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Finding a clean woodstove – A 300-year quest

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ABSTRACT

This paper reports the results of an experimental study carried out over 30 years ago on the combustion and air pollution characteristics of biomass fuels when used with downdraft combustion. Such combustion involves the flow of fuel and air in the same direction (cocurrent) leading to the biomass to gasify first to a combustible mixture including carbon monoxide (CO) and hydrogen (H_2) that will burn in a gas phase with high combustion efficiencies and low total suspended particulates (TSP). It is noteworthy that over 300 years ago, Justell published a report of a similar device that led to apparently very clean combustion.

The study ascertained the extent to which complete combustion is possible in a cocurrent burner using primary air only or using both primary air and secondary air, exploring other variables such as dry or wet woodfuels and control of heat transfer from the combustion zone. The study has resulted in some generalized concepts for cocurrent combustion that link the oxygen requirements to the reactor conditions that impact upon the rate of pyrolysis or devolatilization of the biomass material. Clean combustion can be obtained with very little CO and TSP in the flue gas, with primary air only or a mixture of primary and secondary air. In the latter, the primary must be just enough to operate the device as a gasifier. The device seems to operate above the WHO PM2.5 Emissions Rate Target but meets the Intermediate Emissions Rate Target for cookstoves and easily meets the incoming USEPA emissions standard for woodheating stoves.

Need for clean biomass combustion

Cooking with biomass is, literally, as old as humanity. Indeed, control of fire is the defining criterion of the transition to becoming human (Wrangham, 2009). As human populations increased in size and longevity and settlements increased in density over the millennia, however, the smoke produced by wood and other biomass fires came to be a concern; first as irritation and in modern times in recognition of the significant health impacts it imposes (Smith & Ezzati, 2005). Today, cooking with biomass is thought to be responsible for more lost healthy life years than any other environmental risk factor in the poorest 100 countries of the world. It ranks in the top three of all risk factors of all kinds in these countries, the others being other ancient risks such as those that lead to child malnutrition (IHME, 2018).

Beginning with the "smokeless chulha" programs in India in the 1950s and progressing well into the 21st century, there have been thousands of efforts by academic researchers and both small private companies and NGOs, often backed by national and international agencies, to develop stoves that burn wood and other biomass more cleanly. This has been stimulated recently by publication of the WHO Indoor Air Quality Guidelines, which define the strict pollution emission limits required for a stove to be healthy (WHO, 2014). Efforts are also being made in developed countries to greatly reduce the emissions from wood space heating stoves due to ambient air pollution concerns (Chafe et al., 2015).

Such work, however, has a long history (Brimblecombe, 1987). Indeed, the very first volume of the venerable *Philosophical Transactions* of the Royal Academy of Science published in 1687 in London contained a description of a woodstove that burned wood extremely cleanly (Justell, 1687 – see Supplement 1). This J-stove would be defined as a cocurrent combustor in modern terminology and was subjected, by the author, to a rather unique emissions monitoring technique to prove clean combustion. The author applied an organic, widely available, renewable odorant, "cat piss", to the fuel and if it was not detectable by smell in the exhaust, it was considered clean.

We took up this challenge some 300 years later to test the Justell stove using more modern methods, which we report here. Although another three decades has passed since, we believe the results may still contribute to the ancient but ongoing quest for clean wood combustion. Indeed, downdraft stoves are still today being actively investigated as cookstoves (Sutar, Kohli, & Ravi, 2017).

