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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, standardized laboratory test methods have been developed to characterize and limit wood heater emissions. While these test methods are a key tool for advancing both wood heater technology and environmental regulations, many of the experimental procedures are outdated and provide few actionable insights for improving heater performance. Furthermore, these test methods vary widely around the world and may not adequately capture the performance of wood heaters operating in residences. This study presents a comprehensive review of standardized wood heater test methods to identify fundamental experimental objectives and regulated performance metrics. Using the results of this review, recommendations are provided to make the test methods more accessible and representative of residential performance, while generating actionable data to motivate heater design improvements. This study elucidates the current state of standard test methods, and the developments needed to advance clean wood heater technologies and public policies.

1. Introduction

Relative to the energy they deliver, residential wood heaters are a large source of particulate matter (PM) pollution [1–3]. While only 9% of homes in the United States (US) used wood heaters in 2020, they contributed about 7% of the nation's total annual $PM_{2.5}$ emissions [4,5]. 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 [6]. Given their outsized influence on ambient air quality, many countries have implemented 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 [7–10]. Despite these efforts, residential wood heaters continue to be major drivers of poor air quality in many regions [1,2,5,6].

To mitigate air quality impacts, wood heaters in the US and Europe are required to pass standardized certification tests that demonstrate compliance with regulatory limits. While these tests enable performance comparisons of wood heaters in controlled laboratory environments, they are too cumbersome to perform outside of the laboratory and do not accurately represent in-home performance [11–15]. For instance, many of the test methods neglect to incorporate the impact of startup, reloading, shutdown, user behavior, fuel-wood conditions, and flue draft (i.e., chimney design) on wood heater performance [11,13–15].

This study reviews standard test methods for certification of residential heaters fueled by firewood and wood pellets. This review focuses solely on room heaters that deliver heat directly into the space where they operate. Test methods for central heaters (e.g., boilers, hydronic heaters, and furnaces) will be discussed in a future study. Masonry heaters and fireplaces are not considered in this study because they are not consistently regulated in the US or globally.

For each test method, this study identifies common experimental objectives and regulatory outputs required for characterizing wood heater pollution emissions and thermal performance. The major functional components of each method are categorized and their relative strengths and weaknesses are discussed. This comprehensive review uniquely examines the entire heater test from initial measurements in

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List of abbreviations

ASTM	American Society for Testing and Materials
BAM	Beta attenuation monitors
BSI	British Standards Institution
CSA	Canadian Standards Association
DR	Dilution ratio
EPA	Environmental Protection Agency
FEM	Federal Equivalent Method
IEA	International Energy Agency
ISO	International Standards Organization
MFC	Mass flow controller
NESCAUM	Northeast States for Coordinated Air Use Management
NO_X	Nitrogen oxides
NS	Norwegian Standards
OGC	Organic gaseous compound
PM	Particulate Matter
$\dot{m}_{\text{instruments}}$	Mass flowrate of diluted sample to the instruments
$\dot{m}_{\text{dilution}}$	Mass flowrate of clean dilution air
$\dot{m}_{\text{probe}}$	Mass flowrate of exhaust sampled through the probe
SM	Supplemental material
TEOM	Tapered element oscillating microbalance
US	United States

the laboratory to final reporting of regulated performance metrics. Using this review, recommendations are provided for enhancing, simplifying, and modernizing the test methods. The recommendations focus on making test methods more accessible for in-home assessments (i.e., field or *in-situ* testing) 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 wood heater testing methods that empower air pollution mitigation efforts worldwide.

2. Key components of standardized wood heater test methods

To identify core experimental objectives and generate recommendations for improving the performance characterization of wood heaters, this study reviews standardized wood heater performance and emissions test methods from around the world. The review focuses on standard test methods used to certify wood heater performance relative to regulatory limits. Table 1 lists the reviewed test methods and their major aspects: the country of origin; the type of fuel used during testing; the pollutant emissions monitored during testing; the experimental method for capturing and measuring pollutant emissions from the heater; the method for characterizing overall efficiency; the test cycle structure; and the regulated performance metric(s). A burn cycle is the process of loading a batch of test fuel (or fuel charge) and burning it until the termination of the burn cycle, as defined by the test method. A test cycle is required for certification and consists of several burn cycles, generally conducted at different burn rates. For example, a test cycle can include six burn cycles at three burn rates, such that two replicate burn cycles are conducted at each burn rate. To characterize thermal performance, heat output and overall efficiency are usually reported. Overall efficiency is defined as the ratio of the thermal energy delivered to the room to the total energy content of the fuel consumed [16,17].

Although several countries have published test methods for evaluating wood heaters, not all require regulatory certification. For example, Canada does not require regulatory certification of wood heaters at the national level but has published test methods in CSA B45.1:22 as guidance for provincial regulations [17]. Similarly, Australia and New Zealand published AS/NZS 5078:2007 and AS/NZS 4886:2007 for evaluating pellet heaters, but only consistently regulate cordwood (unprocessed firewood) heaters using test methods AS/NZS 4012-2014 and AS/NZS 4013-2014 [18–21]. Chinese standard GB/T 16157-1996 outlines experimental methods for measuring emissions from stationary exhaust stacks in general, and because wood heaters are not regulated, no information is provided on the fuel requirements, test cycle, overall efficiency determination, and other aspects of testing that are specific to wood heaters [22]. These standards are not reviewed in the main body of this study and instead are described in the Supplemental Materials (SM).

Below is a brief summary of the standardized test methods listed in Table 1 for the regulatory certification of wood heaters. Additional details are provided in the SM.

