Energy for Sustainable Development 71 (2022) 104–117

Contents lists available at ScienceDirect

Energy for Sustainable Development

Retrofitting stoves with forced jets of primary air improves speed, emissions, and efficiency: Evidence from six types of biomass cookstoves

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ARTICLE INFO

Article history:
Received 28 August 2022
Accepted 10 September 2022
Available online 23 September 2022

Keywords:
Turbulence
Excess air
Black carbon
Wood-burning

ABSTRACT

Incorporating jets of forced air into biomass cookstove combustion has been shown to potentially decrease harmful emissions, leading to a variety of designs in recent years. These have shown mixed success in terms of real-world performance, usability, and durability. The Jet-Flame forced draft retrofit accessory was recently developed to implement forced jets of primary air at a low cost into a wide range of types of cookstoves using a small 1.5-W fan housed in a low-cost cast iron body to be inserted beneath the fuel bed of a biomass cooking fire. This research sought to quantify the potential efficiency and emissions performance impacts of the Jet-Flame when installed in six different types of biomass cookstoves (three open or shielded fires and three rocket stoves) versus the natural draft performance of each. The effect of the operating fan voltage was also measured. A series of tests following a modified ISO 19867-1:2018 protocol were performed in the laboratory using the Aprovecho Laboratory Emissions Measurement System (LEMS) equipped with additional oxygen and temperature sensors. Results for each stove carefully tended with a single layer of sticks showed that the global average $PM_{2.5}$ reduction with the Jet-Flame was 89 % relative to the natural draft cases, with larger relative improvements seen in the most rudimentary stoves. CO was reduced by a global average of 74 %, reaching tier 4 or 5 for all stoves. Thermal efficiency was also improved by 34 % when calculated without taking into account the energy content of the remaining char (or 21 % with char), illustrating the value of burning char to provide cooking energy rather than leaving it unburned in the combustion chamber as is common in many natural draft stoves. Time to boil was also reduced by 8 %. In addition, adjusting the voltage of the jet-flame assisted in modulating firepower, improving the usability of the stove. These results indicate a strong potential for the Jet-Flame to help reduce emissions and fuel consumption in a wide range of cookstove designs at a relatively low cost or need for changes in behavior, fuel, or cooking device. The unit also provides enhanced usability in terms of ease of startup, cooking speed, low PM emissions at high power, and burning char. Additional studies are needed to measure performance in the field and under a variety of operational conditions.

Introduction and background

Of the myriad of negative effects resulting from the use of biomass burned in open fires and other vernacular cookstoves as a primary source of energy by 2.5 billion people each day, emissions of particulate matter (PM) are of primary concern due to effects on both health and climate (WEO-2017 Special Report, 2017). These small particles can penetrate deeply into human lungs, causing asthma, COPD, and lung cancer; while also dispersing throughout the atmosphere, where the dark particles composed of soot/black carbon absorb solar radiation and contribute to the greenhouse effect. Research has shown that exposure even to low PM concentrations in Europe decreased the average life span by 8.6 months and that mortality and respiratory disease increased by 0.58 % and 2.07 % respectively for every 10 μg/m^3 increase of PM10 (Xing et al., 2016). Households cooking with biomass, often with the women and children in the kitchen, can see typical concentrations during cooking in the range of 500–1000 μg/m^3 (Pope et al., 2021), while the WHO guidelines recommend a maximum annual average concentration of only 10 μg/m^3 (World Health Organization, 2021). This has resulted in exposure to household air pollution from cooking being identified as the cause of 1.6 million premature deaths each year (Stanaway et al., 2018). Estimates also indicate that household cooking contributes as much as 1.9–2.3 % of global carbon emissions – a similar scale as both aviation and shipping – primarily because it is the

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https://doi.org/10.1016/j.esd.2022.09.013

dominant source of black carbon emissions globally which have an immediate and significant effect on climate (Black Carbon, n.d.; Bailis et al., 2015). Thus, reducing emissions of particulate matter from cooking, both in terms of soot and fine respirable particles, continues to be a primary goal of designers and implementers.

The particulate matter released from cookstoves is a result of the incomplete combustion of the fuel such that carbon is released as Volatile Organic Carbons (VOCs), black carbon, and polycyclic aromatic hydrocarbons (PAH), instead of ideal situation of full conversion to CO_2 and H_2O. To achieve more complete combustion of this fuel carbon, the so-called "three T's" are needed: temperature, (residence) time, and turbulence (mixing). In biomass combustion generally, mixing is the limiting factor (Nussbaumer, 2003). In small-scale devices, adequate mixing is a persistent challenge in addition to sufficient residence time at elevated temperatures (Williams et al., 2012).

Fan-driven primary and/or secondary air supply has been applied to cookstoves to improve mixing in the combustion zone, modulate heat release, and decrease emissions of products of incomplete combustion. Inventories of cookstove emissions to recommend benchmark tiers of performance identified three different configurations of stoves with fans as the cleanest burning in laboratory tests: gasifier stoves using small pieces of wood (Philips HD4012), top-lit-up-draft (TLUD) gasifier stoves (also called inverted downdraft gasifier, or semi-gasifier stoves) using pellets or granular fuel (Oorja, Wood Gas), and stoves with distributed jets of primary air under the fire using small pieces of wood (Wood Flame) (Jetter et al., 2012; MacCarty et al., 2010; Still et al., 2011).

Subsequent field testing has found mixed results in everyday use from these classes of stoves. The Mimi Moto TLUD stove with a variable-speed fan burning pellets supplied by Inyenyeri, a Rwandan social enterprise, on a subscription model was able to achieve dramatic emissions reductions during correct use in the field comparable to ISO Tier-4 for $PM_{2.5}$ and ISO Tier-5 for CO (Champion & Grieshop, 2019). However transient periods of visibly high emissions occurred during lighting, refueling and burnout. Field test runs that included pellet reloading had median emissions factors comparable to ISO Tier-3 for $PM_{2.5}$ but ISO Tier-4 without refueling (Champion & Grieshop, 2019). Excessive smoke, presumably from improper use, was cited as a barrier to adoption during interviews with Inyenyeri subscribers (Seguin et al., 2018). This is consistent with other studies that have highlighted dominant emissions events during lighting, refueling, and changing operating mode for this type of stove in other contexts (Deng et al., 2018; Tryner et al., 2016).

There are also barriers to consistent and sustained use of pellet-burning gasifier stoves displacing traditional stoves and fuels. Affordability and availability is a persistent challenge for purchased fuels in market segments with low and uncertain incomes. Review of simultaneous use of multiple stoves and/or fuels, "stove stacking" found that the ongoing cost of fuel was a barrier to consistent use of cleaner fuels including pellets (Shankar et al., 2020). Surveys with Inyenyeri subscribers and impact assessment of the Inyenyeri service in a refugee setting found affordability a central challenge to consistent use. Cooks were also less likely to use pellets for long-cooking-duration foods such as beans (Glinski et al., 2018; Seguin et al., 2018). Burning food and compatibility with existing cookware was also a concern (Seguin et al., 2018). A commercially viable pellet supply chain has also been elusive. The BP/First Energy Oorja stove and pellet fuel project abandoned the household market when it was not able to recover fuel supply chain costs (Thurber et al., 2014) and Inyenyeri is now dissolved.

In addition, the very low emissions from these fan stoves during lab tests may not be replicated in actual use. The measured emissions factors from the Philips fan gasifier stove were two to eight times higher in field tests in Ghana and Malawi than in the lab, similar to the emissions factor for a laboratory open fire. These field studies did document in-use emissions reductions of the Philips stove relative to in-use measurements of the open fire which were also higher than those measured in the laboratory (Coffey et al., 2017; Jetter et al., 2012; Wathore et al., 2017). The reasons cited for the deterioration of field emissions performance was user behavior such as inappropriate fan setting and overloading the combustion chamber, and fuel variability such as using fuel that was not chopped finely enough. This usability challenge and low-emissions performance depending on frequent feeding of small pieces of wood into the stove was highlighted by (MacCarty et al., 2010). ISO Tier 0 $PM_{2.5}$ emissions in field use may be common to the class of stove. (Wathore et al., 2017) found that the ACE-1 with a similar design and configuration to the Philips had a modest decrease in $PM_{2.5}$ emissions compared to the in-use open fire that were not statistically significant and higher than the Philips emissions.

The common vulnerability of the interventions discussed above is the reliance on prepared fuel to achieve emissions reductions either of commercial pellets or families laboriously chopping fuel into small pieces. In contrast, the side feed Winiarski "rocket stove" codified and promoted by the Aprovecho Research Center (Bryden et al., 2005) has the distinct advantage of being able to burn a wide variety of fuels with minimal preparation. Larger logs must be split to reduce diameter but the length of fuel is unlimited and smaller branches and agricultural residues can be burned without size reductions. In controlled lab tests rocket stoves show emissions reductions and thermal efficiency gains compared to the open fire (Jetter et al., 2012). In field tests the efficiency gains of rocket stoves are robust with studies finding 35 % to 55 % reductions in fuel use per person-meal (Johnson et al., 2011). However, the emissions reductions are not reproduced in the field with the rocket stove having a similar emissions factor to the open fire. Emissions reductions on a person-meal basis were due to thermal efficiency improvements only (Johnson et al., 2011). Reasons for the lab/field discrepancy are differences in fuel and tending practices such as larger, more irregular and higher moisture fuel, infrequent tending, and high fuel loading (overloading) (Johnson et al., 2011). Infrequent tending (once every 10 min) instead of continuous tending increased open-fire WBT4.2.3 $PM_{2.5}$ emissions factors (basis of energy delivered) during the cold start high power phase by 40 % (Jetter et al., 2012). The positive relationship between increasing firepower and increasing emissions has also been documented in natural-draft rocket-type stoves. Beyond 3 kW firepower, emissions dramatically start increasing due to oxygen starving and flame quenching on the cookpot (Agenbroad et al., 2011; Dischino, 2014; Udesen, 2019). In a laboratory setting, rocket stoves were cleaner at medium power than high power (Jetter et al., 2012). The laboratory firepower sweep test found a positive correlation between firepower and emissions but the correlation strength was dependent on fuel type (Bilsback et al., 2018). Analysis of emission mass ratios (mg $PM_{2.5}$/g CO_2) from ISO and WBT tests show the strongest positive correlation with firepower for natural draft wood rocket stoves out of all stove types tested (Champion et al., 2021). While attractive for in-use fuel savings and fuel flexibility, natural-draft rocket stoves have not demonstrated the emissions reductions necessary to protect health when operated in the field at high firepower with local fuels and tending practices.

