Particle-laden flow through an open bifurcation in a vertical duct with rectangular cross-section

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A Lagrangian formulation for dispersed multiphase flow through pipes in parallel proved unstable in steady-state CFD simulations. This paper describes a series of experiments performed to ascertain whether the numerical instability is due to a true transient behaviour that a steady-state simulation will not capture. No evidence of any transient behaviour was found in the tests, but there was a preferential flow of particles through one of the branches, despite a balanced air flow at the beginning of the tests. The tests highlighted the significance which manufacturing tolerances may have on the flow split in parallel conduits.

Introduction

A uniform fuel flow to individual burners is very important in the operation of pulverized coal (PF) fired boilers. Failure to do so, will result in an incorrect fuel/air ratio, inefficient and unstable combustion, slagging, and high flame temperatures at furnace exit, which reduce the creep life of the boiler. As the price of computational power reduces, computational fluid dynamics (CFD) is used increasingly to improve the PF distribution in boilers. Traditionally, a Lagrangian approach to the dispersed phase is used to simulate particle laden flows.

At a particular power station, the mills have two PF pipes attached to the classifier, and these two streams are split into four by an open bifurcation to feed four wall-mounted burners. The PF distribution at this station is notoriously bad.[1] The origin of the problem on this plant is believed to be differences in PF pipe lengths from mill to individual burners, and the lack of the usual measures,[2] such as riffle boxes, to ensure an even PF distribution at the burners. A CFD simulation[3] was performed to identify the root cause of the poor PF distribution and to find ways to improve it. As part of the investigation, a CFD simulation of the upper part of the mill, classifier, and entire PF pipework was carried out. In this particular case, the Lagrangian formulation failed to produce a stable steady-state solution. The numerical simulation indicated that particle flow after the bifurcation is preferentially through one leg, but as the flow and pressure drop through this leg increases, the flow switches to the other leg. This behaviour did not show any clear periodic behaviour, nor any hint of convergence, as shown in Figure 1.

No measurements were available from the actual plant to confirm this observation, and it was decided to verify this presumed transient behaviour experimentally. Conducting such tests on the plant is difficult, since

- access to the plant is limited
- it holds a high safety risk
- control over test parameters is limited
- test equipment must be robust enough to withstand an aggressive environment
- test work should not interfere with the normal operation of the plant

In this particular case, it was cost effective to modify the research group's existing two-phase flow test rig.[4] This paper describes the measurement of air flow laden with small glass beads through an open bifurcation in a vertical duct with a rectangular cross-section. Numerical simulations were conducted, in parallel with the experimental work, to determine whether the inherently more stable Euler/Euler formulation is a viable alternative for PF flow modelling. These simulations were conducted for a single particle size due to the huge demands on computer storage if multiple particle sizes are used.

Literature survey

Work reported in the literature can be divided into three general classes, namely, those that measured bulk properties of particle laden flows, those based on particle image velocimetry (notably Laser-Doppler anemometry) and work, which started to emerge only recently, based on direct numerical simulation of turbulence.

Patterson[5] determined "friction factors" for particle laden flows, analogous to those of single phase flows, in vertical and horizontal pipes in a full scale test rig. Scheerer[6] used a 4:1 scale model to design a four outlet pulverized coal distribution box. His model was made of glass to allow flow visualization. Both studies were restricted to the use of primitive variables such as air-flow rate, particle-feed rate and (static) pressure drop. Even with the best distribution box, Scheerer was unable to obtain a uniform PF distribution in the four outlets. Cook & Hurworth[7] used a 1:27 scale model (glass) to study particle settling, a phenomenon commonly known as roping. Vetter & Vetter[8] developed an empirical model to balance air and PF flows in parallel piping, and applied their model with reasonable

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success in several case studies, whilst Kass & Kaulitz[9] developed a method for measuring air and PF distribution on a working power station. This study contains elements of the work of Patterson[5] and Scheerer,[6] but with a data acquisition system capable of capturing transient behaviour.

McClusskey *et al.*[10] expanded the work of Cook & Hurworth,[7] and used particle image velocimetry to study roping. Frank *et al.*[11] used fibre optics, and Sommerfeld *et al.*[12] and Sommerfeld[13] used Laser-Doppler anemometry to study the collision of small particles against rough walls. A review of flow visualization techniques for particle-laden flows is given by Ervin *et al.*[14] These methods essentially capture the behaviour of individual particles, but are not suitable for the current investigation, since they are limited to extremely low particle concentrations. In the present study, a high particle concentration was required to test the hypothesis that the instability in numerical simulations is due to the particles' influence on the air flow.