1. Environmental Protection Agency (EPA) Method 28R is one of three test methods approved in the US for certifying wood heaters [23]. The test method uses crib wood – a specified grade of dimensional lumber nailed together in a strictly-defined arrangement. Method 28R incorporates ASTM Method 2515-11 for measuring PM emissions using a dilution tunnel and CSA B415.1–10 for characterizing thermal performance [16,24]. At least one burn cycle is required at each of the four burn rates defined in the method. Heat output and overall efficiency must be quantified and reported, but are not regulated.
2. American Society for Testing and Materials (ASTM) E2779-10 is a US EPA approved test method for certifying pellet heaters and uses the same emissions sampling and thermal performance characterization methods as Method 28R [23,25]. At least one burn cycle is required for each of the three burn rates: maximum, medium, and minimum. Like Method 28R, heat output and overall efficiency must be quantified and reported, but are not regulated.
3. EPA ALT-140 is a US EPA approved alternative test method for certifying wood heaters using cordwood [26]. This “alternative method” was approved by EPA’s Office of Air Quality Planning and Standards, as allowed under US regulations. EPA ALT-140 uses the same emissions sampling method as Method 28R but provides different procedures for determining thermal performance [23,24]. The test cycle attempts to represent residential operating conditions and requires three burn cycles at each of the four burn rates: start-up, high-fire, maintenance-fire, and a low-burn. For example, the high-fire burn rate is intended to replicate operational periods when homeowners quickly heat an area after starting or restarting the appliance. EPA ALT-140 is the only approved US certification test method that measures and reports emissions from startup, and includes time-resolved PM emission measurements.
4. EN 16510–1:2022 is an approved method from the European Union for certifying residential solid fuel burning appliances, including wood heaters (cookers, inset appliances, and other appliances are also included) [27].The test method characterizes heat output, overall efficiency, CO emissions, oxides of nitrogen (NO_X), organic gaseous compounds (OGCs), and PM emissions. Emissions are measured directly from the flue, so no dilution tunnel is required. For cordwood, three replicate burn cycles are required at three burn rates defined in terms of heat output: nominal heat output rate (>95% of manufacturer’s rating); partial load (determined by appliance’s maximum heat output); and slow combustion. For pellets, two replicate burn cycles are required at each burn rate.
5. AS/NZS 4012-2014 and AS/NZS 4013-2014 are used for certifying cordwood and coal heaters in Australia and New Zealand [20,21]. AS/NZS 4012-2014 is used for evaluating power output and efficiency of cordwood heaters while AS/NZS 4013-2014 is used for sampling emissions. Similar to the US EPA methods, PM emissions are sampled using a dilution tunnel, and three replicate burn cycles are required at three burn rates: high, medium, and low. This is the

Table 1
Comparison of standardized wood heater test methods used for certification.

Standard Designation (Country of Origin)	Fuel	Emissions Measurement		Overall Efficiency Determination[a]	Test cycle				Regulated Performance Metric	Ref.
		Pollutants Monitored	Emissions Sampling Method		Pretest	Burn Rates	# of required Burn Cycles per Burn Rate	Burn Cycle End Criteria		
EPA Method 28R (United States)	Crib wood per ASTM E2780-10 with exceptions	PM per ASTM E2515-11 with modifications CO per CSA B415.1–10	Dilution tunnel per ASTM E2515-11	Indirect per CSA B415.1–10	Establish bed of embers within prescribed fuel weight limit; operate ≥1 h with controls set to first burn rate test	1. Maximum: Fully open controls 2. 1.25–1.90 kg/h 3. 0.8–1.25 kg/h 4. < 0.8 kg/h	1	≥2 h operation & remaining weight of test fuel is 0.00 kg (0.0 lbs) or less for 30 s	g of PM per h	[23]
ASTM E2779-10 (United States)	Pellets	PM per ASTM E2515-11 with modifications	Dilution Tunnel per ASTM E2515-11	Indirect per CSA B415.1–10	≥1 h operation at max burn rate	1. Max achievable 2. ≤ 50% of max 3. Minimum achievable	1	1. Max: 60 min 2. Med: 120 min 3. Min: 180 min	g of PM per h	[25]
EPA ALT-140 (United States)	Cordwood	PM per ASTM E2515-11 CO, CO_2	Dilution Tunnel per ASTM E2515-11	Indirect	None stated	1. Start-up 2. High 3. Maintenance 4. Low	3	1. Specified by fuel load calculator 2. 90% test fuel burned 3. 90% test fuel burned 4. 90% test fuel burned	g of PM per h	[26]
EN 16510–1:2022 (European Union)	All solid fuels	PM, CO, CO_2, O_2, NO_x, OGC	Flue	Indirect	≥1 h at a burn rate of nominal output or 33 ± 5% for wood logs and 25 ± 5% for peat, lignite or briquettes during slow combustion and recovery tests	1. Nominal (≥95% of rated value) 2. Partial load that is a function of nominal 3. Slow combustion (specified by manufacturer)	3 for wood-based fuels 2 for all other fuels	Cordwood – test fuel is exhausted or CO_2 criteria met Pellets - minimum cycle duration	PM, CO, NO_x, and OGC in mg/m^3 and efficiency[b]	[27]
AS/NZS 4012-2014 & AS/NZS 4013-2014 (Australia/New Zealand)	Cordwood & Coal	PM (CO Optional)	Dilution Tunnel per AS/NZS4013	Direct	Operate at mean average power to establish bed of embers within prescribed fuel weight limit	1. High: Fully open 2. Low: Minimum setting 3. Medium: midpoint of high and low burn time or set using controls	3	±0.5% of test fuel remains	g of PM per kg of fuel burned and efficiency	[20, 21]
PD 6434:1969 & BS 3841–2:1994 (United Kingdom)	Solid fuels	PM CO, CO_2, O_2, VOC, and OGC recommended using EN or ISO standards	Dilution Tunnel or electro-static precipitator per BS 3841–2:1994	Only heat output required per Domestic Solid Fuel Appliances Approved Council	Operate heater to achieve steady-state conditions. Ignition emissions are ignored.	1. Rated output 2. Minimum output 3. Intermediate output if available	5	Sufficient to establish the effects, on smoke emission, of accumulations of soot, shale or ash within the appliance if these can occur.	g of PM per h	[28, 29]
NS 3058–1:1994 & NS 3058–2:1994 (Norway)	Crib wood	PM	Dilution Tunnel per NS3058–2:1994	None specified	≥1 h operation at first burn rate settings. weight of charcoal bed must be 20–25% of first burn rate fuel charge	Four burn rate categories that depend on heater grade	1	Scale indicates burn cycle fuel is completely consumed	g of PM per h	[31, 32]

[a] Defined as the ratio of the total energy content of the fuel consumed minus energy losses through the appliance vent to the total energy content of the fuel consumed [16].

[b] Efficiency is not required to be reported during slow combustion except for appliances that are intended for open and closed door operation.

only test method reviewed in this study that measures overall efficiency directly using a calorimeter room.

6. PD 6434:1969 and BS 3841–2:1994 are methods used in the United Kingdom for certifying appliances as "exempt" from removal in smoke control areas [28–30]. Otherwise, all new heaters must meet EN16510–1:2022 described earlier [27]. PD 6434:196 provides test cycles and reporting requirements, while BS 3841–2:1994 provides emission measurement methods. PD 6434:196 requires five replicate burn cycles at three burn rates: rated output (maximum), minimum and intermediate (if available). The method also requires reporting of PM mass emissions measurements, using BS 3841–2:1994, and heat output. BS 3841–2:1994 outlines two methods for measuring PM mass emission rates: stack sampling using an electrostatic precipitator (ESP) and dilution tunnel sampling using gravimetric filters.
7. NS 3058–1:1994 and NS 3058–2:1994 are approved methods for certifying wood heaters in Norway [31,32]. NS 3058–1:1994 describes the test facility and test cycle while NS 3058–2:1994 describes the PM emissions sampling protocol. Similar to other test methods, PM emissions are sampled using a dilution tunnel and follow the same general procedures as EPA Method 28R [23]. The method requires one burn cycle at four burn rates using crib wood. The burn rate requirements vary depending on the heater's rated power output. This method only reports PM emission rates (grams per hour) and thermal performance is not evaluated.

