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Cooking rice with minimum energy

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Detailed experimental studies on procedures of reducing "On-stove time" and cooking with minimum Energy (Heat) using new energy efficient cooking techniques have been carried out. The total minimum amount of heat, Q_m (after subtracting radiation losses), to be delivered to the pot, the sensible heat required for cooking, h_s, and on-stove time t_1 required to cook 1 kg of dry rice, using a new technique (Technique I) of cooking with a stove of effective power, P_{eff}, 626 ± 10 W are found as 560 ± 6 kJ, 465 ± 5 kJ, and 911 ± 10 s, respectively; while conventional method with pressure cooker (Technique II) required $Q_m = 824 \pm 10$ kJ heat and 1357 ± 16 s on-stove time. The corresponding energy and time without a pressure cooker (Technique III) were 1.5 MJ and 2640 s, respectively. When compared with other published works, our method gives the lowest energy to cook 1 kg of dry rice. The efficiencies of the cooking method for different techniques are evaluated. The Clean Development Mechanism potentials of the new cooking method are also evaluated. The results obtained are expected to help develop new cooking apparatus to cook with the lowest amount of energy and thus conserve food nutrient energy and protect environment by minimizing CO_2 and other toxic emissions associated with all kinds of stoves/ovens. Discussion is made how to apply Technique I in solar cooker to reduce the cooking time. © *2014 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4865794]

I. INTRODUCTION

Rice is a staple food for over half of the world's population.[1] Rice accounts for over 20% of global calorie intake. Over 90% of the world's rice is produced and consumed in the Asian Region by 6 countries (China, India, Indonesia, Bangladesh, Vietnam, and Japan) comprising 44% of the world's population. The world rice production has more than doubled from 150.821×10^6 tons in 1960 (with Asian production of 134.317×10^6 tons) to 406.068×10^6 tons in 2004 (including the region's production of 354.895×10^6 tons). The Asian Region, where more than 61% of the world's population live, adds 45×10^6 more rice consumers annually. Even with decreasing trend in per capita rice consumption with increasing consumptions of other food items of more nutritional values, the global rice consumption is expected to be around 500×10^6 tons annually[1] by 2050.

In India, where majority of the population live in 0.67×10^6 villages, firewood provides 70% of energy for cooking.[2] This produces a lot of toxic gasses resulting in environmental pollution. In African and part of Asian countries with growing population the increasing use of wood fuels (firewood and charcoals) mainly for cooking is giving rise to increased rate of deforestation.[3] This is mainly due to inefficient methods of cooking used and the demand on

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firewood is ever increasing. The consequent increasing deforestation in turn can lead to severe environmental pollution, expansion of deserts and global warming. Increasing depletion of locally available wood supply can lead to reductions in available energy for cooking and heating. This will increase diversion of agricultural residues to fuel use, causing further deterioration of physical environments dependent on tree cover. In developing countries, especially in rural areas, 2.5×10^9 people rely on biomass, such as fuel wood, charcoal, agricultural wastes, and animal dung to meet their energy needs for cooking. In many countries these resources account for 90% of household energy consumption.[4] If the cooking methods can be made highly energy efficient, then demand on these products can be reduced. This can significantly add to the protection of our environment. Excessive usages of energy sources have dual effects on our income and environment.[5–7]

The primary objective of this study is to apply Physics to explore the possibility of finding out a new cooking technique to cook food with the lowest amount of energy so as to lead to considerable savings of energy (fuel) and minimum on-stove-time over the conventional methods used in domestic cooking. Another objective of this work was to find out the absolute minimum or sensible amount of heat required for cooking, h_s, needed to cook 1 kg dry rice at room temperature, to well cooked rice (at boiling point of water). This is termed here as the sensible heat required for cooking, h_s, which includes the heat required for the necessary chemical reactions that may take place for the transformation from the solid rice to the soft rice at the boiling point plus the heat required to increase the temperature from room temperature to the boiling point. Our objectives are limited not to quantify the two separately. The on-stove-time here is defined as the minimum time the cooking pot needs to be put on stove before being transferred to an inexpensive insulating box detailed construction of which has been discussed in our earlier work.[8] Another objective is to estimate the possible Clean Development Mechanism (CDM) Potential of the new method of cooking rice.