Direct numerical simulation was used by Squires & Eaton[15] and Eaton & Fessler[16] to study the interaction of particles and fluid turbulence. The demands this places on computational resources is enormous for all but the simplest configurations, and at this stage, it should be regarded as a future alternative to laboratory experiments, especially when the scale of the variables to be measured becomes so small that conventional experimental methods fail. It was not relevant for the tests described in this paper.

Description of test facility

The high particle to air mass-flow ratios typically encountered in PF producing and transport plant (a typical air/fuel ratio for flow through the mill ranges from 1.5:1 to 2:1), ruled out the use of optical measuring techniques. Instead, only the pressure drop, air flow rates, and particle mass flow rates were measured.

Tests were conducted with spherical glass beads with a size distribution between 38 and 53 μm. Glass beads are of a uniform density, and the narrow size range permitted the use of a single particle size to represent the actual particles in numerical simulations that were carried out in parallel will the experimental work. The sample used in these tests was extracted from a larger sample that has an approximately Gaussian distribution with mean particle diameter of 43.5 μm and a standard deviation of 20.5 μm. A Malvern particle size analyser was used to determine the particle size distribution. A quarter of the sample mass fell within the size range 37−50 μm. The closest standard sieve sizes to extract particles from close to the mean of the sample were 38 and 53 μm, as demarcated by the dotted box in Figure 2. A Gaussian distribution, with the same mean and standard deviation as the actual sample, is represented by the continuous line.

The modular test facility comprised a horizontal inlet section, which was long enough to ensure fully developed flow by the time the flow reached the particle feeder, a test section, particle extraction system, extraction fan and a variable speed motor, as shown in Figure 3. The air inlet velocity was measured with a Pitot tube on the centre line of the inlet section. Ambient temperature was measured in the inlet section with a thermocouple, and the ambient pressure in the laboratory was recorded for density calculations. Both the inlet and test sections were made of 50 mm × 100 mm × 1.6 mm standard rectangular steel tubing.

The particle feeder had a variable speed motor-driven screw feed in the bottom of the bin, and the screw speed determined the particle feed rate. A stirrer in the feeder bin mixed the particles, and ensured an even feed rate by preventing bridging and rat holes forming in the bin. Usually, this would not be a problem with glass beads, but occurs quite frequently when working with PF. The feeder bin was suspended from a fixed cantilever beam. A load cell in the suspension cable recorded the total bin mass.

At the inlet of the vertical test section, the flow was turned through 90°, and then had an uninterrupted run of 3.2 m before it entered the 60° open bifurcation. The test section was made of the same tubing as the inlet section. Static pressure tappings were installed at 0.63 m intervals (ten hydraulic diameters) before and after the bifurcation. Differential pressure transmitters attached to these tappings converted pressure into a 4−20 mA signal, and these were in turn converted into 0−10 V d.c. signals for the data acquisition card. All data were logged continuously on a PC. After the bifurcation, the flow turned downwards through 180°. Initial tests had shown that even though the downstream sections are identical, the air flow through them differs. Two ball valves fitted at the bottom of the downcomers ensured a balanced air flow through the two legs.

From the test section, the two particle laden streams were fed into high-efficiency cyclones, to remove the particles. Particles were collected in two large bins at the bottom of the cyclones, and the bins were weighed before and after each test. With the available equipment, continuous measurement of the bin mass during tests was not possible.

Downstream of the cyclones, the air flow through each leg was measured with orifice plates, mounted in long, straight sections of stainless steel tubes. These orifice plates were deliberately mounted downstream of the cyclones, since no standards on their use with particle laden flows could be found. Finally, ultra fine particles were filtered out of the air streams by a sub-micron paper filter, and the air was exhausted through an extractor fan to atmosphere.

The different modules of the facility were assembled by bolted flanges, with rubber packings to ensure an airtight seal. Air flow through the test facility was controlled by a fan and variable speed motor. The rig, that was designed for tests with PF, was operated under negative pressure, to prevent dust leakage to the environment.

