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**CFD modeling of  
Plasmatron Methane Reformer**

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## **Abstract**

Plasmatron fuel converters have been investigated for the conversion of a wide range of fuels. This is a paper of a series of papers describing an effort to investigate experimentally and computationally plasmatron methane reformers. This paper describes the fluid dynamics modeling of the plasmatron methane reformer, with the hope of understanding air/methane mixture and mixing rates in the region where the plasma is located. The modeling includes fluid dynamic effects, without chemistry.

## 1. Introduction

Understanding the flows in plasmatron reformers is important in order to provide the basis for optimization of the device and minimizing transients. It is useful to have a handle of the mixing conditions (stratified, homogeneous) of the fuel/air prior and past the discharge, as well as determining the mixing rates.

Although there are codes available that can model the chemistry with the complex hydrodynamic flows, we have opted for performing the chemistry and the fluid dynamics separately. The individual problems are complicated enough that solution of a combined dynamic-chemistry model may not provide hints needed an understanding of the processes. However, because of the lack of chemistry in the model, the results obtained with the fluid dynamics code are good only upstream of the discharge region.

In this paper we concentrate in modeling the flows upstream from the discharge, and see how the air/fuel mixing can be modified by changing flow patterns. The goal is to produce an understanding of the level of stratification and the mixing time that can then be used with chemistry codes, the Perfectly Stirred reactor (PSR) [1] and Partially Stirred Reactor (PaSR) [2] chemical reaction codes. The results from the chemistry codes can then be compared with steady state experiments [3] and transient experiments [4].

The background, the applications for small reformers and different plasma reformers are reviewed in the accompanying paper that describes the steady state performance of the plasmatron methane converter [3] and will not be repeated here. The fluid dynamic model is described in section 2. Results for two methods of methane injection are described in sections 3 and 4. Conclusions are presented in section 5.

## 2. CFD model

The geometry of the plasmatron used in the experiments is shown in Figure 1, and has been described in an accompanying paper [3]. Two independent airs are used: the wall air and the swirl air. The wall air is injected in the axial direction at the same axial location where the methane nozzle is located. The swirl air is injected downstream from the wall air and the methane, with a large amount of vorticity. The swirl gas moves the discharge into the central region of the plasmatron, and provides the rotation motion that moves the arc roots on the electrodes to minimize electrode erosion. Two locations for introduction of the methane have been investigated: the methane can be introduced through the axial nozzle, upstream from the plasma, without any air (described in section 3 of this paper); or the methane can be premixed with the swirl air and injected as the plasma gas (described in section 4).

Downstream from the plasmatron head there is a 5 in long section of the reaction extension cylinder which is also included in the model.

The axisymmetric, steady state solution of the fluid dynamics in the plasmatron methane reformer has been calculated using a commercially available CFD code, FLUENT. The

model includes compressibility of the air, using ideal gas. Wall temperatures are at the same temperature as the gas (300K). Inlet conditions in all three ports (swirl air, wall air and methane) are as mass flow rate. The outlet condition is atmospheric pressure.

The effect of changing the grid structure has been investigated to determine the convergence of the problem, by using a grid that has four times the node density, and it has been determined that the mesh is appropriate for the problems investigated in this paper.

The model uses a turbulent model based upon the k-epsilon RNG model, with standard wall functions. The RNG mode is better suited for analysis of flows with substantial swirl, as is the case with the plasmatron methane reformer. The model solved the steady state conditions, using an implicit formulation and segregated solver. The convergence criteria for momentum, swirl, axial and radial velocities, k, epsilon and species concentrations was  $10^{-4}$ . The energy was monitored and controlled, with a convergence criteria of  $10^{-8}$ .

