

Article

Theoretical and Experimental Analysis of Miniaturization of Conventional Oscillatory Flow Technology

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Abstract: The requirement for any configuration of a chemical or biochemical reactor is the presence of efficient mixing to enhance heat and mass transfer as needed for the application of interest. Furthermore, as an Oscillatory Flow (OF) reactor has a combination of flow oscillation and baffled tube configuration, which has the potential to ensure efficient mixing, heat transfer, and mass transfer. In this way, an efficient mixing in an OF reactor is able to tackle any type of resistance in any chemical process from polymer synthesis to enzyme production. It has been observed that an OF reactor improved both conversion and selectivity of the relevant reaction by efficient mixing and transport properties. However, this technology was not still extended to mini-fluidic configuration via process intensification methods and so far, a novel approach for enhanced mixing at reduced scales was not explored. This work explores the application of OF technology in mini-fluidics. The feasibility analysis of Oscillatory Flow Technology in mini channels has been investigated using theoretical correlations from Conventional Oscillatory flow technology in process equipment. As a preliminary step in the process intensification of OF technology in mini channels, The Nusselt number (Nu) and pressure drop values are predicted from the literature and it has been observed that the transfer operations are also improved when oscillatory flow is applied in mini channels compared to commercial mini contactors such as corning heart shaped reactor. The plot between energy dissipation vs. mixing evaluated from theoretical calculations was drawn and compared with mini-fluidic mixers reported in literature. The most common mini-fluidic mixer is corning heart shaped reactor used for comparison with the proposed minichannel. Because of this analysis, the novel mixing geometries was expected to develop for various chemical processing applications. The OFT experimental set up was developed to create oscillatory flow via either forward rotation or backward rotation of valve. Furthermore, pressure vs. time profile and flow vs. time profile for the given OF mini fluidic arrangement is initially investigated and described. Preliminary experimental results are provided for an OF generator, intended for use in subsequent experiments exploring mini-fluidic mixers with OF technology.

Keywords: Oscillatory Flow, Minichannels, Pressure drop, Nusselt Number and Pumping Requirements

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1. Introduction

Some of the most challenging aspects of modern reactor design relates to enhancement of heat and mass transfer performance in a reacting medium through improved contacting and mixing without significantly increasing energy dissipation and operating expenses. This is especially true for recent efforts in process intensification and the application of mini and micro fluidic technology to fine chemical and pharmaceutical industries, where the reduced length scales of the geometries make turbulent operations,

which are prohibitively expensive. Recent years has seen the development, application, and performance characterization of a variety of static and dynamic mixing geometries and strategies to eliminate mass transfer resistances at these reduced scales for homogeneous reacting systems, making mini-fluidics a highly attractive option for synthesizing compounds whose formation kinetics and selectivity are subject to either mass or heat transfer limitations [1].

Frequently, the requirement of mixing is achieved by mechanical agitation in the vessel or else by creating high velocity turbulent flow in either a tube or a pipe as plug flow reactor. However, the reactor geometry and its configuration plays major role in reactor performance and it does influence on the mixing performance in the vessel / reactor and performance in the chemical reactions. Although there are many reactor geometries and configuration used in practice such as smooth pipe, tee mixer, static mixer and stirred tank, the mixing performance doesn't meet specific application and industrial requirements [1].

In the practical scenario, improper mixing is the most important problem in operations of various types of chemical reactors. Mixing and chemical reactions in the reactor design are intimately intertwined. For example, "if the reaction can result in only one product, then the mixing and mass transfer can influence only the reaction rate. However, if more than one product is possible, then the contact between two phases influence on both reaction rate and product distribution as well". These considerations apply to both homogeneous and heterogeneous reaction systems. The effect of mixing in the conventional reactor design is determined by mixing damkohler number (Da_M), a parameter that characterizes the efficiency of mixing in the reactor design. It specifies that a smaller Da_M indicates less effect of mixing and a larger Da_M indicates that mixing will be a concern. Moreover, Mixing is the critical design factor to create turbulence that affects the rate of the reaction and increased transport characteristics of the reaction medium in reactor design. On the contrary, poor and improper mixing in any reactor configuration leads to the formation of side reaction and undesired products especially in the competitive reactions [2]. Mixing plays a vital role to overcome mass transfer limitation in heterogeneous reactions. The mixing in the multiphase reactors influence on the typical parameters such as phases involved, the differences in the physical properties of the participating phases, the inherent reaction nature, residence time required, the mass and heat transfer characteristics of the reaction and rate of the reaction [3].

Even though mixing does influence on heat and mass transfer that, enhances effective reaction rates, selectivity, and the elimination of transport resistances. It could significantly affect the conversion and selectivity within a given reacting system especially in the mass transfer limited reactions. Enzymatic reactions, trans-esterification reactions, Hydrogenation of cyclohexane, p- nitrotoluene and α - methylstyrene are the best examples for mass transfer limited reactions where mixing is the most preferred operations to enhance the mass transfer rate in the chemical reactions. Additionally, in polymerization reactions, the mixing effects on the emulsification of monomers influence on the length of the polymer chains. In multiphase reactions, the rates of chemical reactions are improved by high rates of heat and mass transfer, selectivity and elimination of transport resistances. However, there are short comings in the convention multiphase reactors that are based on the reaction rate. If the reaction is fast, then the mass transfer should be relatively high in order to overcome mass transfer limitations. For better mass transfer, higher interfacial area is preferred. The enhancement of specific interfacial area can increase the overall performance of the reactor. "Mechanical complexity with high maintenance cost, Limitation in flow rates, thick liquids film results in higher mass transfer resistance for three phase reactions are the most common problems in the multiphase reactors [4, 5]"

Based on the mass transfer and reaction kinetics, the reactions are classified into three main groups where mixing mostly influences in it. In fast and very fast reactions, both

conversion rate and selectivity are highly influenced by mixing and reactor design. In addition to it, Mixing also affects reaction rate and mass transfer rate in the reactions. However, Selectivity could be improved by manipulation of interfacial conditions. Mixing design and scale-up of the reactions are very critical to produce successful performance results. In slow reactions, the reaction rate is fast enough that significant reaction occurs in the film formed between the reactants. However, in the case of very slow reactions, the rate of reaction is usually slower than the mass transfer rate where the homogenous reaction kinetics follows. The mixing and mass transfer rates have no influence on the reactions. In this category, mixing does not improve the reaction rate, but blends only the reaction medium. However, In case of poor bulk or macro mixing (i.e., solids settled on the bottom or large dispersed phase drop size) the conversion rate is slow. Furthermore, "The mixing is the most important in processing of mixing sensitive reactions such as Bourne reactions like Diazo coupling between 1-naphthol and diazotized sulfanilic acid, Competitive neutralization of hydrochloric acid and alkaline hydrolysis of monochloroacetate esters with sodium hydroxide and Competitive neutralization of sodium hydroxide and acid hydrolysis of 2,2-dimethoxypropane with hydrochloric acid [6,7]".

The innovation of minichannel reactor technology is to increase the efficiency of various chemical processes via enhancing the selectivity and good control on the chemical reactions. In addition to that, minichannel provides large interfacial area and high heat and mass transfer rates. Because it has small diffusion distances in micro dimensions [8]. The size of minichannel has significant control over the chemical process and heat management in exothermic reactions. This is why; micro reactor technology was used in the fine chemical and pharmaceutical industry for fifty percent of the reaction on continuous process [9].

The miniaturization in channels and ducts is a potential platform for process intensification and offers rapid mixing with good heat and mass transfer rates [10]. The most important advantage of micro channels/micro reactor is the shortest transfer length and small area. However, it has high surface to volume ratios and tiny volumes dominate momentum, heat, and mass transfer. This offers many opportunities for chemical and process engineering in micro reactors. Conventional equipment has typical geometrics in the range of centimeters and produces fluid structures in the range from 100 micrometers to 1 mm. The corresponding diffusion time in gas is 1ms, which is slower when compared to the liquids where the diffusion time is in the range of 1s.

A micro reactor varies from 100 μm to 1mm produce fluid structures with 1 μm . It leads to mixing times shorter than 100 micro seconds in gases and approximately 1ms in liquids. This is why; selectivity and high yield of chemical reactions in micro reactors are increased. As discussed earlier, mixing influence on heat transfer, chemical reactions or separation processes. There are three types of mixing namely distributive mixing, diffusive mixing, and convective mixing involved in the mini/micro channel [9].

