APPLICATION OF MICRO-PIV TECHNIQUE IN EXAMINING THE MIXING BEHAVIOUR IN A NOVEL MICRO-REACTOR

B. Moghtaderi¹, I. Shames², and L. Djenidi³

¹School of Engineering, Faculty of Engineering & Built Environment, The University of Newcastle, NSW 2308, Australia
²Department of Electrical Engineering, Faculty of Engineering, Shiraz University, Iran

ABSTRACT

The present paper summarises the results of an experimental investigation on fluid dynamic characteristics of a novel micro-reactor for production of hydrogen by partial oxidation of methane. The reactor is essentially a tubular vessel fitted with a multi-holed baffle plate. The experiments were conducted on a 1:1 scale replica of the reactor using a laser based flow measurement technique known as Micro Particle Image Velocimetry (Micro-PIV). The application of the baffle plate with an optimised geometry was found to significantly improve the mixing performance of the reactor when compared with a simpler co-axial jet reactor.

1. INTRODUCTION

As an environmentally clean fuel with an extremely high energy storage density (120 MJ/kg), hydrogen can be utilised in fuel-cells to produce heat and electricity [1-2]. The success of fuel cells, however, greatly depends on the availability of suitable technologies for safe and efficient production of hydrogen. Among various alternatives, partial oxidation of methane (POM) is an attractive option because the reaction is extremely fast, particularly, at high temperatures and methane is readily available in many parts of the world. Miniaturisation of this process will further improve the attractiveness of the POM technology particularly for small mobile/onboard applications [3] (e.g. electrical and electronic devices, cars, etc). This is not only due to the light weight and suitable physical dimensions of the resulting hydrogen generator but also because of the typical heat and mass transport intensifications achieved in micro-systems [4-7]. Micro-reactors, unfortunately, often have poor mixing efficiencies as they generally operate under laminar flow conditions owing to their small physical dimensions. As such, the mixing within these reactors is principally due to molecular diffusion rather than the bulk flow mixing due to turbulence [6,7]. Therefore, better mixing efficiencies within micro-systems are always desirable. For this reason, researchers have been working over the last decade on various methods of enhancing the mixing phenomenon in micro-reactors. Of these mixing enhancement methods, the so-called “Streaming Mixing” techniques are of particular interest in microfluidics because the enhanced mixing can be achieved by the proper design of the reactor geometry without the need for mechanical agitation.

We have adopted this approach to improve the mixing in a novel micro-hydrogen-generator being developed in our group for production of hydrogen by partial oxidation of methane. For this purpose we studied the flow structure of the micro-reactor shown in Figure 1 which is an integral part of the hydrogen generator. The aim was to examine the effectiveness of the reactor design in terms of the mixing behaviour of reactant streams by obtaining detailed information on the velocity distribution using the Micro-PIV technique.

2. DESCRIPTION OF THE SYSTEM

The micro-reactor investigated in this study was essentially a tubular vessel fitted with a fuel inlet tube, located co-axially in the main vessel, and a multi-holed baffle plate through which the oxidising agent is introduced. The most innovative feature of this micro-reactor is that it provides a flexible and robust platform for mixing at micro-scale levels by integrating several proven Streaming Mixing strategies [6-7], such as contacting, splitting/recombination, and velocity increase, into a unified system. Contacting of the reactant streams is achieved by using the co-axial jet configuration while the velocity-increase and splitting/recombination are attained by employing the multi-holed baffle plate [8]. This configuration also facilitates the task of parallelisation of the reactor with an appropriate number of identical reactor units to achieve the required overall production rate. The prototype of the generator under development at the University of Newcastle, Australia has about 2500 micro-reactors arranged in 32 reactor assemblies each comprising about 78 parallel micro-reactors similar to that shown in Figure 1 (ID = 300 µm, L = 30 mm).