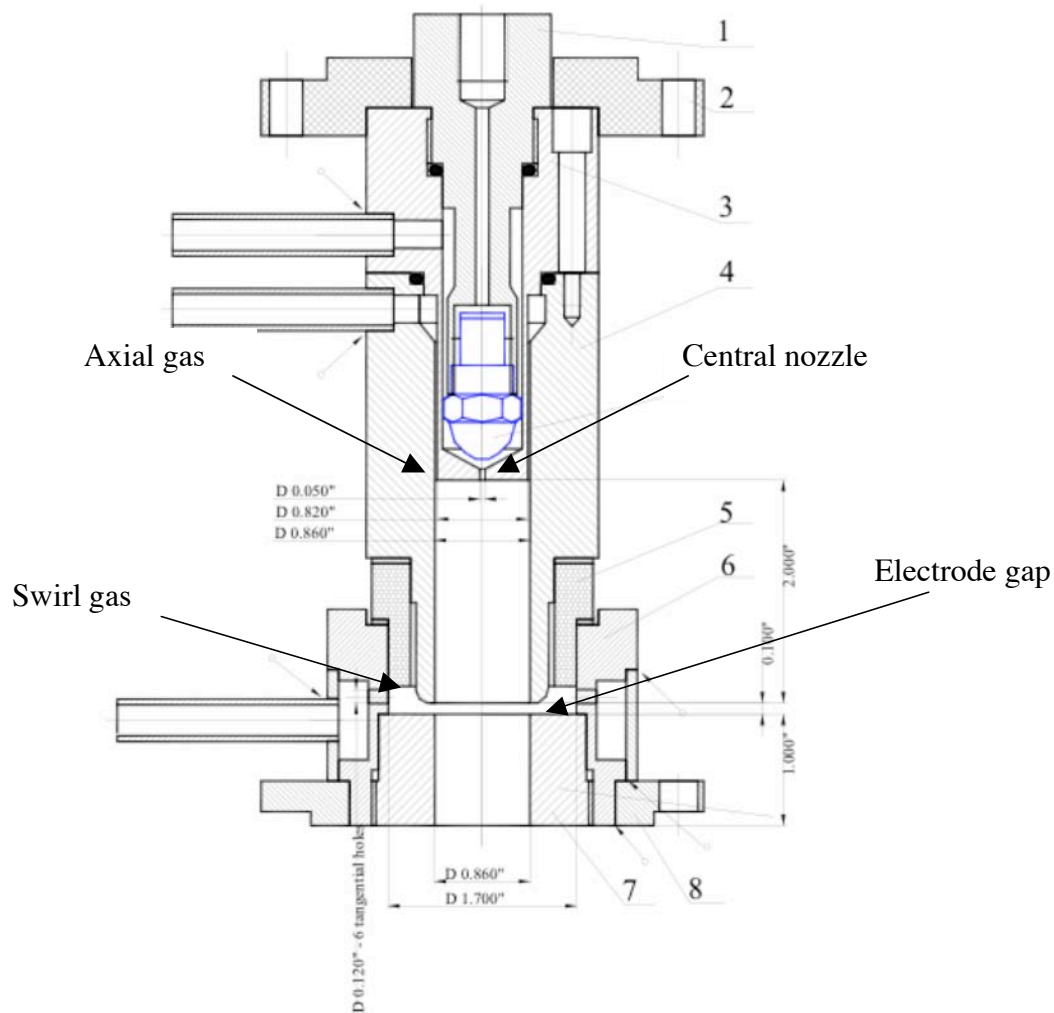
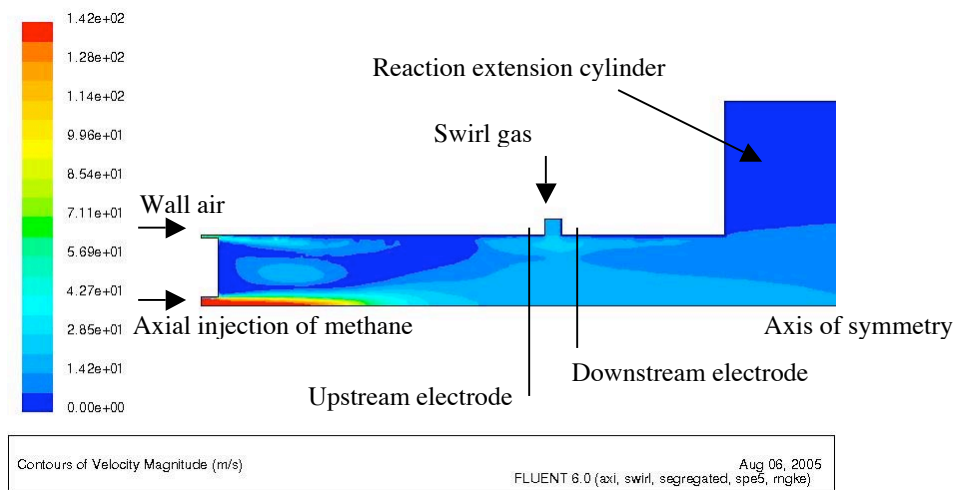


