EXPERIMENTAL AND NUMERICAL ANALYSIS OF DILUTE GAS-PARTICLE FLOW IN A PIPE SECTION

Conference Paper · January 2024

3 authors, including:

Jan-Hendrik Kruger
North-West University
27 PUBLICATIONS **34** CITATIONS
SEE PROFILE

13th South African Conference on Computational and Applied Mechanics (SACAM2024)
22 – 23 January, 2024, Stellenbosch, South Africa

EXPERIMENTAL AND NUMERICAL ANALYSIS OF DILUTE GAS-PARTICLE FLOW IN A PIPE SECTION

Jan-Hendrik Kruger[1]*, Louis le Grange[2], Michael Roberts[3]

* Presenter and corresponding author: janhendrik.kruger@nwu.ac.za
[1,2,3]North-West University, School of Mechanical Engineering
Private Bag X6001, Potchefstroom, 2520

Abstract: Coal-fired power plants depend on the milling and conveying of Pulverised Coal (PC), where the coal is milled down and then distributed through a network of pipes, using pneumatic transport, to individual burners that feed the boilers. These systems can be plagued by various operational problems due to varying flow conditions, which can even lead to unplanned plant breakdowns and illegal emission of pollutants.

The quality of PC gas-particle mixtures and flow stability can be improved by online measurement of particle mass flow and size distributions. A Particle Flow Test Loop (PFTL) was available that includes a blower fan providing gas flow for the system, a solid particle feeder to mix particles with the gas, a number of long pipe sections, and finally, a cyclone separator and gas cleaning system.

To enable particle flow measurements, a new pipe test section for the PFTL was designed and analysed using computational fluid dynamics (CFD) simulations. The multiphase software code Neptune_CFD by EDF was used in conjunction with Ansys Fluent and Siemens Star-CCM+. The final design was manufactured and fitted to the PFTL and can accommodate measurement devices such as an offline isokinetic sampler as well as online laser-based devices. Two-phase CFD modelling was used to predict cross-sectional solid concentrations for comparison with experimental measurements of particle velocity and particle size distribution. In this paper, selected results from the gas-particle flow simulations are presented, together with comparisons to experimental measurements taken inside the PFTL test section.

Key words: Gas-particle flow measurement, two-phase CFD, pulverised coal, pneumatic transport

1 Introduction

The current economic and energy situation in South Africa requires Eskom to continue to use coal-fired power plants for the foreseeable future [1]. Eskom is under continuous pressure to improve plant performance, reduce emissions, and, through regular maintenance, improve general plant availability.

Many coal-fired power plants experience challenges related to the milling and conveying of pulverised coal (PC). The coal is milled to a typical average particle size of 75 μm and then distributed through a network of pipes, using pneumatic transport, to individual burners that feed the boilers. These systems can be plagued by problems such as the variable fineness of the coal, the settling, and the choking of the PC pipes and the variation of the mass flow as the PC enters the burners. These varying flow conditions can cause costly operational problems such as high wear and fouling of the boiler tubes, leading to unplanned plant breakdowns, as well as the emission of toxic pollutants due to poor combustion conditions [2].

A first step towards an improved PC milled quality and gas-particle flow stability is accurate and online measurement of particle mass flow and particle size distribution. Due to extremely challenging

