HEAT TRANSFER ENHANCEMENT THROUGH THE USE OF AN OSCILLATORY FLOW IN CIRCULAR-ORIFICE BAFFLED TUBES: AN EXPERIMENTAL STUDY

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NOMENCLATURE

A_{osc}	Centre to peak amplitude of the oscillatory motion
D	Test tube diameter
d	Baffles orifice diameter
r	Test tube radius
f	Oscillatory motion frequency
L	Consecutive baffles separation distance
Re	Reynolds number
S	Cross-section area
v	Velocity
v_{ref}	Reference velocity. Maximum cross-section average velocity of the oscillatory motion induced in the tube
x	Axial position

Special characters

ρ	Fluid density
μ	Fluid dynamic viscosity

Subscripts

n	Net flow
osc	Oscillatory flow
$piston$	Propelling piston used to produce the oscillatory flow
$tube$	Test tube
max	Maximum value for the variable

ABSTRACT

This work presents an experimental study of the flow pattern in tubes with equally-spaced circular-orifice baffles. Particle Image Velocimetry (PIV) technique is employed in order to obtain the velocity field of the oscillatory flow in the symmetry plane of the region between two consecutive baffles. Experiments have been carried out for oscillatory Reynolds numbers ranging from $Re_{osc} = 26$ to $Re_{osc} = 1500$. The instantaneous and cycle average flow fields have been obtained for the experiments.

The flow has been found to have laminar regime characteristics for $Re_{osc} < 100$ and to be unstable for about $Re_{osc} > 140$. For all tested conditions, a recirculation bubble has been detected when the change in direction of the oscillatory motion takes place. Besides, the bubble is displaced along the cell tank by the flow. This bubble results in some mass transfer between core and peripheral regions of the flow. Furthermore, when the limit of about $Re_{osc} \approx 140$ is overcome, additional instabilities and vortexes appear, which increase with the Reynolds number, and also increase mass transfer.

INTRODUCTION

Heat transfer enhancement inside pipe heat exchangers has been broadly studied. The enhancement techniques are usually applied to flows where the dominating heat transfer mechanism is by conduction between the flow layers. Thus, the aim of enhancement techniques is to increase convection in such flows. The flow mechanisms that promote mixing in tubes are usually related to the continuous separation and reattachment of the flow. For that, the enhancement techniques to be used can be classified in active and passive [1], if they need an external source of power (other than the circulating pump) or not. Passive techniques can be very efficient in promoting convection, depending on the flow conditions, but as a general rule, they are not useful at very low Reynolds numbers [2-4].

The insertion of equally-spaced circular-orifice baffles in tubes has rised the interest of the process intensification community [5]. The validity of this geometry relies on its potential for promoting intense radial mixing and heat and mass transfer when a continuous, low flow rate is superimposed to a fully reversed oscillatory flow. The compound effect of the baffled inserts and the oscillatory flow yields unsteady flow structures characterized by the cyclic dispersion of vortices [6].

Heat transfer enhancement by using this type of insert devices has been experimentally and numerically studied by a few authors [7-9] . The flow structures depend on the Reynolds number of the flow (Re_n) but also on the Reynolds number of the oscillatory motion (Re_{osc}). In tube-side heat transfer enhancements up to sevenfold can be achieved if the appropriate fluid oscillation is superimposed to a very low Reynolds number net flow ($Re_n < 300$). Muñoz et al. [10] used the Particle Image Velocimetry technique to study the behaviour of the net flow in equally-spaced baffles in round tubes with d/D=0.5 and $20 < Re_n < 300$. They assessed the unstable nature of the flow for $Re_n > 160$.

