

A Numerical Study of the Gas-Particle Flow in Pipework and Flow Splitting Devices of Coal-Fired Power Plant

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Introduction

In power plants using large utility coal-fired boilers for generation of electricity the coal is pulverized in coal mills and then it has to be pneumatically transported and distributed to a larger number of burners (e.g. 30-40) circumferentially arranged in several rows around the burning chamber of the boiler. Besides the large pipework flow splitting devices are necessary for distribution of an equal amount of pulverized fuel (PF) to each of the burners. So called trifurcators (without inner fittings or guiding vanes) and “riffle” type bifurcators are commonly used to split the gas-coal particle flow into two or three pipes/channels with an equal amount of PF mass flow rate in each outflow cross section of the flow splitting device.

These PF flow splitting devices are subject of a number of problems. First of all an uneven distribution of PF over the burners of a large utility boiler leads to operational and maintenance problems, increased level of unburned carbon and higher rates of NO_x emissions. Unequal distribution of fuel between burners caused by non uniform concentration of the PF (particle roping) in pipe and channel bends prior to flow splitting devices leads to uncontrolled differences in the fuel to air ratio between burners. This results in localized regions in the furnace which are fuel rich, where insufficient air is present to allow complete combustion of the fuel. Other regions in the furnace become fuel lean, forming high local concentrations of NO_x due to the high local concentrations of O₂. Otherwise unequal PF distribution can impact on power plant maintenance in terms of uneven wear on PF pipework, flow splitters as well as the effects on boiler panels (PF deposition, corrosion, slagging).

In order to address these problems in establishing uniform PF distribution over the outlet cross sections of flow splitting devices in the pipework of coal-fired power plants the present paper deals with numerical prediction and analysis of the complex gas and coal particle (PF) flow through trifurcators and “riffle” type bifurcators. The numerical investigation is based on a 3-dimensional Eulerian-Lagrangian approach (MISTRAL/PartFlow-3D) developed by Frank et al. The numerical method is capable to predict isothermal, incompressible, steady gas-particle flows in 3-dimensional, geometrically complex flow geometries using boundary fitted, block-structured, numerical grids. Due to the very high numerical effort for the investigated gas-particle flows the numerical approach has been developed with special emphasis on efficient parallel computing on clusters of workstations or other high performance computing architectures.

Besides the aerodynamical interaction between the carrier fluid phase and the PF particles the gas-particle flow is mainly influenced by particle-wall interactions with the outer wall boundaries

and the inner fittings and guiding vanes of the investigated flow splitting devices. In order to allow accurate quantitative prediction of the motion of the disperse phase the numerical model requires detailed information about the particle-wall collision process. In commonly used physical models of the particle-wall interaction this is the knowledge or experimental prediction of the restitution coefficients (dynamic friction coefficient, coefficient of restitution) for the used combination of particle and wall material, e.g. PF particles on steel.

In the present investigation these parameters of the particle-wall interaction model have been obtained from special experiments in two test facilities. The results of experimental investigations has been incorporated into the numerical model. Hereafter the numerical approach MISTRAL/PartFlow-3D has been applied to the PF flow through a "riffle" type bifurcator. Using ICEM/CFD-Hexa as grid generator a numerical mesh with approx. 4 million grid cells has been designed for approximation of the complex geometry of the flow splitting device with all its interior fittings and guiding vanes. Based on a predicted gas flow field a large number of PF particles was tracked throughout the flow geometry of the flow splitter. Besides mean quantities of the particle flow field like e.g. local particle concentrations, mean particle velocities, distribution of mean particle diameter, etc. it is now possible to obtain information about particle erosion on riffle plates and guiding vanes of the flow splitting device. Furthermore the influence of different roping patterns in front of the flow splitter on the uniformness of PF mass flow rate splitting after the bifurcator has been investigated numerically.

Results show the efficient operation of the investigated bifurcator in absence of particle roping, this means under conditions of an uniform PF particle concentration distribution in the inflow cross section of the bifurcator. If particle roping occurs and particle concentration differs over the pipe cross section in front of the bifurcator the equal PF particle mass flow rate splitting can be strongly deteriorated in dependence on the location and intensity of the particle rope or particle concentration irregularities. The presented results show the importance of further development of efficient rope splitting devices for applications in coal-fired power plants. Numerical analysis can be used as an efficient tool for their investigation and further optimization under various operating and flow conditions.