After reviewing these standardized test methods, 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 subsections, this review discusses common approaches for each of these key components, identifies fundamental differences and similarities, and evaluates their relative advantages and disadvantages.

2.1. Fuel specifications

All test methods presented in Table 1 specify the type of fuel for testing heaters, and most provide separate procedures for evaluating heaters burning crib wood, cordwood, and pellets. Crib wood is a specified grade or type of dimensional lumber (e.g., Douglas fir). Test cribs are created by cutting crib wood into pieces of uniform length, and then nailing them together into a prescribed geometric arrangement. The crib wood's length and geometric arrangement are defined as a function of the firebox dimensions. Since the size, shape, and chemical properties of cordwood vary significantly, these standardized test cribs are intended to improve repeatability of test results. However, crib wood may not be representative of heater operation and performance in the field, where cordwood is typically used [33].

For cordwood and crib wood, test methods specify the number of pieces that must be loaded into the firebox, the cross-sectional area, the mass of each piece, the wood species, and other factors often as a function of firebox volume [20,23,26–28,31]. For example, EN 16510–1:2022 specifies the cordwood fuel load based on the calorific value of the fuel, nominal heat output, minimum efficiency, and minimum refueling interval [27]. EN 16510–1:2022 also requires cordwood to be free of decay and all loose bark be removed. In the US, the total fuel mass loaded into the heater for each burn cycle is defined as the product of the useable firebox volume (measured on the test unit) and fuel charge density (specified in the test method) [23,26]. For example, EPA Method 28R specifies a fuel crib wood loading density of 112 ± 11.2 kg/m^3 (7 ± 0.7 lbs/ft^3) of useable firebox volume on a wet basis [23]. A heater with a 0.04 m^3 firebox would be fueled with 4.5 ± 0.4 kg (9.9 ± 0.9 lbs) of crib wood for each test cycle. EPA ALT 140 provides a calculator to aid with computing cordwood fuel charge based on firebox volume [26]. Even though these specifications provide some standardization when testing, wood fuels remain inherently variable [14].

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 [25,27]. Some methods specify the grade or type of pellet fuel that must be used during testing. For example, ASTM E2779-10 requires using the grade of pellets recommended by the manufacturer. If more than one grade is listed, then the fuel with the lowest grade is used [34].

Most test methods listed in Table 1 require measurement of fuel properties to ensure the fuel meets specifications [20,23,25–27,31]. 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 or higher heating values are also required for calculating the overall efficiency of the heater. Most methods provide representative chemical composition and heating values for common wood fuels (e.g., Douglas fir or red oak for the US and beech, birch, or spruce for Europe) [16,20,27]. These representative values are used to estimate the heater's thermal performance. Fuel properties can also be measured directly using a laboratory testing service that follows recommended procedures or standards [16,20,23,27].

2.2. Emissions sampling and measurements

All test methods provide experimental procedures for quantifying and reporting the amount of pollutant emissions generated by the wood heater during testing, such as PM or CO. Emission metrics are calculated using procedures specified in each test method. An overview of emission sampling methods is provided in the following subsections. Additional details, including a sampling system schematic, for several of the test methods can be found in Vicente and Alves [3].

2.2.1. Flue and dilution tunnel sampling

Emissions generated by the heater may be sampled directly from the flue or using a dilution tunnel, as shown in Table 1. For direct flue measurements, sampling probes are inserted into the flue or stack of the heater at specified positions. These probes collect emissions samples for one or more instruments to analyze. 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 relatively straightforward to set up, the extremely hot, highly polluted, and water saturated flue exhaust damages most emission instruments. Therefore, flow conditioning equipment, such as a condenser or filter system, are used to protect the instruments by drying, cooling, and/or diluting the exhaust sample, as illustrated in Method EN16510–1:2022 [27].

A dilution tunnel is a dedicated ducting system that captures all exhaust emitted from the flue and dilutes it with ambient air for analysis. Fig. 1 shows a schematic of a dilution tunnel that is representative of those used in many methods. 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 a sampling section. In the sampling section, a pitot tube measures flow velocity, thermocouples measure temperature of the air-exhaust mixture, and sampling probes draw the diluted emissions to the instruments. The sampling section must be long and straight to ensure that the flow profile in the duct is well-developed and pollutants are well-mixed and uniform. Downstream of the sampling section, exhaust passes through a damper, blower, and chimney before being discharged into the atmosphere.

Dilution tunnels are often constructed and operated at dedicated testing facilities because they are large and complex. A dilution tunnel provides cool, dry, and relatively clean air that enables sampling

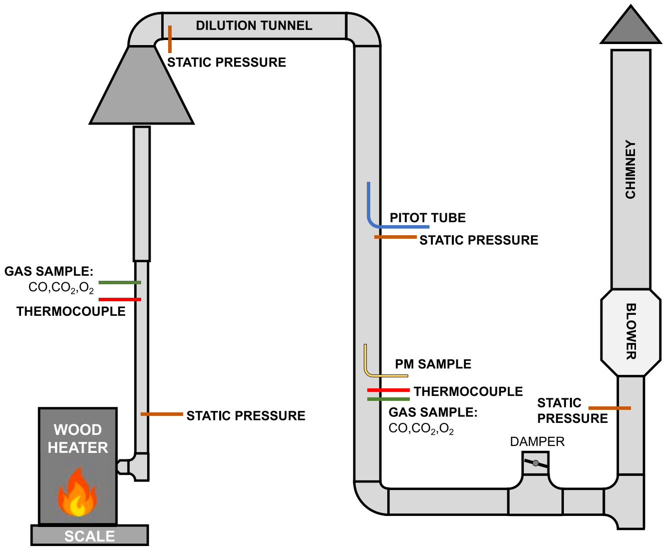

Fig. 1. Schematic of a dilution tunnel used in many standardized laboratory wood heater test methods.

without additional conditioning equipment to most instruments. As such, dilution tunnels simplify the emissions sampling process, which is important when integrating several different instruments together to monitor a variety of pollutants simultaneously. Unlike direct flue measurements, a dilution tunnel mixes the exhaust with ambient air, allowing pollutants to evolve much as they would when discharged into atmosphere. For example, the dilution tunnel allows for secondary PM formation mechanisms to occur much as they would when released into the atmosphere [33,35].