Despite the studies which have been cited, the effects of the oscillatory flow in the flow pattern, the flow structures formation and the heat transfer are not sufficiently described. Experimental data is also required to support further validation of computer-

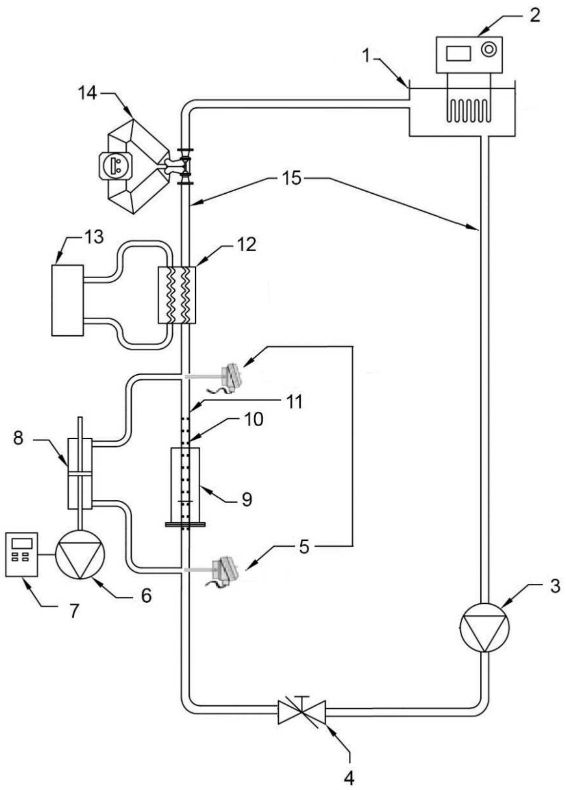

Figure 1. Sketch of the experimental facility. Elements: (1) reservoir tank, (2) electric heater, (3) circulating pump, (4) flow control valve, (5) RTD temperature sensors, (6) piston propelling assembly, (7) frequency converter, (8) piston, (9) visualization tank with surrounding acrylic box, (10) insert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

ized models for the numerical analysis of the problem for further progresses on the design of novel tube insert geometries. In this work, the velocity field in the symmetry plane of a tube with circular orifice baffles is investigated using the Particle Image Velocimetry technique. By using a mixture of propylene-glycol and water as working fluid, the influence on the flow structures of the oscillatory Reynolds number of the main flow has been investigated.

EXPERIMENTAL SETUP

The facility depicted in Fig. 1 was built in order to study the flow pattern in a circular tube with equally spaced insert baffles.

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. The PIV devices arrangement is shown at Fig. 2.

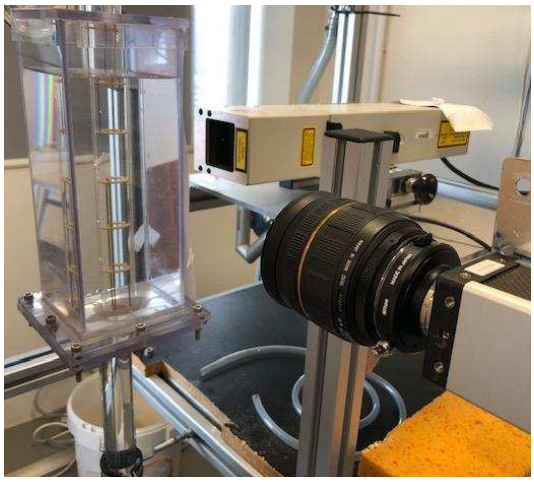

Figure 2. Picture of the PIV system.

The test section consists of a $D = 32$ mm diameter acrylic tube (also shown at Fig. 2) equally spaced insert baffles which are fixed by three aluminium rods. The use of the rods has been avoided in the visualization tank for better results. As shown in Fig. 3, the baffles orifice is $d = 0.5D$ (25% of free area) and the baffles separation distance is $L = 1.5D$.

The oscillatory flow within the test section is produced by a piston installed in parallel to the test section.

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 oscillatory motion induced within the test section has a center to peak amplitude of $0.5D$ and its frequency ranges from 0.1 Hz to 1.3 Hz within the experiments.

