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Mini Review

Rocket Stove—Principle, Advantages and Disadvantages

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Abstract: This mini-review summarizes current knowledge of rocket stoves as a technology for efficient, low-emission biomass combustion. It focuses primarily on two major design configurations: natural-draught J-tube systems and forced-air systems. Their design principles, operational stability, thermal efficiency, fuel consumption, and emission performance are compared with those of traditional open fires and more advanced wood-burning appliances. Available studies indicate that J-tube systems can substantially reduce fuel consumption and emissions of CO and PM2.5 compared with open fires. However, their performance is strongly influenced by combustion-core geometry, fuel properties, and operating conditions. Forced-air systems can provide more stable combustion, lower emissions, and higher efficiency through controlled primary- and secondary-air supply. Their performance nevertheless depends on the appropriate optimisation of airflow rates, nozzle positions, and combustion-chamber geometry. Overall, rocket stove technology provides a promising basis for the further development of efficient, low-emission biomass combustion appliances, including advanced rocket space heaters and rocket boilers.

Keywords: rocket stove; J-tube system; forced-air combustion; biomass combustion; emission reduction; thermal efficiency; fuel consumption; CO emissions; $PM_{2.5}$ emissions

1. Introduction

Wood and other forms of solid biomass have been used as a source of heat and energy since the earliest stages of human civilization. For centuries, biomass combustion represented one of the most accessible ways of providing space heating, food preparation and basic thermal comfort. In many regions, especially in rural areas and developing countries, traditional biomass combustion is still widely used due to the local availability and low cost of fuel. According to the World Health Organization, billions of people worldwide continue to rely on polluting fuels and inefficient combustion technologies, including open fires and simple stoves using wood, crop waste, animal dung and coal for household cooking and heating [1]. However, the use of such fuels in poorly controlled combustion systems is associated with substantial emissions of carbon monoxide, particulate matter and other pollutants, contributing significantly to household air pollution and related health impacts [2]. At the same time, increasing energy demand, energy security concerns and the need to reduce dependence on fossil fuels have renewed interest in biomass as a locally available and renewable energy source [3–5]. Agricultural residues, woody biomass and other solid biofuels therefore remain important energy carriers, particularly in regions where access to modern energy infrastructure is limited [4].

Stationary combustion appliances using solid biomass differ considerably in their construction, level of technical sophistication and emission performance [6]. At the simplest end of the spectrum are open fires and primitive stoves, which are usually characterized by poor control of combustion air, low combustion temperatures and incomplete burnout of fuel [7]. More advanced appliances, such as enclosed wood stoves, masonry heaters, pellet stoves and modern automatically controlled biomass boilers, are designed to improve combustion conditions through controlled air supply, optimized combustion chamber geometry, staged combustion, heat accumulation or automated fuel feeding [8,9]. These technical improvements can significantly increase thermal efficiency and reduce emissions, but they are usually accompanied by higher costs, more complex operation and greater requirements for maintenance [10]. Between these two extremes, there is a broad group of simple but improved biomass combustion devices that aim to combine low construction complexity with better combustion performance. Rocket stoves represent one of the most prominent examples of this approach.

Rocket stoves are biomass combustion appliances designed to achieve high combustion temperatures and intensive mixing of combustible gases with combustion air. Their characteristic geometry and strong natural draught can promote more complete combustion, thereby reducing occurrence of products of incomplete combustion compared with traditional open fires and simple stoves. However, the actual performance depends strongly on the combustion-core geometry, fuel properties, air supply, and operating practice.

In terms of the combustion process, rocket stoves differ from conventional local heaters mainly in that in a relatively small and intensely heated combustion core, a fuel conversion occurs rapidly within a relatively small and intensively heated combustion core [11]. The initial heating and drying of the biomass is followed by devolatilization, during which volatile organic matter and other flammable gases are released from the fuel structure [12]. In the immediate vicinity of the fuel bed, partial gasification may occur simultaneously, especially in areas with limited access to oxygen, while the released gases are subsequently drawn by the strong draught into the high-temperature burnout zone [13]. Compared to conventional stoves, where the combustion chamber can be larger, the temperature field less homogeneous and the mixing of flue gases with combustion air is more dependent on the current operating state, the geometry of the rocket stove supports faster heating, longer residence of flammable gases in the high-temperature zone and more intensive mixing with air [14]. These conditions can positively influence the kinetics of oxidation reactions, in particular the afterburning of CO, light hydrocarbons and soot precursors, thereby contributing to lower emissions of incomplete combustion products [15]. However, the resulting emission and efficiency benefit is not given by the principle of the rocket stove itself, but always by the combination of the geometry of the combustion core, the ratio of primary and secondary air, thrust, humidity and dimensional distribution of fuel, as well as the method of operation [16].

