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Method Comparison Between a Cyclone/Impinger and a Dilution Tunnel for the Characterization of Particulate Matter from a Ferrous Metal Foundry

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Abstract

An evaluation and comparison study of two stack-sampling methodologies for the collection of particulate matter (PM) emissions from iron metal casting operations was completed. A modified EPA Method 201A/202 sampling train (combining cyclone samplers for filterable particulate with an impinger train to capture condensable particulate) was compared to a dilution tunnel sampling method that concurrently collects both filterable and condensable PM. Testing involved the simultaneous collection of continuous stack samples using both the cyclone/impinger and dilution tunnel methods in a parallel sampling configuration over a seventy-five minute period that included metal pouring, cooling, and shakeout processes. Conventional dry sand molds were made of a 4-on gear pattern using Michigan lake sand containing 1.8% of a phenolic urethane No-Bake® binder. Molds were cast using a Class 30 gray iron at 2,600–2,700°F. PM emission samples from both methods were collected on filters and analyzed gravimetrically. PM less than 2.5 µm in aerodynamic diameter (PM2.5) collected from the dilution tunnel sampling method was chemically characterized using energy dispersive x-ray fluorescence, ion chromatography, and a thermal/optical carbon analyzer. Physical characterization of particle size and number distribution was measured by an electric low-pressure impactor. Results indicate that for all casting processes, the PM2.5 mass ratio of the cyclone/impinger method to the dilution tunnel method over-estimates mass by 2 to 4 times. For the pouring and cooling processes alone, the mass ratio increases to over seven times. Condensable particulate contributed 32-38% to the total particulate mass, with the organic containing portion contributing 96-98%, the balance consisting of inorganic particulate. Of the filterable mass, 52 to 59% consisted of particles larger than PM10, while 4–6% are intermediate particles (larger than PM2.5 and smaller than PM10), and 3-5% were less than PM2.5. The PM2.5 was found to be composed of organic carbon (35 -60%), elemental carbon (20-30%), inorganic materials (10 - 20%), and other elements (4-10%).

Introduction

Many US industries have undergone tremendous changes in the last 50 years caused by a variety of technological, economic and environmental factors. By illustration, in 1955, there were 6,150 metal foundries in the U.S. Today this industry has declined to approximately 2,480 foundries.¹ Remaining viable in the face of global competition and domestic pressures requires continual adaptation by this industry. Challenges to the domestic metal casting industry include continuing to deliver high quality products at ever-increasing productivity rates, offsetting the advantage of lower labor costs in geographic areas where the foundry industry has migrated in recent years, and abiding by increasingly more stringent environmental and governmental regulations.

One concern for the American foundry industry in the regulatory arena is the cost associated with compliance to the 1990 Clean Air Act Amendments (CAAA). As part of the requirements of the CAAA, on April 22, 2004 National Emission Standards for Hazardous Air Pollutants (NESHAP) for iron and steel foundries were promulgated. The EPA has identified iron and steel foundries as major sources of hazardous air pollutant (HAP) emissions. The NESHAP standards implement section 112(d) of the Clean Air Act by requiring all major sources to meet HAP emissions standards reflecting application of the maximum achievable control technology (MACT) by April 23, 2007.

Foundries must demonstrate initial compliance to the MACT by conducting performance tests for all emissions sources subject to an emissions limit. The HAPs emitted by facilities in the iron and steel foundries source category include both inorganic and organic compounds. Established EPA Methods 1 through 4 and either Method 5, 5B, 5D, 5F, or 5I, as applicable (to measure PM) or Method 29 (to measure total metal HAP) are required for testing.² To determine compliance with the metal HAP emissions limits, foundries may test for PM as a surrogate. Testing for PM instead of metallic HAPs is a way for foundries to decrease the cost burden of source testing.