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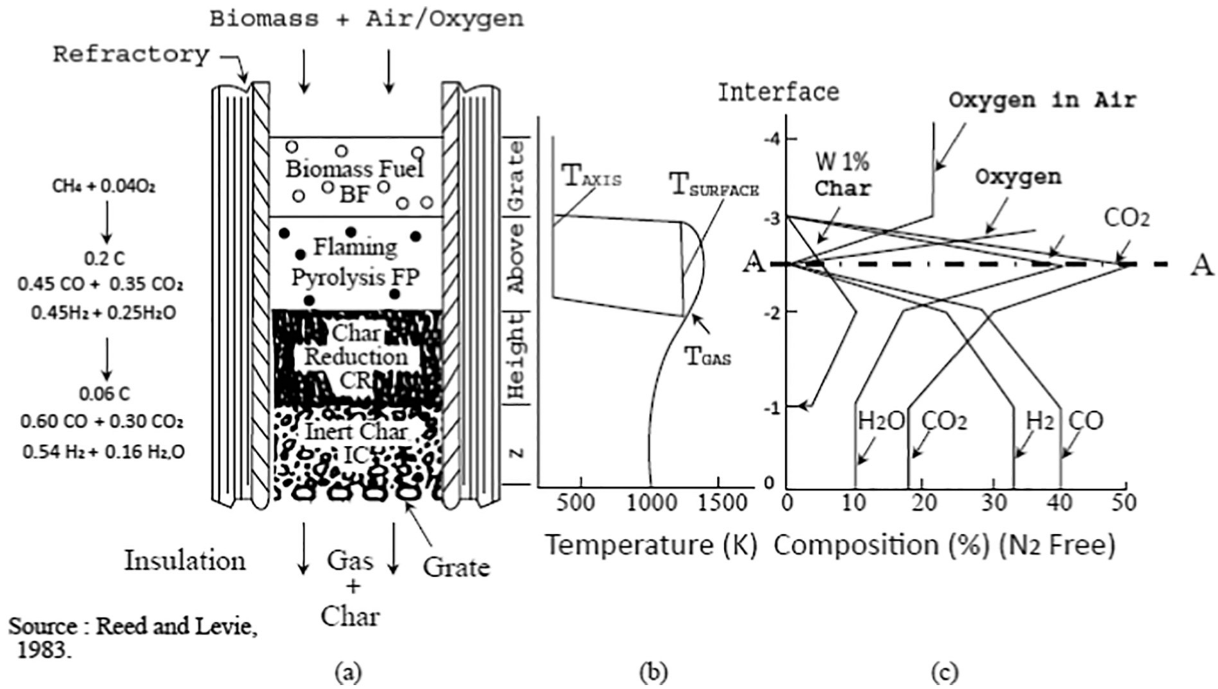

Fig. 1. Schematic of a stratified downdraft gasifier showing: (a) chemical reactions, (b) temperature profiles and (c) gas compositions.

Theoretical aspects of biomass gasification and combustion

The study involved design and fabrication of a suitable combustor test bed as described in Supplement 2. Two 75 mm dia. tubular reactors were used; one made of quartz, the other of steel. Birch dowels 8 mm to 11 mm dia., cut to 37 mm lengths were used as the test fuel. Independent parameters evaluated were combustion air velocity (superficial), fuel moisture, and fuel diameter. The reactor's outward heat transfer was varied by changing the reactor insulation. Their effect on combustion efficiency, air pollution emissions carbon monoxide (CO) and total suspended particulates (TSP) measured as described in Supplement 2, equivalence ratio, fuel reaction rate, and flue gas composition were studied.

A cocurrent combustor has similar reaction zones as that of the gasifier shown in Fig. 1. Gasification and combustion are chemically and thermally similar in many respects. A combustor maximizes sensible thermal energy while a gasifier aims to maximize conversion to fuel gases. The stratified downdraft gasifier was developed by the Solar Energy Research Institute, Colorado (Reed & Levie, 1983). It is characterized by the initial reaction of the fuel volatiles with oxygen in a zone of flaming pyrolysis. The reactions are strongly exothermic and provide the heat to sustain the bed of pyrolysing fuel. Char is formed in the flaming pyrolysis zone and when oxygen is used up, as shown in sec. A-A in Fig. 1, the char reductions occur.

To convert from a gasifier to a combustor, sec. A-A, being the point at which all O_2 is consumed, must be driven down below the grate by

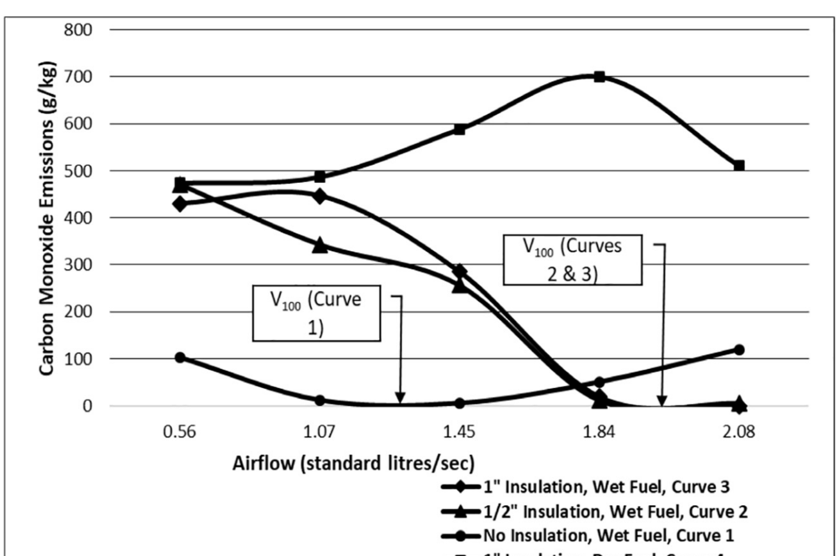

Fig. 2. Effect of airflow on carbon monoxide emissions.

