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A Side-by-side Comparison of Particle Temperature (Tp), Particle Velocity (Vp) Data Collected Using the Accura G3 and the DPV-2000

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A Sulzer-Metco 6P Powder Flame Spray Torch spraying an alumina-titania ceramic powder RX60 6-axis robotic was characterized using an Accura G3(Tecnar Automation; Quebec, Canada) and a DPV-2000 (Tecnar Automation; Quebec, Canada). The two sensors were mounted side-by-side and a robot was used position the torch in relation to each sensor. Process gas flows were set using laminar flow element mass flow controllers. Accura and DPV measurements of particle temperature (Tp) and particle velocity (Vp) were made in succession at each operating condition without changing torch operating conditions. Data for a single designed experiment was collected with both sensors allowing for comparison of the two sensors across the operating space of a typical powder flame spray process.

1 Introduction

A Sulzer-Metco 6P Powder Flame Spray Torch with a "D" Nozzle and a Gun Cooling air cap spraying a 34 micron alumina-titania ceramic powder mounted on a Stäubli RX60 6-axis robotic arm was characterized using an Accura G3(Tecnar Automation; Quebec, Canada) and a DPV-2000 (Tecnar Automation; Quebec, Canada). The two sensors were mounted side-by-side and the robot was used position the torch in relation to each sensor. Process gas flows were set using laminar flow element mass flow controllers. Accura and DPV measurements of particle temperature (Tp) and particle velocity (Vp) were made in succession at each operating condition without changing torch operating conditions, allowing for a side-by-side comparison of the two sensors.

2 Experimental Details:

A designed experiment (2_V^{5-1} Half Fraction Factorial with center points) was used to explore the parameter space of Total Flow (TF), Oxygen to Fuel Ratio (OFR), Standoff Distance (SD), Powder Gas Flow (PG), and Powder Feed Rate (PFR) as measured by both the DPV and Accura G3 particle sensors. The powder gas flow rate was used as the design generator creating a resolution V design. This has the effect that 2 factor interactions are indistinguishable from 3 factor interactions. Powder gas flow was set based on the combined settings of TF*OFR*SD*RPM. The torch cooling air flow was held constant at 100 SCFH.

All of the half factorial experiments were conducted using the following guidelines:

- AF = 100 SCFH (Fixed)
- Range of Factors:
  - TF 85-95 SCFH
  - OFR 1.5-2.5
  - SD 5.5"-6.5"
  - PFR 1.9-3.8 RPM
  - PG 10-20 SCFH
- The experiment was blocked on PFR by necessity. Powder feed rate takes time to stabilize when changed. The experiment was delayed after each block to stabilize PFR.
- Tp, Vp, were measured using the Accura G3
- Tp, Vp, & Dp (particle diameter) were measured using DPV-2000.
- 7 Center Points (CP) were used to monitor data scatter. All runs were randomized except the center points. Two center points were run at the beginning and end of the experiment and three were run at the mid-point of the experiment.
- All runs were made in one day.
- Powder feed rate was verified after each block.

3 Results and Discussion

Table 1 shows the raw data obtained from the half factorial designed experiment. Particle temperature (Tp), particle velocity (Vp) and particle diameter (Dp) data are shown. Table 2 shows a summary of the Tp, Vp, and Dp data obtained with both the DPV-2000 and the Accura G3. Table 3 shows the eight center point runs and analysis of the variability among these runs. Tables 2 and 3 clearly show that differences in average particle temperature and velocity do exist between the DPV-2000 and Accura G3 particle analysis systems. This difference is a result of differences in the way that the DPV-2000 and Accura G3 collect particle temperature and velocity data and in the way that they process that data.

The DPV-2000 collects temperature, velocity, and diameter measurements on individual particles. In order to do this the DPV-2000 has algorithms that determine if the optical signal received is representative of a "good particle". The DPV-2000 algorithms throw out data from small particles because they cannot be distinguished from the background noise that is subtracted from the measurement. This ability to subtract the background

noise makes the DPV-2000 relatively immune to the effects of vapor emissions in the thermal spray plume. As result of these algorithms the DPV-2000 tends not to collect statistics on very small, fast, hot particles. This is considered an acceptable trade because small particles contribute almost nothing to the volume of the coating. The DPV-2000 measures particle size from the intensity of the optical signal received by the particle. This particle size measurement gives an indication of relative particle sizes. The Accura G3 does not collect individual particle statistics and thus includes signals from all particles. It cannot subtract the background vapor emissions and its Tp and Vp data can be affected by those emissions. The Accura G3 is not capable of measuring particle diameter.

Table 1: Raw data from the half factorial designed experiment.

