Masonry Heater Association Of North America

www.mha-net.org

Masonry Heater and Bake Oven Efficiency and Emissions Testing

Draft Course Outline

MHA Technical Committee

Revised: October 14/09

Table of Contents

Outline

The objective is to provide interested participants with enough theory and hands-on practice to allow them to conduct efficiency and emissions testing on masonry heaters in the field. This will include specific recommendations, and hands-on experience with, equipment needed.

- Basic theory of combustion chemistry, emissions, and combustion testing.
- Setting up testing equipment for efficiency and emissions testing.
- TESTO 330-2 combustion analyzer
- Condar Dilution Tunnel – particulate (PM) testing

Workshop Logistics

Workshop is limited to a maximum of xx participants.

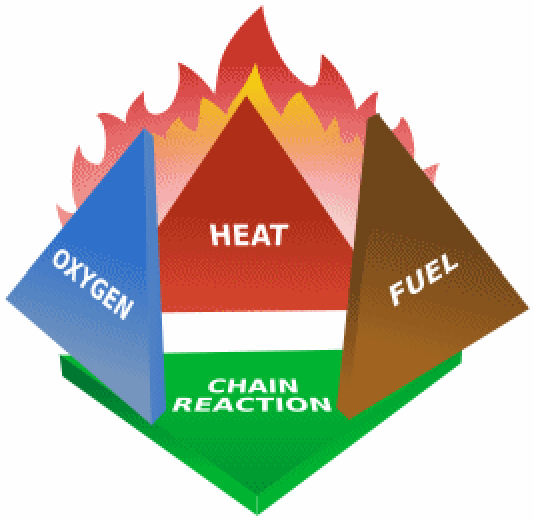
Workshop fee of $xxx includes lunches.

Lodging is not provided.

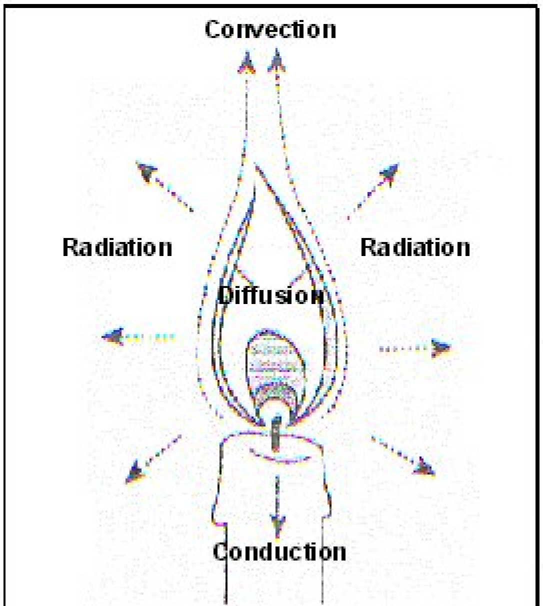
Links to accommodation choices in nearby xxxx

Safety

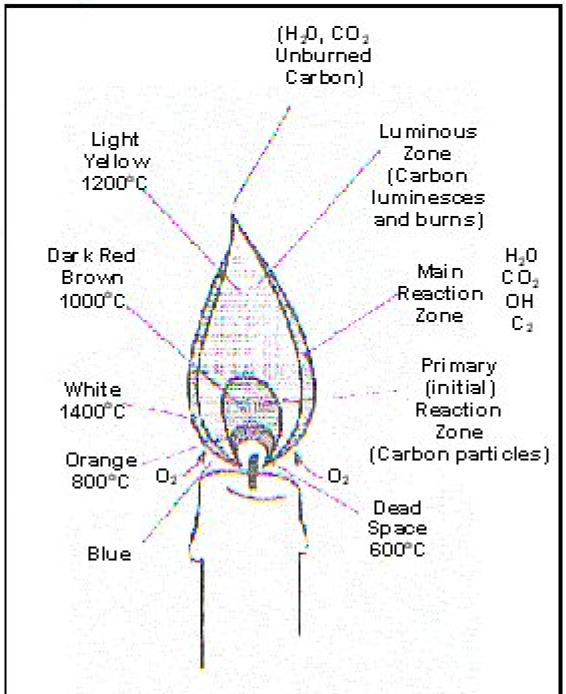
Combustion Chemistry



The burning of the fuel takes place in several distinct regions (as evidenced by the various colors that can be seen within the candle's flame). Within the bluer regions, hydrogen is being separated from the fuel and burned to form water vapor. The brighter, yellower part of the flame is the remaining carbon being oxidized to form carbon dioxide.