Mesh Generation

For purposes of dispelling ropes the bifurcator contains very complex fixtures called rope splitter and riffle box (see Fig. 1). In detail it consists of a system of 64 differently inclined channels and directly attached to these a system of vanes that lead the flux alternating to the both legs of the bifurcator. If a rope meets the riffle box, it is dispelled by the checkerboard like system of channels in several parts that are then distributed uniformly to the both legs because adjacent channels always lead to different legs. The investigation of the real object is very difficult because experiments in a power plant at work are impossible and experiments for a model in original scale would be too expensive due to the large dimensions of the rope splitting device. Experiments are realized by A. Aroussi at the University of Nottingham on a third scale model. Comparisons with this measurements are discussed further.

The construction of a numerical grid is quite difficult because of the complex structure mainly of the fixtures. First of all the 64 channels inclined against each other (see detail of the grid in Fig. 2) are a serious problem especially for a structured grid that consists of hexahedrons (see detail of the grid in Fig. 4). So the grid in this region has to split alternating into different branches that pass either a left inclined or a right inclined channel. To realize this, a thin layer between the sets of left and right inclined channels is not belonging to the gridded area and form a thin wall of

finite thickness. After passing the channels the grid unites again and must map to the guiding vanes that lead alternating to the left and the right leg of the bifurcator and forms a triangular structure (see detail of the grid in Fig. 3), which is also difficult to grid with hexahedrons. In this case the triangle is divided into 3 quadrangles. The shape of these quadrangles is determined by the guiding vanes sitting on the triangles that lead either to the right as seen in Fig. 3 or (alternating) to the left. The position of the guiding vanes marks the block boundaries in the interior of the triangle that cause another difficulty. Since the grid is structured, the subdivisions on the longer (outside of the triangle) edge are to find on the opposite edge. That means a considerable contraction of the grid within these blocks and simultaneously so-called bad angles that are a general problem in the complex bifurcator geometry.

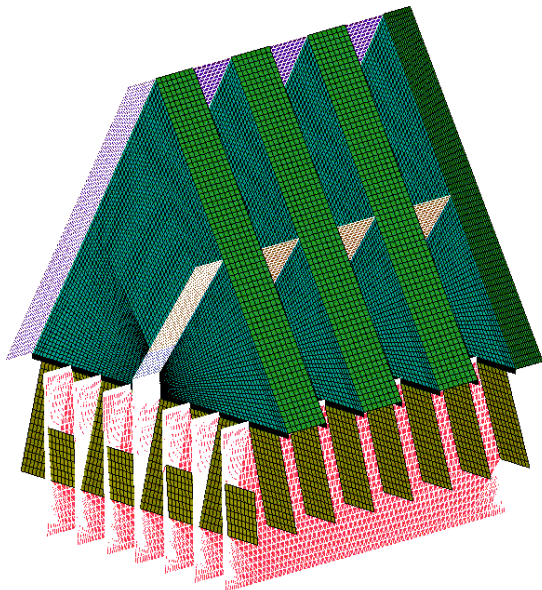


Fig. 1 Whole Fixtures

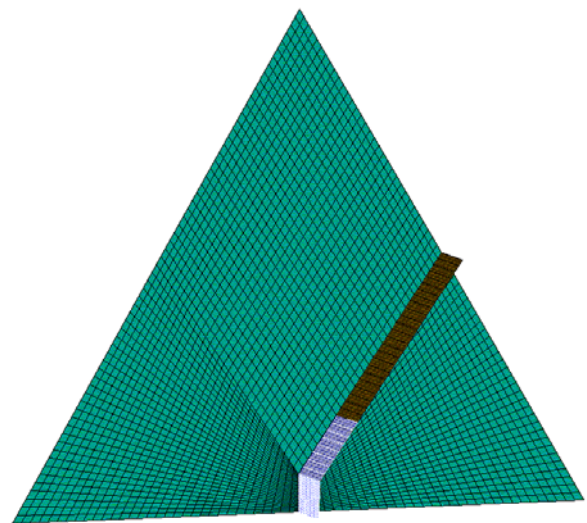


Fig. 3 Element of the Riffle Box

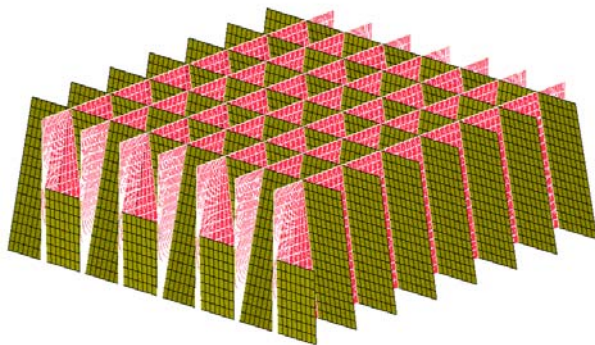


Fig. 2 Grid Detail (Rope Splitter)