3. METHODS AND TECHNIQUES

3.1 The Micro-Reactor Model

The micro-reactor model was a 1:1 scale replica of an actual reactor comprising two co-axial cylindrical vessels and a baffle plate (Figure 1). The main vessel was fabricated by wet etching of fused silica (glass) wafers using a solution of NH₄OH. For this purpose two identical channels (half of the final assembly) were etched in glass wafers using a Polysilicon mask. The fuel inlet tube and the baffle plate were fabricated as a single unit by cutting to shape a small block of glass using the Laser Ablation Micromachining technique. The fuel inlet/baffle plate assembly was glued into one of the channels and then the two wafers were bonded together at high temperatures to make the final structure.
3.2 Experimental
Experiments were conducted in a set-up consisting of: (i) the micro-reactor model, (ii) a closed-loop flow circuit, and (iii) a Micro Particle Image Velocimetry (Micro-PIV) system. The flow circuit included a $10^3 \text{m}^3$ fluid reservoir (tank), a control valve, a flow meter, a syringe pump and connecting tubes.

Unlike standard PIV, volume illumination is used in Micro-PIV measurements primarily because the thickness of the laser light sheet generated by the standard PIV method is typically larger than the characteristic lengths of most microfluidic systems. In Micro-PIV technique, the camera and the laser illumination are introduced through an inverted microscope via a series of fibre optic links. The measurement plane is defined by the numerical aperture of the microscope objective.

Our Micro-PIV system comprised a Quantel TWINS B double pulse Nd:YAG laser system (2 380 mJ @ 532 nm), an inverted microscope (Nikon Eclipse TE2000-U), a Dantec HiSense 80C60 CCD camera with an array size of 1279×1023 pixels, a camera integration package, fibre optic links, a high precision 3-axis motorised stage (AS1000i/3500), a high speed data acquisition unit, and the Dantec Flow-Manager software.

The seed particles were 700 nm red fluorescent polystyrene micro-spheres ($\rho=1050 \text{kg.m}^{-3}$) with a response time of $5\times10^{-9}$ s. The particles were produced and packaged by the Duke Scientific Corporation as aqueous suspensions with 1% solids. Because of relatively high velocities used in the experiments ($\approx 0.3 \text{ m/s}$) the effect of Brownian motion of seed particles was negligible.

The combination of the volume illumination and microscope made it possible to achieve focal depths between 2-45 µm. However, measurement planes were defined with a nominal focal depth of 10 µm allowing us to capture 30 measurement planes across the 300 µm diameter of the reactor model. The spatial resolution in each plane, defined by the size of the interrogation window, was 120×40 pixels corresponding to an area of 20×6.7 µm$^2$. The interrogation windows were overlapped by 50% according to the Nyquist sampling criterion to maximise the amount of information extracted. This yielded velocity vector spacings of 10 µm and 3.35 µm in the stream- and span-wise directions, respectively. To overcome the problem of low particle density in the PIV recordings (the so-called Low Image Density, LID), we employed the “Overlapping” method [7] in which 9 pairs of PIV recordings were overlapped to artificially obtain an enhanced high particle density image pair for cross-correlation. Note that because of low Reynolds numbers, the laminar flow in our set-up can be considered as steady-state during the data acquisition, hence, justifying the use of the Overlapping method. The method has also the added advantage of relatively high signal-to-noise ratio which renders the vector validation post-processing unnecessary.

Experiments were carried out across each measurement plane and were repeated systematically at a fixed flow rate for various combinations of the fuel feed tube and baffle plate geometries (see Table 1). The flow rate was maintained at a rate to provide a nominal $Re$ of 100. The $Re$ number was defined based on the overall reactor diameter ($D$) and the mean velocity over its full cross-sectional area. The flow rate through the central tube of the model reactor was set to 5% of that fed through the annular space. This value was chosen to approximate the fuel/air ratio of the methane/oxygen mixture in the actual reactor. Mixing efficiency was examined in terms of the size and extent of the high/low velocity regions and recirculation zones near the outlet of the fuel feed tube.

To maintain the similarity between the replica and the actual reactor, the $Re$ number of the flow in the replica was kept at the same level as that in the actual reactor ($Re=100$). Since both systems had identical dimensions and operated with similar flow rates, then: ($\rho/\mu$)rep had to be equal to ($\rho/\mu$)act.

Considering that the real system operates with a mixture of methane and oxygen while water is the preferred option for the replica, the dynamic viscosity of water had to be adjusted to maintain the $\rho/\mu$ ratio. This was achieved by adding glycerin to water. As a result, the standard working fluid in this study was a mixture of 98 wt% water and 2% glycerin. A 0.1 wt% mixture of NaI with a sodium-based stabilizer ($\text{Na}_2\text{S}_2\text{O}_3$) was also added to the working fluid to match its refractive index with that of glass. This was to enhance the signal quality of the measurements.