Recent research has focused not only on basic natural-draught configurations, such as J-tube systems, but also on modern forced-air rocket stoves equipped with an actively controlled combustion-air supply [17]. These developments indicate that rocket stoves should no longer be regarded merely as simple appliances governed by draught and heat. It is increasingly being shown that their true properties are the result of a complex interaction between the geometry of the combustion core, the character of the airflow and the quality of the fuel used [18]. Although rocket stoves are often presented as a significantly cleaner and more efficient alternative to traditional methods of biomass combustion, available studies show that their real benefits must always be assessed in a specific context and compared to reference devices [19,20]. A number of laboratory and field measurements confirm that properly designed rocket stoves, which have so far been typically used as stoves mainly in developing countries, can achieve higher thermal efficiency, lower specific fuel consumption and significantly lower CO and $PM_{2.5}$ emissions compared to simple open fireplaces, often by tens of percent [21]. At the same time, however, it turns out that even many “improved” designs do not normally reach the level of emissions recommended by health organizations, especially in real domestic operation, where variable fuel quality and operating methods come into play [22]. A distinction must therefore be made between rocket cookstoves and rocket-based space-heating appliances. Cookstoves are primarily designed for rapid heat transfer to a cooking vessel and are generally evaluated using cooking-oriented test procedures, whereas space-heating appliances are designed for prolonged heat delivery to the surrounding environment. Most studies reviewed in this work concern rocket cookstoves. Consequently, comparisons with conventional wood-burning space heaters are used only to provide a broader technological context and must be interpreted with respect to differences in appliance purpose, operating conditions, and testing methodology. This mini-review therefore summarizes current knowledge on J-tube and forced-air rocket stove systems while maintaining a clear distinction between cooking and space-heating applications.

The novelty of this mini-review lies in its combined assessment of J-tube and forced-air rocket stove systems and in linking current knowledge on rocket cookstoves to the further development of rocket-based space heaters and boilers. The review compares the construction, combustion performance, thermal efficiency, fuel consumption, emissions, and practical limitations of both system types. Based on this comparison, transferable design principles are identified, together with the principal technical limitations and remaining research needs relevant to space-heating applications. Relevant literature was identified through a broad search of scientific publications addressing rocket stoves and related biomass combustion technologies, supplemented by relevant references cited in the selected publications.

2. Construction Variants of Rocket Stoves and Their Performance Characteristics

In the following sections, the terms “rocket cookstove” and “rocket-based space-heating appliance” are used according to the intended function of the system described in each study. Because most experimental investigations concern cookstoves, their reported performance is interpreted using the functional requirements and testing procedures applied in the original studies. Unless otherwise stated, the term “rocket stove” is used as a general designation encompassing both application types.

Rocket stoves exist in several design variants, which differ in both their geometric configuration and level of technical sophistication. Many of these appliances are locally built or constructed using low-cost materials. This review focuses on the two most widespread and extensively documented design configurations of rocket stoves. The first group consists of J-tube systems with natural draught, which represent the traditional form of rocket stoves based exclusively on natural-draught airflow. The second group is forced-air systems, i.e., structures using forced air supply by a fan or blower. These two different concepts represent different approaches to the control of the combustion process and fundamentally differ in the way they affect the temperature field, the combustion regime and the degree of combustion of volatile substances. Subsequently, these differences are reflected in the resulting efficiency, emission behaviour and overall operational stability of the device.

3. J-Tube Systems

The J-tube design represents the most traditional and at the same time the most widespread variant of the rocket stove, used in various modifications for several decades. Their basic geometry is based on the shape of the letter “J” and consists of a fuel feed part, a combustion tunnel and an insulated vertical riser (as shown in **Error! Reference source not found.**) [23]. It is the combination of a short combustion tunnel and a well-insulated vertical riser that creates the characteristic chimney effect, which promotes an intense flue gas flow and a high temperature in the afterburner area [24]. The classic design principles of rocket stoves emphasize that the combustion chamber should be insulated as best as possible to minimize heat loss to the furnace body, and that the vertical part of the combustion core should have sufficient height to create stable draught and rapid removal of hot gases [25].

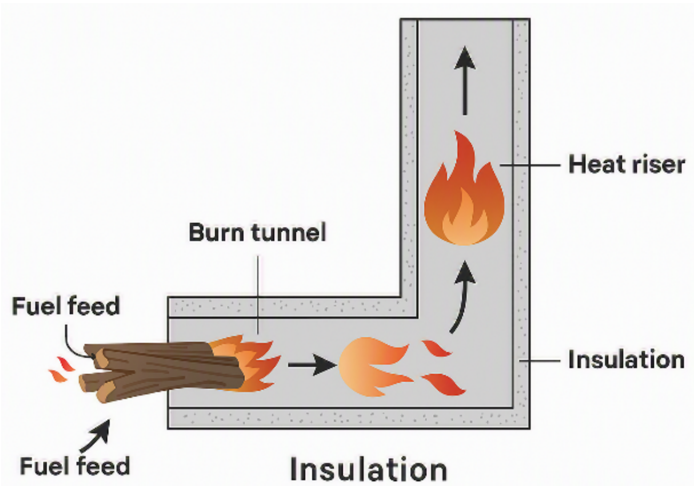

Figure 1. Schematic representation of the basic geometry of a J-tube rocket stove system.