Run Order	Std Order	Total Flow (SCFH)	OFR	Powder Gas Flow (SCFH)	Powder Feed Rate (RPM)	Standoff Distance (in)	DPV Tp	DPV Vp	DPV Dp	Accura Tp	Accura Vp
1	17	90	2	15	2.85	6	2172	47.4	19	2423	53.6
2	18	90	2	15	2.85	6	2206	48.3	18	2408	54.6
3	4	95	2.5	10	1.9	6.5	1991	45.9	24	2127	50.7
4	5	85	1.5	20	1.9	5.5	2409	48.7	17	2854	52.2
5	7	85	2.5	20	1.9	6.5	1935	44.2	24	1961	44.8
6	8	95	2.5	20	1.9	5.5	2009	50.1	21	2206	53.8
7	2	95	1.5	10	1.9	5.5	2541	57.0	19	2897	63.4
8	6	95	1.5	20	1.9	6.5	2351	49.2	17	2616	54.2
9	1	85	1.5	10	1.9	6.5	2382	46.0	19	2623	56.6
10	3	85	2.5	10	1.9	5.5	2050	47.5	22	2308	55.2
11	17	90	2	15	2.85	6	2170	47.2	19	2413	54.0
12	18	90	2	15	2.85	6	2166	47.3	19	2429	55.4
13	19	90	2	15	2.85	6	2140	46.6	19	2421	55.5
14	9	85	1.5	10	3.8	5.5	2345	47.9	20	2753	56.5
15	16	95	2.5	20	3.8	6.5	1901	46.6	24	2032	47.1
16	14	95	1.5	20	3.8	5.5	2351	51.4	17	2849	55.2
17	13	85	1.5	20	3.8	6.5	2251	43.2	18	2531	47.9
18	12	95	2.5	10	3.8	5.5	1961	47.3	24	2258	56.2
19	15	85	2.5	20	3.8	5.5	1983	45.9	21	2186	47.8
20	10	95	1.5	10	3.8	6.5	2351	48.9	20	2564	59.1
21	11	85	2.5	10	3.8	6.5	1915	42.2	26	2102	47.1
22	17	90	2	15	2.85	6	2149	47.4	19	2395	54.5
23	18	90	2	15	2.85	6	2162	47.7	19	2388	55.2
24	-	*90*	*2*	*15*	*2.85*	*6*	*extra center point*			*2388*	*54.9*

Table 2: Summary of DPV-2000 and Accura G3 Data.

	DPV Tp	DPV Vp	DPV Dp	Accura Tp	Accura Vp
Average	2169.2	47.6	20.2	2422.2	53.6
Minimum	1901.0	42.2	17.0	1961.0	44.8
Maximum	2541.0	57.0	26.0	2897.0	63.4
Standard Deviation	181.1	2.9	2.6	256.6	4.2

Table 3: Analysis of Center Point Data

Run #	Tp	Tp Std. Dev.	Vp	Vp Std. Dev.	Dp	Dp Std. Dev.	Flow Rate	Detection Rate	Number of Particles	Accura Tp	Accura Vp
1	2172	240	47.4	7.6	18.8	7.0	20136	389	10179	2423	53.6
2	2206	252	48.3	7.6	18.5	7.1	32716	449	10213	2408	54.6
11	2170	235	47.2	7.3	18.8	6.8	20132	385	10153	2413	54.0
12	2166	241	47.3	7.3	18.9	7.1	17653	393	10236	2429	55.4
13	2140	233	46.6	7.4	19.4	7.2	14675	357	10227	2421	55.5
22	2149	242	47.4	7.3	19.3	7.3	20863	398	10176	2395	54.5
23	2162	237	47.7	7.5	18.8	6.9	21900	404	10159	2388	55.2
24										2388	54.9
Mean	2166	240	47.4	7	19	7	21154	396	10192	2408	54.7
Std. Dev.	21	6	0.5	0.1	0.3	0.2	5637	27	33	16	0.7
Std. Error	8	2	0.2	0.1	0.1	0.1	2130	10	13	6	0.2

Analysis of the DPV-2000 data is shown in Tables 4 – 7. Main effects plots for the DPV-2000 data are shown in Figures 1 and 2. Analysis of the Accura G3 data is shown in Tables 8 – 11. Main effects plots are shown in Figure 3 and 4. It is important to note that main effects were not analyzed for the particle diameter (Dp) data. The particle size distribution in the plume is predetermined by the particle size distribution of the feedstock powder. One Way ANOVA was used to show that there was no statistical evidence that blocking runs by RPM affected the particle temperature for both DPV and Accura data. Kruskal-Wallis Analysis was used to show that there was no statistical evidence that blocking runs by RPM affected the particle velocity for both DPV and Accura data. The K-W test was used because Velocity data were not normally distributed.