The current EPA methods for sampling PM emissions from stationary sources utilize filters and/or impinger trains for catching both filterable and condensable particulates. In general, the exhaust is withdrawn isokinetically from the source and either total PM or PM10 is collected on a glass fiber filter maintained at a specified temperature, and/or the gas stream passes through a series of water impingers to collect condensable PM. The PM mass is determined from the summation of the mass of particles collected on the filter and the mass of PM condensate after the removal of water. The impinger methods generally are thought to overestimate PM emissions because non-condensable gases as well as condensed particles are collected in the impinger train in addition to condensable gases.^{3 & 4} It is believed that stand-alone filter methods generally underestimate PM because vapors that can nucleate or grow upon cooling and dilution after emission from the stack are not accounted for.⁵

An alternative sampling method that uses a dilution tunnel better reproduces the processes experienced by emissions as they exit a stack, and can therefore remedy the discrepancies introduced by a heated filter or cold impinger sampling train. The sampling methodology of a dilution tunnel permits both condensable and filterable particulate to be collected simultaneously. Dilution tunnel methods have the potential to accurately represent particulate concentrations from stack emissions since they simulate the natural physicochemical processes of particulate formation in the atmosphere. In these methods, after leaving the stack, hot exhaust is rapidly cooled and mixed with ambient air allowing gases to nucleate both homogeneously and heterogeneously, and condense on pre-existing particles in processes analogous to those that occur naturally in the atmosphere.^{5 & 6}

Experimental Methods

Test Facility

The primary objective of Technikon is to evaluate the materials, equipment, and processes used in metal casting operations. Technikon is a privately held contract research organization offering emissions research services to industrial and government clients specializing in metal casting operations. The comparative stack emissions testing reported here was conducted at Technikon's Research Foundry under the Casting Emission Reduction Program (CERP), a coalition of government and private industry. The Research Foundry develops new emission measurement procedures for metal casting manufacturing and processes.⁷ The reports detailing these processes can be found on the CERP website.⁸

Most of the HAP and PM emissions from metal casting operations arise from the organic binders that are used in the molds and cores. Emissions originate from evaporation of low boiling point solvent binder components or from thermal decomposition, volatilization, and recombination processes when hot metal is poured into a mold. Organic fumes are also released during the shakeout process.

Description of Testing Program

Molds of a 4-on irregular gear shape were made with Wexford W450 Lakesand. The binder used was an HA International Techniset® (Westmont, Illinois) phenolic urethane No-Bake® mold binder at 1.8% total binder (based on sand) and was composed of number 6000 Part I resin (55%), 6433 Part II co-reactant (45%), and 17-727 Part III activator at 7% of Part I. This binder is designed for iron applications. The amount of metal melted was determined from the poured weight of the casting and the number of molds to be poured. These parameters resulted in an approximate cast weight for each of the gear molds of approximately 122 lbs.

Replicate test pours were executed on eight mold packages, each package consisting of a single mold containing four gear cavities. Mold weight was approximately 325 lbs. The mold package was placed on a test stand that is enclosed in an emission hood that meets EPA Method 204 requirements for a Total Temporary Enclosure. The initial sand temperature and system process air temperature in the hood enclosure were maintained at 80-90°F and at least 110°F, respectively. Molds were poured with Class 30 gray cast iron at 2,600 –2,700°F through an opening in the top of the enclosure. After about 12 to 25 seconds of pouring time, the opening is covered and remains closed for the duration of the test. A complete mold cycle consisted of a forty-five minute period that included the metal pouring and cooling processes, a fifteen-minute shakeout of the mold, and for an additional fifteen-minute cooling period following shakeout. The total mold cycle and sampling time was seventy-five minutes.

Sampling Procedures



Figure 1: Impinger Sampling System

Simultaneous collection of continuous stack emissions was accomplished using a modified Method 201A/202 sampling train (particle cyclone separator followed by an inline glass fiber filter and impinger train) and a dilution tunnel sampling system in a parallel sampling configuration. Method details for the impinger-sampling set-up and test procedure may be found elsewhere.⁹ For these comparison tests, a standard buttonhook type-sampling probe was used to isokinetically remove samples from the center of the 10 cm horizontal stack. At the probe outlet, an electrically and thermally insulated "Y" connector split the flow into the inlets of both sampling systems. Initially, a PM10 cyclone (Graseby Andersen, Smyrna, GA) was installed prior to the impinger train, although to better correlate resultant particulate masses between the two

methods a modified Method 201A/202 that additionally utilized a PM2.5 cyclone was employed for several of the runs (See Figure 1). A schematic of the foundry and sampling components is shown in Figure 2.