Several parametric studies have explored injecting secondary air above the fuel and into the flames of side-feed shielded fires and rocket stoves to improve emissions (Barbour et al., 2021; Caubel et al., 2018, 2020; Dischino, 2014; Hogberg, 2016; Rapp et al., 2016; Udesen, 2019). These studies showed that there is a general tradeoff between reduced $PM_{2.5}$ mass emissions from increasing turbulence and mixing, and increased $PM_{2.5}$ mass emissions from low temperatures and flame quenching. For a given device and operating condition there is an optimal injection setting that balances mixing, temperature, and the power requirements of injecting the air. Overall thermal efficiency is the product of combustion efficiency and heat transfer efficiency. Optimized secondary air injection increases combustion efficiency due to improved mixing (Caubel et al., 2020; Rapp et al., 2016), but lowers heat transfer efficiency from lower temperatures due to the relatively cooler injected air (Udesen, 2019). Of all of the studies only one of the secondary air configurations (Berkeley Shower Stove) achieved the same overall thermal efficiency as the same stove operating natural draft. All other configurations had slightly lower overall thermal efficiencies compared to the same stove operating natural draft. Interestingly, the Berkeley Shower Stove was the only configuration that preheated the secondary air by passing it underneath the fuel bed and char zone. The other configurations used the flame zone to preheat the secondary air. Three studies observed reduced draft and backdrafting (smoke and flames coming out of the front feed door) at certain air injection settings (Dischino, 2014; Hogberg, 2016; Udesen, 2019). Hogberg measured the overall volumetric flow rate through the stove at different secondary air injection flow rates and found that injected secondary air reduced the flow rate past the sticks through the fuel feed door causing increased stick "burnback" where flame propagation down the length of unburned fuel was faster than the fuel feed rate resulting in flames and fugitive emissions outside the stove. Reduced draft from injected secondary air may have other usability impacts as well. The BioLite HomeStove is a commercial side-feed rocket stove with fan-driven secondary air injection. According to the manufacturer, the combustion chamber filled and overflowed with unburned char during extended operation, requiring the cook to remove char from the stove during cooking to make room for more fuel. Reduced primary draft due to secondary air injection may have played a role, however adding a grate inside the stove was reported to have mitigated the problem (ASME ISHOW, 2018). When tested in the lab the BioLite HomeStove had about 35 % of the PM emissions factor as other side-feed rocket stoves (Jetter et al., 2012; Jetter & Ebersviller, 2015). In a field test the HomeStove median emissions factor increased five fold, higher than the field emissions factor measured for the Philips gasifier fan stove (Coffey et al., 2017; Johnson et al., 2019; Wathore et al., 2017). However, this was only 38 % of the emissions factor measured for a side feed rocket stove in the field showing a similar relative emissions reduction as in the lab (Johnson et al., 2011). The HomeStove field median emissions rate was only about three fold higher than in the lab to just inside ISO tier 1. The median firepower was also lower in the field than in the lab, which may explain the 5× increase in emissions factor but only 3× increase in emissions rate. At a median field firepower of 2.7 kW and assuming the field thermal efficiency is the same in the field as in the lab the HomeStove time to boil 5 L of water would be over 40 min, a usability drawback (Jetter et al., 2012; Johnson et al., 2019). Forced secondary air in side-feed rocket stoves have shown emission reductions in the lab and field compared to natural draft rocket stoves and traditional fires but are not yet approaching the levels of field performance necessary to protect health. Forced secondary air retains the fuel flexibility of a side-feed rocket configuration but has the performance drawback compared to natural draft of reduced thermal efficiency and the usability challenge of reduced draft which can cause backdrafting and burnback, contribute to low firepower, and char overflow.

User preference and usability studies have highlighted the factors that drive stove and fuel choices for cooking tasks. Preferences for fuel-stove combinations can be summarized by convenience first, comfort second. In this sense "convenience" encompasses several factors such as cooking speed, ease of use, and compatibility with available and affordable fuel and local cookware and cuisine; and "comfort" relates primarily to smoke exposure and other nuisance factors (Barnes, 1994; Hooper et al., 2018; Moses et al., 2019; Seguin et al., 2018; Thacker et al., 2014; Thurber et al., 2013). For example, a cross-sectional survey of preferences in rural Senegal found that the stated priorities were: 1) large cooking capacity, 2) minimal smoke, 3) rapid heating. However, practical considerations of capacity and speed were found to take priority over reducing smoke exposure (Hooper et al., 2018). The primacy of speed and convenience may explain the observed increase in emissions in the field due to changes in fuel and tending practices. If a forced-draft technique can reduce emissions from side-feed rocket stoves, open fires, and other artisanal stoves already in kitchens around the world, it would allow stoves with high levels of adoption and sustained use to move toward protecting health and clean up the "bottom of the stove stack". Furthermore, technologies that cook cleanly at high power, prevent char overflow during extended cooking, enhance natural draft, and help burn the larger pieces of wetter fuel commonly found in the field align with the preferences of cooks and could potentially overcome the reasons for poor emissions performance in the field.

The Aprovecho Research Center has been developing such a technology for several years. Early on, the WoodFlame grill was identified as an alternative fan-driven configuration to burn wood with a unique air distribution strategy. The primary air holes are uniformly distributed on the floor of the cylindrical combustion chamber to deliver turbulent jets of primary air with no secondary air (Boucher, 2005; Patenaude & Patenaude, 1989). This wood-burning grill was adapted for boiling water for the inventory of cookstove performance and tested well, with comparable lab performance to gasifier stove configurations (MacCarty et al., 2010; Still et al., 2011) and inspired an early forced-draft prototype (Witt, 2005). Aprovecho adapted this air distribution approach (Patenaude, 1988) from the top-feed configuration found in the grill to a side-feed rocket stove configuration that achieved IWA tier 3 high-power PM emissions (Still et al., 2015, 2021), cleaner than the Philips lab performance and an 87 % reduction from a natural draft rocket stove (Jetter et al., 2012).

Barbour et al. (2021) investigated three air injection strategies: primary air jets directed up into the fire from the floor of the combustion chamber based on the Aprovecho/WoodFlame grill approach (Still et al., 2021), secondary air injection into the flames above the sticks developed at the University of Washington (Udesen, 2019), and a hybrid adaptation of both techniques. Parametric testing of different airflow settings for each of the air injection configurations was explored experimentally and with computational fluid dynamics software. Results showed that high-power cold-start $PM_{2.5}$ emissions (mg/MJd) were reduced with all approaches and firepower with wet and dry wood was increased with primary air jets, desirable for usability. However, overall thermal efficiency was lower with all air injection configurations compared to natural draft. Startup emissions were dominant for all air injection techniques, especially the primary air and staged air configurations highlighting the tremendous influence of startup procedure on measured emissions (Barbour et al., 2021). Burn Design Lab (Vashon, WA 98070, USA) and Burn Manufacturing (Ruiru, Kenya) continued developing the hybrid staged air approach now embodied in the Kuniokoa Turbo stove available in the market (https://burnstoves.com/products/wood-stoves/turbo).

Aprovecho Research Center continued developing the primary air jets configuration as a low-cost add-on accessory that could enhance a variety of stove designs that was later recognized by a Tibbetts award and the EPA administrator's award for a small business contractor (EPA SBIR Small Business Receives 2020 Tibbetts Award, 2021). The most promising implementation of 2-mm diameter jet holes identified in (Barbour et al., 2021) parametric testing was further tuned and optimized to the final configuration of 30, 2-mm holes operating with a plenum pressure between 0.75 and 1.25 in. water column pressure as a reasonable compromise for common firepower levels for home cooking. Additional research and development in collaboration with Shengzhou Stove Manufacturer led to a mass-manufactured product called the Jet-Flame (www.Jet-Flame.com). The device is 37-cm long by 11-cm wide and 3-cm high. It operates using a 1–2 W purpose-built fan in a stainless steel housing powered by 5-volt USB which blows air through a cast iron tube into a plenum which is fitted with the grid of small holes (Fig. 1).

The Jet-Flame retrofit has the potential to cook cleanly at high power in many types of existing stoves. The goal of this study was to evaluate the potential for the Jet-Flame to improve thermal efficiency and emissions, compared to natural draft configuration in six types of common stoves, ranging from basic shielded fires to engineered and mass-produced rocket-type stoves.

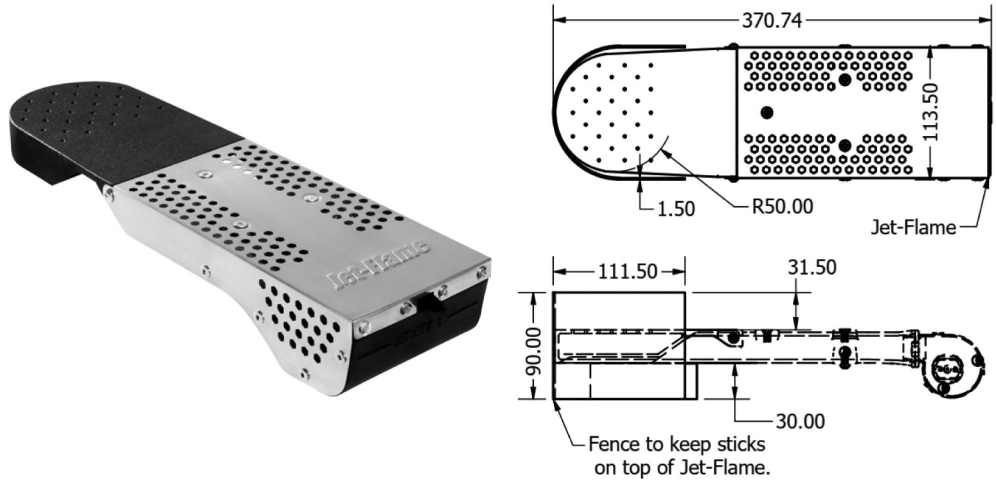

Fig. 1. Jet-Flame A) product and B) CAD drawings.

Methodology

To quantify the laboratory performance of the Jet-Flame in various stoves and at varying fan speeds, efficiency and emissions measurements occurred in two parts:

1) Modified ISO 19867-1:2018 performance testing of six stove types with and without the Jet-Flame. A series of 3 or more replicates per stove both with and without the Jet-Flame were performed to understand the efficiency and emissions implications of the forced-draft primary air.
2) A sweep of the Jet-Flame voltage in a single stove. A series of 69 water boiling test segments of the high mass rocket stove with the Jet-Flame combustion accessory were performed to investigate the effects of varying the voltage supplied to the Jet-Flame fan from 2 to 8 V, resulting in pressure, velocity, and mass flow changes in the air jets. An increase in voltage increases the amount of air driven through the 30 × 2 mm diameter holes of the Jet-Flame and into the combustion chamber.