Figure 1. Schematic diagram of the plasmatron used in the methane reforming experiments and modeling.

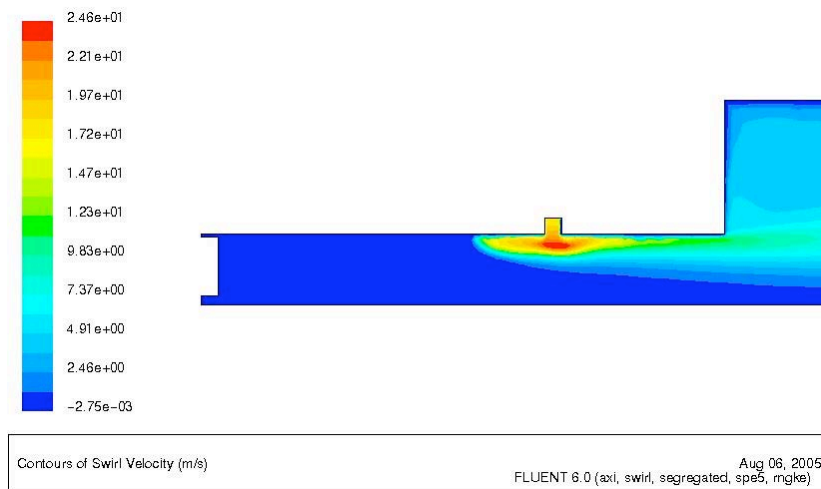
Since no chemistry is included in the model, the model cannot be used to describe the flows downstream from the plasma. The object of these calculations is to determine the conditions at and immediately following the plasma zone. In particular, the presence of recirculating flows that constitute exhaust gas recirculation, are likely to have substantial effect on the performance of the plasmatron methane reformer.

### 3. Axial injection of methane

In this section, the results for the case when the methane is injected introduced through the axial nozzle are presented. Although this is not the best configuration for methane, it is the preferred configuration for liquid fuels, which require air-assist atomization. Axial injection minimizes wall wetting.



(a)

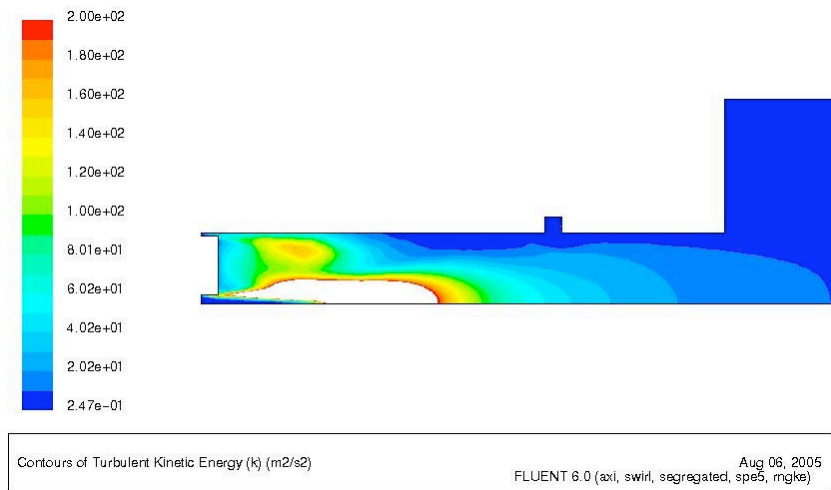


(b)