Table 4: Estimated Effects and Coefficients for DPV-2000 Vp Data

Estimated Effects and Coefficients for DPV Vp (coded units)					
Term	Effect	Coef	SE Coef	T	P
Constant		47.557	0.1210	391.29	0.000
TFC	3.841	1.921	0.1457	13.18	0.000
OFRC	-2.829	-1.414	0.1457	-9.71	0.000
SDC	-3.709	-1.854	0.1457	-12.73	0.000
RPMC	-1.904	-0.952	0.1457	-6.53	0.000
TFC*OFRC	-1.334	-0.667	0.1457	-4.58	0.001
OFRC*SDC	0.741	0.371	0.1457	2.54	0.024
SDC*RPMC	0.771	0.386	0.1457	2.65	0.020
TFC*OFRC*SDC	0.641	0.321	0.1457	2.20	0.046
TFC*SDC*RPMC	1.391	0.696	0.1457	4.77	0.000
S = 0.582886 R-Sq = 97.63% R-Sq(adj) = 95.98%					

Table 5: Analysis of Variance for DPV-2000 Vp Data

Analysis of Variance for DPV Vp (coded units)						
Source	DF	Seq SS	Adj SS	Adj MS	F	P
Main Effects	4	160.544	160.544	40.1361	118.13	0.000
2-Way Interactions	3	11.693	11.693	3.8976	11.47	0.001
3-Way Interactions	2	9.387	9.387	4.6936	13.81	0.001
Residual Error	13	4.417	4.417	0.3398		
Lack of Fit	7	2.764	2.764	0.3949	1.43	0.338
Pure Error	6	1.653	1.653	0.2755		
Total	22	186.041				

Table 6: Estimated Effects and Coefficients for DPV-2000 Tp Data

Estimated Effects and Coefficients for DPV Tp (coded units)					
Term	Effect	Coef	SE Coef	T	P
Constant		2169.2	5.655	383.6	0.000
OFRC	-404.6	-202.3	6.781	-29.8	0.000
SDC	-71.3	-35.6	6.781	-5.3	0.000
RPMC	-76.0	-38.0	6.781	-5.6	0.000
PGC	-43.2	-21.6	6.781	-3.2	0.005
SDC*RPMC*PGC	-28.5	-14.2	6.781	-2.1	0.051
S = 27.1224 R-Sq = 98.27% R-Sq(adj) = 97.76%					

Table 7: Analysis of Variance for DPV-2000 Tp Data

Analysis of Variance for DPV Tp (coded units)						
Source	DF	Seq SS	Adj SS	Adj MS	F	P
Main Effects	4	705675	705675	176419	239.82	0.000
3-Way Interactions	1	3249	3249	3249	4.42	0.051
Residual Error	17	12506	12506	736		
Lack of Fit	11	9815	9815	892	1.99	0.206
Pure Error	6	2690	2690	448		
Total	22	721429				

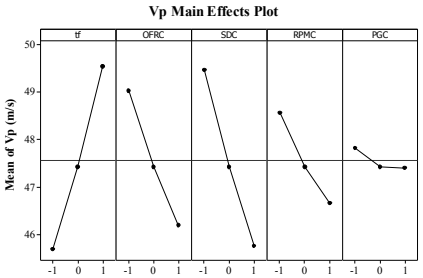

Figure 1: Main Effects Plots for DPV-2000 Vp Data

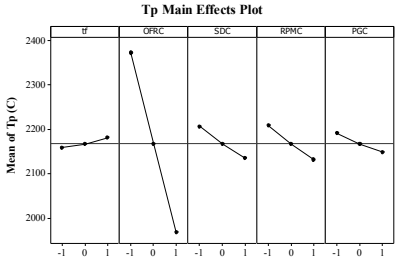

Figure 2: Main Effects Plots for DPV-2000 Tp Data

The main effects shown by the DPV-2000 data for Vp are: TF, OFR, SD and PFR (RPM). Increasing TF increases Vp. Increasing OFR, SD, and PFR decrease Vp. TF is the most significant effect, followed closely by SD and then by OFR and RPM. The main effects shown by the DPV-2000 data for Tp are: OFR, SD, PFR (RPM), and PG. Increasing OFR, SD, PFR, or PG all decrease Tp. OFR is the most significant effect by far. SD, PFR, and PG are of similar but little significance.

