NET FLOW CHARACTERISTICS INSIDE AN OSCILLATORY REACTOR EQUIPPED WITH 3 ORIFICE BAFFLES

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NOMENCLATURE

d	[m]	Orifices diameter
D	[m]	Tube inner diameter
l	[m]	Baffles's separation
U	[m/s]	Bulk velocity
ρ	[kg/m^3]	Density
μ	[kg/(m·s)]	Dynamic viscosity
Re	[-]	Net Reynolds number, $Re = \rho U D/\mu$
Re_{osc}	[-]	Oscillatory Reynolds number
Nu	[-]	Nusselt number

ABSTRACT

Oscillatory Baffle Reactors (OBR) are often found in industrial processes. This type of device is specially intended for chemical reactions with high residence time and moderate or high mixing requirements (usually achieved by increasing the Reynolds number). In order to meet both objectives, a standard pipe heat exchanger would be too big. Therefore, OBRs are designed to produce, on the one hand, a low Reynolds number net flow, which results in a high residence time, and, on the other hand, an oscillatory flow is superimposed to increase mixing. This last effect is enhanced by inserting baffles into the pipe, so that their presence, together with the oscillatory flow, produce high pulsating radial velocities to optimize mixing. Besides, as an additional benefit, heat transfer enhancement due to the enhanced convection is also expected.

Prior studies have proved OBRs to be very effective for the mentioned objectives, and annular baffle designs have been studied in depth. However, to date, there are only preliminary studies regarding other baffle geometries.

The present work presents a complete study of an oscillatory reactor which uses three orifice baffles. The study combines different experimental techniques which provide a full overview of the flow field and its characteristics.

INTRODUCTION

Heat transfer enhancement has being long studied. Active and passive combined techniques are gaining relevance [1; 17], finding remarkable potential applications. This is the case of the Oscillatory Baffled Reactors (OBR) which are usually applied to chemical processes with a high residence time [13], where the combined technique allows the flow to achieve a good mixing. A conventional tubular reactor would require high Reynolds numbers to operate under turbulent flow conditions, which are needed to achieve good radial mixing. However, the former would imply a high bulk velocity and, consequently, an extremely long tube in order to fulfil the high residence time requirement. This problem can be solved by using a combined technique: a set of equally-spaced baffles is introduced in the tube and an oscillatory flow is superimposed on a low net flow. The combination produces a flow characterized by cyclic vortex dispersion upstream and downstream of the baffles. As a result, heat and mass transfer augmentations can be achieved.

Flow patterns are one of the most studied aspects in OBRs. The aim is to identify the influence of the operating conditions on the onset of the flow asymmetry and the chaotic behaviour. The first noteworthy study dates from 1989, when Brunold ([2]) tested several baffle spacings: $l = 1 - 2D$. They observed that the flow oscillation generates vortices downstream of the baffles during both oscillation half cycles, causing an intense mixing. The authors identified the optimal baffle spacing at $l = 1.5D$, a value which is currently a reference for the OBRs design.

Mackay ([6]) performed the first study focused on the instability in OBRs. By using a qualitative flow visualization technique, the authors collected in a map the flow behaviour (asymmetric or not) as a function of the oscillatory Reynolds number, Re_{osc}, and the Strouhal number, St. The equations for both dimensionless numbers are included in the Nomenclature section. For the range of Strouhal numbers tested ($0.3 < St < 2$), the flow was asymmetric at an oscillatory Reynolds number of order 200.

During the past two decades there was a rise in the number of publications related to OBRs, introducing quantitative techniques such as CFD or PIV [12], in contrast with the qualitative visualization performed in previous studies. The main purpose of these studies was the study of the flow patterns, but with some chemical aspects as main goal, e.g., the scale-up [4], mixing and axial dispersion [9] or the viscosity effect on mixing [3]. It should be remarked that all of them were focused on the pure oscillatory flow, so they did not provide information about the net-oscillatory flow interaction.

Fitch ([3]) studied the flow patterns in a baffled tube, for a range of $Re_{osc} = 6 - 5500$ and $St = 1.0$, using PIV and CFD. The authors found a 'channeling' effect with an inefficient vortex formation at very low oscillatory Reynolds numbers, $Re_{osc} = 6$, the symmetrical vortex formation at moderate intensities, $Re_{osc} = 20 - 150$, and the onset of an asymmetric flow at higher values, $Re_{osc} = 500 - 1000$. The effect of the flow patterns on the mixing was studied by the introduction of a new parameter, the axial-radial velocity ratio. This parameter took high values at low Re_{osc}, pointing out a poor mixing due to the prevalence of the axial component of the flow over the radial. The axial-radial velocity ratio decreases sharply with the oscillatory Reynolds number up to a value of ≈ 2.