Emissions measurements

The emissions were analyzed by Aprovecho's Laboratory Emissions Monitoring System (LEMS). The system is in use worldwide and meets the sampling requirements described in ISO 19867-1:2018 (Laboratory Emissions Monitoring System (LEMS), n.d.). In addition, black carbon emissions were quantified based on the Nexleaf photo analysis method (Ramanathan et al., 2011). Details of these systems are available in Appendix A.

In addition to the standard LEMS sensors, the amount of excess oxygen was measured during the voltage sweep at four locations in the pot skirt (front, back, left, right) using Bosch LSU 4.9 automotive wide band zirconia based oxygen sensors with Innovate Motorsports LC2 controllers (Fig. 2). The LEMS recorded the sensor output every 4 s, and the output was averaged over each 30 minute test segment.

The temperature within the combustion chamber of the Heavy Rocket was measured in four locations using 3 mm thick, Inconnel shielded, type K thermocouples. Two of the thermocouple junctions were located within a 2-cm sphere that was positioned 10 cm above the Jet-Flame surface in the center of the combustion chamber cross section. The other two junctions were similarly co-located 20 cm above the Jet-Flame surface. The data were collected every 4 s and are reported as a 30-minute average across the four locations. The thermocouple-based temperature measurements in the combustion chamber are not corrected for radiation from the charcoal or flames.

Stoves tested

Six different common stove models were selected to represent the variety of models to which the Jet-Flame could be applied: three open or shielded fires and three rocket stoves (Fig. 3). The six stoves tested were: a simple open fire with a pot supported by three bricks (Open Fire), an African earthen bucket stove (African Bucket), Asian earthen bucket stove (Asian Bucket), an earthen brick high mass rocket stove (Heavy Rocket), a single door rocket stove with an insulated thin walled refractory cement combustion chamber (Medium Rocket), and a single door rocket stove with an insulated steel alloy combustion chamber (Light Rocket). Minimal modifications were made to the stoves to enable installation of the Jet-Flame including slightly enlarging the door of the two earthen stoves. Additional details on construction, dimensions, and testing of these stoves is available in Appendix B.

Table 1 compares the pot and fuel parameters used for testing the various stoves. Note that the StoveTec SuperPot is a flat-bottomed 23.5-cm diameter cooking pot with an integrated skirt with a 10 mm gap. Tests of the Asian Bucket used the same dimensions of fuel with and without the Jet-Flame. In the other stoves the fuel size was varied to optimize performance and to burn larger pieces of wood which tend to make less $PM_{2.5}$ emissions in the Jet-Flame. The Heavy Rocket and the Light Rocket when tested with the Jet-Flame burned two pieces of dimensionally cut Douglas Fir with a width of 3.8 cm and a height of

Fig. 2. The oxygen sensors in the exit gasses.

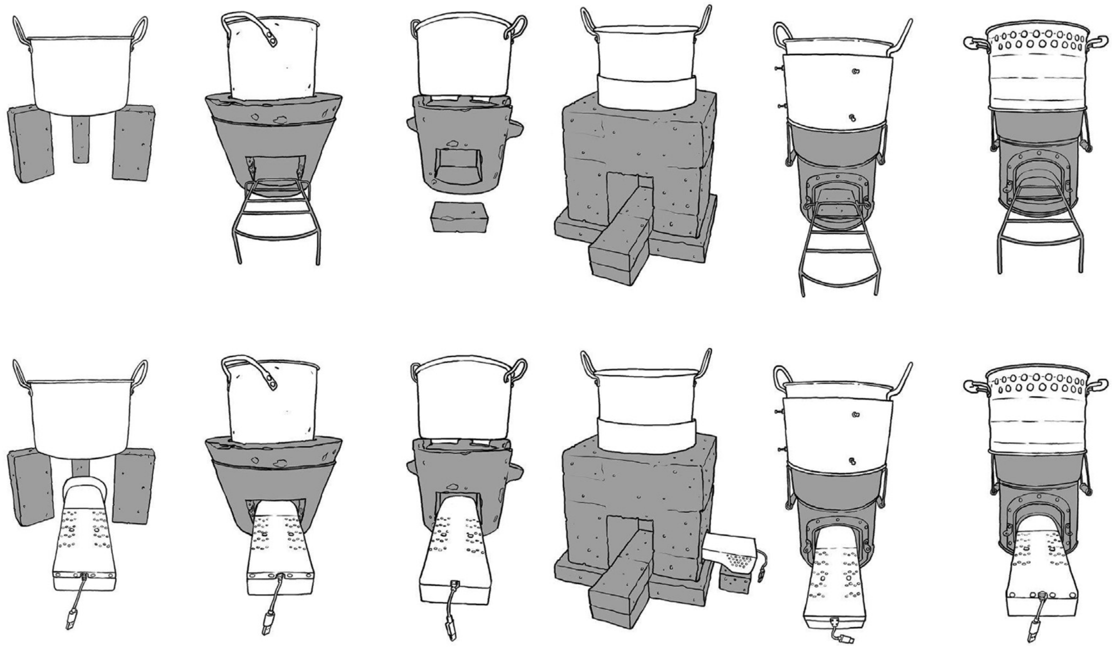

Fig. 3. Tested stoves with (bottom row) and without (top row) the jet flame, including (left to right) open fire, Asian Bucket, African Bucket, Heavy Rocket, Medium Rocket, Light Rocket.

4.3 cm. It was not possible to start and maintain the fire during the 30-minute test with this configuration of wood without the Jet-Flame. The natural draft tests of those stoves were with smaller sticks in order to maintain the target firepower level. The stove operator adjusted the length of the stick within the combustion chamber in order to minimize emissions while maintaining the target firepower for all stove types and fuel combinations.

Testing procedures

The ISO 19867-1:2018 standard provides a laboratory test for cookstoves to be evaluated with performance metrics such as thermal efficiency and emissions released per unit energy delivered to the cooking pot. The procedure involves heating or boiling and evaporating water, but each test phase is carried out for 30 min (plus shutdown time) at an attempted constant power level. The simulated cooking task for all three power levels is to heat water in a pot. Energy that goes into the pot is accounted for by measuring the temperature rise of the water and the mass loss to evaporation. The mass of emissions released by the stove is measured during the full combustion cycle, which includes the startup phase, the steady state phase, and the shutdown phase. The high power test is therefore done with the stove body at room temperature, and the medium and low power tests are therefore done with the stove body heated by the fire to well above ambient temperature.

In the interest of time and repeatability, the standard ISO protocol was abbreviated. Details of the testing and startup procedure are provided in Appendix C.

Results and discussion

Part 1: potential improvements from Jet-Flame forced air

Table 2 summarizes the power, time to boil, efficiency, and emissions for the six stoves with and without the Jet-Flame.

Firepower and cooking power

Table 2 and Fig. 4 show the firepower and cooking power for each stove pair, natural draft (ND) and with the Jet-Flame (FD). The percent change is shown for each stove pair in the table. As seen in Fig. 4 for each test pair, firepower is lower but cooking power is slightly higher in forced-draft mode with the Jet-Flame. In the rocket stove test pairs the firepower and cooking power was higher in forced-draft mode than natural draft. As discussed in the introduction PM emissions tend to increase with increasing firepower in rocket stoves. The relative emissions reductions of Jet-Flame forced draft discussed below are even stronger considering the higher firepower operation.

Thermal efficiency

ISO 19867 specifies two measures of thermal efficiency for wood fuel. Thermal efficiency with char subtracts the energy content of the char remaining at the end of the test from the energy content of the wood burned for the efficiency calculation. Thermal efficiency without char counts the remaining char as burned fuel. Thermal efficiency

Table 1
Test parameters.

	Open Fire		African Bucket		Asian Bucket		Heavy Rocket		Medium Rocket		Light Rocket	
	ND	FD	ND	FD	ND	FD	ND	FD	ND	FD	ND	FD
Pot diameter (cm)	24	24	24	24	22	22	24	24	26	26	SuperPot	SuperPot
Volume (L)	3	3	5	5	5	5	5	5	5	5	5	5
Skirt length (cm)	N/A	N/A	N/A	N/A	4	4	7	7	15	15	16	16
Skirt gap (mm)	N/A	N/A	N/A	N/A	15	15	6	6	6	6	10	10
Fuel width × height (cm)	1.0 × 1.8	1.5 × 3.8	0.9 × 1.5	3.8 × 4.3	1.5 × 3.8	1.5 × 3.8	1.0 × 1.8	3.8 × 4.3	1.5 × 1.8	2.0 × 1.8	1.2 × 2.0	3.8 × 4.3
Number of sticks	8	4	5–10	2	3–4	4	5–6	2	4–5	4	4–5	2

Table 2
% Difference between Jet-Flame and natural draft performance. 90 % confidence interval is shown. For the operating conditions of Firepower and Cooking power, values in italics denote a significant difference, indicating a difference in operation. For the other test metrics values in italic denote no statistical difference, indicating no difference in performance.