Candle Flame Energy Flow*



Candle Flame Reaction Zones, Emissions, and Temperature*

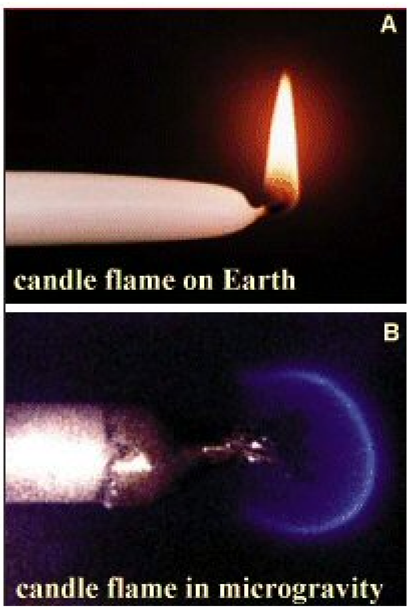
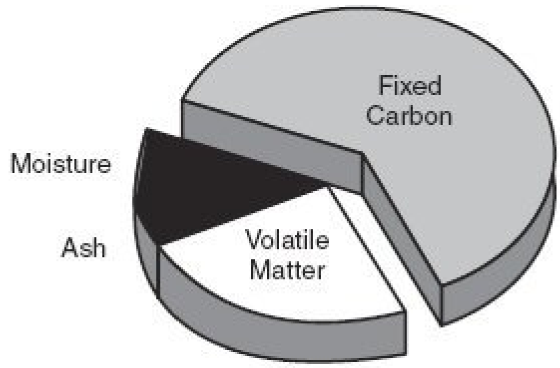


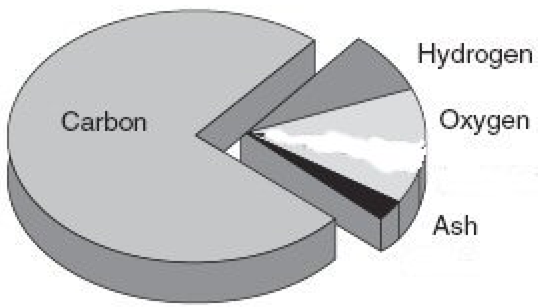
Photo courtesy NASA

Fire forms a sphere in microgravity.

1. Proximate analysis



2. Ultimate analysis:



Elementary analysis

Wood has a complicated chemistry, but it can be broken down into an elementary analysis as follows:

Carbon	(C)	41.0%
Hydrogen	(H_2)	4.5%
Oxygen	(O_2)	37.0%
Water	(H_2O)	16.0% (Air dried)
Ash		1.5%

Combustion reactions

During complete combustion, the following reactions take place:

C	+	O_2	=	CO_2
$2H_2$	+	O_2	=	$2H_2O$

During incomplete combustion, we get:

2C	+	O_2	=	2CO

All of these reactions are exothermic. They result in a conversion of chemical energy into heat:

1kg C	+	2.67kg O_2	=	3.67kg CO_2	+	32,000 BTU or 9.6 kWh
1kg C	+	1.33kg O_2	=	2.33kg CO	+	9,500 BTU or 2.9 kWh
1kg CO	+	0.57kg O_2	=	1.57kg CO_2	+	9,500 BTU or 2.9 kWh
1kg H_2	+	8.0kg O_2	=	9.0kg H_2O	+	135,000 BTU or 40.5 kWh

Combustion air

The theoretical combustion air requirement is 3.6 cubic metres per kilo of (dry) wood. This is known as stochiometric air, or 100% excess air.

In reality, more than the theoretical amount of air is required, since some air passes through the firebox without taking part in the combustion. This is called excess air.

Excess air = CO_2max./CO_2measured
The maximum CO_2 possible in wood fuel flue gas is 20.9%

For good combustion, we need around 200% -- 300% excess air.