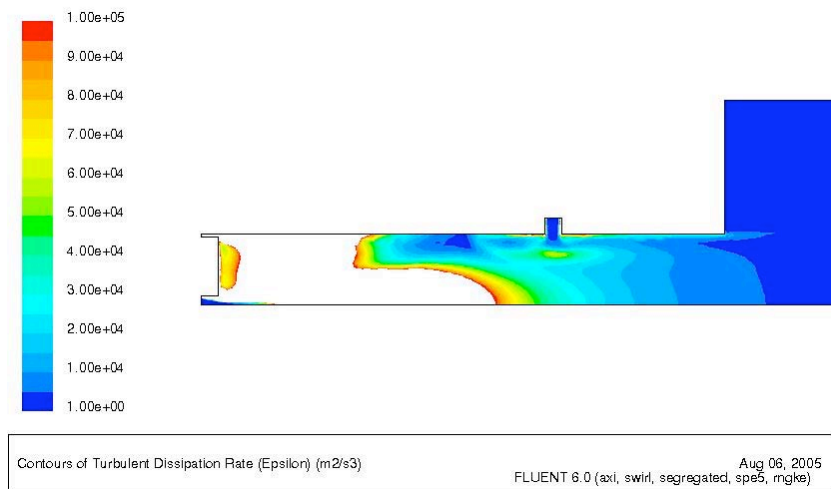
Figure 2. Contours of constant (a) velocity magnitude; (b) swirl velocity

The swirl air and wall air flows in the model are 1.29 and 2.59 g/s respectively, while the input of methane is 0.45 g/s, corresponding to an O/C ratio of about 1.8. The high O/C corresponds to that shown experimentally to produce good conversion of the methane and moderate hydrogen yield in a non-catalytic reactor. The wall air is injected without swirl, but the plasma gas has a swirl ratio of 12/40 (radial to tangential speed).

Figure 2 shows the velocity profiles in the plasmatron head and the entrance to the reaction extension cylinder. The left region in Figure 2 corresponds to the top of the plasmatron in Figure 1 (as the plasmatron is axially symmetric only half of the plasmatron in Figure 1 is shown, rotated clockwise 90 degrees,). The flows are labeled in Figure 2 (a). Only a small section of the reaction extensions cylinder is shown, as the model is not applicable to this region. The methane is injected through the axial nozzle and at the extreme left of the figure.



(a)



(b)

Figure 3. Contours of constant (a)  $k$ , turbulent kinetic energy; (b)  $\epsilon$ , dissipation rate

The injection velocity of the methane is high (on the order of 120 m/s). The velocity has to be high in order to provide the narrow radial distribution of the methane that results in stratification of the methane, with high concentration on axis. The methane velocity decreases to the bulk velocity downstream, but upstream from the electrode gap region. The swirl gas (in this case, air) has swirl velocities on the order of 20 m/s in the plasmatron, with velocities decreasing to about 10 m/s downstream from the plasma region. It should be noted that the swirl gas flows upstream from the injection point, resulting in longer residence time in the plasmatron. As the swirl flows modify the plasma, it part of the plasma, and the upstream root of the plasma, should move upstream from the electrode gap. This has been observed experimentally.

The turbulence parameters  $k$  (turbulent kinetic energy) and  $\epsilon$  (turbulent kinetic energy dissipation) are shown in the Figure 3. These parameters are important for the chemical modeling because they drive the turbulent mixing. The mixing time, which is the time for mixing of the flows, is determined by the ratio of  $k$  to  $\epsilon$ ,  $\tau_{\text{mixing}} \sim k/\epsilon$ .  $k$  is in the range from 1-5  $\text{m}^2/\text{s}^2$  in the plasma region, while  $\epsilon$  varies from  $2 \cdot 10^4 - 6 \cdot 10^4 \text{ m}^2/\text{s}^3$ . The mixing time, for these conditions, vary from 0.1 – 0.5 ms