The modified Method 201A/202 impinger method for collection of condensable particulate matter was conducted by Technikon, LLC per-





sonnel, while the dilution tunnel sampling was performed by personnel from Desert Research Institute (DRI) using the DRI Source Dilution Sampling System, which is similar to that of EPA Conditional Test Method 39.¹⁰ Particulate emission samples for both the Method 201A/202 sampling train and the dilution tunnel sampling system were collected during the entire mold cycle.

The DRI dilution tunnel system, referred to as The DRI Source Dilution Sampling System (See schematic in Figure 3), draws 20-25 liters per minute (lpm) of sample through a venturi flow meter. Concurrently, ambient air at a flow rate sufficient to obtain a predetermined target dilution ratio passes through a High-Efficiency Particle Arresting (HEPA) filter to remove PM, followed by a Granulated Activated Carbon (GAC) bed to remove gaseous species and volatilized PM. The clean, cool ambient air is mixed with the sample gas. At the end of the mixing zone, the diluted sample is drawn into an



aging chamber where nucleation and particle growth may occur. At the outlet of the aging chamber, PM larger than 2.5 µm in aerodynamic diameter is removed by PM2.5 cyclones. A full operational description of the system may be found elsewhere.¹¹

PM emission samples from both methods were collected on filters and analyzed gravimetrically. Filterable mass was determined as the difference between pre- and post-sampling filter weight. For the modified Method 201A/202 sampling method, QM-A type quartz fiber filters (Whatman, Hillsboro, OR) were used to collect the filterable particulate after separation by the cyclone. For the DRI Source Dilution Sampling System, the mass of PM2.5 was measured on Teflonmembrane filters with an MT 5 microbalance (Mettler-Toledo, Columbus, OH).

Condensable PM (CPM) was collected in the impinger portion of a Method 5 type sampling train for the modified Method 201A/202. The solution from the impingers was extracted with methylene chloride to separate the organic and aqueous fractions. After separation, both the organic and aqueous portions were taken to dryness and the residues weighed. All extraction procedures followed the protocols outlined in EPA Method 202.⁸

To ensure the collection of sufficient condensable particulate matter for gravimetric analysis in the impingers, several test runs were sampled for the duration of two mold cycles, whereas one mold cycle supplied sufficient sample for the dilution tunnel.

Measured metal casting and dry sand process parameters included the weights of the casting and mold, weight loss on ignition values for the mold prior to the test, and metallurgical data. Monitored stack parameters included stack temperature, pressure, volumetric flow rate and moisture content. All parameters were maintained within prescribed ranges in order to ensure the reproducibility of the sampling runs and are shown in Table 1.

	Sample Number				
Test Parameter	$2A^1$	Average 3A and 3B ²	$3C^2$	Average 4A and 4B	
Sand Dispensing Rate, lbs/15 sec	30	30	30	30	
Calculated Standard % Binder	1.78	1.78	1.78	1.78	
Calculated % Binder (based on sand)	1.81	1.81	1.81	1.81	
Mold Weight, lbs	328.5	327.8	332.0	329.4	
Calculated Total Binder Weight, lbs	5.85	5.84	5.91	5.86	
1800F Loss On Ignition, %	1.81	1.59	1.73	1.75	
Pouring Temp, °F	2721	2635	2623	2637	
Pouring Time, sec.	68	41	29	44	
Cast Weight (all metal inside mold), lbs.	122.0	105.5	95.6	113.9	
Process Air Temperature in Hood, ⁰F	124	121	134	123	
Ambient Temperature, oF	64	66	66	66	
Mold Age When Poured, hr	43	55	48	39	
Test Length, min	36	75	75	71	