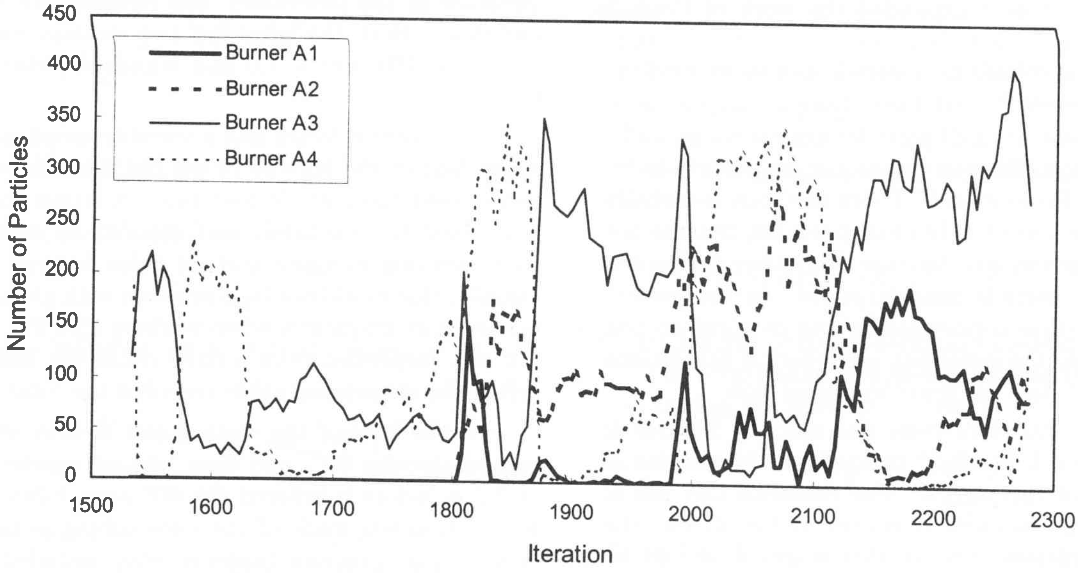

Figure 1 Predicted PF distribution at burner mouth (all particle sizes)

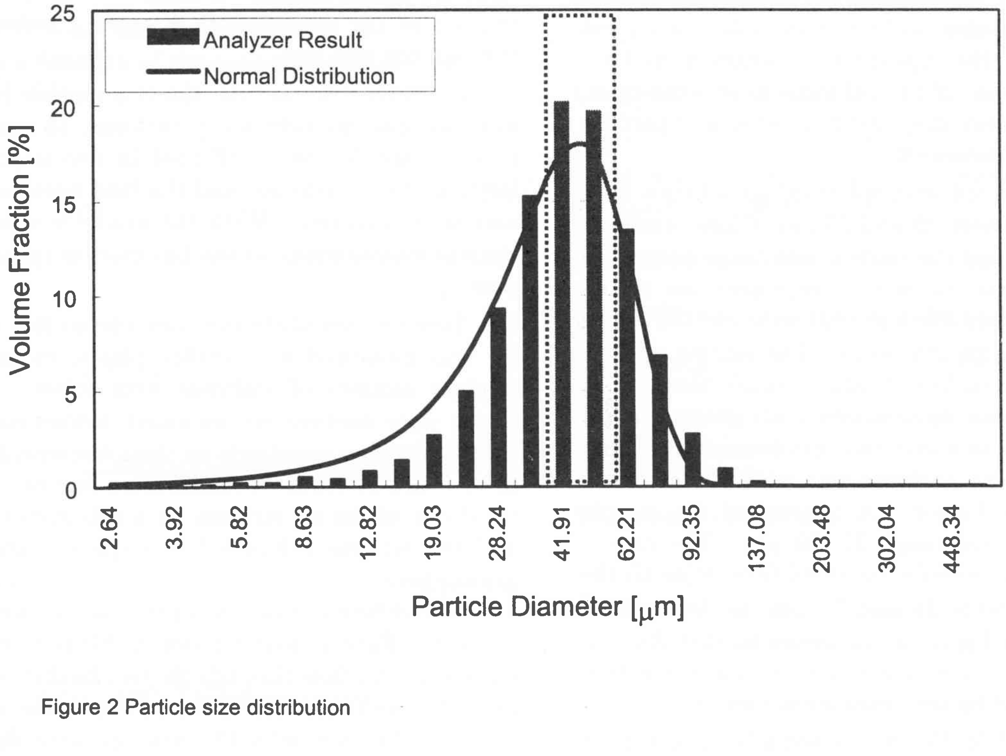

Figure 2 Particle size distribution

Test procedure

Calibration records for all equipment were kept in accordance with the requirements of ISO 9002. Before a series of tests, these records were consulted to ensure that calibration certificates were still valid. Load cell and scale readings were confirmed against a set of test weights.