In micro channels/micro reactors, the reactor performance relies on the input operating variables such as rates of chemical reaction and mixing characteristics, which controls effectively. The micro reactors has comparable mass transfer coefficient with conventional reactors such as fixed bed reactor and CSTR. Hence, mass transfer limited reactions are well suited in micro channels. This reactor improves the performance of rapid and highly exothermic or endothermic reactions and ensures process safety in a production environment. The nominal dimensions of micro reactors varied from 50 to 500 μm . This configuration produces a high specific surface and allows an effective heat and mass transfer rates. However, it has drawbacks like small flow rates per channel or high fabrication cost. Micro channel is used for synthesis of nanoparticles where mixing required efficiently resulting nanoparticles in droplet flow, emulsions with rapid chemical reactions. However, it has only limited advantages and there is some operational problem such as laminar conditions in the continuous process. Even though mixing is the basic

need in the micro channels, it offers laminar conditions and enhances rate and selectivity of chemical reaction.

Considerably less progress has been made for multi-phase systems, particularly those involving immiscible liquid phases (i.e. solvent extraction) or an entrained or precipitating solid (i.e. crystallization). The first requires narrow operating constraints to ensure consistent flow pattern behavior and to avoid the formation of emulsions, which can complicate downstream separation. The latter is plagued by reliability concerns, where dead-zones and local surface roughness in complex passive mixing geometries can provide nucleation sites for sedimentation/crystallization and eventually lead to plugging of the system. The two accepted methods for scaling mini-fluidic technology from prototype to commercial production volumes have also presented unique challenges for multi-phase systems: distributor design, peripheral duplication, and systems integration when “numbering up” mini-fluidic plates; or changes in performance and flow patterns during re-design when increasing characteristic length scales of the geometries to accommodate higher production targets. The progress in the design of mini-fluidic systems are found in open scientific literature for various applications such as compact heat exchanger designs to numerous industrial production systems, however, it has not yet reached a mini-fluidic processing technology within industry [9].

This work explores an alternative operating platform for multi-phase mini-fluidic contactors based on oscillatory flow reactor (OFR) technology previously reported for conventional-scale geometries. Through a theoretical analysis of the benefits and principles of operation of the OFR technology at reduced length scales, the potential performance of mini-fluidic geometries is explored and necessary geometry modifications discussed to take advantage of the oscillatory flow nature. The preliminary design of an experimental test platform of mini-fluidic OFR technology is being explored in the present investigation.

2. OFR Technology at Conventional Scales

The Oscillatory flow reactor has been involved in various chemical processing and operations since two decades. The OFT (Oscillatory Flow Technology) has been reflected as pulsation in extraction column. However, OFT is implemented in both smooth channels and micro channels. The literature reported that OFR technology has been successfully implemented in Trans-esterification of oils into biodiesel [11], protein refolding [12], Gas-liquid operations, crystallization and preparation of nanoparticle [13, 14]. The OFR technology resolves the design problem in the conventional tubular plug flow reactor such as long residence time, maximum Reynolds number, and long L/D ratio. The generation of Oscillatory, flow or pulsation flow in reactors affects the transport properties of the medium. An oscillatory flow or pulsation flow offers an efficient alternative means of agitation in much process equipment, which operates both batch and continuous process. Generally, the oscillation of fluid offer the formation and dissipation of eddies in the chemical reactors, which enhances the heat and mass transfer rates in the process equipment. In addition to that, the most important feature of oscillatory baffle mixing is that mixing can be controlled to a very high degree of precision, and offers a wide range of mixing conditions from soft mixing to very intense mixing in the process equipment. Furthermore, Oscillatory flow could be used to improve wide variety of chemical engineering unit operations and also in the process including heat transfer, mass transfer and multiphase mixing, particle suspension, plug flow operation in continuous reactors, filtration, bioreaction and fermentation [15,16].

2.1. Advantages of OFT in process equipment

Usually, the mixing process and efficient transport of heat and mass in any type of process equipment is highly expected. These expectations are achieved by operating process equipment in turbulent flow and by providing the baffles in the equipment.

Generally, external mixing is provided to enhance the rate of heat and mass transfer and to maintain the concentration gradient for chemical reaction takes place inside the reactor. An oscillatory flow offers an efficient alternative means of agitation that involved nowadays in many process equipment both batch and continuous process as well. Generally, the oscillation fluid offer the formation and dissipation of eddies in the chemical reactors, which enhance the heat and mass transfer rates in the process equipment. In addition to that, the most important feature of oscillatory baffle mixing is that mixing can be controlled to a very high degree of precision, and offer a wide range of mixing conditions from soft mixing to very intense mixing in the process equipment [17].

The oscillatory flow in the process equipment improves fluid mixing in the flow path. The movement of oscillating fluid interacts with each baffle to form vortices and eddies and the result gives efficient mixing and uniform distribution of substances. Usually, the oscillatory flow offers the increased heat transfer rate when it is implemented in heat exchangers equipped with baffled tube it industrial practice, Oscillatory flow in the heat transfer equipment increases the heat transfer coefficients with lower oscillatory Reynolds number in conventional tubular reactors. It is observed that the heat transfer rate increases with increase in oscillatory Reynolds number and Oscillatory flow mixing has a significant enhancement effect on tube side heat transfer, particularly in the low Reynolds number throughput regime, which would correspond to long residence times in the reactor [17].

In case of gas liquid contacting systems, the mass transfer coefficient is increased by the implementation of oscillatory flow in the mass transfer equipment. In addition to that, when oscillatory flow applies to the plug flow reactor, the optimum residence time distribution (RTD) would be achieved. Comparing with conventional tubular reactors, an OFR allows long residence times in a reactor, which has reduced length-to-diameter ratio [17].

2.2. Characteristics of Oscillatory flow

The motivation of development of OFR is to improve reaction performance such as mass transfer rates in chemical engineering operations. The Oscillating flow reactor is initiated by the tube fitted with orifice type baffles mounted transverse to the flow, which produces chaotic mixing in the flow path. The application of periodic fluid oscillations to a cylindrical column containing evenly spaced orifice baffles is the fundamental concept of OFT which functions by either batch or continuously in horizontal or vertical tubes. Sometimes, the oscillation and pulsation were created by means of diaphragms, bellows, or pistons, at one or both ends of the tube and sharp edge in the flow path. Though Oscillation and Pulsation increase the transport properties of the reaction medium, it was created by a column provided with periodic sharp constrictions called baffles and it produces oscillatory flow mixing and the eddies produced by the flow restrictions resulted into significant enhancement in transport processes such as heat transfer, mass transfer, particle mixing, separation, liquid –liquid reaction, polymerization, flocculation and also crystallization. OFR is not like as conventional reactors where a minimum Reynolds number should be maintained. Nevertheless, In OFR, the net flow was not affected by mixing phenomena, results in longer residence times in a reactor having reduced length to diameter ratio [17].

The mixing in an OFR is an efficient mechanism, where fluid moves from the walls to the centre of the tube and forms convention currents through eddy. The variables affecting mixing intensity are the oscillation frequency, f , and amplitude x_0 . The flow becomes progressively more complex as the oscillation frequency and amplitudes increase. So far, Oscillating equipment may be classified into motion of some intrinsic elements of the column and hydraulic transmission. The first one is reciprocating plate columns in which the pulsation is generated by means of an upwards –downwards motion of plates. The latter is typically generated by systems using positive displacement

pumps using either plug or membrane to introduce the feed into the column. In addition to that, the oscillation in pneumatic oscillating systems is generated by means of a pressurized gas, which propels the liquid contained in a parallel branch to column. "Another arrangement is self-propelled oscillators, where the liquid entering the columns, through a pulsation chamber results in fluid oscillations [1]"

The mechanism of Oscillatory flow mixing is explained in the [Figure 1](#) and [Figure 2](#). In these figures, the oscillation and eddies are produced by sharp edges in the tubes that are perpendicular to a periodic and fully reversing flow. The flow patterns of OF Mixing exhibit a complicated eddy-mixing pattern due to the presence of wall baffles. The nature of OF Mixing are characterized by a few fundamental dimensionless groups namely the classical Reynolds number Re , the oscillatory Reynolds number Re_o and the strouhal number Str [17].