 Table 1.
 Summary of Casting Process Parameters

¹ Power outage after 36 minutes

 2 Sample 3B, 3C only three of four casting cavities filled.

Results

Impinger Method

The results of the PM emissions tests provided the mass of filterable and/or condensable particulate from the binder/sand/metal sample. Filterable PM from the modified Method 201A/202 was determined gravimetrically using an analytical balance (Mettler-Toledo AE163, Columbus, Ohio). CPM was determined by weighing the residues of the organic and aqueous extracted fractions from the impinger train. The sum of both fractions represents the total CPM for the impinger train method.

Mass emission rates were calculated using laboratory analytical results, the measured source data, and the weight of each casting. The concentration of the emitted PM was calculated by multiplying the PM mass in the sample with the ratio of total stack gas volume to sampling volume. The total stack gas volume was calculated from the measured stack gas velocity and duct diameter, and corrected to dry standard conditions using the measured stack pressures, temperatures, gas molecular weight and moisture content. The total mass of particulate was then divided by the weight of the metal poured to provide emissions data in pounds of particulate matter per ton of metal. Mass concentration results are shown in Table 2 for the impinger method. Table 2 includes calculated lb/ton values for both filterable and condensable particulate from the various collected size fractions, as well as the organic and inorganic components extracted from the condensable fraction collected from the impinger train.

	Particulate Size	Sample Number			
	Fraction	2A	3A& 3 B	3 C	4A& 4B
	>PM10	0.092	6.580	4.256	6.178
	<pm10< td=""><td>1.238</td><td>ND^1</td><td>ND</td><td>ND</td></pm10<>	1.238	ND^1	ND	ND
Filterable	2.5 <pm<10< td=""><td>ND</td><td>0.595</td><td>0.455</td><td>0.408</td></pm<10<>	ND	0.595	0.455	0.408
Particulate	<pm2.5< td=""><td>ND</td><td>0.366</td><td>0.304</td><td>0.535</td></pm2.5<>	ND	0.366	0.304	0.535
	Post Impinger Filter	0.097	0.003	0.000	0.006
	Total Filterable	1.426	7.544	5.015	7.128
Condonsable	Organic	1.219	4.225	2.973	3.270
Dorticulato	Aqueous	0.040	0.070	0.102	0.141
Falticulate	Total Condensables	1.259	4.295	3.075	3.411
Filterable and	Total PM	2.684	11.838	8.090	10.538
Condensable	Total <pm10< td=""><td>2.593</td><td>5.258</td><td>3.834</td><td>4.360</td></pm10<>	2.593	5.258	3.834	4.360
Particulate	Total <pm2.5< td=""><td>1.355</td><td>4.663</td><td>3.379</td><td>3.951</td></pm2.5<>	1.355	4.663	3.379	3.951

Table 2.Summary of Average PM Emission Results from
Modified Method 201A/202 lb/ton of metal

¹ND= Not Determined

Concentrations for the samples that combined two mold cycles (3A, 3B and 4A, 4B) were averaged using combined sample times and cast weights. These two tests as well as Sample 3C utilized both a PM10 and a PM2.5 cyclone. For this reason, the <PM10 fraction from the first cyclone was not collected, but underwent additional separation in the second cyclone. Sample number 2A included data only from the pouring and partial cooling of the mold due to a power failure from an areawide blackout caused by bad However, this weather. shortened pour presented a unique opportunity to measure the PM resulting from these two processes alone, without the contribution from the shakeout process. In addition, sampling for this test used only a PM 10 cyclone, whereas the other tests used both PM 10 and PM 2.5 cyclones.

Figures 4, 5 & 6 show mass concentration data in lb/ton metal, normalized to 100 percent. In comparing the three runs sampled under similar conditions using the same PM10/PM2.5 cyclone sampler and impinger train it is readily apparent that excellent reproducibility was obtained (Figure 4): for each of these runs, 52-59% of the filterable mass consisted of particles larger than













PM10, 4–6% are intermediate particles larger than PM2.5 and smaller than PM10, and 3–5% were less than PM2.5. Condensable particulate (combined organic and aqueous fractions) contributed 32-38% to the total particulate mass, with the organic containing portion contributing 96-98%, the balance consisting of inorganic particulate.