The fuel feed part does not always have to be purely horizontal. In practice, in addition to the classic side feeding, variants with a slightly to moderately inclined feeder are also used**,** which improve visual control of combustion and at the same time facilitate spontaneous sliding of fuel into the combustion zone. Such a solution can simplify operation and contribute to a more uniform dosing of smaller pieces of biomass, especially when burning small twigs or other light piece fuel (for a better visual idea, the **Error! Reference source not found.**) [26]. However, the exact optimal inclination angle cannot be determined as a universally valid value from the available literature, because the resulting behaviour of the system depends on the specific geometry of the combustion core, the type of fuel, the operating mode and also on the physic-mechanical properties of the fuel, especially its granulometry, composition, bulkiness and bulk angle [27].

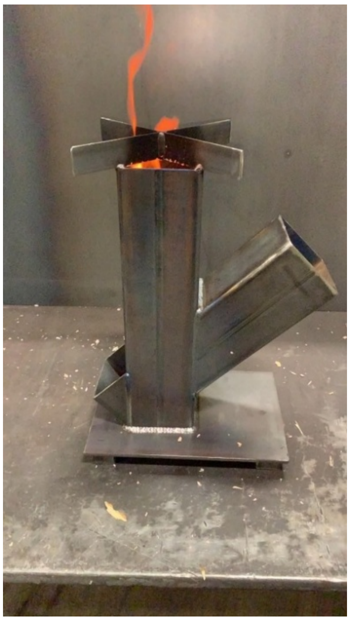

Figure 2. Example of a metal J-tube rocket stove with an inclined fuel feed section and a vertical heat riser.

In terms of performance, J-tube systems are most often associated with household cooking and with low- to medium-power devices designed for lump biomass. For example, for a specific PRSv5 natural draft solution, an optimal working range of approximately 0.2–1.3 kW is stated, which corresponds well to use for normal home food preparation [20]. However, in addition to these small household appliances, there are also larger natural draft designs for community or institutional use, so J-tube cannot be equated exclusively with very small cookstoves [28]. At the same time, the current literature suggests that forced-air systems are not necessarily always designed only for "higher power ratings", but are more advantageous especially where a wider and more controllable combustion power range, higher firepower and better response to changes in operating mode are required [26]. The difference between J-tube and forced-air designs therefore lies not only in the absolute value of power, but above all in the way it is achieved and regulated.

This simplicity of design is one of the main reasons why J-tube systems have become the basis of many low-cost cookers and heaters, especially in developing countries, where they replace traditional open fireplaces with high fuel consumption and unfavourable emission parameters. Laboratory and numerical studies show that properly designed natural draft rocket stoves can achieve higher thermal efficiency, lower specific fuel consumption and significantly lower CO and $PM_{2.5}$ emissions compared to an open fireplace, often in the order of tens of percent [29]. At the same time, however, it is true that the performance and efficiency of these devices cannot be faithfully described by a single fixed value, because their behaviour changes significantly with the instantaneous heat input and with the intensity of combustion. Therefore, in experimental studies, it was recommended to evaluate the natural draft structure using the input power—thermal efficiency characteristic rather than just one laboratory efficiency value [30].

In addition to the traditional role of cookers and simple heaters, the J-tube principle has also appeared in other applications in recent years. In the commercial practice of developed countries, for example, outdoor and patio units can be found, using the "rocket stove" principle for local heating and at the same time to create a distinctive visual effect of the flame [31].

The main weakness of J-tube systems is that they work exclusively with natural-draught flow and without active combustion air supply control. Draught stability and combustion quality are therefore sensitive to external conditions, equipment geometry, fuel quality and the method of fuel stoking. CFD and experimental work show that the resulting flow, mixing of flammable gases with air, heat transfer and combustion efficiency are fundamentally influenced by seemingly small geometric changes, such as the height of the pot support, the shape of the cone deck, the size of the inlet cross-section, the intake of secondary air or the presence of baffle elements [25,29]. In these studies, CFD models are primarily used to evaluate airflow, temperature distribution, air–fuel mixing, and heat transfer and to assess the effects of changes in combustion chamber geometry, air-inlet dimensions, and pot position. However, the reliability of the results depends on the selected boundary conditions and on the turbulence, combustion, and heat-transfer models used. CFD predictions should therefore be validated against experimental measurements and interpreted as a complementary design tool rather than as a substitute for physical testing.