Figure 1. Oscillatory flow in a baffled tube shows the formation of eddies in the fluid path and mechanism of mixing in Oscillatory baffle column. (With permission from A.P. Harvey, M.R. Mackley, T. Seliger. "Operation and optimization of an oscillatory flow continuous reactor" *Ind Eng Chem Res*, 40 [23] (2001), pp. 5371–5377)

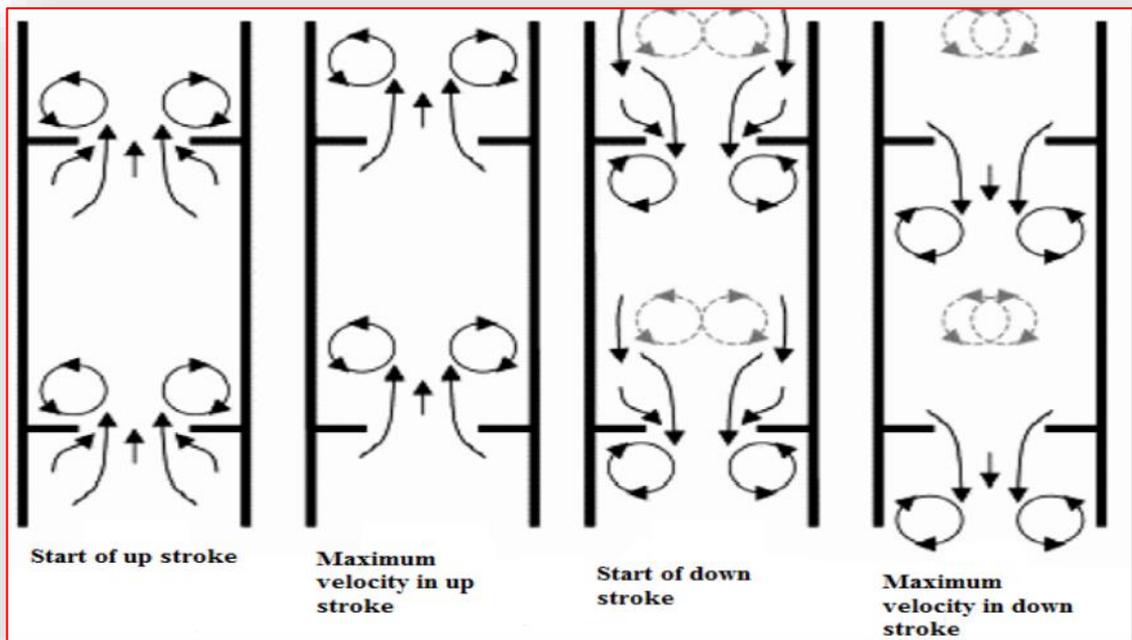


Figure 2. Different stages of Oscillatory flow in the channel. (With permission A.P. Harvey, M.R. Mackley, T. Seliger. "Operation and optimization of an oscillatory flow continuous reactor" *Ind Eng Chem Res*, 40 [23] (2001), pp. 5371–5377

2.2.1. Net Flow Reynolds Number

It is used as the indicator of the type of flow in question and captures all the parameters

$$Re = \frac{Du\rho}{\mu}$$

2.2.2. Oscillatory flow Reynolds number

$$Re_o = \frac{2\pi f x_o D}{\mu}$$

2.2.3. Strouhal Number

$$Str = \frac{D}{4\pi x_o}$$

The above dimensionless numbers are used to characterize the Oscillatory flow technology.

2.3. Heat Transfer in Oscillatory flow mixing

Usually, Heat transfer in forced convection in tubular systems depends on the flow conditions in the tube. When the flow is turbulent, the rates of heat transfer are relatively high due to the presence of radial mixing. However, there is an absence of radial mixing when the flow is laminar in tubes. So, the oldest way to improve the rate of heat transfer in the tubes is to use baffles or static mixer inserts which could modify the flow pattern,

and promote radial mixing as well as it improves the conductive heat transfer. However, this insertion could lead to design that is more complex in helical coil arrangements. Recent trends in process engineering have accepted the implementation of oscillator flow in the tubes, which promotes efficient mixing. When tubes are periodically baffled, then the oscillatory flow promotes heat transfer and chaotic mixing in the tube. Kiel and Baird concluded that the heat transfer is enhanced when oscillatory flow is implemented in tubes in the shell and tube heat exchanger. Further, Mackley et al observed that the oscillatory flow enhances the heat transfer and also a seven fold increase in tube side nusselt number in oscillatory flow arrangement in a tube to a low Reynolds number, Re , bulk flow ($Re < 200$) compared to steady un baffled flow. Mackley et al has been proved that oscillatory flow leads to a substantial enhancement in tube side heat transfer in a shell and tube heat exchanger. Further it has been observed that the greatest advantage of oscillatory flow appears to be found at low net flow Reynolds numbers (low tube flow rates) with 30 fold improvement in Nusselt number. Oscillatory flow is a novel method of mixing using a combination of regularly spaced sharp edges and a periodic reversing flow, which can offer process advantageous in both continuous and batch mode. It offers excellent radial mixing and controllable axial dispersion that enhances the heat transfer in process equipment. It concluded that the rate of heat transfer increases with increase in oscillatory Reynolds number when compared to the net flow Reynolds [17-19].

2.4. Mass Transfer in Oscillatory Flow mixing

Since 1996, the mass transfer has been investigated for reciprocating columns and oscillatory flow in baffled tubes. It has been noted that the oxygen mass transfer coefficient KLa is increased six fold times in the baffled tubes with oscillatory flow in oxygen water system. Further, the oscillatory flow is capable to mix two phases and produce effective mass transfer where diffusion is limited.

The OFR technology is successfully suitable for process intensification for various chemical and biochemical processes. Most of the process equipment developed from emerging technologies, and plant operations notably shrinks their size and drastically increasing their process efficiency. Process intensification is the novel method for process design that helps to lead to size reduction of process equipment or process plants by 10 or 1000 times.

In addition to that, Process intensification enables a dramatic increase in production capacity with in the given equipment volume. Further, it offers many advantages such as lower costs, energy efficient process, inherently safer design, and sustainable development. Oscillatory flow technology is one of the most process intensification method in the reactors and applicable to many process modification. In process industry, there is a potential for oscillatory flow mixing to be employed as compact and efficient tubular reactor and there is a more chance for process intensification in various chemical processes. There are many works exploited with oscillatory flow mixing and its reactor configuration.

It is observed that the oscillatory flow reactor improved both conversion and selectivity of reaction by improving the liquid mixing, residence time characteristics and thermal control. In addition, there are advantages of process intensification using reactor based on oscillatory flow mixing such as highly compact, continuous, parallel tube reactor configuration, versatile multi tube configurations (thermal profiling and multiple feed/product side streams), smaller L/D ratio than other conventional tubular reactors, fine control over the mixing, temperature profile, RTD, Solids suspension and size distribution. Due to handling of smaller volumes of reactants in the reactor, there is a significant improvement in process safety, especially in the case of exothermic reactions [1,17]

2.5. Implementations of Oscillatory flow in mini fluidics and microfluidics

Recent developments in mini and micro fluidic technology intensifies traditional chemical reactor technology has led to research in recent years on explores mixing at small length scales where traditional methods (agitation, turbulence) are either impractical or prohibitively expensive. Passive and active mixing strategies have been developed for this new scale of operation, ranging from static mixing geometries to ultrasonic vibration, and various methods. One challenge on many of these mixing processes is that the mixing cannot be controlled independently of process throughput, where many of the geometries have a limited operating region.

Limited research has been performed for oscillatory or pulsatile flow in minifluidics, partly due to a change in the mechanism of mixing. Therefore, this work explores the application of OFR technology to minifluidic scales based on a review of operating heuristics for OFR technology and the practical limitations in sub-millimeter geometries. The objective of this work is to analyze the induction of oscillating field in mini-channel and construction of oscillatory flow reactor and characterization of its hydrodynamic performance [20].

3. Scaling of OFR concepts to mini-fluidic scales

3.1. Theoretical Analysis of feasibility of Conventional Oscillatory Flow reactor into minifluidics

The requirement for any configuration of a chemical/biochemical reactor is the presence of efficient mixing to enhance heat and mass transfer as needed for the application of interest. Furthermore, an OF reactor is a combination of both flow oscillation and baffled tube configuration. It has the potential to ensure the efficient mixing and effective heat and mass transfer [1]. However, this technology has not yet been extended to mini-fluidic devices, and is being explored as a novel approach for enhanced mixing at reduced scales. This work explores the application of OF technology in minifluidics. As a preliminary step in the process intensification of OF technology in minichannels, The Nusselt number and pressure drop are predicted and compared to smooth pipes. Theoretical calculations of energy dissipation are compared with mixing existing mini-fluidic mixers available in literature, illustrating the need to develop novel mixing geometries [4].

The Conventional OFR has been used in many chemical processing and engineering applications such as biodiesel, protein folding and gas-liquid operations. It is observed that the Oscillatory motion creates eddies that lead to uniform efficient mixing than that of conventional Stirred tank reactor. Further, It has low and uniform shear, increased heat and mass transfer, compact design and easy to scale up. The present analysis proves that OFR in minichannel improves the momentum and heat transfer than smooth minichannel with absence of OFT.