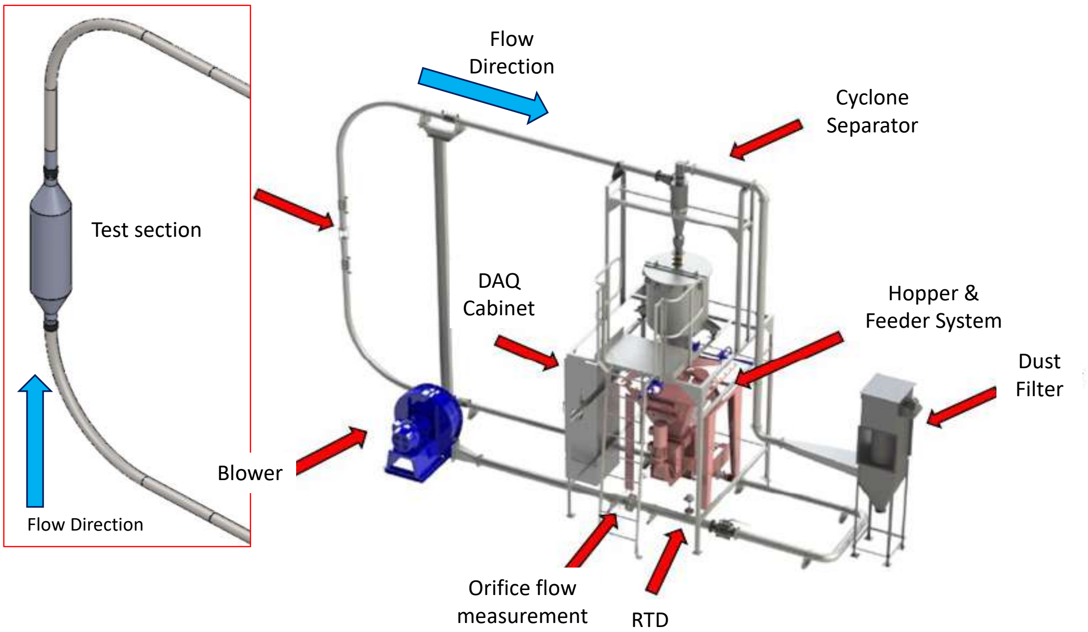


Figure 1: PFTL Test rig

operational conditions in an actual power plant, obtaining experimental measurements is fraught with difficulty, especially when high accuracy and repeatability is required for comparison with research simulations.

A Particle Flow Test Loop (PFTL) was developed by Colin F. du Sart [3] for the original purpose of investigating the settling velocities of PC in pipes. The PFTL shown in Fig. 1 includes a blower fan that provides gas flow to the system, a solid particle feeder to mix the particles with the gas, several long sections of pipe, and finally a cyclone separator and a gas cleaning system. The facility was conceived and developed at the University of Cape Town in 2016 and transferred to the North-West University in 2020 for further research focussing on the evaluation of different gas-particle flow measurement techniques.

2 Problem statement

The original PFTL test section was developed to investigate the velocity of particle settling and therefore had the same diameter as the feeder pipe sections. A new and larger test section was required that would induce the required flow conditions and could be used with online and offline particle flow measurement instruments (see red frame detail in Fig. 1).

3 Aim and Objectives

The aim of the study was to develop an operational test facility for particle flow measurements, satisfying the following objectives:

- Commission gas-particle test loop facility that produces gas-particle flow.
- Develop a test section for industrial-sized measurement devices.
- Perform measurements using a laser-based measuring probe (Parsum IPP70, [4]).
- Validate CFD simulations with measured results.
- Enable demonstrations and training for academic staff and students.

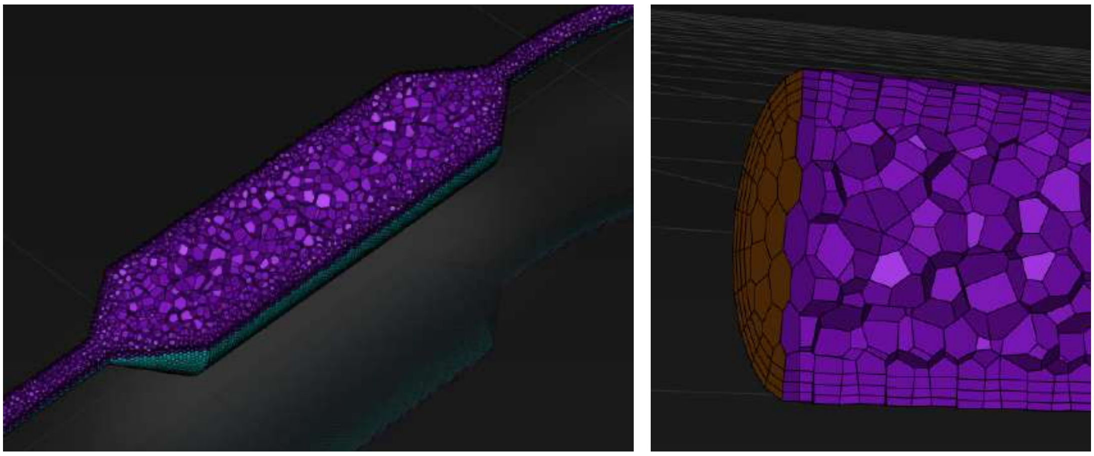


Figure 2: Mesh setup

4 Materials and Methods

The general methodology was to perform detailed computational fluid dynamics (CFD) simulations of gas-particle flow in the test section using three different approaches, and compare those results with experimental measurements and ascertain if validation is possible.

4.1 Simulation methodology

Three approaches were used during simulation development: first, clean air simulations were performed using Ansys Fluent [5] to get a general idea of flow patterns within the test section. Following that, two commonly used gas-particle flow modelling methods were used to incorporate gas-particle interaction, namely an Euler-Lagrangian gas-particle model (using Siemens Star-CCM+, [6]) and an Euler-Euler two-fluid model (using EDF Neptune_CFD, [7]).

Software packages from different vendors were specifically chosen to facilitate verification between model predictions and implementation strategies.

4.1.1 Clean air simulations

Clean air flow simulations were set up in Ansys Fluent to obtain a baseline flow pattern understanding [8]. The predicted flow velocity profiles were compared with the air velocity measurements taken by a pitot tube that traversed the test section.