Closely related to this is the issue of power regulation, which is significantly more difficult in J-tube designs than in forced-air systems. With a natural draft stove, it is possible to influence the air supply to a certain extent by changing the cross-section of the fuel inlet or position, but the regulation of the amount of fuel and its dosage is usually less precise and more dependent on the operator. If the power is reduced by simply restricting the combustion air, there will indeed be a slowdown in combustion and a decrease in firepower, but if the airflow is restricted too much, the oxidation of volatile components can worsen and CO emissions increase [25,32]. From a design point of view, ideal power regulation requires not only combustion air supply control, but also the most even and predictable fuel supply so that the appropriate fuel/air ratio is maintained to the widest possible extent [23,33]. In practice, this can be achieved, for example, by appropriate shaping of the fuel shaft, the use of a fuel support or limiting the size of the added pieces so that the fuel enters the reaction zone gradually, not in large doses [27].

Regarding the height and length of the flame, the available literature does not provide a single universal value for J-tube systems that can be taken over into a technical text without reservation; Current review work rather emphasizes that the behavior of biomass-burning cookstoves is strongly dependent on the geometry, material, height of the combustion part, the method of air supply and operating conditions [34,35]. However, available experimental and design studies confirm that the character of the visible flame is closely related to the instantaneous combustion output, the rate of release of gaseous combustibles from the fuel, the quality of their mixing with air and the velocity of flow in the reaction space [36]. A longer and more pronounced flame is therefore associated with a higher firepower and with a larger volume of volatile components released over time, while with limited air supply, an inappropriate air-to-fuel ratio or less favorable geometry, the flame may be shorter, less stable, potentially resulting in higher emissions of products of incomplete combustion [37]. In decorative outdoor variants, on the other hand, a visually long flame can be deliberately supported by the design of the device and a transparent combustion tube, but in the case of kitchen and low-emission J-tube systems, the goal is not the longest possible flame, but the most complete and stable afterburning of gases in a compact reaction space [38].

Overall, J-tube systems can be characterized as technically simple, operationally economical and structurally very interesting devices, which, if well designed, can offer a significant improvement compared to open fireplaces. Their main advantage is passive operation without a fan and without external energy, while the main limitation remains the limited ability to precisely control the fuel/air ratio and the associated sensitivity to geometry and operation. It is this combination of simplicity and at the same time high design sensitivity that explains why J-tube systems remain an important reference concept for the development of more modern rocket stove devices, but at the same time why they are increasingly compared in recent research with variants with more active combustion control or with more advanced combustion modifications.

4. Forced-Air Systems

Forced-air systems are rocket or related biomass stove configurations in which natural draught is not the sole driving force of the combustion process. Combustion air is actively supplied by a fan or blower, enabling improved control of the total airflow and its distribution between the primary and secondary air streams, and also affects the flow velocity, and the direction of the inlet [39]. Therefore, under-fire, over-fire or staged air injection is more often used in modern forced-air devices, and the resulting effect is not only due to the presence of the fan itself, but especially to the quality of the designed air distribution system and its interaction with the flowing flammable gas in the reaction zone [40].

From a technical point of view, the main advantage of the forced-air system is the ability to work separately with primary and secondary air and thus influence the different phases of combustion. The primary-air stream promotes pyrolysis and combustion of the solid fuel and char within the fuel bed, while the secondary air ensures the oxidation of volatile components and the afterburning of gases above the fuel or in the post-combustion zone [41]. Experimental and CFD studies show that the mere presence of air injection does not automatically guarantee a better emission result. While introducing air into the flame zone can improve mixing and reduce the total weight of the emitted particles, it can simultaneously increase the number of ultrafine particles and locally cool the flame if set up incorrectly [42]. Forced-air designs are not "cleaner" just because they use a fan; Their benefit depends on the optimization of flow rates, the geometry of the inlet openings and the position of the nozzles relative to the main gas stream. In addition to CO and particulate matter, a comprehensive emission assessment should also consider NOx, whose formation during biomass combustion is influenced particularly by the nitrogen content of the fuel and combustion-air distribution. The available rocket cookstove literature provides only limited and insufficiently comparable NOx data, representing an important research gap that cannot be comprehensively addressed within the scope of this mini review. Moreover, potentially elevated local combustion temperatures may promote the formation of thermal NOx through the oxidation of atmospheric nitrogen. However, thermal NOx formation generally becomes significant only at sufficiently high temperatures, whereas fuel-bound nitrogen is typically the dominant source of NOx during solid biomass combustion [43]. Therefore, NOx was not quantitatively compared in this mini review because it is reported less consistently than CO and PM2.5 in the rocket cookstove studies considered.

