A review of regulatory standard test methods for residential wood heaters and recommendations for their advancement

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Abstract

In many regions, residential wood heaters are a leading source of harmful air pollution but only satisfy a small portion of local heating demands. In response, many countries have implemented standardized laboratory tests to characterize and limit wood heater emissions. While these test standards are a key tool for advancing both wood heater technology and environmental regulations, many of the experimental methods are outdated and provide few actionable insights for improving heater performance. Furthermore, these test standards vary widely around the world and may not adequately capture the performance of wood heaters operating in residences. In this study, we present a comprehensive review of wood heater testing standards to identify fundamental experimental objectives and regulated performance metrics. Using the results of this review, we provide recommendations to make existing test methods more accessible and representative of residential use, while providing actionable performance data to motivate heater design improvements. Overall, this study elucidates the current state of laboratory testing standards, and the advancements needed to better develop clean wood heater technologies and policies.

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Highlights

- Standardized laboratory tests do not represent heater performance in residences
- Harmonized test protocols for field and lab would help quantify true performance
- Direct dilution of flue exhaust enables emissions characterization in the field
- Time resolved particulate measurements support rapid innovation and improvements
- Measuring flue flow-rate is difficult and required to calculate total emissions

Keywords: Wood heaters; Standardized testing; Air pollution; Thermal performance; Particulate emissions; Emissions regulations

List of Abbreviations

ASTM	American Society for Testing and Materials
BAM	Beta attenuation monitors
BSI	British Standards Institution
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
CSA	Canadian Standards Association
DR	Dilution ratio
EPA	Environmental Protection Agency
FEM	Federal Equivalent Method
ft	Feet
g	Grams
IEA	International Energy Agency
ISO	International Standards Organization
kg	Kilograms
kW	Kilowatt
kWd	Kilowatt delivered
lbs	Pounds
m	Meters
MFC	Mass flow controller
mg	Milligrams
min	Minutes
NESCAUM	Northeast States for Coordinated Air Use Management
NO_X	Nitrogen oxides
NS	Norwegian Standards

O_2	Oxygen
OGC	Organic gaseous compound
PM	Particulate Matter
$Q_{instruments}$	Flowrate of diluted sample to the instruments
$Q_{dilution}$	Flowrate of clean dilution air
Q_{probe}	Flowrate of exhaust sampled through the probe
s	Seconds
SM	Supplemental material
TEOM	Tapered element oscillating microbalance
US	United States

1.0 Introduction

Relative to the energy it delivers, residential heating using wood is a large source of particulate matter (PM) pollution [1,2]. Less than 2% of homes in the United States (US) use wood heaters as the main heat source and contribute to about 6% of the nation's total annual $PM_{2.5}$ emissions [3,4]. Similarly, wood heaters and boilers satisfied about 29% of the European Union's residential heating needs in 2018 and accounted for over 57% of the health-related social costs attributed to air pollution from the residential heating sector [5]. Given their outsized influence on ambient air quality, many countries have national regulations that limit pollution emissions from residential wood heaters. Along with local regulations, such as mandatory curtailment on days with high pollution levels, national emission limits have proven effective at mitigating adverse impacts on public health and the environment [6–9]. Despite these efforts, however, residential wood heaters continue to be major drivers of poor air quality in many regions, partly because their popularity has been growing steadily over the last twenty years. In the US, the number of households using wood as a primary heating source increased by over 30% from 2005 to 2012, and similar trends have been observed across Europe [6,10,11]. This increase has been driven by economic factors (wood fuel consumption typically increases with rising fossil fuel and electricity prices), public policy incentivizing alternative fuel sources, and a growing public perception that firewood is more sustainable than heating oil or natural gas [1,12]. As residential wood heating continues to proliferate, it is increasingly important to update regulations while simultaneously supporting the development of cleaner and more efficient wood heaters.

While wood-heater regulatory emission limits are periodically revised and updated, the standard test methods for certifying compliance remains unchanged. For example, the US Environmental Protection Agency (EPA) decreased PM emission limits for all new wood and pellet heaters in 2020, but the standard EPA test method to measure PM emissions (Method 5) has not been significantly revised since its introduction in 1971 [13,14]. As a result, the experimental protocols and equipment are antiquated. Furthermore, data collected using these methods does not comprehensively characterize wood heater performance or inform opportunities for improvement. For example, validating improvements for specific periods of operation (e.g., startup, reloading, shutdown) is impossible using the single, time-integrated PM-mass emission measurement prescribed by most standard methods [15]. Existing standard test methods also require burdensome experimental setups that cannot be used to evaluate heater the performance in the field (i.e., in homes). Consequently, heaters are tested in the laboratory under operating conditions that may not be representative of actual residential use [16–18].

In this study, we elucidate the current state of standardized wood heater testing and present concrete recommendations for advancement. We review ten standard test methods from around the world for laboratory characterization of residential heaters fueled by firewood and pellets. This review focuses solely on room heaters that deliver heat directly into the space where they operate. Standard methods for central heaters (e.g., boilers, hydronic heaters, and furnaces) will be discussed in a future study, while masonry heaters and fireplaces will not be considered.

For each standard test method, we identify common experimental objectives and regulatory outputs required for characterizing wood heater pollution emissions and thermal performance. We categorize major functional components of each method and discuss their relative strengths and weaknesses. This comprehensive review uniquely examines the entire heater test from initial measurements in the laboratory to final reporting of regulated performance metrics. Using this review, we provide recommendations for enhancing, simplifying, and modernizing the standard test methods. The recommendations focus on making standard methods more accessible to stakeholders and representative of residential use, while providing more meaningful performance data that better motivates technology and policy innovations. Ultimately, this review aims to facilitate inclusive discussions for developing and adopting new biomass heater testing methods that empower air pollution mitigation efforts worldwide.

2.0 Key Components of Wood Heater Testing Standard

To identify core experimental objectives and generate recommendations for improving performance characterization of wood heaters, we reviewed national and international wood heater testing standards. We only included standards approved for regulatory testing and certification. A brief overview of each standard is provided below:

1. US EPA Method 28 for determining PM emissions from heaters fueled with firewood or pellets. Method 28 outlines the heater testing cycle, and PM emissions are captured and measured using Method 5G (dilution tunnel) or Method 5H (flue) [14,19–21]. Both emissions sampling methods are reviewed in Section 2.1.
2. ASTM Method E2779 for determining PM emissions from pellet heaters. PM emissions are captured and measured using a dilution tunnel, as outlined in ASTM Method E2515. Emissions of carbon monoxide (CO) and carbon dioxide (CO_2) may also be optionally monitored to characterize heater thermal efficiency and heat output indirectly (as reviewed in Section 2.3) [22,23].
3. ASTM Method E2280 for determining PM emissions from wood heaters. This method is identical to ASTM Method E2279 except for the test cycle (as outlined in Section 2.4) [24].
4. Canadian Standards Association (CSA) Method B415.1 for determining PM, CO, and CO_2 emissions from pellet and wood heaters. This method standard is largely similar those issued by the US EPA and ASTM International. It uses a dilution tunnel to capture and measure emissions from the heater, and characterizes thermal performance indirectly [25].
5. Method EN16510-1 from the European Union for certifying solid-fueled heater, including wood and pellets. The standard uses direct flue sampling to monitor PM, CO, CO_2, nitrogen oxides (NO_X), and organic gaseous compound (OGC) concentrations emitted from the flue [26,27].
6. Method GB/T 16157-1996 from the Chinese State Environmental Protection Administration for monitoring PM and gaseous pollutant emissions from stationary stacks (not specific to residential combustion appliances) [28].
7. International Standards Organization (ISO) DIS13336 is experimentally similar to the US and Canadian methods, but applies to all solid-fueled heaters, not just wood, and uses a calorimeter room to characterize thermal performance directly (see Section 2.3) [16].

8. Method AS/NZS4012 from Australia and New Zealand is largely identical to Method DIS13336, but defines regulated emission limits since it is issued by a national regulatory body [16]. Regulated performance and emission metrics are detailed in Section 2.5.
9. British Standards Institution (BSI) Method PD6434 uses an electrostatic precipitator mounted to the heater flue or chimney to capture and measure PM emissions from solid-fueled heaters [16].
10. Norwegian Standards (NS) Methods NS3058 and NS3059 are also similar to the CSA Method B415.1 and follow the same general experimental methods and testing protocols [16].