One of the studies mainly focused on the flow behaviour was performed by Zheng ([16]). The authors developed a 3D model, which was validated with PIV results. The model is used to obtain a two-dimensional map which shows the level of flow symmetry as a function of the Strouhal number and the oscillatory Reynolds number, i.e., pure oscillatory flow conditions. The authors observed that the maximum oscillatory Reynolds number at which the flow becomes asymmetric is 225, at a Strouhal number of 1.0. For $St < 0.5$, there is a reduction of the critical oscillatory Reynolds number. At $St = 0.1$ the asymmetry can be seen at $Re_{osc} = 100$. It is finally highlighted that, in spite of not being a clear correlation, there is a connection between the flow asymmetry and the mixing intensity.

Another aspect which has been a focus of attention since the OBRs conception is heat transfer. It has been motivated by the need of a right sizing of thermal circuits for heat addition or removal when endothermic or exothermic reactions take place in the OBR, or when the temperature is a key factor for the reaction.

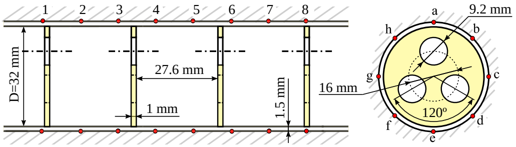
Mackley ([8]) studied heat transfer in a tube with equally-spaced one-orifice baffles. The range of dimensionless numbers tested was a Prandtl number of 124, a net Reynolds number, Re, between 100 and 700 and an oscillatory Reynolds number of 200-1600 (for a given net Reynolds number). The main conclusions were: 1) under steady flow conditions the baffles imply a significant heat transfer augmentation in comparison to a smooth tube, 2) under compound flow conditions (net and oscillatory flow) the effect of the oscillation on heat transfer was limited in the absence of baffles, while there was a significant increase for the baffled tube. Mackley ([7]) extended the previous study, carrying out two experimental campaigns: the first focused on the study of the oscillating amplitude, and the second on the superposition of the net and the oscillatory flow. Regarding the amplitude, the effect on the Nusselt number was found to be moderate, with a slight increase for lower oscillating amplitudes (and the same maximum oscillatory flow velocity). The authors confirmed that an increase on the Re or the Re_{osc} imply a higher heat transfer rate. They found that at high net Reynolds numbers, i.e., when the velocity ratio Re_{osc}/Re is reduced, all the results converged to the steady flow results ($Re_{osc} = 0$). The research group P4G [14], from Cambridge University, studied the heat transfer in OBRs obtaining similar conclusions.

Law ([5] studied a similar OBR under cooling conditions and constant wall temperature. The tested ranges were: $Re = 200 - 1400$, $Re_{osc} = 0 - 2700$ and $Pr = 4.5 - 9$. The authors found that, for all the net Reynolds numbers tested, at high values of the oscillatory Reynolds number the Nusselt number converged to a given value. According to the authors, this observation could be related to the minimum axial dispersion observed by Smith ([15]) in the range of oscillatory Reynolds numbers 800-1000. Above that range, the radial mixing and the perturbation of the boundary layer would not rise.

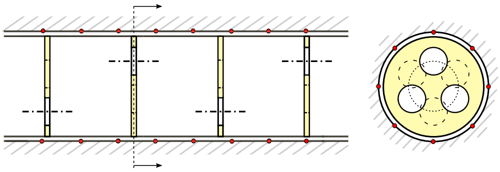
Regarding the heat transfer studies pointed out in this introduction, the minimum net Reynolds number tested is of the order of 200, a value which has been identified as the critical net Reynolds number for baffle inserts in recent studies [10]. Therefore, it would be interesting to extend the tested ranges to conditions where the net flow would be laminar and, consequently, there would exist a poor heat transfer under steady flow conditions.

This work presents a rigorous experimental study of the net flow through a three-orifice baffled tube, using different experimental techniques: heat transfer characterization and flow field visualization. Heat transfer has been measured under uniform heat flux conditions. The study is focused on analyzing the flow pattern characteristics and relating it to the device's heat transfer performance. Besides, two arrangement of the three orifice baffles have been analyzed for comparison purposes.