ISO metrics	Units	Open Fire	African Bucket	Asian Bucket	Heavy Rocket	Medium Rocket	Light Rocket	Global average
Firepower ND	kW	7.7 ± 1	5.7 ± 0.5	5.6 ± 0.4	4.4 ± 1	4.2 ± 0.2	5.5 ± 0.5	5.5
Firepower FD	kW	5.1 ± 0.2	4.8 ± 0.2	4.5 ± 0.1	4.8 ± 0.6	4.5 ± 0.2	5.6 ± 0.7	4.9
Firepower % change/ND	%	*−33 ± 8*	*−15 ± 8*	*−21 ± 4*	10 ± 21	*8 ± 7*	2 ± 14	−11.2
Cooking power ND	kW	1 ± 0.1	1.1 ± 0.1	1.5 ± 0.2	1.3 ± 0.3	1.9 ± 0.1	2.1 ± 0.1	1.5
Cooking power FD	kW	1 ± 0	1.1 ± 0.2	1.8 ± 0.1	1.7 ± 0.2	2.2 ± 0.1	2.6 ± 0.3	1.7
Cooking power % change/ND	%	7 ± 12	5 ± 15	*24 ± 15*	*30 ± 24*	*16 ± 8*	*25 ± 13*	19
Time to boil 5 L, 75C ND	min	34 ± 6	33 ± 4	22 ± 3	22 ± 3	21 ± 2	16 ± 2	25
Time to boil 5 L, 75C FD	min	38 ± 3	31 ± 3	18 ± 3	20 ± 1	17 ± 1	13 ± 1	23
Time to boil 5 L, 75C % change/ND	%	*11 ± 19*	*−5 ± 14*	−21 ± 14	*−10 ± 11*	−18 ± 10	−19 ± 10	−8
Thermal efficiency without char ND	%	13 ± 0.5	15.9 ± 1.2	26.2 ± 2.5	30.9 ± 1.8	35.6 ± 0.7	34.9 ± 2.4	26.1
Thermal efficiency without char FD	%	20.8 ± 0.6	22.8 ± 1.7	41.1 ± 2.9	35.1 ± 0.9	44.4 ± 2.7	46.5 ± 3.6	35.1
Thermal efficiency without char % change/ND	%	60 ± 6	44 ± 16	57 ± 15	14 ± 6	25 ± 7	33 ± 12	34
Thermal efficiency with char ND	%	15.3 ± 0.6	18.7 ± 1.9	29.8 ± 2.3	32.8 ± 2	41 ± 1.1	38.7 ± 1.6	29.4
Thermal efficiency with char FD	%	21.1 ± 0.6	23.1 ± 1.6	41.8 ± 2.7	35.1 ± 0.9	45.4 ± 1.9	47.1 ± 3.5	35.6
Thermal efficiency with char % change/ND	%	38 ± 5	24 ± 16	40 ± 12	7 ± 6	11 ± 5	22 ± 9	21
CO emissions factor, energy delivered ND	g/MJd	9 ± 1.3	8.9 ± 4.1	2.4 ± 1.3	11.2 ± 2.3	7.3 ± 1.9	8 ± 2.5	7.8
CO emissions factor, energy delivered FD	g/MJd	2.3 ± 0.2	1.8 ± 0.7	1.5 ± 0.3	2.7 ± 0.9	2.6 ± 1.4	0.7 ± 0.2	2.0
CO emissions factor, delivered % change/ND	%	−74 ± 5	−79 ± 13	−36 ± 27	−76 ± 8	−64 ± 19	−91 ± 3	−74
PM2.5 emissions factor, energy delivered ND	mg/MJd	1340 ± 196	872 ± 295	487 ± 113	600 ± 201	393 ± 136	911 ± 343	767
PM2.5 emissions factor, energy delivered FD	mg/MJd	197 ± 30	113 ± 31	61 ± 31	61 ± 16	48 ± 17	27 ± 13	84
PM2.5 emissions factor, delivered % change/ND	%	−85 ± 3	−87 ± 6	−87 ± 7	−90 ± 4	−88 ± 5	−97 ± 1	−89
BC emissions factor, energy delivered ND	mg/MJd		86 ± 21	56 ± 0	76 ± 14	65 ± 4	350 ± 137	190
BC emissions factor, energy delivered FD	mg/MJd	9 ± 4	9 ± 3	5 ± 2	10 ± 2	7 ± 2	5 ± 5	7

with char is greater than or equal to thermal efficiency without char because the amount of char remaining is greater than or equal to zero (ISO 19867-1:2018, 2018; Eqs. (6) and (7)). The WBT protocol and historical lab testing reports of "thermal efficiency" report thermal efficiency with char (WBT 4.2.3, 2014). This distinction can be important depending on the tendency of the stove to accumulate char. Stoves without grates and with low draft can accumulate significant amounts of char. For example the African Bucket stove pictured in the field in (Wathore et al., 2017) is filled with ash and unburned char. Depending on local practices, that char could be used for additional cooking or may be lost as it slowly burns to ash between cooking events. Thermal efficiency with char is the best case scenario, and thermal efficiency without char is the worst case. Actual practice will fall somewhere in between. The 5 min shutdown procedure of the ISO protocol allows some time for char to burn but depending on airflow rates in a particular device significant char may still be present at the end of a test. The modified ISO protocol used in this test series is similar to the WBT in that it does not include a shutdown phase.

The tendency to burn or conserve char has usability implications as well. Excessive char buildup means that the energy in the char isn't available to the cooking system and can crowd out space in the combustion chamber for new sticks of wood. This is particularly a challenge for bigger pieces of wetter wood where heat from the char is needed to keep the sticks burning. On the other hand, rapid char combustion can cause the fire to burn out quickly if left unattended. Frequent tending requirements are highlighted as usability problems that impede adoption (Moses et al., 2019; Thacker et al., 2014). Logically there must be some intermediate rate of char combustion that maintains a steady-state char bed for a given combustion condition preventing overflow or burnout and strikes a usability balance for tending frequency. The ISO definition of thermal efficiency with/without char will hopefully bring new attention to this aspect of stove performance in the lab and field studies.

As shown in Table 2, and Fig. 5, the addition of the Jet-Flame improved both measures of thermal efficiency for all stoves tested and the size of the change depended on the stove type. The Jet-Flame also helped burn the char as it was formed with air blowing directly into the char bed underneath the sticks so there was little accumulated char at the end of the test, keeping the with/without char thermal efficiency metrics close together. Generally the stoves with lower natural draft thermal efficiency and with higher thermal mass improved the most with the Jet-Flame. The greatest absolute improvement was observed during testing of the Asian Bucket stove, where it moved from 26 to 41 % thermal efficiency without char. The greatest percent improvement was the open fire, which increased 60 % from 13 % without char natural draft to 21 % with the Jet-Flame. Notably, the thermal efficiency with char for the natural draft open fire case (15.3 %) was nearly

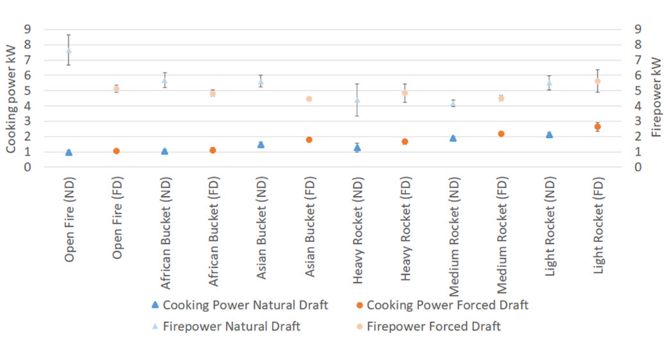

Fig. 4. Firepower and cooking power for forced and natural draft conditions. Error bars show 90 % confidence interval.

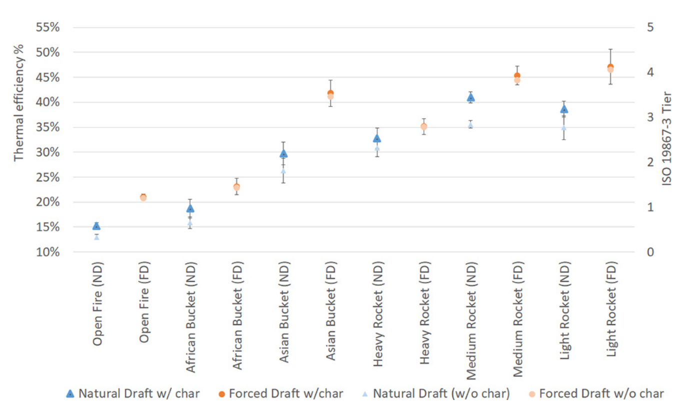

Fig. 5. Thermal efficiency with and without char for forced and natural draft conditions. Error bars show 90 % confidence interval.

identical to the 15 % reported by Jetter et al. (2012). The Asian Bucket stove with a 4-cm sunken pot tested above 40 % (with and without char) with the Jet-Flame and could potentially improve with a longer pot skirt by increasing the flow path of the hot exhaust gasses against the pot. High-mass stoves generally have lower cold-start thermal efficiencies as heat from the fire flows into heating the body of the stove instead of the pot of water. The Jet-Flame with stick fence inserted into the high-mass earthen Asian Bucket stove may have been able to insulate the fire and reduce heat loss. The low-mass rocket with a super pot had the highest thermal efficiency overall, over 45 % on both thermal efficiency measures with the Jet-Flame. Thermal efficiency with char over 45 % is higher than all stoves tested by Jetter et al. (2012) except for one and matches the efficiency of the Mimi Moto (Clean Cooking Catalog-Mimi Moto, n.d.). TLUD gasifier stoves like the Mimi Moto produce char that may or may not be used for cooking. These data show that the addition of the Jet-Flame is able to bring the thermal efficiency of simple, low-cost stoves up to ISO tier 4, and on par with much more expensive devices.

These findings of increased thermal efficiency with Jet-Flame forced air are in contrast to previous work with air injection. As discussed in the introduction, secondary air injected into the flames generally lowers thermal efficiency due to lowering the temperature of the flame zone unless perhaps if it is preheated in the char zone as in the Berkeley Shower Stove configuration (Rapp et al., 2016). Barbour et al. (2021) found that all forced draft configurations, including Jet-Flame style forced primary air, lowered thermal efficiency. Perhaps the modified ignition procedure in this study with char in the combustion chamber from startup helped maintain elevated temperatures at all phases of the test resulting in improved efficiency. The cast iron plenum of the Jet-Flame absorbs heat from the char burning on top acting to preheat the primary air as it enters the fire, similar to the Berkeley Shower Stove that performed well for thermal efficiency. Further study is needed to explore how jets of primary air influence thermal efficiency.

Emissions

Table 2 and Fig. 6 show that the Jet-Flame can produce dramatic emissions reductions in a wide variety of stove models in lab tests with a low-smoke startup procedure, careful tending, and a single layer of low-moisture lab-wood sticks. The $PM_{2.5}$ emissions factor was reduced by a global average of 89 % for all stoves. The largest absolute reduction was the open fire from ISO Tier 0 to ISO tier 2, just outside ISO Tier 3 (based on the conservative bound of the 90 % confidence interval as prescribed by ISO). The highest percent reduction was the low-mass rocket from ISO Tier 0 to ISO Tier 4. The other stoves tested improved from ISO Tier 0 or 1 to Tier 3. Emissions measurements vary between test protocols and testing labs (Champion et al., 2021; Jetter & Kariher, 2009). However, the modified ISO protocol used in this series is similar to the WBT with an extended duration, and general comparisons about performance levels are possible. WBT cold start test results of the Mimi Moto pellet gasifier stove (34 mg/MJd (Champion et al., 2021), 14 mg/MJd (Clean Cooking Catalog-Mimi Moto, n.d.)), Philips gasifier fan stove (73.7 mg/MJd (Champion et al., 2021)), and the BioLite Home Stove with fan-driven secondary air (138 mg/MJd (Jetter & Ebersviller, 2015)) are relevant comparisons. At 27 mg/MJd, the Light Rocket with Jet-Flame has similar performance to the Mimi Moto for PM 2.5, between the results reported by two different testing labs. The medium and high-mass rocket and Asian Bucket stove with the Jet-Flame performed better than the Philips gasifier in the lab. The Jet-Flame assisted African Bucket stove had the same ISO tier 3 rating for PM, and lower PM emissions than the BioLite HomeStove.

