# Coal Flow Control System Development

**1000433**

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# ABSTRACT

A study has been initiated to develop a device(s) to control the A/F ratio to each pipe from a two or three way coal splitter (with or without a riffler) in a utility boiler coal delivery system. The Allegheny Power Armstrong Unit 1 is serving as the host site and test case. This work objective is being met through a three phase interactive program involving Field Testing, CFD modeling and Physical Models.

Field measurements of air and coal flows at the exhauster exit and coal pipes were performed in order to establish baseline performance. The purpose of the test was to gather boundary condition and validation data for the physical and numerical modeling efforts. The testing performed to date has shown the effects of auxiliary air, coal flow rate, and orificing on coal pipe balance. The exhauster exit data showed a strong, consistent pattern of coal flow along the outside wall of the exhauster. The total coal is in close agreement with that measured in the pipe.

The CFD modeling for a uniform inlet conditions has shown that the momentum of the coal carries a higher percentage of the coal to the center pipe. However with the center pipe restricted the impact on the coal flow distribution is much less than on the airflow. When the skewed inlet boundary condition data from the field test were evaluated along with a restricted outlet on the left hand pipe a redistribution of the coal flow occurs that is similar but not identical to the field data. The model also shows that there is a redistribution of the particle sizes in the coal pipes.

The limited physical model data also shows the dominance of the particle momentum in causing more flow to enter the center pipe for a uniform inlet condition. Orificing of this center pipe also had less effect on the coal distribution than on the air flow distribution as predicted by the CFD model.

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# 1
# INTRODUCTION

Most power generators deliver coal pneumatically to their boilers through a system of pipes from the mill to the burners. Often coal pipe splits are made such that the coal is divided into two, three or four streams from a single stream. The systems are designed to try to deliver a uniform coal distribution to each burner but this goal is usually not achieved in practice. Orifices are used to help balance the flows which sometimes works and often helps balance the dirty air or coal conveying air to the burners. But more likely than not, the coal will still not be balanced between pipes. Thus, there is a need to better understand the factors which contribute to the mal-distribution of coal from splitting systems and to develop methods to better balance the coal flow from these systems. In a separate TC agreement, Allegheny Power is working with EPRI to incorporate a combustion optimization system that will include on-line monitoring of primary air, coal, and secondary air flows to the burners. This is being done at the Armstrong Plant Unit 1 which is a 180 MW front-wall fired boiler built in 1958. One issue that has arisen is that the current coal flow balance between the burners is significantly non-uniform. Test data indicate that the burner-to-burner coal flow rates vary by as much as 100% from the average flow. It is therefore advantageous to conduct a study at the Armstrong station to evaluate the coal distribution problem using the extended instrumentation at that plant and to apply these results to the generic problem.

## Objective

The objective of this work is to develop a device(s) to control the A/F ratio to each pipe from a two- or three-way coal splitter with or without a riffler. Features of the system will include the following:

- Maintain an air to coal ratio over all pipes within 10% of the mean over a range of mill operating conditions from 40% to 100% load.
- Low fabrication and installation costs
- Minimal or controllable maintenance requirements

The Allegheny Power Armstrong Unit 1 is serving as the host site and test case. Focus will be on the system of pipes at one end of a ball tube at the host site.

## Approach

This work objective is being met through a three phase interactive program involving Field Testing, CFD Modeling and Physical Models. Results in each of these areas to date are reported in the sections that follow.

# 2
# FIELD TESTING PROGRAM

Field measurements of air and coal flows within the exhauster and coal pipes were performed in order to establish baseline performance. The testing was performed on the Allegheny Power Armstrong Station Unit 1 during the period August 9 through 12, 2000. Matt Fleming and Kevin Linfield were the ASC engineers who completed the tests.

The purpose of the test was to gather boundary condition and validation data for the physical and numerical modeling efforts. In addition to providing data for the modeling, testing provides a better understanding of the operation of the coal delivery system as a whole.

The testing primarily focused on the 1A2 exhauster and its associated coal pipes (numbers two, four, and six). For one test all twelve pipes on Unit One were tested. The object of the testing is to examine how the coal flow profile at the exhauster outlet affects the flow split to the three pipes. In addition, the impact of operational parameters such as auxiliary air flow rate, total coal flow, and coal pipe orifice size on the system was examined

## Methodology

Testing was performed at two locations on the 1A2 system; at the exhauster discharge before the splitter and on the individual coal pipes.

The location of the test ports for the exhauster discharge measurements is shown in Figure 1. Note that this picture was taken before the test ports were installed. Five equally spaced test ports were installed on the exhauster at the indicated locations. Data obtained at the exhauster discharge includes air velocity profile, primary air flow rate, coal flow profile, total coal flow rate, static pressures, and temperatures. ASC's Advanced Coal Flow Measurement System (ACFM) was used to perform the testing.

The ACFM is a fully computer-controlled PC-based isokinetic extraction type coal flow testing system. It utilizes a dirty air probe for air velocity measurement and a specialized coal sampling probe for coal flow measurement. The isokinetic extraction rate is computer controlled and adjusted point-by-point to maintain 100% isokinetic extraction across the velocity profile. A relative humidity (RH) probe is part of the coal sample train. The RH probe makes it possible to determine the primary air moisture mass fraction and hence the true air density, velocity, and moist air flow rate. This data is included in the report generated for each test.

The system also includes a load cell weighing system for the coal sample. The system measures the amount of coal collected at each individual traverse point, thus the coal flow *profile* at the exhauster outlet is determined. The traverse grid consisted of five test ports across the exhauster outlet and seven points across the depth of the exhauster at each test port for a total of thirty five points. The exhauster outlet data will be primarily used for the physical and numerical model boundary conditions.

Testing was also performed in the three pipes fed by the exhauster. The data obtained includes air velocity profile, primary air flow rate, coal flow rate, temperature, static pressure, and air moisture mass fraction. The ACFM system was also used for the coal pipe testing. However, the ACFM was used in combination with the Rotorprobe coal sampling head. The ACFM was programmed to perform the coal pipe test as specified in ISO Method 9931. The L/D correction specified in Annex B of the method was also used. Note that with the Rotorprobe sampling head, it is not possible to determine the coal flow profile within the pipe.

The test ports for Exhauster 1A2 are shown in Figure 2. The test ports are about ten feet directly above the top of the splitter. In order to ensure accurate, repeatable results, each pipe was tested twice in succession for each test. If the results did not agree within 5% (coal flow rate), then the pipe was re-tested until consistent data was obtained.

The original test matrix is shown in Figure 3. The test matrix includes the following factors: output damper position, exhauster 1A1 status (on/off), auxiliary air flow, and coal pipe orifice position. The tests are numbered one through twenty. The original goal of the test had been to make measurements at the exhauster outlet and in the coal pipes for every test. Unfortunately, due to time constraints and testing delays, only tests 1, 2, 4, 5, 6, 13, 14, 17, and 18 were performed. These tests covered the high and low output damper positions, the mid range tests were dropped. Exhauster outlet data was obtained only for tests 5, 6, 13, 14, and 17.

## *Results*

A table summarizing the results of all the tests is shown in Table 1. The table includes exhauster data, coal pipe data, and operational data logged by the Unit DCS. Comparisons between the exhauster and pipe data are also made.

### Coal Pipe Data

Overall, the coal pipe results showed excellent repeatability. Air flow rates were typically repeatable within 1% and coal flow rates were repeatable within 3%.

Typically, coal pipe velocity traverses are performed using two ports at ninety degrees to each other. It should be noted that on many pipes on Unit 1 only one of the two ports was usable. Except on pipes 3, 8, 10, 12 the smaller (1” NPT) was not usable. The ports were unusable either due to inadequate clearance to insert the probe or because blockage within the port would not allow the probe to be inserted. Test port locations were good (flat velocity profile) on the 1A2 and most other pipes so this did not have a large impact on the accuracy of the air flow rate measurements.

### Exhauster Outlet Data

Air velocity profile plots for Tests 5, 6, 13, 14, and 17 are included as Figures 4, 5, 6, 7, and 8, respectively. Coal flow profile plots for Tests 5, 6, 13, 14, and 17 are included as Figures 9, 10, 11, 12, and 13, respectively. These plots show a plan view cut at the exhauster inlet. The test ports are along the X axis (horizontal), numbered left to right (see Figure 1). The probe insertion direction is along the Y axis (vertical). Traverse point number one is the point furthest from the test port. On this exhauster, coal and air are entering on the left side (Port 1 side).

Looking at the air velocity plots, one trend is immediately apparent. Air velocities are high toward the inside, with low velocities along the outside of the fan scroll. This trend is what one would expect from a centrifugal fan with flat, radial vanes. A second observation is that for Tests 5 and 6, velocities are low on the left side of the exhauster and for Tests 13, 14, and 17 they are low along the right side. It appears that output damper position (68% for Tests 5 and 6, 38% for Tests 13, 14, and 17) affects the velocity profile.

During the testing, velocities along the outside wall were found to be very erratic. In some cases, ten second averages varied from +20 ft/sec to -140 ft/sec (6 m/sec to -43 m/sec). This is not too surprising, considering the amount of turbulence due to the fan and the presence of the coal. This degree of turbulence should be kept in mind when looking at the integrated total air flow measured at the exhauster. Table 1 compares the air flow measured at the exhauster with the total measured in the coal pipes. As can be seen, the flow measured at the exhauster is typically about 10% lower than in the pipes (with the exception of Test 14, which is 29% lower, no explanation). One possible reason for this is the multi-dimensionality of the flow at the exhauster exit. The dirty air probe is a one dimensional probe; any multi-dimensional flow would cause the probe to read low.

Another possibility is the cross sectional area used to integrate the flow. The test ports are at the inlet of a flow expansion (the splitter box), so there is some estimation as to the proper cross sectional area to use. The cross sectional area used is that of the straight rectangular duct immediately upstream of the ports (see Figure 1), not the slightly larger area of the expanding section at the plane of the ports. This was done under the assumption that the expansion was too abrupt for the flow to follow and hence the upstream area is more representative.

The coal flow plots are not quite as satisfying as the air velocity plots. The plots for Tests 5 and 6 are fairly reasonable looking. The coal flow is seen to be heaviest along the outside wall of the exhauster and the total integrated coal flow agrees fairly well with that measured in the pipes (Test 5 -0.2%, Test 6 +15.1%). The plots for Tests 13, 14, and 17 however do not show any discernable pattern. The output damper was at 38% for these tests (versus 68% for Tests 5 and 6), but the total coal flow (as measured in the pipes) was just as high for Tests 13 and 17 as for Test 6. Also for Tests 13, 14, and 17, the total coal flow measured at the exhauster is substantially lower than in the pipes, -82.4%, -35.9%, and -35.7%, respectively. There appears to be no explanation for this disagreement.

Currently, the load cell system on the ACFM has a fairly large variability associated with it. A parametric test was performed involving holding the coal sampling probe a fixed location in the exhauster and sampling the same point multiple times (a total of 21 times). Ideally, these samples would all indicate the same coal flow rate. However, the samples indicated a variability in coal flow of about 20% at one standard deviation. How much of this variability is due to the equipment and how much is due to actual variations in the coal flow is difficult (if not impossible) to estimate.

The effect of auxiliary air on total coal is shown in Table 2. For the two pairs of Tests 5 and 6 (output damper 68%) and 13 and 14 (output damper 38%) the auxiliary air was varied while all other parameters were held constant. The table shows that opening the auxiliary air damper from 5-10% to 75% reduces coal flow by about one third, even when the output damper position is not changed.

The effect of total coal flow on coal flow balance is shown in Table 3. The table shows that coal flow balance is good at low coal flow rates (for both high and low auxiliary air settings), within +/-4%. When the output damper is opened and coal flow rates increase, the balance goes out as much as +29%/-26%.

The effect of orificing on coal flow balance is shown in Table 4. For Tests 2, 4, and 6 the isolation gate on Pipe 2 was set to open (normal condition), slightly closed, and more closed positions, respectively. Pipe 2 was chosen because is had the highest coal in Test 2. The table shows that closing the valve had a large impact on balance. The coal flow in Pipe 2 dropped from +29.3% to -39.1%. Note that this was done without dropping the air velocity in Pipe 2 to excessively low levels. There was a large impact on air balance, although the two moved together only somewhat proportionately. Note that air flow was well balanced for Test 2.

The relationship between total coal flow and classifier differential pressure (DP) is shown in Figure 14. It was shown above that the auxiliary air setting has a significant impact on coal flow rate, even with output damper setting held constant. Figure 14, which includes all data for Exhauster 1A2, shows that classifier DP and total coal flow correlate very well for all conditions tested. Note that there is some second order character to the relationship. Also note that the condition of passing through point zero/zero was imposed on the curve fit (zero DP at zero coal flow).

### *Conclusions*

The testing performed to date has provided valuable insight into the operation of the exhauster and the influence of various factors.

- Coal pipe data is very good. Repeat tests were very consistent. The effect of auxiliary air, coal flow rate, and orificing on coal pipe balance can be clearly seen. Nine of the twenty conditions in the test matrix were tested.
- Exhauster data is somewhat lacking. Only five conditions of the test matrix were covered and no repeat tests were performed. Two of the tests show a strong, consistent pattern of coal flow along the outside wall of the exhauster. The total coal is in close agreement with that measured in the pipe. For three of tests, however, the measured coal flow differs substantially from the coal pipe measurements. In addition, these tests do not show any pattern to the coal flow profile.

There is a definite need for additional testing. Additional testing would focus on the following items:

- Improved exhauster sampling technique. Increasing the per-point sample time from 20 to 80 seconds would greatly reduce variability in the coal sample weights. Reducing the diameter of the hose running from the probe to the filter bag would increase the coal transport velocity. This would reduce fallout in the hose and the lag associated in moving from one traverse point to the next. It may also be possible to reduce variability in the load cell mechanism itself.
- Complete more tests on the test matrix. The remaining tests would be prioritized and performed on a cost/benefit basis. In particular, exhauster data has not been obtained for

Test 1, which is the most common operating condition of the exhauster. Several repeat tests should be made on the exhauster for this important test.

- A set of tests of particular importance are 1, 2, 13, and 14. The coal pipe data showed that simply increasing the coal flow rate had a big impact on coal pipe balance (see Table 3). It would be interesting to see what the coal flow profile at the inlet to the splitter is for these cases.

- Clean air testing. Clean air data at a few test conditions would be very valuable. Clean air data would allow running the numerical and physical models under a greatly simplified set of conditions. The model predictions (coal pipe balance) could then be verified. Clean air conditions would also allow verification of the air velocity profile at the fan exit. This would verify that high coal concentrations are not leading to erroneous air velocity reading from the dirty air probe.

Overall, the results to date are very encouraging. The coal pipe data is lacking only in quantity, not quality. ASC believes that the quality of the exhauster data can be greatly improved simply with a little refinement in technique and a little more time in the field. One other item of note; ASC will probably be able to field two ACFM systems for a follow-up test. This would speed up testing by about 75%, making a follow up test much more productive.