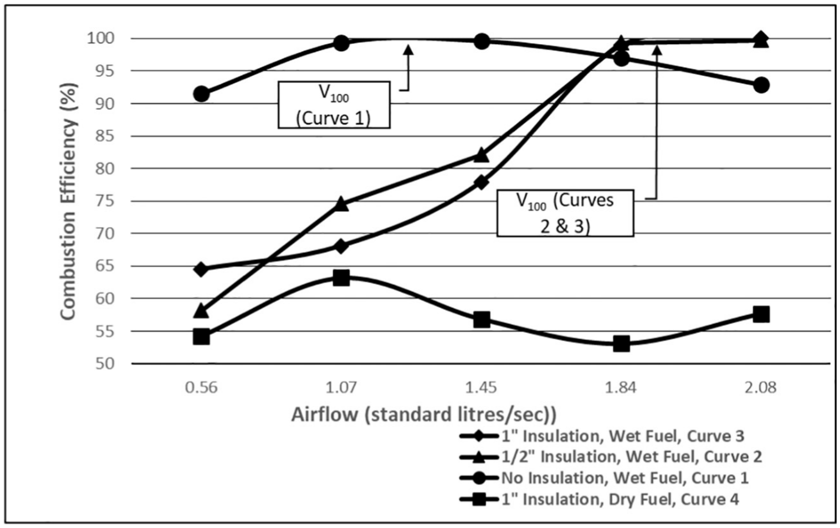

Fig. 3. Effect of airflow on combustion efficiency.

increased air velocity or suppression of pyrolysis. Such suppression can be performed by using wet fuels or by increasing the heat transfer from the combustion zone e.g. no insulation. The zones in the gasifier/combustor used is illustrated and further described in Supplement 3.

Experimental runs and findings

Tested by one operator, various combinations of quartz and steel reactors with dry and wet fuels (Islam, 1985, MS Thesis) and heat insulation or no heat insulation were investigated over a period of three years. The latter studied the effects on the combustion parameters when the heat transfer from the outside of the biomass reaction zone to the surroundings was varied. The variation was obtained by using thermal insulation of varying thickness outside the reaction zone of the two types of tube reactors (quartz and steel).

The fuel used in the experiments had two types of moisture content (wet or dry): 55% (dry basis) and 9% (dry basis).

Fig. 2 illustrates a plot of carbon monoxide emission factor for different reactor conditions of using wet or dry fuels and varying the thickness of reactor insulation.

The four reactor conditions are:

- 1" Insulation, Wet Fuel, Curve 3
- 1/2" Insulation, Wet Fuel, Curve 2
- No Insulation, Wet Fuel, Curve 1
- 1" Insulation, Dry Fuel, Curve 4

As can be seen, three of the curves reach almost zero levels of CO emission. It is seen the CO concentration decreases with increasing airflow in all the cases. Curve 1 shows that CO reaches almost zero levels when using wet fuels without insulation. The volume flow of air at which they reach the low levels is offset along the X-axis depending upon the outward transfer of heat from within the reactor. The latter part of Curve 4 shows a sharp decline, and a continuation of this trend would bring it to low levels of CO emission at an estimated (extrapolated) airflow of 2.5 standard liters per second (slps). The kink or hat like profile of Curve 4 is very prominent. It is noticed that shifted to the left along the X-axis, Curve 3 has a similar peak. Curves 2 and 1 have not developed a peak because the initial airflow was too high. Similar CO emission peaks were also observed during the many runs in which the volume flow of air under the peak was 0.57 slps. This agrees with the argument that more heat transfer from the reactants shifts the CO emission peak as well as the point of lowest CO emission to the left.

The volume flow of air at which CO reaches almost zero levels may.be referred to as V_{100} for that particular set of reactor conditions i.e. fuel wetness, heat insulation, material of reactor (steel or quartz). V_{100} denotes a high combustion efficiency. As is seen in Curve 1, increasing airflow beyond V_{100}, encourages more production of CO. At this point, the system, as was mentioned earlier, started to extinguish.

Fig. 3 plots combustion efficiency[1] as a function of airflow for different reactor conditions. It can clearly be noticed that the V_{100} for these Curves denoting high combustion efficiency are also the same as the V_{100} airflows discussed under Fig. 2. The position of the V_{100} is found to shift to the right for reactor conditions involving more insulation or drier fuels. It is also observed that Curve 4 shows a low combustion efficiency during most of the airflows, until at the highest airflow tested, an increasing tendency is noticed.