Efficiency

Combustion efficiency measures how much of the wood's chemical energy is released during the burn. This is typically around 96 - 99% for most good masonry heaters. The chemical loss consists of unburned carbon monoxide and hydrocarbons that exit the chimney.
Heat transfer efficiency measures how good the appliance is at delivering the released energy to your house instead of out the chimney (stack). One way to define it is in terms of stack loss, something that can be measured with combustion testing equipment.
For wood, we will ignore the fact that the wood changes continuously in chemical composition as it goes from cordwood to charcoal, and assume an average composition. We've already dealt with the chemical loss due to incomplete combustion. There are three other types of stack loss.

Latent heat loss

This results from the fact that you are burning hydrogen into water, and not condensing it from the flue gas to recover the "heat of vaporization". You are also boiling off the liquid water content of the wood into water vapor. It takes about 2,000 BTU to turn a kg of liquid water at 212ºF to a kg of gaseous water at 212ºF. Note that this loss does not involve a change of temperature, but rather a change of state from liquid to gas. It is termed latent heat, as opposed to sensible heat which is something you can sense as a temperature change. This is an unavoidable loss, unless you use a condensing chimney to reclaim the latent heat, as in a high efficiency gas furnace.

For wood that is at 20% moisture content, this ends up being about a 13% loss. In Europe, efficiency is defined using the lower heating value (LLV) of wood rather than the higher heating value (HHV) as in the North American definition. In other words, the latent heat loss is not counted. To translate a European efficiency number to an equivalent NorthAmerican number, you need to subtract 9 – 13%, depending on the moisture content of the wood.

Stack temperature

The gas leaving the chimney is above ambient temperature, which represents an efficiency loss. The stove is usually designed to keep the temperature in the chimney gas above 200ºF to prevent water condensation, which is undesirable unless your chimney is built specifically to handle it. You also need to maintain draft, which is difficult to do below about 150 ºF. Some jetted combustion air system only function well with strong draft, requiring a higher chimney temperature. In Kachelofen design, 350 ºF is a typical exit temperature from the heater into the chimney.

Excess air

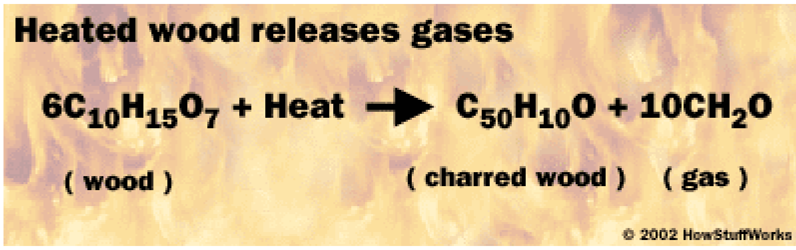
If you are moving excess air through the system, it ends up at the stack temperature. Therefore, the more excess air, the higher the loss. With a masonry heater, we can pretty much pick whatever stack temperature we want in the design process. The main challenge is controlling excess air. Wood needs 200% to 300% excess air, or complete combustion will be hard to achieve and we will see elevated CO levels in the stack.

It is interesting to note that the theoretical maximum efficiency possible with a non condensing woodburning system burning wood at 20% moisture is about 83% overall efficiency.

Overall efficiency = Combustion efficiency × Heat transfer efficiency.

A very good real world number for a masonry heater is about 75% overall.

Wood Combustion



- The (gas) portion of the above equation represents the intermediate combustion products
- In smoldering combustion, some of these intermediate products produce tars
- In flaming combustion, tars don't form. Instead, soot particles form
- In clean combustion, the soot particles burn to CO_2

Emissions

Carbon Monoxide – CO

- Colorless, odorless gas
- Harmful to health in small concentrations, particularly long term
- Poisonous, can cause death in large concentrations
- Oxidizes to CO2 in the atmosphere, so is usually a localized problem
- CO problems are usually associated with urban areas and automobiles
- Measurable with a gas analyzer

5.4.3 General Behavior of Hot CO

In practice, CO emissions have high sensitivity to combustion conditions. We know that CO increases as oxygen and temperature decrease. We also know that the difference between low levels of CO (<200 ppm) and high levels (>2000 ppm) can be 0.1% to 0.2% mole fraction O_2. In other words, CO production is highly nonlinear with respect to temperature and oxygen fraction.

Particulates – PM (particulate matter)

Soot

Emission of soot from a large diesel truck, obviously without particle filters.