An important design topic is the design of secondary air injection. Special design tools have also been developed for fan-driven systems, which show that the maximum reduction of $PM_{2.5}$ occurs when the radial penetration of the secondary nozzles reaches approximately the diameter of the transverse flow, as a favorable trade-off is achieved between mixing quality, air-injection energy requirements and thermal efficiency [44]. This also explains why it is emphasized in the literature that forced-air cookstoves must be designed not just as a "natural draft + fan", but as a system in which the distribution of primary and secondary air is part of the combustion architecture itself. For an illustrative visual idea, the following is attached **Error! Reference source not found.**, where different variants of the arrangement of individual components are displayed [11].

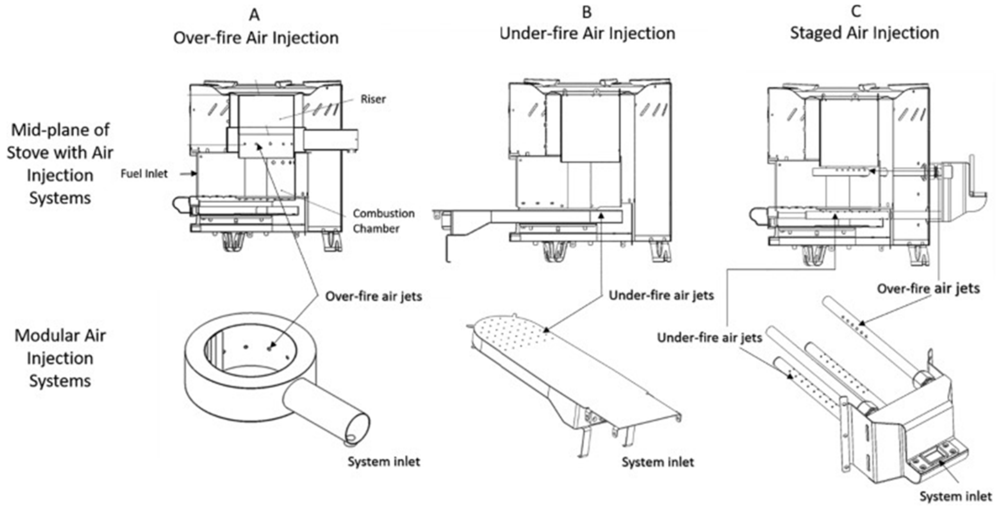

Figure 3. Forced-air system layout options.

Another important design limitation of forced-air cookers is the power source for the fan. While some systems use a battery or external charging, some designs are based on thermoelectric electricity generation (TEG) from heat loss. The forced draft clean combustion cookstove with a thermoelectric generator achieved an electrical power of 4.5 W at a temperature difference of 240 °C, while the cooker itself showed a thermal efficiency of around 44% [45]. This type of solution is particularly interesting from the point of view of system autonomy, as it reduces dependence on external charging, but at the same time increases design complexity and demands on thermal management integration. For a better visual idea, it is included **Error! Reference source not found.**, which shows an example of a commercially available BioLite HomeStove forced-air biomass cooker with an integrated thermoelectric system for powering the fan and USB output option [46].

Figure 4. Example of the forced-air biomass cookstove with an integrated thermoelectric system.

Compared to natural-draft designs, forced-air systems generally have better power control options, but there are limits here as well. With the newly developed forced draft gasifier stove with optimized insulation and airflow rates, it has been shown that thermal efficiency gradually decreases with increasing secondary flow, while CO and $PM_{2.5}$ emissions show a characteristic U-shape trend, i.e., they first decrease and then increase again as the secondary air increases [47]. In the study, a ratio of 4:6 primary to secondary air led to the lowest CO and $PM_{2.5}$ emissions, with the emission factors CO and $PM_{2.5}$ at optimized flow rates Approx. 1.7 $g \cdot kg^{-1}$ fuel a 0.11 $g \cdot kg^{-1}$ fuel [47]. This fits well with the general understanding that the forced*air system must be optimized not only in terms of air sufficiency, but also in terms of its distribution among the individual combustion zones.

In terms of fuels, forced-air systems have been stage-tested with a significantly wider range of biomass fuels than is common with simple J-tube stoves. Systems burning wood chips, pellets, crop residues, dung, coconut shell or agroresidue pellets have been described [45,47,48]. In the case of household gasifier cooking stoves, in a direct comparison of natural versus forced draft, a thermal efficiency of 22.7% was achieved with the WBT (Water Boiling Test) for the natural draft and 25% for the forced draft variant, while the burning time of 0.8 kg of fuel was approximately 65 min for the natural draft and 40 min for the forced draft system [48]. This shows that forced-air designs can provide higher instantaneous power and shorter cooking times, but at the same time they can be more sensitive to combustion chamber geometry, fuel quality and proper flow settings.