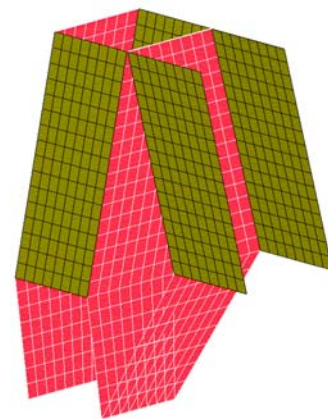


Fig. 4 Element of the Rope Splitter

The result of the grid generation process are grids with up to 4 millions of cells depending on the concrete case of application. The examples differ for instance from the form of the incoming flow region. So the inlet channel geometries had been varied for different real installation conditions of the bifurcator (straight or bended inlet; varying inlet channel length).

Computations and Results

The computations were performed on a cluster of 12 PC with Athlon processors running under the operating system RedHat Linux. The predictions start with an uniformly distributed inlet velocity of 30 m/s. Results of the computations can be seen in Fig. 5 and Fig. 6. Fig. 5 gives an

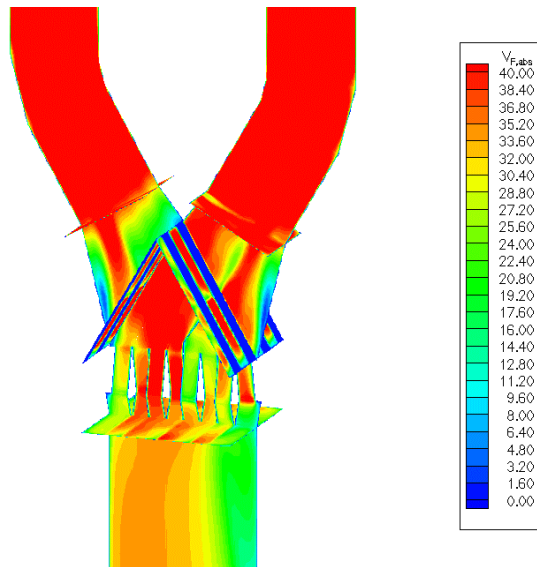


Fig. 5 Velocity Distribution

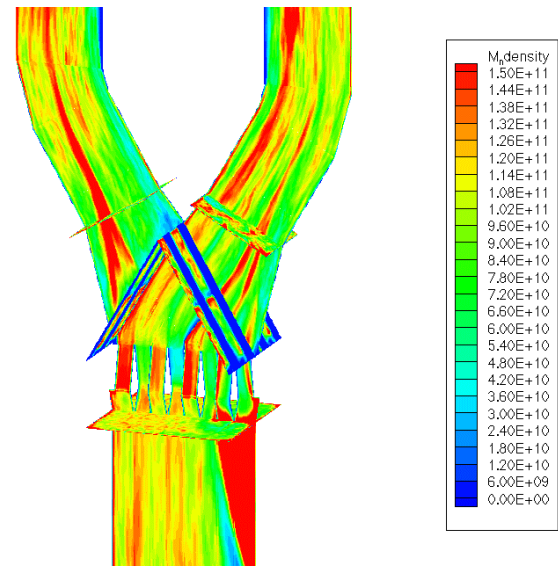


Fig. 6 Particle Number Density

impression of the velocity field in the bifurcating region, when a bend is situated upstream at the input side. Such a bend is used to generate a rope for testing the function of the rope splitting devices. This is to observe in Fig. 6, where the ropes emerging from the bend and the resulting Taylor vortex are dispelled and the particles are distributed to both legs relatively uniformly. Especially the particles of higher diameters were carried to the left because of their higher mass and the resulting higher inertia. The principle function of the bifurcator with the riffle box is good to observe. Although the particles were to find mostly on the left of the cross-section in front of the bifurcator, the riffle box makes sure that the particle mass flow is subdivided nearly uniformly to both legs of the bifurcator. Also to observe is the function of the guiding vanes especially in the upper parts of the riffle box. The particles concentrate near these vanes due to inertial effects and form certain ropes (the red areas in Fig. 6) that will be redistributed upstream over the whole cross-section by particles interaction with the fluid turbulence.