The gravimetric $PM_{2.5}$ filters were analyzed for black carbon (BC) to estimate the filter loading based on the Nexleaf photo analysis service of filter color (Ramanathan et al., 2011). Due to the relatively high emissions from the stoves operating natural draft, the BC loading was over the upper limit of detection discussed in the methods section on several natural draft test runs. The gravimetric filter process was adjusted for the Light Rocket natural draft test (noted in the methods) to keep the BC filter loading in range of the Nexleaf system. The values reported for natural draft in Table 2 are therefore a lower-bound estimate for the African Bucket, Asian Bucket, Heavy Rocket, and Medium Rocket due to over range measurements, and a measurement within range for the Light Rocket. The true BC emissions factor natural draft for the other stoves is expected to be similar to the Light Rocket. Future work can adjust the sample duration or flow rate to ensure filter loadings are within range. A study found good correlation between the Nexleaf photo estimate of BC and reference instruments for EC but the correlation differed by aerosol type and was modestly affected by filter media suggesting that a calibration for local conditions was necessary for improved accuracy (de la Sota et al., 2017). The estimates of BC emissions factor (mg/MJd) reported in Table 2, and Fig. 7 for each stove pair suggest a general trend that can be investigated further with more precise methods.

Despite the limitations of the BC emissions factor estimates in this study, dramatic reductions were observed. The largest absolute and percent reduction was for the Light Rocket (345 mg/MJd, 98 %). Even with likely severe under estimates of BC all stoves achieved at least 87 % reductions in BC. The true reductions are likely higher due to the natural draft baseline being over the limit of detection. While uncertainty remains in the climate impacts of aerosols, BC is recognized as climate

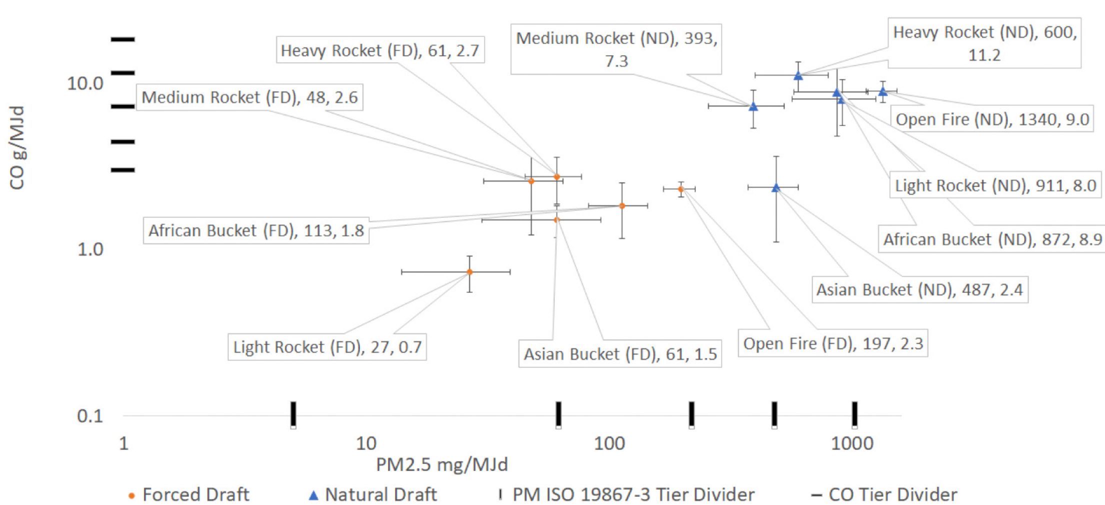

Fig. 6. ISO Tier Mapping for CO and $PM_{2.5}$ per $MJ_{delivered}$ for the natural (blue triangle) and forced draft (orange dot) cases. Note the log scale on both axes.

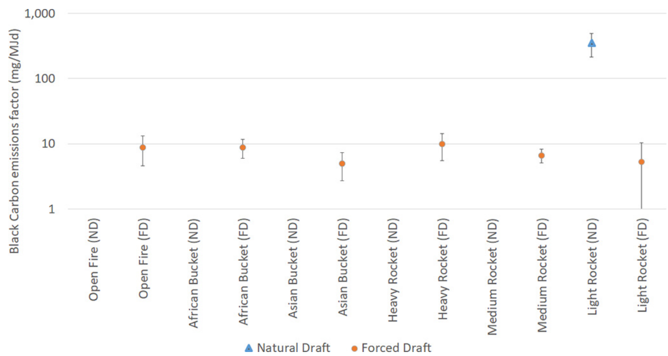

Fig. 7. BC emissions factor and BC% of PM.

warming while organic carbon (OC) and other components of PM are generally recognized as climate cooling (MacCarty et al., 2008). The BC fraction of total $PM_{2.5}$ gives a general indication of the short-term climate forcing potential of the emitted aerosols. With the Jet-Flame, the lowest BC fraction was the open fire at 5 % and the highest was the Light and Heavy Rockets at 19 %. In laboratory and field assessments, rocket-type stoves were found to have a higher PM fraction of BC than open fires (Champion et al., 2021; Johnson et al., 2011; MacCarty et al., 2008). In a high-power cold start WBT lab test with low-moisture wood (8.3 % wet basis), the BioLite Home Stove had a 98 % BC fraction of $PM_{2.5}$. However, with higher moisture wood (17.6 % wet basis), the BC fraction dropped to 38 % of total $PM_{2.5}$ for a lower BC emissions factor (mg/MJd) even though total PM was higher (Jetter & Ebersviller, 2015). This suggests that BC emissions are sensitive to fuel characteristics and combustion conditions. A study comparing BC emissions from a variety of stove-fuel combinations found that in the field, BC fraction of PM in rocket-type stoves was lower than the very high levels found in lab testing (Garland et al., 2017). The differences in fuel type and tending practices between lab tests and everyday use described previously could explain this difference in BC fraction, consistent with the BioLite HomeStove results. The approximately 20 % BC fraction of the rocket stoves with Jet-Flame in this lab performance study is lower than other lab studies of rocket stoves suggesting that the Jet-Flame could potentially reduce climate forcing impacts from BC aerosols by both reducing BC emissions factors and the percentage of BC in PM2.5. Simulated field use in the lab and follow-up field studies of the Jet-Flame in everyday use are needed to better understand how jets of primary air, fuel properties, and tending practices interact to influence BC emissions factor and BC fraction of PM, both with climate impacts.

Similar, dramatic reductions were measured for CO emissions factors with a global average reduction of 74 % (Fig. 6 and Table 2). The largest absolute reduction was in the Heavy Rocket (8.5 g/MJd), and the largest percent reduction (91 %) was in the Light Rocket. Adding the Jet-Flame resulted in all of the stoves achieving Tier 4 or 5 for CO.

These results demonstrate the ability for the Jet-Flame retrofit to improve emissions performance of a wide variety of simple, low-cost stoves with user-friendly, fuel-flexible, side-feed stick configurations to match the lab performance of some of the best performing commercial stoves in the market today. Note that these lab results were achieved with an optimized, smokeless startup procedure with char and alcohol, and careful tending with lab wood. Actual performance in the field will be lower with kindling, paper, or kerosene startup (Fedak, 2017), less careful tending, and non-ideal wood (Johnson et al., 2011). Field performance with the Jet-Flame is likely more sensitive to changes in fuel and tending practices (Wathore et al., 2017) than gasifier stoves using pellets (Champion & Grieshop, 2019). Additional investigation is needed to explore how emissions performance can be maintained under simulated field conditions in the lab followed up by field trials and exploration of the user training and behavior change communication needed to support the intervention and achieve meaningful emissions reductions in everyday use.

Part 2: voltage sweep

A set of linear regressions were performed independently on a pairwise basis for the data from the Jet-Flame voltage sweep including high-power cold-start and high-power hot-start test runs. Table 3 shows the set of Pearson's r correlation coefficients (Cohen & Cohen, 2003) where Jet-Flame voltage, test-average temperature, and firepower (column headings) were the independent variables, and test-average firepower, temperature in the combustion chamber, and excess air in the pot skirt (rows) were dependent variables. This set of dependent variables were thought to be intermediate pathways that would influence the performance indicators, including CO, $PM_{2.5}$, and BC emissions factors. Pearson correlations indicated that Jet-Flame voltage had a significant impact on all of the intermediate pathways, on a scale ranging from 0 as not predictive to 1 as perfectly predictive, and sign indicating whether a direct or inverse relationship. The correlations were significant in the sense that they were more likely to occur than the correlation between two normally distributed random variables at 95 % confidence for the given sample sizes (Cohen & Cohen, 2003).

These tests showed that voltage had a strong influence on firepower and combustion chamber temperature. There was an even higher correlation between combustion chamber temperature and firepower. Firepower inversely tracked excess air in the pot skirt, although average temperature in the combustion chamber had the highest association with excess air. These correlations quantify the connection between the various factors simultaneously changing with the Jet-Flame fan voltage. As the fan voltage increases the Jet-Flame plenum pressure increases, increasing the air mass and volume flow, momentum, and turbulent kinetic energy injected into the char bed and burning sticks. The airflow then interacts with the fuel and fire-tending practices. As explained in the Methodology section, the tending procedure was to break off the charred tip of the burning stick to maintain the woody part fully inserted in the combustion chamber, unless there was visible smoke, then the sticks were withdrawn until the visible smoke subsided. There was no specific firepower level or CO_2 concentration targeted, so effectively the sticks were fed into the fire as fast as they burned without making smoke visible to the red-laser light-scattering realtime PM sensor.

Our working hypothesis for what is happening is as follows. As the Jet-Flame voltage increased, with corresponding increases in injected airflow, momentum, and mixing (turbulent kinetic energy), the char burned faster and hotter, which in turn helped burn the sticks faster, increasing the firepower, firepower intensity (kW firepower per grate area), and temperature. With increasing heat and mixing, less residence time and excess air was needed to achieve close to complete combustion with low visible PM. This type of positive feedback loop was carefully curated by the test protocol. The startup procedure with 20 g charcoal facilitated low-smoke, high-temperature ignition, and high power operation, and constant tending ensured that the Jet-Flame primary air was always blowing into a strong fire. We observed that oversupply of primary air blowing into a weak fire can cause excessive cooling and increased emissions so improved performance is dependent on matching the airflow to combustion conditions. In addition, the Jet-flame enabled two sticks of kiln dried Douglas fir 3.8-cm

Table 3
Pearson's r correlations with operational variables ($N = 57$), all values shown are significant at 95 % confidence.