3.1.1. Mini-fluidic contactors for Mixing

Mini/Micro-channels are used in a variety of devices incorporating single-phase liquid flow. The applications of minichannels/ micro channel are involved in various micro-machined devices such as micro-pumps, micro-valves, and micro-sensors. Additionally, Minichannels played a crucial role in the biological and life sciences for analyzing biological materials, such as proteins, DNA, cells, embryos, and chemical reagents. Mini-channels and Micro-channel acts as a plug flow reactors where two chemical species are mixed prior to introducing them into a reaction chamber/ contacting junctions. The hydrodynamic properties and heat transfer are enhanced through static mixing geometries. In addition to that, the wall surface effects are absent in liquid flows in mini/microchannels. The OF in the smaller flow passage could enhance the rate of heat transfer i a chemical reactor, and heat flux dissipation in microelectronic devices, higher heat transfer performance in the channels. However, the liquid flows at mini/micro scale

cause a higher pressure drop per unit length [21,22]. Figure 3 shows various contacting system in mini-fluidic system and applicable for multi-phase mini fluidics.

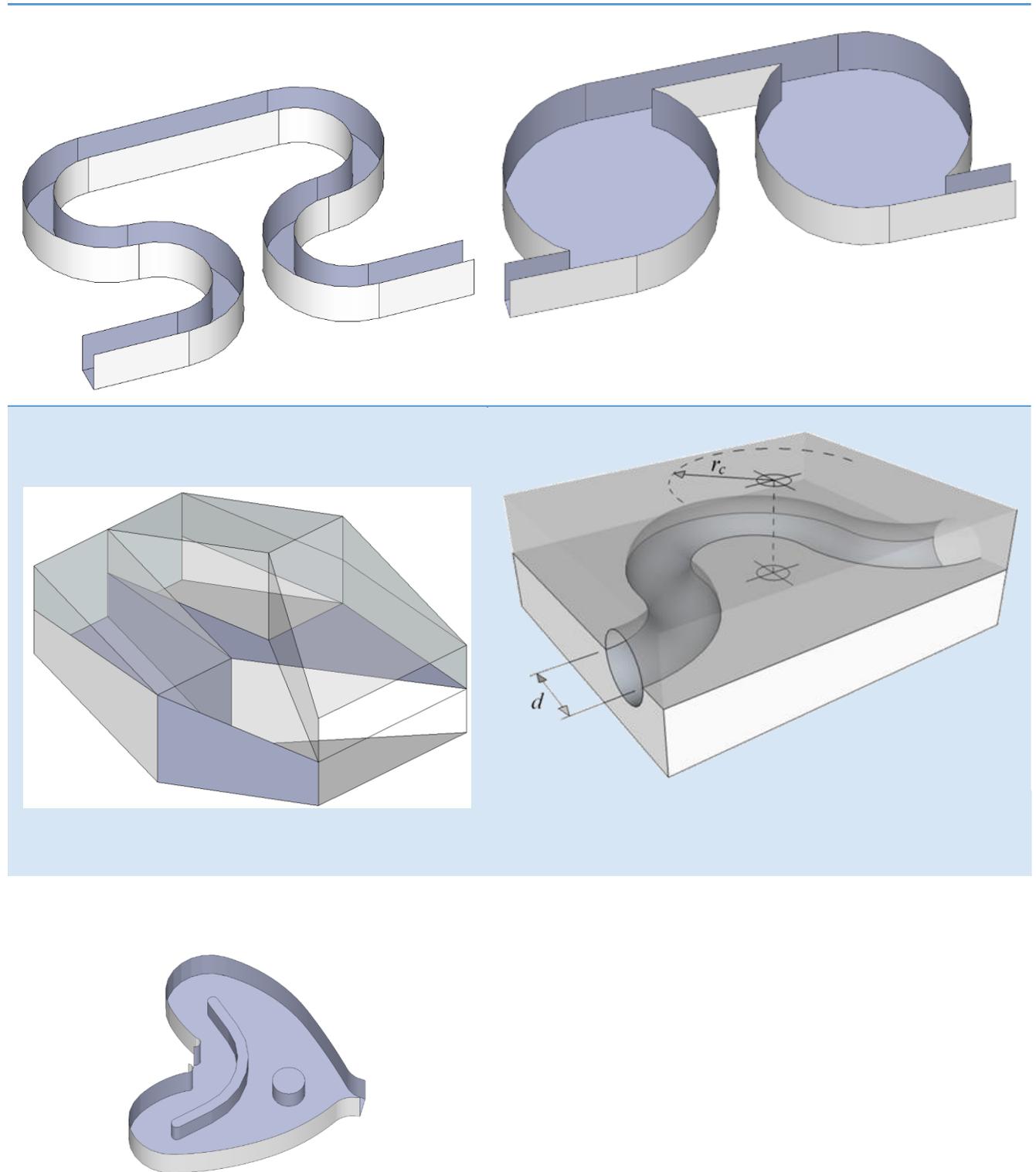


Figure 3. Various contacting system in mini-fluidic system and applicable for multi-phase mini fluidics (A.Donaldson and S.Kirubanandan, 2013) [28].

Figure 4 shows the concept of single-phase mini-fluidics containing three regions namely contactor, mixing region and reaction region. Contactor functions the onset of mixing two phases thoroughly and then it is allowed to pass into the mixing region. Mixing region has lowest residence time and cause high-energy dissipation due to various bends in the channels and diameter of the channel. The third section is the reaction region, which offers high residence time and low energy dissipation.

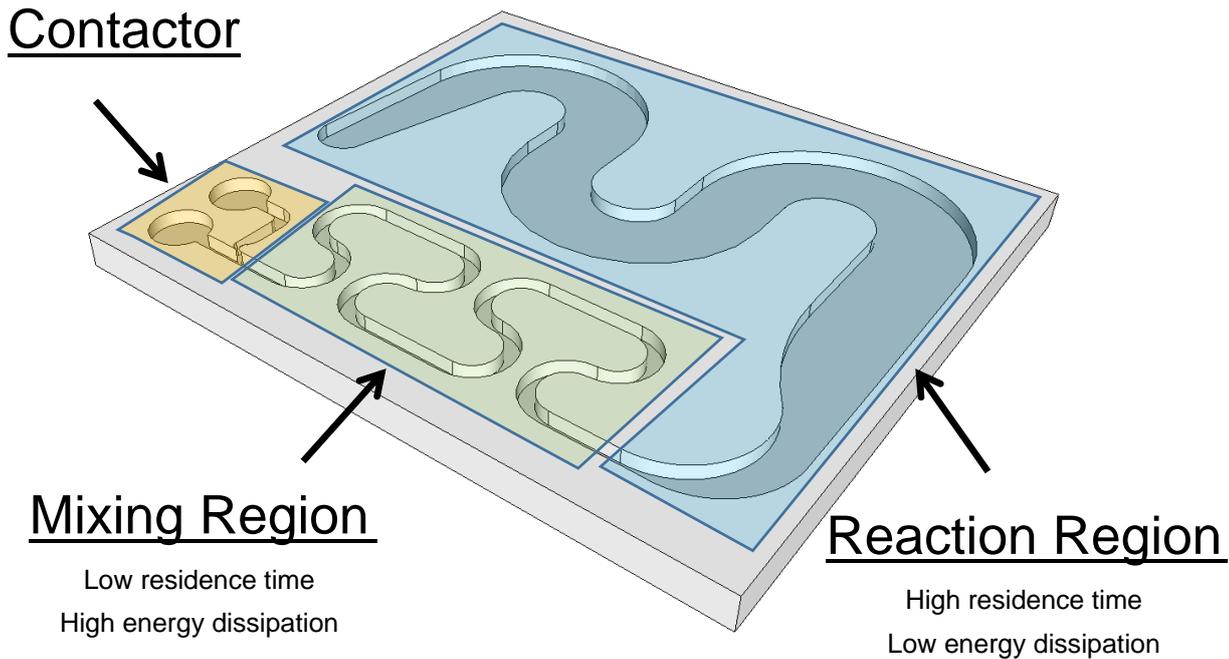


Figure 4. Single-phase mini-fluidics (A.Donaldson, S.Kirubanandan, 2013) [28].

3.2. Correlations Used

The present investigation outlines the preliminary feasibility studies to evaluate Oscillatory flow technology in miniaturized channel (Diameter of minichannel $\sim 1\text{mm}$ and orifice diameter $\sim 0.6\text{mm}$), exploring the effect of this miniaturized dimension on heat transfer coefficient and pressure drop in a minifluidic OFR [23].