- Requires a flame to form
- Carbon ("lamp black")
- Black smoke
- Very lightweight. You can have black smoke, yet a low PM number
- Test filters are black, but have no smell
- Measurable by sucking through a filter
- Doesn't require a dilution tunnel to measure, because there is nothing to condense

Tar

- Requires absence of flame (smoldering) to form
- Complex, semi-volatiles
- Condense at different temperatures
- Blue smoke. Smoke is blue from diffraction of light, due to the very small particle size
- 90% of particles are smaller than 1 micron (= 0.001 mm)
- The wavelength of blue light is 0.5 microns
- Contains PAH's – polycyclic aromatic hydrocarbons – a major health concern, can be carcinogenic

PM2.5

- particulate matter smaller than 2.5 microns
- A blood corpuscle is 6 microns, so these particles are in the biologically active size range
- Measurable with a filter, but requires cooling first, by diluting with air (dilution tunnel)
- Heavy, gives a high PM number
- Test filters have a very distinctive "creosote" smell. If there is no soot, the filter can be yellow, like a cigarette filter

Volatile Organic Compounds – VOC's

- No universal definition
- Some don't condense into particulates at outdoor air temperatures
- Therefore not measurable with filters

Reference Material:

The two basic types of (carbon based) woodstove emissions

Source: Emission Factors and Real-Time Optical Properties of Particles Emitted from Traditional Wood Burning Cookstoves
C.A. Roden, T.C. Bond, S. Conway, A.B.O Pinel, ENVIRONMENTAL SCIENCE & TECHNOLOGY / VOL. 40, NO. 21, 2006

- More than two billion people use biofuels such as wood, crop residue, and dung as their primary energy source for domestic needs such as heating and cooking .
- Biofuel is responsible for a significant fraction of global black carbon (BC) and organic carbon (OC) aerosol. It is estimated to contribute 20% of primary pyrogenic BC and OC globally and 33 and 65%, respectively, of energy-related pyrogenic BC and OC.
- Although these values are similar to the estimated contribution of diesel engines, 37 and 16% of energy-related BC and OC, biofuel sources have been far less studied than vehicular emissions.
- BC and OC are important contributors to the Earth's radiative balance; estimates of climate forcing range from 0.27 to 0.54 and -0.04 to -0.41 W/m_2, respectively, compared with a CO_2 forcing of 1.45 W/m_2.
- In addition to emitted quantities, the chemical composition and optical properties of emissions must be known for climate modeling.
- Most of the particles from biofuel combustion are carbonaceous, and the difference between BC and OC is important.
- Black carbon absorbs radiation, warming the atmosphere and cooling the ground, while organic carbon primarily scatters light, cooling both the ground and atmosphere.

Particulates Comparison: Oil Burners

Source: "Low Sulfur Heating Oil in the Northeast States: An Overview of Benefits, Costs and Implementation Issues"
NESCAUM, Boston, December 2005

- Both solid particles and condensable liquid droplets are generated from most combustion sources including heating oil burners.
- Most of the particulate matter emitted by combustion sources is classified as fine PM with diameters less than 2.5 microns ($PM_{2.5}$).

- Primary particulates include unburned carbonaceous materials (soot) that are directly emitted into the air.
- Secondary particulates, such as sulfates, are formed after sulfur dioxide is emitted into the air from combustion sources burning sulfur-containing fuels.
- Particulate matter less than 10 microns in size (PM_{10}) is linked to a number of adverse health outcomes including asthma, bronchitis, cardiac arrhythmia, and heart attacks (reference 9). Sulfates are also the primary cause of regional haze and acid deposition in the Northeast.
- Direct PM emissions from residential and small commercial oil burners in the form of soot have decreased by approximately 95 percent over the past three decades.
- Sulfates that condense in the outdoor air after being emitted by oil heating equipment are now the predominate form of PM associated with emissions from heating oil burners. Reducing the sulfur content of the fuel can lower sulfate emissions.

Combustion and emissions testing:

Why Test?

- Research and Development: - build better heaters
    - Example: suppose you want to develop an automated bypass damper?
    - What are the tradeoffs between efficiency and ease of operation?
- Field Certification: - verify that a one-off custom heater performs properly
- Gives us more leverage when we are dealing with regulators

What are we trying to measure?