Table 1 provides a comparison of the ten testing standards. The table includes the standard's (1) country of origin, (2) appliance type, (3) fuel type, (4) pollutant emissions monitored during testing, (5) experimental method for capturing and measuring pollutant emissions from the heater, (6) method for characterizing thermal efficiency (if any), (7) the structure and content of the test cycle, (8) the number of test-runs required for each test cycle, (9) a brief description of the test-runs, (10) the minimum duration of a complete test cycle, and (11) the regulated performance metrics (if any). A detailed description of each standard protocol can be found in Section S-1 of the Supplementary material (SM).

It should be noted that some standards could not be fully categorized in Table 1. For instance, Chinese standard GB/T 16157-1996 outlines experimental methods for measuring emissions from stationary exhaust stacks in general, and so no information is provided on the fuel requirements, test cycle, thermal efficiency determination, and other aspects of testing that are specific to wood heaters only [29]. Similarly, the table does not describe the test-runs implemented in the standards from ISO, AS/NZS, BSI, and Norway because the method summaries are adapted from a review by the International Energy Agency (IEA) that did not include this information [16].

Based on the results from the review summarized in Table 1, five key components stood out as necessary for meaningful characterizations of wood heater performance: (1) Fuel specifications, (2) Emissions sampling and measurements, (3) Thermal performance characterization, (4) Test cycles, and (5) Regulated performance metrics. In the following sections, we discuss common approaches for each of these key components, identify

fundamental differences and similarities, and evaluate their relative advantages and disadvantages.

2.1. Fuel Specifications

All standards presented in Table 1 specify the type of fuel for heater testing, and most provide separate procedures for evaluating firewood and pellet heaters. For wood heaters, test methods are available for using test crib wood or cord wood (unprocessed firewood). Test crib wood are created by cutting a specified grade or type of dimensional lumber into pieces of uniform length, and then nailing them together into a prescribed geometric arrangement. The lumber's length and geometric arrangement are defined as a function of the firebox dimensions. Since the size, shape, and chemical properties of cord wood vary significantly, these standardized test crib arrangements are intended to improve repeatability. However, test crib wood may not be representative of heater operation and performance in the field, where cord wood is typically used [30]. For cord wood testing, protocols specify the number of cord wood pieces that must be loaded into the firebox, the cross-sectional area, the mass of each piece, the wood species, and other factors as a function of firebox volume. These specifications introduce a certain degree of standardization to cord wood testing, although the fuel itself remains inherently variable [17].

For both test crib wood and cord wood testing, the total fuel mass loaded into the heater for each test-run is defined as the product of the usable firebox volume (measured on the test unit) and fuel charge density (specified in the standard). For example, EPA Method 28 specifies a fuel charge density of 112 ± 11 kg (247 ± 24 lbs) of fuel per cubic meter of usable firebox volume. So, a heater with a 0.04 m^3 firebox would be fueled with 4.5 ± 0.4 kg (9.9 ± 0.9 lbs) of cord wood or 2x4 lumber fashioned into a crib for each test-run [19].

When testing pellet heaters, the fuel hopper is simply filled with pellets according to the manufacturer's specifications. The fuel hopper must contain enough fuel to ensure continuous operation for the duration of the entire test cycle (up to 12 hours). Some standards specify the grade or type of pellet fuel that must be used during testing. For example, ASTM Method E2779 requires using the grade of pellets recommended by the manufacturer. If more than one grade is listed, then the standard recommends using the fuel with the lowest grade [22].

For both firewood and pellet heaters, all standards require fuel properties be measured

and meet specifications. For example, the moisture content of the fuel is measured using electrical resistance or an oven drying method (the mass of the fuel is measured before and after drying, and the difference represents the mass of water in the fuel) to confirm it is within the prescribed limits. The chemical composition and lower/higher heating values are also required for calculating the heater's thermal efficiency. Most standards provide representative chemical composition and heat content values for common wood fuels (e.g., Douglas fir or red oak). These representative values can be used to estimate the heater's performance, but supporting protocols are cited for measuring fuel properties directly and are often analyzed at a dedicated facility. All test methods also require firewood is free of decay and bark.

EPA Method 28, ASTM Method E2780 and CSA Method B415.1 all provide identical fueling procedures for firewood and pellet heaters (both test crib and cord wood instructions are included) [19,24,25]. Method EN16510 and those from Australia/New Zealand, the UK and ISO support testing of solid-fueled heaters in general [16,26,27]. For example, EU Method EN16510 provides a harmonized framework for characterizing and standardizing any solid fuel such as coal, coke, and peat, in addition to cord wood and pellets [26].

2.2. Emissions Sampling and Measurements

All standards provide experimental protocols for quantifying and reporting the amount of pollutant emissions generated by the wood heater during testing. While the test methods vary, all require continuous emission sampling of targeted pollutants (e.g., PM or CO) from the exhaust or flue of the wood heater. Wood heater emission metrics are calculated using methods specified in each standard. An overview of emission sampling methods is provided in the following subsections.

2.2.1. Flue and dilution tunnel sampling

As shown in Table 1, emissions generated by the heater may be sampled directly from the flue or using a dilution tunnel. For flue measurements, the sampling probes of emission instruments are inserted into the flue or stack of the heater at specified positions. For example, Figure 1 illustrates the flue sampling set-up prescribed by EPA Method 5H [21]. Typically, a dedicated section of flue incorporates secure and well-sealed mounting points for the sampling probes, thermocouples, and other instruments (e.g., a pitot tube to measure flow velocity). While

flue sampling is straightforward to set-up both in the laboratory and field, the extremely hot, highly polluted, and water saturated flue exhaust is destructive to most pollutant-measurement instruments. Flow conditioning equipment, such as the condenser and filter system recommended by EPA Method 5H, prevents damage to the instruments by drying, cooling, and/or diluting the exhaust sample [21]. Although this approach is effective at protecting instruments, it may reduce the accuracy of the pollutant measurements collected [30,31].

A dilution tunnel is a dedicated ducting system that captures all exhaust emitted from the flue and dilutes it with ambient air for analysis. Figure 2 shows the dilution tunnel specified in EPA Method 5G, which is representative of those used in other standards [23]. The system contains a conical collection hood that is positioned directly above the heater flue. An electric blower draws the diluted exhaust from the hood through a steel ducting system that includes two 90-degree elbows, baffles, and a sampling section. The baffles ensure thorough mixing of the ambient air and flue exhaust. In the sampling section, a pitot tube measures flow velocity, thermocouples measure temperature of the air-exhaust, and sampling probes draw air-exhaust to the pollutant instruments. To ensure that the velocity profile of the air-exhaust in the duct is fully-developed and pollutant concentrations are uniform, the sampling section is a minimum of 2.74 m (9 ft) of straight duct. Downstream of the sampling section, the air-exhaust passes through a damper and the blower before being exhausted to the atmosphere through a chimney.

Since dilution tunnels are large and complex, they are often constructed and operated at dedicated testing facilities. While this restricts the characterization of heaters in the field, the dilution tunnel provides cool, dry, and relatively clean air that enables direct sampling (without additional conditioning equipment) to most emissions analyzers. The dilution tunnel greatly simplifies the emissions sampling process and becomes especially important when integrating several different instruments together to monitor a variety of pollutants simultaneously. Furthermore, the dilution tunnel cools the exhaust and allows it to evolve naturally like it would when released to atmosphere. Sampling diluted exhaust from the dilution tunnel also provides pollution measurements that are representative of those emitted under normal operating conditions [30,31].

2.2.2. PM emissions

All standards in Table 1 require measurements of the total PM mass emitted during the heater test and most required the gravimetric filter method. GB/T Method 16157-1996 and PD Method 6434 require a fibrous cartridge (rather than filter paper) and an electrostatic precipitator mounted on the heater's chimney, respectively [16,28]. These alternative protocols are functionally identical to the gravimetric filter method, differing only in the apparatus used to capture PM for weighing on a balance.