If PM10 rather than total PM is considered (Figure 5), the proportionate contributions increase to 9-12% and 7-12% for intermediate PM and PM2.5, respectively, while that for condensable PM increases to 79-82% of the total particulate mass.

Although Sample 2A test conditions varied from the others in the shortened testing period that was composed of pouring and partial cooling before the run was terminated, as well as in the use of a single PM 10 cyclone, the condensable PM2.5 fraction contribution remained consistent with the other samples at 97% organic and 3% inorganic (Figure 6).

During shakeout, the mold physically breaks down releasing particulates, heat and fumes causing an increase in larger particulate due to suspension, and finer particulate due to nucleation and

growth. The duration of the processes in the mold cycle including the pouring, cooling and shakeout and increase in temperature at shakeout is illustrated in Figure 7.

Dilution Tunnel Method

PM collected and measured from the dilution tunnel method represents both filterable and condensable particulate and is presented in Figure 8 as PM2.5 mass concentration results in lbs/ton.

On a lb/ton metal basis, the Dilution Tunnel Sampling Method resulted in PM2.5 concentrations ranging from 0.84 to 1.8 as is shown Figure 8 for Samples 3A, 3C, 4A, and 4B. Without the contri-



Figure 7: Stack Temperature Profile





bution from the shakeout process, the pouring and cooling processes (which are evidenced by Sample 2A) resulted in an approximate ten-fold decrease in PM2.5.

In addition to gravimetric analysis, particulate matter less than 2.5 μ m in aerodynamic diameter (PM2.5) from the Dilution Tunnel Sampling Method was analyzed for 40 elements using energy dispersive x-ray fluorescence (ED-XRF), organic and inorganic carbon was determined by a DRI Model 2001 thermal/optical carbon analyzer, and particle size and number distributions were measured by an Electric Low Pressure Impactor (ELPI) that collected data continuously during testing. Ion chromatography was used for the analysis of gaseous ammonia and chloride, nitrate, sulfate, and ammonia ions. Results from these analyses are reported elsewhere.¹⁰

Method Comparison

Because the Dilution Tunnel Sampling Method uses a PM2.5 cyclone, further discussion will focus on results related to PM2.5. Unlike the impinger method for PM sampling, there is no distinction in the dilution tunnel method between condensable or filterable particulate as both are collected on the filters after the cyclones. Comparisons to this method are therefore based on the summation of the filterable and condensable PM2.5 obtained from the filter and impinger of the modified Method 201/202A method.

In comparing the total PM2.5 mass ratio results for all the samples run under identical conditions (which excludes Sample 2A), the impinger method shows an overestimation of 2.16 to 4.04 times that obtained by the Dilution Tunnel Sampling Method, as shown in Figure 9. For the metal pouring and cooling processes, which were sampled separately in Test 2A, the mass ratio increases to over seven times. Different mechanisms between pouring and cooling, and shakeout result in variations in particle number and size distributions.

The comparative mass fraction of PM2.5 is less than the other size fractions regardless

Figure 9: Method Comparison of PM2.5 Emissions, Ib/tn Metal



of which particulate size range is considered, although as the size fraction under examination decreases the proportionate amount of PM2.5 increases. It is not unexpected that the mass of PM2.5 is less than that of the larger particles since in general the mass of fine particulate is less than that of coarse particulate. Results from the ELPI indicate the PM2.5 mass for these samples is composed mainly of particles larger than 0.215 um, which is illustrated in the graph in Figure 10.