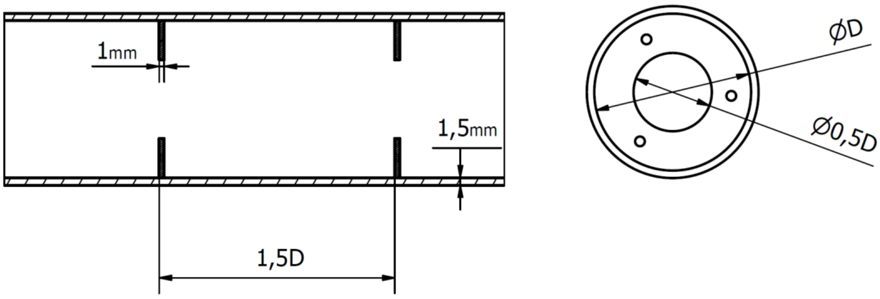

Figure 3. Sketch of the insert device.

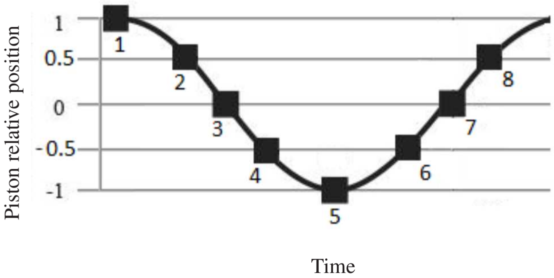

Figure 4. Visualized positions of the oscillatory motion cycle.

RESULTS

As it has been previously stated, the device under study is able to work with a net flow and a superimposed oscillatory flow. Consequently, two Reynolds numbers can be defined in order to completely define the fluid-mechanical non-dimensional problem. On the one hand, the *net Reynolds number* characterizes the net flow,

$$Re_n = \frac{\rho \overline{v}_n D}{\mu} \quad (1)$$

where ρ and μ are the fluid density and viscosity, $\overline{v}_n$ is the cross-sectional average velocity produced by the net flow. On the other hand, the *oscillatory Reynolds number* characterizes the oscillatory flow,

$$Re_{osc} = \frac{2\pi f A_{osc} \rho D}{\mu} \quad (2)$$

where f is the oscillation frequency and A_{osc} is the centre to peak amplitude of the oscillatory motion produced in the flow.

The experiments have been carried out without net flow $Re_n = 0$, and for oscillating flows ranging from $26 < Re_{osc} < 1500$. In order to obtain the cycle average flow field, between 20 and 50 cycles have been recorded, depending on the flow complexity.

Due to the oscillatory motion, there are no stationary conditions to be observed, the fluid field is continuously changing. The cycle average velocity field shows the average flow field on each point of the cycle. In this document, the 8 most significant points of each cycle are be presented (see Fig. 4). Besides, three experiments have been selected for representation, with $Re_{osc} = 46,\ 148,\ 1500$.

In order to keep non-dimensional variables, distances (in axial and radial directions) are divided by the tube diameter D and velocities by the so called *reference* velocity, v_{ref}. It is defined as the maximum cross-section average velocity of the oscillatory motion induced in the tube, and has been calculated by applying the continuity equation between the piston chamber and the test tube.

$$v_{ref} = v_{piston,max} \frac{S_{piston}}{S_{tube}} \quad (3)$$

Fig. 5 shows the average flow field for an experiment with $Re_{osc} = 46$. Four positions are shown for each half-cycle, and, as it can be observed, the structures at opposite positions in the cycle are symmetric. When the cycle begins, the piston is at one of its end positions and starts its movement towards the other end. In the figure, at Position 1, it can be appreciated that a jet which goes from left to right is beginning to take form, due to the sudden acceleration of the piston. The maximum observed velocity is reached at position 3, when the piston velocity is maximum. When the oscillatory flow changes direction (positions 1 and 5) a recirculation is created in the peripheral region, which results in mass transfer in this area. The maximum core velocity in the observed fields (position 3 & 7) is above 3 v_{ref}, while the maximum measured counter flow velocity is about $-0.5\ v_{ref}$.