Simple thermodynamics equations were used to determine the actual amount of heat, Q_N, that needs to be delivered to the pot, minimum heat, Q_m (after subtracting radiation losses), and the sensible heat required for cooking, h_s, required to cook 1 kg of dry rice using the new technique (technique I) using an insulating box. Without using any insulating box, we also determined Q_N, minimum heat, Q_m, for the conventional method of cooking by pressure cooker (technique II) and the conventional method of cooking without pressure cooker, i.e., with open lid under normal atmospheric pressure (technique III). At the same instant, on-stove time, t_1 was also noted in each case. t_1 depends on the power of stove used and is not constant. For technique I, this is the minimum time at which the food (containing 1 kg of the raw food item along with other ingredients) inside the pot will attain the maximum temperature after being put on stove. For the pressure cooker used in this study, this temperature is calculated to be 113.3 °C. This temperature is attained at the time of first hearing of the whistle from the pressure cooker valve. To this effect the present study has attempted to conserve fuel (energy) and time while minimizing smoke pollution. Methods of estimating radiation losses have been discussed for estimation of Q_m and h_s in this work.

The results obtained so far can help designing a new pressure cooker, which can be self-timed to cook with the sensible heat required for cooking, h_s. In addition to saving on-stove time, the new technique could yield a highly improved method of saving food nutrients,[9] which are destroyed when food is subjected to excessive heat and cooked for long time.

II. MATERIALS AND METHODS

The raw rice and the ingredients (salt, pepper, tomatoes, magi, groundnut oil, onion, and kitchen spices) were purchased from Jimeta market of Adamawa state, Northern Nigeria. In the new technique, which is termed as technique I, the sealed pressure cooker pot containing 1 kg of dry rice (washed), 1.6 l of water, and the said ingredients were mounted on top of the stove ($P_{eff} = 626$ W) and was allowed to stay till the time of hearing the first whistle (i.e., 1st exhausting steam of cooking). The initial temperature, T_a, of the materials inside the pressure cooker pot was noted. Temperature of the external surface, T_p, of the pot was noted every 2 min interval (Fig. 1). Immediately after the first whistle, the pot was removed from the stove and

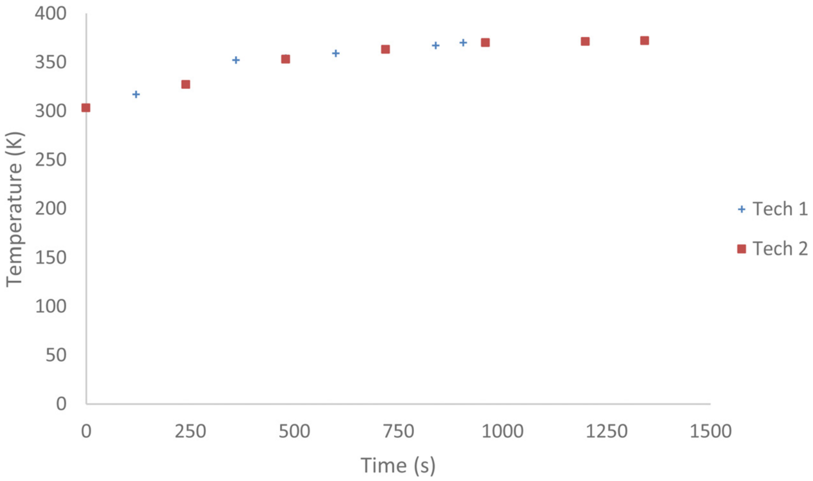

FIG. 1. Time on stove vs. temperature of the outside surface of the closed pressure cooker pot in technique I (new method) and technique II (see text).

transferred into an insulating card board box[8] whose inner surfaces were lined with three layers of highly reflecting and smooth aluminum foil (without kinks) sandwiched in-between with plain sheet of white paper. In technique I, the hot pressure cooker pot remained in the box for 30 min to complete the rest of cooking of rice by the internal heat conserved by the Fabry-Perot type reflecting surfaces (Fig. 1).

In technique II, the pressure cooker pot with the same amount of food contents was allowed to stay on stove for 7 more minutes after the hearing of the first whistle and then the pot was allowed to cool. This timing is in line with the published data of the Pressure cooker manufacturer (Table I), taking into account of power of stove and amount of food. In technique III, with the same amount of food content as in techniques I and II, the pressure cooker pot was used without the lid, allowing water to evaporate while rice is being cooked. In this method, some amount of water had to be added twice for boiling and to prevent the burning of rice. A few grain of rice was checked from time to time until very soft before removal from stove. In both techniques II and III, T_p was noted every 4 min interval before removal from stove (Figs. 1 and 2). No insulator box was used for techniques II and III. The technique III is mostly used still in developing countries to cook rice.