	Voltage	Temperature	Firepower
Temperature	0.80		
Firepower	0.89	0.94	
Excess air	−0.66	−0.92	−0.88

tall by 4.3-cm wide cut from 2 × 4 dimensional lumber to be burned, larger than the 1-cm × 2-cm pieces of Douglas fir test wood used with the natural draft stoves. Anecdotally we observed during preliminary testing that larger pieces of wood were associated with lower PM emissions with the Jet-Flame, agreeing with a study that found lower average emissions (not statistically significant) with larger wood in a natural draft stove (L'Orange et al., 2012). Future work can further explore the interaction between Jet-Flame injected air characteristics, fuel properties, tending practices, combustion zone conditions, and the influence on temperature, firepower, and excess air.

Relating these intermediate pathways to outcomes on emission factors for these experiments, Table 4 shows that emissions were inversely correlated with voltage, temperature, and firepower, and directly correlated with excess air. The strongest correlation for CO and PM was with temperature, while BC correlated most strongly with Jet-Flame fan voltage. The correlation strength was highest with CO, less strong with PM, and weakest with BC. The trend identified here of decreasing emissions with increasing firepower with variable speed Jet-Flame forced air (negative Pearson's r correlation coefficients) is counter to the trend in natural draft side-feed rocket stoves discussed in the introduction.

Natural draft test runs were also completed with the Heavy Rocket at varying firepower. When emissions data from the natural and forced draft cases are compared on the same figure against firepower (Fig. 8), the divergence in trend becomes clear. For example, at 2 kW during these tests the Jet-Flame reduced PM emissions from the natural draft case by about 50 %. As firepower increased natural draft to 5 kW, the PM emissions factor increased by approximately a factor of three. With Jet-Flame forced air, the emissions factor reduced by about half from 2 kW to 5 kW increasing the Jet-Flame PM reduction to about 90 %. PM emissions factors remained low out to 8 kW, the maximum value tested in this series. The spread seen in the Jet-Flame PM data illustrate the sensitivity to operation. At 5 kW, a cluster of test runs around 60 mg$PM_{2.5}$/MJd confirms the data from the paired testing discussed in part 1. Using the cooking power curves from (Jetter et al., 2012) and assuming the same thermal efficiency as measured during the paired tests of part 1, an 8 kW fire can boil 5 L in about 11 min with very little PM. This ability for a Jet-Flame assisted earthen rocket stove to lower emissions factor at increasing firepower is a unique feature highly valued by cooks that prefer fast, high-power cooking with low smoke.

Also plotted in Fig. 8 is the Jet-Flame fan voltage vs. firepower. The direct correlation is clear and the spread of firepower at each fan voltage indicate how tending practices also influence firepower. The connection between fan voltage and firepower confirms that a cook can control the firepower and maintain low emissions by adjusting the Jet-Flame fan, an additional usability benefit. CO emissions factors trended lower with increasing firepower for both natural and forced draft cases, with Jet-Flame significantly lower at all power levels.

Fig. 9A and B shows the relationship between combustion chamber temperature and emissions, illustrating that both PM and CO are inversely correlated with temperature, and CO-temperature is the strongest correlation in Table 4. Whether these reductions are due to the effects of temperature alone or co-correlated with other factors cannot be separated in this study. An increase in temperature is known to increase the rate of CO oxidation which in turn leads to lower emissions for a combustion environment with a given amount of oxygen and mixing (Baldwin, 1987; Gottuk et al., 1995; Nussbaumer, 2003). However, as detailed above, under the operating conditions of this study, combustion chamber temperature increases with increasing firepower and fan voltage, with a corresponding increase in injected airflow, momentum, and turbulent kinetic energy for improved mixing.

Table 4
Pearson's r correlations with emissions factors per MJ delivered ($N = 57$ for CO and $PM_{2.5}$, $N = 47$ for BC), values in italics are not statistically different from a random correlation at 95 % confidence.

	Voltage	Temperature	Firepower	Excess air
CO	−0.59	−0.87	−0.76	0.81
$PM_{2.5}$	−0.46	−0.72	−0.57	0.70
BC	−0.46	−0.37	−0.34	*0.24*

The PM-temperature correlation is not as strong, however there may be more factors involved in PM emissions than for CO. For example, char is known to be chemically active and plays a role in tar cracking, changing the chemical composition and sooting tendency of the pyrolysis gasses (Boroson et al., 1989). In biomass gasification, the flow velocity through the gasification zone determines the gasification temperature, syngas composition, and tar content (Reed et al., 1999). If a similar effect occurs in wood stick combustion, the elevated temperatures and enhanced char activity due to the Jet-Flame injected air could change the gas composition and sooting tendency, introducing another feedback loop between Jet-Flame air and emissions that could contribute to the trend of decreasing emissions with increasing firepower. Ash is another important consideration with forced primary air. The high-temperature oxygen-rich conditions in the fuel zone that tend toward low emissions of products of incomplete combustion can lead to increased volatilization of the inorganic ash components and can increase PM emissions by an alternate pathway (Lamberg et al., 2011; Nussbaumer, 2003). This tradeoff between low-tar producer gas and increasing volatile ash PM was documented in small-scale gasification of low-ash wood pellets and high-ash cow manure (Kirch et al., 2020). The low ash content of the Douglas fir test wood used in this study (0.8 %) may have reduced the impact of the ash PM pathway in these results. In addition, the role of charcoal in wood-stick combustion in cookstoves is not well understood. For example, recent CFD cookstove simulations simplified the combustion domain with constant release of volatiles from fixed volumes representing the stick without a model of the char packed bed. These simulations then neglect the interaction and feedback loops between primary airflow, char burning, firepower, and temperature (Barbour et al., 2021; Miller-Lionberg, 2010; Pundle, 2019; Udesen, 2019). Additional investigation is needed to explore how primary air injection directly into the fuel bed influences particle formation and growth to fully understand the drivers of reduced emissions at higher firepower observed in this study with the Jet-Flame, opposite the natural-draft trend.

Conclusions and future work

The Jet-Flame cookstove accessory is a new low-cost commercial product that can retrofit existing biomass stove designs to inject turbulent jets of primary air into the combustion zone from below the fire. This configuration potentially retains the usability advantage of being able to burn unprocessed, large sticks of locally collected fuels in existing stove designs with already high adoption rates. Fuels with high moisture content also light and burn more readily (Barbour et al., 2021), and char is burned to completion as useful energy, due to the forced primary air. Use of the accessory also enhances performance by increasing thermal efficiency and lowering emissions of products of incomplete combustion, and extending the firepower range and controllability to achieve the fast, high-power cooking with low smoke that cooks prefer.

Six common single-pot stove designs were tested as both natural draft and with the Jet-Flame to assess the retrofit potential of the Jet-Flame. In laboratory water boiling tests following a modified ISO 19867-3 protocol similar to the Water Boiling Test 4.2.3 with optimized low-smoke startup procedures and a carefully tended fire of test-wood sticks, we observed dramatic emissions reductions and performance improvements. Retrofitted stoves demonstrated an average 89 % reduction in PM, 74 % reduction in CO, 96 % reduction in BC, and 34 % improvement in thermal efficiency without char. The Jet-Flame retrofit was able to help simple, low-cost existing stoves

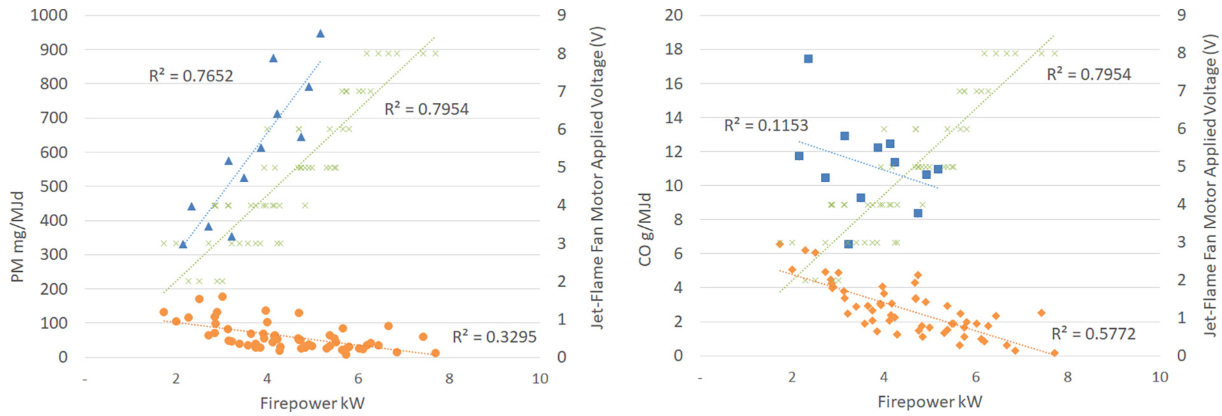

Fig. 8. A) $PM_{2.5}$/MJd and B) CO/MJd vs. Firepower for Jet-Flame operating at 2–8 V and natural draft. Orange markers are forced draft, blue markers are natural draft, and green Xs are Jet-Flame fan motor voltage.

burning sticks to match the lab results of some of the highest-performing stoves in the market using processed biomass fuel.

The Jet-Flame fan voltage sweep section of this study assessed the potential for the Jet-Flame to maintain low emissions over a range of firepowers by adjusting the voltage to the fan driving the jets of forced primary air. We showed that with increasing Jet-Flame voltage and airflow, firepower and cooking power increased while $PM_{2.5}$ and CO decreased. This is counter to the natural draft trend for $PM_{2.5}$ emissions that typically increase with increasing firepower in rocket-type stoves. The Jet-Flame achieves high-power, fast cooking with low smoke, and enhanced ability to modulate firepower by adjusting the Jet-Flame fan desired by cooks.

Particle number emissions and particle size distribution remain an open question needing additional exploration. Previous studies found that secondary air injection under certain conditions can increase emissions of ultrafine particles and shift the particle size distribution toward a larger percentage of smaller particles (Caubel et al., 2020; Rapp et al., 2016). Health risks due to small particles may remain even as PM mass is reduced. However, the mechanisms of particle formation and growth may be different between the secondary air injection configurations of those studies, and the primary air injection used in the Jet-Flame in this study, and follow-up investigation is needed.

While these laboratory results indicate the potential of the Jet-Flame accessory to reduce emissions and increase efficiency in the lab, performance in real-world context will likely differ due to changes in use, operation, fuel characteristics, and tending practices. Further exploration is needed to determine the mechanisms driving the emissions reductions and to optimize the control parameters of the Jet-Flame forced primary air such as mass flow rate and velocity under a variety of operating conditions with different fuels and tending practices in various combustion chamber geometries.