The flow pattern is qualitatively similar for the experiments with low Reynolds numbers $Re_{osc} < 100$. The flow has characteristics of the laminar regime, as it is stratified in stable layers and no significant mass transfer (other than the above mentioned recirculation) between them is observed. The laminar characteristics of the flow can be appreciated in Fig. 6, where the instantaneous flow fields of the same position for four consecutive cycles are plotted. The results show the same velocity field in all four cases, without any chaotic or unstable pattern.

Fig. 7 shows the cycle average flow fields for the experiment with $Re_{osc} = 148$. As in the previous case, the structures of each half-cycle are symmetric. The average patterns are similar to the ones of the experiment with lower Reynolds number, although

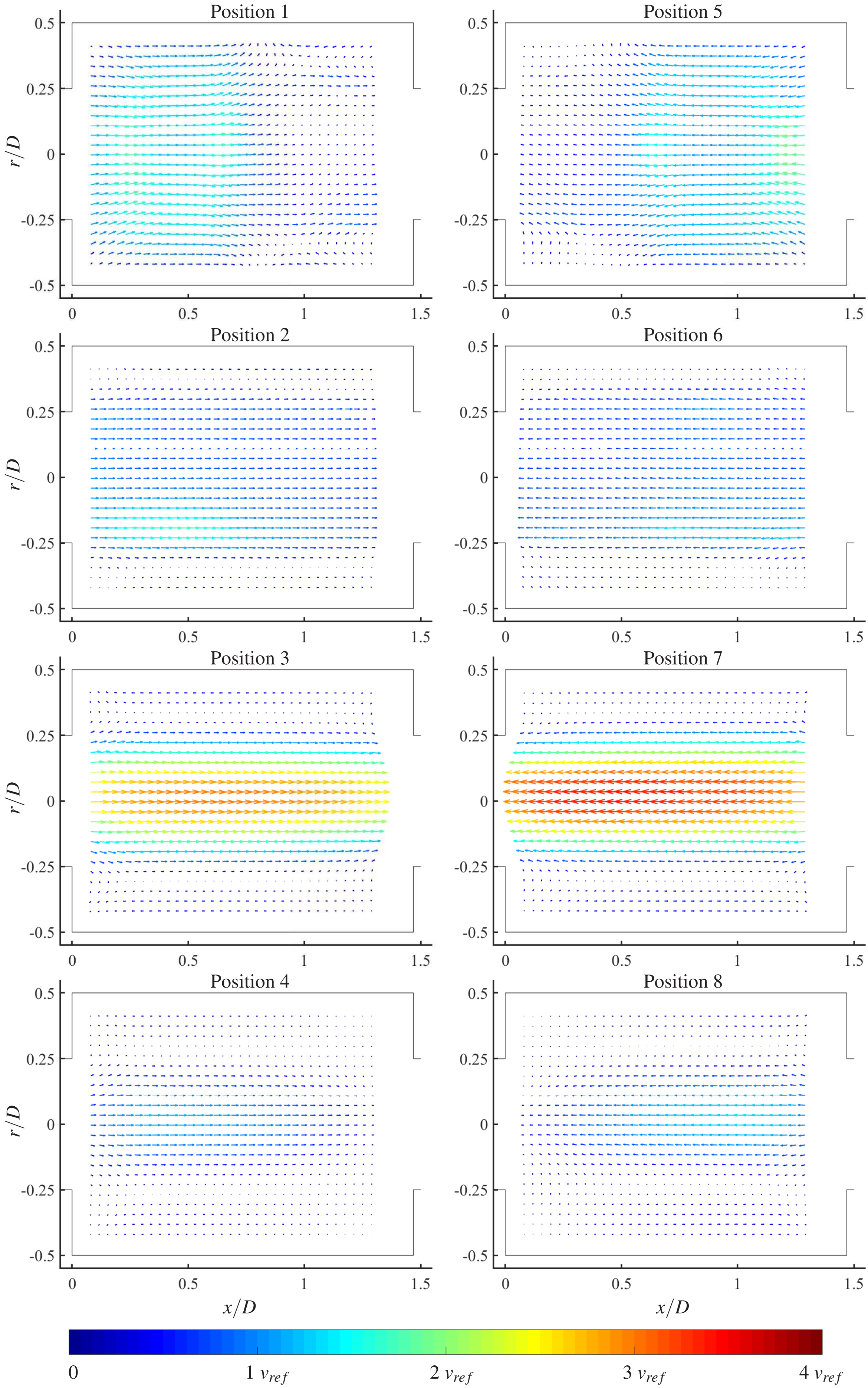

Figure 5. Average flow field results at $Re_{osc} = 46$ for different cycle positions.

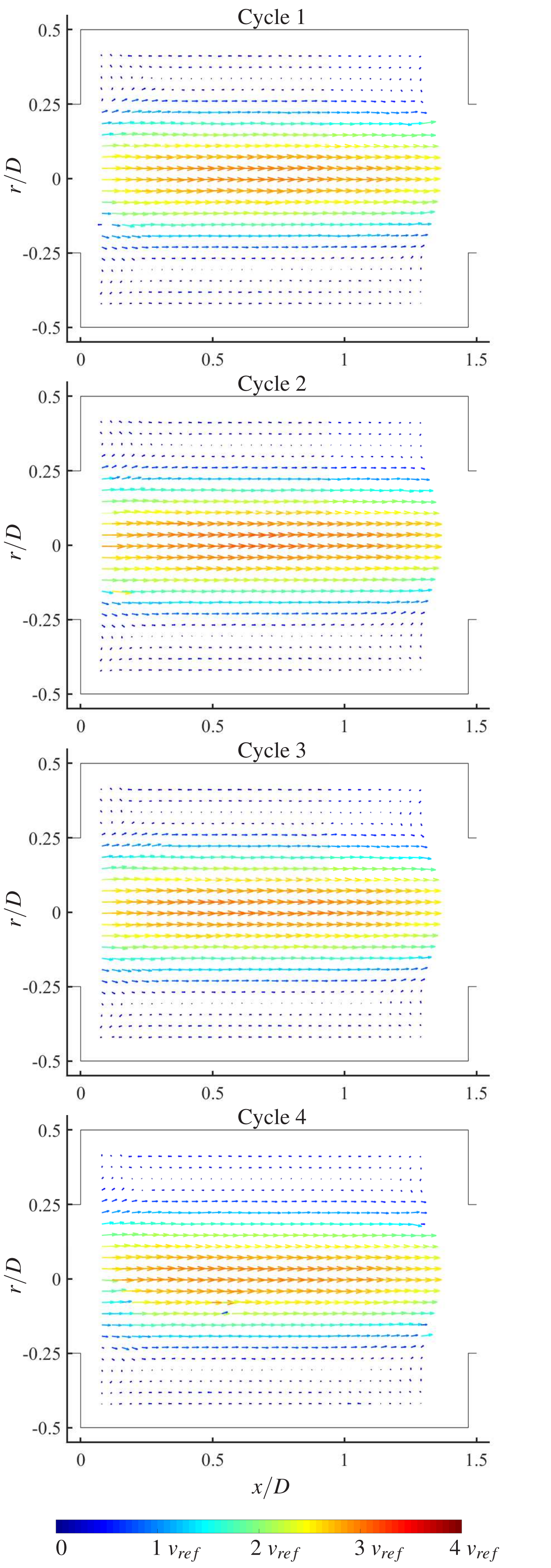

Figure 6. Instantaneous flow field results at $Re_{osc} = 46$ at position 2 of consecutive.

there are also dissimilarities; for this experiment higher velocity differences between the core flow and the peripheral region can be observed, as well as stronger recirculation and counterflows in the peripheral region. The maximum core velocity in the observed fields (position 2 & 6) is about 6 v_{ref}, while the maximum measured counter flow velocity is about -1 v_{ref}.