The gravimetric filter method measures total PM mass by drawing exhaust at a specified flow rate through a fibrous filter that collects PM. The exhaust may be sampled from the flue or dilution tunnel using a vacuum pump. Throughout sampling, the standard requires that the filter flow-rate is periodically checked and adjusted to remain constantly proportional to the flue or dilution tunnel flow-rate. For example, if the filter flow-rate is initially five times higher than the flue flow-rate, then this ratio of five to one is held constant throughout the test. The mass of PM collected is determined by subtracting the weight of the filter measured before and after the test. The total volume of exhaust sampled through the filter is determined directly using a dry gas meter or indirectly by integrating flow rate measurements collected at regular time intervals. With these data, the average PM mass concentration is calculated.

Unlike many other pollutant measurement techniques, gravimetric PM filters can be used with exhaust sampled directly from the flue. Heat and moisture resistant filter materials, such as quartz or glass fibers, enable direct flue sampling; however, flue PM mass measurements may not accurately represent heater PM emissions in the atmosphere. Under normal operation, volatile organic compounds (e.g., tars) exhausted from the flue cool, nucleate, and condense from their gaseous state to form secondary PM pollution in the atmosphere. When sampling hot exhaust directly from the flue, these organic compounds remain in their gaseous state and pass through the gravimetric filter with little or no deposition. Therefore, a cooling and condensing system is typically implemented to evolve the PM precursors for collection at a second backup filter, downstream of the first [32–34].

Figure 3 shows the gravimetric filter set-up for direct flue sampling in EPA Method 5H [21]. In this system, the sample lines leading to the probe and the first filter holder are maintained at 120ºC to prevent moisture condensation and particle loss. After collecting PM on the first heated filter, the sample passes through a series of impingers immersed in cold water to

condense volatile organic compounds that are collected on the second filter. Although this process helps condense volatile organic compounds, the chemical evolution and condensation may not be complete due to the short residence time. As a result, the total PM mass measured from the flue (the sum of the mass collected on the two filters) is prone to underestimating heater emissions to the atmosphere.

Gravimetric PM filters collected from a dilution tunnel are more representative of exhaust in the atmosphere because the exhaust is mixed thoroughly with ambient air prior to sampling, mimicking normal residential operation [30,31]. Gravimetric filters are also a straightforward and accurate method for gathering a single, time-integrated measurement of the PM mass emitted during the sampling period. While collecting PM emissions on the filter itself is relatively straightforward, the complete measurement process can be experimentally cumbersome. For example, filters must be conditioned and weighed to an accuracy of ~0.1 mg both before and after sampling. This process requires at least 24 hours and an expensive microbalance housed in its own conditioned room or chamber. Due to the cost and time required to prepare and weigh gravimetric PM filters, it is often a bottleneck during heater testing. Furthermore, each filter only provides a single time-integrated PM mass measurement, which is sufficient for regulatory certification but does not provide information on when PM was emitted during operation. As result, it is difficult to identify operating conditions that result in elevated PM emissions, or inform potential heater design improvements using gravimetric measurements alone.

2.2.3. Gaseous emissions

Some standards also require time-resolved measurements of CO and CO_2 concentrations in the flue. The US standards use these concentration measurements to calculate the heater's thermal efficiency and heat output (see Section 2.3) [14,19–24]. CSA Method B415.1 also requires calculation of the CO emission rate [25]. EN Method 16510 requires time-resolved monitoring of CO, CO_2, oxygen (O_2), NO_X, and OGC concentrations in the flue [26]. GB/T Method 16157-1996 provides instructions for monitoring up to 16 gaseous pollutant species, but only requires CO, CO_2, and O_2 concentration measurements [28]. All standards that require gaseous pollutant measurements provide experimental protocols for flue sampling with real-time analyzers. GB/T Method 16157-1996 provides instructions for measuring emissions using

chemical analysis, but this method is out-of-date and may be carryover from the original 1996 publication [28].

2.2.4. Measurement of exhaust flow rate through the flue and dilution tunnel

Time-resolved, dilution tunnel or flue flow rate measurements are needed to calculate total pollutant mass-emissions during heater testing. If emissions are sampled in a dilution tunnel, accurate flow rate measurements may be easier to obtain because the exhaust is highly diluted and traveling at high velocities. For time-resolved flow rate in a dilution tunnel, most standards require using a pitot tube to measure velocity in the sampling section (see Figure 2). Then, flow rate is calculated using the internal duct diameter, sampling section temperature, and barometric pressure. The standards also specify minimum duct flow velocities to ensure measurements are accurate and within operation limits of the pitot tube. Since exhaust is highly diluted, a standard-type pitot tube may be used with minimal risk of clogging. Other flow measurement devices such as orifice plates, hot-wire anemometers, and integrating grids may also be used to measure flow rate.

If emissions are sampled from the flue, flow rate may be more difficult to measure accurately because flue flow rates are often below minimum detection limits of available instruments. Furthermore, the harsh conditions (e.g., high temperature, high pollutant concentrations) may cause instruments to fail. As a result, many standards estimate flue flow rate using a mass balance equation that approximates the heater's wood combustion process. The mass balance equation relies on measurements of the fuel mass burned, the chemical composition of the fuel, and CO/CO_2 concentrations in the dilution tunnel. Assumptions about the fuel composition and the combustion process are also provided, but may introduce error to the flue flow rate calculation. For example, representative fuel composition values listed may not accurately represent the actual fuel used for testing. Additionally, the mass balance equation assumes the fuel is entirely converted to CO, CO_2, methane (CH_4), and water, ignoring all other emissions [35]. Furthermore, the fuel is assumed to fully combust leaving a fixed amount of ash (typically assumed to be 0.5% of the initial fuel mass). These kinds of assumptions may decrease the accuracy of the exhaust flow rate calculation, especially if combined, and lead to unreliable emissions and thermal performance results.

While most standards rely on the mass balance equation to approximate flue flow rate,

the US EPA also provides experimental protocols for direct measurement using an S-type pitot tube or a tracer gas [14,21]. S-type pitot tubes operation is the same as standard-type pitot tubes but have large static and dynamic ports that resist clogging in high emission environments. While S-type pitot tubes are appropriate for stationary stacks with relatively high flow velocities, like those at powerplants, the flow velocities in wood heater flues may be too low for accurate operation (see EPA Method 5) [14]. Alternatively, EPA Method 5H outlines a tracer gas protocol specifically for measuring flue flow rate [21]. In this method, a tracer gas (i.e., Sulfur dioxide) of a known concentration is injected into the flue at a constant rate, it mixes with heater's exhaust, and the resulting concentration is measured further downstream to calculate flow rate. Although this method provides a reliable measurement, it requires a cylinder of the tracer gas, accurate measurement of the injection flow rate into the flue, and a dedicated tracer gas analyzer outfitted with sample flow conditioning equipment (e.g., a combustor, filter, and condenser). This additional equipment and the associated experimental procedures can be time consuming and costly.

2.3. Thermal Performance Characterization

While all standards focus on characterizing pollutant emissions (particularly PM) from wood heaters, some also require measuring thermal efficiency and heat output. Thermal output from room heaters can be measured directly using a calorimeter room or calculated indirectly using fuel consumption, exhaust temperature, and flow rate through the flue. A calorimeter room is a well-sealed enclosure that surrounds the heater with a controlled volume of air. During testing, the air temperature in the room is monitored continuously, and some air is circulated to prevent suffocating the heater; the flow rate and temperature of the circulated air is also recorded. Although the calorimeter room is experimentally burdensome, it provides highly accurate thermal performance results because it directly measures heat output to surrounding air. ISO DIS13336 and AS/NZS4012 are the only standards that recommend the calorimeter room [16].

Thermal performance may be calculated indirectly using measured gaseous pollutant concentrations in the flue. If a dilution tunnel is used, however, additional equipment is required to measure exhaust temperature and CO/CO_2 concentrations in the flue. Exhaust flow rate may also be measured using a pitot tube or tracer gas, or may be approximated using a mass balance

equation (see Section 2.2.4). Using these data, the chemical and latent energy losses through the flue are calculated at regular time intervals throughout the testing period. The heat output is then calculated as the difference between the energy released by the combusted fuel (i.e., the product of fuel mass and lower heating value) and the estimated energy lost through the flue. Using this same energy balance, thermal efficiency can also be determined. Given the many different measurements and intermediate calculations required, the indirect determination of thermal performance is more susceptible to experimental inaccuracies and calculation errors than the calorimeter room.