Quantity of kerosene, V_k, used was estimated after each cooking trial in all the three techniques (Table II). The estimation of the amount of energies used in the three methods are made

TABLE I. Reference cooking time for different food items.

Food name	Food (kg)	Water (kg)	Cooking time (min)[a]	Cooking situation	Remark
Rice	1.5	1.2	5	Done	
Porridge	0.2	2	10	Done	Natural cool
Spareribs	1	0.6	15–18	Done meat	Natural cool
Pig leg	1	0.8	20–25	Done meat	Slice
Old chicken	1.5	1	25	Cut meat off bones	Slice
Young chicken	1	0.6	20	Cut meat off bones	Whole chicken
Pork	1	0.5	15	Done meat	Slice
Beef	1	0.6	15	Done meat	Slice
Lamb/Goat	1	0.8	15	Cut meat off bones	Slice
Fish	1	0.45	10		Cutting piece steam

[a] Time counted from first exhausting gas of cooking (i.e., first whistling). Stove power 1 kW.

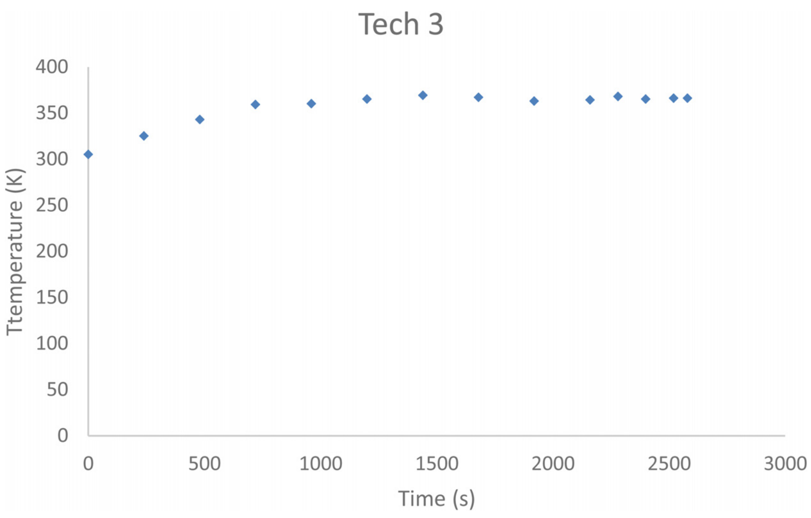

FIG. 2. Time on stove vs. temperature of the outside surface of the closed pressure cooker pot in technique III (see text).

and compared with other published data. Discussion is made how to save considerable amount of energy in cooking using the simple insulating box and thus reduce environmental pollution.

The analysis of the reflection and transmission of heat rays from the various layers of the aluminum foil and white paper combinations (that lined the inner walls of the insulating box) show that most of the heat remains confined within the box by repeated reflections by the first two layers and a small fraction remains confined within the rest of the layers and the card board of the insulating box. In fact, even after 30 min the outside surface of the box remains only slightly higher than room temperature. Quantity of kerosene used was estimated after each cooking trial in all the three techniques. The estimation of the amount of energies used in the three methods is made and compared with other published data. Discussion is made how to save considerable amount of energy in cooking and thus reduce environmental pollution.

Multi-Insurance Safe Type Aluminum Alloy Pressure Cooker Company Ltd. (SHUNJIN), Shunjin, China, 2003. The counting time of cooking for this research work was compared with the cooking time table of the conventional method of cooking employed by “Multi-Insurance Safe Type Aluminum Alloy Pressure Cooker Company Ltd.,” Shunjin, China, 2003.

A. Data collection with the new technique of cooking rice

In all the three techniques I, II, and III, major observed data are the temperature of the outside surface of the cooking pot and time after putting the pressure cooker on the stove and the

TABLE II. Comparison of on-stove time and energy involved in the techniques and the conventional method of cooking. Thermal rating power of the stove, $P_{eff} = 626$ J/s.

	Technique I	Technique II[a]	Technique III[a]
t_1 (min) ± 2 sec	15.11	22.37	44
Q_N	567.5 kJ ± 6	832.0 kJ ± 10	1.65±0.05 MJ
Q_m	560 kJ	821.7	1.6 MJ
h_s	465 kJ	[b]	[b]
V_k (ml) ±2	31	47	81
Net energy used: $E_s = V_k \times H_k \times \rho_k$	1.069 MJ	1.620 MJ	2.793 MJ

[a] Δm was negligible for technique I. H_k = Lower heat content of kerosene = 43.1 MJ/kg. ρ_k = density of kerosene = 800 kg/m^3.