**Figure 1.  Exhauster 1A2 Test Ports**

**Figure 2.  Coal Pipe Test Ports**

**Figure 3. Initial Test Matrix**

| Test # | 1A2 Output Damper Position | 1A1 Status | 1A2 Aux Air | Variable Orifice | Pipes Tested |
|---|---|---|---|---|---|
| 1 | 62 | On | L/P | N | All |
| 2 | 62 | On | H | N | 1A2 Only |
| 3 | 62 | On | L | 20% Closed | 1A2 Only |
| 4 | 62 | On | H | 20% Closed | 1A2 Only |
| 5 | 62 | On | L | 40% Closed | 1A2 Only |
| 6 | 62 | On | H | 40% Closed | 1A2 Only |
| 7 | 56 | On | L | N | 1A2 Only |
| 8 | 56 | On | H | N | 1A2 Only |
| 9 | 56 | On | L | 20% Closed | 1A2 Only |
| 10 | 56 | On | H | 20% Closed | 1A2 Only |
| 11 | 56 | On | L | 40% Closed | 1A2 Only |
| 12 | 56 | On | H | 40% Closed | 1A2 Only |
| 13 | 38 | On | L | N | 1A2 Only |
| 14 | 38 | On | H | N | 1A2 Only |
| 15 | 38 | On | L | 20% Closed | 1A2 Only |
| 16 | 38 | On | H | 20% Closed | 1A2 Only |
| 17 | 38 | On | L | 40% Closed | 1A2 Only |
| 18 | 38 | On | H | 40% Closed | 1A2 Only |
| 19 | 62 | Off | L | N | 1A2 Only |
| 20 | 62 | On | L | N | 1A2 Only |

# Table 1: Test Matrix Summary

| Test # | Date | Time | Output Damper Position (%) | Auxiliary Air Damper (%) | Auxiliary Air Flow | 1A1 Status | Isolation Gate Setting | Classifier DP (IWC) | Exhauster Amps |
|---|---|---|---|---|---|---|---|---|---|
| 1 - 1A1 | 9/12/2000 | 11:40 - 13:19 | 61.8 | 5.3 / L | 2.62 | On | Full Open | 2.36 | 14.6 |
| 1 - 1A2 | 9/12/2000 | 13:36 - 14:46 | 61.6 | 5 / L | 2.35 | On | Full Open | 3 | 15.5 |
| 1 - 1B1 | 9/12/2000 | 7:07 - 8:30 | 67.4 | 5.5 / L | 2.29 | On | Full Open | 2.45 | 16.1 |
| 1 - 1B2 | 9/12/2000 | 8:56 - 11:18 | 62.2 | 5.1 / L | 0.93 | On | Full Open | 2.65 | 14.9 |
| 2 | 9/9/2000 | 15:55 - 17:34 | 61.8 | 75 / H | 19.7 | On | Full Open | 1.98 | 15.1 |
| 4 | 9/10/2000 | 17:02 - 18:23 | 67.5 | 75 / H | 18.3 | On | Slightly Closed | 1.56 | 14.3 |
| 5 | 9/10/2000 | 10:18 - 12:41 | 68.3 | 5.3 / L | 1.9 | On | More Closed | 2.48 | 14.6 |
| 6 | 9/10/2000 | 12:51 - 16:09 | 67.9 | 75 / H | 17.8 | On | More Closed | 1.45 | 13.8 |
| 13 | 9/11/2000 | 9:26 - 11:47 | 38 | 10.6 / L | 4.7 | On | Full Open | 1.98 | 14.1 |
| 14 | 9/11/2000 | 11:54 - 14:25 | 38 | 75 / H | 23.6 | On | Full Open | 1.31 | 14 |
| 17 | 9/11/2000 | 14:50 - 15:59 Pipes 17:45 - 18:42 Exh | 37.9 | 16.4 / L | 4.5 | On | More Closed | 1.71 | 13.3 |
| 18 | 9/11/2000 | 16:14 - 17:27 | 37.8 | 75 / H | 21.6 | On | More Closed | 1.04 | 13.2 |

| Test # | Exhauster Discharge Pressure (IWC) | Unit Gross Load (MW) | Exhauster Coal Flow (lbm/hr) | Exhasuter Air Flow (lbm/hr) | Pipe Coal Flow (lbm/hr) | Pipe Air Flow (lbm/hr) | Pipe Air/Coal Ratio | Coal Difference | Air Difference |
|---|---|---|---|---|---|---|---|---|---|
| 1 - 1A1 | 14.5 | 173 | Not Tested | Not Tested | 36,465 | 55,693 | 1.53 | NA | NA |
| 1 - 1A2 | 12.1 | 173 | Not Tested | Not Tested | 35,251 | 48,546 | 1.38 | NA | NA |
| 1 - 1B1 | 11.4 | 173.1 | Not Tested | Not Tested | 34,158 | 49,388 | 1.45 | NA | NA |
| 1 - 1B2 | 12.9 | 172.4 | Not Tested | Not Tested | 30,751 | 48,410 | 1.57 | NA | NA |
| 2 | 14.9 | 175.2 | Not Tested | Not Tested | 27,500 | 61,140 | 2.22 | NA | NA |
| 4 | 15.9 | 167.5 | Not Tested | Not Tested | 23,815 | 55,789 | 2.34 | NA | NA |
| 5 | 14.2 | 175.6 | 31,807 | 39,238 | 31,857 | 45,512 | 1.43 | -0.2% | -13.8% |
| 6 | 16.4 | 167.6 | 24,810 | 47,664 | 21,554 | 53,145 | 2.47 | 15.1% | -10.3% |
| 13 | 8.6 | 160 | 4,754 | 40,822 | 26,940 | 45,245 | 1.68 | -82.4% | -9.8% |
| 14 | 11.8 | 159.8 | 12,105 | 41,191 | 18,896 | 58,032 | 3.07 | -35.9% | -29.0% |
| 17 | 10 | 160 | 15,244 | 37,578 | 23,692 | 41,628 | 1.76 | -35.7% | -9.7% |
| 18 | 13.2 | 159.8 | Not Tested | Not Tested | 15,033 | 52,885 | 3.52 | NA | NA |

**Figure 4. Exhauster Air Velocity Profile – Test 5**

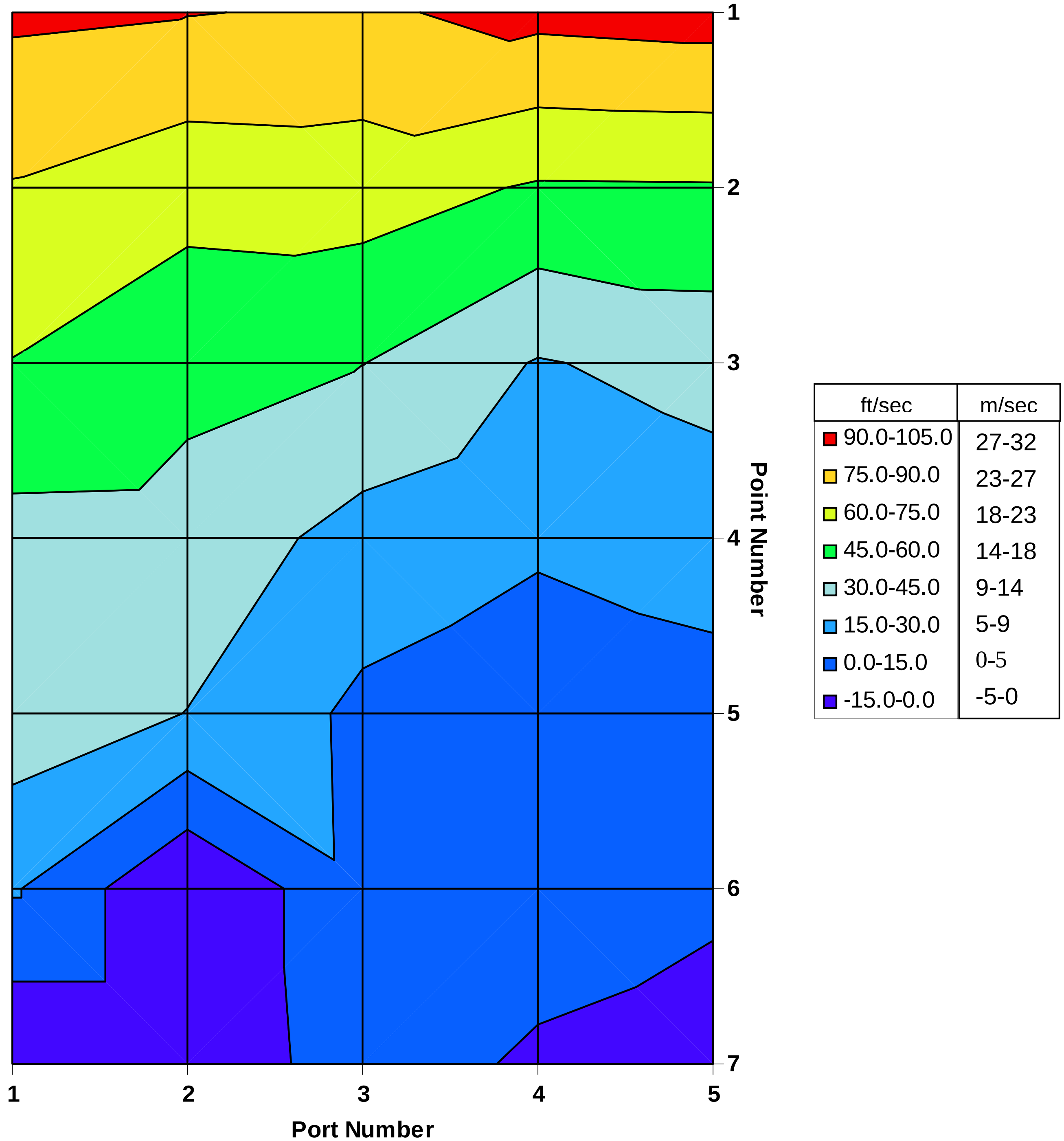
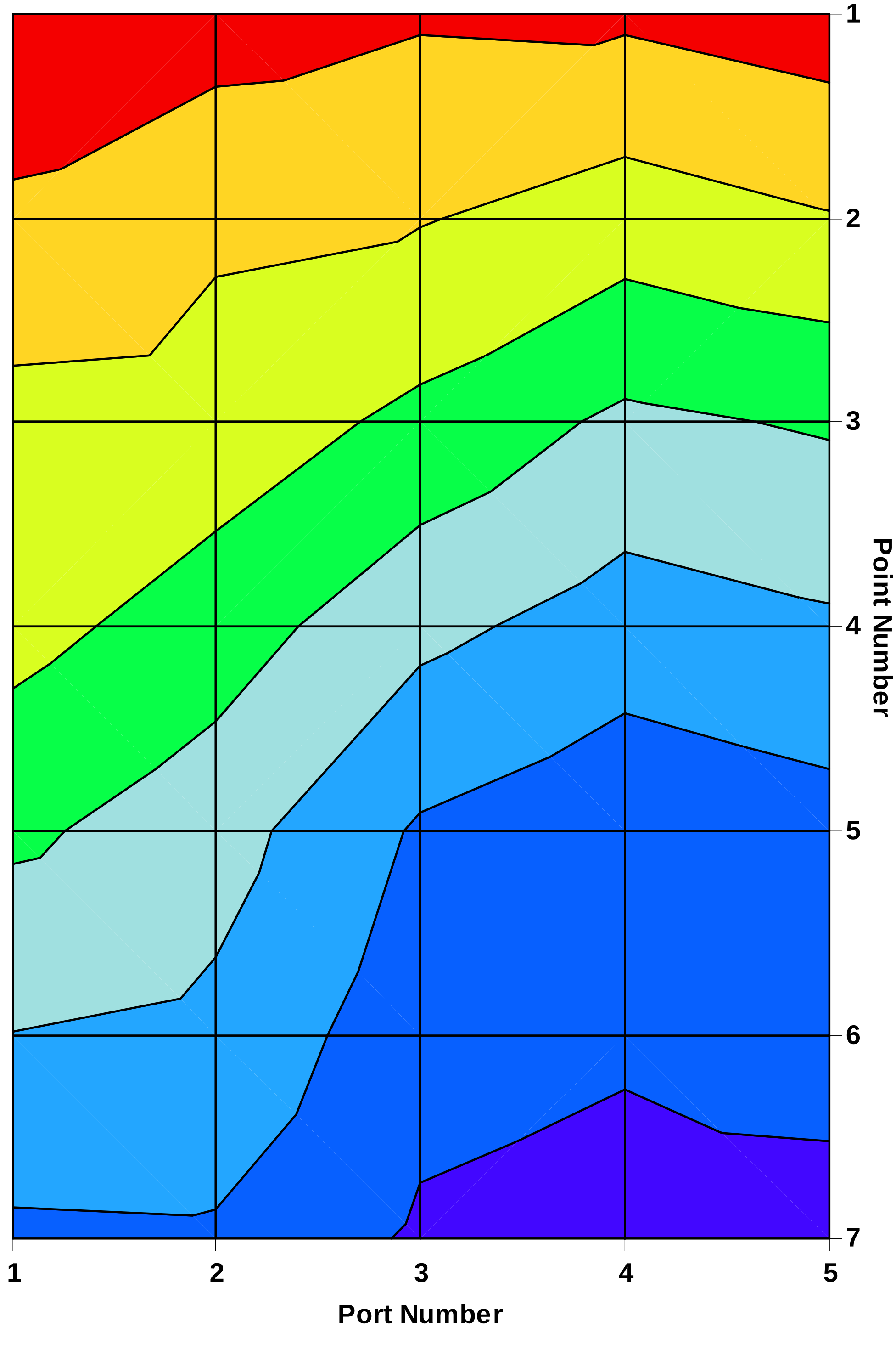


**Figure 5. Exhauster Air Velocity Profile – Test 6**




| ft/sec | m/sec |
|---|---|
| 90.0-105.0 | 27-32 |
| 75.0-90.0 | 23-27 |
| 60.0-75.0 | 18-23 |
| 45.0-60.0 | 14-18 |
| 30.0-45.0 | 9-14 |
| 15.0-30.0 | 5-9 |
| 0.0-15.0 | 0-5 |
| -15.0-0.0 | -5-0 |