The feed rate from the particle feeder had to be determined for each particle type to correlate screw speed (measured variable) against particle mass flow rate. To calibrate, the feeder bin was cleaned thoroughly with compressed air, and then loaded with approximately 10 kg of the particles to be used in the tests. The feeder was then emptied at a fixed screw speed into a bucket on a platform scale. Readings from both the load cell and scale were recorded continuously, and a feed rate extracted from it. Identical tests were conducted at different screw speeds, and a correlation of feed rate as a function of screw speed was therefore obtained. A linear relationship exists between these two variables. The feed rate is required to determine the correct particle to air mass flow ratio at which tests should be conducted.

The pressure drops across the two orifice plates were compared before each test, and the right-hand side flow control valve adjusted until the pressure drop across the two orifices, and hence air flow through the branches, were balanced.

Once the combination of feeder speed and air inlet velocity that will yield the desired test condition was known, testing could commence. Before the test, both cyclone bins were cleaned thoroughly and weighed. All zero checks were performed and recorded. The feeder speed was set, the fan started and its speed increased until the required air inlet velocity was obtained. Clean air data were recorded for approximately one minute, before the feeder was started. Two-phase flow data were logged continuously, even after the feeder was empty, but when the fan was still running to sweep possible particle deposits away. After the tests, both cyclone bins were weighed, and particles sieved to determine whether a significant amount of particle breakage had occurred during the tests. Data for analysis were extracted from a test period when the feed rate was linear.

The particle to air mass flow ratio was prescribed for each test. Due to the short duration of tests (approximately 5 minutes), it was impossible to adjust the air flow during tests to obtain the correct particle loading, and an iterative procedure was used instead. Air was drawn through the rig, and the velocity in the inlet section recorded. When particles were introduced into the air stream, the air inlet velocity invariably dropped due to the added resistance of the particles. The new air inlet velocity and drop in air inlet velocity were both recorded. Then the particle feeder was loaded again, and the initial value of the air inlet velocity adjusted accordingly. The iterative loop was repeated until the required particle to air mass flow rate was achieved. Once the air inlet velocity that gave the correct particle load was known, actual testing could commence. Each test was followed by a re-run at the same conditions, and test results were compared for repeatability. A listing of averaged test data is presented in Table 1.

Table 1 Listing of averaged test data

Variable	Test 1	Test 2	Test 3
Air inlet temperature, °C	25.33	24.39	23.63
Ambient pressure, Pa	88 775	88 775	88 954
Relative humidity, %	27	27	27
Air inlet velocity, m/s	26.06	26.29	26.75
Air inlet mass flow, kg/s	0.1222	0.1236	0.1265
Particle feed rate, kg/s	0.0622	0.0622	0.0622
Particle to air mass flow ratio	0.509	0.503	0.492
Δp_a, left-hand split, Pa	13.41	17.02	16.10
Δp_{ap}, left-hand split, Pa	−6.19	−5.94	−12.95
Δp_a, right-hand split, Pa	35.04	37.19	37.83
Δp_{ap}, right-hand split, Pa	35.17	35.93	41.85
m_a, left-hand orifice, kg/s	0.0617	0.0625	0.0643
m_{ap}, left-hand orifice, kg/s	0.0614	0.0622	0.0606
Particle mass, left hand, kg	9.06	10.50	8.86
Particle mass, right hand, kg	9.96	11.59	9.70

Discussion of data

When particles are released, the pressure drop across the right-hand side orifice plate drops by 1 kPa, from an initial reading, with air flow only, of 10 kPa. This indicates a reduction in air flow through that branch. The pressure across the left-hand side orifice plate remains virtually the same, even though the flow through the two branches was balanced before the test. This happened in all three tests. On average, the air flow through the right-hand branch was 9.5% lower than the flow through the left.

Samples from both cyclone bins were sieved after each test to determine whether there was a difference in particle size distribution between the two bins. There were no discernable differences in the particle size distribution, nor any indication of particle breakage during tests; at least not to the extent that could be detected by sieving results. Even with very good sampling procedures, a margin of error of up to 20% is not uncommon in sieving results.