The $Re$ number of the flow in the replica was kept at $Re=100$. Since both systems had identical geometrical dimensions, the $Re$ number was defined based on the overall reactor diameter ($D$) and the mean velocity over its full cross-sectional area. The flow rate through the central tube of the model reactor was set to 5% of that fed through the annular space. This value was chosen to approximate the fuel/air ratio of the methane/oxygen mixture in the actual reactor. Mixing efficiency was examined in terms of the size and extent of the high/low velocity regions and recirculation zones near the outlet of the fuel feed tube.

To maintain the similarity between the replica and the actual reactor, the $Re$ number of the flow in the replica was kept at the same level as that in the actual reactor ($Re=100$). Since both systems had identical dimensions and operated with similar flow rates, then: ($\rho/\mu$)rep had to be equal to ($\rho/\mu$)act. Considering that the real system operates with a mixture of methane and oxygen while water is the preferred option for the replica, the dynamic viscosity of water had to be adjusted to maintain the $\rho/\mu$ ratio. This was achieved by adding glycerin to water. As a result, the standard working fluid in this study was a mixture of 98 wt% water and 2% glycerin. A 0.1 wt% mixture of NaI with a sodium-based stabilizer ($\text{Na}_2\text{S}_2\text{O}_3$) was also added to the working fluid to match its refractive index with that of glass. This was to enhance the signal quality of the measurements.

4. RESULTS AND DISCUSSION

Figure 2 illustrates a typical velocity vector map obtained from the first set (Set 1, see Table 1) of experiments for a model reactor without the baffle plate but otherwise a standard geometry (i.e. co-axial jet). This particular figure shows an axial plane view of the region near the central inlet tube. As can be seen, owing to greater velocities of the fluid jets in the annular space, velocity profiles close to the outlet of the central tube exhibit steep gradients with minimums not only at vessel walls but also along the axis of symmetry. These profiles, however, quickly vanish and are replaced by typical laminar flow parabolic velocity profiles at downstream locations greater than two reactor diameters (i.e. 600 µm).

Figure 3 shows a velocity vector map obtained from the second set of experiments (Set 2) for the standard geometry. Similar to Figure 2 only the regions close to the central tube are shown. Clearly, there is a dramatic difference between the flow field shown in Figure 3 and that of the simple co-axial jet configuration shown in Figure 2. Unlike the previous case, there is a relatively large reverse flow region, accompanied by two recirculation zones, near the central tube outlet. The recirculation zones are formed as a result of the outward flow of fluid particles in radial direction caused by the formation of an stagnation point immediately in front of the central tube. The existence of the reverse flow and recirculation zones in the vicinity of the central tube implies that the flow structure in this region must be dominated by convective effects (i.e. bulk flow). This greatly enhances the mixing of the fluid streams when compared with the simpler case of the co-axial

---

1 An alternative way of resolving the LID problem is to use the “Ensemble Correlation” method [7] using a much higher number of image pairs (typically 100). However, this approach was found to be beyond our capabilities and was not employed.
jet for which the mixing phenomenon is dominated by the time scale for molecular diffusion [8].

As mentioned before, apart from the first two sets of experiments, several other sets of tests were carried out to closely examine the impact of the reactor geometry on the mixing phenomenon. On this basis, the third and fourth sets of experiments (Set 3 and Set 4) were conducted to investigate the effect of reducing the size of the central tube diameter on the recirculation / reverse flow zones in front of the central tube. The results have been summarised in Figures 4 and 5 for cases with 50% and 83% reduction in the central tube diameter, respectively. Evidently, as the diameter of the central tube is decreased, the recirculation / reverse flow zones disappear, implying that the enhancement to mixing achieved with the standard geometry is diminished. This can be assigned to the fact that the reduction of the central tube diameter increases the velocity of the co-axial jet exiting from the central tube. The increased velocity associated with the higher momentum of the jet pushes the stagnation point further and further away from the central tube outlet. For certain central tube sizes (like those shown here) the jet momentum becomes so high that it significantly reduces the entrainment of the fluid jets exiting the baffle holes (i.e. when baffle plate jets turn towards the axial axis) and, thereby, prevents the formation of the reverse flow region. As a result, the reverse / recirculation zones fade away and the flow structure becomes very much similar to that of a simple co-axial jet configuration having no baffle plate.

