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CFD Modelling of the Aerodynamics in a Solar-Enhanced Vortex Gasifier (SVG)—Part I. Validation Case

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ABSTRACT

A Computational Fluid Dynamics (CFD) model of a solar-enhanced vortex gasifier (SVG) has been developed. The SVG developed by Professor Aldo Steinfeld's group at ETH Zurich employs a critical quartz window to keep particles in the reactor and control the atmosphere. The motivation for the development of a CFD model is to allow the aerodynamics in the SVG to be optimised and prevent particles from depositing on the quartz window. The present paper reports the validation of the CFD model for an isothermal flow in a solar chemical reactor, chosen due to the lack of data under reacting conditions. The solar chemical reactor chosen for validation has similar swirling flow patterns to those in the SVG and measurements of velocity in this chemical reactor are available in literature. Three turbulence models, namely, a Baseline (BSL) Reynolds Stress model, Speziale, Sarkar and Gatski (SSG) Reynolds Stress model and Shear-Stress-Transport (SST) model are used to simulate the flows in the solar chemical reactor. It is found that the prediction of all three models are in reasonable agreement with the experimental data while the prediction of the BSL and SSG models are slightly better than that of the SST model. The BSL model is also being used to predict the flow in the SVG and some preliminary results are reported in the accompanying paper also presented at the conference.

INTRODUCTION

Solar-driven gasification is an emerging technology to transform low-grade carbonaceous feedstocks into synthesis gas, also known as "syngas". Several types of solar gasifiers have been proposed, developed and tested at the laboratory and pilot scales, e.g. the indirectly irradiated packed bed reactor, the directly irradiated vortex flow reactor and the indirectly irradiated entrained flow reactor (Piatkowski et al., 2011). Of these gasifiers, the directly irradiated vortex flow reactor, which is also called the solar enhanced vortex gasifier (SVG), is found to have the highest energy conversion efficiency (Piatkowski et al., 2011).

Steinfeld and co-workers at ETH, Zurich have developed a laboratory-scale SVG and evaluated it using both experimental measurements and modelling methods since the 90's. Figure 1 shows their SVG (Z'Graggen et al., 2006), which includes a cylindrical reactor cavity, an aperture, a front cone and a quartz window (from right hand side to left hand side in Figure 1). Carbonaceous particles and water/steam are injected from one particle feeding inlet and steam injection ports, respectively. The flow of the steam and particles drives a vortex flow in the reactor as a result of their tangential components of inlet velocities. The concentrated solar radiation passes through the quartz window, then the aperture and is absorbed by the particles in the reactor cavity.

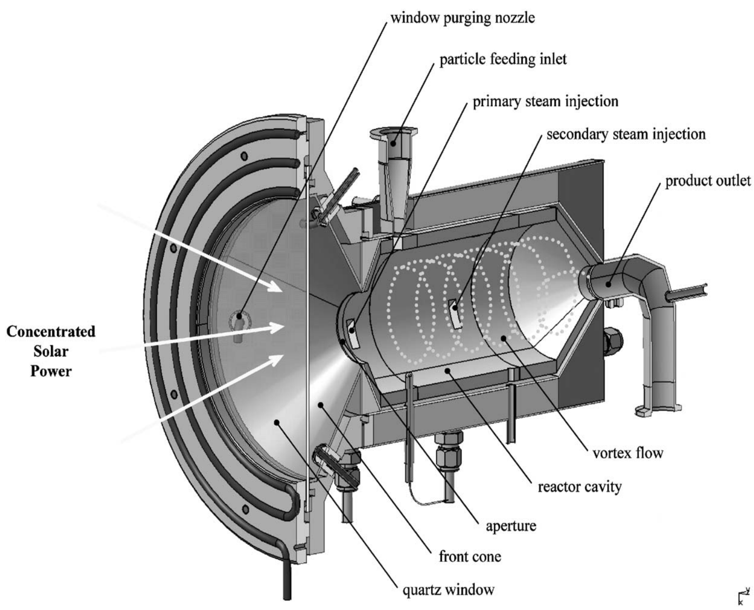

Figure 1: A scheme diagram of the solar vortex gasifier (Z'Graggen et al., 2006).