**Figure 6. Exhauster Air Velocity Profile – Test 13**

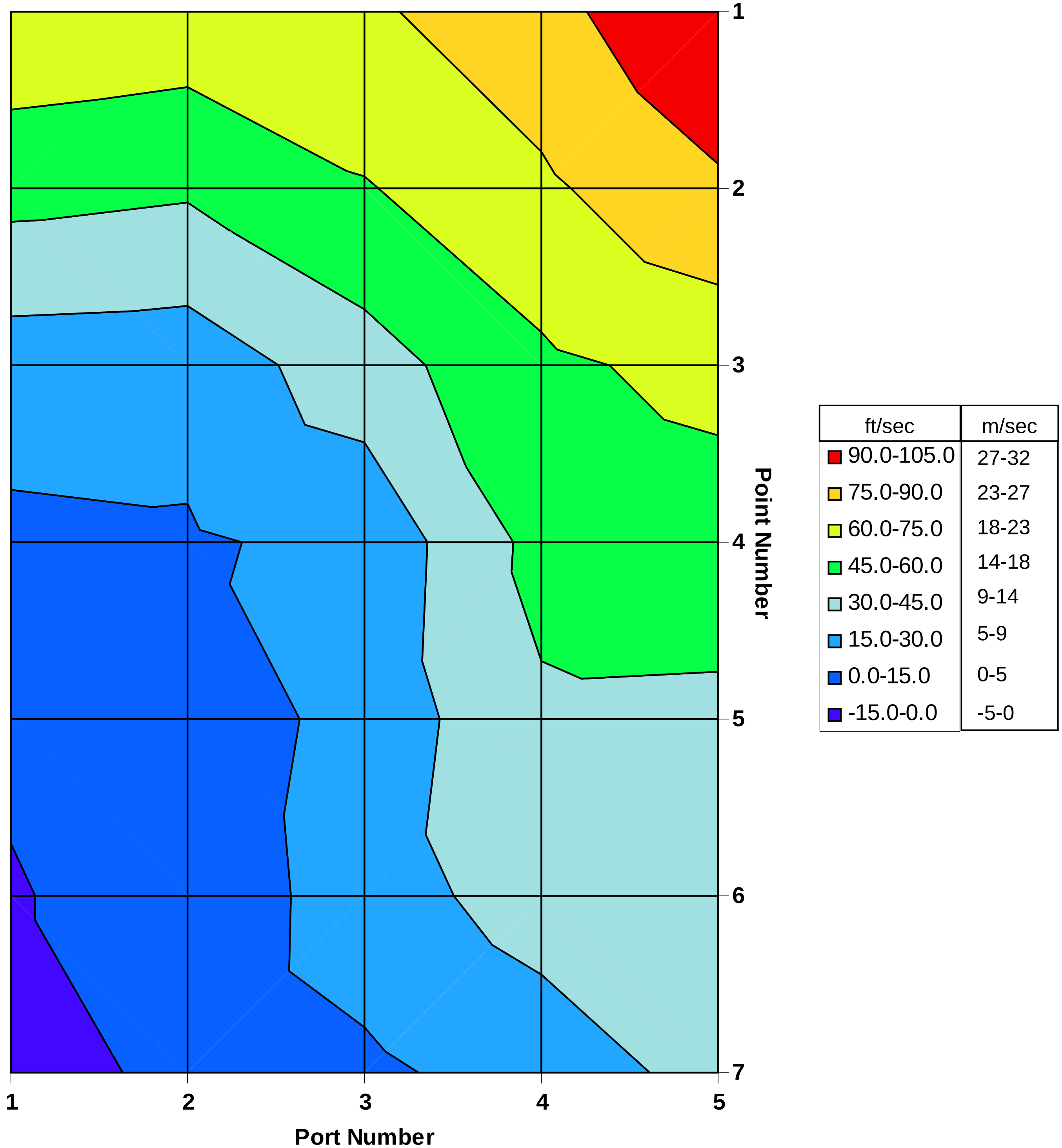
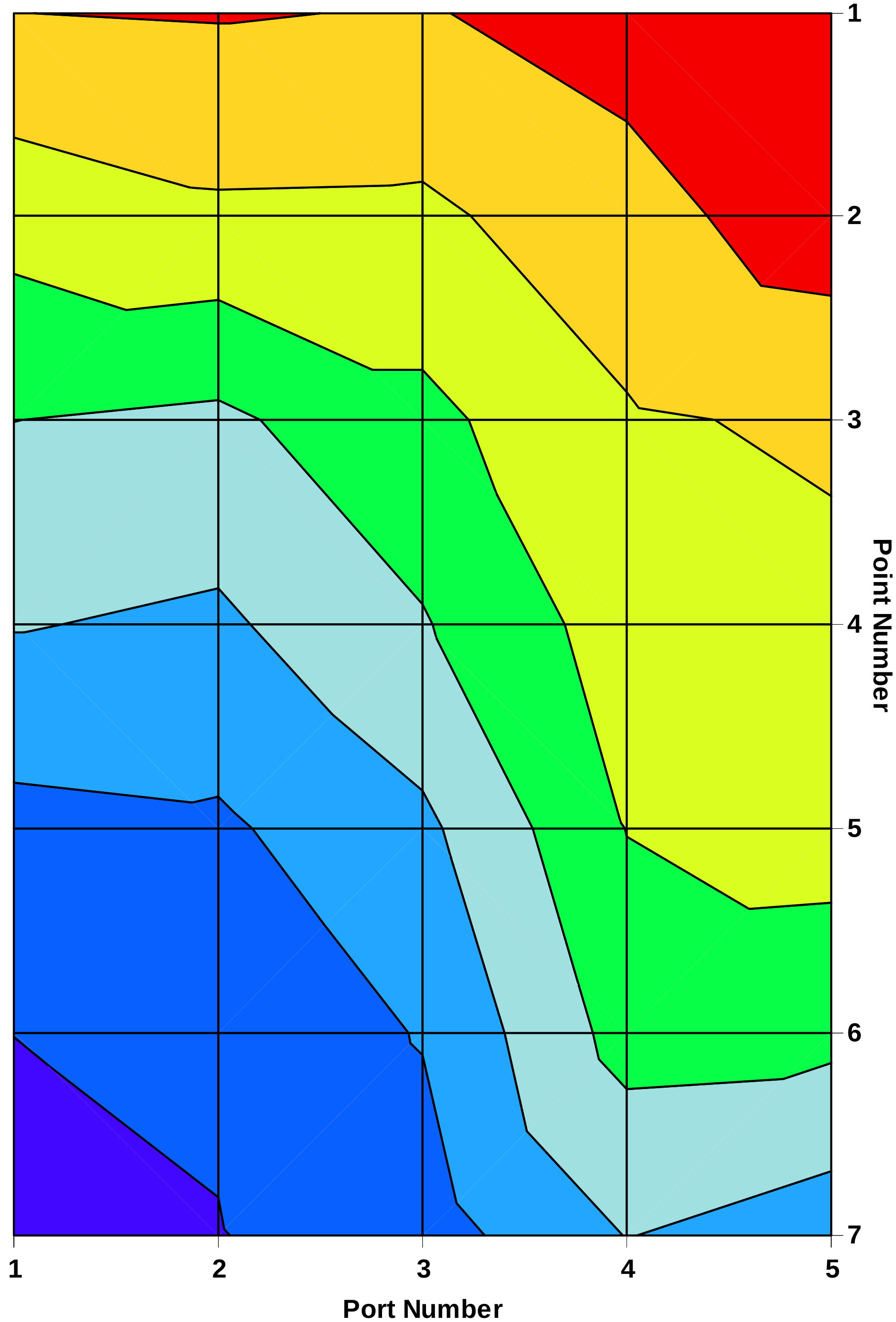


**Figure 7. Exhauster Air Velocity Profile – Test 14**




| ft/sec | m/sec |
|---|---|
| 90.0-105.0 | 27-32 |
| 75.0-90.0 | 23-27 |
| 60.0-75.0 | 18-23 |
| 45.0-60.0 | 14-18 |
| 30.0-45.0 | 9-14 |
| 15.0-30.0 | 5-9 |
| 0.0-15.0 | 0-5 |
| -15.0-0.0 | -5-0 |