2.2.2. PM emissions

All test methods in Table 1 require measurements of the total PM mass emitted during the test cycle using gravimetric analysis [21,23,25–27,29,32]. Gravimetric analysis measures total PM mass by drawing exhaust at a specified flow rate through a fibrous filter that collects PM. The exhaust is sampled from the flue or dilution tunnel using a vacuum pump. The standards specify sampling conditions for gravimetric analysis. For example, BS 3841–2:1994 requires isokinetic sampling (the velocity in the sample probe is equal to the velocity in the dilution tunnel) while EN16510–1:2022 and AS/NZS 4013-2014 requires the flow rate through the filter remain constant throughout sampling [21,27,29]. The remaining test methods require periodic monitoring and adjustment of the filter flow rate so it remains constantly proportional to the flue or dilution tunnel flow rate throughout sampling [23,25,26,32]. 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 comparing the mass of the filter before and after the test. The total volume of exhaust sampled through the filter is determined directly using a dry gas meter or by integrating flow rate measurements collected at regular time intervals. With these data, the average PM mass concentration is calculated.

Unlike other pollutant measurement techniques, gravimetric PM filters can sample exhaust directly from the flue using heat and moisture resistant materials, such as quartz or glass fibers. However, these direct flue measurements may not accurately represent heater PM emissions released into the atmosphere. Under normal operation, semi volatile and low volatility 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 [27,36–38].

EN16510–1:2022 is the only method in Table 1 that requires gravimetric sampling directly from the flue. In this method, the gravimetric sample lines, filter, and filter holder are maintained at 180 °C (356 °F) to prevent moisture condensation and associated particle loss [27,39]. OGCs that condense into PM at ambient temperatures are measured after the heated filter using a flame ionization detector operating at 180 °C (356 °F). Since all emissions are sampled hot, the PM mass collected on the filter is lower than it would be when sampled at ambient temperatures, and the OGC measurements only provide an indirect indication of the condensable PM mass that was not collected on the filter [39].

Gravimetric PM filters collected from a dilution tunnel better represent emissions exhausted to the atmosphere because the exhaust is mixed thoroughly with ambient air prior to sampling, thereby allowing condensable PM species to be collected [33,35]. In general, gravimetric filters are a straightforward, accurate, and time-tested method for gathering a single, time-integrated measurement of the PM mass emitted during the sampling period.

While collecting PM emissions on the filter 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 h 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 (both before and after sampling), it is often a bottleneck when testing heaters.

Each filter yields a single time-integrated PM mass measurement over the sampling period (e.g., 1 h or a burn cycle), which does not provide enough information to characterize transient variations in PM emissions during the sampling period (e.g., startup). This lack of information makes it difficult to pinpoint operating variables that result in elevated PM emissions, or to inform potential heater design improvements using gravimetric measurements alone. EPA ALT-140 recommends using a tapered element oscillating microbalance (TEOM) to collect time-resolved PM mass concentration data throughout the test cycle [26]. Additional details about the TEOM and its operation are discussed in Section 3.3.

As an alternative to the gravimetric filter method, BS 3841–2:1994 also allows using an electrostatic precipitator mounted on the heater's chimney [29]. This method is functionally identical to the gravimetric filter method, differing only in the apparatus used to capture PM for weighing on a balance. Data comparing the methods is also provided, and demonstrates good agreement [29].

2.2.3. Gaseous emissions

Most test methods in Table 1 require time-resolved measurements of CO and CO$_2$ concentrations in the flue to calculate overall efficiency, as discussed in Section 2.3 [23,25–27]. EN 16510–1:2022 requires time-resolved measurements of CO, CO$_2$, O$_2$, NO$_X$, and OGC concentrations in the flue. Average concentrations of CO, NO$_X$, and OGC in the flue for each burn rate are reported and must be below regulatory limits defined in the standard [27]. Test methods that require gaseous pollutant measurements provide experimental procedures for flue sampling with time-resolved analyzers [23,25–27].

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

Except for EN16510:2022, all the test methods reviewed in Table 1 use time-resolved measurements of flow rate through the dilution tunnel to calculate the total mass of pollutants emitted during a test cycle. The test methods typically require a pitot tube to measure velocity in the dilution tunnel's sampling section, as illustrated in Fig. 1 [23,25,26,29,32]. The test methods specify minimum duct flow velocities to ensure accurate data collection within the operational limits of the pitot tube. Since the heater exhaust is highly diluted with ambient air, pollutant concentrations are low and fouling of the pitot tube's pressure port can be readily mitigated. Other flow measurement devices such as orifice plates, hot-wire anemometers, and integrating grids may also be used to measure flow rate in the dilution tunnel [16,24]. Unlike the other methods, EN16510:2022 does not calculate the total pollutant mass emitted (see Section 2.5), and therefore does not require flow rate measurements to report heaters' emissions performance [27].

Most of the test methods in Table 1 also require measurements of the exhaust flow rate through the flue to characterize thermal performance (see Section 2.3) [21,23,25,26,32]. However, exhaust flow rate is difficult to measure directly using a pitot tube or other device because flow velocities are very low, and the exhaust is extremely hot and polluted. Instead, the test methods indirectly calculate exhaust flow rate using a mass balance equation that approximates the heater's wood combustion process [21,23,25,26,32]. The mass balance equation relies on measurements of the fuel mass burned, the chemical composition of the fuel, and concentrations of CO and CO_2 in the flue. Assumptions about the fuel composition and the combustion process are provided, but may introduce errors to the flue flow rate calculation. For example, fuel is assumed to fully combust and leave a fixed amount of ash (typically assumed to be 0.5% of the initial fuel mass). Additionally, the mass balance equation assumes that the fuel is only converted into CO, CO_2, CH_4, and water, ignoring all other emissions [40]. While these types of assumptions may decrease the accuracy of the exhaust flow rate calculation, the mass balance equation circumvents the challenges of direct flow rate measurements in the flue.

2.3. Thermal performance characterization

While all test methods focus on characterizing pollutant emissions (particularly PM) from wood heaters, some also require measuring thermal performance, such as overall efficiency and heat output [20,23,25–28]. Heat output can be measured directly using a calorimeter room or calculated indirectly using measurements of fuel consumption, exhaust temperature, and flue flow rate. A calorimeter room is a well-sealed enclosure that surrounds the heater with a controlled volume of air [20]. 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. A calorimeter room can also quantify both radiant and convective heat output from the appliance, providing a more comprehensive understanding of heater performance and overall efficiency [41]. AS/NZS 4012-2014 is the only test method in Table 1 that requires a calorimeter room for determining overall efficiency [20].