An interesting transition between purely natural draft and fully forced draft devices are hybrid draft systems. In the case of the newly developed hybrid draft biomass cookstove, it has been numerically and experimentally proven that the influence of secondary airflow is crucial not only on efficiency, but also on CO and $PM_{2.5}$ emissions. The tested device has achieved Tier 3 in efficiency and Tier 4 (according to ISO/IWA 11:2012) in CO and $PM_{2.5}$ emissions experimentally and numerically, surpassing standard natural draft systems [47]. At the same time, it turned out that the material solution of the structure can also significantly affect the performance of the hybrid draft system. For the two variants with different combustion chamber and insulation materials, both configurations met the Tier 5 for CO, Tier 4 for $PM_{2.5}$ and durability, however, the combination of stainless steel combustion chamber and perlite showed the best overall performance [49].

It is also important to distinguish between laboratory and semi-real world/field results. In a semi-real setting in Malawi, it was shown that the Philips gasifying stove consumed only 31% fuel compared to a traditional three stone fire, generating about 38% CO and 22% $PM_{2.5}$ compared to baseline [50]. At the same time, however, the same research showed that even lower-Cost intermediate stoves can be important in terms of real-word performance, as the price/performance ratio may be more important for adoption than achieving the absolute lowest laboratory emissions. This is an important addition to a purely technical point of view: with forced-air systems, not only combustion quality is decisive, but also operational simplicity, compatibility with local fuels and user-friendliness.

5. Performance, Fuel Consumption, Emissions and Efficiency of Rocket Stoves and Their Indicative Comparison with Conventional Combustion Systems

5.1. Thermal Performance and Fuel Consumption

The differences between the J-tube and forced-air designs are most noticeable in thermal output, fuel consumption, emission characteristics and overall combustion process efficiency. While the previous chapters described the design principles of individual systems, it is the quantitative comparison of operating parameters that allows for an objective assessment of their practical benefits and at the same time to place them in the context of commonly used combustion plants.

In terms of thermal performance, both J-tube and forced-air systems cover a relatively wide range of operating modes. Most natural-draft rocket stoves are designed primarily for home cooking and work in the low to medium power range. In the case of simple natural draft biomass stoves, parameters such as firepower, thermal efficiency, specific fuel consumption and burning rate are usually monitored, and it is their mutual relationship that shows that the resulting output cannot be separated from the type of fuel, the geometry of the combustion chamber and the operating mode [51]. For example, firepower values in the range of 0.458–3324 kW, thermal efficiency of 17.2–33.1% and mean specific fuel consumption of 0.019–0.089 kg per monitored unit of power or cooking task were measured in the case of the two-burner natural draft biomass cookstove [52].

Another useful reference point for evaluating natural draft systems is provided by a work focused on the practical evaluation of a typical improved biomass cookstove, which has been designed for multi-fuel usage, better user-friendliness, lower emissions and higher efficiency [51]. This cooker has been designed for 2 kW energy output and a fuel consumption rate of 1.5 $kg \cdot h^{-1}$, with firepower of 7 kW, turn down ratio of 3.23 and specific fuel consumption of 85 $g \cdot l^{-1}$ set within the modified WBT and at the same time, approximately 75% lower $PM_{2.5}$, 63% lower CO and a significant increase in thermal efficiency were observed compared to a traditional cooker [51].

With forced-air systems, the performance behavior is generally more stable and more controllable, as the fan allows you to actively adjust the combustion air supply and thus the intensity of combustion. In a specific comparative laboratory work, three forced draft fuel wood and coconut shell cookers were tested, evaluating not only their fuel flexibility, but also their thermal efficiency, specific fuel wood consumption, burning rate and firepower [53]. For example, in the case of the OorjaPlus cooker, a relatively stable thermal efficiency of around 32–33% was found in all phases of the test when burning wood chips, while when using a coconut shell, the efficiency in cold start and hot start modes dropped to approximately 29–29.3%, but increased to 47% in the simmering phase [53]. The highest burning rate was recorded for TERI when burning wood chips, with an average of approximately 23 $g \cdot min^{-1}$, and when switching to coconut shell, the thermal efficiency has only decreased by 3–7%, which shows the relatively good fuel flexibility of this design [53].

5.2. Emission Performance Based on Water Boiling Test

In addition to thermal efficiency, emissions are one of the most important variables in the evaluation of biomass cookers. A basic reference comparison is provided by the standardized WBT, which allows different technologies to be compared under uniform laboratory conditions. One of the most cited studies of this type is the work of MacCarty et al., which compares the traditional three-stone hearth (three-stone fire), J-tube rocket cooker and forced-air design [54].

The results summarized in **Error! Reference source not found.**. were obtained under controlled laboratory conditions using the 2003 University of California-Berkeley revised Water Boiling Test, Version 3.0. The test consisted of three phases: a cold-start high-power phase, a hot-start high-power phase, and a 45-min simmering phase conducted at approximately 3 °C below the local boiling temperature. Standard uncovered pots containing 5 L of water were generally used; a 2.5 L pot was used for low-power stoves that were unable to boil 5 L of water. Each stove was tested at least three times, and the coefficient of variation for fuel consumption, CO emissions, and particulate matter emissions was required to be 25% or lower. An overview of the reported parameters is provided in **Error! Reference source not found.** [54].