**Figure 8. Exhauster Air Velocity Profile – Test 17**

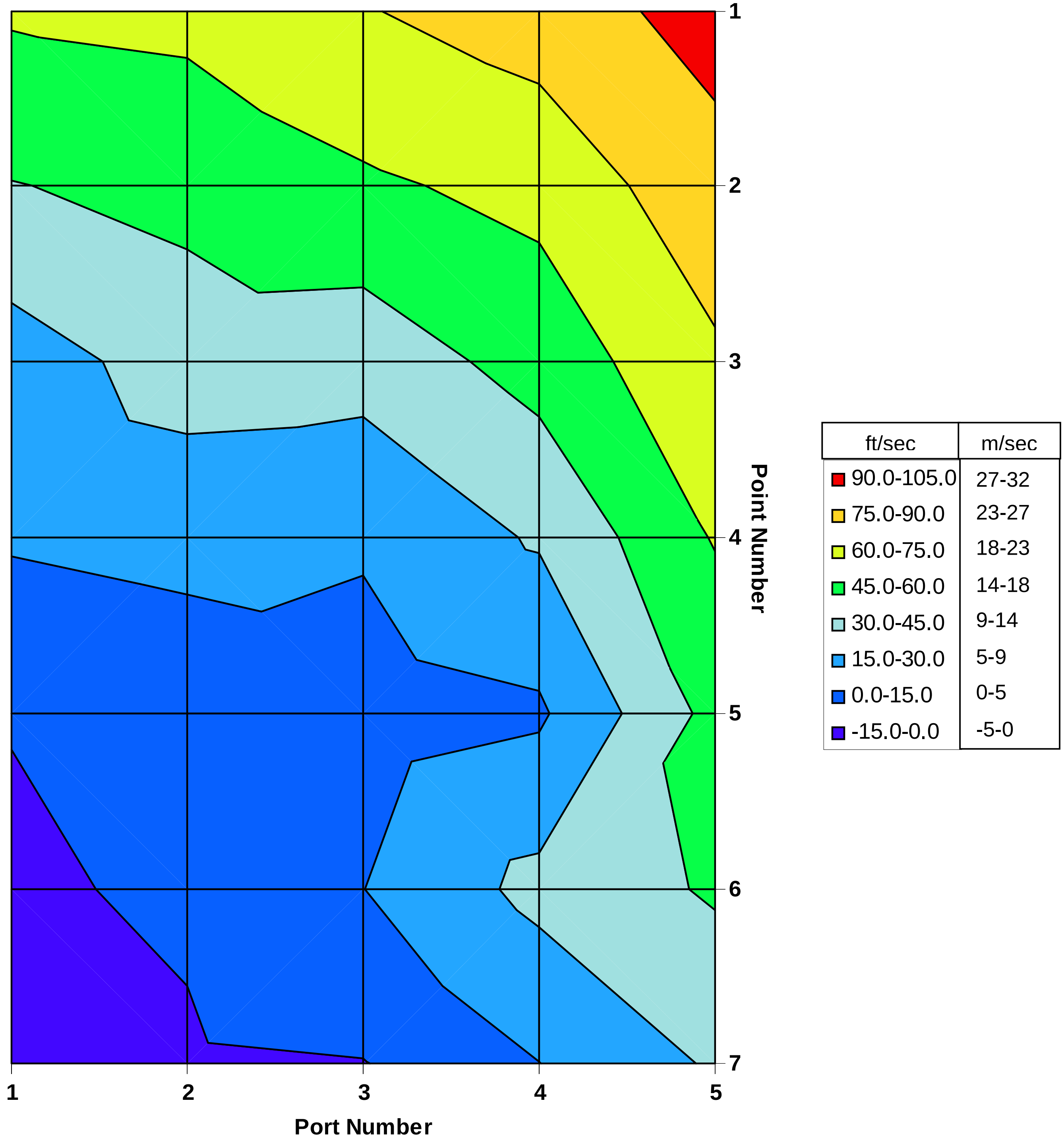


**Figure 9. Exhauster Coal Flow Profile – Test 5**

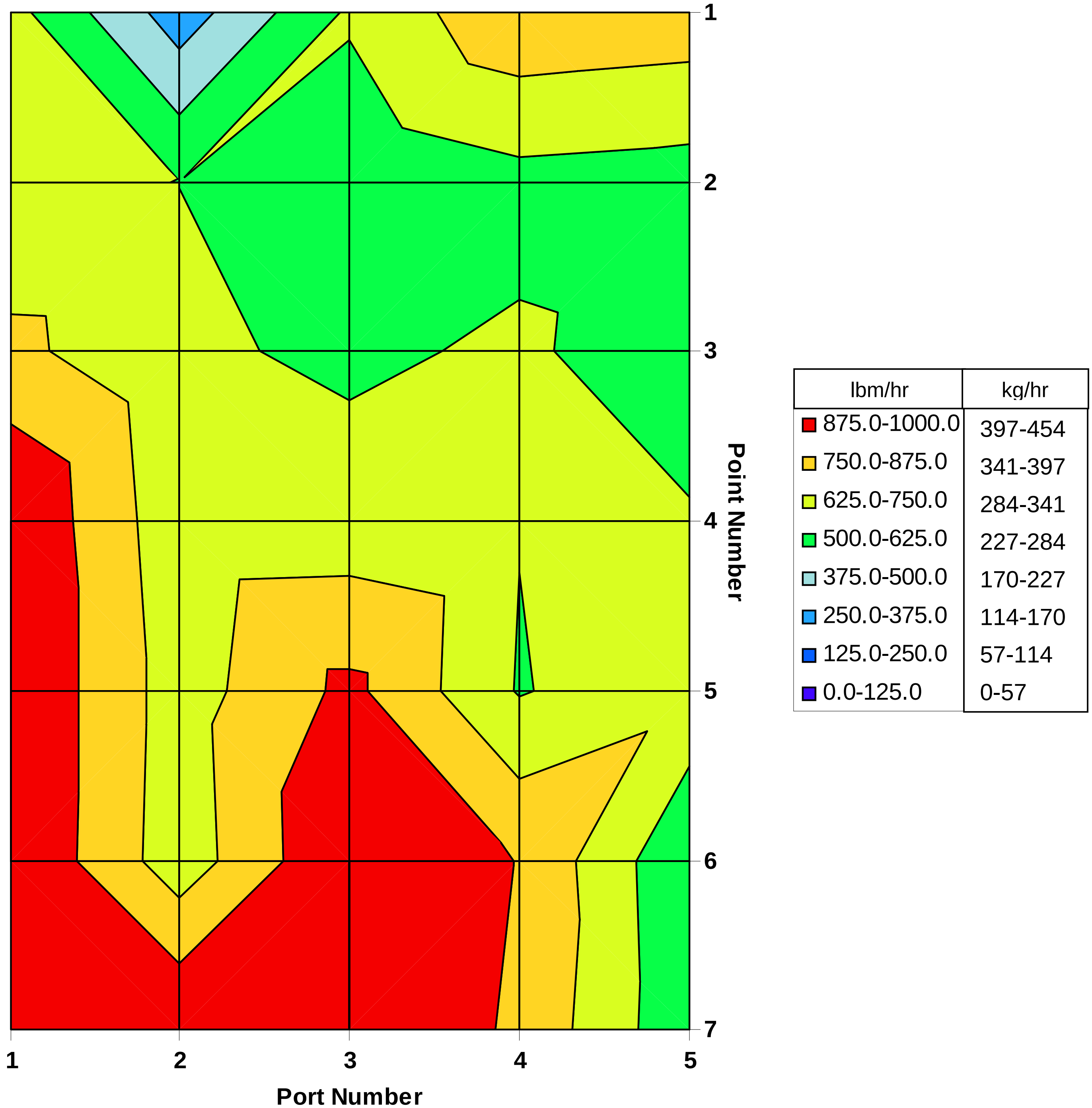


**Figure 10. Exhauster Coal Flow Profile – Test 6**

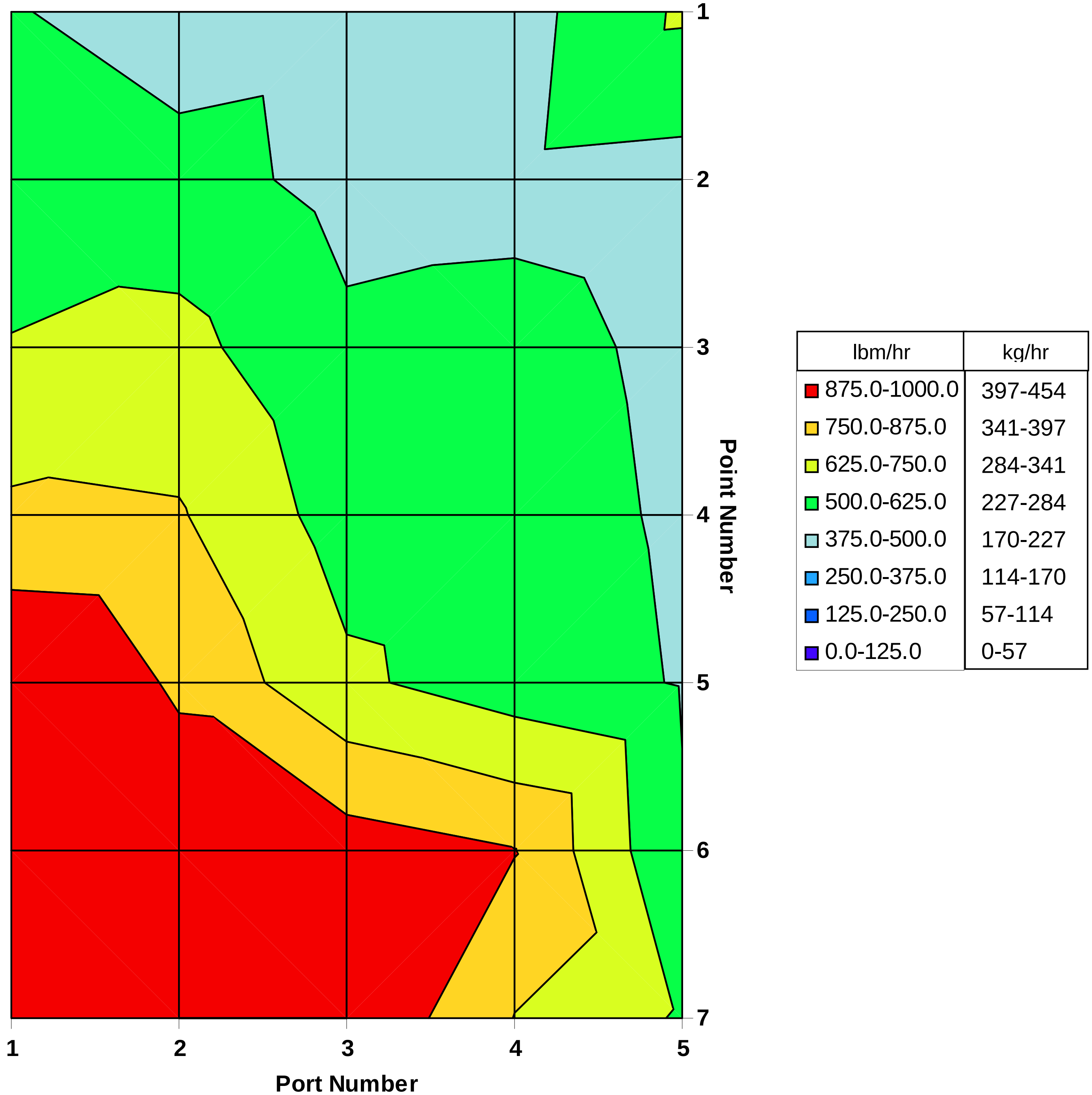


**Figure 11. Exhaustier Coal Flow Profile – Test 13**

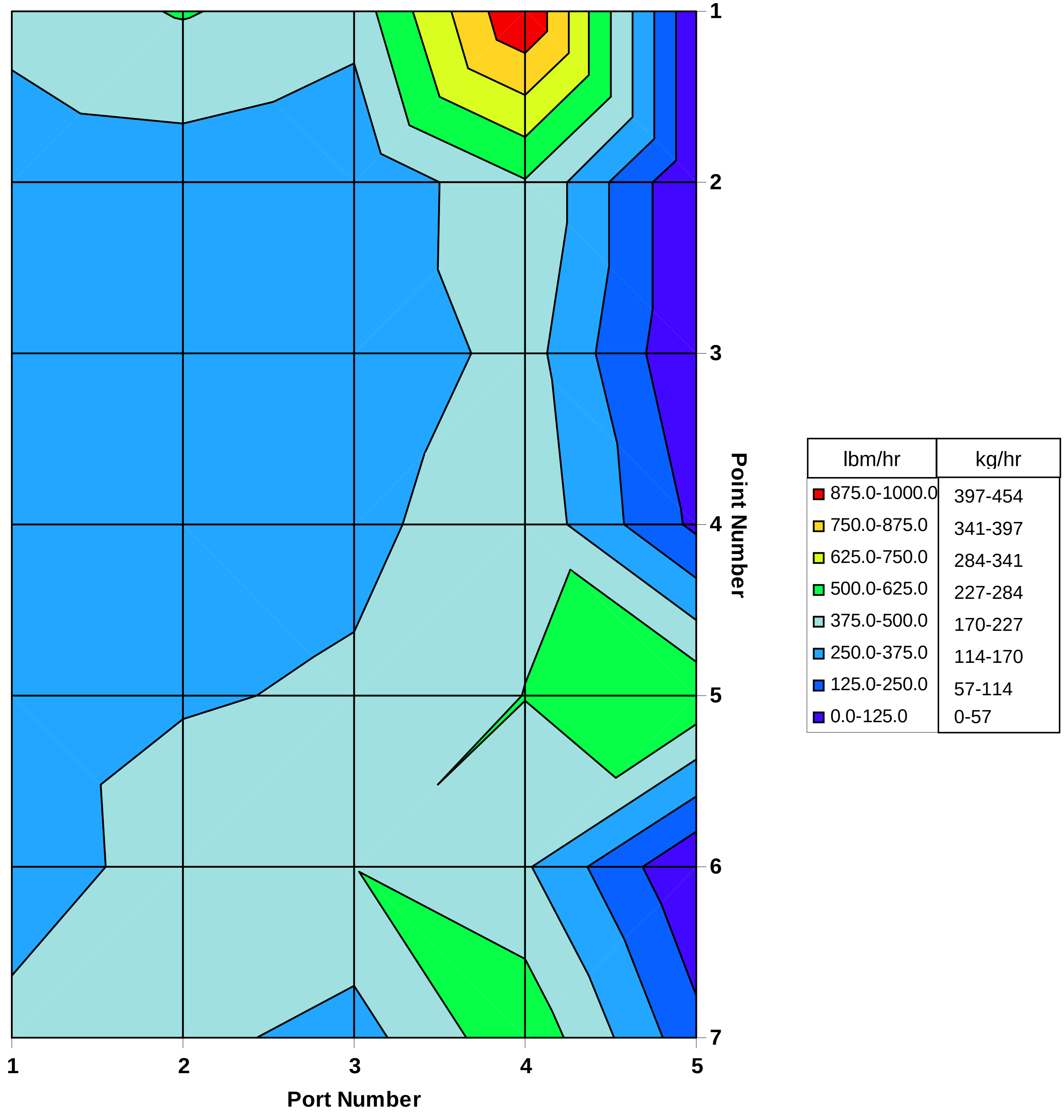


**Figure 12.  Exhauster Coal Flow Profile – Test 14**

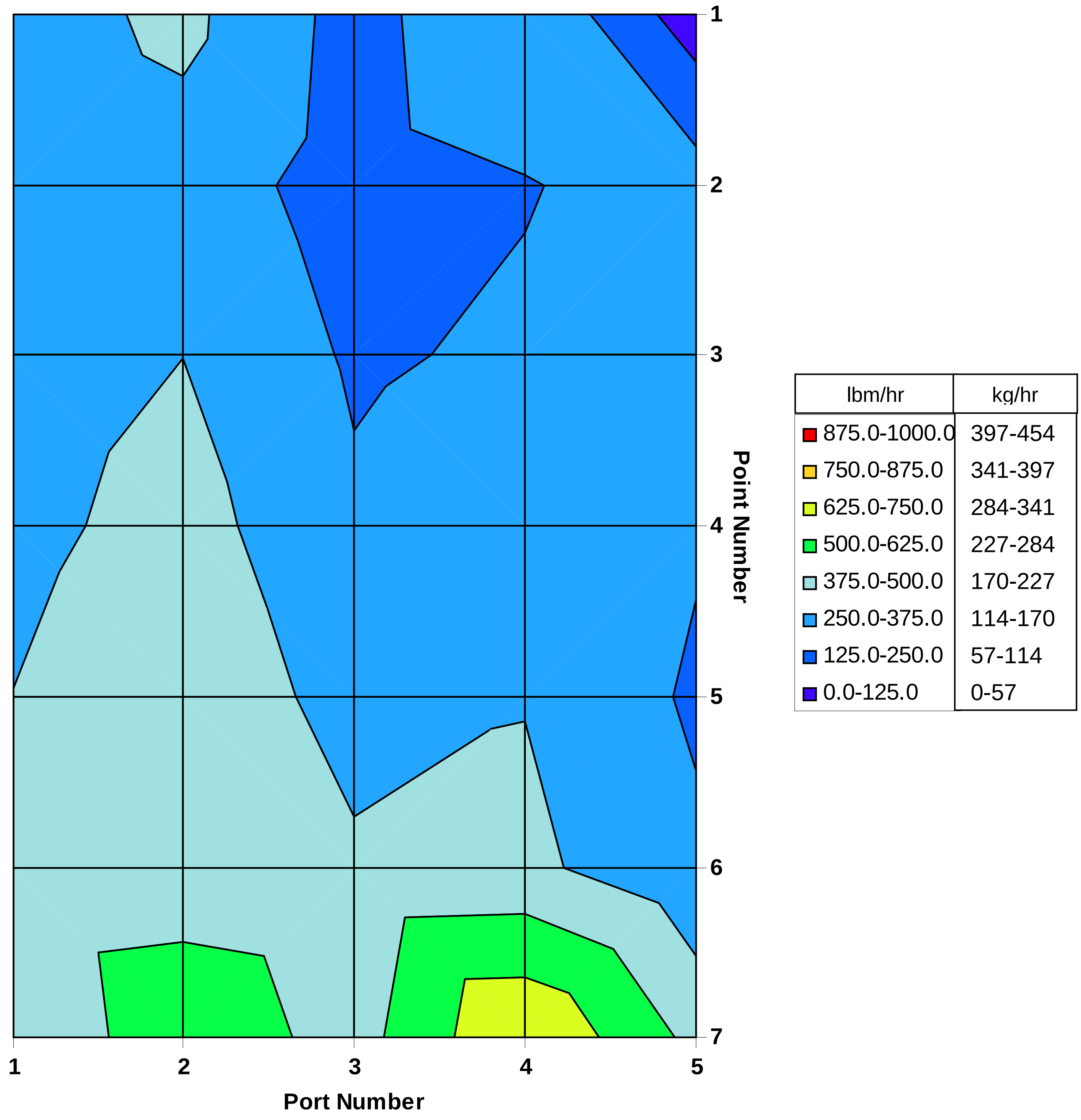


**Figure 13. Exhauster Coal Flow Profile – Test 17**

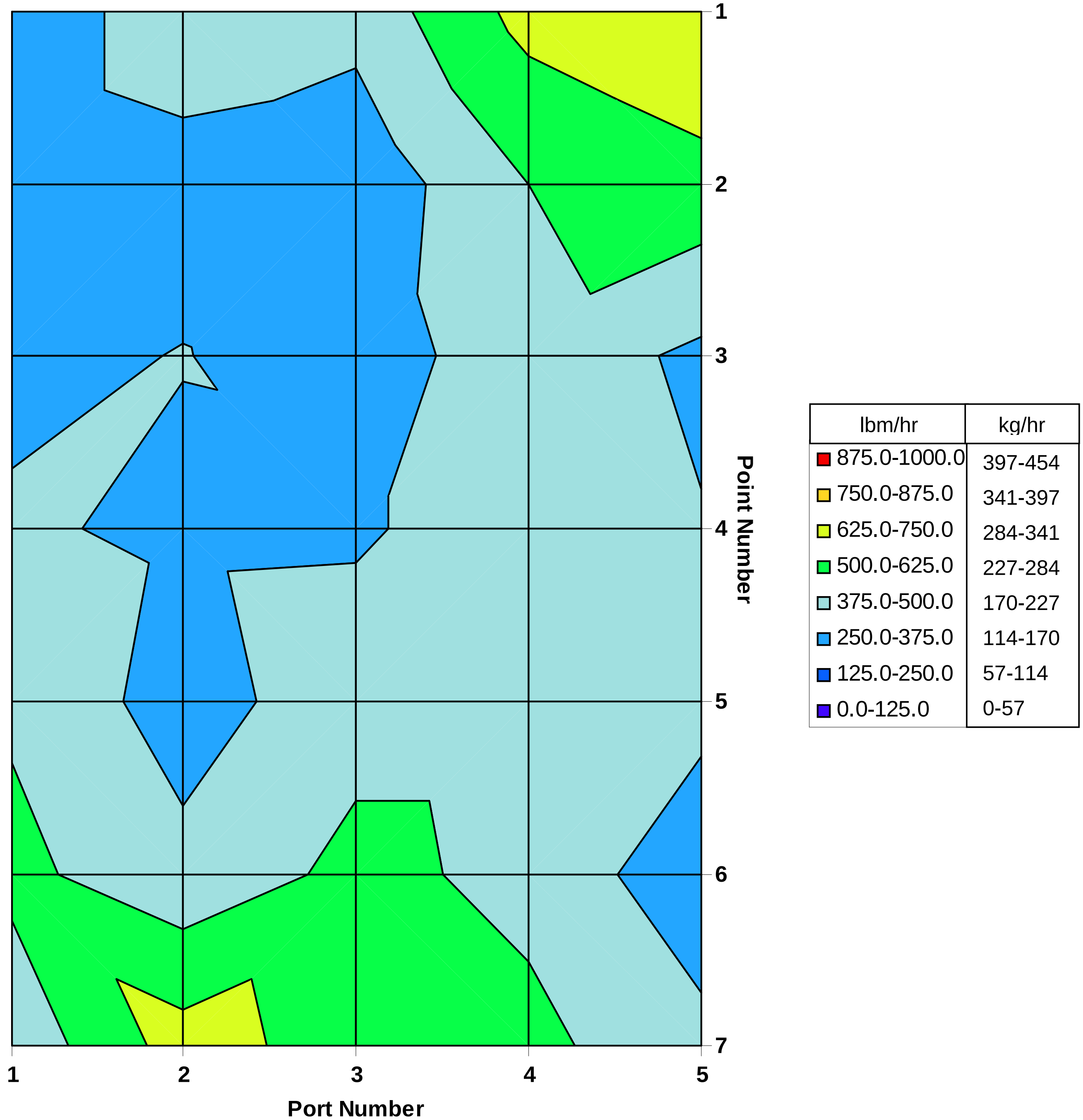


**Table 2. Effect of Auxiliary Air on Total Coal Flow**

| Test | Aux Air Damper | Coal Flow (lbm/hr) (kg/hr) | Output Damper |
|---|---|---|---|
| 5 | 5.3 | 31,857 / 14,463 | 68.3 |
| 6 | 75.0 | 21,554 / 9,786 | 67.9 |
| | | | |
| 13 | 10.6 | 26,940 / 12,231 | 38.0 |
| 14 | 75.0 | 18,896 / 8,579 | 38.0 |

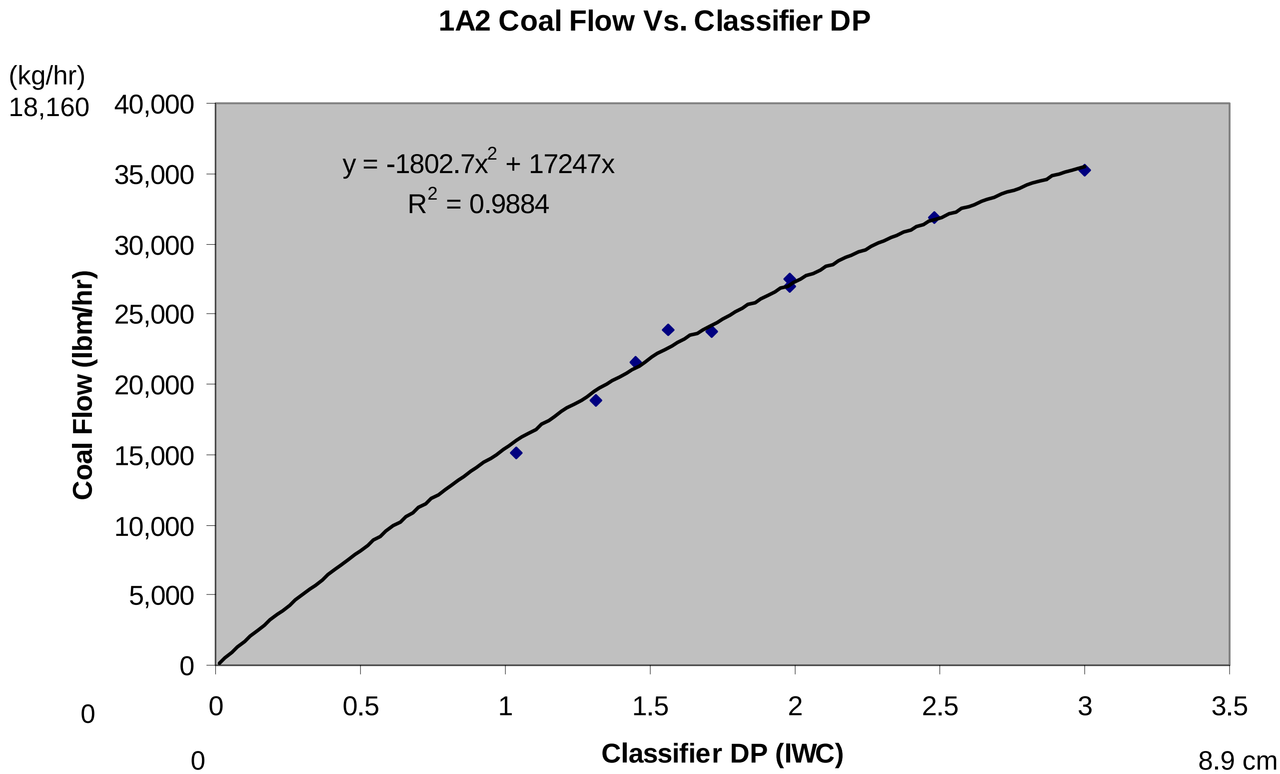
**Table 3. Effect of Total Coal Flow on Coal Flow Balance**

| Test | Output Damper (%) | Aux Air Damper (%) | Total Coal Flow (lbm/hr) / (kg/hr) | Total Air Flow (lbm/hr) / (kg/hr) | Pipe 2 | Pipe 4 | Pipe 6 |
|---|---|---|---|---|---|---|---|
| 1 | 61.6 | 5.0 | 35,251 / 16,004 | 48,546 / 22,040 | 13.2% | 10.5% | -23.7% |
| 13 | 38.0 | 10.6 | 26,940 / 12,231 | 45,245 / 20,541 | -2.4% | 2.9% | -0.5% |
| | | | | | | | |
| 2 | 61.8 | 75.0 | 27,500 / 12,485 | 61,140 / 27,758 | 29.3 | -3.6% | -25.7% |
| 14 | 38.0 | 75.0 | 18,896 / 8,579 | 58,032 / 26,347 | -3.3% | 3.3% | 0.0% |