The numerical domain encompassed the test section, as well as the inlet and outlet bend sections (see Fig. 1) so that the effects of the flow momentum were adequately captured in the test section. An example of the mesh in the test section is shown in Fig. 2, where the inner polyhedral cells with inflation layers can be seen.

Notable mesh parameters included a local target mesh size of 0.01 m and growth rate of 1.2, with a minimum surface mesh size of 0.02 m and maximum of 0.03 m. The domain boundaries consisted of a velocity inlet and pressure outlet, with adiabatic walls for the structure. The internal boundary layers (a.k.a. prism or inflation layers) were defined as three layers with a smooth transition growth rate of 1.2 and transition ratio of 0.27. The polyhedral volume mesh was defined with a maximum cell length of 0.07 m and growth rate of 1.3.

The air flow in the PFTL is controlled by setting the fan motor frequency and for the case shown in Fig. 3 the control frequency was set at 50 Hz, which corresponds to an average flow rate of 0.134 kg/s with an air temperature of 49.4°C.

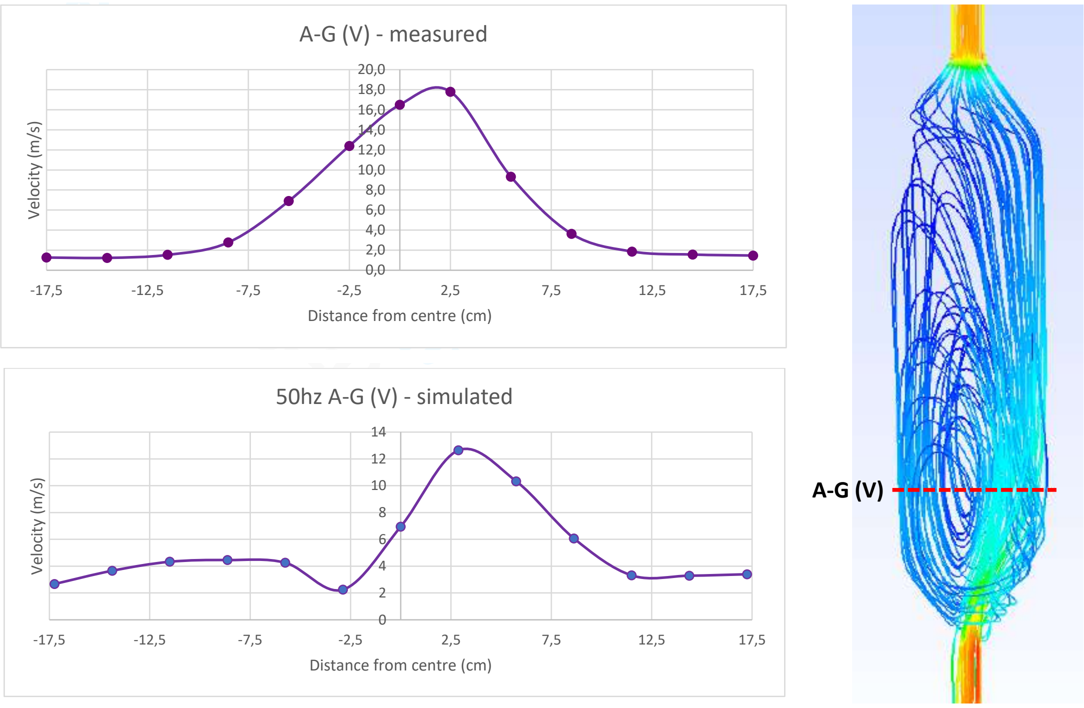


Figure 3: Clean air simulations

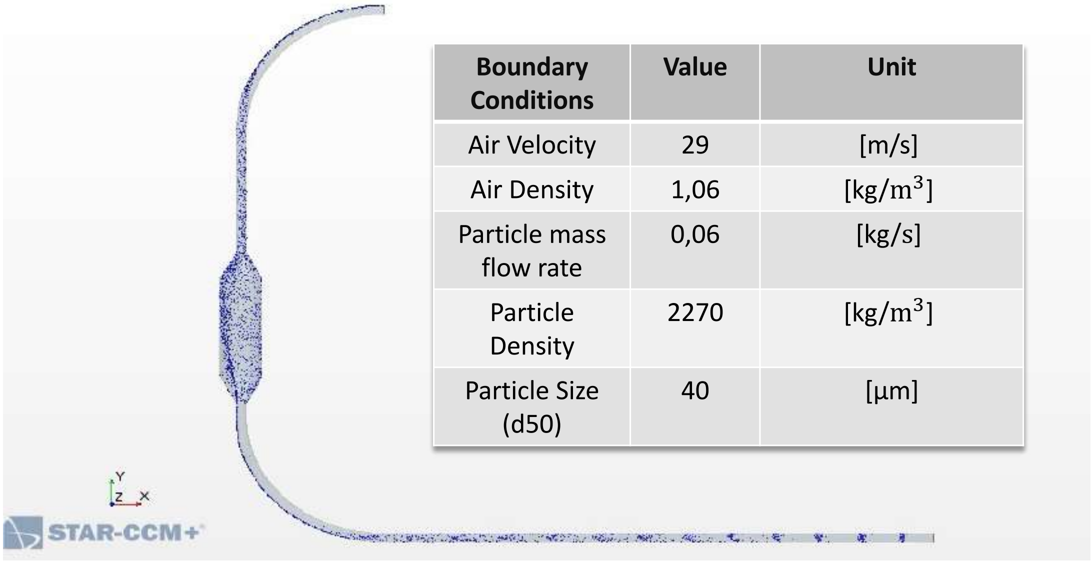
The streamlines in Fig. 3 clearly indicate the high-speed air flow stream moving to the outer region inside the test section. Measurements of velocity profiles in the A-G (V) plane support the general trend of the velocity profile, as predicted by the simulations. The discrepancy of about 6 m/s can be attributed in part to the highly directional measurement characteristic of the pitot tube, while the flow inside the test section actually experiences a high degree of recirculation that complicates any measurement of flow properties.