- Efficiency, so that we burn less wood
- Emissions, so that we minimize air pollution and ***<u>comply with regulations</u>***

Summary of the Heater Testing Cycle

1) **Measure the fuel going into the firebox**
   - Descriptive: Wood species, wood geometry, kindling sequence
   - Quantitative: Weight, number of pieces, length, circumference, moisture content

2) **Measure what comes out the stack**
   - Stack temperature
   - Stack gas composition: oxygen or carbon dioxide, carbon monoxide
     - Nitrogen does not change, so no need to measure it
     - Also don't need to measure water vapor, oxides of nitrogen, sulfur
   - Emissions
     - Particulates (smoke and soot)
     - CO (already covered by gas analysis)

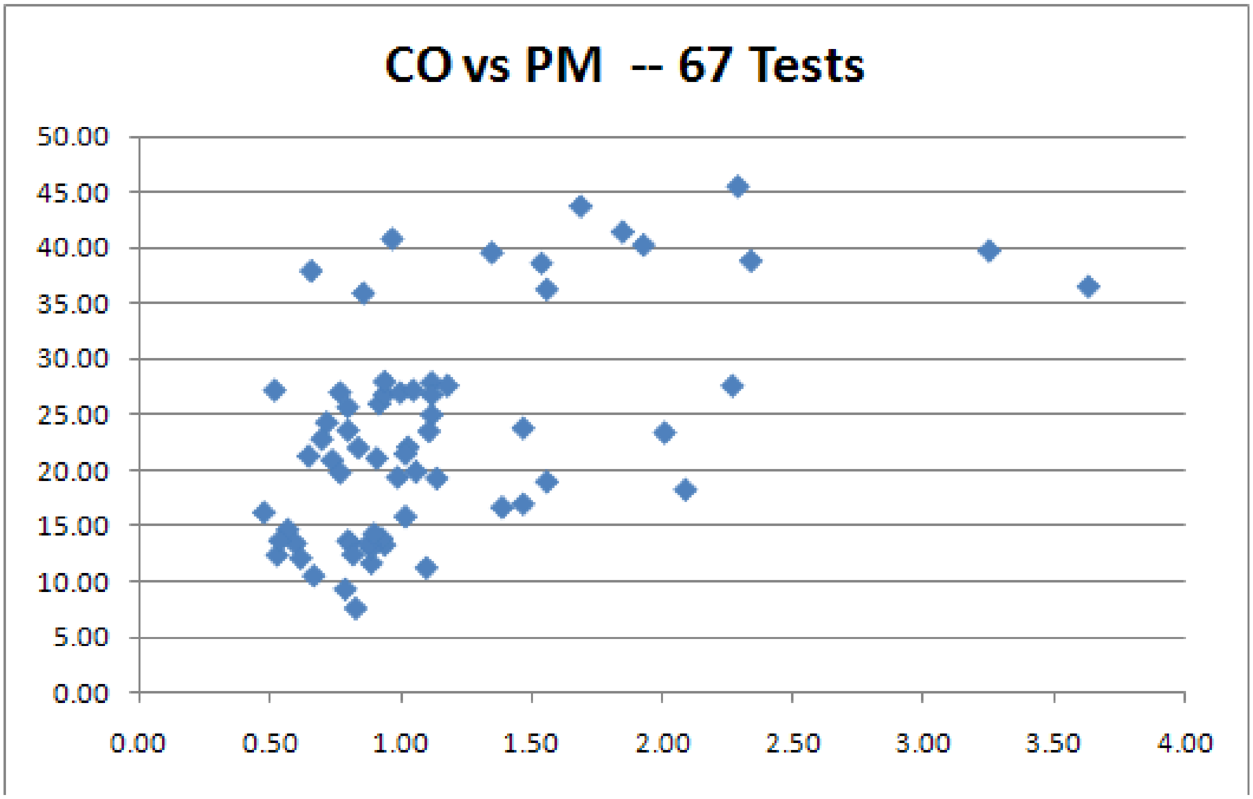
3) **Calculate**
   - Can be automated with computerized spreadsheet templates
   - Does not require specialized knowledge anymore, except to interpret the results

4) **Display Results**
   - We are looking at extremely complicated phenomena
   - It would be nice to get easily comparable results, but that remains a dream
   - Graphic results such as time lapse photography, and the shape of curves on graphs, help to make sense of it all and lead towards insight

5) **Analyze**
   - Once you have many results, you can start to mine them for insight
   - Quality control of the data is job #1, otherwise you are mining garbage

6) **Document**
   - MHA wants to develop a certification program for heater field testing
   - By standardizing the procedure and the data reporting, it will allow us to build a long term performance database
   - This will benefit the heater community and the environment
   - It also enables us to be pro-active in the regulatory realm, with a credible supplement to existing approaches

Example Research Question:



Is there a relationship between CO numbers and PM numbers in masonry heaters?