2.4. Test Cycles

Table 1 shows that most standard test cycles for room heaters consist of three or four test-runs conducted at varying fuel burn-rates. Most standards specify the burn-rate for each test-run absolutely (e.g., kg of fuel per hour) or relative to the maximum burn-rate. EN Method 16510 defines a heat output setting for each test-run (instead of burn-rate), relative to the nominal value specified by the manufacturer [26]. Each standard prescribes the minimum number of test-runs that must be conducted at each burn-rate. For example, EPA Method 28 has a test cycle with four different burn-rates, and at least one test-run must be conducted for each burn-rate (see Table 2) [19].

As shown in Table 1, the only difference between test cycles for firewood and pellet heaters is the criteria used to define the end of each test-run. For firewood heaters, test-runs end when the fuel batch in the firebox has been fully exhausted, while test-runs for pellet heaters end after a prescribed operational period (e.g., one hour at medium burn-rate). This distinction arises because pellet heaters are typically designed to run for 12 hours or more before refilling the fuel hopper: too long for a practical test-run. Additionally, all room heater standards require that the test appliance reach a steady operating temperature prior to the first test-run in the cycle. This ‘pre-ignition period’ lasts at least one hour and ensures that performance is always evaluated at thermal equilibrium (i.e., the heater is neither heating up from ambient conditions nor cooling down), regardless of the heater’s size or mass.

The end of a test cycle may be determined using the remaining mass of fuel in the heater (e.g., test-run ends when fuel mass drops to ~0 kg) or CO_2 concentrations in the flue (e.g., CO_2 concentrations approach ambient concentrations). Ending the test-run based on fuel mass

requires a dedicated platform scale under the heater. This dedicated scale may be redundant because the standards only require a single measurement of the total fuel mass combusted during the test-run, and this is usually already measured separately as the fuel is loaded into the firebox. However, the scale provides time-resolved fuel consumption data that can be useful for more in-depth characterizations of heater performance. For standards that require gaseous pollutant monitoring, no additional equipment is needed to use CO_2 concentrations to define the end of the test-run [26,27].

The fundamental purpose of standardized test cycles is to provide uniform operating conditions for repeatably evaluating and comparing heater performance. While this is useful for establishing compliance to regulatory standards, the emissions and performance results may not be representative of real-world operation. For example, test cycles typically evaluate the heaters at steady state operation and do not account for warm-up, cool-down, fuel loading, and other transient periods needed to operate the heater. In response to these shortcomings, European researchers have developed a laboratory test cycle that more closely represents residential heater operation, known as the beReal method (this is a draft method, not adopted for regulatory testing). To inform this method, the researchers conducted a survey of over 2000 European households to quantify the prevalence of different wood heater types and typical patterns of operation [36]. For example, the survey revealed that 62% respondents use room heaters (as opposed to a central heater or boiler), and 65% of respondents adjust heat output settings during operation [37]. Motivated by these insights, the beReal method focuses on evaluating room heater performance at a variety of heat output settings, and includes several transient adjustment periods. The test cycle also includes ignition, burn out, and other required phases of heater operation that are omitted from regulatory standards.

While the beReal test cycle makes a well-informed estimation of residential operation, the survey data also reveals that heater users are highly diverse, and their habits cannot be captured by a single test cycle. For example, the beReal method focuses on characterizing heater operation at intermediate heat outputs because 53% of respondents report this behavior [37]. However, this same decision also dismisses nearly half of respondents who primarily operate their heater at the highest or lowest setting. Given the absence of dominant user behaviors, laboratory test cycles must balance between accurately representing residential operation and providing replicable experimental procedures for characterizing heater performance consistently.

2.5. Regulated Performance Metrics

All the standards presented in Table 1 focus on quantifying the PM mass emitted by wood heaters, but only those issued by regulatory bodies (e.g., the US EPA or CSA) mandate emission limits. For example, the US EPA 2020 emission limits for room heaters fueled with firewood or pellets requires all wood heaters (catalytic and noncatalytic) to emit no more than 2.0 grams of $PM_{2.5}$ per hour if tested using crib wood and 2.5 grams of $PM_{2.5}$ per hour if tested using cord wood and an approved method [13]. In EN Method 16510, PM emission limits are defined in terms of average concentration emitted to the atmosphere (mg/m^3 normalized to 10% or 13% oxygen content in the flue). This European standard does not define specific PM emission limits and only requires heaters to meet the manufacturer's specifications. This is because each country is establishes their own emission limits [26].

EN Method 16510 is the only standard in Table 1 to regulate gaseous pollutant emissions. Specific gas concentration limits are not defined, heaters must meet or exceed the manufacturer's specifications during testing [26]. In Denmark and Sweden, regulators specifically limit the concentration of gaseous pollutants (CO and OGC) that may be emitted from the heater flue. For example, Danish heaters with < 50 kW of thermal output may only emit CO concentrations of up to 5000 mg/m^3 [6]. While many standards provide protocols for evaluating the heater's thermal performance, we found that only Sweden regulates heater efficiency.[6] The US EPA and CSA both require reporting of the heater's thermal efficiency, but do not define regulatory limits.[25,38] The US EPA also requires reporting of the CO mass emission rate (in grams per hour, like PM) [38].

Regulators primarily focus on reducing PM mass emissions because they indicate that the combustion process has improved, thus reducing emission of other harmful pollutants (i.e., CO) and improving thermal performance [39]. However, regulating PM emissions alone may not be the most effective method for motivating the development and adoption of cleaner, more efficient heaters [6,9,17]. For example, mandating thermal efficiency improvements may incentivize users to invest in newly compliant units to benefit from the fuel savings, thereby accelerating the replacement of outdated heaters [30,40]. Unfortunately, scientific research in this area is sparse; although new heaters must meet increasingly stringent PM emission requirements as standards are updated, assessing whether these PM reductions enhance other

aspects of performance (e.g., thermal efficiency) is difficult because the relevant metrics are either not reported or derived inconsistently between standards [30].

2.5.1. Normalization of PM Mass Emissions

Test standards for room heaters normalize PM mass emissions by time or mass of fuel combusted. For example, US EPA and CSA limit PM emission rate (g of PM per hour), as illustrated in Table 3, while Norwegian regulators limit the fuel-specific PM emission factor (g of PM per kg of fuel) [6,13,25]. While both metrics are intuitive and broadly applicable to any type of wood heater, neither reflects the capacity to deliver thermal energy to the user. For example, two heaters may have the same PM emission rate or factor, but if one delivers more thermal energy within that unit of time or mass of fuel combusted, the metrics will not reveal this crucial performance difference. A solution is to normalize emissions by thermal energy or power delivered, as is done in standard test methods for central heaters (i.e., boilers and furnaces) [41,42]. However, normalization of emissions is not straightforward for room heaters; direct measurement of thermal output with a calorimeter room is experimentally burdensome, while indirect methods have limited accuracy (see Section 2.3). Since central heaters deliver heat to a working fluid (i.e., air or water), direct and accurate measurement of energy output to a simulated load is much more straightforward [41,42]. This experimental difference may account for the different emission normalizations used for room heaters and central heaters.

It should be noted that normalization by heat output (e.g., grams of PM per megajoule delivered) also has inherent limitations, as it does not capture the time required to deliver the thermal energy. While two appliances may have the same energy-specific PM emission factor, one may deliver this energy output more rapidly than the other. Therefore, it is more representative to normalize PM mass emissions by thermal power output (e.g., grams of PM per kilowatt delivered), since this also captures the time rate at which energy is provided to the user - an important performance consideration.