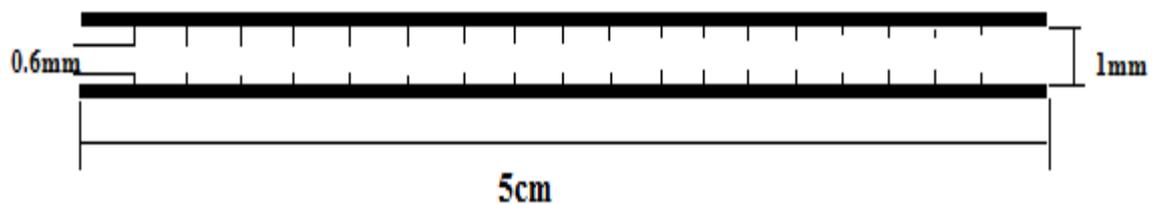


Figure 5. The prototype model of mini channel (Not to scale) (K.Shanmugam, 2013, 2016) [30,31].

3.2.1. Pressure Drop correlation for Smoothed Pipe Channel

The pressure drop for a minichannel is similar to the pressure drop in smooth pipes and it is a function of friction factor and velocity of the flowing fluid.

The Darcy Equation is given by [21,24]

$$\Delta P = f_D \frac{\rho u^2}{2} \frac{L}{D}$$

3.2.2. Pressure Drop Correlation for Conventional Oscillatory flow reactor

The pressure drop due to net flow through a baffled tube can be obtained by the standard equation for flow through an orifice modified to account for the summation of m_t (total number of identical baffles)[25].

$$\Delta P_{\max} = m_t \frac{\rho U^2}{2C_o} \left(\frac{1}{S^2} - 1 \right)$$

Additional forces such as Oscillation and Pulsation forces in the minichannel modify the above equation.

Similarly for conventional oscillatory flow (Ref. 1)

$$\Delta P_{\max} = m_t \frac{\rho (U + 2x_o f_o)^2}{2C_o} \left(\frac{1}{S^2} - 1 \right)$$

3.2.3. Energy dissipation equation for Conventional Oscillatory Flow reactor

The energy dissipation equation for OFR is given by and it is valid for struoughl number less than 0.2.

$$\varepsilon_v = \frac{2m_t \rho (x_o \omega)^3}{3\pi C_o^2 z} \left(\frac{1}{S^2} - 1 \right)$$

Str > 0.2, The equation will be

$$\varepsilon_v = \frac{3m_t \rho (\omega)^3 x_o^2 l}{Sz}$$

$$\varepsilon_n = \Delta P \cdot \frac{a_c}{V} \cdot U = \Delta P \cdot \frac{U}{Z} \cdot \zeta$$

The total power dissipation for a baffled tube subject to a net flow and an oscillatory flow is then found by the sum of the steady flow equation.

$$\varepsilon_t = \varepsilon_n + \varepsilon$$

3.2.4. Energy dissipation equation in Pipes

The power dissipation for a baffled tube can be obtained using the standard equations for fluid flow in rough pipes based on fanning friction factor.

$$\varepsilon_p = 2f_{fanning} \frac{(\text{Re}_{net} \mu)^3}{D^4 \rho^2}$$

This equation would be used by specifying a minimum Reynolds number to achieve sufficient mixing (e.g Re > 2100) and then to calculate the volume, length and diameter required to achieve the required throughput in order to compare the power dissipation and reactor length to an OFR of identical throughput.

3.2.5. Heat Transfer Correlation for Minichannel

The Nusselt number for laminar flow is 3.66. Within the transition region, it can be calculated as (Ref. 4)

$$Nu = 1.615 \left(Re Pr \frac{D}{L} \right)^{1/3}$$

3.2.6. Heat Transfer Correlations for Conventional Oscillatory Flow reactor

For conventional oscillatory flow (Ref. 5),

$$Nu = Pr^{1/3} \left[0.36 Re^{0.6} + 0.8 \frac{Re_o^{1.7}}{Re + 10000} \right]$$

For Conventional Oscillatory Flow Reactor

$$Nu = 0.0035 Re^{1.3} Pr^{1/3} \left[0.36 + \frac{Re_o^{2.2}}{(Re + 800)^{1.25}} \right]$$

3.3. Pressure Drop Correlation

3.3.1. Pressure drop and Heat Transfer in Micro/Minichannels

It has been observed that the heat transfer coefficient for fully developed laminar flow is unaffected in the minichannel/micro channel. The Nusselt number (Nu) for fully developed laminar flow in a square channel under constant heat flux conditions is 3.61.

It is given by

$$Nu = \frac{hD}{k}$$

$$h = \frac{NuD}{k}$$

However, the decrease in the diameter of the channel increases the heat transfer coefficient. In addition to that, the friction factor varies inversely with Reynolds number. Similarly, in heat transfer, The Reynolds number is constant for fully developed laminar flow. The frictional pressure drop per unit length for the flow of an incompressible fluid is given by:

$$\frac{\Delta P_f}{L} = \frac{2fG^2}{\rho D}$$

Where pf/L is the frictional pressure gradient, f is the Fanning friction factor, G is the mass flux, and ρ is the fluid density. For a fully developed laminar flow, it has been proved that the pressure gradient increases with decrease in channel diameter.

3.3.2. Single Phase Liquid Flow in Micro channels and Minichannels

3.3.2.1. Fully developed and developing turbulent flow

The following equation by Blasius is used extensively for determining the friction factor:

$$f = 0.0791 Re^{-0.25}$$

3.3.2.2. Energy Dissipation Rate for Minichannels

Energy Dissipation Rate for Tangential micromixer:

$$\text{Energy Dissipation Rate} = \frac{\Delta P \cdot u}{\frac{V}{A}}$$

Energy Dissipation rate is defined as the pressure drop multiplied by the ratio of superficial velocity to channel length.

3.3.2.3. For Single Channel with rectangular sections

The hydraulic diameter indicates the characteristic length for the flow through this cross section $A_c = bh$ and is determined for a rectangular cross section with perimeter P .

$$d_h = \frac{4A_c}{P} = \frac{2bh}{b+h}$$

For a circular cross-section, the square of the hydraulic diameter equals the geometry.

$$A_c = d_h^2$$

The cross sectional area of the rectangular channel $A_c = bh$ can be approximated by the square of the hydraulic diameter.

The hydraulic diameter can be correlated with the volumetric flow rate and the mean flow

$$d_h = \left(\frac{V}{w}\right)^{1/2}$$

$$\text{Re} = \frac{\rho d_h W}{\eta} = \frac{d_h W}{\nu}$$

3.3.2.4. Pressure Loss Coefficient

$$\zeta = N \frac{C_f}{\text{Re}^n} \frac{Li}{d_{H,i}}$$

$$\Delta P = N \frac{C_f}{\text{Re}^n} \frac{Li}{d_{H,i}} \frac{\rho}{2} W^2$$

$$\varepsilon = \frac{\Delta P V}{m}$$

The correlation for the pressure loss in the mixing channel is simplified to

$$\Delta P = N \frac{C_f}{\text{Re}^n} \frac{Li}{d_{H,i}} \frac{\rho}{2} W^2$$

3.4. Heat Transfer in minichannels

3.4.1. Norbert Kockmann et al, 2005 Heat Transfer in Bended micro channels

The higher Re numbers led to the formation of vortices in bed which in turn increases the heat transfer and Nusselt number.

$$Nu_q = 0.664 \text{Pr}^{1/3} \left(\text{Re} \cdot \frac{d_h}{L} \right)$$

With L as the length of channel. The equation is valid for the developing laminar flow in short channels and tubes with $dh/L > 0.1$.

3.4.2. Leveque's Equation

$$Nu = C_h (\zeta_{total} \cdot Re^2 \cdot Pr \frac{d_h}{L})^{1/3} \text{ for Single channel with rectangular cross section}$$

For fully developed laminar flow, the value of Nusselt number is constant and it is independent of flow rate

$$Nu = 3.656$$

For circular cross section and constant wall temperature, this value is also treated as good approximation for non-circular channels.

For laminar developing flow and transition region.

$$Nu = 1.615 (Re \cdot Pr \cdot \frac{d_h}{L})^{1/3}$$

The flow rate, fluid properties and entrance effects are expressed in terms of Reynolds number, prandtl number ($Pr = \nu a^{-1}$) and ratio of hydraulic diameter to element length respectively. Short channel elements have high heat transfer coefficient, while it decreases with increase in length. For turbulent flow:

$$Nu = 0.023 Re^{4/5} Pr^{1/3} (1 + (\frac{d_h}{L})^{2/3})$$

For $Re < 10$, the value of Nusselt number and constant heat flux is 4.2 and 3.66 respectively.