Table 1. Results for selected cookstove types obtained using the Water Boiling Test Version 3.0 [54].

Parameter	Unit	Three-Stone Fire	J-Tube	Forced-Air
Energy use	MJ/test	21.8	10.6	15.3
CO	g/MJ	65	14	4
$PM_{2.5}$	mg/MJ	1674	1289	1001
Fuel use	g	1253	699	792
Time to boil	min	38.1	22.3	13.2

The results show a gradual improvement in combustion quality during transition from the traditional open fireplace to more modern designs. Compared to a three-stone fireplace, the J-tube cooker reduced fuel consumption by approximately 44% and CO emissions by almost 80%. The forced-air design then achieved the shortest boiling time and at the same time the lowest emissions of all the compared devices [44].

However, it should be emphasized that the data comes from laboratory study that was created before the introduction of the current ISO 19867 methodology. Direct comparisons are therefore limited to the appliances evaluated within this study under the same WBT Version 3.0 conditions [54]. The measured values should not be directly compared with results from more recent studies using different test protocols, sampling procedures, operating conditions, or methods of emission evaluation. Nevertheless, this study remains an important reference documenting the performance of the tested rocket cookstoves compared with a traditional three-stone fire under uniform laboratory conditions [44].

5.3. Comparison with Modern Combustion Technologies

While the WBT results provide a useful historical reference framework, modern studies using ISO 19867 methodologies allow for a more accurate assessment of current rocket stove technologies [55]. A summary of the values reported in the more recent literature is given in **Error! Reference source not found.**. To extend the comparison, data representing modern certified lump wood stoves used for local household heating were also included in the table. The CO and PM emission values were taken from a study by Kistler et al. [56], which evaluated the operation of modern certified stoves with a nominal output of 8 kW, while the efficiency is based on the parameters of current certified devices meeting the requirements of the European Ecodesign legislation [57].

Table 2. Performance and emission comparison of three-stone fires. Rocket stoves and modern wood stoves.

Parameter	Unit	Three-Stone Fire	J-Tube (Natural Draft)	Forced-Air	Modern Wood Stove
Thermal efficiency	%	10–15	25–35	35–45	70–85
CO	g/MJ	50–90	10–20	1–10	2
$PM_{2.5}$	mg/MJ	3000–7000	300–1000	50–300	Not reported *

* The table includes devices intended for different purposes and values obtained using different testing methodologies. The results should therefore be considered indicative and should not be interpreted as a direct comparison of functionally equivalent appliances. $PM_{2.5}$ data were not reported for the modern wood stove. The available value of 67 $mg{\cdot}MJ^{-1}$ represents PM_{10}, which is not directly comparable to the $PM_{2.5}$ values reported for the cookstove categories.

Unlike older studies, significantly sharper differences between individual technologies can be observed in modern data. J-tube systems achieve approximately twice the efficiency of traditional open fireplaces and at the same time significantly reduce CO and $PM_{2.5}$ emissions. However, particulate matter emissions remain in the order of hundreds of $mg{\cdot}MJ^{-1}$, which reflects the limitations of self-gravity combustion without active air supply control. Forced-air systems, on the other hand, achieve the highest efficiencies (35–45%) and at the same time the lowest emissions of the monitored pollutants. Thanks to the controlled distribution of primary and secondary combustion air, they can ensure better gas mixing, a higher degree of oxidation of volatile components and a more stable combustion process.

A comparison with modern lump-wood space heaters provides a useful technological context, although these appliances are not functionally equivalent to rocket cookstoves. Modern wood stoves are designed primarily for prolonged space heating, whereas most rocket stove systems evaluated in the available literature are cookstoves optimized for rapid heat transfer to a cooking vessel. Modern certified wood stoves generally achieve higher overall efficiencies, while their reported emission performance may be comparable to that of well-designed forced-air cookstoves. However, these values are commonly obtained using different testing procedures, operating cycles, system boundaries, and emission metrics. The data presented in **Error! Reference source not found.**should therefore be interpreted as an indicative comparison of combustion performance rather than as a direct ranking of equivalent appliance categories.

Other results from real operations show that the evaluation of forced-air systems cannot be limited to lump wood or pellets. When burning fuel wood, dung cake and crop residue, the forced draft cooker achieved a thermal efficiency in the range of 30–35% in the rural kitchen, while it was only 16–27% for the natural draft stove and 15–17% for the traditional fireplace [58]. At the same time, compared to a traditional cooker, $PM_{2.5}$ concentrations have been reduced by 21–57% and CO by 30–74%, showing that Forced-air systems retain their emissions advantage even with a wider range of solid biofuels [58].