Most test methods require the indirect calculation of thermal performance using measurements of fuel mass consumption, and exhaust flow-rate, temperature, and gaseous pollutant concentrations [23,25–27]. The exhaust flow rate is approximated using a mass balance equation (see Section 2.2). Using these data, the chemical and latent energy losses through the flue are calculated at regular time intervals throughout the test cycle. If a dilution tunnel is used, additional equipment is required to measure temperature and gaseous pollutant concentrations in the flue (at least CO and CO_2). The heat output is then calculated as the difference between the energy released by the combusted fuel (taken as the product of fuel mass consumed and either the lower heating value or the higher heating value depending on the accounting of sensible heat) and the estimated energy lost through the flue [16,26,27]. This same energy balance is also used to determine overall efficiency.

Previous research shows good agreement between indirect methods and the calorimeter room when determining overall efficiency [42,43]. For example, one study found that the overall efficiency differed by an average of 2.0% across 26 tests, while another study found an average difference of less than 1% across four tests. Given this high level of agreement, it is likely that most test methods use indirect methods of thermal performance evaluation simply because calorimeter rooms are complex and expensive [44].

2.4. Test cycles

For all test methods, Table 1 shows that a test cycle includes three or four burn cycles conducted at varying fuel burn-rates or fuel loading conditions. Most test methods specify the burn-rate for each burn cycle absolutely (e.g., kilograms of fuel per hour) or relative to the maximum burn-rate that the heater can achieve. For example, EPA Method 28R and NS3058–1:1994 define burn rates absolutely, while ASTM E2779-10, PD 6434:1969, and AS/NZ 4012-2014 define burn rates as a function of the maximum heater output [20,23,25,28,31]. Alternatively, EN 16510–1:2022 defines a heat output setting for each burn cycle relative to the nominal value specified by the manufacturer, and EPA ALT-140 defines the mass of the fuel load for each burn cycle [26,27].

Each test method also defines the minimum number of replicate burn cycles that must be conducted at each burn-rate in order to complete a certification test. For example, AS/NZS 4012-2014 requires a minimum of three replicate burn cycles at the three different burn-rates (9 burn cycles in total) [20]. EPA ALT-140 also requires three replicate burn cycles for each burn rate, while PD 6424:1969 requires five replicate burn cycles and EPA Method 28R, ASTM E2779-10, and NS3058-1:1994 only requires one burn cycle for each burn rate [23,25,26,28,31].

The definition for the end of each burn cycle varies between test methods and heater types. Pellet heater test methods define an operating period for each burn cycle (e.g., 60 min at high burn-rate) since pellet heaters are typically designed to run for 12 h or more before refilling the fuel hopper [25,27]. Most crib wood and cordwood test methods define a fuel mass, percentage of fuel load consumed, or CO_2 concentration in the flue to define the end of the burn cycle [20,23,26,27,31]. Ending the burn cycle based on fuel mass requires a dedicated platform scale under the heater. This dedicated scale is largely redundant because the test methods only require a single measurement of the total fuel mass combusted during the burn cycle for performance evaluation, which is usually measured separately prior to loading the fuel 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 test methods that require gaseous pollutant monitoring in the flue, no additional equipment is needed to end the burn cycle based on CO_2 concentration in the exhaust.

Most test methods require a 'pre-ignition' burn cycle prior to conducting the first burn-cycle at a defined operating condition (e.g., burn rate, primary air setting, etc.) [20,23,26–28,31]. The pre-ignition period lasts at least an hour, until a bed of embers is established to ignite the first burn rate test or the heater reaches steady-state operating temperatures. This ensures that performance is evaluated at thermal equilibrium (the heater is neither heating up from ambient conditions nor cooling down), regardless of the heater's size or mass. EPA ALT-140 is the only method that does not require a pre-ignition period and includes heater ignition in the high-fire burn cycle [26].

The fundamental purpose of the test cycle is to provide uniform operating conditions for repeatably evaluating and comparing heater performance. While this is useful for establishing compliance to regulations, the emissions and performance results may not be representative of residential operation [11–15,45,46]. For example, many test methods do not account for start-up, cool-down, fuel loading, and other transient periods that occur during normal operation. In response to these shortcomings, European researchers 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 certification 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 [47]. 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 [48]. 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 standardized test methods. The Northeast States for Coordinated Air Use Management (NESCAUM) built upon the principals of the beReal method to create EPA ALT-140, which aims to reflect the operational practices typical of homes in the US [45,46,49,50].

While the beReal test cycle makes a well-informed estimation of residential operation in Europe, 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 [48]. However, this same decision also dismisses nearly half of respondents who primarily operate their heater at the highest or lowest setting. Similarly, procedures for EPA ALT-140 are based on temperature data collected from 20 US homes over one or two heating seasons. This study indicated that temperature profiles of the external wall of the stack were highly irregular, and they were not able to accurately capture fuel reloading events [45]. Given the diversity of user behavior, laboratory test cycles must balance between accurately representing residential operation and providing replicable experimental procedures for consistently characterizing heater performance.

2.5. *Regulated heater emissions and performance metrics*

All the test methods in Table 1 require that PM mass emissions be reported in units that match the country's regulatory emission limits. For example, the US EPA's test methods report PM in grams per hour, matching units for the 2020 emission limits summarized in Table 2 [51]. Similarly, EN 16510–1:2022 reports PM emissions in terms of average mass concentration in the flue (mg/m^3 calculated to 13% O_2 content, dry), in order to match European regulations [27,52].

Some test methods also include regulations for thermal performance and gaseous pollutant emissions, while others only provide reporting requirements [20,21,23,25–27]. For example, a recent European Union regulation (Commission Regulation (EU) 2015/1185 May 24, 2015) is being applied in countries across Europe to limit the emission of all gaseous pollutants (CO, OGC, and NO_X) reported by EN 16510–1:2022 [27,53]. This regulation also requires wood heaters to meet a minimum overall efficiency. On the other hand, the US EPA's 2015 New Source Performance Standards requires reporting of CO mass emission rate (in grams per hour) but it does not currently regulate CO emissions [54].

While regulating PM and gaseous emissions may help improve air quality, it may not be the most effective method for motivating the development and adoption of cleaner, more efficient wood heaters [7,10,14,55]. For example, mandating minimum thermal performance requirements may help incentivize users to invest in newly compliant units to benefit from the fuel savings, thereby accelerating the replacement of outdated heaters [33,56]. Similarly, tax credits or grants that incentivize the purchase of cleaner and more efficient heating appliances, such as heat pumps, also support the replacement of outdated wood heaters [57]. Unfortunately, scientific research in this area is sparse. New heaters must meet increasingly stringent PM emission requirements as regulatory limits get updated, and assessing whether these PM reductions enhance other aspects of performance desirable to users (e.g., overall efficiency, energy security, social and emotional needs) is difficult because the relevant metrics are either not reported or are derived inconsistently between test methods [33,55].