2.5.2. Calculation of Integrated Emission Metrics

For regulatory compliance, most standards calculate integrated emission metrics such as emission rates or emission factors. PM emission rates are calculated for each test-run in a standard test cycle and a single, weighted-average PM emission rate is reported. While this

single PM metric provides a clear regulatory benchmark that is easy to mandate, it is susceptible to manipulation and may not represent true heater performance. For example, the ASTM standards assign a weight of 0.2 to PM emissions rates for high burn-rate test-runs, while low and medium burn-rate test-runs have a weight of 0.4 [22,24]. Since test-runs at medium and low burn-rates contribute twice as much to the weighted-average, heaters optimized to operate at lower burn-rates may receive lower overall scores. As a result, manufacturers may decide to improve heater performance for only the low and medium burn-rates because these have the greatest mathematical influence on the final test cycle score.

To better capture actual heater emissions, US EPA and CSA weight PM emission rates using a 'probability' function (ranging from 0 to 1) that depends on the average fuel burn-rate (see S-1.1 and S-1.4 in the SM for details). These probabilities were designed to represent the distribution of wood heater burn-rates across the nation [17]. Although these probabilities may better capture heater operation, the static relationship between probability and burn-rate may still bias heater emission results.

In addition to weighted-average PM emission rates, CSA certification requires heaters with and without catalytic converters to meet published emission limits for each test run [25]. The emission limits are functions of fuel burn-rate and are used to regulate each phase of certification testing. To prevent performance bias, establishing appropriate emission limits for each burn-rate is critical.

3.0 Recommendations for simplifying wood heater performance evaluation

The review in Section 2 reveals several opportunities for improving the test methods to make them more accessible and provide more actionable data for motivating technology and policy innovations. Specifically, we recommend the following: 1) using direct dilution of the heater flue sample to enable emissions evolution and field testing; 2) modernizing gravimetric emissions sampling equipment to obtain more accurate PM emission results; 3) supplementing gravimetric PM measurements with time resolved instruments to better characterize heater performance and identify opportunities for improvements; 4) measuring exhaust flow rate directly in the flue to more accurately measure emission rates; and 5) harmonizing experimental

procedures and equipment for field and laboratory testing. Each of these recommendations is discussed in detail in the following sections.

3.1. Direct dilution of the heater flue sample

Direct dilution of flue exhaust combines the benefits a full-capture dilution tunnel and direct flue sampling by enabling portable measurements of emissions under conditions that simulate stack gas entry and mixing in the ambient atmosphere. In a direct dilution system, emissions are sampled from a probe mounted at the center of the flue (matching standard practice) and then mixed with clean air in diluter with a dedicated mixing section (see Figure 4). This mixing section ensures the sample concentration is uniform and representative of emissions sampled using a full capture dilution tunnel. Clean dilution air may be provided from a gas cylinder or an air compressor with a PM filter. The flow of clean dilution air is aligned with the flue emissions inlet in the development section to prevent the impaction of particles onto the diluter walls. The fully-mixed, diluted flow then passes to the instrumentation suite for analysis.

The dilution ratio (the ratio of clean dilution air to flue exhaust) is controlled by varying the flow rate of clean air into the diluter relative to the flow rate of air analyzed by the instruments. By mass balance, the difference between these two flow rate settings is equal to the flow rate of exhaust drawn from the flue probe. Therefore, the dilution ratio (*DR*) can be expressed as function of the controlled variables as follows:

$$DR = \frac{Q_{dilution}}{Q_{probe}} = \frac{Q_{dilution}}{Q_{instruments} - Q_{dilution}} \qquad (1)$$

where $Q_{dilution}$, Q_{probe}, and $Q_{instruments}$ represent the flow rate of clean dilution air, exhaust sampled through the probe, and diluted sample drawn by the instrumentation suite, respectively. For example, if a dilution ratio of 10 is desired and the instruments draw 11 LPM, the dilution flow rate must be set to 10 LPM, and the remaining 1 LPM will be drawn through the flue probe. A purge pump may be added to the instrumentation suite such that the total flow rate of diluted exhaust drawn from the diluter can be varied flexibly without adjusting the instruments' flow rate settings (which may adversely affect their measurement performance). Mass flow controllers (MFC) are common and relatively inexpensive devices that can easily measure, record, and

control both $Q_{dilution}$ and $Q_{instruments}$. If zero-air (devoid of CO_2, CO, and other combustion products) is used for dilution, the dilution ratio can also be independently verified by monitoring a gas concentration (e.g., CO_2) in both the flue and the diluted sample.

Often, the flow rate through the sample probe and the heater flue must be monitored continuously because standards require that the ratio of these two flow rates (known as the proportionality ratio) be held constant throughout testing. In order to keep both the dilution and proportionality ratios constant, $Q_{dilution}$ and $Q_{instruments}$ must be adjusted concurrently (see S-2.1 in the SM for details). A closed-loop control system may be implemented to automatically set the two flow rates values as function of the exhaust velocity, the desired dilution, and the proportionality ratios. This system could be created using a digital sensor to monitor the exhaust flow rate in the flue, two MFC units, and a computer to process the exhaust velocity measurements and generate corresponding MFC commands.

Although direct dilution is not used in standard heater testing, it has been investigated and implemented during wood heater research and development. For example, Kinsey et al. compared cord wood heater emissions analyzed with a total-capture dilution tunnel to those measured with a direct dilution system. Despite the inherent variability of the cord wood heater's performance and the limited dataset, the study finds that the PM mass emission data from the direct dilution system and the dilution tunnel agree closely for most experimental conditions [33]. The EPA also provides a reference method for stack emission dilution using a venturi diluter, but state that this "method is not an alternative to EPA Method 17 or EPA Method 5" and cannot be used for regulatory heater certification [43]. While venturi diluters are common, they are susceptible to clogging and the effective dilution ratio may be challenging to measure [44]. Other researchers have designed portable, direct dilution systems to facilitate stationary stack sampling in the field [45]. For example, Meyer et al. used a flue extension and venturi diluter to sample PM emissions directly from residential heaters in Australia (see Figure 5) [29,44].

Overall, a direct dilution system combines the convenience and portability of direct flue sampling with the core advantages of a dilution tunnel–the cooled and diluted sample is easier for pollution instruments to analyze and more closely replicates pollution emission to the atmosphere during normal residential use. In addition to the research described here, a wide variety of direct dilution methods have been developed for other air quality monitoring applications, such as characterizing diesel engine emissions, and could be readily adapted for

wood heaters [46,47].

3.2. Modernizing the gravimetric emissions sampling equipment

Many wood heater testing standards recommend antiquated equipment that may be cumbersome or too complex to implement. For example, the recommend system for measuring volume of gas sampled through the filters includes a dry gas meter, a system for conditioning the sample flow prior to the dry gas meter, and a redundant orifice and manometer to enable flow rate adjustments during setup and testing [21]. This complex system could be replaced using a single MFC after the filters (see Figure 6).

The modernized gravimetric system illustrated in Figure 6 also incorporates a diluter, as described in Section 3.1. Since the diluter promotes complete evolution of PM precursors, it eliminates the need for impingers or condensers, like those prescribed by EPA Method 5H [21]. Similarly, the diluter also negates the need for heated filters and samples line, as dilution with cool and dry air prevents water condensation in the sampling system. The second filter could also be removed from the modernized system, as the diluted sample flow promotes complete PM capture on the first filter. The second filter has been retained in Figure 6 to comply with standard procedures.

This modernized system also enables automated data collection and simplifies other standard procedures. Specifically, North American standards require the user to manually monitor the gravimetric sampling system and log data throughout the test-run: Every ~10 minutes, total volume measurements are logged from the dry gas meter, sampling conditions are recorded, and the probe flow rate is adjusted to maintain a constant proportionality ratio [14,19–25]. Using a MFC and diluter, this entire experimental procedure can be automated (see Section 3.1 for maintaining a constant proportionality ratio). Furthermore, the sampling system from EPA Method 5H includes three temperature sensors and a vacuum pressure gauge that can be omitted because MFC units already monitor these parameters [21]. The proposed modernized system only retains a single temperature sensor between the two filters to comply with standard experimental procedures. Overall, the system presented in Figure 6 could greatly simplify the hardware and experimental procedures required for measuring accurate and replicable gravimetric PM, while making it more accessible to researchers and manufacturers.