In Fig. 7 the operation of the riffle box is illustrated by drawing a number of particle trajectories. The particles were injected in the stream in a cross section that forms a distinct rope, which would leave the bifurcator completely through one leg in absence of the riffle box. But the rope is distributed relatively uniform to both legs due to two effects: First the rope is dispersed only under the influence of the turbulent motion in the flow and therefore enters more than one of the 64 channels. Secondly the rope is distributed by the riffle box to the both legs, because a particle is guided through the other leg, when it enters an adjacent channel even in the case when the rope is situated very close to one wall (or even in a corner). This situation can be found e.g. when one or more bends are close to the inlet of the bifurcator.

In addition to the computations of the bifurcator with internals a variation without internals, but with a relatively long pipe with three bends at the input side was investigated (see Fig. 9).

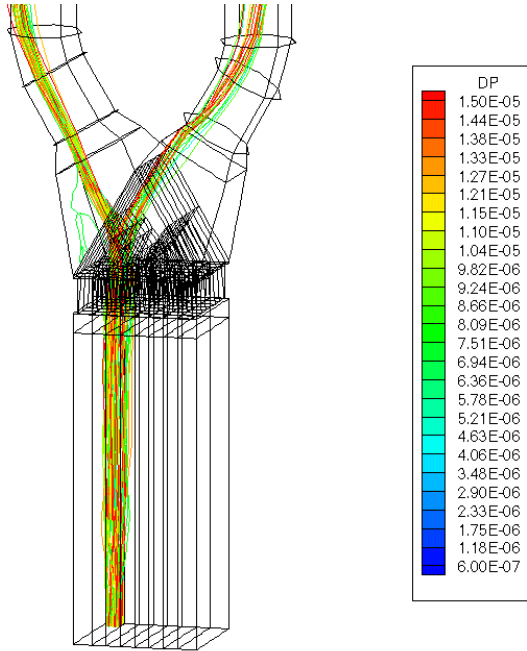


Fig. 7 Rope Splitting by the Bifurcator

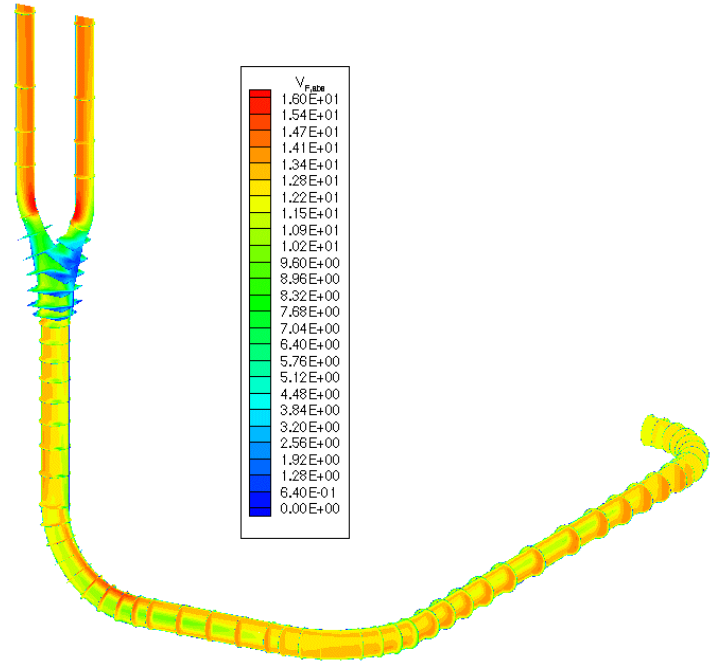


Fig. 8 Bifurcator with Pipework; Velocity Distribution

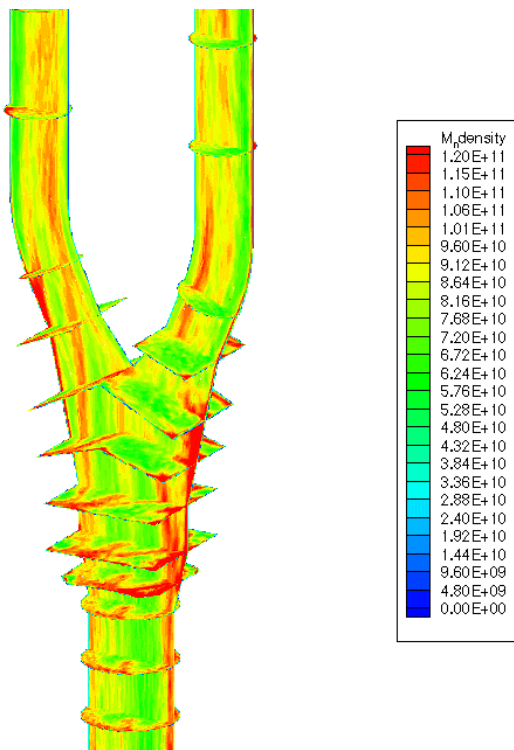


Fig. 9 Particle Number Density in a Bifurcator without internals (Detail)