**Table 4. Effect of Orifice on Coal Flow Balance**

| Test | Orifice | Total Coal Flow (lbm/hr) / kg/hr) | Total Air Flow (lbm/hr) / (kg/hr) | Coal Flow Balance | | | Air Flow Balance | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Pipe 2 | Pipe 4 | Pipe6 | Pipe 2 | Pipe 4 | Pipe 6 |
| 2 | None | 27,500 / 12,485 | 61,140/ 27,757 | 29.3% | -3.6% | -25.7% | -6.5% | 2.4% | 4.1% |
| 4 | Some | 23,815 / 10,812 | 55,789 / 25,328 | -11.1% | 16.3% | -5.3% | -25.5% | 12.9% | 12.6% |
| 6 | More | 21,554 / 9,786 | 53,145 / 24,128 | -39.1% | 27.1% | 11.9% | -40.5% | 21.8% | 18.7% |

**Figure 14. Correlation Between Classifier DP and Total Coal Flow**



# 3
# COMPUTATIONAL FLUID DYNAMICS MODELING

The primary design development tool for the coal flow splitter is the Computational Fluid Dynamics (CFD) model. This model will allow detailed analysis of the flow characteristics within the splitter, including the ability to understand the root causes of various flow phenomena. The modeling effort is being performed in two stages: 1) Baseline modeling, and 2) Design development. As of this writing, three different models have been completed. All fall under the category of Baseline, either to directly compare to the test data or as preliminary models.

## Methodology

The CFD model domain begins at the exhauster fan outlet and ends within the coal pipe approximately 14 inches downstream of the splitter. This geometry is shown in Figure 15. The first two runs were based on a model having 42,000 computational cells, and the third run was based on a model having 54,500 cells. The calculation of the velocity field and the coal particle trajectories includes the influences of two-phase flow. This is necessary since the coal mass loading is significant.

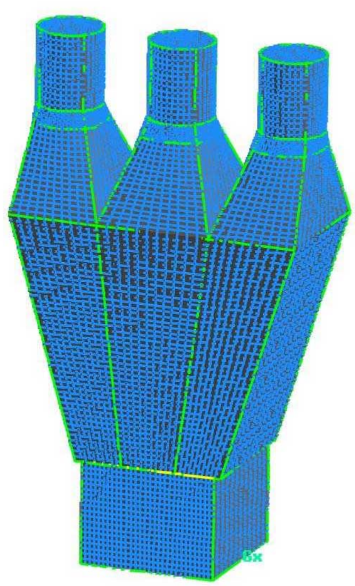


**Figure 15. CFD Model of Splitter Geometry**

For the first two baseline runs (Run 1 and Run 2), 10,440 particles were utilized. Ten different particle sizes were used ranging in diameter between 30 and 200 microns. The mass distribution of these particles was based on a Rosin-Rammler distribution. For the third run, 560 particle streamlines have been utilized. These were divided up into 4 size ranges. The mass loading of each particle size is currently being assumed based on previous test data. The actual particle size distribution at the exhauster outlet for the Armstrong Mill 2A2 has yet to be determined from the coal samples obtained in the field testing. For the third run, the total mass of the incoming coal has been distributed among the four particle sizes in the following manner:

| Particle Diameter (microns) | Percent of Coal Mass |
|---|---|
| 50 | 60.2 |
| 120 | 24.8 |
| 200 | 13.0 |
| 350 | 2.0 |

**Table 5. Initial Particle Size Distribution for Third Baseline Model**

### *Run 1 – Uniform Flow*

The initial baseline run utilized an idealized inlet flow condition. This run was completed before the testing occurred and acted as an initial check of the model. A perfectly uniform velocity and coal loading profile were established at the model inlet. The air flow rate was set to 35,595 lb/hr (16,160 kg/hr) at 392°F (200°C). The coal flow rate was 16,927 lb/hr (7,685 kg/hr) with the mass loading per particle size range as noted above.

The model exit condition consisted of a constant pressure for each of the three coal pipes. This basically simulates a condition where all three pipes are exactly the flow resistance between the splitter and the furnace (i.e., same length, number of bends, burner geometry, etc.).

#### Results

Results for Run 1 are shown in Figures 16 through 18. Interestingly, the center pipe receives almost twice as much coal flow as the two outboard pipes but slightly less air flow. The outboard pipes receive nearly the same amounts of coal and air due to the perfect symmetry of the geometry and inlet conditions. Only the randomness of the coal trajectories (turbulence effects) causes a variation between the two.

The plot of Figure 16 shows that the velocity along the side walls of the splitter is very low. There is actually a small recirculation region evident due to the fact that flow cannot stay attached to the wall, which features an expansion angle of about 17 degrees from the vertical. Typically a 7 degree angle is required to maintain attached flow (in a single phase flow situation). Table 6 gives the air and mass flow distribution.

Figure 17 provides velocity data at select horizontal planes. The uniformity of the inlet flow is clearly evident, as is the low velocity region near the side walls of the splitter. Corner effects are also notable.

Particle streamlines are shown in Figure 18 for Run 1. All 10,440 streamlines are plotted, so the figure is somewhat difficult to interpret. It is evident that there is little particulate activity near the side walls of the splitter. This follows from the air velocity patterns noted above. The particle streamlines are colored by size, and there is a notable concentration of larger particle sizes in the outboard pipes. This is to be expected since the larger particles have more difficulty spreading out due to momentum effects.

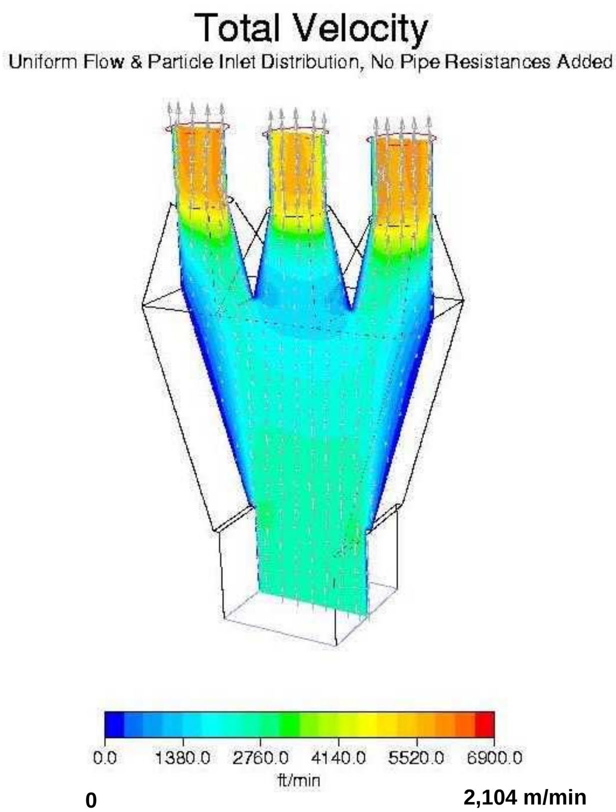



**Figure 16. CFD Run 1 Total Velocity – Side View**

**Table 6. CFD Run 1 – Air and Coal Flow Distribution**

| Splitter Data | | |
|---|---|---|
| **Pipe** | **Air Flow (lb/hr) / (kg/hr)** | **Coal Flow (lb/hr) / (kg/hr)** |
| Left | 12,246 / 5,560 | 4,468 / 2,028 |
| Center | 11,103 / 5,041 | 8,007 / 3,635 |
| Right | 12,246 / 5,560 | 4,452 / 2,021 |
| **Total** | **35,595 / 16,160** | **16,927 / 7,685** |

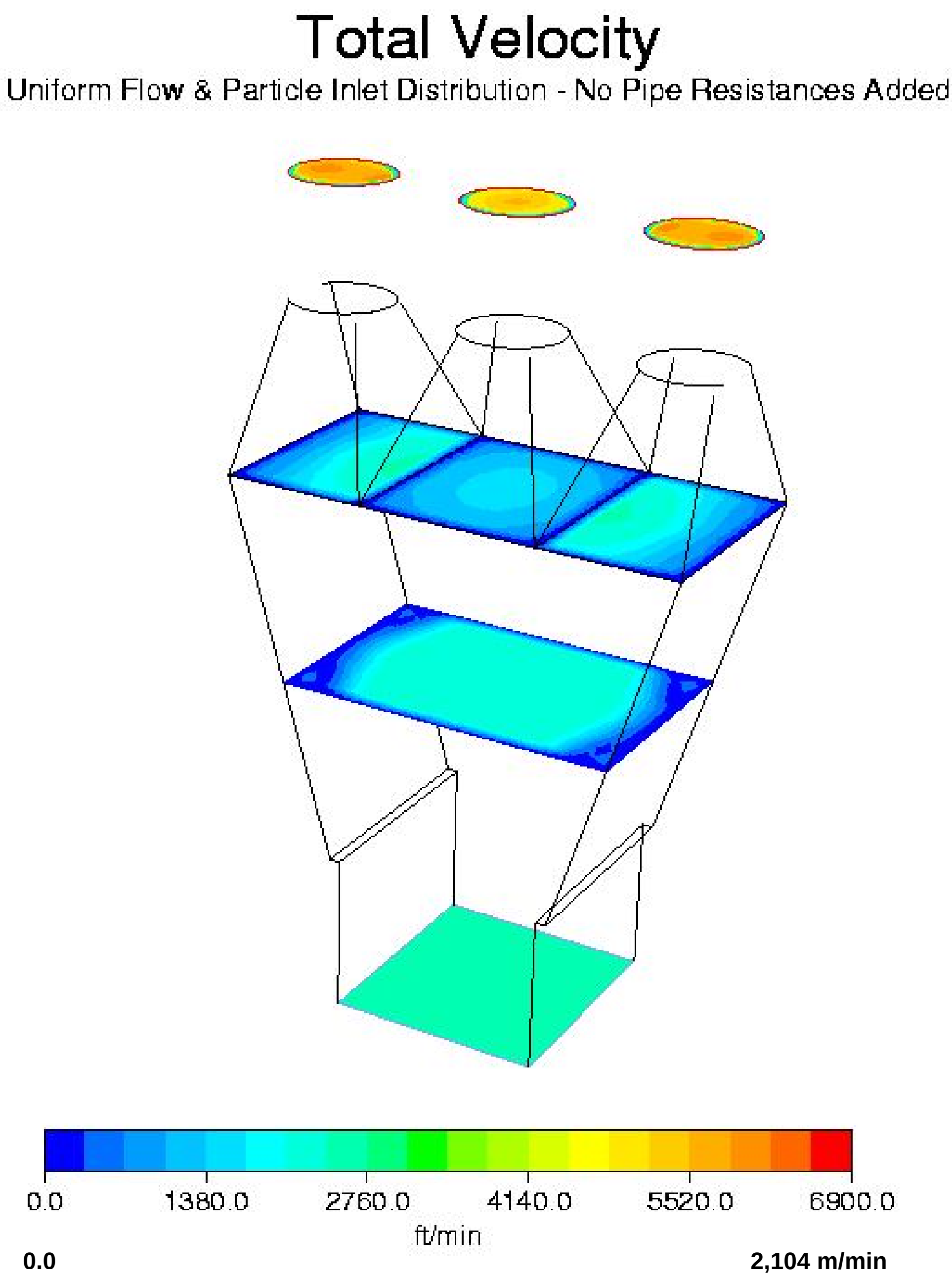



**Figure 17. CFD Run 1 total Velocity – Plan Views**

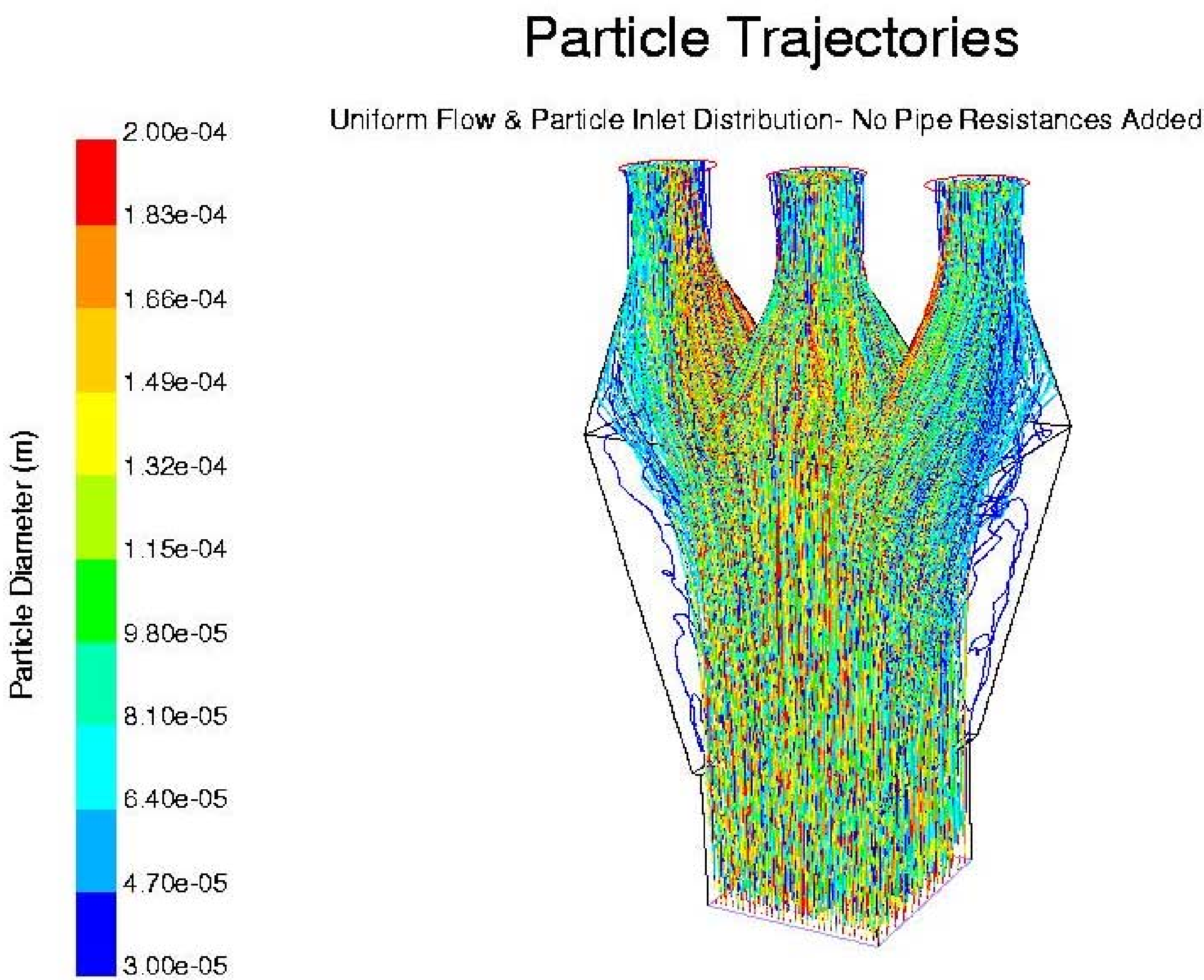



**Figure 18. CFD Run 1 Particle Streamlines**

### *Run 2 – Center Pipe Restricted*

In order to understand some of the sensitivities of the coal splitter system, one simulation was performed with a flow restriction in the center pipe. This is basically a representation of an orifice or some other device which blocks a certain percentage of the pipe cross section. In the case of Run 2, a resistance was utilized which reduced the air flow to the center pipe by 22% over the previous case.