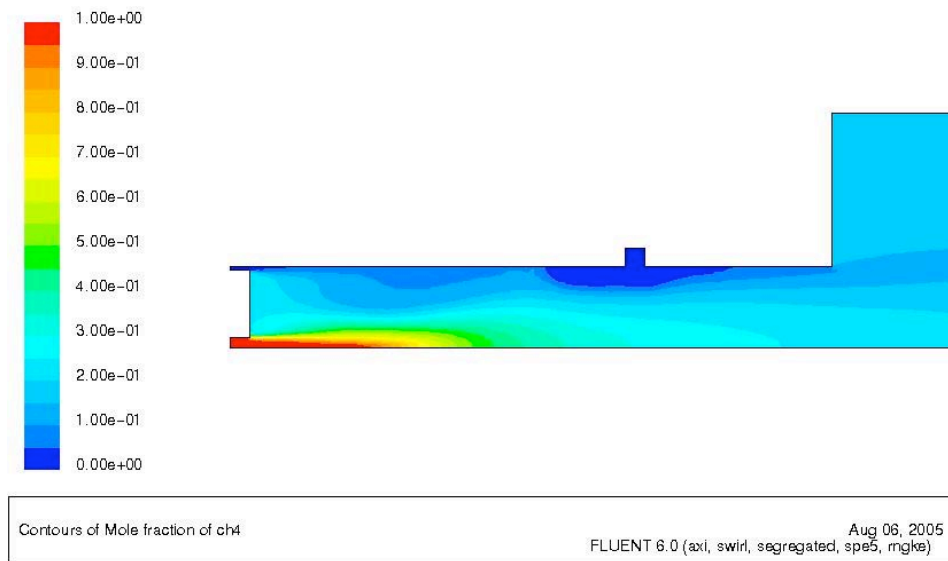


Figure 4. Contours of constant methane molar concentration

The molar concentration of methane is shown in Figure 4. The methane is stratified in the plasmatron head region, with highest concentration on the axis, decaying radially. It is thought that reforming in plasmatron fuel converters proceeds through a two-stage process, as described in the experimental and chemical model papers [1,2]. Reforming is maximized when there are substantial regions with stoichiometric methane/air mixture. The partial mixing is expected to result in ignition of some regions with good flammability characteristics, with mixing controlled reaction proceeding through the low flammability region. Both the Perfectly Stirred Reactor model [1] and the Partially Stirred reactor PaSR model [2] are used in the accompanying papers to investigate partial mixing

Only in the region of the reaction extension cylinder the methane and air are well mixed. It should be noted that there is no methane present within the strong swirl next to the plasma electrode. It is thought that the lack of fuel in this plasma region is responsible for poor experimentally determined reforming performance in the case of axial methane injection, and has suggested introduction of at least some of the fuel through the swirl gas. This condition will be discussed in the next section.

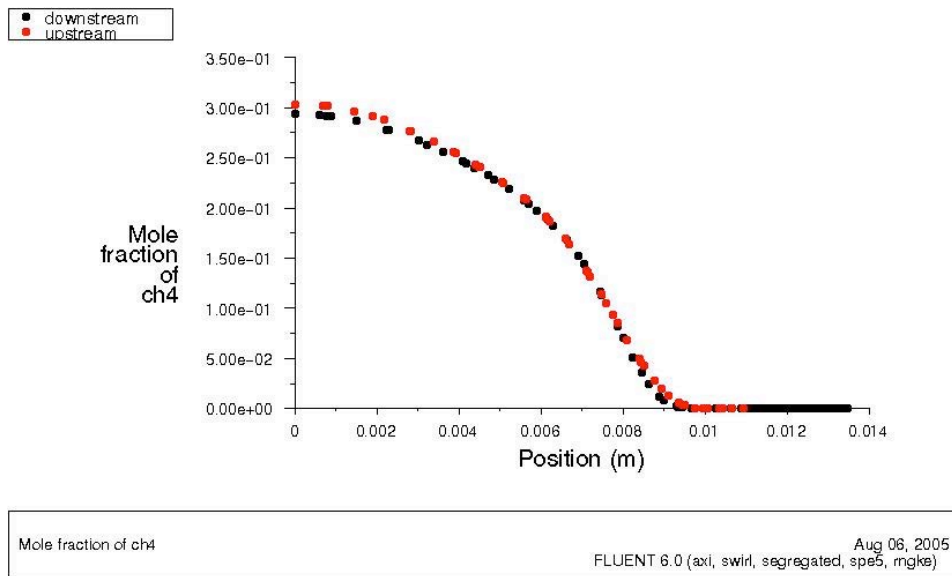


Figure 5. Radial molar concentration of methane along a radius at planes coinciding with the upstream and the downstream electrodes, shown in Figure 2(a).