However, performance under real-world conditions may differ substantially from laboratory results [6]. In household operation, combustion is affected by variations in fuel species, piece size (characteristic dimension), moisture content, fuel load per batch, stove maintenance, and operator behavior. Natural-draft J-tube cookstoves are particularly sensitive to changes in chimney draught, blockage of air passages and inlets to the combustion process, and irregular manual refueling, which may reduce combustion stability and increase pollutants content in the flue gas. Forced-air systems provide better control of the air supply but depend on the reliable operation of the fan, availability of electricity or charged batteries, and regular cleaning of air inlets and nozzles. Additional practical limitations include the need for frequent fuel handling, limited turndown capability, possible smoke release to the surrounding areas during ignition and refueling, and the compatibility of the appliance with locally available fuels and cooking practices.

For a better interpretation of the achieved values, it is advisable to place the J tube and forced air systems in the context of commonly used conventional heat and cooking sources. A portable butane tourist stove normally operates at around 2.2 kW at around 160 $g{\cdot}h^{-1}$, which corresponds more to the middle of the power range of simpler biomass cookstoves [59]. A single-zone portable induction hob is often rated for approximately 1.8 kW, i.e., for a power comparable to low- to medium-power natural draft cookers [60]. On the other hand, a conventional small wood-burning room heater is typically classified in the 3–5 kW category in European practice, while even stoves with a nominal output of 5 kW often operate in the range of 2–4 kW during normal operation [61]. For example, the specific Rochester 5 kW Wood Stove certified model has a nominal power of 5 kW and a net efficiency of 83.4%, which is significantly higher than most biomass cookstoves, but with a different principle of use, greater heat accumulation and different installation requirements [61]. It follows that most simple J tube systems overlap more with portable stoves in terms of performance, while more powerful forced air or hybrid biomass cookstoves can extend into the area of smaller room stoves; However, a direct comparison is always only indicative, as biomass studies usually work with metrics such as Fire Power and Specific Fuel Consumption, while for conventional appliances, the rated output is given.

6. Conclusions

The mini review shows that rocket stoves represent a technically simple, but from the point of view of the combustion process, a very interesting alternative to traditional open fireplaces and simple biomass stoves. Their main benefit lies in better regulation of flue gas flow, more intensive mixing of flammable gases with combustion air and achieving higher temperatures in the reaction zone. These factors lead to increased thermal efficiency, reduced fuel consumption, and reduced emissions of CO and particulate matter compared to conventional open biomass combustion methods.

J-tube systems can be evaluated as the basic and structurally simplest variant of rocket stoves. Their advantages are passive operation without the need for electricity, low design requirements and the ability to achieve significantly better parameters than open fireplaces. At the same time, however, their operating properties are strongly dependent on the geometry of the combustion core, the quality and size of the fuel, the method of stoking and the immediate draught conditions. The limited ability to precisely regulate the ratio of fuel and combustion air subsequently translates into higher sensitivity to the operator and a greater difference between the results achieved in the laboratory and the actual operation.

On the other hand, forced-air systems represent a more advanced design solution that allows you to actively control the amount, distribution and direction of the incoming combustion air. Thanks to this, it is possible to influence the course of pyrolysis, the oxidation of volatile components and the combustion of flue gases more effectively. Available studies show that a controlled supply of primary and secondary air can lead to higher operational stability, lower CO and $PM_{2.5}$ emissions, and overall better combustion efficiency. At the same time, however, forced-air systems cannot be understood as just a simple addition of a fan to the original design; Their real benefit depends on optimizing the geometry, air flows, nozzle position, thermal insulation, and the interaction between the airflow and the fuel bed.

A comparison with modern combustion devices shows that rocket stoves, especially in forced-air design, can come close to some advanced biomass combustion technologies in terms of emissions. However, in terms of overall efficiency, modern certified wood stoves or boiler units still achieve higher values, which is related to their different purpose of use, a larger combustion chamber, more sophisticated combustion control and a longer retention time of flue gases. Therefore, a direct comparison must be interpreted with caution, as rocket stoves are often evaluated primarily as cookers in the literature, while modern stoves and boilers are designed primarily for long-term heating.

In terms of further development, the optimization of combustion chamber geometry, riser height and insulation, primary and secondary air supply, fuel feeding, and power regulation remains crucial. However, most of the available experimental evidence concerns cookstoves operating in relatively short test cycles. The transfer of the rocket combustion concept to space-heating appliances and rocket boilers therefore requires dedicated long-term testing focused on heat output, controllability, operational stability, safety, and emissions under representative operating conditions. Particular attention should also be paid to fuel variability, user behaviour, and changes in natural draft, as these factors can substantially affect efficiency and emission performance. These findings provide a basis for the subsequent design and experimental evaluation of advanced rocket space heaters and rocket boilers.

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