#### Results

The results of Run 2 are depicted in Figures 19 through 21. Figure 19 clearly indicates the change in the air velocity profile. The tabulated numbers in Table 7 show that while the air flow rate to the center pipe decreased by 22%, the coal flow rate only decreased by 12%. ASC has noted a similar trend numerous times in the past—orifices in coal pipes have a primary influence on air flow rate but a secondary influence on coal flow rate. In this case, the additional back-pressure of the orifice does cause the coal to spread out more in the splitter, but since back-pressure alone cannot reduce the particle momentum, a considerable amount of coal still travels to the center pipe.

The velocity patterns in plan view sections, shown in Figure 20, are similar to those for Run 1. The higher velocity flow traveling toward the outer pipes can be seen initiating in the center plane of the splitter. The streamline plot of Figure 21 is very similar to that for Run 1, including the concentration of larger particles following the inboard wall of the outboard pipes.

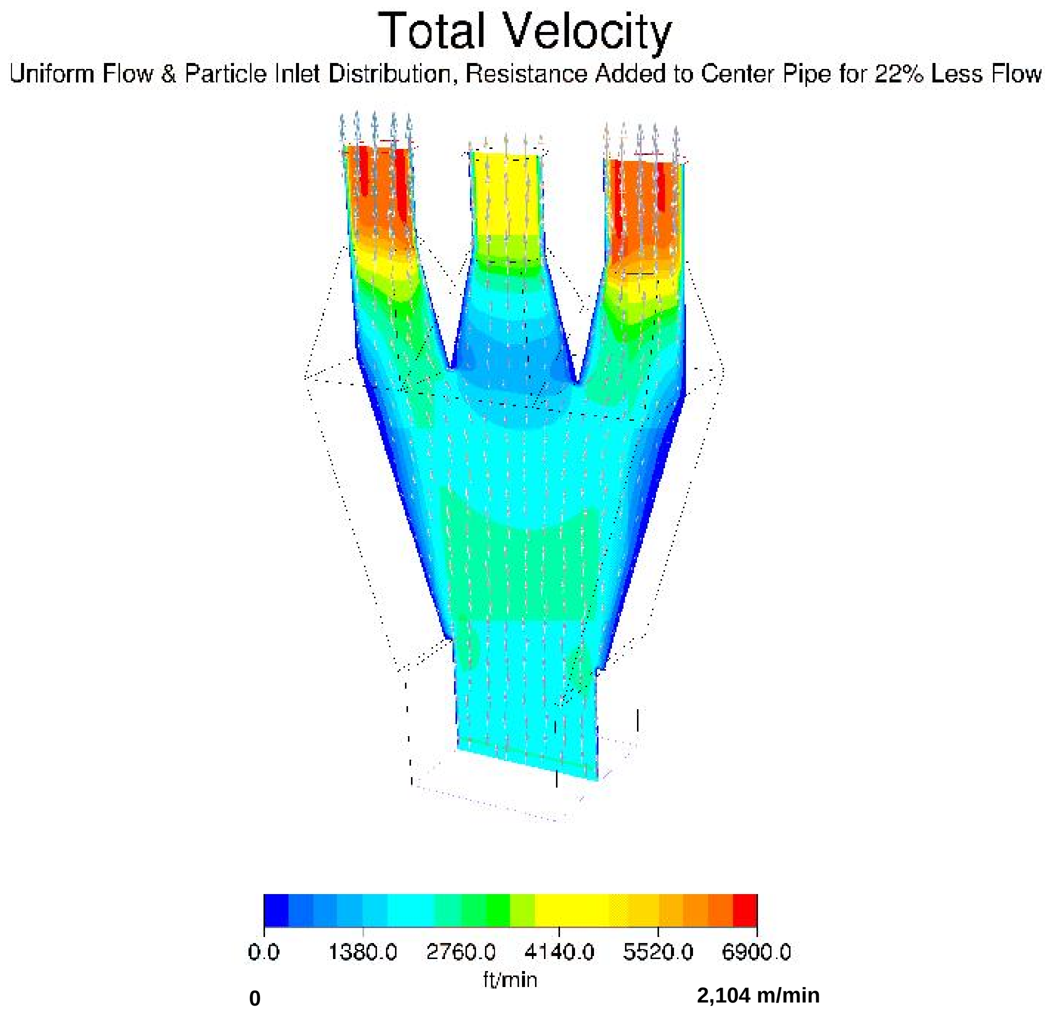



**Figure 19. CFD Run 2 Total Velocity – Side View**

**Table 7. CFD Run 2 – Air and Coal Flow Distribution**

| Splitter Data | | |
|---|---|---|
| **Pipe** | **Air Flow (lb/hr) / (kg/hr)** | **Coal Flow (lb/hr) / (kg/hr)** |
| Left | 13,466 / 6,114 | 4,917 / 2,232 |
| Center | 8,671 / 3,937 | 7,041 / 3,197 |
| Right | 13,462 / 6,112 | 4,979 / 2,260 |
| **Total** | **35,599 / 16,162** | **16,937 / 7,689** |

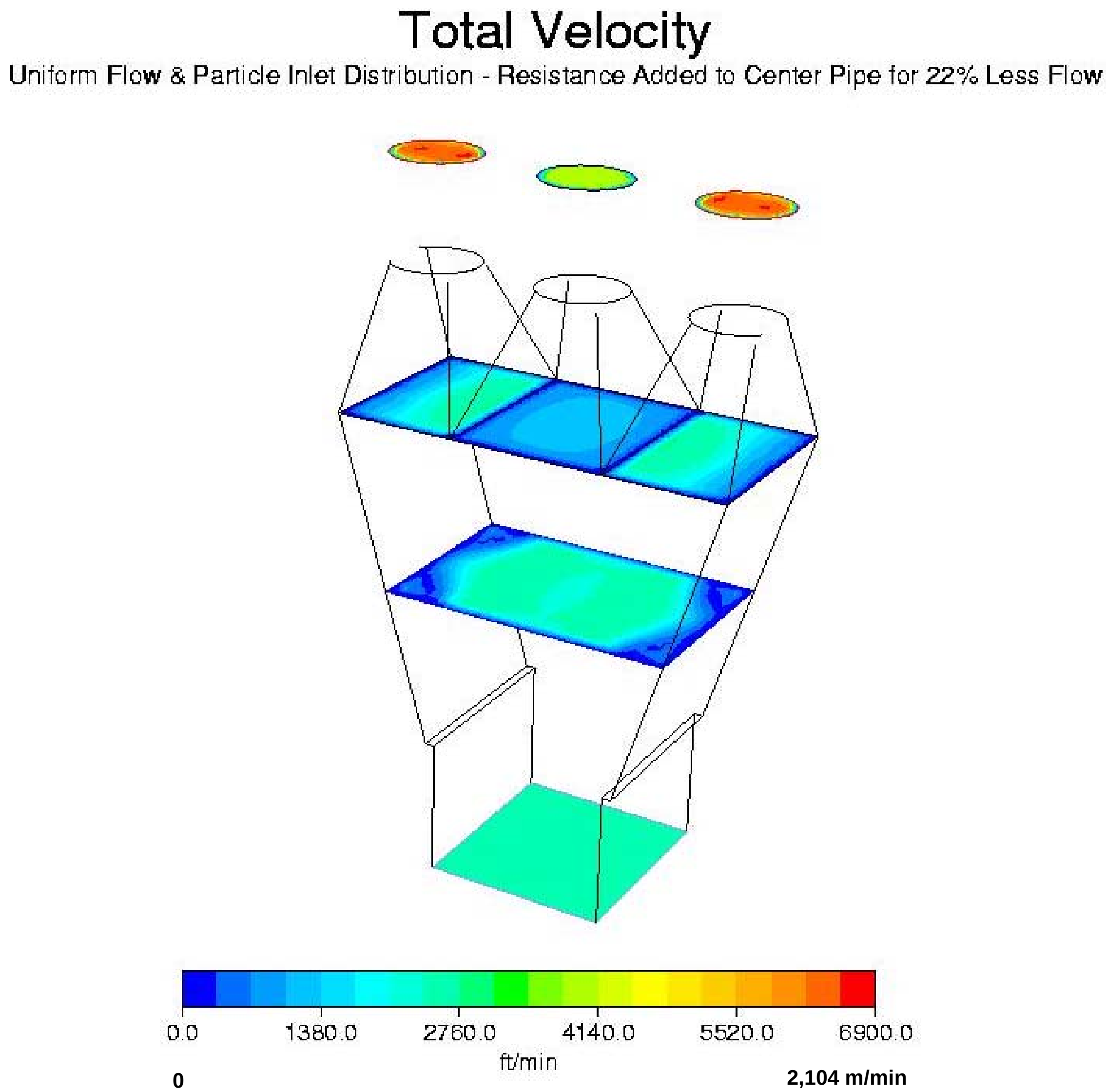



**Figure 20. CFD Run 2 total Velocity – Plan Views**

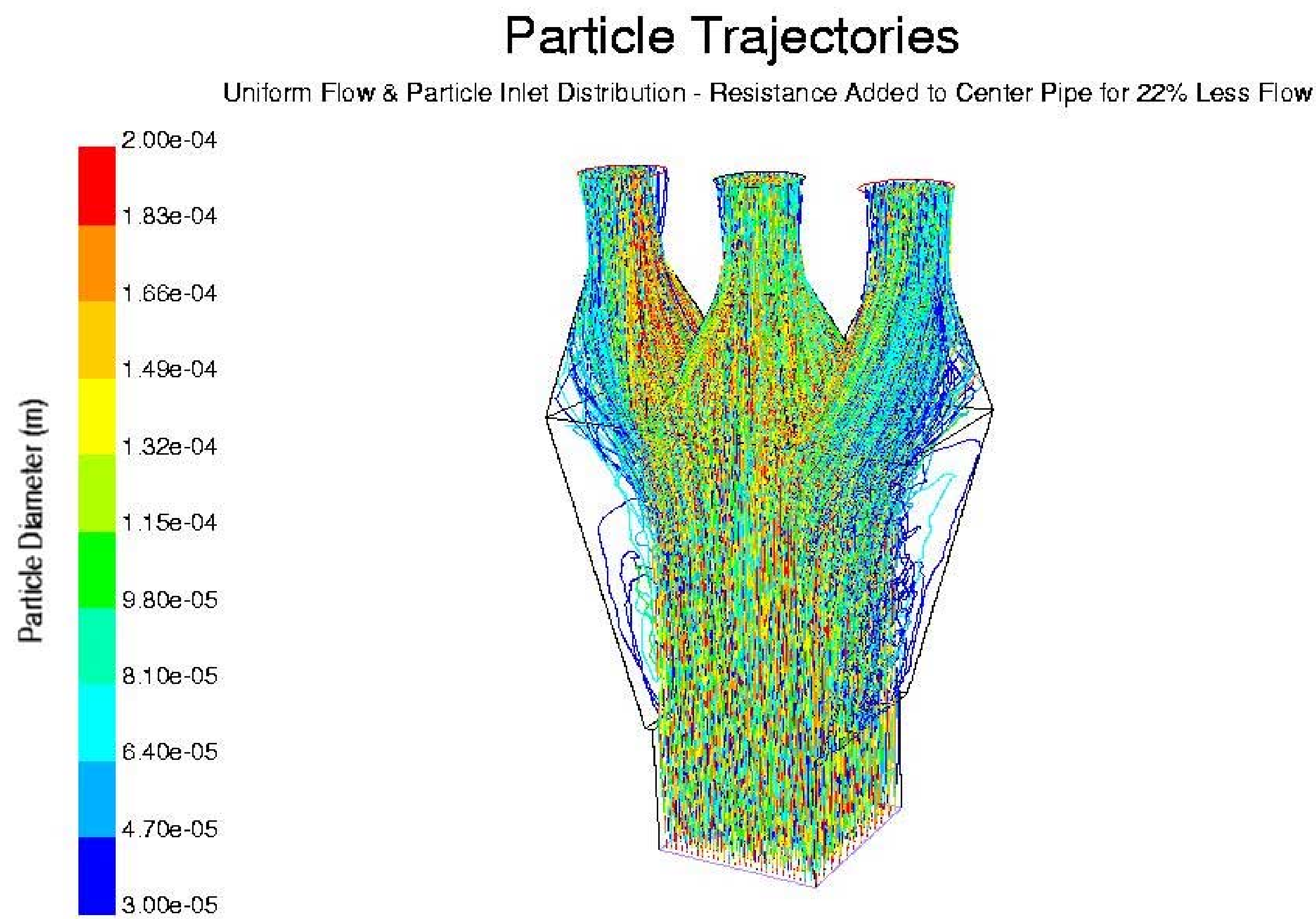



**Figure 21. CFD Run 2 Particle Streamlines**

### *Run 3 – Field Test 5*

This simulation featured the first "true" baseline case. The exact air velocity and coal mass loading profiles as measured during the testing for Configuration 5 were incorporated into the model. The assumed particle size distribution mentioned previously is still utilized since actual data is not yet available. The total air mass flow rate was 39,479 lb/hr (17,923 kg/hr) and the coal flow rate was 31,501 lb/hr (14,301 kg/hr).

Since the testing effort provided system pressure data as well as velocity and coal flow data, the model was further updated to account for variations in the coal pipe geometry. This basically entailed the addition of a "coal pipe resistance" at the outlet of each of the three pipes. The resistance value is calculated from the pressure drop between the splitter and the furnace and accounts for differences in piping geometry, orifices, etc. This addition will allow more accurate predictions of the model.

During the field testing, Configuration 5 featured an attempt to alter the flow resistance of Pipe 2 by closing the pipe shut-off damper. This damper closure has been added to the model as well, and is modeled as a solid plate blocking 50% of the coal pipe cross section

#### Results

The results of Run 3 are shown in Figures 22 to 24. There are several notable differences between this run and the previous two uniform-inlet cases. Figure 22 shows a definite skewing of the air flow profile at the exhauster exit. The air favors the left side in the model, which is closer to Pipe 2. This is also tabulated in Table 8. A lower velocity region is shown at the exhauster exit on the right side.