Table 2
United States Environmental Protection Agency (US EPA) emissions limits for new woodstoves and pellet stoves [51].

	PM Limit
Step 1: For all stoves without current US EPA certification	• 4.5 g/h of operation for catalytic and noncatalytic heater. • Limit is for crib testing. If tested with cordwood, emissions test method must be approved, and stoves must meet crib wood limit.
Step 2: All woodstoves and pellet stoves	• 2.0 g/h for catalytic and noncatalytic heater, if emissions are tested using cribs • Alternative limit: 2.5 g/h, if tested with cordwood; method must be approved

3. Recommendations for improving 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 innovations. Using these insights, the following are recommended: 1) using direct dilution of the heater flue sample to more easily enable representative sampling of emissions; 2) modernizing gravimetric emissions sampling equipment to obtain PM emission results more easily and accurately; 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; 5) harmonizing experimental procedures and equipment for field and laboratory testing; and 6) reporting pollutant mass emissions normalized by thermal power, in addition to existing metrics.

3.1. *Direct dilution of the heater flue sample*

Direct dilution of the flue exhaust combines the benefits of full-capture dilution tunnel and direct flue sampling by enabling portable measurements of emissions under conditions that simulate stack exhaust 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 Fig. 2). 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. In the development section, the flow of clean dilution air is aligned with the flue emissions inlet to prevent the impaction of particles onto the diluter walls. The fully-mixed, diluted flow then passes to the instrumentation suite for analysis.

It should be noted that the exhaust sample could be diluted with ambient air, similarly to the dilution tunnel method. However, this is experimentally burdensome because ambient PM concentrations must also be monitored to account for their contribution to the heater's emissions measurement. Additionally, variations in ambient pollutant concentrations (both gaseous and particulate) may introduce uncertainty in the results. For example, heater emissions may be higher on a more polluted day due to increased secondary PM formation, and could misrepresent the heater's underlying performance. As such, direct dilution with filtered or compressed air is more straightforward, and reduces uncertainty when characterizing heater performance.

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 mass flow rate settings is equal to the mass 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:

$$DR = \frac{\dot{m}_{dilution}}{\dot{m}_{probe}} = \frac{\dot{m}_{dilution}}{\dot{m}_{instruments} - \dot{m}_{dilution}} \tag{1}$$

where $\dot{m}_{dilution}$, $\dot{m}_{probe}$, and $\dot{m}_{instruments}$ represent the mass flow rate of clean dilution air, exhaust sampled through the probe, and diluted exhaust drawn by the instrumentation suite, respectively. Mass flow controllers (MFC) are common and relatively inexpensive devices that

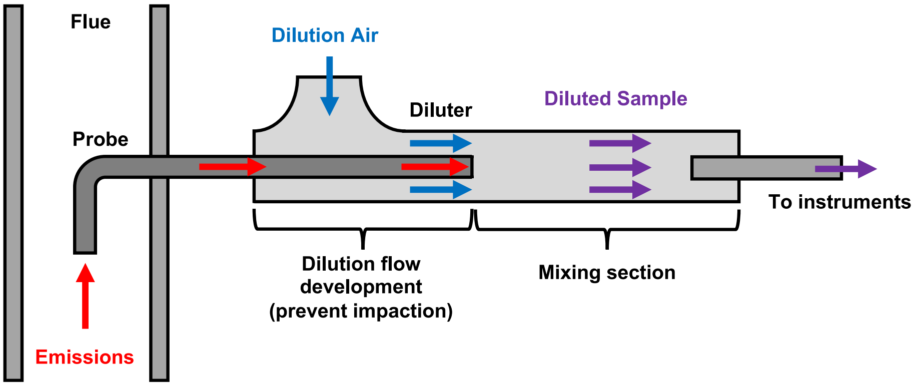

Fig. 2. Direct dilution system. Emissions are sampled directly from the heater flue, mixed with clean air in the diluter, and pass to the instruments for analysis.

can easily measure, record, and control both $\dot{m}_{dilution}$ and $\dot{m}_{instruments}$. 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 ($\dot{m}_{probe}$) and the heater flue must be monitored continuously because test methods 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, $\dot{m}_{dilution}$ and $\dot{m}_{instruments}$ 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 a 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 standardized test methods, it has been investigated and implemented during wood heater research and development. For example, Kinsey et al. compared cordwood heater emissions measured from a total-capture dilution tunnel to those measured with a direct dilution system. Despite the inherent variability of the cordwood 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 [37]. Schön and Hartmann investigated a porous tube dilutor and found it to be reliable for determining the PM emission in an undiluted hot flue gas stream during normal heater operation [39]. The US EPA also provides a reference method for stack emission dilution using a venturi diluter, but states that it cannot be used for regulatory heater certification [58]. While venturi diluters are common, they are susceptible to clogging and the effective dilution ratio can be challenging to verify [59].

Other researchers have designed portable, direct dilution systems, similar to the one shown in Fig. 2, to facilitate stationary stack sampling in the field [60,61]. For example, Meyer et al. used a flue extension and venturi diluter to sample PM emissions directly from residential heaters in Australia (see Fig. 3) [59,62]. Similarly, the Condar Method is a direct diluter system that assumes volumetric flow is conserved, thereby reducing the number of MFCs required. This method has demonstrated good agreement with AS/NZS 4013 during field studies in New Zealand [61,63].

Overall, direct dilution 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 simulates emissions evolving in the atmosphere. 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 heater testing [60,64]. However, these efforts also show that direct dilution systems should only be used after careful validation. For instance, one study found that too little dilution of diesel exhaust may lead to an overestimation of PM emissions and vice-versa [65].

3.2. Modernizing the gravimetric emissions sampling equipment

Many wood heater test methods recommend antiquated equipment that may be cumbersome or too complex to implement in field testing. For example, all test methods recommend using a drying system, a dry gas meter, and a flow adjustment device to control the sample flow rate through a pair of gravimetric filters that ensure complete PM capture [21,23,25–27,29,32]. This complex system can be replaced using a single MFC located downstream of the gravimetric filters. Fig. 4 illustrates a more modern gravimetric sampling system that integrates a MFC along with the direct dilution system described in Section 3.1 (see Fig. 2). Since the diluter promotes more complete condensation of PM precursors, it also eliminates the need for impingers or condensers, like those prescribed by in other test methods [16,21,24,29]. 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 and associated particle loss. While the second gravimetric filter has been retained in Fig. 4 to comply with existing test methods, it could also be removed from the modernized system because the diluted sample flow promotes complete PM capture on the first filter. Overall, these kinds of compact and simplified systems would greatly simplify the hardware and experimental procedures required for measuring

Fig. 3. Flue extension and venturi diluter mounted to the outlet of wood heater chimney [59].

accurate and replicable PM mass emissions, while making it more accessible for field measurements [66].