4.1.2 Euler-Lagrangian Simulations

The Euler-Lagrangian approach solves the gas flow as an Eulerian fluid using a continuum framework [9]. Particle motion is calculated by calculating the dynamic fluid forces on individual particles (or groups of particles) and tracking their movement through the numerical domain. Newton's second law with discrete time steps is used as the basis of the modelling approach, and a strength of the method is that a high-resolution solution of particle movement can be obtained, but with a strong one-way effect of gas flow on particles. However, the method breaks down when large amounts of particles need to be considered (such as in dense particle-laden flows with a strong interactive coupling between phases).

In Fig. 4 a snapshot of the particle movement for 40 μm particles is shown as calculated by Star-CCM+ [6], which illustrates the flow pattern in which the particles flow to the outside of the inlet bend and then continue to the outside of the test section, before recirculating. The simulation parameters are shown in the included table, where it must be noted that the air velocity indicated is the velocity inside the diameter of the small pipe and that the average flow rate corresponds to the other examples.

The volume fraction of the particles as plotted in Fig. 5 gives additional insight into the behaviour of the particles in the test section. The three plotting planes are indicated in their positions relative to the test section, and the formation of a core of high velocity particles can be seen on plane A (also with the position offset to the outside of the bend); the particle concentration then disperses as the flow moves upwards, as shown on planes B and C. It must be remembered that these plots only show the scalar volume fraction and are not an indication of particle velocity or flow direction.



Boundary Conditions	Value	Unit
Air Velocity	29	[m/s]
Air Density	1,06	[kg/m^3]
Particle mass flow rate	0,06	[kg/s]
Particle Density	2270	[kg/m^3]
Particle Size (d50)	40	[µm]