The instantaneous flow fields of the same position (position 2) for four consecutive cycles for $Re_{osc} = 148$ are plotted at Fig. 8. Although the velocity fields are similar, some random vortices are detected, which are different for each flow field. The results attest the presence of some chaotic patterns, and not negligible fluctuating components of the velocity (between the same position in different cycles).

The results for the non-dimensional average flow pattern of the experiments up to $Re_{osc} = 1500$ are quite similar to the one with $Re_{osc} = 148$ represented in Fig. 7. However, the instantaneous flow fields of the same position (position 2) for four consecutive cycles plotted at Fig. 9, do provide further information. There are some similarities between the flow fields, but a significant number of vortices are detected, which are different for each flow field. And all of the instant velocity fields differ significantly from the average velocity field. Therefore, the flow can be safely classified as highly chaotic, with significant fluctuating velocity components (when comparing the same position for different cycles).

CONCLUSIONS

The flow visualization allowed the authors to determine the flow pattern as a function of the Reynolds number. The change in direction produced by the oscillatory nature of the flow, has been found to produce recirculation bubbles in all the experiments.

For $Re_{osc} < 100$ the flow has laminar characteristics, and the mass transfer between the peripheral and core regions of the flow is solely due to the recirculation produced by the change in direction. For these experiments, the maximum velocity detected in the flow patterns for the full cycle is about 3 times the maximum cross-section average induced velocity.

For higher values of the oscillatory Reynolds number $Re_{osc} > 140$, chaotic components have been detected in the flow, which have been found to increase with the Reynolds number. Such chaotic structures increase significantly mass transfer in radial direction. For these experiments, the maximum velocity detected in the flow patterns for the full cycle is about 5-6 times the maximum cross-section average induced velocity and the counter flow significance is higher than for lower Reynolds numbers.

The results suggest than significant transfer enhancements could be achieved by the use of a superimposed oscillatory flow to the net flow, and that this enhancement would be even higher if $Re_{osc} > 140$. Furthermore, the obtained average flow fields can be used to develop and validate a numerical model, in order to extend the conclusions of this study.