Declaration of competing interest

Authors SB, DE, DS, NM acknowledge a financial interest in sales of the Jet-Flame and technologies used in this research, and they could potentially benefit from this research.

Acknowledgements

Development of the Jet-Flame was supported by EPA SBIR II contract EP-D-18-009, Intellectual Ventures Global Good, and grant #EE0006285 from the U.S. Department of Energy. This work has not been reviewed by the EPA or DOE, and any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the EPA or DOE. Support for laboratory equipment was provided with support from the Osprey Foundation. Support for David Evitt's graduate studies investigating turbulent jets of injected primary air came from Shengzhou Stove Manufacturer. We appreciate assistance from George Howe on the statistical analysis of the firepower sweep data. We thank Kim Still for assisting the experimental data collection and processing at Aprovecho.

Appendix A. Emissions testing system

The LEMS captures all of the emissions released from a stove and mixes them in a dilution tunnel before sampling. A radial flow blower pulls the stove emissions and dilution air through the hood and tunnel

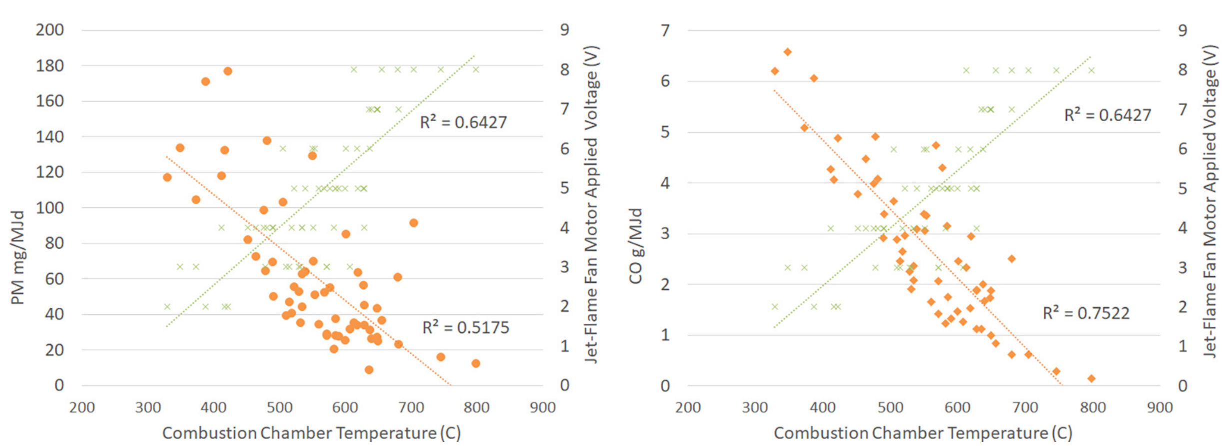

Fig. 9. A) $PM_{2.5}$/MJd and B) CO/MJd vs. combustion chamber temperature for Jet-Flame operating at 2–8 V. Orange markers are emissions, green Xs are Jet-Flame fan motor voltage.

and the volumetric flow rate through the tunnel is recorded. Time-resolved PM, CO and CO_2 concentrations in the dilution tunnel are measured by sensors, while a pump and filter system pulls a separate sample from the dilution tunnel so that the average concentration (within the dilution tunnel) of $PM_{2.5}$ over the test period can be determined. Specialized software is used for post-processing of the measured data to report the ISO 19867-1 performance metrics, and the ISO 19867-3 Voluntary Tiers of Performance, which are based on the mass of emissions measured.

The LEMS dilution tunnel volumetric flow rate is determined based on measurements made by a Honeywell HSC series differential pressure transducer with a $\pm 1''$ W.C. range and a type K thermocouple. The pressure transducer outputs an analog signal based on the pressure drop measured across a Nailor FSA-06 flow grid. The flow grid is a four point, amplified Pitot static array that provides a low pressure drop through the system and a strong differential pressure signal, averaged across the entire duct cross-section. The temperature measurement is made near the gas sample location and the temperature drop between the flow grid and the sample ports is assumed to be negligible. Bernoulli's equation is used with the dynamic pressure measurement of the flow grid, and the temperature within the duct to derive the volumetric flow rate of the diluted stove emissions. The static pressure within the duct is measured during calibration of the flow grid and makes a slight correction to the determination of volumetric flow rate following ISO 19867-1.

Real-time measurements of CO, CO_2, and PM are recorded by the LEMS Sensor Box. The electrochemical CO sensor is an Alphasense CO-AF with a range of 0 to 5000 ppm and is temperature compensated during post processing. The CO_2 sensor is a Cozir-A GC-00022 with a range of 0 to 10,000 ppm that uses a non-dispersive infrared (NDIR) absorption based measurement to determine the CO_2 concentration and outputs ppm. Both sensors undergo three point calibration using reference gas certified to ± 1 % of nominal by Mesa Labs (California). A custom scattering photometer gives an indication of time resolved PM. It uses a 650 nm red laser and its average output is calibrated against gravimetric measurements from each test phase.

The gravimetric system gives a direct measurement of average $PM_{2.5}$ during the testing period. A vacuum pump pulls emissions through the sample line and the critical orifice, which holds the flow at a steady 16.7 L/min. A cyclone particle separator is used so that only particles with a diameter of less than 2.5 μm are collected on a 47 mm glass fiber filter while the pump is on. The filter is conditioned in a desiccator before being pre- and post-weighed at 0.01 mg resolution using a Citizen CX265 balance. The calculation of the total $PM_{2.5}$ mass emitted by the stove is based on the ratio of the gravimetric sample volumetric flow rate and the volumetric flow rate through the dilution tunnel, as is specified in Eq. (3) of the ISO standard (ISO 19867-1:2018, 2018).

The Black Carbon (BC) filter loading was measured on each filter for each 30 minute test period using the Nexleaf photo analysis service. This technique agrees with reference instruments for BC and elemental carbon (EC) to within 20 % (Ramanathan et al., 2011). Note, BC refers to the optical properties and EC to the chemical and thermal properties of aerosols thus are related but distinct measurements (Petzold et al., 2013). The Nexleaf analysis yields a filter loading of BC on the filter in units of $\mu g/cm^2$. For these tests, 47 mm diameter Pall A/E glass fiber filters were used which have a catchment area of 12 cm^2. Multiplying the filter loading by the catchment area yields the BC sample mass. The total amount of BC emitted during the test period was derived based on the ratio of the dilution tunnel flow rate to the filter sample flow rate in the same way that the $PM_{2.5}$ emissions rate is derived as per Eq. (3) in the ISO 19867-1:2018 standard. The BC metric shown in this report is the emissions factor of BC on the basis of energy delivered to the cooking pot. The ratio of the BC emissions factor to the $PM_{2.5}$ emissions factor is also reported. Note the Nexleaf BC estimate has upper and lower limits of detection based on filter color, i.e. if the filter is "too white" or "too black" the Nexleaf BC system is unable to correctly determine the BC filter loading. To prevent BC measurements that were over-range 100 mm glass fiber filters were used and changed every 15 min of run time (two filters during a 30-minute test).

Appendix B. Cookstove construction and operation details

During the Modified ISO 19867-1:2018 performance testing, firepower was maintained between 4 to 8 kW to achieve cooking power in the range of 1 to 3 kW. For forced-draft mode with the Jet-Flame with the Open Fire, African Bucket, and the Asian Bucket the thermal efficiency of these stoves was higher and the operating firepower was reduced to match the cooking power and time to boil from natural-draft mode.

B.1. Open Fire

The Open Fire was constructed from 19-cm tall bricks, approximately 6-cm taller than those in the Jetter et al. (2012) study. A 24 cm in diameter stainless steel pot was used with no skirt. The pot was filled with 3 L of water. The smaller quantity of water was used to ensure that the natural draft mode would boil within 30 min. Sticks were placed on a layer of bricks to ensure that the heat from the fire did not travel too quickly through the metal floor of the LEMS hood. There was no grate under the sticks. The sticks had a cross section of 2-cm tall by 1-cm wide and were fed from all three sides of the fire. To achieve a cooking power similar to the other stoves, the flames from the open fire approached the handles of the pot. Maintaining a high firepower in an open fire necessitates that the sticks be crossed and in multiple layers.

The Open Fire with Jet-Flame used the same 19-cm tall bricks. Since the bottom of the Jet-Flame is not flat, a 3-cm tall brick was placed under one side of the Jet-Flame so that it would be level with the floor. A 9-cm tall steel "fence" was installed around the Jet-Flame in order to keep the sticks from falling off the air injection surface of the Jet-Flame. The same fence was used in the other two earthen stove tests where the diameter of the combustion chamber was greater than the diameter of the Jet-Flame air injection surface. The fence rested on the floor and protruded above the Jet-Flame surface by 3 cm.

B.2. Asian Bucket stove

The Asian wood burning bucket stove was modified for the purpose of these tests. The removable brick that normally creates the wood burning mode fuel feed door within the top perimeter of the stove was glued in place so that the top perimeter was continuous. The charcoal mode grate was removed and the sticks were fed in through the charcoal mode air inlet. A stick support was used in natural draft mode which rested on the floor. The stick support elevated the sticks 2.5 cm above the floor of the combustion chamber. The fuel feed door was 11-cm high and 8-cm wide.

The pot supports were cut down to a height of 6 mm. Pots with a diameter greater than 24.5 cm could rest on those supports. The internal pot supports, which are used for pots with a diameter of less than 24.5 cm, remained intact. A 21.8-cm stainless steel flat bottomed pot was used for these tests and was filled with 5 L of water. The internal pot supports kept it 17 cm from the floor of the stove meaning it was sunken into the stove by 4 cm. The diameter of the pot was such that the pot supports were not able to keep it vertical – the pot had to be installed at an angle of about 15°. Had the pot been a few millimeters wider the internal pot supports would have maintained it in a vertical position.

During forced draft mode the Jet-Flame was installed through the fuel feed door. The distance between the front of the Jet-Flame and the back of the combustion chamber was such that the air injection holes of the Jet-Flame were centered within the combustion chamber. The 9-cm tall stick fence was used to keep the fuel on top of the Jet-

Flame and the depth of the Jet-Flame within the combustion chamber was established with a brick that was cut to length. The depth of the Jet-Flame within the combustion chamber was such that the air jets were centered within the diameter of the pot.