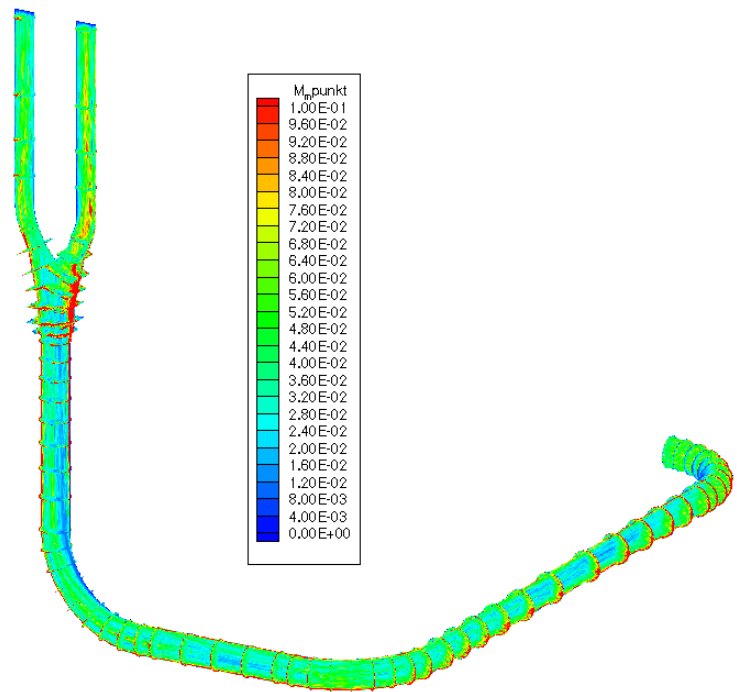


Fig. 10 Mean Particle mass Flow in a Bifurcator without internals

This geometry was chosen, because for this case exists measurement data (obtained at Nottingham University by Aroussi; for comparison see below). Also the rope generation by bends is illustrated in this case. Besides the velocity distributions a number of statistical quantities of the particle phase was investigated. For example the distribution of the mean particle number density (see Fig. 9) was predicted by tracking $450 \times 450 = 202500$ particles through the geometry.

Obviously is the complex structure of the velocity field. Starting with the profile of a standard pipe flow it changes strongly by the three bends. Induced by the first bend two vortices emerge, the so called Taylor vortices. Under the influence of the centrifugal force these vortices are situated behind the bend at the outer side of the pipe. The next bend causes the same effect and additionally induces a rotation in the flow around the main-axis of the bifurcator. This rotation is essentially to observe in the part of the pipework that leads after the last bend directly to the bifurcation. The two vortices emerged by all the bends rotate around the bifurcator axis and therefore two “jets” hit the bifurcator. The rotating flow in front of and in the bifurcator is to observe in Fig. 9 to Fig. 12.

In accordance with the experimental conditions, the gas volume flow rate through the two outlets is set to equal rates. Together with the two rotating “drilled” jets this restriction may lead to complicated situations in the flow field. This is important for the discussion of the results of the predictions of the particle phase, mainly the particle mass flow rates to the outlets compared with the experimental results.

The particle number density distribution in Fig. 9 shows the preferred location of the particles. The predictions for the particle phase were performed with two different particle materials. So a coal (PF) usual for power plant conditions is used. Particle size distribution was measured with a Malvern particle sizer. On the other side predictions are made with ceramic hollow spheres used for the experiments on the bifurcator test rig in Nottingham. The size distribution is also based on an analysis made in Nottingham. Because the particles are relatively small and light, they follow essentially the flow of the gas. Good to observe are the two drilled ropes that enter the bifurcator in accordance to the remarks made before concerning the gas flow. The particles form two ropes that move to the bifurcator in the last strait part of the pipe as a double helix.

A major problem in such large 3D Lagrangian particle simulations is the statistical reliability of the obtained results. Even the high number of 202500 particles can not ensure that every grid cell is crossed by at least one particle. The comparison with a calculation with 102400 particles, however, shows that the chosen number is completely sufficient to point out the behavior of the particle phase. For integral quantities as the mass flow rate through the outlets still fewer particles give quite reliable results. For the two outlets of the bifurcator we obtained the particle mass flow ratios 48.14% : 51.86% with 22500 particles, 48.93% : 51.07% with 102400 particles and 48.74% : 51.26% with 202500 particles.