3.3. Supplement gravimetric PM measurements with time resolved instruments

Supplementing gravimetric filter measurements with time-resolved PM mass concentration data could vastly expand our understanding of wood heater performance during different operational phases. The three most common classes of real-time PM instruments are 1) tapered element oscillating microbalance units, 2) beta attenuation monitors, and 3) optical monitors.

Tapered element oscillating microbalance (TEOM) units: TEOM units capture particulate matter in the sample on a filter or impactor plate mounted to the tip of an oscillating microbalance. As the mass of PM collected on the filter increases, the frequency response of the oscillating microbalance changes predictably and is correlated to PM mass concentrations in real time [48]. Since the TEOM's measurement proxy is directly related to particle mass, it is often more reliable and accurate than other detection methods. TEOM units are a US Federal Equivalent Method (FEM) for ambient PM monitoring, and are also commonly used to characterize air pollution sources, such as diesel engines [49]. In both these applications, TEOM units have shown strong correlations with traditional gravimetric methods, although they require calibrations specific to the ambient sampling environment or emissions source [50–53].

Currently, the Northeast States for Coordinated Air Use Management (NESCAUM) has published the only standard operational procedure for characterizing wood heater emissions using a TEOM unit [54]. While TEOM units are not currently used for regulatory heater certification, TEOM units are commonly used to characterize wood combustion emissions, and shown that calibrated measurements agree closely with standard gravimetric filters over a wide range of PM emission rates [33,47,53,55,56]. A drawback of the TEOM is that it's collection filter must be replaced when it becomes overly loaded with PM. This can complicate the characterization of highly polluted heater exhaust, as it requires excessively frequent filter replacement. Furthermore, it also should be noted that TEOM units are large and expensive, thereby limiting their utility outside of a dedicated laboratory environment.

Beta attenuation monitors (BAM): BAMs measure the intensity of beta radiation transmitted through a fibrous filter that continuously collects PM. As PM from the sampled air flow deposits on the filter, the intensity of beta radiation attenuates predictably over time, and this attenuation rate is correlated to PM mass concentrations in the sample flow [57]. BAMs are also a US FEM commonly used for ambient monitoring, although careful calibration is required

as measurement performance is affected by environmental conditions, PM composition, and other factors [52,58,59]. Researchers have used BAMs to measure ambient PM emissions from combustion sources, such as wildfires and cookstoves, but emissions are always sampled ambiently and not directly from the source [60,61]. Therefore, additional research is needed to evaluate the utility of the BAM for characterizing wood heater emissions. Like the TEOM, the BAM's filter must be replaced when it becomes overly loaded with PM, and it is a large and expensive instrument not well suited to applications outside of a dedicated laboratory setting.

Optical PM Monitors: There several different types of optical PM monitors, but the most common relies on light scattering to detect suspended particles. In these instruments, a beam of light shines through a flow of sampled air, and a photodiode measures the light scattered by suspended particles as they pass through the beam. By analyzing the light signals detected by the photodiode, the instrument uses static assumptions on the particles' refractive index, shape, and density to estimate the mass concentration of PM in the sample flow [62]. Since these particle properties vary depending on the emissions source, atmospheric humidity level, and other factors, optical PM monitors must be regularly calibrated against gravimetric filter measurements and corrected for erroneous sensitivity to environmental fluctuations and other external factors [63–67].

Optical PM monitors are widely used for air quality monitoring because they are relatively inexpensive, portable, and easy to use [53,66,68,69]. While some researchers have used optical instruments for characterizing wood heater emissions, the practice is not widespread and none of the regulatory testing standards mandate their use [44,70]. While most particles emitted by wood combustion are smaller than 300 nm in diameter, optical PM instruments cannot accurately detect these fine particles [55,71–76]. The sensitivity of light-scattering methods diminish sharply below 300 nm, and so optical monitors inherently underestimate PM emissions from combustion sources. Optical measurements may be readily calibrated against gravimetric filter measurements collected concurrently, but this constant calibration limits the utility of optical monitors as a stand-alone method [70,77]. Further research and validation are needed to understand these limitations and determine the frequency of gravimetric calibrations required to enable the responsible adoption of optical PM monitors in this field.

3.4. Direct Measurement of flue exhaust flow rate

Accurate measurements of the exhaust flow rate through the flue are critical for characterizing total mass emissions and thermal performance. Most standards rely on complex mass-balance calculations to estimate the exhaust flow rate with limited accuracy, and would benefit from more reliable and robust direct measurement methods. However, direct exhaust flow rate may be challenging to measure accurately as flue exhaust velocities from residential wood heaters are low (1 to 3 m/s or 200 to 600 ft/min) and exhaust temperatures are high (up to 250ºC) [66,78–80].

Typically, flue flow velocities are measured using an S-type pitot tube, tracer gas injection, or a hot-wire anemometer. S-type pitot tubes are commonly used because they resist fouling in the polluted flue exhaust, but standard models are only rated to measure velocities of at least 2.4 m/s (475 ft/min) at 250ºC. Below this velocity, the differential pressure generated is less than 2.5 Pa (0.01 inches of H_2O) and becomes exceedingly difficult to measure accurately [81].

Tracer gas injection can be used to accurately measure low exhaust velocities, but it is harder to implement. The required concentration of tracer gas for a given analyzer is straightforward to accommodate, as the flow rate of the tracer gas can be adjusted (i.e., if concentrations are below the instrument's limit of detection, increase the injection flow rate). However, the system requires a dedicated flow rate meter, gas detector, cylinders of tracer gas, and any necessary plumbing or sample flow conditioning [17].

Hot-wire anemometers are also capable of accurately measuring low flow velocities, but only a few models can withstand a harsh flue-exhaust environment (e.g., high temperatures and pollutants). They operate by measuring the electrical current required to maintain a heated wire at constant temperature while exposed to a flow of air or exhaust. As the wire increasingly cools through convection at higher flow velocities, higher electrical currents are required to maintain the temperature. The correlation between electrical current and convection provides a method for calculating flow velocity [82]. Only a few commercially available hot-wire anemometers can withstand temperatures greater than 300ºC and have limits of detection below 1 m/s (200 ft/min) [83–85]. These units are also portable and easy to use – the probe is inserted into the duct or flue exhaust flow. While high-temperature anemometers are well suited to measure flue velocities, they are expensive, highly specialized instruments that are only available from a limited number

of manufacturers. Furthermore, the authors have found only one reference of their use for direct emissions sampling applications [86]. Therefore, additional research is needed to verify that these devices perform accurately in polluted exhaust flows, especially since some manufacturers warn that PM may accumulate on the hot wire and affect velocity measurements.

3.5. Harmonized experimental procedures and equipment for field and laboratory testing

Harmonized experimental procedures should be developed to enable field and laboratory testing that is readily comparable and more accurately informs performance during normal operation in residences. While regulatory frameworks do not require field evaluation or management of existing heaters (like a 'smog-check' for residential heaters), complementary datasets from the lab and field would help to develop improved certification methods, mandate better informed emission limits, advance other regulatory mechanisms (e.g., mandatory curtailment periods), and inform design improvements that are demonstrably effective during normal heater operation (rather than during laboratory tests).

Harmonized equipment should include instruments that are user-friendly, accurate, and practical in the field. This system should be portable, provide a direct dilution system that samples directly from the flue (as outlined in Section 3.1), and incorporate robust instruments to simultaneously measure real-time gaseous and particulate emissions concentration. Gravimetric PM should also be included for calibration relative to regulatory standards, but some aspects of the procedures should be simplified or streamlined to enable practical field testing (e.g., pre and post sample conditioning).

The harmonized experimental procedures should include simple, standardized test cycles that are easily repeated and replicated. Wood heater operation is inherently variable due to the nature of the combustion process, fuel properties, and user operation. While pellets and other processed fuels are fairly uniform, testing variability is exacerbated when testing with crib wood or cord wood [87]. Replicate testing should be conducted to determine the heater's performance within prescribed statistical bounds, and the number of replicate tests should be dictated by the desired degree of statistical confidence [88]. For example, a procedure may require that replicate testing be conducted until the 90% confidence interval about the average PM emission factor calculated for all test cycles is $\geq 20\%$ of the average value. For all performance and emissions

metrics, both the test cycle average value and uncertainty should be reported. This testing approach would greatly increase confidence in the experimental results, and reward heaters that consistently perform below the regulated limit.