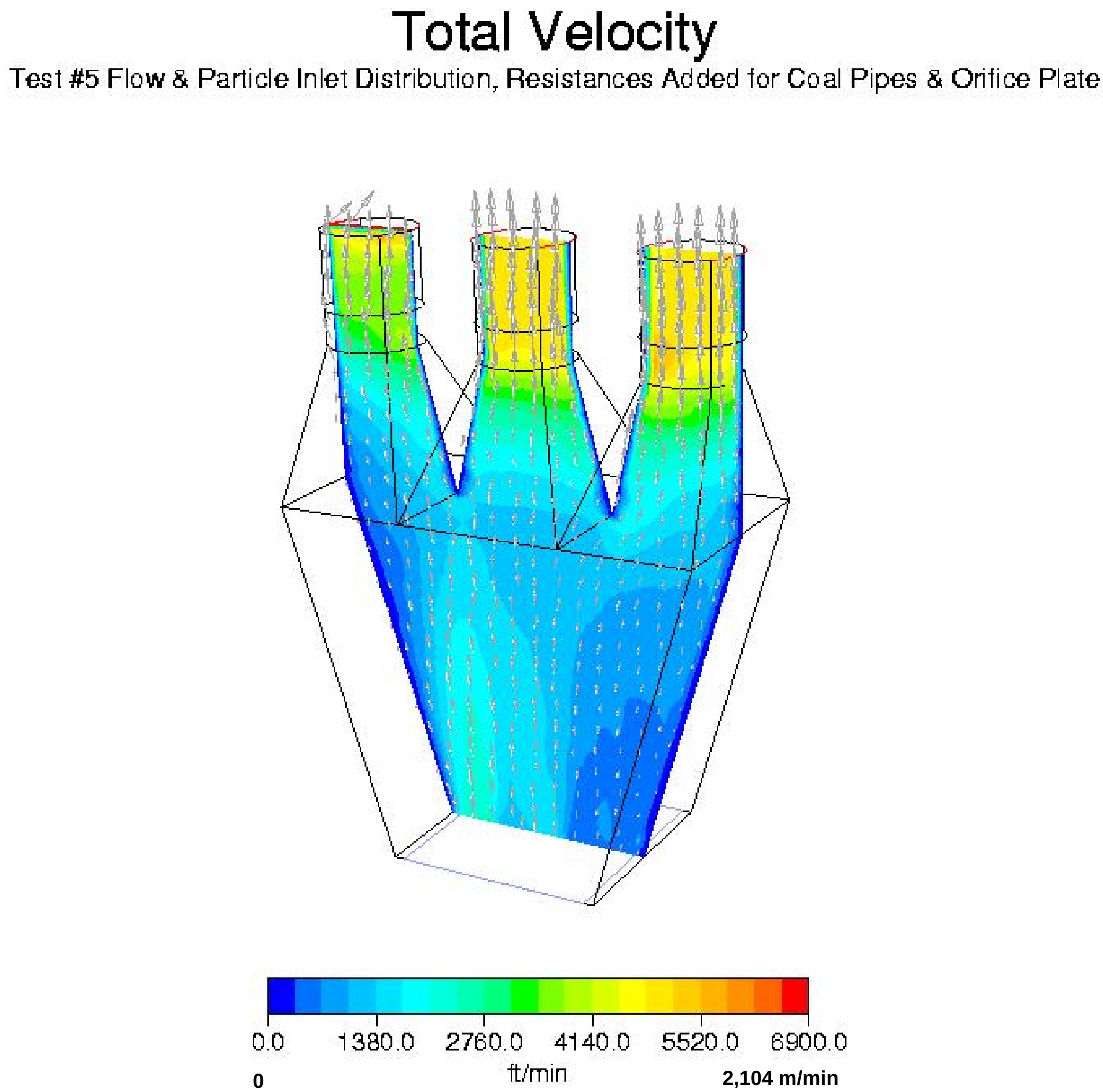



**Figure 22. CFD Run 3 (Test 5) Total Velocity – Side View**

**Table 8. CFD Run 3 (Test 5) – Air and Coal Flow Distribution**

| Splitter Data | | |
|---|---|---|
| **Pipe** | **Air Flow (lb/hr) / (kg/hr)** | **Coal Flow (lb/hr) / (kg/hr)** |
| 2 (Left) | 10,508 / 4,771 | 9,509 / 4,317 |
| 4 (Center) | 14,693 / 6,671 | 9,037 / 4,103 |
| 6 (Right) | 14,278 / 6,482 | 12,955 / 5,882 |
| **Total** | **39,479 / 17,923** | **31,501 / 14,301** |
| Exhauster Exit Data | 39,238 / 17,814 | 31,807 / 14,440 |

Recall from Figures 8 and 9 the measured velocity and coal loading profiles at the exhauster exit. The air velocity pattern was highly non-uniform. This mal-distribution in the splitter is better depicted in Figure 23. The highest air velocities exist on the back side of the splitter (the same side as the exhauster). The flow slightly favors the right side over the left side.

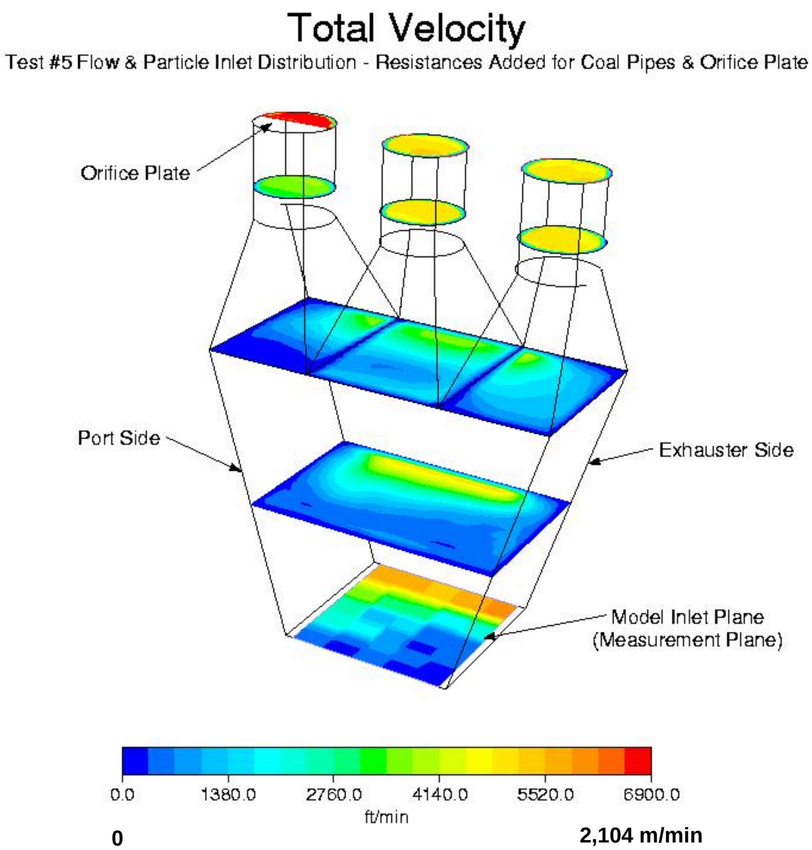



**Figure 23. CFD Run 3 (Test 5) Total Velocity – Plan View**

Since the highest coal concentration at the exhauster exit was in the front left in this view (favoring the corner opposite the exhauster towards Pipe 2), it is not surprising that the shutoff gate of Pipe 2 was closed in an effort to better balance the coal flow. The model predicts that this amount of closure is too much—more coal is directed to Pipe 6 now.

Figure 23 also shows the shutoff damper, labeled "orifice plate" in the figure. The blockage was estimated to be 50% (based on measured flow and pressure data); the exact value was not known due to the mechanics of the damper.

Figure 24 shows the particle trajectories for Run 3. Though the pipe with the highest coal mass flow is Pipe 6 (the right-hand pipe), the streamline plot seems to show more particles traveling to Pipe 4 (the center pipe). The difference is the fact that more of the smaller particles enter Pipe 6 in the model, and the smaller particles account for more total mass (see Table 5). Thus, the model is predicting a difference in particle size distribution in each pipe.

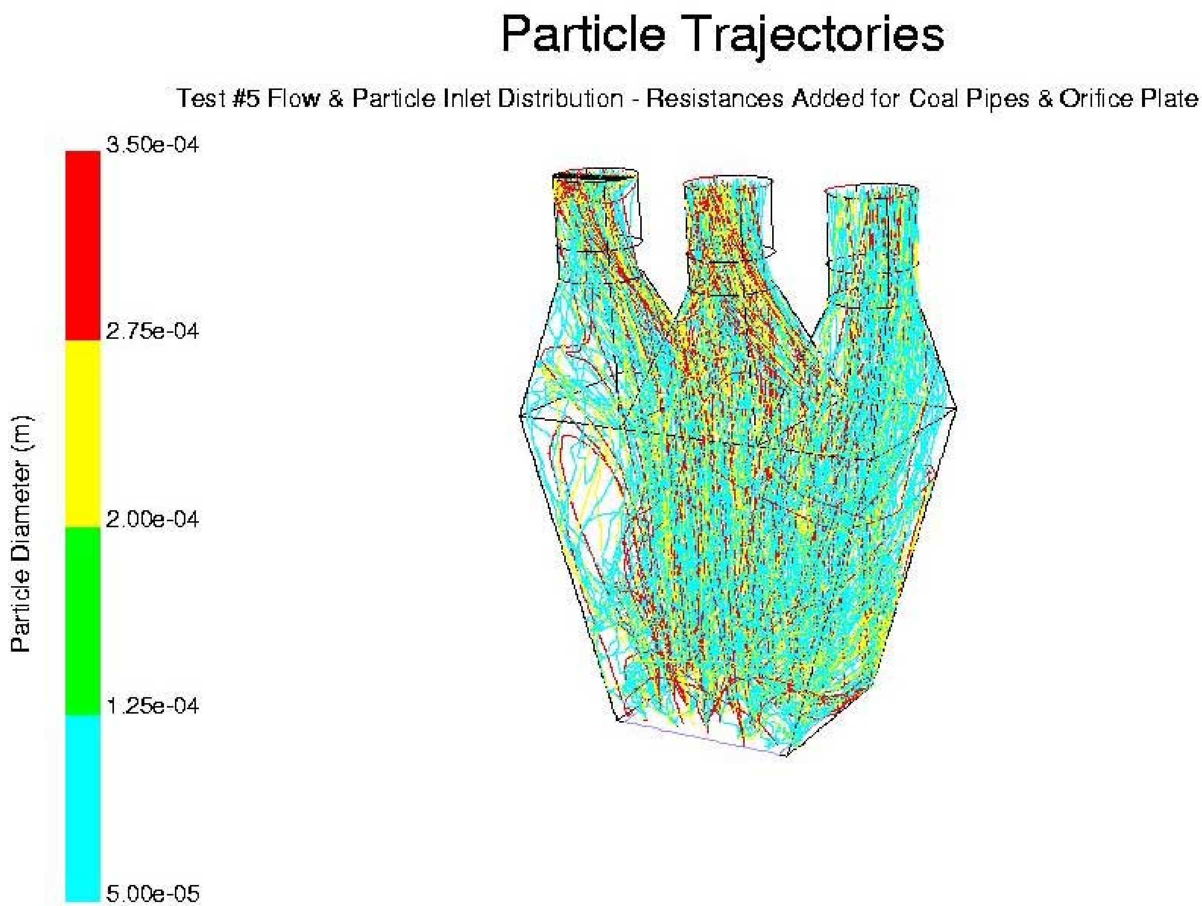



**Figure 24.  CFD Run 3 (Test 5) Particle Streamlines**

### *Correlation to Test Data*

The flow split of air and coal is tabulated in Figure 22 and is repeated with the test data for Test 5 in Tables 9 and 10.  The model in its current state does not show as accurate correlation as desired.  Though the flow percentage of air to each pipe has the right trend, the actual data indicates considerably less flow to Pipe 2.  The model trends for coal flow are not quite right. Both the model and test data have the least coal flow to Pipe 2, but the model indicates the most coal flow to Pipe 6 instead of Pipe 4, as the data shows.

| Pipe | Model Air Flow (lb/hr) / (kg/hr) | % of Total Flow | Test Air Flow (lb/hr) / (kg/hr) | % of Total Flow |
|---|---|---|---|---|
| 2 | 10,508 / 4,771 | 26.6 | 8,832 / 4, 010 | 19.4 |
| 4 | 14,693 / 6,671 | 37.2 | 18,191 / 8,259 | 40.0 |
| 6 | 14,278 / 6,482 | 36.2 | 18,489 / 8,394 | 40.6 |
| **Total** | **39,479 / 17,923** | | **45,512 / 20,662** | |

**Table 9. Model Correlation to Test 5 Air Flow Data**

| Pipe | Model Coal Flow (lb/hr) / (kg/hr) | % of Total Flow | Test Coal Flow (lb/hr) / (kg/hr) | % of Total Flow |
|---|---|---|---|---|
| 2 | 9,509 / 4,317 | 30.2 | 6,915 / 3,139 | 21.7 |
| 4 | 9,037 / 4,103 | 28.7 | 13,915 / 6,317 | 43.7 |
| 6 | 12,955 / 5,882 | 41.1 | 11,027 / 5,006 | 34.6 |
| **Total** | **31,501 / 14,301** | | **31,857 / 14,463** | |

**Table 10. Model Correlation to Test 5 Coal Flow Data**

ASC has been examining this miscorrelation and plan to pursue four model refinements to achieve better correlation. Three involve altering the model inlet conditions and the other the model geometry. First, there is a large discrepancy in the test data as to the air flow rate through the system for Test 5. The exhauster velocity traverse integrated to 39,238 lb/hr (17,814 kg/hr) of air while the coal pipe measurements indicated 45,512 lb/hr (20,662 kg/hr) of air was present. The model utilized the exhauster air flow rate, and perhaps this should be scaled up to the measured pipe flow rate.

Secondly, the Run 3 model only utilized 35 particle starting locations, corresponding to the 35-point test grid used in the coal sampling. This resulted in only 560 particle streamlines being tracked instead of the over 10,000 in the previous two runs. In general, the model is more accurate if more particle streamlines are used. A useful refinement to the model would thus be adding additional starting locations. The measured test data would have to be interpolated to obtain a mass loading at these additional points.

Thirdly, the actual fineness data should be incorporated into the model. The sensitivity of the model results to fineness has not been examined, but since the model is predicting different particle paths for different sizes, it seems prudent to incorporate the correct fineness information rather than an assumption.

Fourth, the shutoff damper position in this model was assumed and it appears that the model's value requires further closure. This is evident by both the air and coal predictions of the model being higher than the data for Pipe 2.

It is anticipated that these refinements of the model will lead to better correlation. If issues still exist after these adjustments, then further actions may be required to ensure model accuracy.

# 4
# PHYSICAL FLOW MODELING

In order to examine the flow characteristics within the splitter in more detail, a 1/3 scale physical model of the system was also constructed. A primary benefit of this model over the CFD model is that actual observation of flow patterns within the splitter are possible for certain operating conditions. As the old saying goes, “seeing is believing,” and the physical model will thus provide some critical information. A disadvantage of the scale model, however, is that two-phase flow characteristics do not scale well. Thus, the model may not match the full scale, real world case very well.

Fortunately, the combination of the physical and CFD models will allow a very detailed engineering analysis to be performed. The physical model is being utilized qualitatively to examine trends and gain an understanding of the important flow characteristics in the system. The CFD model will be used to provide the more specific, quantitative output.

As of this writing, only preliminary runs have been completed with the physical model. These have shown that the system operates well and the procedures in place to measure and analyze the flow characteristics are adequate. A number of sensitivity runs have been completed in order to understand the importance of various model operating parameters.

## Methodology

The 1/3 scale physical model operates under negative pressure, and thus does not include a scale representation of the exhauster fan. Instead, the model inlet features a bell-mouth to provide a smooth velocity profile. The model has a long inlet duct in which flow obstructions (i.e., perforated plates) can be positioned to condition the incoming flow. Thus, with the proper obstructions, any incoming velocity profile can be simulated. To date, only a uniform inlet velocity has been modeled, but since the completion of the onsite testing this can now be refined to match the measured velocity profile.

The test section of the model consists of the splitter region and the initial straight sections of the three coal pipes. Each pipe continues roughly 40 feet from this test section and travels through a particle collection filter and a centrifugal fan. Thus, the particulate traveling through each pipe is collected so that the mass flow split can be measured and the flow rate of air through each pipe is individually adjustable via a damper at the fan inlet.

A schematic of this system is shown in Figure 25 and photographs of the actual model in Figures 26 and 27.

The particulate used with the model is a polyester bead material with a specific gravity very close to that of coal. The particle size is nominally mesh size 50, which is larger than the actual size distribution in the real world system. A smaller size material was not selected due to the increasing difficulty in material handling and the fan sizing requirements to overcome the pressure loss of a finer filter media.

The fans were set to match the full scale air velocities within the splitter and piping network using ambient temperature air.