Fig. 4 illustrates a plot of fuel reaction rate as a function of airflow for steel reactors using dry and wet fuels and having insulated and uninsulated walls. An examination of the Curves 1, 2 and 3 reveal that in each case, the fuel reaction rate (R_{fu}) rises to a maximum ($R_{fu,max}$). The volume flow of air (V) at this point is designated as V^*. Increasing V beyond V^* forces R_{fu} to decrease. The first portion of Curves 1, 2 and 3 appear very similar to the curve profile found for dry fuels. This is superimposed as Curve 5. Notice that due to lack of sufficient airflow, the curve did not reach V^*. It may therefore be reasoned that the reactor under a particular set of operating conditions can operate at the same reaction rate at two different airflows. During initial runs, it was judged that manifestation or differences of reactor operating conditions (e.g. fuel size) was not very apparent below an airflow of 0.57 slps.

While it is difficult to plot Curve 6 on this figure because of only one airflow for a run with dry fuel, but no insulation, it has been attempted to do so. Knowing the steady state R_{fu} to be 1.18 kg/h at an airflow of 2.34 slps, and assuming R_{fu} to be 1.68 kg/h when V was 1.72 slps, Curve 6 has been estimated. $R_{fu,max}$ for Curve 6 (steel reactor) appears to be much higher than $R_{fu,max}$ for Curve 5 (quartz reactor). This can be understood when one considers that the outward heat transfer from the quartz reactor is 1890 W compared to a heat loss of 941 watts from a steel reactor.

Combustion using wet fuel in the steel reactor having 1" and ½" thick ceramic insulation experienced no problems in unsteadiness or flame extinction. The carbon dioxide in the duct, which is an indicator of the rate of fuel reaction as well as the concentration of CO_2 in the flue gas, showed a reasonably steady value at any particular airflow.

[1] Combustion efficiency refers to chemical energy loss in chimney through CO and CH_4, but does not account for higher hydrocarbons and TSP.

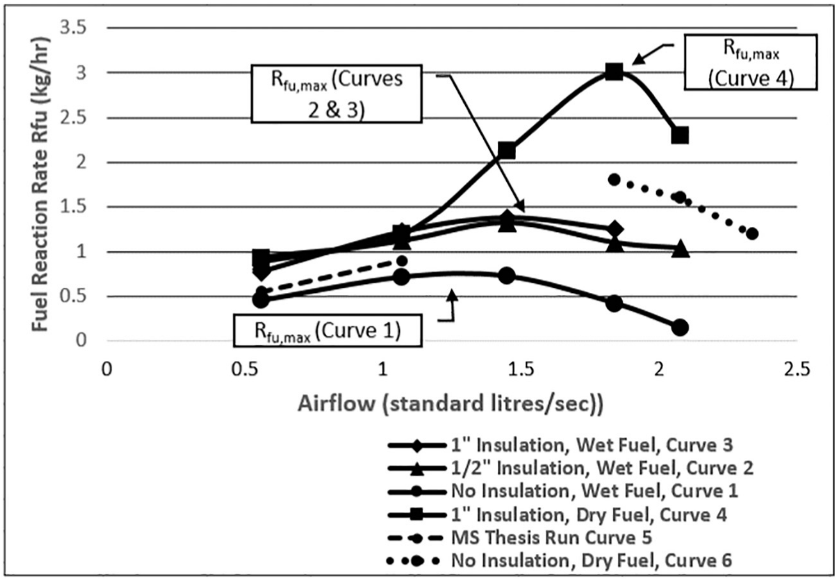

Fig. 4. Effect of airflow on fuel reaction rate.

The response time lag between the airflow change and the monitor response was found to be 10 s. On the other hand, wet fuel combustion without insulation was steady at lower airflows but underwent flame extinction at higher airflow. The runs performed with dry fuels were again found to have steady combustion. On using 1" thick insulation with dry fuel, it was observed that approximately 6 1/2" of steel above the grate was a bright red hot.

The strategy for the run using dry fuel without insulation was different from the others in some respects. The airflow given to the system at 2.34 slps was the highest ever given. The judgement that the system needed more airflow when combusting dry fuel was deduced from initial runs. Subsequent runs however suggested that in conjunction with increased airflow, the depth of the char reduction zone must be small in order to achieve good combustion. The airflow in Curve 6 was therefore taken quickly after lightup to 1.12 slps, and then to 2.34 slps shortly thereafter to avoid reduction zone buildup. All data points in this run were taken at the constant airflow of 2.34 slps. During the run, it was seen that the heated steel, signified by red color above the grate moved down below the grate. The 3" steel nipple section below the grate and the tee joint became red hot. It was as if the combustion zone had separated from the pyrolysis zone above the grate and had moved downwards. Such a phenomenon was not observed in any of the other runs.

It can be seen that either (a) the higher the insulation and less heat transfer from the reactor zone or (b) the drier the fuel, the higher airflow it takes for the system to reach stoichiometric conditions. Stoichiometric condition is the minimum requirement of air for complete combustion.