3.3. Supplement gravimetric PM measurements with time-resolved instruments

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

Tapered element oscillating microbalance (TEOM): The TEOM captures 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 [67]. Since the TEOM's measurement proxy is directly related to particle mass, it is generally more accurate than other time-resolved 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 [68]. In both these applications, TEOM units have shown strong correlations with traditional gravimetric methods, although they require calibrations specific to the ambient sampling environment and emissions source [69–72].

EPA ALT-140 requires two TEOM units (one for dilution tunnel sampling and one for ambient air sampling), along with gravimetric PM samples [26]. The test method includes operational procedures to ensure that the TEOM data is accurate and less susceptible to the volatilization of organic compounds [26,73,74]. While a few studies have investigated using TEOM instruments to characterize wood combustion emissions, further research is needed to confirm robust agreement with gravimetric filters in this application [37,74–76].

While TEOM units are capable of providing time-resolved PM mass data, they are large, expensive, and possibly challenging to use reliably during *in-situ* wood heater emission sampling. For example, the collection filter in the TEOM is prone to overloading in highly polluted environments. Even with dilution, the TEOM filter may require replacement multiple times in a burn cycle while a traditional gravimetric filter may last multiple burn cycles before overloading [74]. Additionally, TEOM measurements may report large fluctuations (positive and negative) as nitrates, OGCs, and other compounds volatize [77,78]. Several experimental procedures have been investigated to address these issues, such as the Filter Dynamic Measurement System that measures both nonvolatile and semi-volatile mater simultaneously, and denuders to remove volatile organic compounds from the sample entirely. However, research shows that the resulting data are still subject to erroneous interference, and further work is needed to validate their use for the certification of wood heaters [79,80].

Beta attenuation monitors (BAM): The BAM measures 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 [81]. BAM units are also a FEM commonly used for ambient monitoring in the US, although careful calibration is required to account for environmental conditions, PM composition, and other factors [71,82,83]. Researchers have used BAM units to measure ambient PM emissions from combustion sources, such as wildfires and cookstoves, but emissions were sampled ambiently, not directly from the source [84,85]. Therefore, further research is needed to evaluate the utility of the BAM for characterizing wood heater emissions. Additionally, because the BAM is large, expensive, and may require excessive sample dilution to prevent filters from overloading, it may not be ideal for *in-situ* wood heater emission sampling.

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 [86]. 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 these external factors [87–91].

Optical PM monitors are widely used for air quality monitoring because they are relatively inexpensive, portable, and easy to use [72,90,92,93]. While some researchers have used optical instruments for characterizing wood heater emissions, the practice is not widespread and none of the test methods reviewed mandate their use [59,94]. Most particles emitted by wood combustion are smaller than 300 nm in diameter and optical PM instruments cannot accurately detect fine particles of this size [95–101]. The sensitivity of light-scattering instruments diminishes sharply for particles less than 300 nm in diameter. So, optical PM monitors inherently underestimate PM number concentrations 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 [94,102]. 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 application.

3.4. Direct measurement of flue exhaust flow rate

When sampling directly from the flue, accurate measurements of the heater's exhaust flow rate are critical for characterizing total mass emissions and thermal performance. The test methods in Table 1 rely on complex mass-balance calculations to estimate the exhaust flow rate indirectly, and more robust methods of direct measurement could be implemented. However, direct measurement is challenging because exhaust velocities from residential wood heaters are low (1–3 m/s or 200–600 ft/min) and exhaust temperatures are high (up to 250 °C) [90,103–105].

Flow velocities in the flue can be measured using a pitot tube

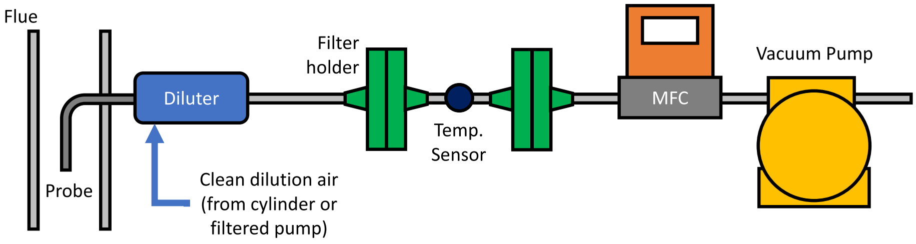

Fig. 4. Modernized and simplified gravimetric PM filter system for direct flue sampling.

(standard or S-type), tracer gas injection, a hot-wire anemometer, or a vane anemometer. The US EPA has published methods for direct flow rate measurement using an S-type pitot [106]. S-type pitot tubes operate in the same way as standard-type pitot tubes but have large static and dynamic ports that resist clogging in highly polluted flows. 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 in some cases [107]. S-type pitot tubes are only rated to measure velocities above 2.4 m/s (475 ft/min) at 250 °C. 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 [108].

Alternatively, the US EPA also provides procedures for measuring flue flow rate using a tracer gas [106]. In this method, a tracer gas 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 can provide reliable measurements, 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.

Hot-wire anemometers measure flow velocities by monitoring the electrical current required to maintain a heated wire at constant temperature while exposed to a flow of air [109]. Only a few commercially available hot-wire anemometers can withstand the harsh flue-exhaust environment (temperatures greater than 300 °C) and have detection limits lower than 1 m/s (200 ft/min) [110,111]. These units are also portable and easy to use, as the probe is simply inserted into the flue. While high-temperature anemometers are well suited to measure exhaust velocities in wood heater flues, they are expensive, highly specialized instruments that are only available from a limited number of manufacturers. Furthermore, there are no references demonstrating the use of hot-wire anemometers in direct emissions sampling applications. 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 [110,111].

Vane anemometers, such as the Höntzsch ZS25/27, have also been used to measure the hot flue gas velocity during short periods in polluted exhaust streams [13,112–115]. These anemometers operate by measuring the rotational speed of a vane (propeller) in the flow. However, their use is not widespread in this application, likely because the mechanical nature of the system is inherently susceptible to fouling from PM pollution in the exhaust.