- This is an example of an open technical question.
- In North America, PM emissions are regulated. In Europe, CO emissions are regulated.
- Europe is starting to regulate PM
- CO is easy to measure with a gas analyzer
- PM is tricky and expensive to measure, requiring a laboratory dilution tunnel setup.
- Fortunately, PM measurements in heaters can be simplified because we don't make tar. This allows us to use the Condar portable dilution tunnel, do field testing, and get reliable numbers.
- This was only learned by experience. MHA and Lopez Labs has pioneered this approach
- European heater testing until recently was for CO only, and the assumption was always that a clean burn in terms of CO will also give you a clean burn in terms of PM
- Based on the above graph, what do you think?
- Measurement always trumps assumptions

Real World Regulation Example:

The following is a portion of the agenda from the WESTAR NSPS Meeting Agenda, Nov 17 – 19 in Portland Oregon, at OMNI-Test:

> **“Meeting Objective/Outcome:** The purpose of the meeting is for regulatory agencies and the regulated community to discuss changes to the Woodstove NSPS.”
>
> NSPS = New Source Perfomance Standards, the name for EPA woodstove regulations.

1:00-3:15 Test Method
- EPA, ASTM, CSA
- Fuel specifications (species and dimensions)
- Low burn rate test
- Visible emissions
- Alternatives to accommodate technological advances
- Efficiency
- Durability testing

3:15-3:30 Break

3:30-5:00 Technology, Operational Variables
- Catalytic, noncatalytic, pellet (including consumer operation variables)
- Certification (lab) results vs. in-use emissions
- Foreign technology

5:00 Adjourn for the day

Thursday, November 19

8:00-9:15 Product Certification/Laboratory Accreditation
- 3rd Party Certification/Accreditation
- Oversight/Audits
- Compliance assurance (including site-built fireplaces)

9:15-9:30 Break

9:30-11:30 Potential Operator Standards
- Visible emissions
- Fuel
- Site restrictions
- Stack heights

- Owners manual allowances

11:30-1:00 Lunch (on you own)

1:00-3:00 Level/Form of Standard – Parameters included in Compliance Demonstration

- Best Demonstrated Technology
- Performance/design standards
- G/hr, #/MBtu heat output
- Emission weighting
- Efficiency
- Implementation (compliance deadlines, etc.)

Instrument and Testing Concepts

Calibration and Repeatability

- Difference between precision and accuracy
- Calibration gas
- Zero and Span
- Drift
- Within Laboratory Repeatability
- Inter Laboratory Repeatability
- Instrument certification by EPA (Testo 350)

Data Quality

- Q&A Standards
- Traceability
- Chain of possession

Automated Testing

- State of technology
- Software
- Instrument features: auto dilution, auto zero, auto rinse

Using the Testo 330-2

Description

- Portable flue gas analyzer
- Commonly used by chimney sweeps in Germany to verify gas and oil furnace efficiency, which is required by law
- Measures draft, stack temperature, O_2, CO
- Automatic operation by computer possible

Calibration

Operation

- CO dilution
- Monitoring the sample pump rate

Data Collection and Storage

- Samples continuously. 30 sec. is a reasonable sample interval to set, otherwise the data file gets too large
- Real time data display and gas graph
- Data file is exported as an Excel spreadsheet, after the test is finished

Maintenance

- Sensors
- Calibration records
- Filters
- Water trap
- Cleaning

Condar Dilution Tunnel

Ministry for the Environment
Manatū Mō Te Taiao
Environmental stewardship for a prosperous New Zealand
Tiakina te taiao kia tonui a Aotearoa

Appendix 3: Portable Emissions Sampler

Based on Applied Research Services Technical Bulletin 72 (2005)

The portable emissions sampler captures particulate emissions using a method based on Oregon Method 41 (OM41). This method is also known as the Condar Method.