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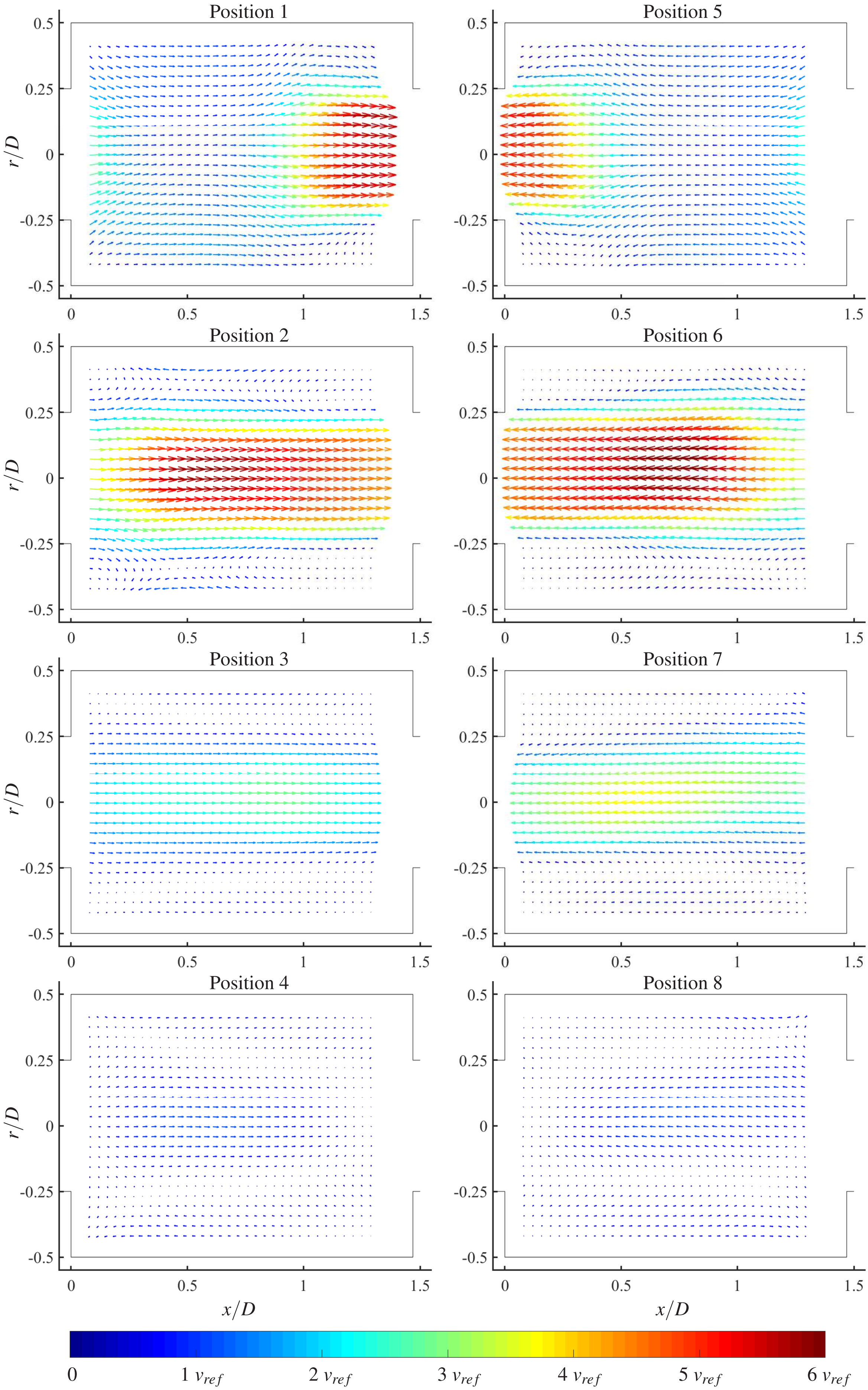

Figure 7. Average flow field results at $Re_{osc} = 148$ for different cycle positions.