## Preliminary Model Results

The modeling effort to date has focused on the influence of various parameters on the mass flow split of particulate to the three pipes. These parameters include:

1. Particulate injection technique.

2. Mass loading distribution of particulate at the exhauster exit.

3. Coal pipe orificing.

Each is discussed below in more detail.

### *Particulate Injection Technique*

Three basic methods have been evaluated. One involves using a single nozzle particulate injection. The main advantage of this system was that both the particulate flow rate and velocity could be controlled to some extent. This was accomplished with a pressurized sandblaster. The nozzle was traversed across a sixteen-point grid at the exhauster outlet to achieve a uniform particle distribution spatially. The main disadvantage of this system is that with only a single injection point, no significant particle-particle interaction is possible.

A second method involved starting the particles at the bell mouth inlet in a uniform mass loading. This was accomplished by positioning a screen at the inlet and allowing particulate to be picked up off the screen by the incoming air. The particulate at the test section inlet would thus be traveling at approximately the air velocity with a uniform mass loading. This system allowed for some particle-particle interaction, but the mass loading was very low compared to the real world air-to-coal ratios of 1.8 to 3.0. With this method, however, there is no way to control the particle mass distribution at the exhauster exit plane.

The third method involved using a gravity-feed system of four large nozzles. Tests were conducted feeding particulate through one nozzle at a time and all four simultaneously. The simultaneous test was the only method that allowed the mass loading to approach the actual air-coal ratio of a power plant. It lacked the flexibility to accurately control the mass loading distribution at the exhauster exit plane, but it did allow visualization of particle-particle interaction effects not visible in the other methods.

Results from various tests with these three methods are provided in the following tables. Repeatability tests show very good consistency in the data.

A basic conclusion is that the model predicts similar trends for each method—more coal to the center pipe. The low particulate mass loading cases (air-to-coal ratio 20+) using the single nozzle and uniform (screen) distribution methods and the one-at-a-time large nozzle method (air-to-coal ratio 10) indicated considerably more coal to the center pipe (~60-70%). The simultaneous four large nozzle case with an air-to-coal ratio of 2.6 indicated less of an imbalance, but still 50% of the coal traveled to the center pipe. Interestingly, the CFD model Run 1 predicted approximately 50% of the coal to the center pipe for a mass loading of 2.1.

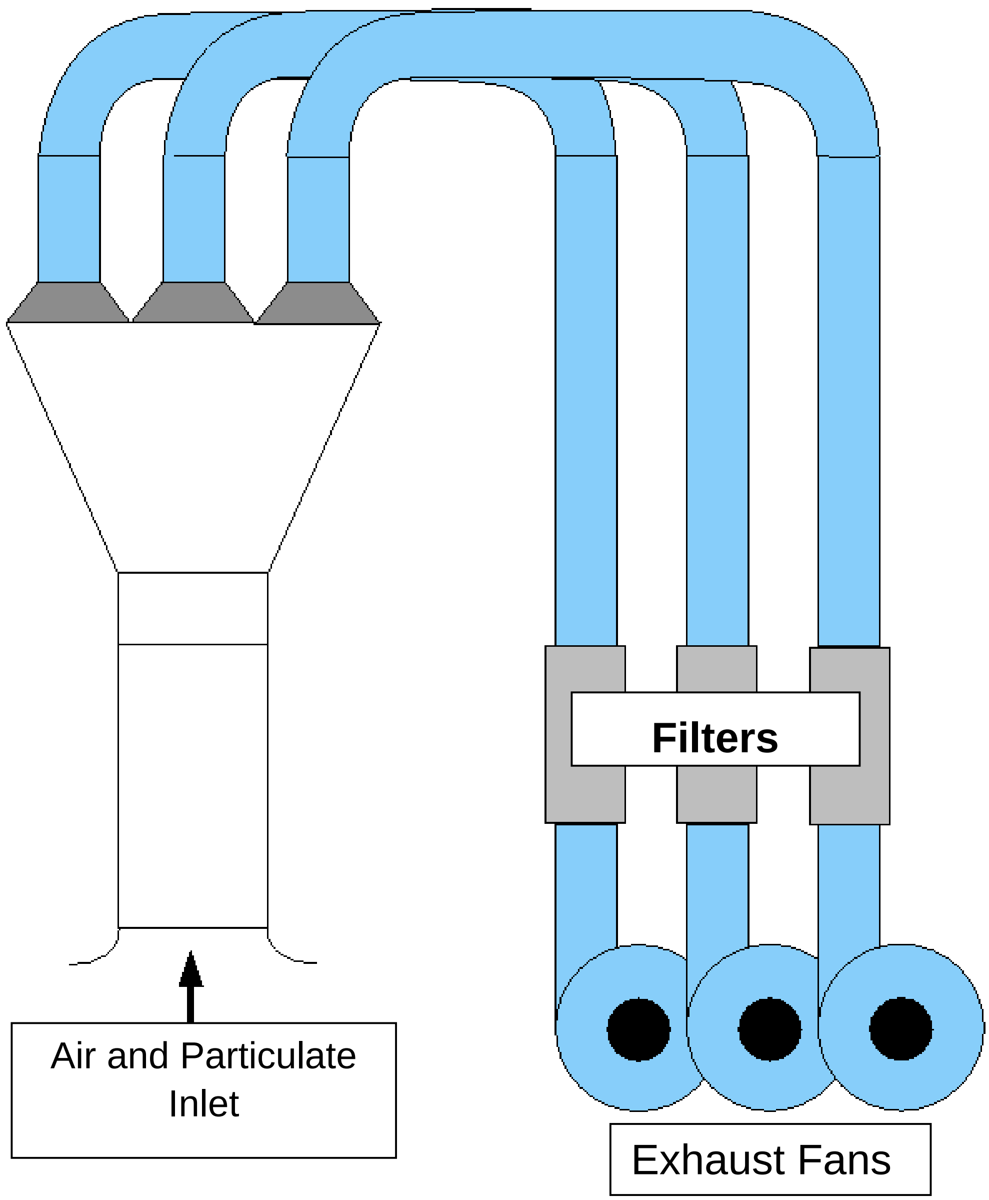



**Figure 25.  Coal Flow Splitter Physical Model**

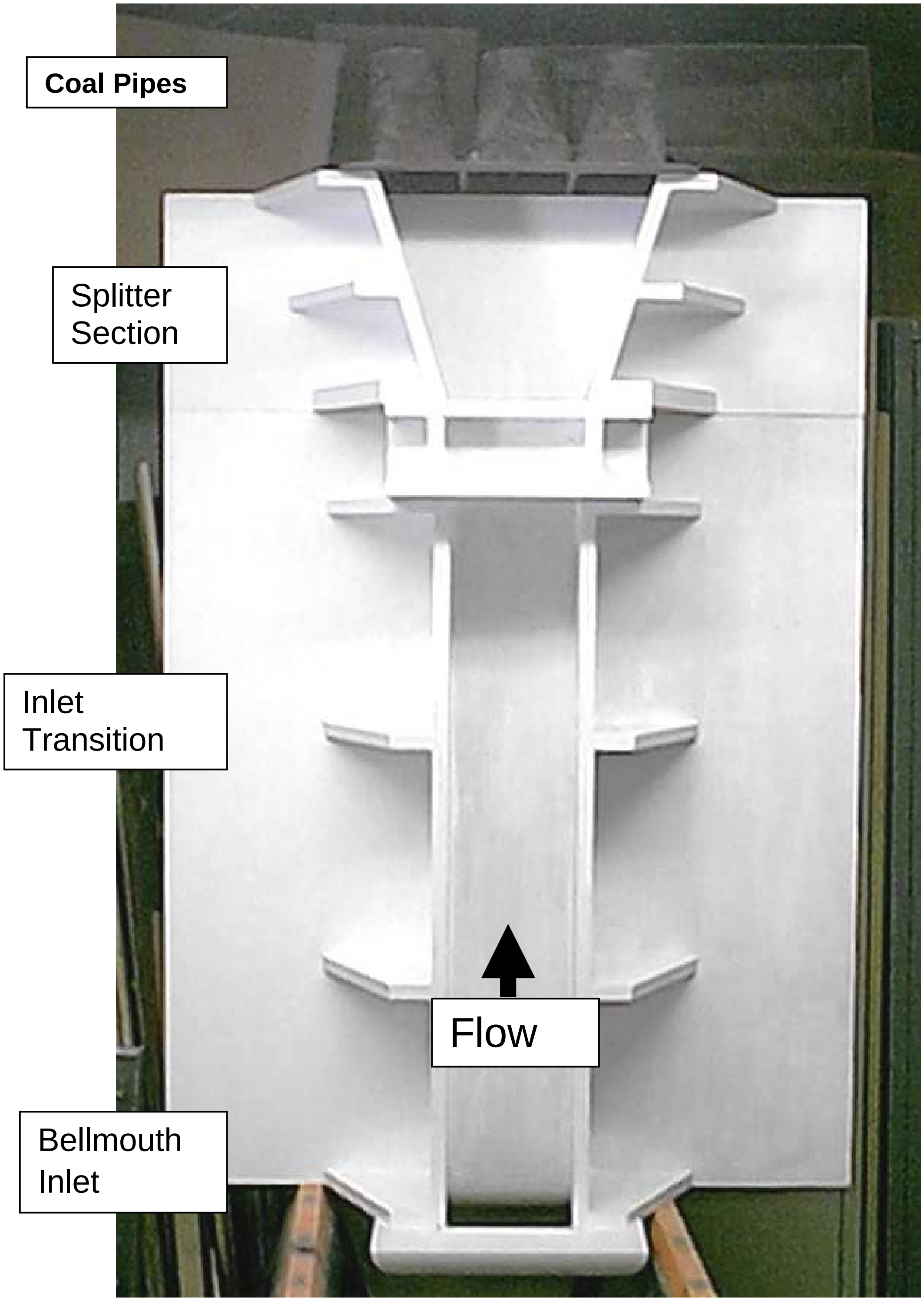



**Figure 26. Photo of ¼ Scale Physical Model**

**Figure 27 Close up of Splitter and Pipe Inlets**

**Test 1 – Single Nozzle**

| | COAL SPLIT (%) | AIR SPLIT (%) |
|---|---|---|
| **PIPE 1** | 16.18 | 33.33 |
| **PIPE 2** | 73.77 | 33.33 |
| **PIPE 3** | 10.05 | 33.33 |

**Test 2 – Single Nozzle Repeatability**

| | COAL SPLIT (%) | AIR SPLIT (%) |
|---|---|---|
| **PIPE 1** | 6.95 | 33.33 |
| **PIPE 2** | 72.95 | 33.33 |
| **PIPE 3** | 20.1 | 33.33 |

**Test 3 – Screen at Bell Mount**

| | COAL SPLIT (%) | AIR SPLIT (%) |
|---|---|---|
| **PIPE 1** | 16.22 | 33.33 |
| **PIPE 2** | 70.21 | 33.33 |
| **PIPE 3** | 13.56 | 33.33 |

**Test 4 – Four Large Nozzle Configuration, One Nozzle at a Time Feed**

| | COAL SPLIT (%) | AIR SPLIT (%) |
|---|---|---|
| **PIPE 1** | 20.82 | 33.33 |
| **PIPE 2** | 59.85 | 33.33 |
| **PIPE 3** | 19.33 | 33.33 |

**Test 5 – Four Large Nozzle Configuration, One Nozzle at a Time Feed, Repeatability**

| | COAL SPLIT (%) | AIR SPLIT (%) |
|---|---|---|
| **PIPE 1** | 17.18 | 33.33 |
| **PIPE 2** | 56.49 | 33.33 |
| **PIPE 3** | 26.34 | 33.33 |

**Test 6 – Four Large Nozzle Configuration, One Nozzle at a Time Feed, Repeatability**

| | COAL SPLIT (%) | AIR SPLIT (%) |
|---|---|---|
| **PIPE 1** | 20.60 | 33.33 |
| **PIPE 2** | 53.93 | 33.33 |
| **PIPE 3** | 25.47 | 33.33 |

**Test 7 – Four Large Nozzle Configuration, Simultaneous Feed**

| | COAL SPLIT (%) | AIR SPLIT (%) |
|---|---|---|
| **PIPE 1** | 24.72 | 33.33 |
| **PIPE 2** | 50.92 | 33.33 |
| **PIPE 3** | 24.35 | 33.33 |

**Test 8 – Four Large Nozzle Configuration, Simultaneous Fee, Repeatability**

| | COAL SPLIT (%) | AIR SPLIT (%) |
|---|---|---|
| **PIPE 1** | 22.56 | 33.33 |
| **PIPE 2** | 47.74 | 33.33 |
| **PIPE 3** | 29.70 | 33.33 |

### *Mass Loading Distribution at Exhauster Exit*

Since the field data was not available at the time, the physical model was utilized to examine some extreme variations in the coal mass loading profile at the exhauster exit. This was accomplished with the single nozzle injection method using the sandblaster. The nozzle position was varied along a single line at the exhauster exit plane instead of the sixteen-point traverse grid. Four different lines were utilized along the back wall, right wall, front wall, and left wall of the splitter inlet. The front wall and side wall cases would be expected to be similar due to the splitter symmetry, but obviously the side wall traverses would favor an outboard pipe.

Interestingly, the front wall and back wall tests were not consistent. It is believed that during the back wall test the nozzle was pointed slightly off-vertical, resulting in skewed data. This points out another deficiency of the single nozzle method: it is very sensitive to nozzle directionality.

**Back Wall**

| | COAL SPLIT (%) | AIR SPLIT (%) |
|---|---|---|
| **PIPE 1** | 23.60 | 33.33 |
| **PIPE 2** | 74.16 | 33.33 |
| **PIPE 3** | 2.24 | 33.33 |

**Left Wall**

| | COAL SPLIT (%) | AIR SPLIT (%) |
|---|---|---|
| **PIPE 1** | 0.00 | 33.33 |
| **PIPE 2** | 4.57 | 33.33 |
| **PIPE 3** | 95.43 | 33.33 |

**Front Wall**

| | COAL SPLIT (%) | AIR SPLIT (%) |
|---|---|---|
| **PIPE 1** | 30.18 | 33.33 |
| **PIPE 2** | 43.18 | 33.33 |
| **PIPE 3** | 26.64 | 33.33 |

**Right Wall**

| | COAL SPLIT (%) | AIR SPLIT (%) |
|---|---|---|
| **PIPE 1** | 89.31 | 33.33 |
| **PIPE 2** | 10.58 | 33.33 |
| **PIPE 3** | 0.11 | 33.33 |

### *Coal Pipe Orificing*

Finally, an examination of restricted flow to one pipe took place. The air flow to the center pipe was reduced to half that of the two outside pipes. Again the single nozzle sandblaster injection method was utilized across the sixteen-point (4 x 4) grid. As a control, one test with equal airflow split (similar to Test 1 above) was performed. As a final test, the uniform particle distribution (screen) injection method was utilized. Surprisingly, there was no change in the coal flow distribution for either case. This is contrary to the CFD model and field measurements and warrants further investigation.

**Control Test**

| | COAL SPLIT (%) | AIR SPLIT (%) |
|---|---|---|
| **PIPE 1** | 23.79 | 33.33 |
| **PIPE 2** | 64.19 | 33.33 |
| **PIPE 3** | 12.03 | 33.33 |

**Reduced Flow to Center Pipe, Single Nozzle Coal Injection**

| | COAL SPLIT (%) | AIR SPLIT (%) |
|---|---|---|
| **PIPE 1** | 21.59 | 40.00 |
| **PIPE 2** | 66.78 | 20.00 |
| **PIPE 3** | 11.64 | 40.00 |

**Reduced Flow to Center Pipe, Uniform (Screen) Coal Injection**

| | COAL SPLIT (%) | AIR SPLIT (%) |
|---|---|---|
| **PIPE 1** | 17.74 | 40.00 |
| **PIPE 2** | 65.28 | 20.00 |
| **PIPE 3** | 16.98 | 40.00 |

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