The main functions of the quartz window are to control the atmosphere in the gasifier and prevent the loss of particles from it. However, the window is vulnerable to the deposition of high temperature particles on it and to the condensation of steam on it. Purging nozzles (shown in Figure 1) are therefore installed into the Front Cone, through which a purge gas is injected, with a view to cooling the window and preventing particle deposition. However, the purging flow is less than 100% effective and any deposition will cause severe damage and eventual failure of the window due to the extreme solar flux, leading to very high particle temperatures. Hence, there is a need for improved understanding of the complex aerodynamics in the reactor and of validated computational models to allow the optimisation of the purge jets within the reactor.

Relative to the experimental methods, CFD can offer faster, cheaper and more detailed information of fluid velocities, temperature distribution and particle concentrations. Nevertheless, to the authors' best knowledge, only few CFD studies of SVG have been reported in literature. Z'Graggen et al. (2008) developed a two-phase reactor model and used it to optimize the geometrical configuration and operational parameters such as the feedstock's initial particle size, feed rates and solar power input. The calculated temperature distribution, steam conversion rates and carbon conversion rates were validated against experimental data. However, no validation of the aerodynamics flow-field, such as velocities and flow patterns were reported, because no detailed data of the flow field are available.

In order to gain the confidence in predicted aerodynamics in the SVG, a CFD model of an alternative solar chemical reactor developed by Meier et al. (1996) was chosen for model development and validation. This solar chemical reactor, shown in Figure 2, has many similar features to the SVG and also generates a swirling flow-field. Furthermore, sufficient details of the geometry and measurements of the isothermal gas flows are reported to enable model development and validation.

In light of the above, the aim of the present paper is to compare for the Meier reactor, the performance of three turbulence models, namely, the Baseline Reynolds Stress Model (BSL), the Speziale, Sarkar and Gatski (SSG) Reynolds Stress Model and Shear-Stress-Transport (SST) model. In particular we aim to compare the predictions against measurements for isothermal air flow speeds at four locations in the reactor.

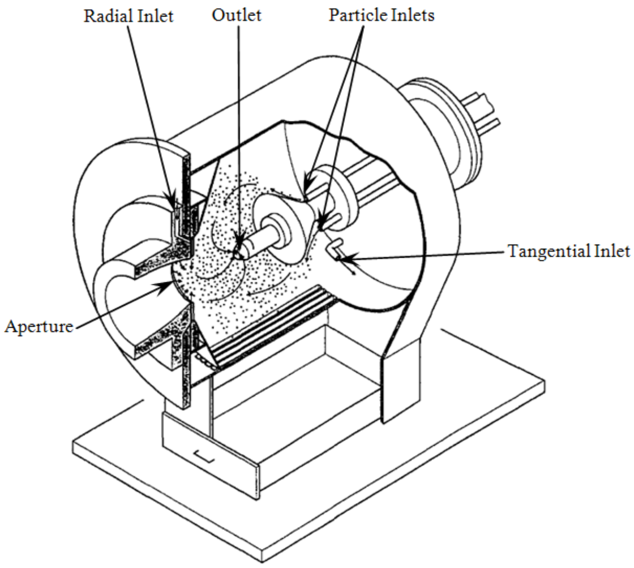

Figure 2: Schematic diagram of the reactor of Meier et al. (1996) chosen for model validation.