Comparison of the numerical results with measurements

Comparisons of the measured and computed velocity distributions are possible on the basis of the PIV-measurements made at Nottingham University. There were measured velocity profiles in several cross sections in the 6” main pipe (inlet side) as well as in the both 4” pipes behind the bifurcation (output side). The location of the measuring points is to see in Fig. 11 (drawing from Nottingham University).

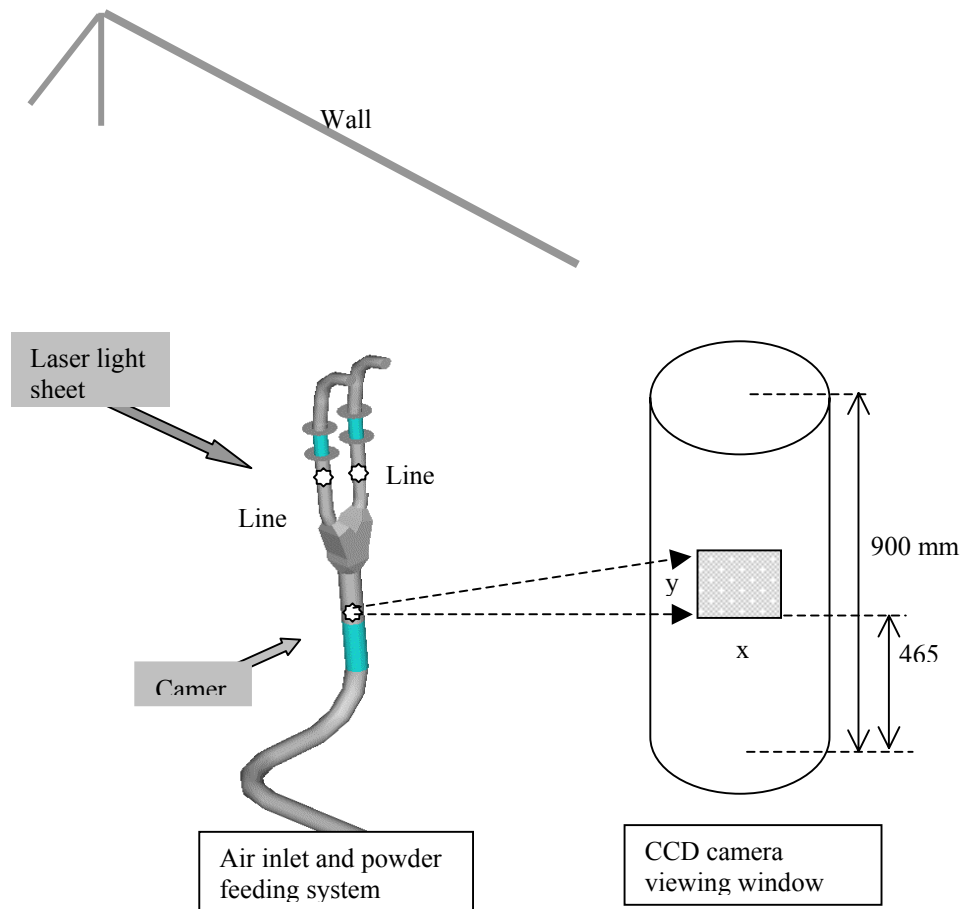


Fig. 11 Principal Location of the Measuring Points

At first some general remarks on the comparability of the appropriate results. A general problem is the compliance of the boundary and initial conditions in the experiment and the computation as well. So we require a uniform distribution of the velocity over the cross section of the inlet pipe. That's why we tried to compute the flow from a point relatively far from the bifurcator entrance region. But it isn't fully to obviate that we have influences of the pipework before our input cross section on the flow as well as such from the particle feeding unit.

The observed flow pattern in our investigated model with three bends is a rotating double rope or a so called double helix and cause an unsymmetrical velocity field. Due to this reason, the velocity distributions on a certain line in a certain cross section are highly influenced by the angular position of this double helix. Because we have the described differences in the boundary conditions, the ropes won't have exactly the same position in the experiment and the computation, respectively. Under this point of view, the relatively high differences between experiment and computation are to be seen and declared.

Fig. 12 and Fig. 13 show the comparison of longitudinal and transversal velocity component, respectively, in the right outlet 4" pipe. The relative big differences especially in the transversal case are to consider under the aspect of small absolute values of this component. When the curves are shown in the same measure as in figure 2 (maximum value 15 m/s), the curves are much closer together as in the presentation displayed below.