[b] Definition of h_s does not apply for techniques II and technique III since it is the barest minimum or sensible heat (excluding all losses and heat required to heat the pot, latent heat of evaporation, etc.) to transform 1 kg of dry rice to cooked rice.

final removal time. In our experiments a mercury thermometer accurate to ±1 °C was used. We present the data for the three techniques in Figs. 1 and 2.

B. Data analysis

All the symbols used in this analysis are defined in the Appendix. It is to be noted that when the pot's outer wall temperature (T_p) does not change with time, then it is nearly equal to the temperature (T_i) of the inner wall. That this is so can be understood from the following theoretical consideration. The rate of heat-transfer (q_1) from inner wall of the pressure cooker to the outer wall, $q_1 = K_{Al}(T_i - T_p)/d$. This is balanced by the heat transfer (q_2) due to radiation from the outer wall. We have neglected heat loss due to air-convection. Thus $q_2 = \sigma\varepsilon_{AL}({T_p}^4 - {T_a}^4)$; σ = Stefan-Boltzmann constant; T_a = Ambient temperature. In the present case $K_{Al} = 238$ w/m·K, $d = 3\,\text{mm} = 3 \times 10^{-3}$ m. Thus $q_1 = 238(T_i - T_p)/3 \times 10^{-3} = 79 \times 10^3(T_i - T_p)$ using typical value of $T_p = 98\,°\text{C}$. And $q_2 = 5.67 \times \varepsilon_{AL} \times 10^{-8}(371^4 - 305^4)$. We take the emissivity ε_{AL} as equal to the average value (0.22) of the published data on emissivity of aluminum of various types.[10(a)] Balancing $q_1 = q_2$ when T_p does not change. $T_i - T_p = 5.67\varepsilon_{AL}((3.71)^4 - (3.05)^4)/79 \times 10^3 = 1.6 \times 10^{-3} = 0.0016$ K.

Thus, $T_i \approx T_p$ due to high thermal conductivity of aluminum. This is also true when the temperature is rising at a low rate 0.5 C/s.

Measurement of internal temperature of the pot: As mentioned above even though the inner wall temperature of the pot is nearly equal to the outer wall, the inner wall temperature is not exactly equal to the steam temperature of food inside the pot (there is always a temperature gradient from the center of the pot to the wall). In the absence of sophisticated instrumentation, the following method was used to determine the steam temperature inside the pot inside when it whistled,

$$F = mg = W_v, \tag{1}$$

$$\text{therefore pressure,}\ P_{in} = P_o + W_v/A_v. \tag{2}$$

Here the correction due to escaping steam is not included. It is difficult to estimate this correction. Temperature of the steam, T_s, was determined from steam temperature pressure relation[10(b)] to be 114 °C. The actual temperature may be about a degree higher than this because of dissolved salt and other ingredients.

C. Calculation of Q_N and Q_m from the observed data

In our earlier paper,[8] the power of the stove was calculated to be 650 W using the emissivity of the aluminum pot as one for the calculation of the radiation losses. When we use the average value (0.22) of emissivity of aluminum from the published data of emissivity of different aluminum surfaces,[10(a)] we recalculated the power of the stove, P_{eff}, to be 626 W from the data in Ref. 8. This power P_{eff} is the time rate of delivery of energy from the stove to the bottom of the cooking pot. In our case the pot's bottom area is much greater than the area of the flame. This is to ensure that heat convection from the flame is minimum when the pot is put on stove. This P_{eff} is not to be confused with the burning power of the stove, P_{br}. P_{br} is equal to the product of fuel consumption rate and the heat content of the fuel (kerosene). P_{br} depends on volume of kerosene in the stove and the wick height, but $P_{eff} = H_{tr} \times P_{br}$. H_{tr}, the heat transfer ratio, is dependent on stove design and can be assumed to remain constant as long as the pot's bottom surface area is appreciably greater than the flame surface area. During our experiment the same pot that was used to determine[8] P_{eff} was also used to cook rice and the kerosene level and the wick height were maintained the same to ensure same P_{br} and hence same P_{eff}. The total heat required, $\mathbf{Q_N}$, for cooking 1 kg dry rice using the three cooking techniques I, II, and III is just the power of the stove, P_{eff}, multiplied by the on-stove-time, t_1. t_1 for the new technique (i.e., technique I), technique II, and technique III are: $t_1 = 15.11$, $t_1 = 22.37$ min, 44 min, respectively. $P_{eff} = 626$ W. Thus $Q_N = 567.5$ kJ, 832.0 kJ, and 1.65 MJ, respectively, for techniques I, II, and III.