B.3. African Bucket stove

The African Bucket stove has a bucket-shaped fired ceramic body with side-fed stick entrance at the bottom. It has a single 3.5-cm thick ceramic wall that creates a combustion chamber measuring 20.7-cm tall (floor to bottom of pot), 16 cm in diameter at the base, and 20.7-cm diameter at the top. It has a fuel opening that is 10.5-cm wide and 10.5-cm tall at the center of the arch. The pot supports have a height of 24 mm. ARC modified the stove to accommodate the Jet-Flame for the purpose of this comparison as follows: the fuel door was squared off and enlarged to 11-cm wide by 10.5-cm tall. When the Jet-Flame was used, a 9-cm tall steel "fence" was installed around the Jet-Flame in order to keep the sticks from falling off the air injection surface of the Jet-Flame. Using the Jet-Flame reduced the height of the fuel opening to 6.5 cm, and the floor-to-pot distance to 18 cm.

B.4. Heavy Rocket stove

The high-mass brick rocket stove is a side-fed stick stove made from 4 layers of unfired sand and clay bricks. It has a stove top with a square opening that is 11.5-cm wide and 10-mm tall pot supports. The fuel door is 12-cm wide by 15-cm tall. The square combustion chamber is 23-cm deep. The floor to pot distance is 31 cm, reduced to 25 cm with the Jet-Flame. The Jet-Flame was installed from the side of the stove by cutting off half of one of the bottom bricks based on suggestions from field reports that side insertion was preferred over front insertion to protect the jet-flame during cooking and keep it cleaner. When inserted from the front the plug with USB connection was found to be vulnerable and in the way of cooking. The Jet-Flame was pushed against the side wall. The empty space that was left between the flat inside wall of the combustion chamber and the curved end of the Jet-Flame was filled with small pieces of brick. The stove was tested with the 7-cm tall corrugated pot skirt that comes with the stove. The corrugations are such that the distance from the pot to the skirt ranges from 0 to 12 mm, so the average distance is about 6 mm.

B.5. Medium Rocket stove

A thin walled refractory cement combustion chamber in the StoveTec single door rocket stove surrounded by ceramic fiber insulation was used in these tests to represent a medium-weight rocket stove option. The Jet-Flame was designed to fit in the combustion chamber of this stove, filling the floor area. The round steel stove body has a fuel door that is 11.5-cm wide by 10.5-cm tall. The stove top is cast iron with 6 mm tall pot supports. The combustion chamber is 17-cm deep, the riser is 10-cm in diameter. The distance from floor to pot is 26.8 cm, reduced to 21.8 cm with the Jet-Flame added. When used with natural draft, a wire stick support raises the sticks 3 cm above the combustion chamber floor.

B.6. Light Rocket

A steel alloy combustion chamber in the StoveTec single door rocket stove surrounded by ceramic fiber insulation was used in these tests to represent a low-mass rocket stove option. The Jet-Flame was designed to fit in the combustion chamber of this stove, filling the floor area. The stove top is cast iron with 6 mm tall pot supports. The round steel stove body has a fuel door that is 11.5-cm wide by 10.5-cm tall. The combustion chamber is 17-cm deep, the riser is 10 cm in diameter. The distance from floor to pot is 26.8 cm, reduced to 21.8 cm with the Jet-Flame added. When used with natural draft, a wire stick support raises the sticks 3 cm above the combustion chamber floor.

Appendix C. Startup and testing procedure

For part 1, the tests of 6 stoves, only high power cold start tests were performed. The startup emissions were recorded following the standard, but the shutdown procedure was omitted. This modified ISO protocol is similar to the high-power cold-start phase of the water boiling test (WBT) except the ending criteria is 30 minute elapsed time instead of when the pot of water boils as in the WBT (WBT 4.2.3, 2014).

During part 1 the stoves were continuously fed with dimensionally cut Douglas Fir lumber that had a wet basis moisture content of between 10 % and 13 %. The lumber did not contain bark. Pieces of wood with knots or sap veins were not burned. The size of the wood varied for each stove configuration, as did the pot and skirt, and is noted in the description of the stoves.

Startup procedure can have a dramatic impact on measured emissions especially if the stove is relatively clean during operation (Fedak, 2017). (Barbour et al., 2021) found that 87 % of PM emissions occurred during the first 3 min of a water boiling test with forced primary air. For this testing series an ignition procedure was developed that minimizes startup emissions. For the Jet-Flame forced-draft tests 20 g of charcoal left over from a previous test with the same Douglas fir fuel was soaked with 10 g of alcohol and placed in the combustion chamber on top of the primary air holes of the Jet-Flame. The alcohol was ignited and allowed to burn for 30 second natural draft and then the Jet-Flame fan was turned on and the sticks were fed into the fire. The charcoal with Jet-Flame primary air builds heat quickly with little visible smoke.

An optimized starting procedure was also used during the natural draft tests. A crib of pencil-sized kindling was built and 10 g of alcohol was poured on top and ignited. A band saw was used to cut slits into the end of the first sticks fed into the fire to aid in the ignition process for all tests. Time resolved plots of $PM_{2.5}$ are shown in Fig. C.1 for a typical Jet-Flame optimized start (top) vs. a typical Natural Draft optimized start (bottom) of the Asian Bucket Stove. In this example the startup emissions were not significantly different then the emissions during steady state for both the natural draft and forced draft cases.

The fire was maintained by keeping the sticks pushed all the way to the back of the combustion chamber. The charcoal that forms at the end of the sticks was gently broken off periodically (and left in the combustion chamber) in order to keep the woody part of the stick in contact with the back of the combustion chamber. The feed rate was also slowed or the stick was retracted slightly when the stove tester observed an emissions spike from the light scattering based particulate matter sensor of the LEMS. The concentration of CO_2 in the dilution tunnel was observed and used to maintain a steady firepower from test to test. With a LEMS dilution tunnel dynamic pressure reading of 0.3 in of H2O the target CO_2 reading was between 2300 and 3000 ppm. This range was easy to maintain during Jet-Flame testing, but difficult during natural draft stove testing.

During part 2, the firepower sweep of the Jet-Flame voltage, the heavy rocket stove was fed with kiln-dried Douglas Fir lumber that had a wet-basis moisture content of between 10 and 13 %. Each test segment was 30 minute long and performed in groups of three so that one was a cold start with startup emissions, following the part 1 startup procedure, and the two following were hot starts. The fire was not extinguished between tests so the hot starts did not include startup emissions, and none of the tests included the shutdown procedure. The sticks had a cross section of 3.8-cm tall by 4.3-cm wide. As in part 1, the woody part of the stick was maintained at the back of the combustion chamber unless the stove tester observed an emissions spike from the real-time particulate matter sensor and pulled the stick back, but otherwise there was no attempt to control the average feed rate of the fuel for a given fan voltage setting.

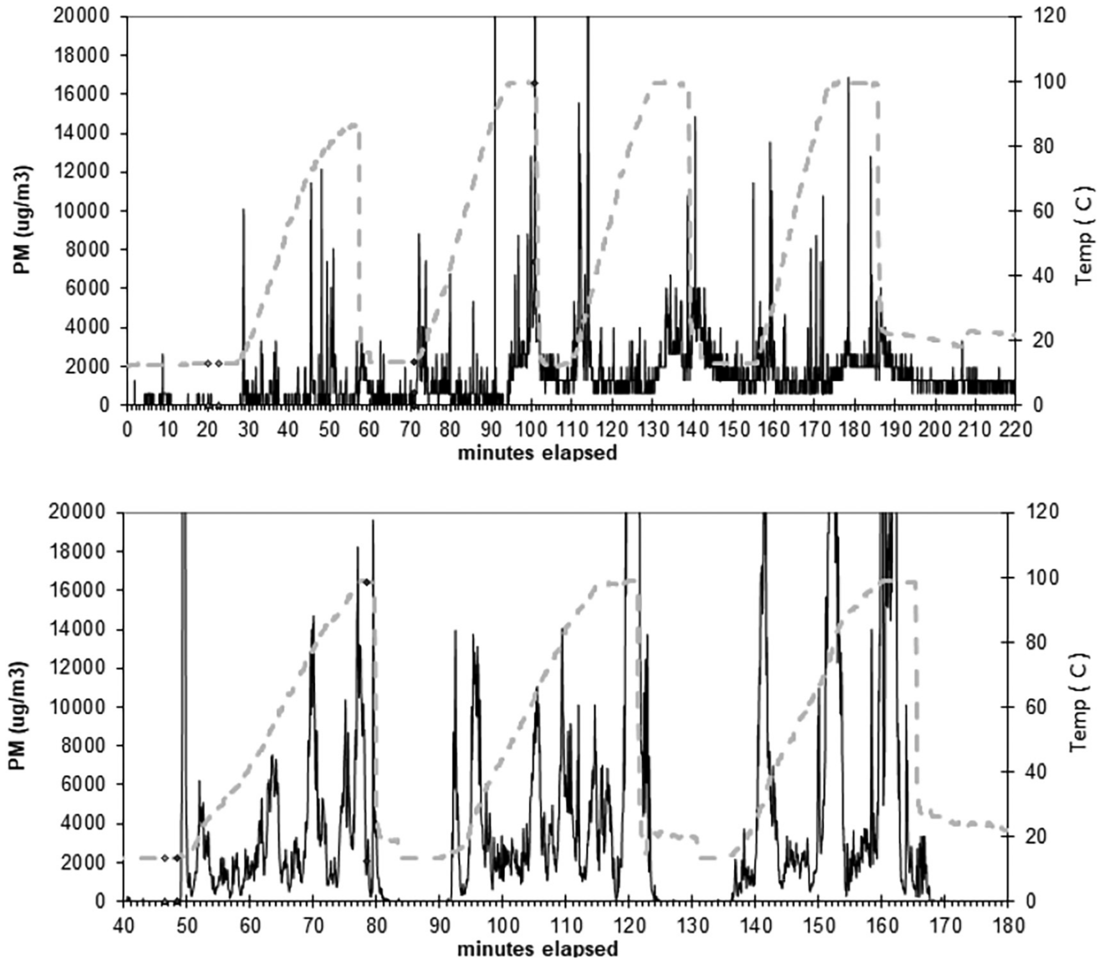

Fig. C.1. Real-time example emissions plot - Forced Draft (top) and Natural Draft (bottom) showing PM (solid line) and temperature (dashed line).

During part 1, the Jet-Flame was powered by USB standard 5 V as one would find during actual use. During part 2, a variable voltage power supply was used to supply between 2 and 8 V to the DC motor in the fan. Tests were performed at 9 V, but are not reported here because at the 9 V setting there was backdraft. The minimum setting of 2 V was chosen because the fan motor operates intermittently at voltages below that point. During part 2, the stove was tested with a stainless steel flat bottom pot that had a diameter of 24 cm and was filled with 5 L of water. The stove was tested with the 7-cm tall corrugated pot skirt that comes with the stove. The corrugations are such that the average distance from the pot to the skirt ranges from 0 to 12 mm, so the average distance is about 6 mm.

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