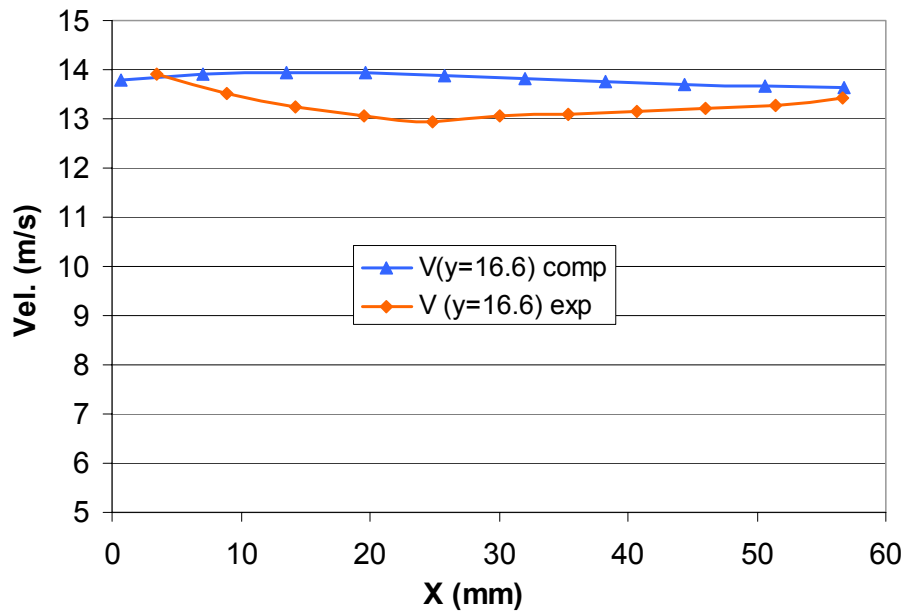


Fig. 12 Comparison of computed and measured velocity (longitudinal component) in pipe 1

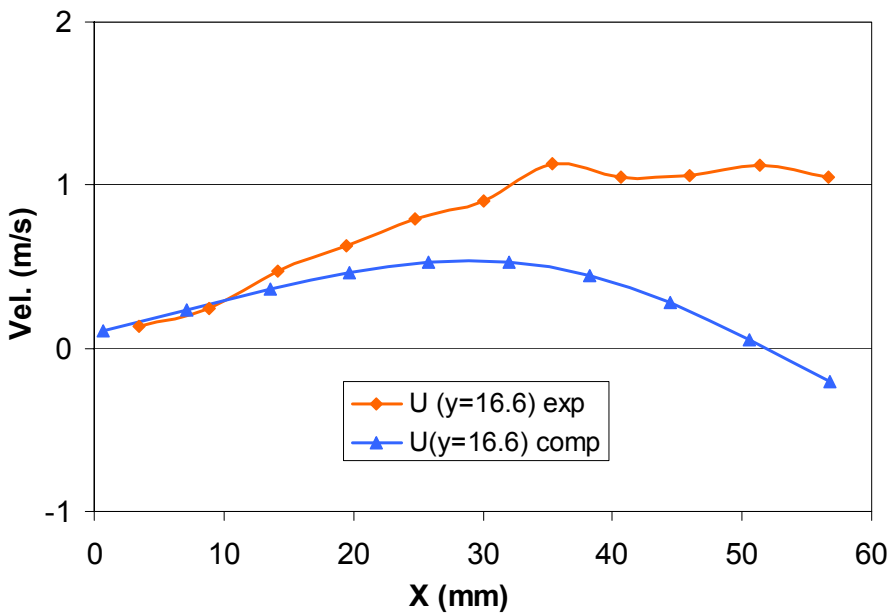


Fig. 13 Comparison of computed and measured velocity (transversal component) in pipe 1