EXPERIMENTAL SETUP AND PROCEDURE



(a) Aligned baffle arrangement.



(b) Opposed baffle arrangement.

Figure 1: Geometry of the studied device and thermocouple disposition (thermohydraulic facility) for two different baffles arrangement.

To begin with, the device under test (Figure 1) is described. It consist of a $D = 32$ mm diameter pipe with equally spaced inserted baffles. Each baffle has three $d = 9.2$ mm orifices and the baffles' separation is equal to three times the orifices' diameter, $l = 3 \times d$. The two different baffle arrangements are shown in

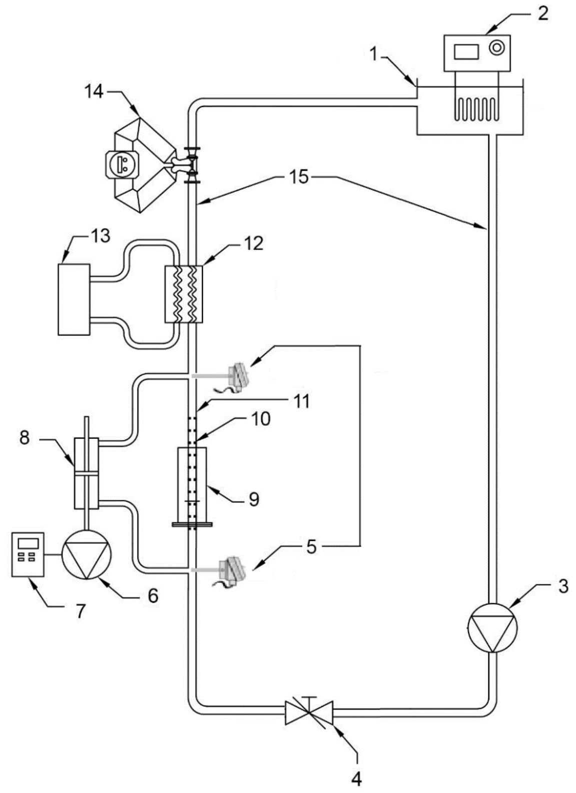


Figure 2: Sketch of the experimental facility. Elements: (1) reservoir tank, (2) electric heater, (3) circulating pump, (4) flow control valve, (5) RTD temperature sensors, (6) piston propelling assembly, (7) frequency converter, (8) piston, (9) visualization tank with surrounding acrylic box, (10) insert device, (11) acrylic pipe, (12) heat exchanger, (13) high precision cooling machine, (14) Coriolis flowmeter, (15) loop pipes.

the figure. In the first arrangement (see Fig. 4a), every baffle has the same angular position. In the second one (see Fig. 4b), the baffles' angular position changes 180° for consecutive positions.

In this work, two experimental facilities have been used: a visualization facility and a thermohydraulic one.

The visualization facility is depicted in Fig. 2. It was built in order to study the flow pattern in a circular tube with equally spaced insert baffles, by using Particle Image Velocimetry. The piston (8) of the sketch is not used for this work.

Cooling is provided through a plate heat exchanger by a high precision cooling machine. Heating and final working fluid temperature control is carried out by an electric heater located in the upper reservoir tank. A Coriolis flowmeter and a control valve are used to control and monitorize the working flowrate.

A 1280x1024 pix CMOS camera and a 808 nm laser are used for particle image velocimetry visualization (PIV) of the flow symmetry plane. With this aim, the flow is seeded with 57 microns polyamide. Besides, the camera has been equipped with MACRO (x10) lenses in order to increase the image quality and resolution.

The test section consists of an acrylic tube with the insert baffles, which are fixed by three aluminium rods. The use of the rods has been avoided in the visualization tank for better results.

Flow visualization has been accomplished using Particle Image Velocimetry (PIV) within the symmetry plane of the tube. The camera viewed the illuminated plane from an orthogonal direction and recorded particle images at two successive instants in time in order to extract the velocity over the planar two-dimensional domain. A 1 mm thick light sheet is created by a pulsating diode laser. A computer synchronizes the camera shutter opening and the laser shot at sampling frequencies between 20 and 200 Hz. The criterion for an experiment to be considered valid is to obtain a Signal-to-Noise-Ratio greater than 2 for more than 90% of the interrogation areas in a PIV processed image pair.