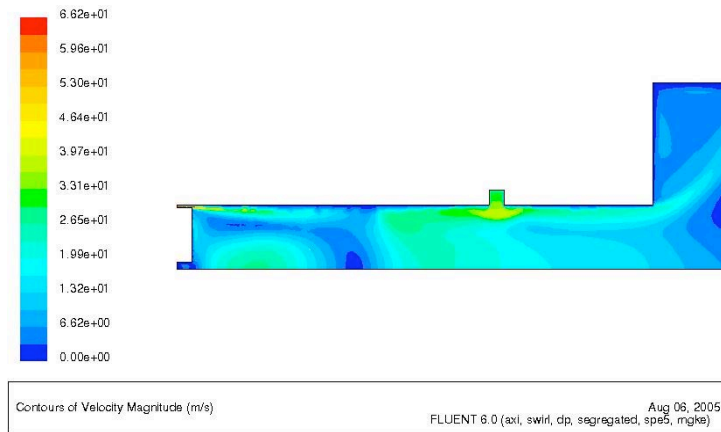
The radial concentration of methane, measured along a radius upstream and downstream from the electrode gap (shown in Figure 2(a)), is shown in Figure 5. As expected, because the swirl flow does not contain any methane, the upstream and downstream concentrations are very similar.

Stoichiometric combustion of methane occurs for a methane molar concentration of 9% (at an O/C = 4). As the methane concentration gradient is large in the zone where the methane concentration is 9%, the zone with approximately stoichiometric methane/air mixtures is small.

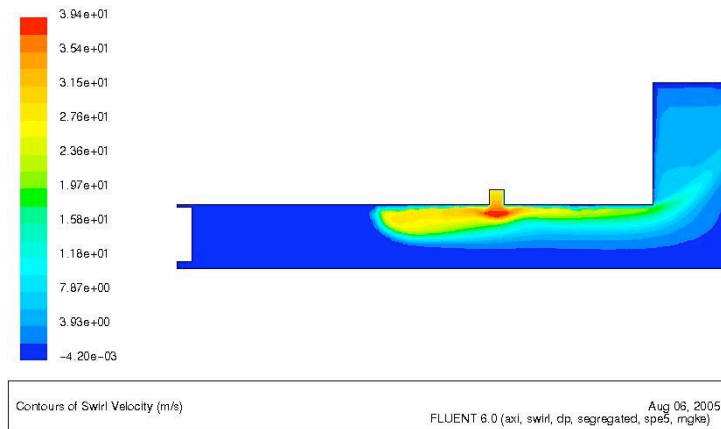


#### 4 Methane injection with swirl gas

In this section, results will be shown for the case when the methane is premixed with the swirl air, and injected through the gap between the two electrodes, with strong vorticity. In this case, there is no input through the axial nozzle, and wall air and swirl air flows at the same levels as in section 3. (\*\*\*\*\* I do not think so... \*\*\*\*\*)



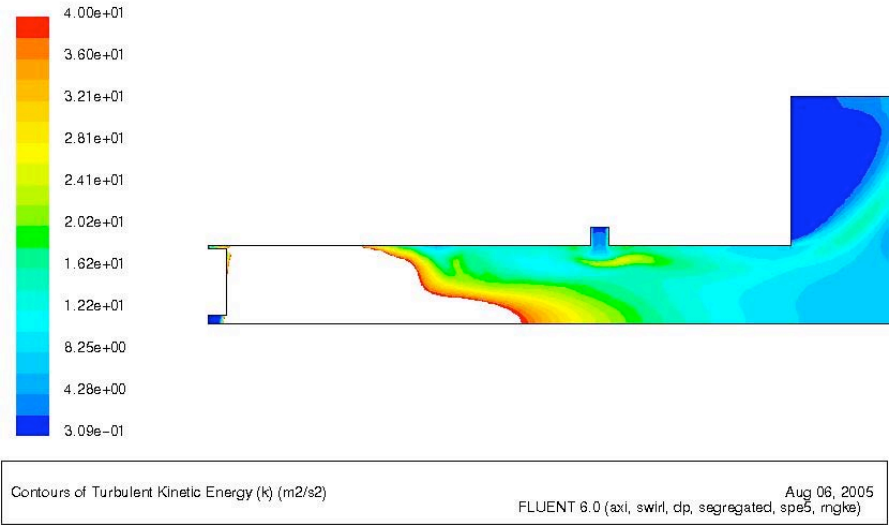
(a)