In order to facilitate replicate testing in the field, standard test cycles should be shorter than current standard laboratory tests. Standard laboratory test may require up to 12 hours to complete (see Table 1), which is not practical for field testing, especially if multiple tests are required. Since test cycles focus on steady-state operation, emission rates and performance should remain constant and may be characterized over a shorter sampling period [78,80,89]. Some studies also suggest longer sampling periods when testing heaters with low emissions to ensure enough gravimetric PM is collected for weighing. However, these concerns can be overcome by adjusting the dilution ratio of the sample and the flow rate through the gravimetric filter or corresponding instruments [87,89]. Test cycle duration may also be reduced by omitting intermediate test phases, as the high and low burn-rates should bound performance [17]. Further research is needed to confirm these assertions.

Although some steady-state phases may be eliminated, the harmonized procedures should include transient operational phases, such as startup, shutdown, or refueling. Previous research shows that approximately one-third of wood heater emissions may be attributed to startup and shutdown [15]. While transient emissions may not merit direct regulation, they provide valuable insights for improving wood heater design and accurately modeling impacts on human health and the environment.

Performance metrics should also be normalized by the useful output of the heater (e.g., thermal power delivered to the user, in unis of kWd). Many air-quality regulation-metrics are normalized by useful output to motivate development of cleaner technologies that also meet user needs. For example, the US EPA's vehicle emission limits are normalized by the number of miles driven, not by the duration of the test drive or the volume of fuel consumed [90]. Similarly, normalizing heater performance metrics by thermal power delivered will help identify heaters that meet regulation requirements while increasing adoption by addressing user needs.

4.0 Conclusion

In this review, we provided a comprehensive overview of national and international wood and pellet heater testing standards, and identified common experimental objectives and regulatory outputs. We also provided recommendations for simplifying and modernizing the test methods to make them more accessible in the lab and field, and encourage technology and policy innovations.

We found that regulations primarily focus on the reduction of PM mass emissions and most regulatory limits are defined in terms of PM emission rate (g per hour). Wood heater testing protocols tend to follow the same basic template: the heater is operated at various power settings, emissions are sampled either directly from the flue or using a dedicated dilution tunnel, and PM mass emissions are measured using a gravimetric filter system. For most standards, a weighted average of PM mass emissions from each power setting is determined and reported for regulatory certification. In order to enhance, simplify, and modernize these existing test methods, we recommend the following:

- **Direct dilution from the flue:** Total capture systems are difficult to build, complex to operate, and require a dedicated facility. Instead of diluting all emissions from the heater, exhaust may be sampled directly from the flue and diluted using a dedicated device. This direct dilution approach is much easier to implement and preserves many of the advantages associated with total capture dilution systems, such as maintaining the atmospheric evolution of PM precursors.

- **Supplement gravimetric PM measurements with time resolved data:** The determination of PM emissions using gravimetric filters serves as the cornerstone of all certification protocols: it is robust, accurate, and straightforward to implement. However, this approach only provides a single time-integrated measurement over the sampling period. To fill this gap, real-time PM instruments should be adopted for heater testing, and several PM measurement technologies are reviewed here for this purpose. While data from these instruments would be valuable, they cannot be expected to replace gravimetric filters entirely without a significant research effort to validate their accuracy.

- **Modernize the equipment and procedures:** Many of the standards recommend using outdated equipment, such as dry gas meters for flow rate measurement. Modern mass flow controllers, digital data loggers, and other modern equipment commonly used in other air quality monitoring fields should be incorporated. Procedures could also be simplified to facilitate testing. For example, the dual inline filters used in some gravimetric systems could be replaced with only a single filter since direct dilution systems promote complete evolution of PM emissions, and filters typically achieve capture efficiencies greater than 99%. These changes would significantly reduce experimental effort with little to no loss of accuracy or data.

- **Measure flow rate through the heater flue directly:** Accurate flue flow-rate measurements are critical for reliably calculating total pollutant emissions and thermal performance. Many standards recommend indirect calculation methods that are prone to error. Instead, flue flow rates may be measured directly using S-type pitot tubes or other devices that can withstand the harsh flue environment.

- **Harmonized testing protocols for the field and laboratory:** Standardized laboratory tests may not be representative of normal heater operation in residences. Therefore, harmonized experimental procedures for laboratory and field testing should be developed to bridge these discrepancies. Test equipment should be user-friendly, accurate, and practical for field use. Test protocols should include the following: simple and short test cycles that are easily repeatable to validate the consistency of performance results; tests that evaluate transient and steady-state operation; and performance metrics normalized by the heater's useful output (e.g., thermal power delivered to heating space). Having complementary datasets from the lab and field would support development of improved certification tests, regulatory emission limits, and heater design.

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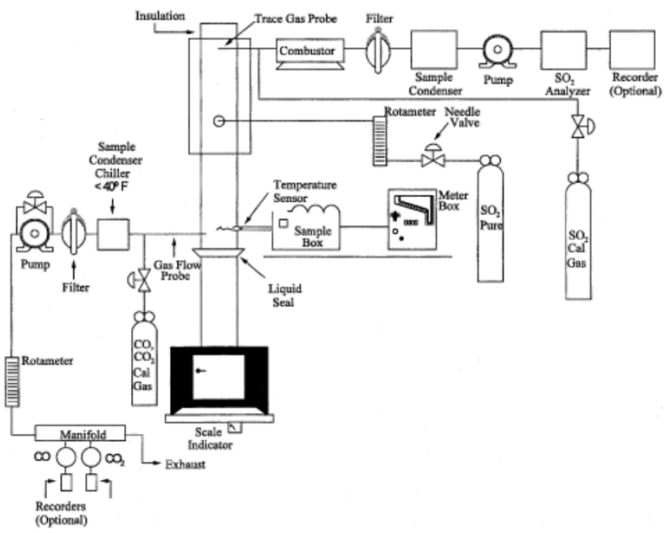

Figure 1. Experimental set-up for EPA Method 5H: Determination of Particulate Matter Emissions from Wood Heaters from a Stack Location [21].

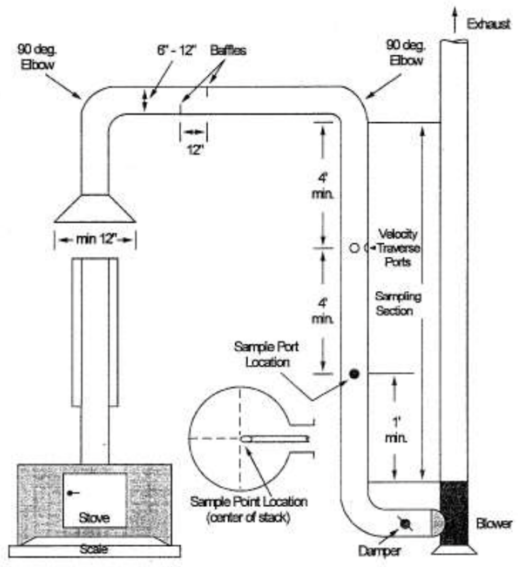

Figure 2. Experimental set-up for EPA Method 5G: Determination of Particulate Matter Emissions from Wood Heaters (Dilution Tunnel Sampling Location) [20].