The thermohydraulic facility is shown in Fig. 3. It consists of three independent circuits. The second and third circuits are used to regulate the temperature of the reservoir tank (1). Test fluid was pumped from the open reservoir tank (1) by a train of three variable-speed gear pumps (2), which worked individually or simultaneously during the tests. The flow rate was measured by a Coriolis flow-meter (3). The baffles are installed in the main circuit (5). The test section was a thin-walled, 2 m long, 316L stainless steel tube with 37 equally-spaced insert baffles. The inner and outer diameters of the tube were 32 mm and 35 mm, respectively. Pressure drop is measured by a set of highly accurate capacitive differential pressure transducers (8).

Heat transfer experiments were carried out under uniform heat flux (UHF) conditions. The tube was heated by Joule effect through AC in the tube wall. Power was supplied by a 6 kVA transformer (9) connected with copper electrodes to the tube. A variable auto-transformer was used for power regulation. The loop was insulated by an elastomeric thermal insulation material to minimize heat losses. The overall electrical power added to the heating section was calculated by measuring the voltage between electrodes and the electrical current. Fluid inlet (4) and outlet (7) temperatures were measured by submerged type RTDs (Resistance Temperature Detector). A total of 64 thermocouples were installed at the test section (6) at 19.5D from the first thermocouple to ensure fully developed thermal conditions. The thermocouples are installed in groups of eight (varying their angular position) at six axial positions.

An uncertainty analysis has been carried out for the thermohydraulic experiments, baring into account the uncertainty of measurements and the number of experimental results to be averaged out. The methodology is detailed in [11]. The obtained average and maximum uncertainties, respectively, are of 3.4% and 4.9% for the Reynolds number and 7.1% and 11.5% for the Nusselt number.

RESULTS

Firstly, particle image velocimetry visualization technique has been applied to obtain the isothermal flow pattern within the two geometries under study, depicted in Fig. 1. The results for $Re = 440$ are shown in Figure 4. For both sub-figures (a) and

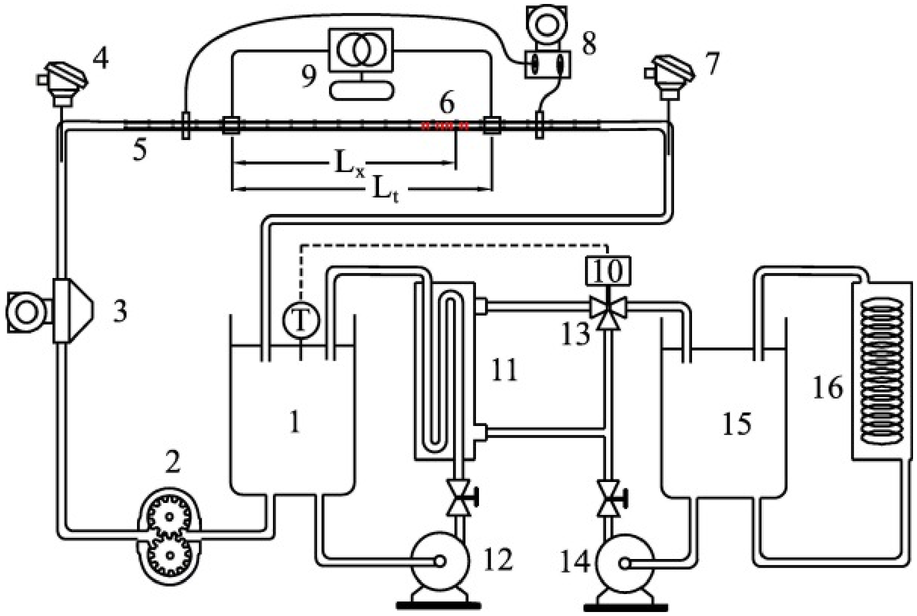


Figure 3: Experimental set-up. (1) Reservoir tank, (2) Pumping system, (3) Coriolis Flowmeter, (4) PT-100 Class B 1/10 DIN temperature sensors, Inlet, (5) Baffles, (6) Wall thermocouples, (7) PT100, Outlet, (8) Pressure transducer, (9) Autotransformer, (10) PID Controller, (11) Heat Exchanger, (12) Centrifugal Pump, (13) Three way valve, (14) Centrifugal Pump, (15) Reservoir tank, (16) Chiller.