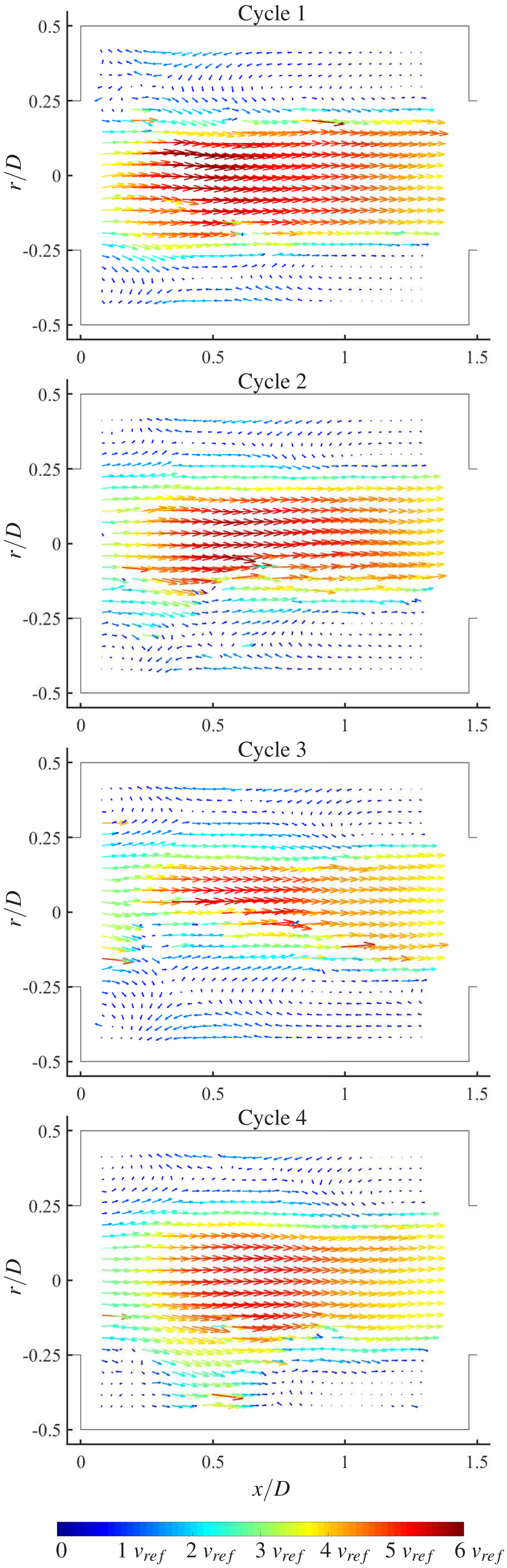

Figure 8. Instantaneous flow field results at $Re_{osc} = 148$ at position 2 of consecutive.

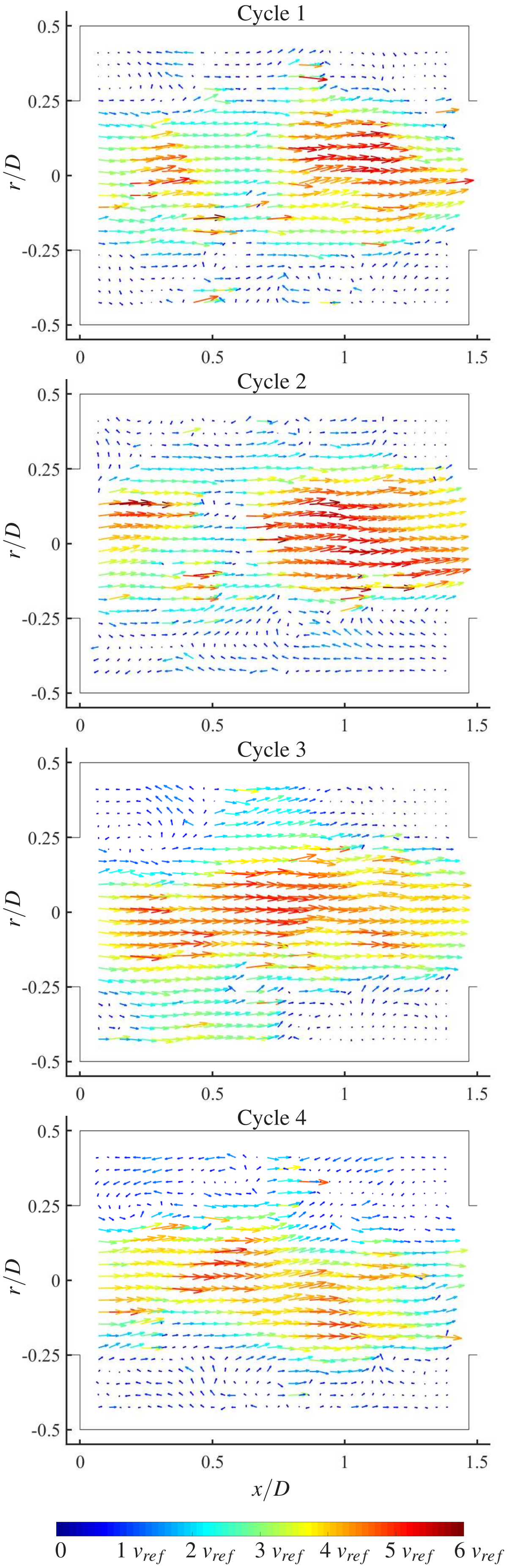

Figure 9. Instantaneous flow field results at $Re_{osc} = 1500$ at position 2 of consecutive.

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