Figure 4: Discrete particle flow movement

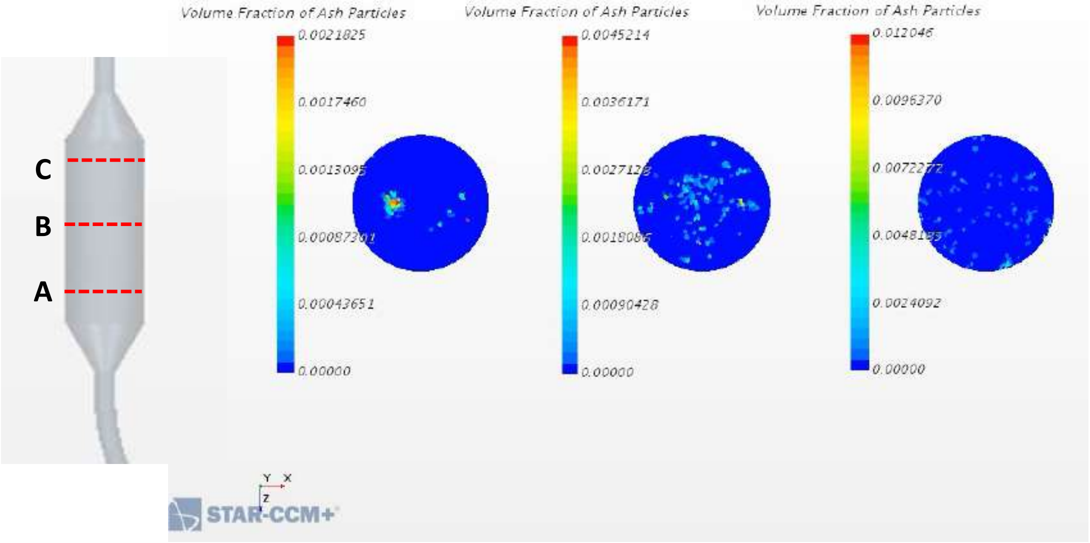


Figure 5: Volume fraction of particle phase - Euler Lagrangian

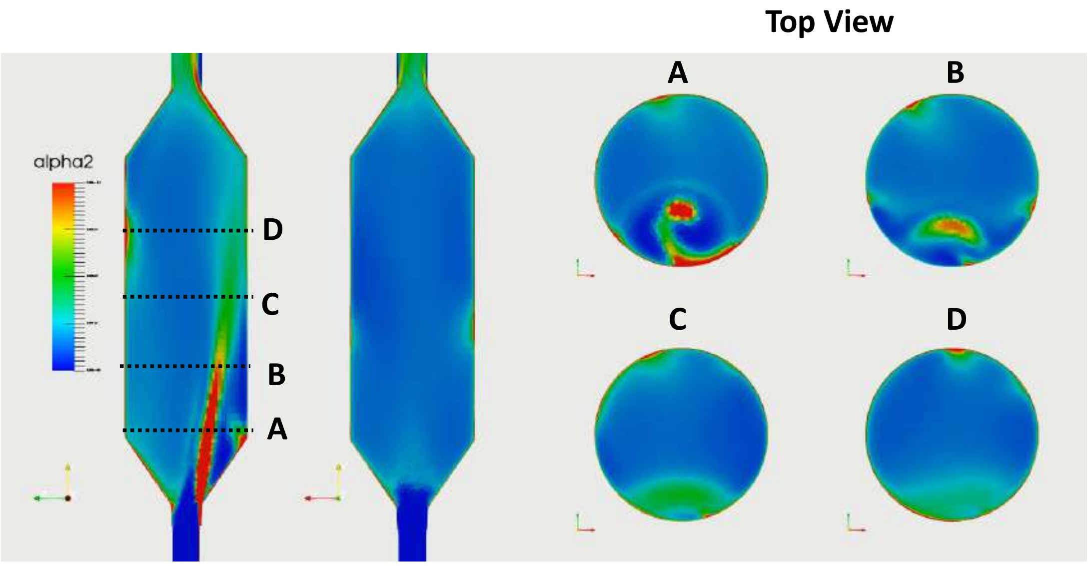


Figure 6: Volume fraction of particle phase - Euler Euler

4.1.3 Euler-Euler Simulations

The Euler-Euler approach (a.k.a. the Eulerian or two-fluid approach) considers both particles and gas as interpenetrating fluids [9]. A strength of the method is that a strong interaction between gas flow and the particle phase can be modelled, making it well suited for densely laden gas-particle flow situations. Compared to an Eulerian-Lagrangian approach, it is also much more computationally efficient for dense flow, especially when transient flow is modelled.

In Fig. 6 the volume fraction of the particle phase is shown, as calculated by using Neptune_CFD from EDF [7], for the same operating conditions as in the other examples. Four cut planes were defined from A to D, and the particle concentration plume can be seen where it appears strongest in plane A and then disperses from plane B through to D. On plane D a slightly higher concentration of particles can also be seen on the opposite side of the main plume, which is due to the onset of recirculation.

4.2 Experimental methodology

4.2.1 Features of test section

The test section illustrated in Fig. 7 had to satisfy several design requirements, while still achieving the main objectives. These design features were the most important:

- Due to the existing pipe work of the test rig, there was a limitation on the length of the test section.
- The diameter of the test section was restricted by the length of the Parsum and Gravimat probes, thus also prescribing a certain aspect ratio for the test vessel.
- The requirement of being able to use various instruments with their own, but different, inlet ports necessitated a rotating test section, so that cross-sectional flow profiles can still be measured using single-line traversals.
- The test section should induce repeatable, quasi-steady-state gas-particle flow profiles.
- Recirculating gas-particle flow should be induced to evaluate the instrumentation under adverse measurement conditions.

