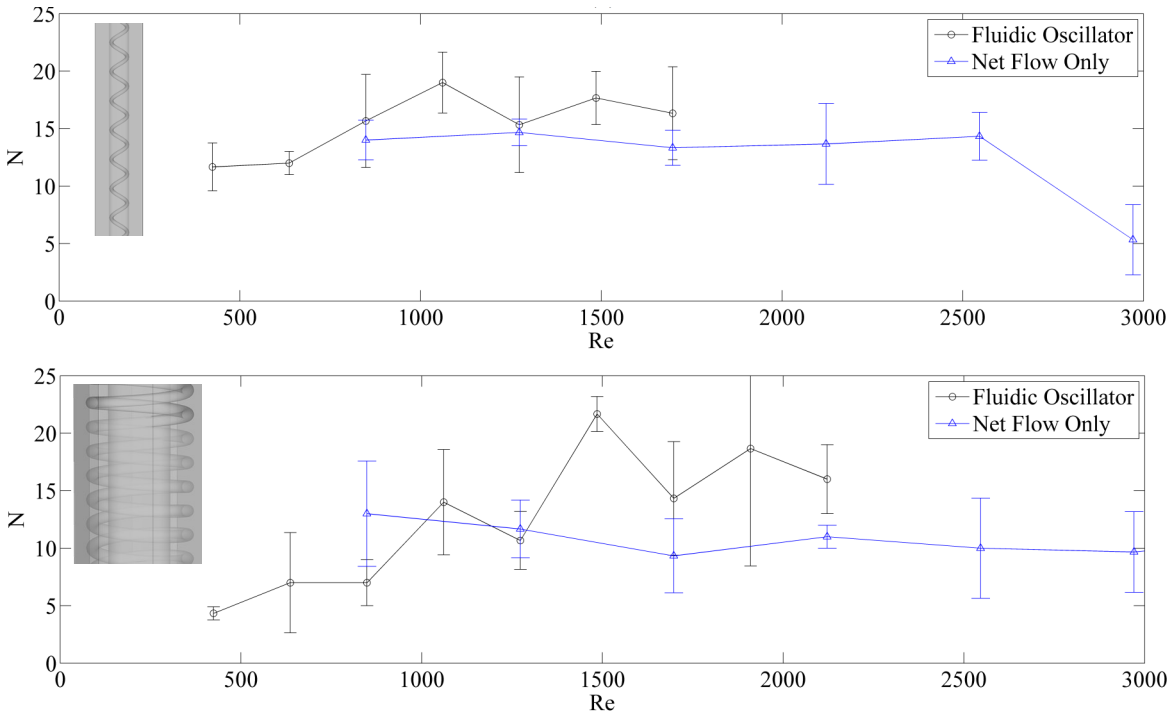


Fig. 5—Number of equivalent tanks-in-series vs Re

Current Outputs of the Research

- JR McDonough, R Law, AP Harvey. *Intensification of transport phenomena using 3D printed fluidic oscillators*. Keynote talk to be presented at the 10th World Congress of Chemical Engineering, Barcelona, Spain (2017)
- JR McDonough, R Law, L Short, J Kraemer, AP Harvey. *Applications of 3D printed fluidic oscillators to process intensification*. Poster presented at ChemEngDayUK, Birmingham, UK (2017)
- JR McDonough, R Law, J Kraemer, AP Harvey. *Effect of geometrical parameters on flow-switching frequencies in 3D printer fluidic oscillators containing different liquids*. Chemical Engineering Research and Design 117 (2017) 228-239

Potential PhD Project

There is vast potential for further characterization, optimization and application of these devices as a flow chemistry platform. Anyone interested in applying for a PhD in this area should contact Prof Adam Harvey (adam.harvey@ncl.ac.uk).