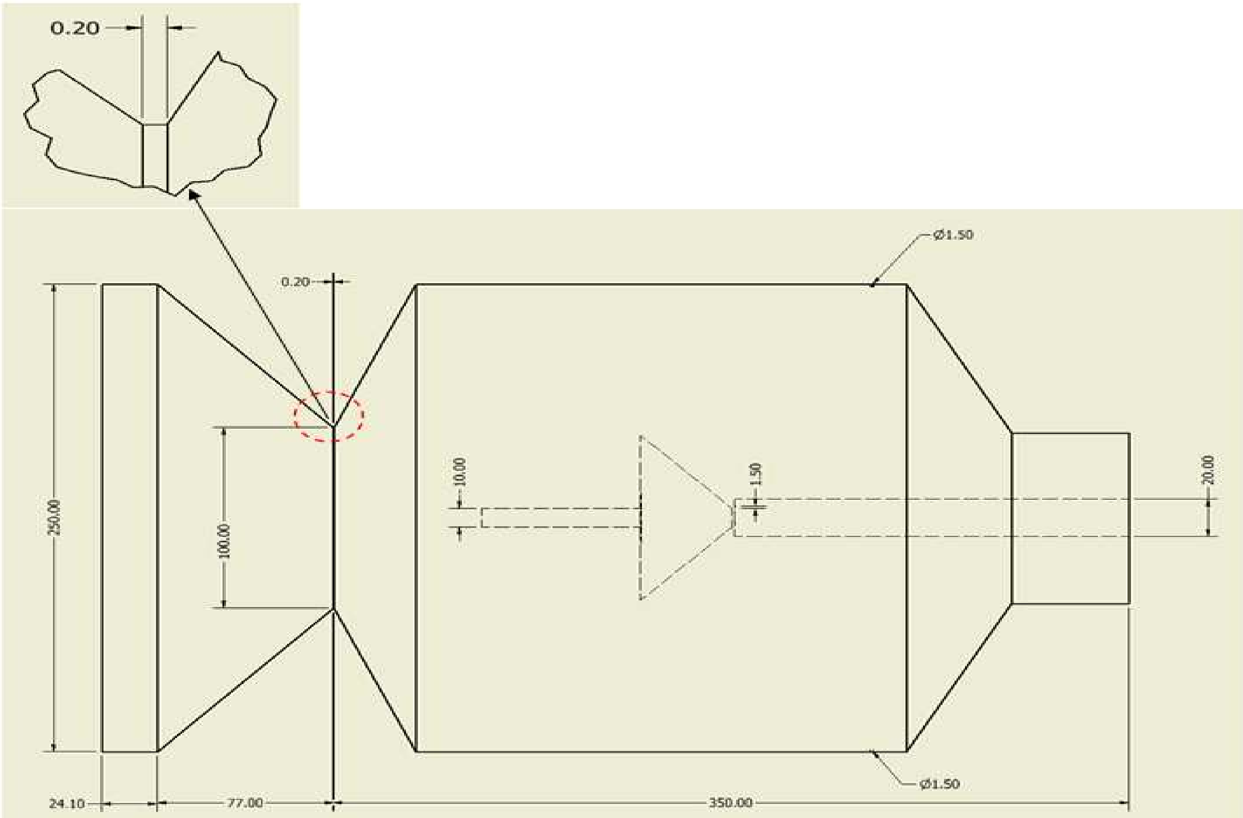

Figure 3: Dimensions of the Meier reactor in mm (Meier et al., 1996).

MODEL DESCRIPTION

Figure 3 presents the dimensions of the Meier reactor. The geometry of the computational model for this reactor was developed using the software ANSYS/Designmodeler 14.0. It is important to note that there is no quartz window in this reactor, so that ambient air can flow in and out of the reactor from the left hand end of the reactor.

ANSYS/Meshing was used to generate the unstructured mesh shown in Figure 4. The mesh quality was checked for skewness, aspect ratio, orthogonality, and expansion factor. The total number of nodes and elements number are 498,262 and 1,579,684, respectively.