Fig. 5 is a plot of equivalence ratio as a function of airflow for various reactor operating conditions. Equivalence ratio denotes the actual amount of airflow compared to stoichiometric conditions i.e. an equivalence ratio of 1 represents zero excess air. At low airflows, the

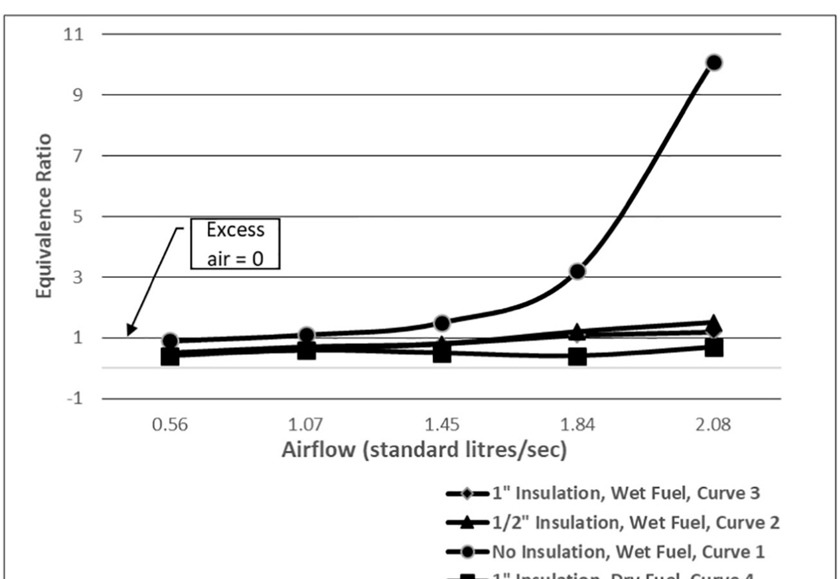

Fig. 5. Effect of airflow on equivalence ratio.

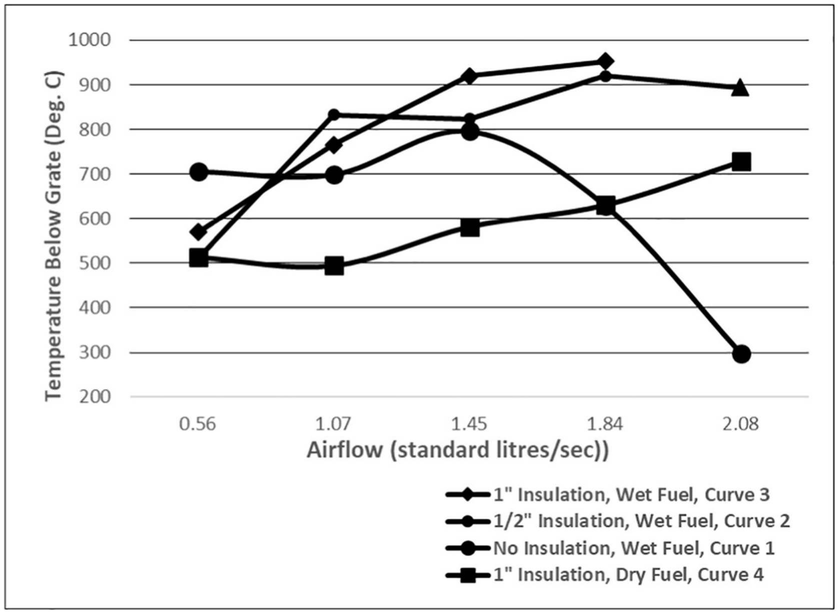

Fig. 6. Effect of airflow on temperature below grate.

equivalence ratio is markedly closer to each other for all reactor conditions than at high airflows. It can be seen clearly that the higher the insulation or drier the fuel, the higher airflow it takes for the system to reach stoichiometric conditions. Stoichiometric condition is the minimum requirement for complete combustion. In conjunction with Figs. 3 and 4, it can be inferred that forcing more air into the system after Rfu levels off to Rfu max, and thereby decrease Rfu, encourages the equivalence ratio to rise rapidly. In Curve 4, Rfu is reached at 1.84 slps, and the corresponding increase in equivalence ratio thereafter is clearly evident.

Fig. 6 is a plot of temperature below the grate as a function of airflow for various reactor operating conditions. As a downdraft combustor, it is worth recalling that the flame is below the grate. The curve 4 has the lowest temperature, likely (by referencing with Fig. 3) due to its low combustion efficiency and operating in a gasifier mode.

Table 1 provides a summary of the various combinations of experimental runs. Each set represents 2–3 runs to ensuring repeatability. The data gives an indication that good combustion can be attained by wet fuels or by using secondary air (SA). The data outlined in green indicate that the CO Emission Factor and the TSP Emission Factor go hand in hand and become very low together.