(b), the arrangement is the same, the graph on the left side shows the average flow field, while the other two show instantaneous flow fields. As we can observe, in both geometries conditions are not stationary, the flow changes in time and shows turbulent nature characteristics, with temporary vortex formations. On the one hand, for the aligned baffle geometry, the average flow field shows a dominating jet which links consecutive baffle holes and a recirculation on the other side. On the other hand, for the opposed geometry a strong jet is also observed downstream the baffle whole, but dissipates at around the middle section of the inter-baffle gap. Besides, for the opposed baffle arrangement, the fluid path is longer, due to the required change of direction caused by the misalignment.

Secondly, pressure drop test have been carried out for the device under study. The isothermal flow has been measured for Reynolds numbers ranging from 10 to 1000 for the two geometries under study. Fig. 5 shows the results for the aligned baffles' arrangement in black and for the opposed one in blue and red. For both cases, a significant change in the flow is detected: laminar flow is observed for low Reynolds numbers and transitional and turbulent regimes are also be identified (in accordance with visualization results). For the aligned geometry, transition to turbulence happens at about $Re = 90$, while it happens for lower Reynolds numbers ($Re = 50$) for the misaligned geometry. For both cases, the flow is fully turbulent for $Re = 440$ in accordance with visualization results.

Finally, Fig. 6 shows Nusselt number results in uniform heat flux conditions for both geometries in $Re \in [50, 1000]$. While a clear change in the Nusselt number trend is detected due to the flow regime transition for the aligned geometry, the same is not true for the misaligned one. A probable explanation for this, is the implicit high fluid mixing in the misaligned geometry even at low Reynolds numbers, due to the direction changes caused by the holes' misalignment. In fact, heat transfer rates are significantly higher in laminar conditions for the opposed baffles' arrangement than for the aligned one.

The errorbar in figures 5 and 6 represent the 95% confidence interval for the represented results according to the uncertainty analysis.

CONCLUSION

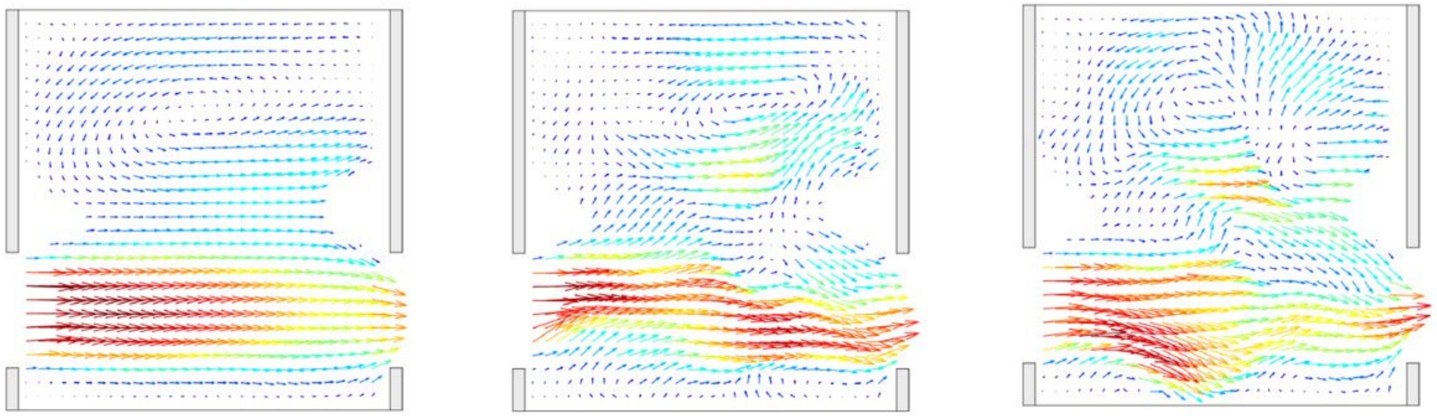
The work presents a full experimental study of the net flow inside a specific design of Oscillatory Baffle Reactor which consist of a smooth pipe with inserted baffles, having each baffle three holes. Experiments have been carried out for two different baffle arrangements.