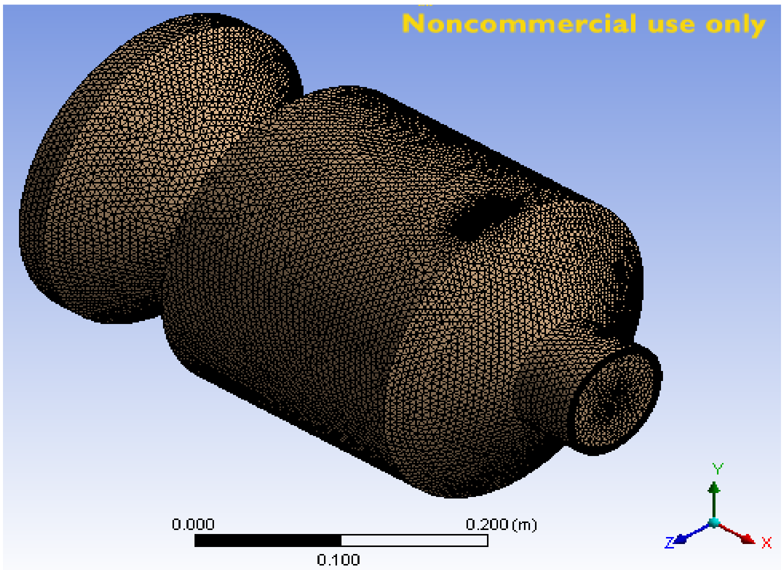

Figure 4: Mesh of the model of the Meier reactor.

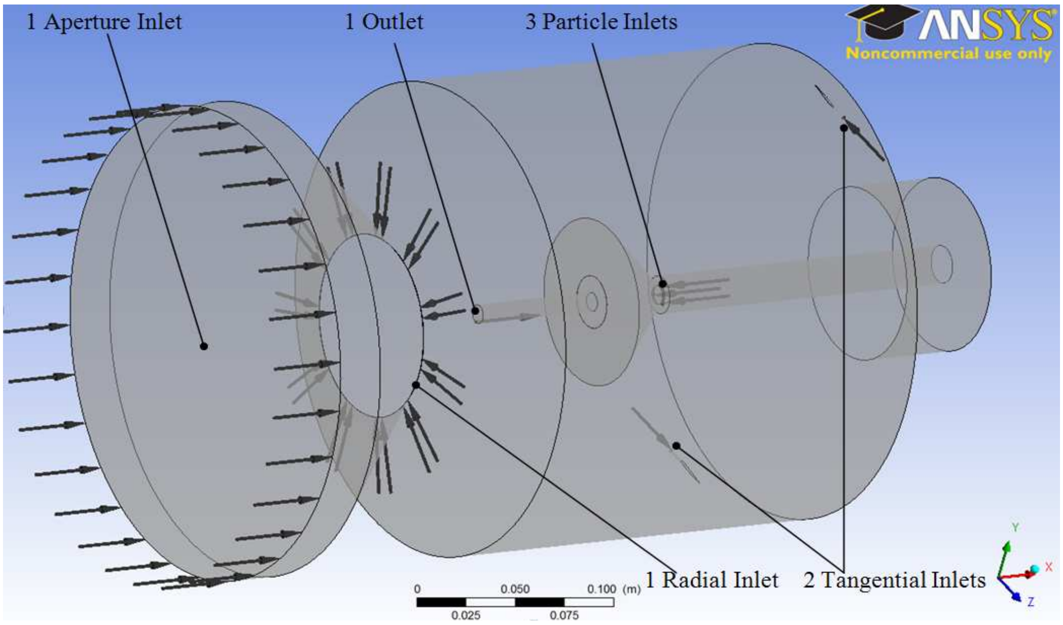

Figure 5: Boundaries of the model of the Meier reactor.

Table 1: Boundary Details.

Boundary type	Boundary Details
Aperture Inlet	Normal velocity 0.0789 m/s
Radial Inlet	Normal velocity 5.7 m/s
Particle Inlets	Normal velocity 122 m/s
Tangential Inlets	Normal velocity 120 m/s
Outlet	Static Pressure 0 atm

The temperature of the isothermal air-flow was set to 25˚C in the model, to match that in the experiment. Air enters in the reactor through three controlled inlets, two tangential and one radial inlet and also as an induced flow through the Aperture inlet as shown in Figure 5. Table 1 lists the detailed conditions for the boundaries. More details of dimensions and boundary conditions can be found in Meier et al. (1996).

The commercial CFD software ANSYS/CFX 14 was employed to predict the steady state air flows in the reactor. The governing equations were discredited using the finite-volume approach.

The turbulence in the air flow was modelled by the three turbulence models, BSL, SSG and SST, respectively. The convergence criteria for the air phase properties was set to 4×10^{-5} of the RMS.