With an increase in Re numbers, Vortices develop at the entrance of the side channels and increase the heat transfer, which can be described with the flowing relations

$$Nu = 0.664 Pr^{1/3} \left(Re \cdot \frac{d_h}{L} \right)^{1/2}$$

For T Junction, Transition flow regimes

$$\frac{Nu}{Pr^{1/3}} = \frac{Sh}{Sc^{1/3}} = 0.404 (\lambda Re^2 \frac{d_h}{L})^{1/3}$$

This correlation is valid for turbulent flow ($Re > Re_{crit}$) and for a wide range of Pr and Sc numbers.

With transitional friction factor,

$$Nu = C_{Nu,trans} (Re^{5/3} Pr \frac{d_h}{L})^{1/3}$$

In turbulent flow, the friction factor is constant and Nu number becomes

$$Nu = C_{Nu,turb} (Re^2 Pr \frac{d_h}{L})^{1/3}$$

4. Data Analysis on OFT at Miniscale

4.1. Pressure Drop Vs Net flow Reynolds Number

Figure 6 illustrates the relation between Reynolds number and pressure drop in a OF reactor. It is observed from Figure 6 that the pressure drop of the Oscillatory Flow

Technology in minifluidics channel is increased with increase in Reynolds number. Compared to smooth pipe, the pressure drop is lesser in minichannels and it varies between 0 and 2500 across Reynolds number. The pressure drop in minichannel with OFT is increased by the additional forces such oscillation and pulsation of the flow. A sudden increase in pressure drop is found for the flow with Reynolds number less than 150 and gradually it stabilizes after 500. This could be due to increase of velocity of the flow and fluid frictions in the channel.

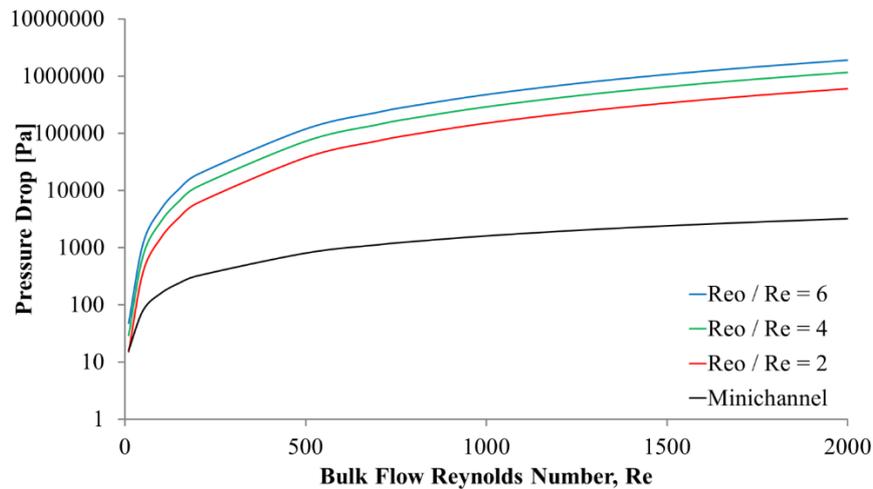


Figure 6. Pressure drop vs. Re for increasing Re_o/Re ratios for a 1mm diameter, 5cm long flow path containing 10 baffles with $S=0.36$ and $C_0=0.6$.

4.2. Heat transfer Analysis

From [Figure 7](#), it is observed that the heat transfer coefficient for minichannel with OFT is increased than that of smooth channel. The heat transfer coefficient is increased by oscillation and pulsation of fluids in the flow path. Moreover, Oscillation and Pulsation increases formation of the eddies which increase the convection currents and heat transfer coefficient [26]. During the oscillation and pulsation, the eddies formed due to oscillation and pulsation increase forced convection. As a result, the heat transfer coefficient was enhanced.

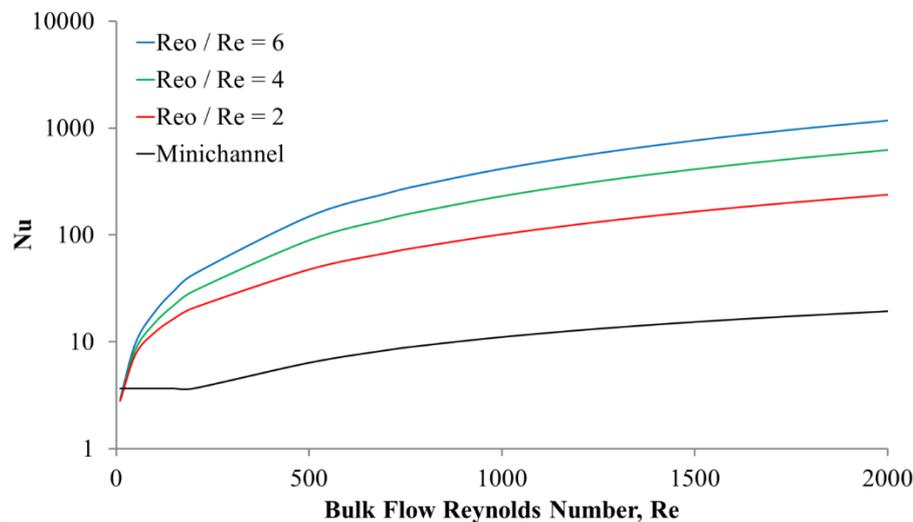


Figure 7. Nusselt vs. Re for increasing Re_o/Re ratios for a 1mm diameter, 5cm long flow path containing 10 baffles with $S=0.36$ and $C_o=0.6$. (The data collected from correlations on oscillatory flow reactor)

4.3. Energy Dissipation Studies

An increase in Nusselt number was predicted for OF in minichannels with increase in Re_o . It is observed from [Figure 8](#) that oscillation and pulsation creates eddies in flow path, enhances convection currents and heat transfer. An interesting point of note is that the energy dissipation required (i.e. pumping requirements) to achieve an equivalent increase in Nu becomes higher as the intensity of oscillations increase. This would suggest that the most efficient OFR technology would create the eddies at the lowest possible Re_o/Re ratio. The development of mixing geometries which are specifically designed to take advantage of the pulsating flow is thus of interest. The pressure drop predicted within the test case is reasonable, and can be achieved using the newly constructed experimental system

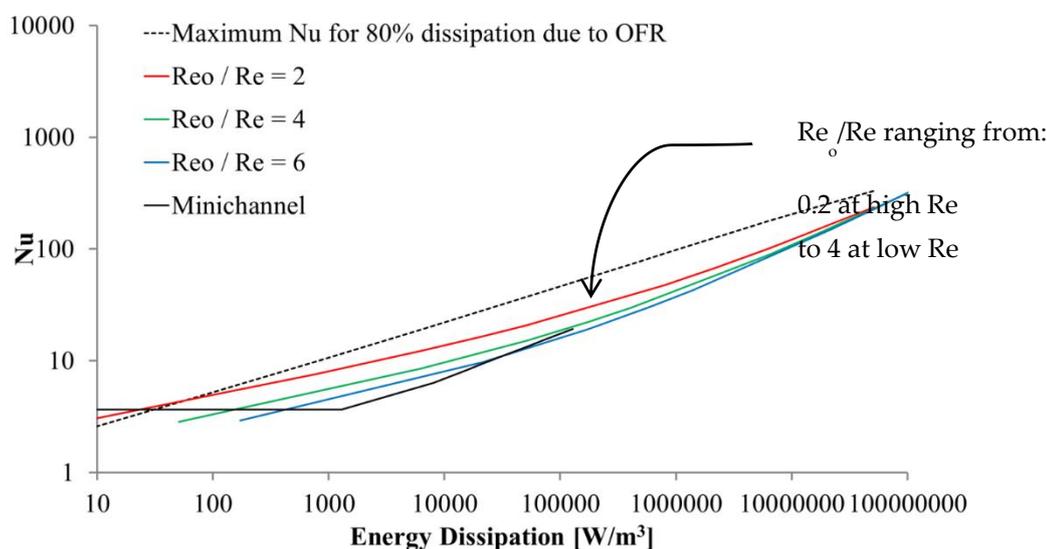


Figure 8. Nusselt vs. Energy Dissipation for increasing Re_o/Re ratios for a 1mm diameter, 5cm long flow path containing 10 baffles with $S=0.36$ and $C_o=0.6$.