For the first one, the three holes are aligned between consecutive baffles.For this case,

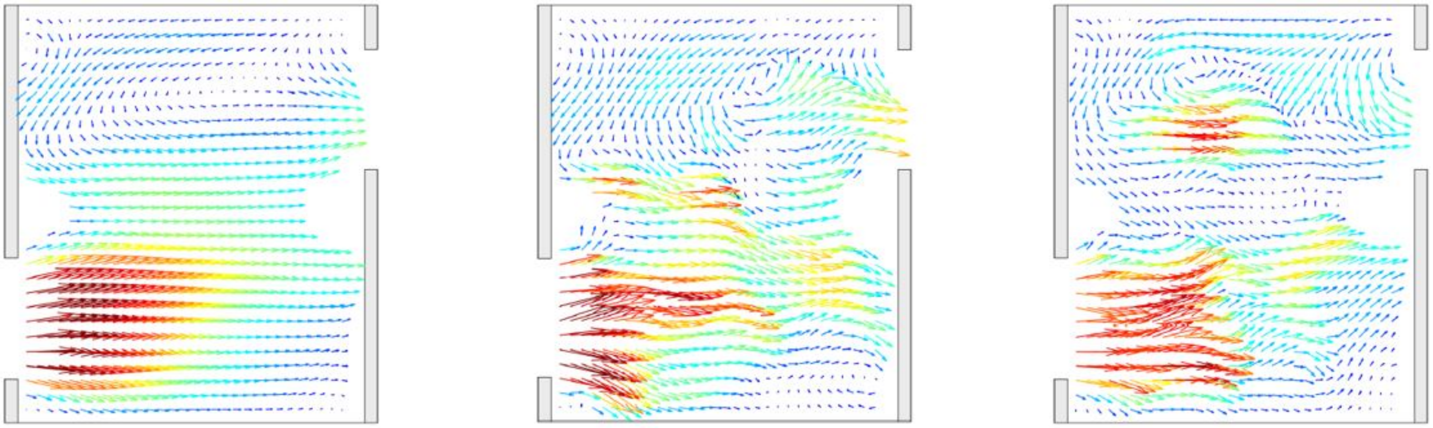
1. The flow pattern is dominated by a strong jet formation which connects consecutive holes, and the recirculation produced by it in the surrounding areas.
2. Pressure drop results show that the flow regime changes from laminar to turbulent at about $Re = 50$.
3. A change in the Nusselt number trend, with an increase in the heat transfer rate, when the flow becomes of turbulent nature.

For the second geometry under analysis, the three holes baffles are placed in opposed positions for consecutive baffles. The results in this case show that:

1. A strong jet is also formed downstream the baffles wholes, but it dissipates at around the intermediate position between



(a) Aligned baffle arrangement. Left: average flow pattern; center and rigth: instantaneous flow patterns.



(b) Opposed baffle arrangement. Left: average flow pattern; center and rigth: instantaneous flow patterns.

Figure 4: PIV velocity fields at $Re = 440$ for the geometries under study.

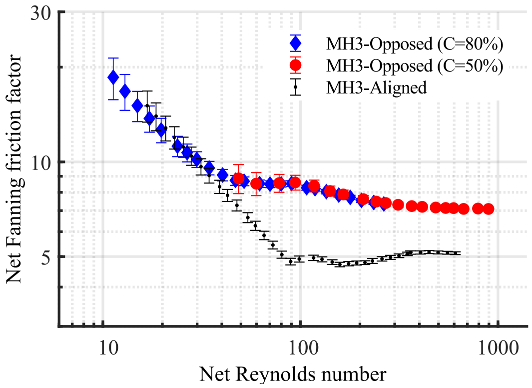


Figure 5: Net Fanning friction factor vs net Reynolds number for both MH3 baffle types .

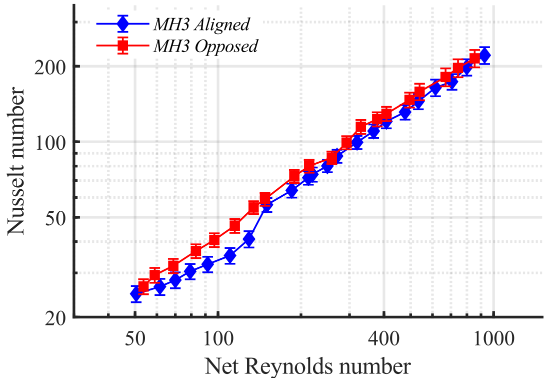


Figure 6: Nusselt number vs net Reynolds number for both MH3 baffle types .

consecutive baffles, due to the required change of direction caused by the misalignment of the baffles. In this arrangement, recirculations are also observed.

2. Pressure drop results show that the flow regime changes from laminar to turbulent at about $Re = 90$.
3. A change in the Nusselt number trend is not clearly observed with the flow regime transition, as heat transfer rates are already high in laminar conditions.

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