Results

Figure 6 presents the air velocities predicted by the three turbulence models together with the measurements, and also with the previous prediction by the standard k-ε model reported by Meier et al. (1996). Comparisons are shown at the axial locations of x/L=0.086, 0.200, 0.314 and 0.457, with five to seven data points per traverse

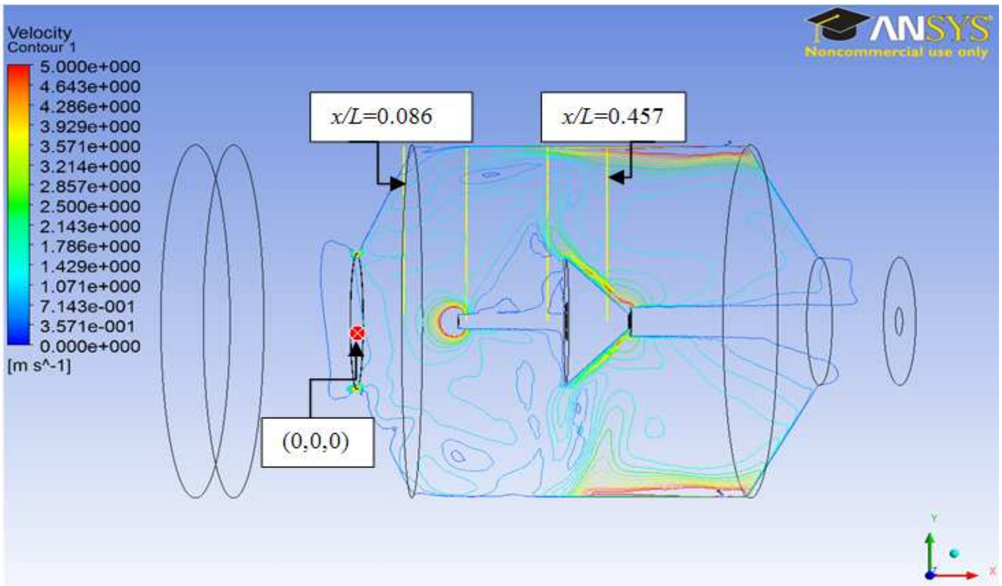

Figure 6: The locations of the four traverses and the predicted velocity contour in the reactor, where *x* defines as the distance from initial point to the traverses and *L* is 350 mm defined as the distance from initial point to the right end of the reactor.