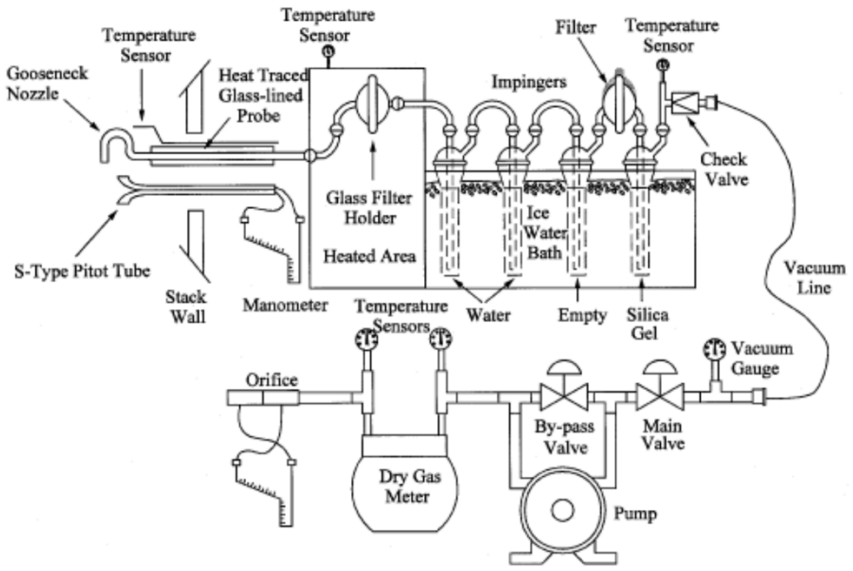

Figure 3. Gravimetric PM sampling set-up for EPA Method 5H [21]. The schematic represents the 'Sample Box' shown in Figure 1.

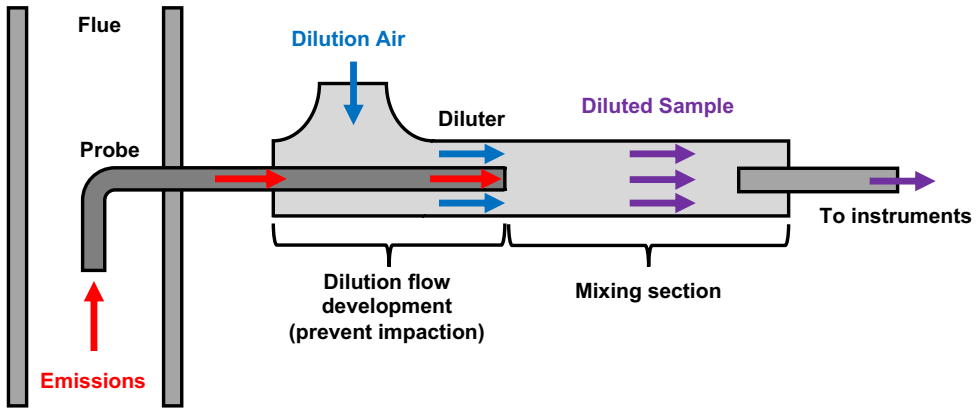

Figure 4. Direct dilution system. Emissions are sampled directly from the heater flue, mixed with clean air in the diluter, and pass to the instruments for analysis.

Figure 5. Flue extension and venturi diluter mounted to the outlet of wood heater chimney [44].

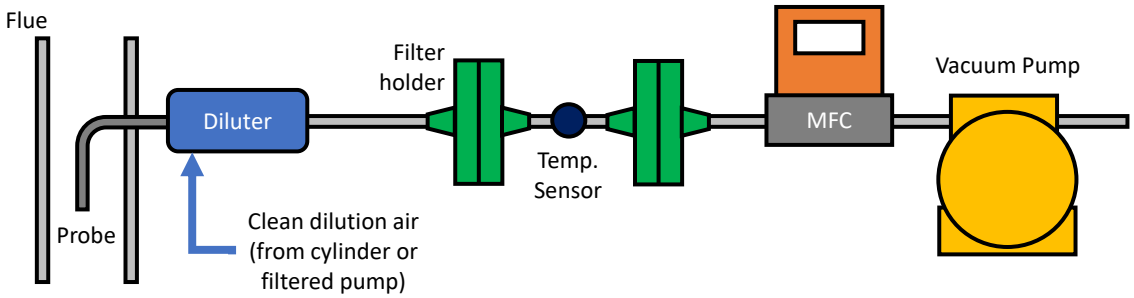

Figure 6. Modernized and simplified gravimetric PM filter system for direct flue sampling.

List of Tables

Table 1. Comparison of wood heater testing standards used worldwide.

Standard Designation (Country of Origin)	Fuel	Emissions Measurement		Thermal Performance: Efficiency Determination	Test cycle				Regulated Performance Metric	Ref.
		Pollutants Monitored	Emissions Sampling Method		Test cycle overview	Number of test-runs	Test-run description/duration	Minimum test cycle duration		
EPA Method 28 (United States)	Pellets/ Firewood	PM (CO and CO_2 optional)	Dilution tunnel (Method 5G) or flue (Method 5H)	None	• 4 burn-rate categories • Specified in Kg/h (Table 2)	≥ 1 per category (≥ 4 per cycle)	• ≥ 1 hour pre-ignition (for firewood, ends when 20-25% of fuel remains) • ≥ 2 hour test-run (for firewood, ends when no fuel remains)	12 hours	g of PM per hour	[14,19–21]
ASTM E2779 (United States)	Pellets	PM (CO and CO_2 optional)	Dilution tunnel (ASTM E2515)	Optional (Indirect)	• 3 burn-rate categories • Specified in Kg/h or % of maximum (Table 3)	≥ 1 per category (≥ 3 per cycle)	• ≥ 1 hour pre-ignition • See Table 3 for test-run durations	9 hours	None	[22,23]
ASTM E2780 (United States)	Firewood	PM (CO and CO_2 optional)	Dilution tunnel (ASTM E2515)	Optional (Indirect)	• 3 burn-rate categories • Specified in Kg/h or % of maximum (Table 4)	≥ 1 per category (≥ 3 per cycle)	• ≥ 1 hour pre-ignition (for firewood, ends when 20-25% of fuel remains) • ≥ 2 hour test-run (for firewood, ends when no fuel remains)	9 hours	None	[24]
CSA B415.1 (Canada)	Pellets/ Firewood	PM, CO, CO_2	Dilution tunnel	Indirect	• 4 burn-rate categories • Specified in Kg/h or % of maximum (Table 5)	≥ 1 per category (≥ 4 per cycle)	• ≥ 1 hour pre-ignition (for firewood, ends when 20-25% of fuel remains) • ≥ 2 hour test-run (for firewood, ends when no fuel remains)	12 hours	g of PM per hour (or g of PM per MJ delivered)	[25]
EN16510-1 (European Union)	Solid fuels	PM, CO, CO_2, O_2, NOx, OGC	Dilution tunnel and/or flue	Indirect	• 3 heat output phases • Manufacturer defines burn-rate	**Firewood:** ≥ 3 per phase (≥ 9 per cycle) **Other:** ≥ 2 per phase (≥ 6 per cycle)	• ≥ 1 hour pre-ignition • ≥ 1 hour per test-run (see Table 7)	**Firewood:** 12 hours **Other:** 9 hours	PM, CO, NOx, and OGC concentrations and efficiency	[26,27]
GB/T 16157-1996 (China)	N/A	PM, CO, CO_2, O_2	Flue	Not applicable: Stack emission measurement standard						[28]
ISO DIS13336* (International)	Solid fuels	PM, CO	Dilution tunnel	Direct	• 3 burn-rate categories	≥ 3 per category (≥ 9 per cycle)	Not specified		None	[16]
AS/NZS4012* (Australia/NZ)	Solid fuels	PM	Dilution tunnel	Direct	• 3 burn-rate categories	≥ 3 per category (≥ 9 per cycle)			g of PM per Kg of fuel	[16]
PD 6434* (United Kingdom)	Solid fuels	PM	Electrostatic precipitator on flue	Not specified	• 3 burn-rate categories	≥ 5 per category (≥ 3 per cycle)			g of PM per hour	[16]
NS3058/NS3059* (Norway)	Firewood	PM	Dilution tunnel	Not specified	• 4 burn-rate categories	≥ 1 per category (≥ 4 per cycle)			g of PM per Kg of fuel	[16]

*These standards were not reviewed directly. Standard summaries are cited from [16].
Note: Firewood comprises both test crib wood and cord wood

Table 2. EPA Method 28 fuel burn-rate categories for room heater testing [19]. At least one test-run is conducted in each category to complete this test cycle.

	Category 1	**Category 2**	**Category 3**	**Category 4**
Burn-rate (kg/h)	< 0.80	0.80 to 1.25	1.26 to 1.90	Maximum
Minimum Number of Test-runs	1	1	1	1