Results and discussion

The profiles of fuel reaction rate (R_{fu}) vs superficial air velocity (V) obtained after many combinations of runs are shown in Fig. 7. The apex of each curve denoted by V^* and $R_{fu,max}$ reflect inability of R_{fu} to increase any further; being limited by boundary layer diffusion. Complete combustion occurs very soon afterwards at V_{100}.

One of the most important burner characteristics observed was stability at each combustion air velocity, denoting steady state operation of a continuous flow reactor. With primary air (PA) combustion, values of combustion efficiencies were found to be as high as 99.7%. Correspondingly, CO emissions were 3 g/kg, and TSP less than 1 g/kg. Higher moisture contents or more reactor heat losses required less velocity for complete combustion. With PA and SA (two-stage combustion device) complete combustion was again obtained. In this case, the primary air was controlled to operate the system as a gasifier, so that the fuel gas generated had maximum combustibility and temperature approaching the slowdown of the reduction reactions. This resulted in easy ignition with introduction of secondary combustion air.

The good combustion obtained by PA only or by PA + SA offers options to a designer of actual biomass combustion systems. In systems required to burn moist fuel or transfer heat from the

Table 1
East-West stove, laboratory prototype combustor.

Test	Moisture Content %	Fuel Reaction Rate kg/h	Secondary Air	CO Emission Factor g/kg	TSP Emission Factor g/kg	Combustion Efficiency %
1	6	0.59	No	319	45.5	75.6
2	9	1.00	No	410	17.4	68.0
3	9	0.88	No	385	56.7	70.0
4	9	0.89	No	433	22.7	67.0
5	12	0.75	No	336	13.5	77.5
6	33	0.85	No	***9.7***	***0.3***	99.5
7	9	0.91	Yes	***12.4***	***0.1***	99.3
8	9	0.94	Yes	***3.2***	***0.8***	99.7
9	9	0.86	Yes	***5.4***	***0.3***	99.8

*each line is the mean of two or three individual experiments.
**birch dowels 1.5 inch long, 5/16 and 7/16 inch diameter.

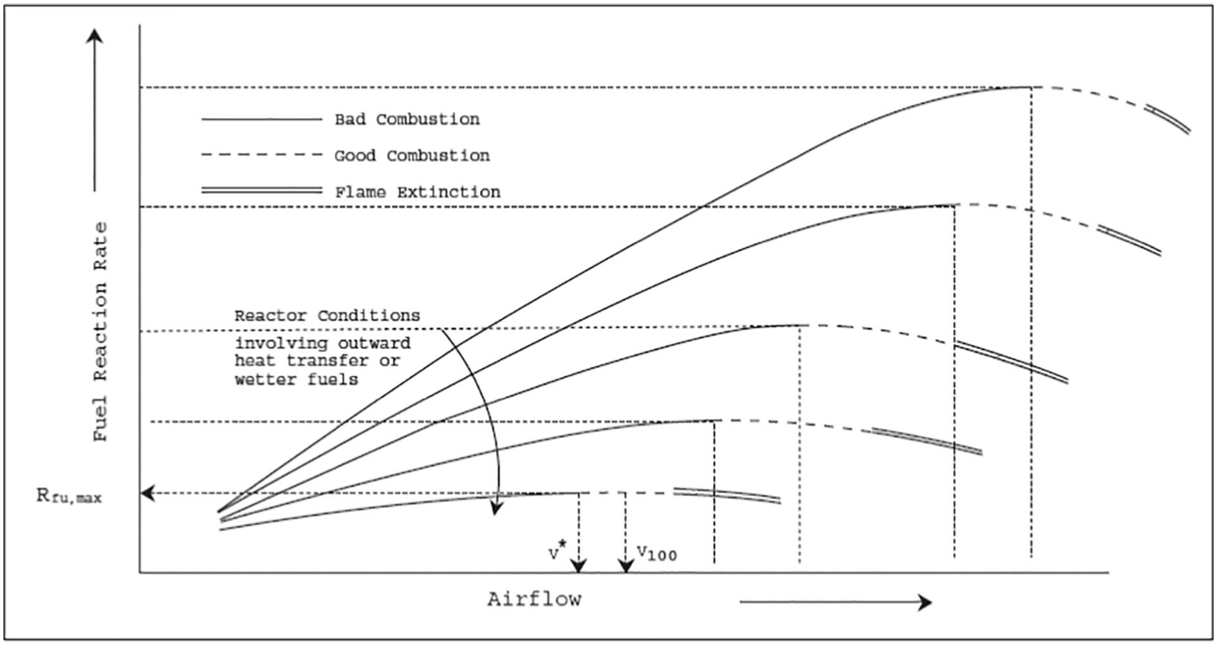

Fig. 7. Generalized family of curves for the behavior of fuel reaction Rate (R_{fu}) as a function of superficial air velocity. The maximum fuel reaction rate for a particular curve is at the airflow V*, while the complete combustion occurs immediately afterwards at an airflow designated as V_{100}. Reactor conditions involving outward heat transfer i.e. lower insulation or wetter fuel – both leading to slower devolatilization rate – force the curves downward.

combustion zone (e.g. domestic heating stoves), a PA system may be suitable. On the other hand, use of a dry fuel and insulated combustion chamber (like a boiler furnace) would tilt the favor towards systems with PA + SA. The PA + SA system would also handle occasional wet fuels by shutting down the SA and operating the burner as only a PA system.