Principle of operation

The sampling head includes a dilution system to dilute and cool the flue gas. This simulates the dilution and cooling that occurs when flue gases mix with ambient air, and results in condensation of oily compounds such as polyaromatic hydrocarbons, which can then be captured on the filter.

Flue gases are drawn into a manifold through the sample probe. Dilution air is also drawn into the manifold through small holes in its face. The diluted gases are then drawn through two filters, which collect the particulate emissions.

Details of the sampler

General

The sampler includes a sampling head (detailed below), which captures the sample of particulates. In addition, flue temperature is measured, flue gases are analysed continuously for oxygen and carbon dioxide content, and the carbon dioxide content of the diluted gas stream is analysed. The sampler also contains gauges to monitor and set gas flows through the sample head and flue gas analysers, canisters of drying agent to remove water vapour from the gas streams, a gas meter to quantify the sample flow, and a vacuum sensor to monitor filter loadings.

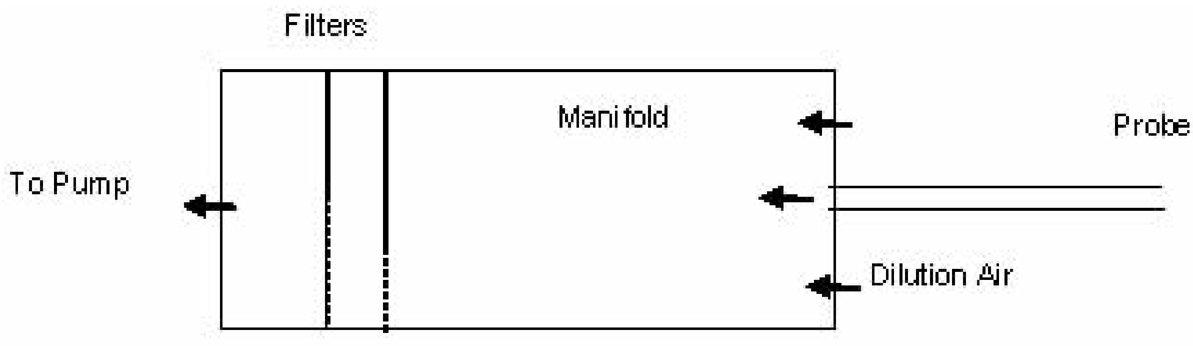
The sampler contains two analysis trains, which are programmed to start and stop at a flue temperature of 100°C. The calculation of the emissions rate is made using results from both analysis trains. The first sampling train draws diluted flue gases on to a filter and gives the weight of particulates per litre of flue gas (Wp/V). The other sampling train performs a gas analysis, which gives the volume of flue gas per kg (dry weight) of fuel burned (V/Wf). This is done directly from the analysis and does not rely on a knowledge of how much fuel was burned.

The chemistry of the process means a fixed amount of fuel requires a well-defined volume of air to burn it completely and generate a known volume of flue gas. If exactly this amount of air is supplied, then the volume of flue gas produced per kg of fuel burned is also known. Under these conditions the flue gases contain no oxygen (it would have all been used up). In reality additional air is supplied. This additional air will dilute the flue gases and result in a measurable amount of oxygen in the flue gases, which allows the degree of dilution to be calculated and hence the actual volume of flue gas per weight of fuel burned.

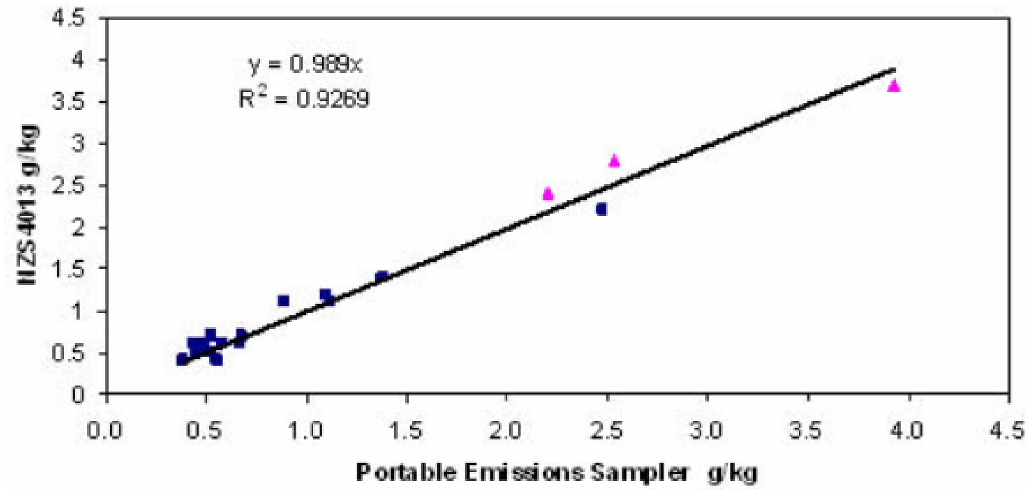
Dividing the first result by the second ([Wp/V]/[V/Wf]) gives the emissions rate (Wp/Wf). Filters on the samplers were changed daily, and where possible the sampler was run for seven days in each household. The sampler is interfaced to a laptop computer, which activates the sampling pump when the heater is operated and the flue temperature rises. The computer is also used to log data.