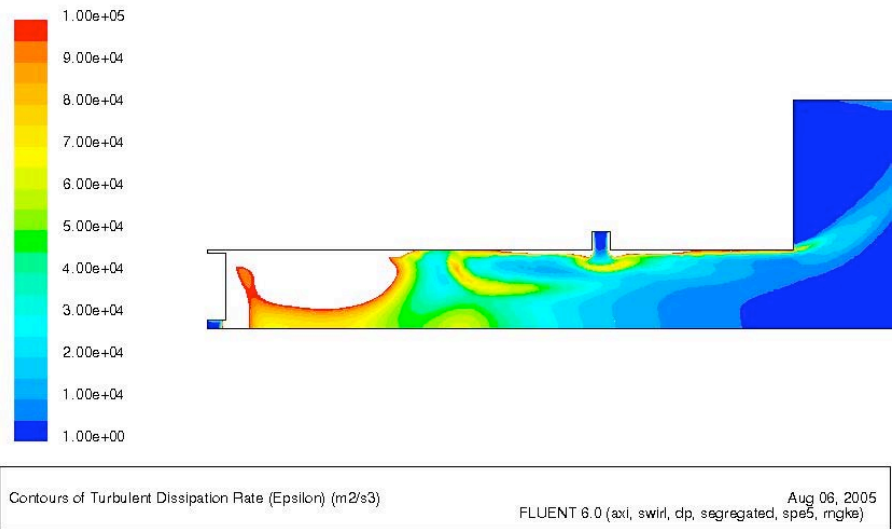
(b)

Figure 6. Same as Figure 2 but for case of methane through swirl port.

Figure 6 shows contours of constant magnitude of the velocity magnitude and the swirl velocity for the same air flows as Figure 2, but for methane through mixed with the swirl air. The swirl velocities are larger, due to the increased flow of swirl gas (which now contains also the methane, about 100 lpm STP in Figure 6, vs 60 lpm in Figure 2). The swirl motion also moves further upstream in Figure 6 than in Figure 2.



(a)



(b)

Figure 7. Same as Figure 3 but for methane injected through the swirl port.

The turbulence parameters,  $k$  and  $\epsilon$ , do not change substantially in the region of the plasma when the location of the methane injection is varied, as can be seen by comparing Figure 3 and 7. Thus, the mixing time is not sensitive of the place of injection of the methane.

However, the methane concentration profile changes substantially in the two cases. Contours of constant methane concentration are shown in Figure 8 for methane through the swirl port. The gradients are in the opposite direction from that of figure 4, with highest concentration near the wall and smallest near the axis.