The pressure drop signal as measured across the two orifice plates showed some noise, but no periodic behaviour, as shown in Figure 4. The amplitude of the noise is larger for the right-hand orifice plate than for the left. This noise probably originated from vibrations in the feeder bin, which resulted in a fair amount of scatter from the mean feed rate, as illustrated in Figure 5. Similar behaviour, although at a lower frequency, was exhibited by the air inlet velocity. The available data did not support the theory of alternating particle flow through the two branches, since one would expect both pressure drop signals at the orifice plates to react simultaneously, or slightly out of phase, but in opposite directions, had that been the case. In all the tests, it appeared that only the flow through the right-hand side orifice plate was affected. At the relatively low air velocities (25 m/s) at which these tests were conducted,

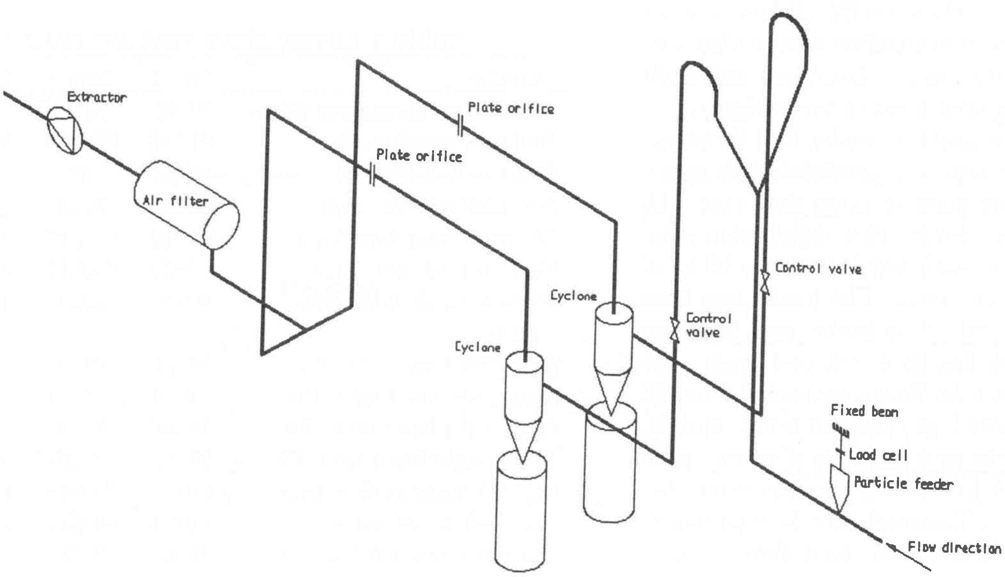

Figure 3 Schematic lay-out of test facility

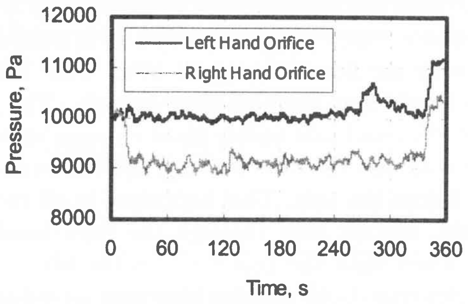

Figure 4 Pressure drop across orifice plates

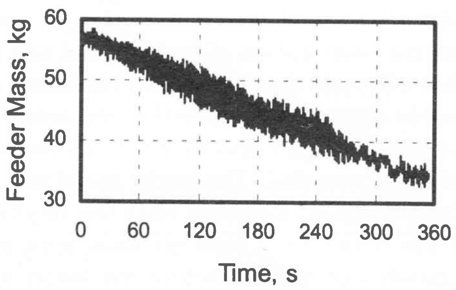

Figure 5 Feeder discharge rate

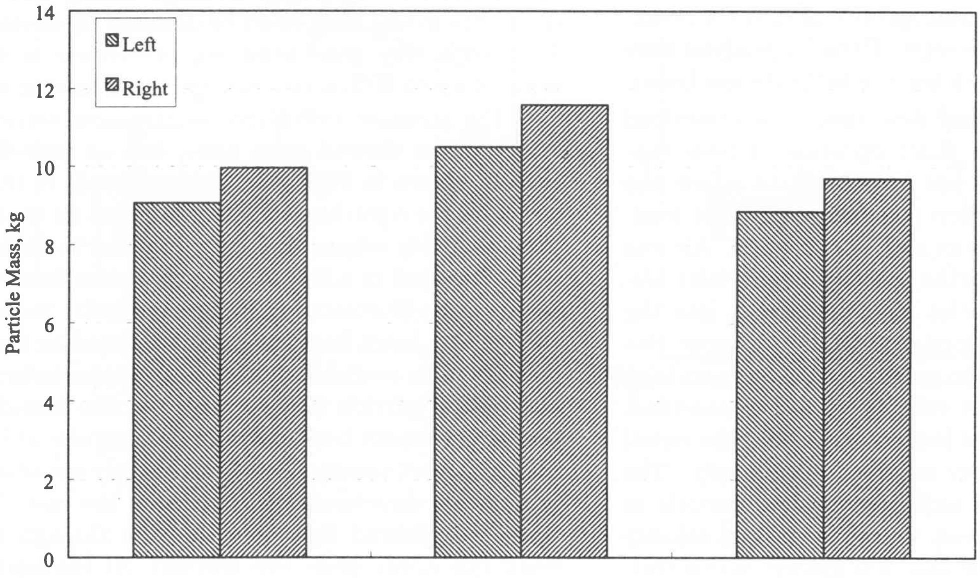

Figure 6 Particle mass collected in each cyclone bin for three tests

it is highly unlikely that any changes in the particle to air mass flow ratio would occur faster than the data sampling frequency of 37 Hz.

Consistently more particles were captured in the right-hand cyclone bin than in the left, as shown in Figure 6. This is seen as the reason for the reduction in air flow through that branch, rather than the result of it, since the flow has to overcome the added resistance of the particles. If this phenomenon was flow-driven, a lower velocity as recorded at the right-hand orifice plate should have lead to a lower particle flow through the right-hand branch as well.

The pressure readings at the split were suspect. The pressure tappings p_{left} and p_{right} were both positioned 10 hydraulic diameters downstream of the split, to allow re-attachment of the flow well upstream of them. When the flow through the two branches is balanced, one would expect the same pressure difference between p_0 and p_{left}, and p_0 and p_{right}, respectively. With clean air, these readings differed by a factor of two. Although the difference appears large, the flow decelerated after the split (the two branches have the same cross-sectional area as the vertical arm, therefore the flow cross-sectional area after the split is double the area before the split), and approximately 280 Pa static pressure was regained after the spilt. The drop in total pressure between the two branches differed by approximately 13%. The orifice plates, on the other hand, indicated the same flow through both branches.