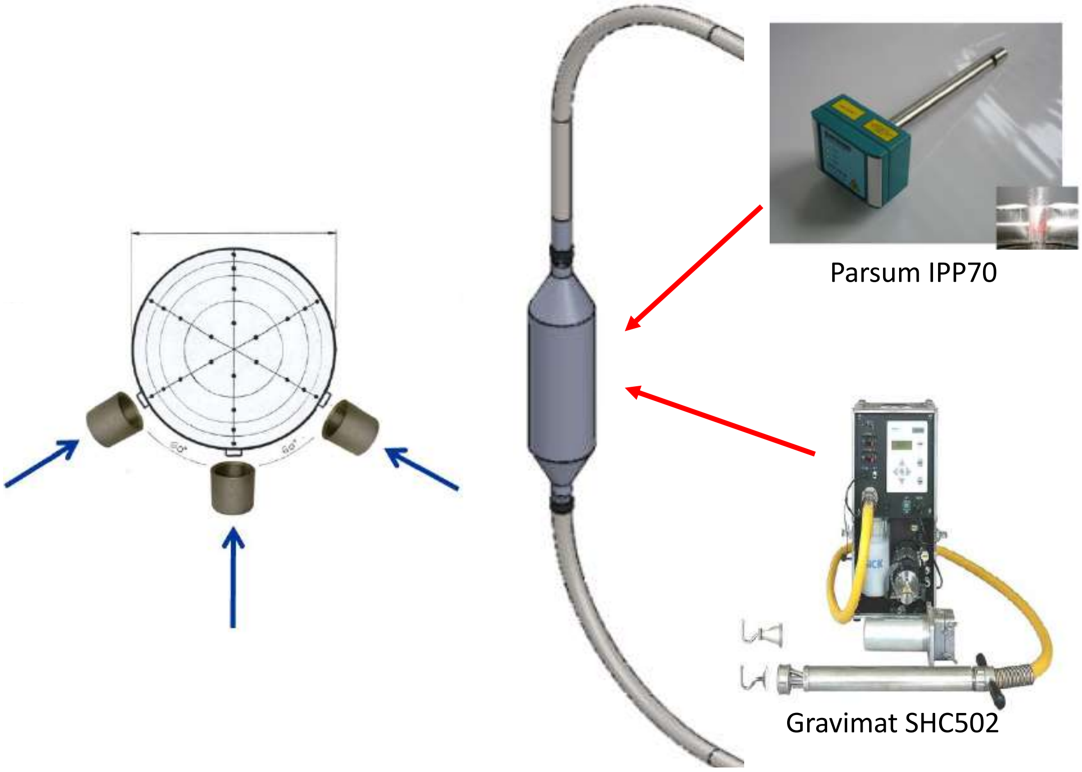


Figure 7: Features of test section

4.2.2 Experimental Measurements

The test rig with the Parsum IPP70 probe installed is shown in Fig. 8. The probe required its own digitiser and software to enable measurements to be taken. After the rig was turned on, the fan motor frequency was selected as required to generate a specific average flow velocity. Once the air flow temperature stabilised, the particle feeder mechanism was activated to feed the particles into the loop so that measurements can be taken.

In Fig. 9 a diagram of the measurement plane with two lines of traversal locations can be seen. The horisontal line with fewer measuring points is for the Gravimat SHC502 isokinetic sampler [10], while the vertical line contains the laser probe locations. Keep in mind that the plane as shown will be rotated to enable the measurement of a complete cross-sectional profile.

After initial tests with the isokinetic sampler, it became clear that the offline nature of this method would be completely unsuited to the objectives of the project, and further work focused on the online laser probe.

For a certain angle of rotation of the test section, the Parsum IPP70 probe [4] was then traversed by hand through the test section, stopping precisely at the locations indicated in Fig. 9. The controlling software measured and recorded the particle size distribution, as well as the particle velocity distribution. When a specific traversal line was completed, the test section was rotated to the next angle, and the process was repeated again, until all the angles of rotation were covered.

5 Results and Discussion

The laser probe measured the particle velocity, and gave the particle count for a specific situation. Of these two quantities, only the particle velocity measurement can be directly compared with the simulated values, while the particle count only gives an indication of possible trends.