4.4. Comparison with other Geometries

[Figure 9](#) shows the energy dissipation studies compared with the heart shape geometry which has the hydraulic radius of 0.67 mm. Corning “Heart” reactor consists of internal curve and distanced cylindrical stem. This reactor has complex geometry and capable of producing intensive mixing of the fluids. At lower energy dissipations, OFR’s have the potential to offer significant heat transfer performance improvements. When comparing with corning heart reactor, OFR is good for heat transfer performance improvements at lower energy dissipations and a potential alternative for commercial minichannel reactors like corning heart reactor.

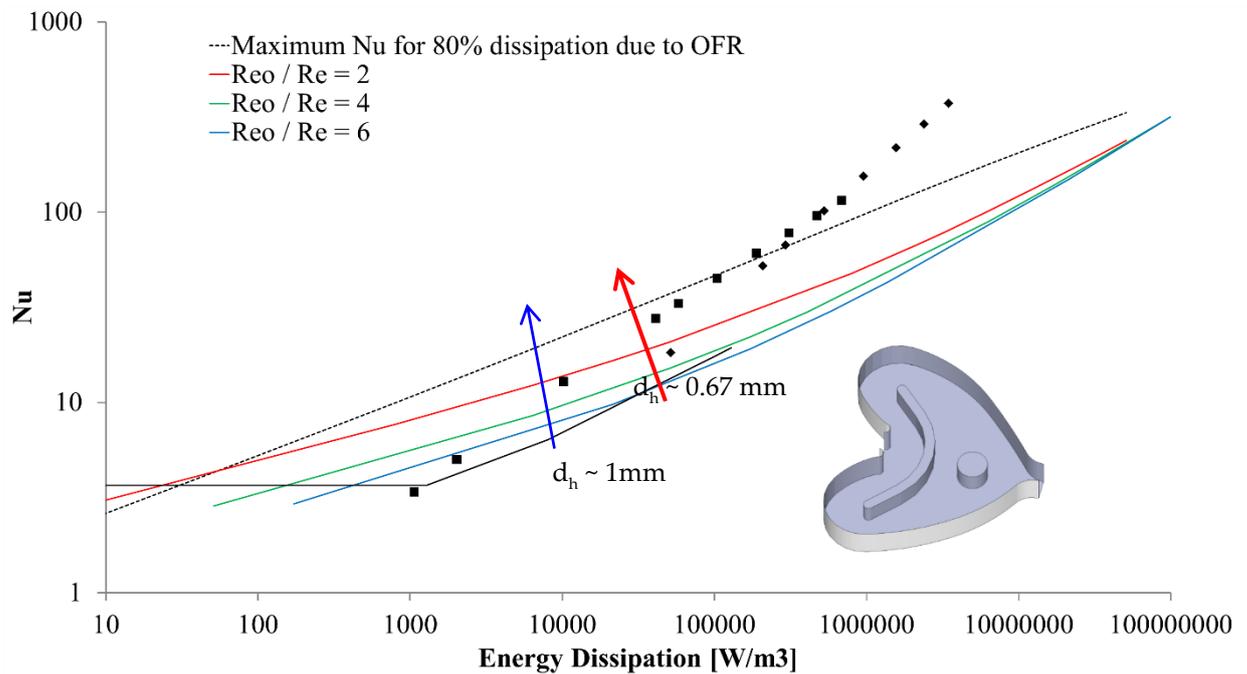


Figure 9. Comparison to other geometries (Data from Plouffe P., Anthony R., Donaldson A., Roberge D.M., Kockmann N., Macchi A., ICNMM 2012) [28,29]

5. Experimental Analysis

The present experimental investigation deals with Development and characterization of a “high-frequency” oscillating pressure field generator (0 to 30 hz) with significant displacement capabilities. The experimental analysis of contactor designs specifically for Oscillatory flow should be performed. Figure 10 shows the design of coupled high-speed switching device for alternating the pressure field. It works Resistance model & characterization of flow (fluid displacement vs. time under oscillatory conditions).

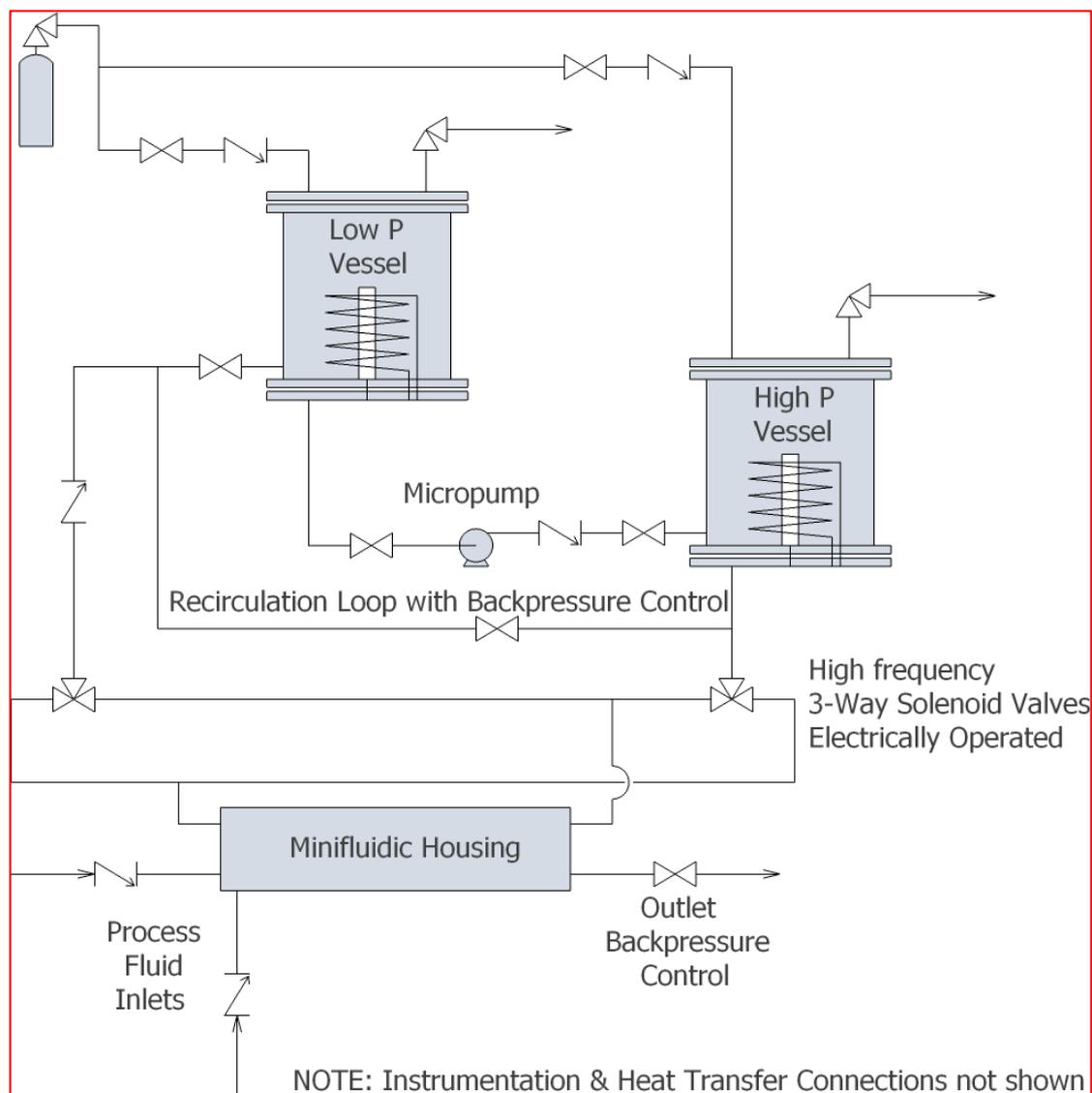


Figure 10. Experimental Setup of Oscillatory Flow System.

Figure 11 shows the rotating valve for producing oscillation and pulsation flow in the fluid line of the experimental set up. In this valve configuration, the oscillation and pulsation was produced by the rotation of the valve either in forward or in backward direction. The pressure-driven flow is used to avoid potential cavitations. The rotation of valve produces the oscillatory flow in the flow path. The performance of Oscillation depends on the rotation and absence of fluid leakage in the valve assembly. In addition to that, the physical property of the fluid such as density and viscosity also plays a major role. The curve for pump in the experimental set up and valve positioning in the experimental setup was added in the [supplementary information](#). With these information, the following plots have been developed.