Fig. 8 shows CO profiles obtained after many runs. The velocities for maximum CO (V_g) and minimum CO (V_{100}) are shown. V_g is the point of operation for a gasifier or a PA + SA system, while V_{100} for a combustor operating on PA only. As illustrated in Fig. 3, combustion efficiency is very high at V_{100} and there is a shift of the curves with insulation. Table 1 indicated that CO and TSP go hand in hand and become very

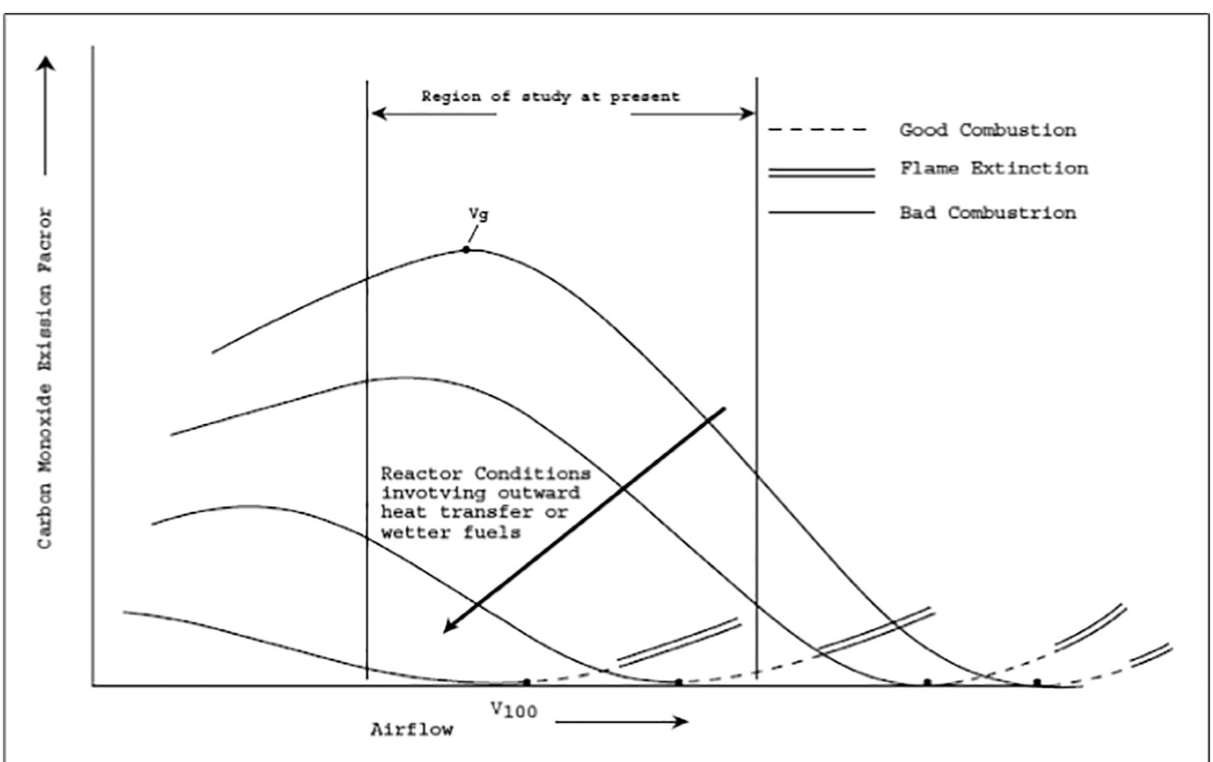

Fig. 8. Generalized family of curves for the behavior of carbon monoxide emission factor (EF_{CO}) as a function of superficial air velocity. The maximum CO for a particular curve is at the airflow Vg, where it is behaving as a gasifier and is the best position for a system using secondary air (SA), while the complete combustion with PA only occurs afterwards at an airflow designated as V_{100}. Reactor conditions involving outward heat transfer i.e. lower insulation or wetter fuel – both leading to slower devolatilization rate – force the curves to the left.

low together – a sign of good combustion with respect to both CO and TSP, in the region immediately after V_{100}.