Figure 8: Test rig photo

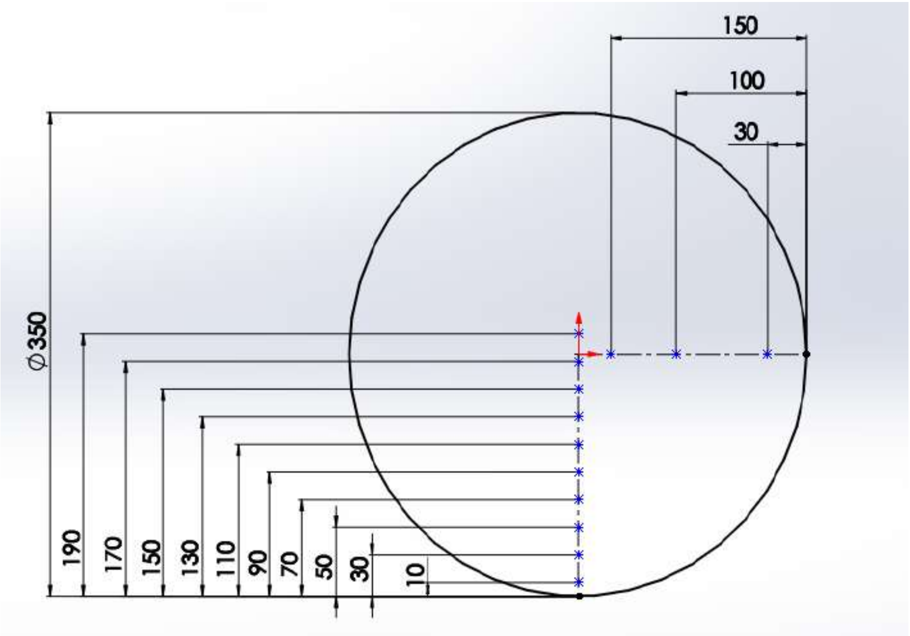


Figure 9: Probe traversing locations

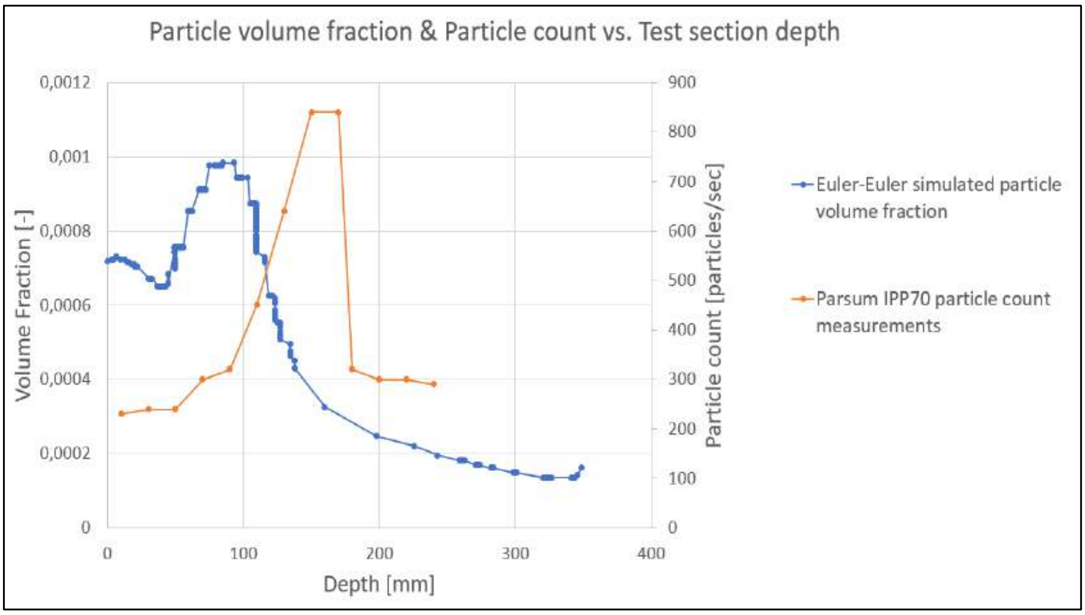


Figure 10: Particle volume fraction vs test section depth

When considering the changes in volume fraction and particle count over the depth of the test section, as shown in Fig. 10, interesting conclusions may be drawn (recall that the Euler-Euler simulations do not determine individual particle properties, unlike the probe which does count individual particles). The simulated volume fraction shows the maximum concentration about halfway between the inlet and the centre of the section.The probe, however, shows the maximum particle count measurements closer to the centre of the test section.

It is encouraging that there is actually some semblance between the trends of the two quantities, even though these are fundamentally different quantities and are not required to exhibit the same behaviour. The particle count can, for example, be influenced by particle recirculation, which can cause particles to be counted several times when located in the (what would be predicted by the simulation) same volume fraction region. There is also a complex relationship between die particle size distribution of the actual particles used in the test rig and the manner in which the two-fluid simulation handles such particle concentrations.

The velocity profiles shown in Fig. 11 exhibit a strong correlation between the simulated air and particle velocities, underscoring the strong effect of the gas phase on particles in dilute phase mixtures. The IPP70 measured particle velocities again show a profile peak that is located more towards the centre of the test section, however, it is at least of a comparable magnitude (within about 3 m/s of the simulated values).

An important point to note with relation to the Parsum IPP70 probe is that due to the design of the probe, it also has a strict directional measurement bias (similar to a pitot tube) and that measurement errors may be introduced when the directions of particle movement and the probe's measurement slot do not align closely.

6 Conclusion

In conclusion, most of the project objectives were completed. The gas-particle test loop facility was successfully commissioned and produced gas-particle flow that could be controlled and measured. The test section was constructed for the industrial-sized measurement devices, and both the isokinetic sampler and the laser probe could be used to complete basic exploratory measurements. In addition, this level of