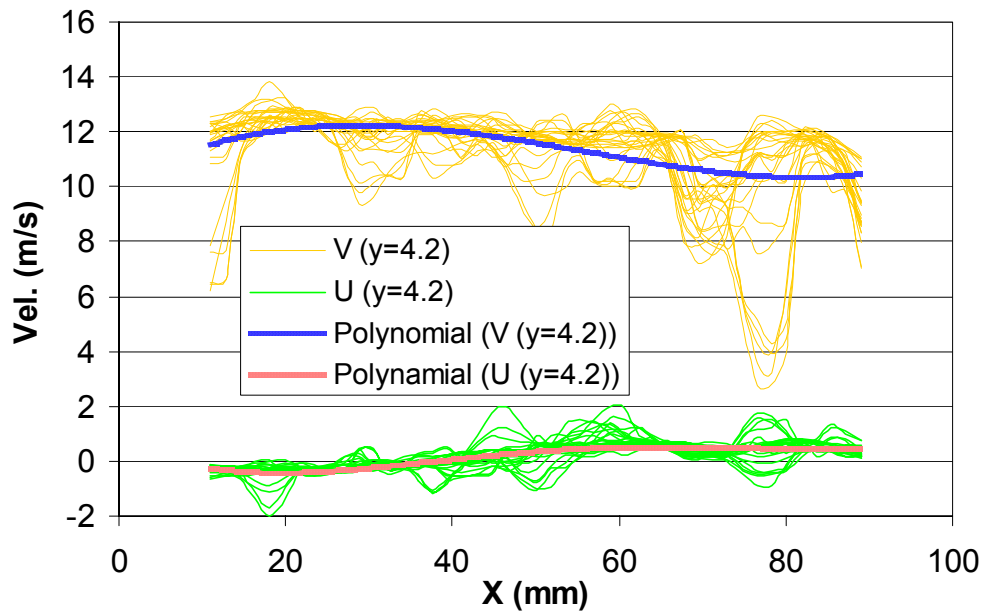


Fig. 14 Measured longitudinal and transversal component of the velocity in pipe 3

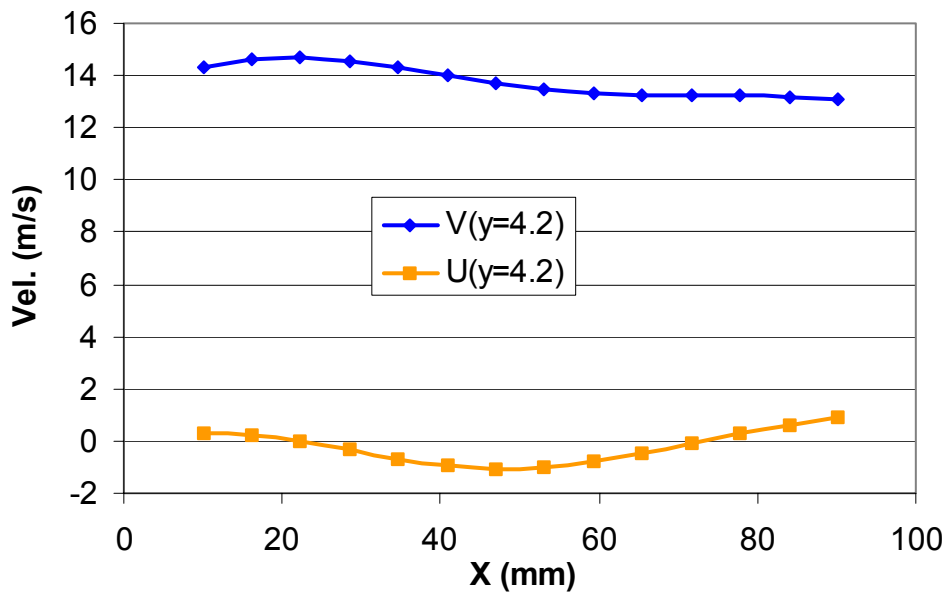


Fig. 15 Computed longitudinal and transversal component of the velocity in pipe 3

It is to state, that we are able to reflect the principle behaviour of the flow, but cannot achieve consistence in all detail. So the values of computed and measured velocities in the cases shown in

Fig. 12 and Fig. 13 are relatively of the same order, but the trend of the curves somewhat differs. Otherwise we have the problem in Fig. 14 and Fig. 15, that the trend is relatively good displayed but the order of the absolute values differs more than in the case of pipe 1.

Conclusions

The underlying goal of the predictions of the bifurcator was to investigate and to verify the principle function of this component in the complex pipework of a coal fired burner. Thereby the dispelling of ropes, emerging mainly from bends in the pipework, was of special interest. It is to state, that the variant with the complex inner fittings consisting of rope splitter and riffle box is very qualified for dispelling ropes. Even when a rope is situated close to a corner of the incoming channel, it is nearly completely dispelled and the mass flow is divided relatively uniformly to the both outlets. This has to be paid with a higher pressure loss than in the case with non internals.

The numerical predictions are a well suited and effective instrument to investigate the flow of gas and particles in the bifurcator and to support the experiments and make them more effective. The behaviour of the flow is principally properly displayed. For example the double helix ropes emerging mainly from the bends in the pipework downstream from the bifurcator can be observed in our results. The comparison of distinct velocity profiles is somewhat difficult because of the reasons given above.

Acknowledgements

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