Figure 10: Percent PM2.5 Mass Distribution by Size Fraction as Determined by ELPI

Particle Size Fraction (Microns)

The resultant chemical analysis and elemental speciation conducted by DRI on the PM2.5 collected from the Dilution Tunnel Sampling Method represented by Sample 3A is shown in Figure 11 as a pie chart. As illustrated by this figure, most of the PM2.5 mass for the samples was found to be composed of organic carbon (35 - 60%), elemental carbon (20 -30%), inorganic materials (10 -20%), and other elements (4 -10%). Unidentified materials range from 0 - 20% of the total mass. This unidentified fraction is the difference between the gravimetric mass and the reconstructed mass determined through chemical speciation.

Figure 11: Chemical Analysis of PM2.5 from Sample 3A Obtained by Dilution Tunnel Sampling



Conclusions

An evaluation and comparison of two stack-sampling methodologies for the collection of particulate matter was undertaken using emissions from gray iron metal casting operations, including metal pouring, cooling and shakeout processes. The data indicate that the traditional methods for PM collection using a cooled impinger sampling train overestimate the amount of emitted particulate. Metal pouring and cooling processes contribute less to particulate formation than does the shakeout process. More extensive comparative testing needs to be conducted at a production foundry to further understand the relationship between process event and particulate formation and release.

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References

- ¹ Capacity Utilization, Foundry Trends: Facts & Figures about the US Foundry Industry; American Foundry Society: Schaumburg, Illinois. www.afsinc.org (accessed March 2005).
- ² Environmental Protection Agency; 40 CFR Part 63; 2004, National Emission Standards for Hazardous Air Pollutants for Iron and Steel Foundries; Final Rule; *Federal Register /* Vol. 69, No. 78 / Thursday, April 22, 2004 / Rules and Regulations; 21906-21940.
- ³ Corio, L.A.; In-Stack Condensable Particulate Matter Measurements and Issues; JAWMA. **2000**, 50, 207-218.
- ⁴ Holder, T.E.; Goshaw, D.G.; Richards, J.R. Artifact Formation in Method 202 Sampling Trains Used to Measure Condensable Particulate Matter Emissions from Portland Cement Kilns; in Proceeding of A&WMA's 94th Annual Meeting and Exhibition, Orlando, Florida, June 24-28 2001; A&WMA: Pittsburgh, PA, 2001; Paper 94-451.
- ⁵ Hildemann, L.M.; Gass, G.R., Markowski, G.R. A Dilution Stack Sampler For Collection Of Organic Aerosol Emissions: Design, Characterization And Field Tests. *Aerosol Science* & Technology, **1989**, 10,193-204.
- ⁶ Lee, S.W.; He, I.; Young, B. Important Aspects in Source PM2.5 Emissions Measurement and Characterization from Stationary Combustion Systems; *Fuel Processing Technology*, 2004, 85, 687-699.
- ⁷ Trombly, J. Recasting a Dirty Industry, *ES&T*. **1995**, 29, 76A-78A.

⁸ CERP website is <u>www.cerp-us.org</u>.

- ⁹ Environmental Protection Agency; *Emission Measurement Technical Information Center Test Method*. Method 5:Particulate Matter (PM) Stationary Sources http://www.epa.gov/ttnemc01/archprom/m-05.html; Method 17: Particulate Matter (PM) Instack Filtration http://www.epa.gov/ttn/emc/promgate/m-17.html; Method 201A: PM10 Instack, CRS (Constant Sampling Rate) http://www.epa.gov/ttn/emc/promgate/m-201a.html; Method 202: PM Condensible Particulate Matter http://www.epa.gov/ttnemc01/methods/method202.html (accessed March 2005).
- ¹⁰ Chow, J.C.; Watson, J.G.; Wiener, R.W. Method No. 508: PM2.5 Sampling and Gravimetric Analysis by Federal Reference Method. In *Methods of Air Sampling and Analysis*, Lodge, J.P., editor. Air and Waste Management Association, Pittsburgh, PA; in preparation. 2004.

¹¹ Chang, M-C. O.; Chow, J. C.; Watson, J. G.; Glowacki, C. R.; Sheya, S. A.; Prabhu, A.; *Characterization of Fine Particulate Emissions from Casting Processes*; submitted for publication 2004.