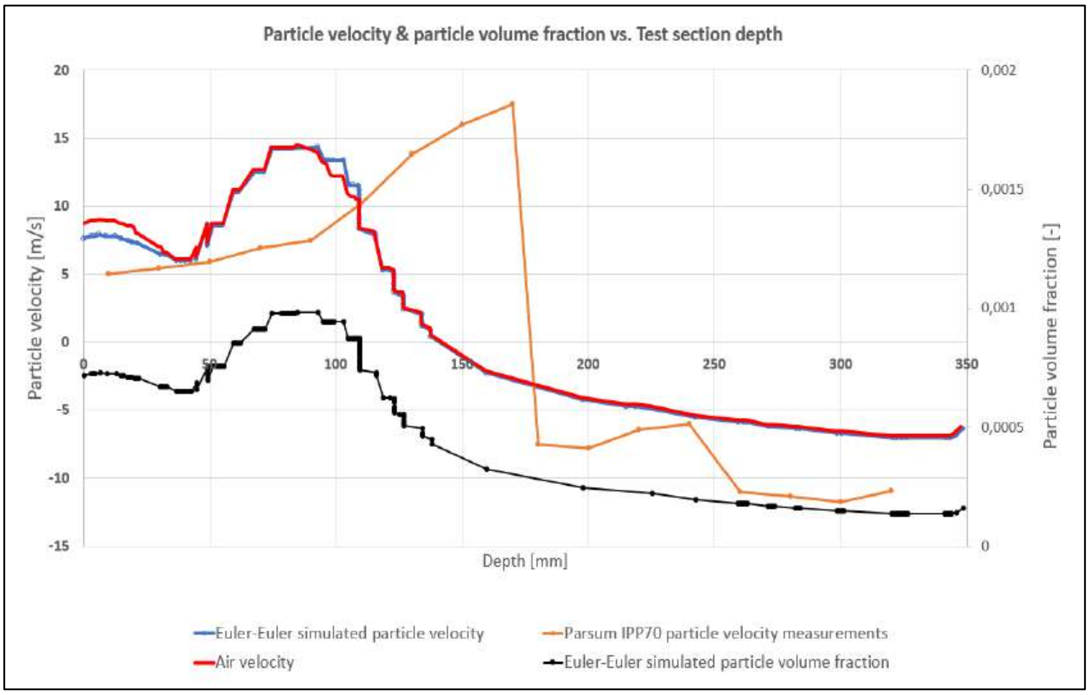


Figure 11: Particle velocity vs test section depth

functionality is already useful for demonstration purposes and training of staff and students.

Subsequent investigations were performed with the Parsum probe, where the particle count and particle velocity profiles were determined for a variety of test cases. However, comparisons with the simulated profiles for velocity and particle concentrations were inconclusive, even though there was encouraging agreement in terms of the large-scale trends.

Recommendations for future work include investigating the use of a more uniform particle medium to reduce the effect of the PSD on measurements. The viability of flow simulations that capture the details of the probe geometry and its measurement slot can be evaluated to obtain more appropriate comparisons between experimental measurements and simulated quantities.

Nomenclature

CFD	Computational Fluid Dynamics
PC	Pulverised Coal
PFTL	Particle Flow Test Loop

References

[1] Department of Mineral Resources and Energy. “Integrated Resource Plan 2023”. In: *Republic of South Africa Government Gazette* 49974 (2024).

[2] Hamresin Archary. “Condition Monitoring and Performance Optimisation of Pulverised Fuel Vertical Spindle Type Mills”. Master of Science in Engineering. Johannesburg: University of the Witwatersrand, 2015. 225 pp.

[3] Colin F. du Sart. “Design and prototyping of a test facility to investigate the transport properties of dilute phase gas-particle flows applicable to coal-fired power plants”. Masters of Science degree in Mechanical Engineering. Cape Town: University of Cape Town, 2017. 355 pp.

[4] Dieter Petrak, Stefan Dietrich, Günter Eckardt and Michael Köhler. “In-line particle sizing for real-time process control by fibre-optical spatial filtering technique (SFT)”. In: *Advanced Powder*

Technology, International Journal of Sciences & Technology of Powders & Particulate Materials 22.2 (2011), p. 18.

[5] Ansys, Inc. *Ansys Engineering Simulation Software*. ANSYS, Inc., 2023. URL: `https://www.ansys.com/`.

[6] Siemens Digital Industries Software. *Simcenter STAR-CCM+, version 2020.1*. Version 2020.1. 2020.

[7] Lavieville, J., Quemerais, E., Mimouni, S., Boucker, M. and Mechitoua, N. *NEPTUNE CFD V1. 0 Theory Manual*. Rapport interne EDF H-I81-2006-04377-EN Rapport NEPTUNE Nept_2004_L, 1(3). EDF, 2006.

[8] Rayden Peyper. "Identification of flow patterns and losses in the particle flow test loop's test section using CFD". Final Year Project Report. Potchefstroom: North-West University, 2022. 70 pp.

[9] Andrew L Gerhart, John I Hochstein, Philip M. Gerhart. *Munson, Young and Okiishi's Fundamentals of Fluid Mechanics*. 9th ed. Wiley, 2021.

[10] SICK AG. *Operating Instructions Gravimat SHC502 (Gravimetric Dust Concentration Measuring System)*. 8007941. SICK Engineering GmbH, 2014. URL: `https://cdn.sick.com/media/docs/6/16/316/operating_instructions_shc502_gravimat_en_im0011316.pdf`.