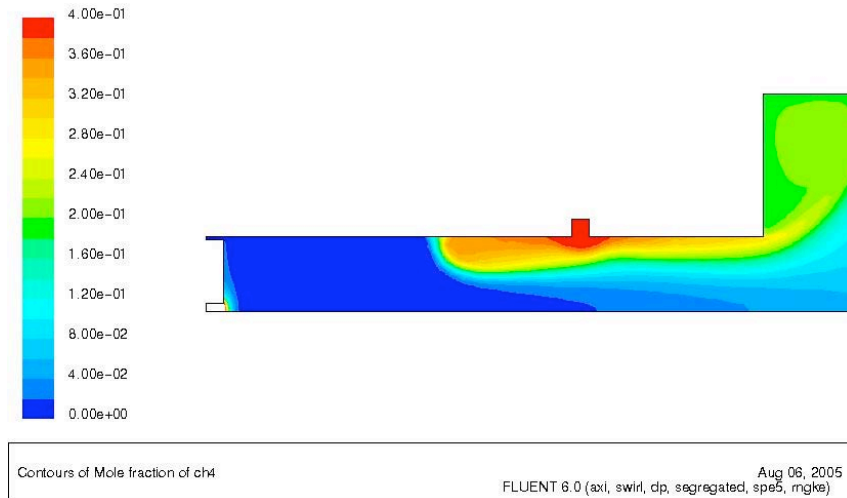


Figure 8. Molar concentration of methane for the case of methane premixed with swirl air.

Figure 9 shows the molar concentration of methane at the location of the upstream and downstream electrodes. As opposed to the case shown in Figure 5, the gradients in the methane concentration are small near the region with stoichiometric methane/air mixture (at around a radius of 0.055 m), which results in a larger fraction of the methane near combustion conditions, and should be better suited to two-stage reforming. The location of the stoichiometric conditions is not that different from the case shown in Figure 5, but it is substantially larger because the gradients are smaller.

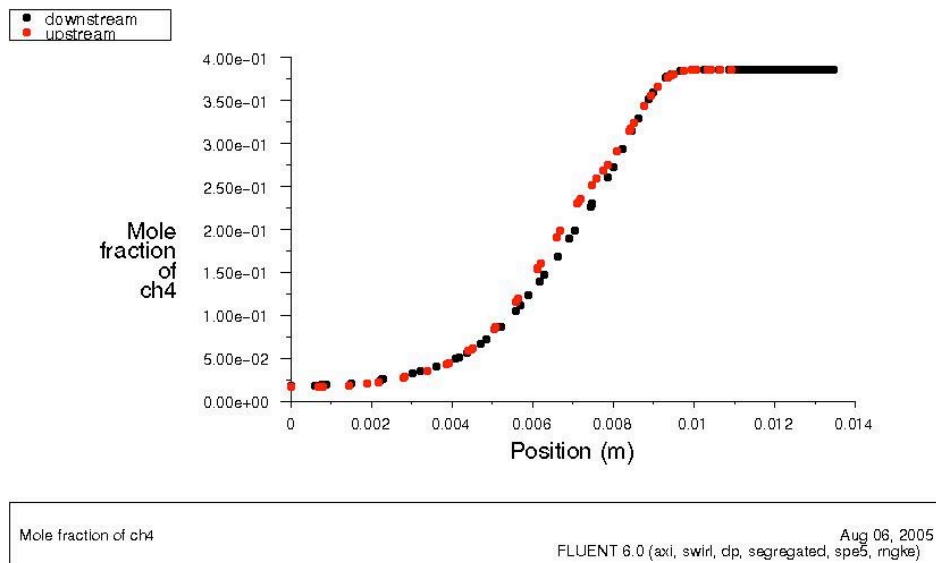


Figure 9. Radial concentration of methane at the location of the upstream and downstream electrodes.

In this case, there is a difference between the upstream and downstream planes, as the methane is part of the swirl flow, and some of it moves upstream while the rest moves downstream.

Thus, the conditions generated in the case of methane premixed with the swirl air are more conducive to two-stage reforming than that for axial injection of methane. Results not shown in this paper indicate that premixing the methane with the wall air has similar methane concentration profiles than the case with axial injection, and thus should have comparable reforming characteristics. It has been experimentally shown [3,4] that the case of methane through the swirl port results in improved reforming (defined as methane conversion at a given overall O/C and at a given power).

## **Conclusions**

Computational fluid dynamics tools have been used to investigate the effects of alternative injection points for the fuel, in this case, methane. The purpose was to determine the characteristics of the air/fuel mixture at the location of the plasma, as well as to determine the mixing rates. It was determined that changes in injection point changes significantly the distribution of the methane in the region of the plasma, but does not significantly change the mixing parameters at this location.

This information will be used in accompanying papers to investigate the characteristics of methane reforming in plasmatron fuel converters.

## **Acknowledgements**

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