Summary

Our technical conclusions are:

1. The reasons presented in the discussion under Fig. 8 would lead one to believe that for a particular set of reactor conditions, a profile for CO emission could be drawn as a function of airflow. Fig. 2 shows four such profile curves for four reactor conditions. As is shown, the region under study is very narrow. The assumption of such a profile would fit experimental data reasonably well.
2. The behavior of the fuel reaction rate R_{fu} as a function of airflow can be expected to have the profile shown in Fig. 7 and carbon monoxide as in Fig. 8. For different reactor conditions involving less outward reactor heat transfer or lower fuel moisture content, $R_{fu,max}$ is shown to increase. Correspondingly, V_{100} also increase. The zone of extinction follows after the region or good combustion for each reactor condition when the air velocity exceeds the flame stability.
3. Wet fuel in an uninsulated quartz tube reactor is the easiest to combust efficiently as the V_{100} required is the lowest. This is followed by wet fuel used in a uninsulated steel reactor, and then dry fuel in uninsulated quartz reactor. Insulated steel reactors with ½" and 1" insulation using wet fuel have progressively need of higher V_{100}. The highest V_{100} experimentally tested so far has been for dry fuel in an uninsulated steel reactor. Under all these conditions, very good combustion efficiencies and stable flame have been obtained. The V_{100} requirement for using dry fuel in an insulated steel reactor has not yet been achieved.

Our best runs achieved 0.1 g TSP[2] per kilogram of wood, but this device is termed a combustor because it had no provision for extracting the heat for cooking and was tested with standardized wood dowels. Thus, the results are difficult to compare with modern pollution metrics for biomass cookstoves, for example the WHO Indoor Air Quality Guidelines, which are framed in mass of emissions per hour for a family cookstove using normal fuel (WHO, 2014). If one assumes a consumption rate of 1 kg/h, however, it would seem not to meet the current WHO Emission Rate Target (ERT) for unvented combustion of 0.23 g $PM_{2.5}$/min, but just meet the Intermediate ERT value of 1.75 mg/min. The CO emissions rate at the best TSP rate, 12.4 g/kg, would not quite meet the ERT, but the best CO emissions rate, 3.2 g/kg, would meet it easily. Additional testing would be needed in a cooking mode to be sure, however. This performance would be far better, however, than the current US EPA standard for wood space heating stoves (@~2 kg per hour; 32,000 BTU/h–4.5 g PM2.5/h) and substantially better than the new standard set to come into force in 2020 (2.0 g/h) (USEPA, 2018).

Now to be done is to test against modern cat piss.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.esd.2019.07.005.

References

Brimblecombe, P. (1987). *The big smoke: A history of air pollution in London since medieval times* (1st Edition). London: Imprint Routledge.

Chafe, Z., Brauer, M., Heroux, M., Klimont, Z., Lanki, T., Salonen, R., & Smith, K. R. (2015). *Residential heating with wood and coal: Health impacts and policy options in Europe and North America.* Bonn, Germany: World Health Organization.

Institute of Health Metrics and Evaluation (IHME) (2018). Global Burden of Disease. *Accessed Oct*, 30http://www.healthdata.org/gbd.

Islam, N. (1985). *Experimental study of small scale downdraft combustion for combustion efficiency and combustion generated air pollution.* MS Thesis Honolulu, USA: Mechanical Engineering, Univ. of Hawaii.

Justell, R. S. S. (1687). An account of an engine that consumes smoak, shown lately at St. Germans fair in Paris. *Phil. Trans.*, *1687*(16), 78.

Reed, T. B., & Levie, B. (1983). *A simplified model of the stratified downdraft gasifier.* Golden, Colorado: Solar Energy Research Institute.

Smith, K. R. (1987). *Biofuels, air pollution, and health: A global review.* New York: Plenum.

Smith, K. R., & Ezzati, M. (2005). How environmental health risks change with development: The epidemiologic and environmental risk transitions revisited. *Annual Review of Energy and Resources*, *30*, 291–333.

Sutar, K. B., Kohli, S., & Ravi, M. R. (2017). Design, development and testing of small downdraft gasifiers for domestic cookstoves. *Energy*, *124*, 47–460.

USEPA (2018). EPA certified wood stoves. *Accessed Nov*, 14https://www.epa.gov/burnwise/epa-certified-wood-stoves.

WHO (2014). *Indoor air quality guidelines: Household fuel combustion.* Geneva, Switzerland: World Health Organization.

Wrangham, R. (2009). *Catching fire: How cooking made us human.* New York: Basic Books.

[2] Modern standards are set against $PM_{2.5}$, but 90% or more of TSP measured immediately post-combustion of woodsmoke is probably $PM_{2.5}$ (Smith, 1987).