To calculate $\mathbf{Q_m}$ from the observed data, we have to subtract from Q_N the total heat, Q_{rh} radiated out from the pot's surface. Thus $\mathbf{Q_m = Q_N - Q_{rh}}$. This is the energy that were required (excluding the wastage due to radiation/convection, etc.) for the cooking by a given technique. In this calculation, we have neglected the heat loss by air-convection/conduction and assumed that there was no heat loss from the bottom surface of the pot in contact with the flame of the stove. It was not easy to estimate these losses in our experiments. The method of calculation of radiation losses, $\mathbf{Q_{rh}}$, is described below for technique I and applied to techniques II and III.

In Fig. 1, it is seen that from t = 0 min to t = 6 min the temperature rise of the pot (containing food) is quite fast compared to the interval from t = 6 min to t = 15.11 min. We calculate the radiation heat losses Q_{rh1} and Q_{rh2} separately using the following method:

$$Q_{rh} = \int \varepsilon_{AL} \sigma A \left(T^4 - {T_a}^4\right) dt, \tag{3}$$

$$Q_{rh} = \int \varepsilon_{AL} \sigma A \left(T^4 - {T_a}^4\right) \frac{dt}{dT} dT, \tag{4}$$

$$Q_{rh} = \int \varepsilon_{AL} \sigma A \left(T^4 - {T_a}^4\right) \left|\frac{dt}{dT}\right|_{av} dT, \tag{5}$$

$$Q_{rh} = \varepsilon_{AL} \sigma A \left|\frac{dt}{dT}\right|_{av} \int_{T_1}^{T_2} \left(T^4 - {T_a}^4\right) dT\,. \tag{6}$$

From Fig. 1, for technique I:

(1) For the time interval of 0 to 6 min, $\left|\frac{dt}{dT}\right|_{av} = 7.33$ s/°C,
And $T_1 = 30 + 273 = 303$ K, $T_2 = 79 + 273 = 352$ K
taking[10a] $\varepsilon_{AL} = 0.22$, $Q_{rh1} = 1.62$ kJ.
(2) For the time interval 6 min to 15.11 min, $\left|\frac{dt}{dT}\right|_{av} = 30.37$ s/°C,
And $T_1 = 79 + 273 = 352$ K
$T_2 = 97 + 273 = 370$ K, $Q_{rh2} = 7.02$ kJ.

Thus total radiation loss $Q_{rh} = Q_{rh1} + Q_{rh2} = 8.73$ kJ for the new method (technique I).

Following similar procedures, Q_{rh} for techniques II and III was calculated (using data in Figs. 1 and 2) to be 14.61 kJ and 60 kJ. Thus Q_{rh} for techniques I, II, and III are 8.73, 14.61, and 60 kJ, respectively.

D. Calculation of h_s

To calculate h_s from the observed data, we have to subtract the heat required $m_p c_p (T_p^{/} - T_a)$ to heat the pot from T_a to $T_p^{/}$ (see Appendix) and the latent heat of evaporation for the amount of water of mass Δm steamed out. This latter quantity is $\Delta m(L_v)$. Subtracting these two quantities we get the expression for h_s,

$$h_s = \{Q_m - m_p c_p (T_p^{/} - T_a) - \Delta m(L_v)\}. \tag{7}$$

The pressure P_{in} of Eq. (2) corresponds to the steam temperature, T_s, 113.3 °C.[10(b)] It is assumed $T_i = T_p$ from previous heat balance equations. By measuring loss of weight Δm, h_s can then be calculated from Eq. (7) above if Q_m is known. The values of Q_N, Q_m, and h_t so determined are given along with V_k in Table II. Note that for techniques II and III, the idea of h_t does not apply. In Table II, we have also included the net energy used in cooking rice with the three techniques.