The influence of the baffle plate geometry on the flow structure and mixing phenomenon near the central tube outlet was examined in experimental Sets 5-7. Results [9] indicate that for the smaller hole configuration the velocity and momentum through the holes are greatly increased causing a notable reduction in the extent of the recirculation and reverse flow zones. Compared with the standard geometry (Figure 3), the stagnation point in front of the central tube moves upstream towards the tube outlet. In the case of the larger hole configuration, the impact of the baffle plate seemed to be more pronounced as the stagnation point and reverse flow / recirculation zones disappeared altogether.

Figure 6 summarises the results obtained from the seventh set of experiments in which the effect of baffle hole radial location was examined. In this particular figure, the baffle holes have been moved outwards in radial direction by as much as 30 µm (i.e. R1 = 105 µm). Only half of the flow domain is shown so a comparison can be made with the base case. As can be seen, once again a relatively small change in the baffle geometry creates a dramatic change in the flow structure. In particular, the extent and strength of the reverse flow/recirculation zones have considerably increased. Therefore, the standard geometry can be optimised by moving the baffle holes radially outwards.

The final set of experiments was dedicated to study the effect of Reynolds number. This was motivated by the fact that in real situations the micro-reactor may be operated over a range of flow rates all with a similar fuel/oxidizer ratio. The Re in the final set of experiments was varied from the base value of 100 to 300 at increments of 50. The summary of results for a Re number of 300 at a region close to the central tube and baffle plate is depicted in Figure 7. As shown, the reverse flow / recirculation zone immediately in front of the central tube are very similar, both in terms of size and velocity magnitude, to those of the base case for a Re of 100 (Figure 3). However, the recirculation zones near the reactor wall appear to be larger. A closer examination of the results for other Reynolds numbers showed very similar flow features implying that an increase in Re number results in a general expansion of the flow field and mixing patterns in the axial direction, leading to an overall enhancement of the mixing phenomenon. It must be highlighted, however, not all flow features expand in proportion to Re. This is in contrast to many other types of laminar flow (e.g. laminar confined jets [8] laminar free jets [10], sudden expansion duct flow [11]) where the flow features expand linearly with the Reynolds number. The difference can be partly assigned [8-9] to the combined effects of the convective and diffusional transports in the cross-stream direction, particularly in regions close to the baffle plate and central tube. Such combined effects do not generally exist in other types of laminar flows. In the case of laminar confined jets, for example, the cross-stream flow is dominated by diffusion transport while the transport in stream-wise direction by inertial forces (i.e. convective effect).

CONCLUSIONS

The following conclusions can be drawn from the experimental results presented in this paper: (a) the baffle plate configuration considerably enhances the mixing performance of the reactant stream in the micro-reactor investigated, (b) the baffle plate and central tube geometries were found to have dramatic impacts on the flow structure and mixing patterns and, as such, the reactor geometry has to be optimised to achieve the desirable performance, (c) for the range of Re studied here, the optimum reactor geometry is that with similar central tube and baffle hole diameters with baffle holes located close to the reactor wall, and (d) increasing the Reynolds number enhances the mixing performance.

REFERENCES

Figure 2: The velocity vector map for a model reactor without the baffle plate.

Figure 3: The velocity vector map for a model reactor with the standard geometry (Figure 1).

Figure 4: The velocity vector map for a model reactor with a central tube diameter reduced by 50% from the standard geometry ($d_1 = 30 \, \mu m$).

Figure 5: The velocity vector map for a model reactor with a central tube diameter reduced by 83% from the standard geometry ($d_1 = 10 \, \mu m$).

Figure 6: (a) the velocity vector map for half of a model reactor with baffle holes in a different radial location from that of the standard geometry, $R_1 = 105 \, \mu m$, and (b) the vector map for half of the standard geometry.

Figure 7: The velocity vector map for a model reactor with standard geometry at $Re = 300$. 