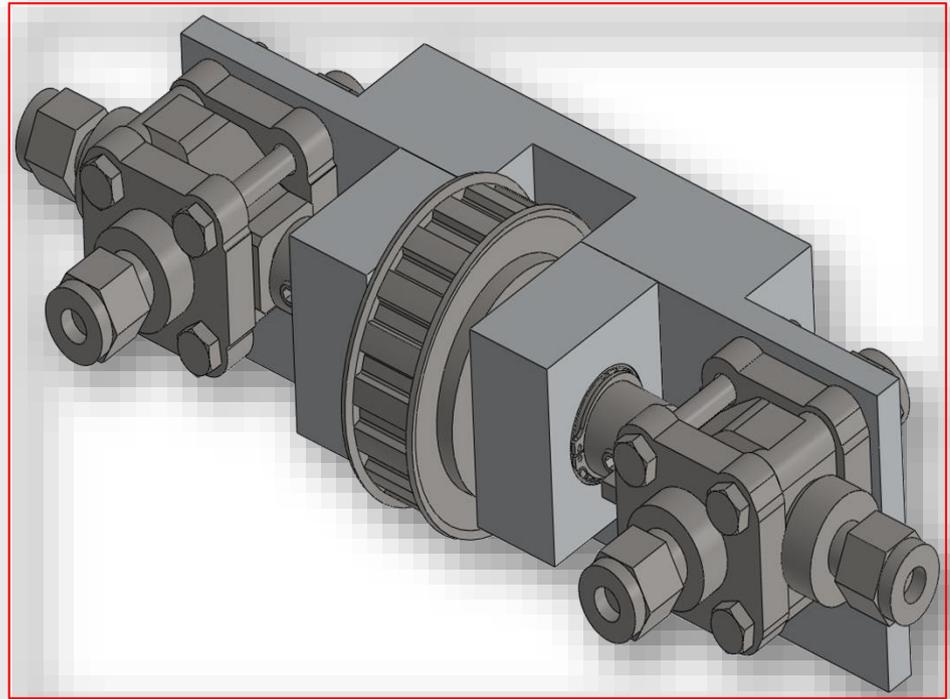


Figure 11. Valve for creating oscillatory flow in fluid line in the experimental set up.

The graph (Figure 12 and Figure 13) confirms that the experimental setup produces the oscillation and pulsation in the flow path. However, the outcome of oscillation is noisy due to leakage of liquids in the valve assembly while rotating. In addition to that, Generated Oscillatory flow at two different frequencies (1.17 hz and 2.93 hz) $Re_0 = 8731$, based on the L/d estimated for both flow paths between sensors and pressure-based flow assumptions.

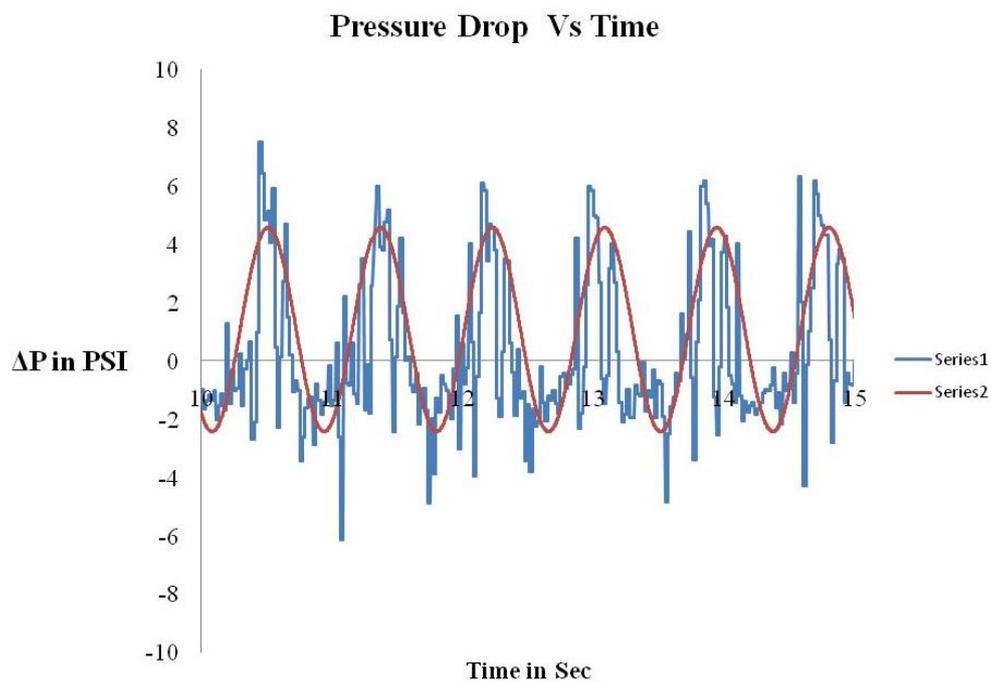


Figure 12. Pressure gradient created by the experimental set up at 69 RPM and 1.17 Hz.

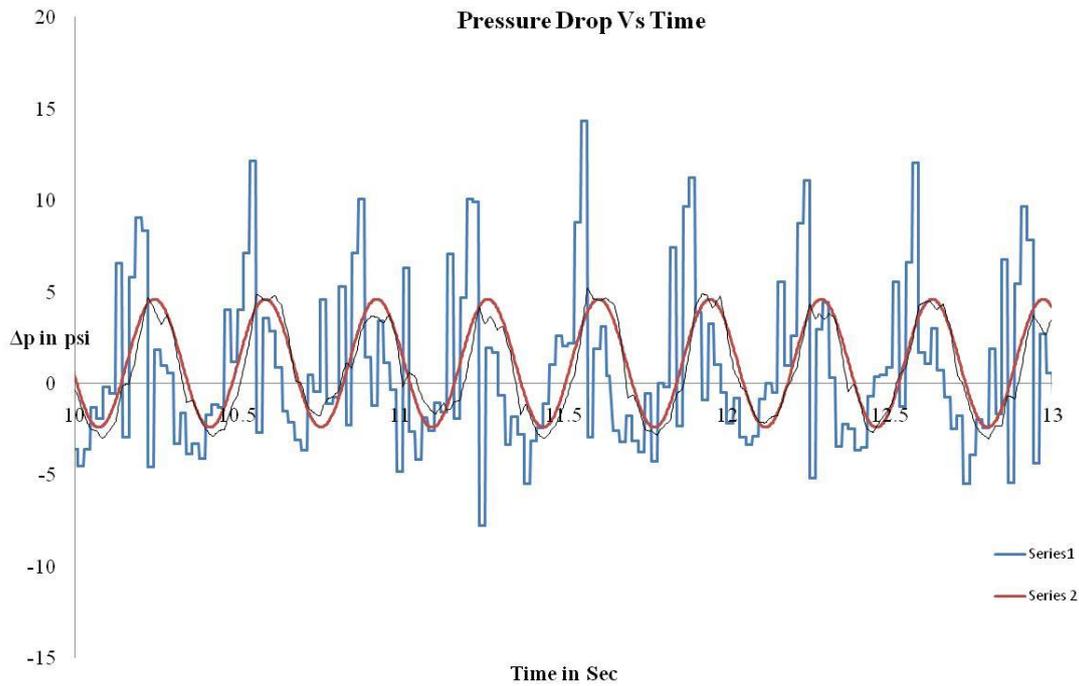


Figure 13. Pressure gradient created by the experimental set up at 175 RPM and 2.93 Hz.

6. Discussion

“The minichannels are required to bring these services such as a fluid into intimate contact with channel walls and bring fresh fluid to the walls and remove fluid away from the walls as the transport process is accomplished [21]”. The transport properties of fluids are affected by the configuration and dimension of the channel. For an instance, the decrease in diameter of channel and the increase in surface area/volume ratio are advantageous for better transport process. However, in the chemical engineering point of view, even though the channel size becomes smaller, some of the conventional theories should be revised to evaluate the better performance of the transport processes. In addition to that, there are some deviations to validate the process in the mini/micro channels such as entrance and exit loss coefficients and measurement of certain parameter at micro scale. The present investigation proves that the implementation of Oscillatory flow technology in minichannels enhances the momentum and heat transfer process such as pressure gradient and heat transfer coefficient respectively and the minichannels would be operated by OFT with expected energy input.

7. Conclusion

From the present investigation, it was found that that rotating valve assembly was able to generate an oscillatory pressure field that could potentially apply in the low energy dissipation region. The preliminary feasibility of OFT in minichannels has been investigated and theoretical analysis suggests that the OFT in minichannels showed an increase in Nusselt numbers at equivalent energy dissipation relative to a smooth pipe at reduced dimensions. The design of mini-fluidic channels specifically for oscillatory flow was performed and tested experimentally to evaluate momentum, heat, and mass transfer performance relative to both a smooth pipe, and minifluidic contacting devices. A number of challenges still exist in its use, specifically in terms of inducing net flow, avoiding leaks, and characterization at higher oscillation frequencies with signal noise.

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