Sampling head

The sampling head consists of a stainless steel dilution manifold (length 100 mm, internal diameter 49 mm) fitted with two end caps. One end cap is fitted with a short probe with a glass insert. The probe is inserted into the flue so that the inlet is near the flue centre. Dilution air is admitted to the manifold via 12 x 1 mm diameter holes in the face of the end cap. The sample is collected on two 47 mm glass fibre filters (Gelman Type A/E Cat No 61631) mounted on two filter holders fitted to the other end cap of the manifold.



Schematic of Condar Dilution Tunnel



Text description of figure

This is a scatter plot showing emissions results from NZS4013 in grams per kilogram on the y-axis. Emissions using the portable emissions sampler is given on the x-axis in grams per kilogram. A line of best fit is drawn where y equals 0.989 x with an R squared value of 0.9269.

Comparison Between Condar and Laboratory Dilution Tunnel Method

Using the Condar dilution tunnel

Filters

- Description
- Handling
- Static electricity
- Dessication
- Weighing
- Loading
- Unloading
- Reweighing
- Filing

Operation

- Maintaining constant sample rate

Advanced Concepts

- Proportional Sampling
- Isokinetic Sampling

Appendix: TESTO 330-2 combustion analyzer

testo 330-2 LL

technical data:

Parameter	Measuring Range	Accuracy	
O_2 Long Life Sensor	0 to 21 Vol.%	±0.2 Vol.%	
CO, (H_2-compensated) Long Life Sensor	0 to 8,000 ppm	±10 ppm or ±10% rdg. ±20 ppm or ±5% of rdg. ±10% of rdg.	at 0 to 200 ppm at 201 to 2,000 ppm at 2,001 to 8,000 ppm
Auto CO dilution	8,000 to 30,000 ppm		
NO	0 to 3,000 ppm	±5 ppm ±5% of rdg. ±10% of rdg.	at 0 to 100 ppm at 101 to 2,000 ppm at 2001 to 3,000 ppm
NO (low meas.)	0 to 300 ppm	±2 ppm ±5% of rdg.	at 0.0 to 40.0 ppm at 40.1 to 300.0 ppm
Draft and pressure	-4 to 16" H_2O 0 to 80" H_2O	±0.2" H_2O ±1% of rdg. 1.5% of rdg.	at 0 to 20" H_2O at 20 to 40" H_2O at 40 to 80" H_2O
CO_2 (calculated)	0 to CO_2 max		
Temperature	-40 to 1832°F		
Efficiency	0 to 100%		

specifications:

Description:	
Operating temp range:	23 to 113°F
Storage/transport range:	-4 to 122°F
Power supply:	lithium ion rechargeable, AC 6.3V/1.2A
Dimensions:	10" x 3.5" x 2.5"
Weight:	1.5 pounds
Memory:	400 locations
Display:	Monochrome, 160 x 240 pixels
Battery charge time:	>6 hours

Warranty:	
Instrument:	48 months
Sensors:	
CO & O_2 sensor:	48 months
NO sensor:	24 months
Flue gas probe:	24 months
Thermocouple:	12 months
Rechargeable battery:	12 months

Optional probes:

Ambient CO	0 to 500 ppm
Gas Leak	0 to 10,000 ppm
Ambient CO_2	0 to 10,000 ppm

Long lasting pre-calibrated sensors

testo, Inc. • 800-227-0729 • e-mail: info@testo.com • testo350.com

Appendix: TESTO 350 emission analyzer

Evaluation