Once the flow was seeded with particles, a negative pressure drop was recorded for the left-hand branch, confirming the reduction in air flow through that branch indicated by the orifice plate. The imbalance total pressure drop between the two branches had increased to 27%.

It is believed that these uneven pressure readings result either from manufacturing tolerances on the bifurcation, or the mounting of pressure tappings. The bifurcation cannot be inspected from without and the quality of the workmanship can only be confirmed by cutting it open.

Conclusion

The experimental work provided no evidence of the presumed periodic behaviour in the particle distribution between two long, parallel branches with a common origin and discharge point. In all the tests, consistently higher particle flows, and as a consequence, lower air flows, were recorded through one branch. This preferential flow is probably due to manufacturing tolerances, rather than anything to do with particle dynamics. It might have been sufficient to prevent any periodic behaviour from the start and, in this respect, the tests were inconclusive. Controlling manufacturing tolerances down to where they have no influence on the flow at all, will be extremely difficult, expensive, and perhaps not possible at all.

Typical PF sampling times on an operational plant are of the order of 30 minutes, and are incapable of capturing high frequency fluctuations in air or particle flow rates. They do, however, show rather large variations, up to 15%, in the fuel flow to the individual burners.

Numerical simulations of the tests[17] suggest an even particle split when a uniform particle distribution is imposed at the bottom of the vertical section. The simulations assume a perfect geometry, and utilize constant pressure outlet boundaries a short distance downstream of the bifurcation. When particles are introduced at the location of the feeder, the same instability, observed in earlier simulations, manifests itself again. At this stage, it is believed that this is an inherent characteristic of the Lagrangian approach to dispersed two-phase flows. Simulations with the particles described in an Eulerian framework[18] tend to support this view. The Eulerian formulation introduces deficiencies of its own, and does not seem to be a feasible alternative for dispersed multiphase flows at this stage.

The tests have highlighted the effect of manufacturing tolerances on actual plant performance; an aspect that is usually not accounted for in numerical simulations based on drawings.

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