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 characterizes 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 test methods, mandate better informed emission limits, inform other regulatory measures (e.g., mandatory curtailment periods), and validate that design improvements are demonstrably effective during normal heater operation rather than during laboratory tests alone.

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 time-resolved gaseous and particulate emissions concentration. Gravimetric PM should also be included for calibration, but some aspects of the methods should be simplified or streamlined to enable practical field testing.

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 [116]. Replicate testing should be conducted to characterize the heater's performance within prescribed statistical bounds, and the number of replicate tests should be dictated by the desired degree of statistical confidence [117]. 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 factor. For all performance and emissions metrics, both the test cycle average value and uncertainty should be reported. This approach would greatly increase confidence in the experimental results, and reward heaters that perform consistently.

In order to facilitate replicate testing in the field, test cycles should be shorter than current laboratory test methods. Typical laboratory test methods require about 8–12 h to complete, which is not practical for field testing. Since test cycles focus on steady-state operation, emission rates and performance should remain constant and may be characterized over a shorter sampling periods [103,105]. Test cycle duration may also be reduced by omitting intermediate burn cycles, as the high and low burn-rates should bound performance [14]. Further research is needed to confirm these assertions.

Although steady-state burn cycles may be shortened overall, the harmonized procedures should capture transient phases of operation, such as startup, shutdown, or refueling. Previous research shows that approximately one-third of wood heater emissions may be attributed to startup and shutdown [118]. Similarly, harmonized experimental procedures should also consider the impact of chimney draft on heater performance, as previous research indicates that higher drafts decrease overall efficiency and may impact pollutant emissions [13,119]. While transient emissions and draft may not merit direct regulation, they provide valuable insights for improving wood heater design and accurately accounting for impacts on human health and the environment.

3.6. *Report pollutant mass emissions normalized by thermal power*

When reporting the mass of pollutants emitted, most standards normalize by time (known as the emission rate, with units of grams per hour) or the mass of fuel consumed (known as the emission factor, with units of grams per kilogram of fuel consumed) [21,23,25–27,29,32]. While these metrics are informative and broadly applicable to any type of wood heater, neither reflect the heater's core utility to the user: the delivery of thermal power. For example, two heaters may have the same PM emission rate or factor, but if one delivers more heat within that unit of time or mass of fuel combusted, neither metric will reveal this crucial performance difference. Fundamentally, heaters are always rated in terms of thermal power (kW) because this design parameter alone dictates the appliance needed to satisfy a given application (i.e., heat a home of a certain size). Therefore, it naturally follows that the mass of pollutants emitted should also be normalized by thermal power (g of PM per kW output), as is already done in standard test methods for central heaters such as boilers and furnaces [120,121]. This normalization allows for meaningful side-by-side comparisons of heaters' air quality impacts, as it clearly indicates how much pollution a heater will emit while satisfying a particular heating demand.

While normalization by thermal power is critical to the characterization of heater emissions, it should be reported in addition to emission rate and factor rather than as a replacement to either, as these metrics also provide important information for heater designers, regulators, and policymakers. For example, emission factors are used in the national emission inventories that inform public policy and help maintain acceptable ambient air quality levels throughout the US [5,122].

It is likely that the normalization of pollutant mass emissions by thermal power is not widespread for room heaters because characterizing their thermal performance requires significant experimental investments and analysis (see Section 2.3). Since central heaters deliver heat to a working fluid (i.e., air or water), direct and accurate measurement of thermal power output is more straightforward [120,121]. While this experimental difference should be acknowledged, all room heaters require a thermal power rating for their sale and deployment, and therefore the requisite information is generally already available.

Finally, it should be noted that normalization by heat output (grams per megajoule) 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 metric, it would not capture that one may deliver this energy more rapidly than the other. This information is critical to heaters' application, and again underlies heaters' rating in terms of thermal power, not energy capacity.

4. Conclusion and Recommendations

This review provides a comprehensive overview of wood heater test methods from around the world, and identifies common experimental objectives and regulatory outputs. Using this overview, recommendations were developed for simplifying, modernizing, and enhancing the test methods to make them more accessible, and encourage technology innovations.

Regulations primarily focus on the reduction of PM mass emissions and have regulatory limits defined in terms of PM emission rate (grams per hour), emission factor (grams of PM per kilogram of fuel burned) or concentration (grams of PM per cubic meter). Standardized wood heater test methods tend to follow the same basic template: the heater is operated at various burn rates, emissions are sampled either directly from the flue or using a dilution tunnel, and PM mass emissions are measured using a gravimetric filter system. For most test methods, average PM mass emissions are determined for each burn rate and reported for regulatory certification. Motivated by the review of existing test standards, the following recommendations were developed to simplify, modernize, and enhance wood heater testing.

- **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 portable device. This direct dilution approach is much easier to implement than total capture dilution tunnels and preserves many of the associated advantages, such as maintaining the atmospheric evolution of PM emissions.
- **Supplement gravimetric PM measurements with time-resolved data:** The quantification of PM emissions using gravimetric filters serves as the cornerstone of all certification test methods: 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, wood heater test methods should adopt time-resolved PM instruments. EPA ALT-140 already includes a TEOM, and other PM measurement technologies presented in this review should also be evaluated. While data from any time-resolved 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 test methods 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 field testing. For example, the dual inline filters required by some test methods could be replaced with a single filter since direct dilution systems promote more 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. Current test methods recommend indirect calculation methods that are prone to error. Instead, flue flow rates may be measured directly using S-type pitot tubes, high temperature anemometers, or other devices that can withstand the harsh flue-exhaust environment.
- **Harmonize test procedures for the field and laboratory:** Standardized laboratory test methods 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 both lab and field use. Test procedures should include simple, replicable test cycles that rapidly evaluate both transient and steady-state operation. Complementary datasets from the lab and field will support development of improved certification tests, regulatory emission limits, and heater designs.
- **Report pollutant mass emissions normalized by thermal power:** Heaters are rated in terms of their thermal power, as this is the core utility they deliver to the user. The normalization of pollutant mass emissions by thermal power (grams of PM per kW output) allows meaningful side-by-side comparisons of heaters and their impact on air quality. This metric clearly indicates how much pollution a heater will emit while satisfying a given heating demand. The power-normalized metric should be reported in addition to existing emission metrics (such as emission factors) currently required by regulators.

Credit author statement

Julien J. Caubel: Conceptualization, Methodology, Validation, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Rebecca Trojanowski:** Methodology, Validation, Data curation, Writing – review & editing, Visualization, Project administration, Funding acquisition. **Thomas Butcher:** Writing – review & editing, Project administration, Funding acquisition. **Vi H. Rapp:** Conceptualization, Methodology, Data curation, Writing – original draft, Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.rser.2023.113501.

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