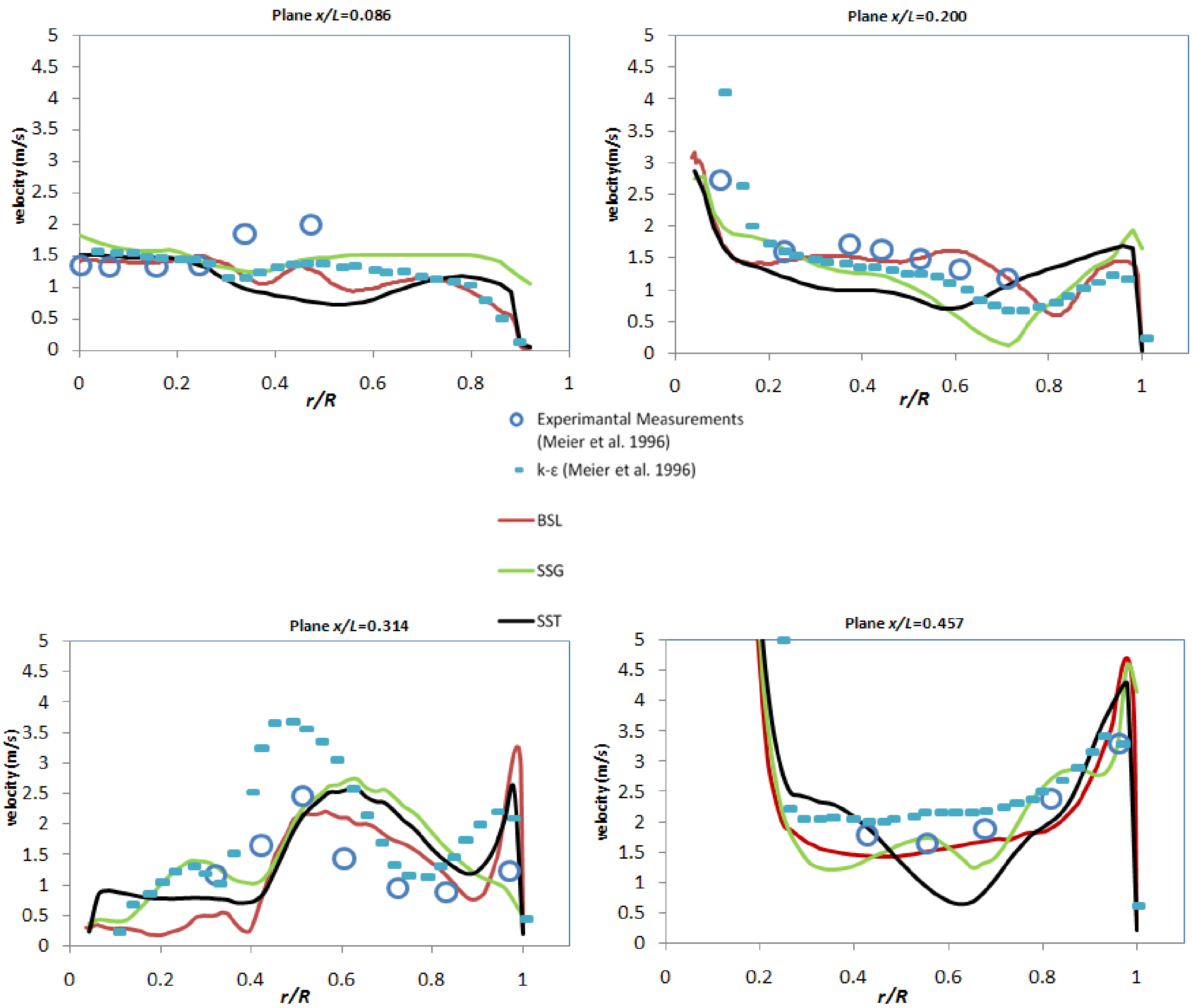

Figure 7: Comparison of CFD predictions with experimental data along four radial traverses, where *r* is the radial distance from initial point and *R* is the radius of the reactor, 125mm.

At *x/L*=0.086, all turbulence models under-predict the velocity at *r/R* =0.32 and 0.48. However, the greatest under-prediction of all models is given by the SST model, which is 44% and 62%, respectively. At *x/L*=0.200, the BSL model gives predictions that agree well with the measurements at seven points. From *r/R*=0.1 to *r/R*=0.6, the SST model generally under-predicts the velocity, with the average value about 39%. From *r/R*=0.37 to *r/R*=0.72, the SSG model under-predicts the velocity, which is about 47% below the measures evenly.

At *x/L*=0.314, BSL and SST models under-predict the velocity for *r/R*<0.51 and over-predict the velocity at locations with *r/R*>0.51. The predicted velocities of the standard k-ε model from the literature are much higher than the experimental results over the range 0.4<*r/R*<1. At *x/L*=0.457, the predicted velocities of BSL show better agreement with the measured data than those of other models.

Generally, all three models give predictions that are in reasonable agreement with the measurements. The flow trends along the four lines in the reactor are captured by the models. Among these models, BSL and SSG models provide the best agreement with the measurements, especially at *x/L*=0.086 and *x/L*=0.457. The slightly better performance by the two Reynolds Stress Models is consistent with the statements in the ANSYS CFX-Solver Modelling Guide (2009), 'the Reynolds Stress models are more suitable to complex flows, especially for free shear flows with strong anisotropy, like a strong swirl component'.

CONCLUSION

All three turbulence models were found to yield reasonable agreement with the experimental data in the Meier et al. (1996) reactor. However, the BSL and SSG Reynolds Stress models were found to give better agreement than the SST model. For this reason, the BSL or SSG model has been chosen to simulate the flow in the closely related SVG configurations. Some preliminary results of this SVG model are reported by Jing Yu, also presented in the conference.

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