Table 8: Estimated Effects and Coefficients for Accura G3 Vp Data

Estimated Effects and Coefficients for Accura G3 Vp (coded units)					
Term	Effect	Coef	SE Coef	T	P
Constant		54.714	0.2814	194.41	0.000
TFC	3.956	1.978	0.199	9.94	0.000
OFRC	-5.286	-2.643	0.199	-13.28	0.000
SDC	-4.113	-2.057	0.199	-10.33	0.000
RPMC	-1.753	-0.876	0.199	-4.40	0.001
PGC	-5.206	-2.603	0.199	-13.08	0.000
OFRC*SDC	-1.734	-0.867	0.199	-4.36	0.001
OFRC*PGC	1.288	0.644	0.199	3.23	0.006
TFC*OFRC*SDC*RPMC*PGC	-3.473	-1.736	0.3447	-5.04	0.000
S = 0.796013 R-Sq = 97.66% R-Sq(adj) = 96.42%					

Table 9: Analysis of Variance for Accura G3 Vp Data

Analysis of Variance for Accura G3 Vp (coded units)						
Source	DF	Seq SS	Adj SS	Adj MS	F	P
Main Effects	5	362.776	362.776	72.5552	14.51	0.000
2-Way Interactions	2	18.665	18.665	9.3323	14.73	0.000
5-Way Interactions	1	16.082	16.082	16.0823	25.38	0.000
Residual Error	15	9.505	9.505	0.6336		
Lack of Fit	8	6.245	6.245	0.7806	1.68	0.255
Pure Error	7	3.260	3.260	0.4657		
Total	23	407.027				

Table 10: Estimated Effects and Coefficients for Accura G3 Tp Data

Estimated Effects and Coefficients for Accura G3 Tp (coded units)					
Term	Effect	Coef	SE Coef	T	P
Constant		2408.1	6.573	366.4	0.000
TFC	28.9	14.5	4.648	3.11	0.009
OFRC	-563.4	-281.7	4.648	-60.61	0.000
SDC	-219.6	-109.8	4.648	-23.62	0.000
RPMC	-39.6	-19.8	4.648	-4.26	0.001
PGC	-49.5	-24.8	4.648	-5.33	0.000
OFRC*SDC	35.4	17.7	4.648	3.81	0.002
OFRC*RPMC	33.7	16.9	4.648	3.63	0.003
OFRC*PGC	-53.2	-26.6	4.648	-5.72	0.000
SDC*PGC	-19.4	-9.7	4.648	-2.09	0.059
RPMC*PGC	30.2	15.1	4.648	3.25	0.007
TFC*OFRC*SDC*RPMC*PGC	42.3	21.2	8.050	2.63	0.022
S = 18.5904 R-Sq = 99.73% R-Sq(adj) = 99.48%					

Table 11: Analysis of Variance for Accura G3 Tp Data

Analysis of Variance for Accura Vp (coded units)						
Source	DF	Seq SS	Adj SS	Adj MS	F	P
Main Effects	5	1481770	1481770	296354	857.50	0.000
2-Way Interactions	5	26023	26023	5205	15.06	0.000
5-Way Interactions	1	2387	2387	2387	6.91	0.022
Residual Error	12	4147	4147	346		
Lack of Fit	5	2332	2332	466	1.80	0.232
Pure Error	7	1815	1815	259		
Total	23	1514327				

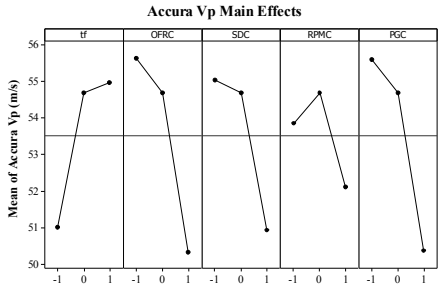

Figure 3: Main Effects Plots for Accura G3 Vp Data

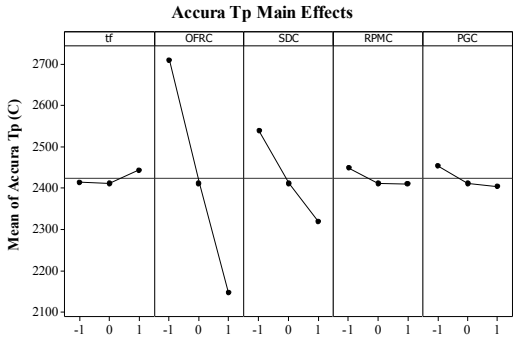

Figure 4: Main Effects Plots for Accura G3 Tp Data

The main effects shown by the Accura data for Tp are: OFR and SD. Increasing OFR and SD decreases Tp. OFR is the most significant effect by far. The main effects shown by the Accura G3 data for Vp are: TF, OFR, SD, PFR (RPM) and PG. Increasing TF increases Vp. Increasing OFR, SD, PFR and PG decrease Vp. This analysis shows that OFR is the most significant effect, followed closely by PG and then by SD, TF, and RPM.

4 Conclusions

The Accura G3 and DPV-2000 do generate slightly different Tp and Vp data when used to measure the same plume. The DPV-2000 reports slightly lower Tp and Vp numbers than the Accura G3 because of the DPV-2000 does not collect data on very small particles. Both systems show similar Tp and Vp trends. However, when the DOE data is analyzed the DPV-2000 data shows more differentiation of main effects, especially for Vp, than the Accura G3 data. Both are appropriate tools for characterizing thermal spray processes.

5 Acknowledgement

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