III. DISCUSSION

In this research, our focus has been to determine Q_N (the heat to be delivered to the pot containing the cooking material), Q_m (= $Q_N - Q_{rh}$), the sensible heat h_s, for cooking 1 kg of dry rice. Table II gives t_1, Q_N, Q_m, and V_k for all the three techniques I, II, and III and h_s determined from technique I. The experiments above determined the total heat $Q_N = 567$ kJ delivered to the pot in cooking 1 kg of dry rice using technique I. The Q_m and the sensible heat h_s were calculated to be 560 and 465 kJ, respectively. It appears that these quantities (i.e., Q_N, Q_m, and h_s) also depend on quantity of water used while Q_N, Q_m, can also depend on the vessel used. In the determination of these quantities, we have used 1.6 l of water to ensure that the cooked rice is quite soft. When 1.2 is of water is used (as per Table I) with 1 kg of dry rice, the cooked rice is hard. Thus amount of water can be adjusted between 1.2 l and 1.6 l, depending on the taste of the consumer. If the amount of water used is less than 1.6 l, the values of Q_m and h_s will be still further lower following the new method of cooking. For example, if 1.2 l is used, the values of Q_m and h_s are expected to be around 455 kJ and 360 kJ, respectively. The time t_1 for which the pot has to be on the stove (i.e., on-stove-time) before being transferred to the insulating box depends on stove power and thus it will also be reduced. In our experiments the stove power, P_{eff} was quite low 626 W and with that power it took only 15.11 min on-stove-time to cook the rice.

The idea of the sensible heat h_s is very important. It gives us the bare minimum heat required to cook one kg of rice excluding all other heat—all forms heat wastages, and the heat required to heat the pot and the heat required to evaporate water during rice cooking. The above figures of Q_N and Q_m were determined by finding out the effective power of the stove, P_{eff}. This is the heat delivered to the cooking pot by the stove per second. It is different from the fuel burning power P_{br} of the wick kerosene stove due to heat transfer ratio, H_{tr} as mentioned earlier. In technique 1 (the new innovative technique), the net fuel energy used is the lower heat content of 31 ml of kerosene (Table II). This is 1.069 MJ. We have used the lower heat content of kerosene (http://en.wikipedia.org/wiki/Kerosene#Heating_and_lighting). If we use the higher heat content this value is 1.146 MJ. However, the lower heat value is the more appropriate, since it gives the actual heat available from burning of the kerosene.

There have been only a few experiments on determination of minimum energy needed for cooking. The detailed experiments carried out by Carlsson-Kanyama and Bostrom[11] in their studies of "Energy Uses for Cooking and Other Stages in the Life Cycle of Food" found that the minimum energy required for cooking one portion of rice (0.06 kg.) was 0.12 MJ on hot plate and 0.23 MJ in Microwave oven, when they cooked 0.24 kg of rice. We can safely assume that the heat transfer ratio from hot plate is quite close to unity. That way, the minimum energy (assuming linearity relation) to cook 1 kg of dry rice required 2 MJ of energy in their method. Even if we use the figure 1.069 MJ that was burned in our experiment, we used far less energy than the minimum energy used by them. Anoopa *et al.*[12(a)] carried out detailed studies on the energy uses in cooking rice using different fuels and stoves. Their studies showed that the energy uses depend on the quality of rice also. They concluded that parboiled rice requires more energy than raw rice. Their detailed experiments gave a value of minimum energy of 1.97 MJ (equivalent to 45 ml kerosene) required for cooking 0.5 kg of raw rice on electric stove. Electric stove is expected to have a better heat transfer ratio than kerosene stove. These latter figures are, however, expected to be lower than 3.94 MJ per kg of rice when 1 kg of dry rice is cooked at one time using their method. We clearly see that our method used much lower fuel energy (1.069 MJ) to cook 1 kg of rice. However, because of low heat transfer ratio of kerosene wick stove, the net energy that was delivered to the pot to cook the rice was $Q_N = 567.5$ kJ in technique I while the actual energy burned was 1.069 MJ. Thus, according to our investigation, if we could improve the stove's overall efficiency, by improving H_{tr} (as in some burner kerosene stove) the net energy to be used can be close to the figure $Q_N = 567.5$ kJ, in cooking 1 kg of dry rice. A considerable amount of energy can thus be saved by adopting our method of cooking (i.e., technique I). In our experiments, the heat transfer ratio, H_{tr}, may be calculated from the data presented in Table I by using the relation: $H_{tr} = Q_N/E_s$. For techniques I and II, it is 0.53 and 0.51. These ratios are in agreements with the reported investigation[12(b)] on wick kerosene stove. For technique III, the value $H_{tr} = 0.59$ may not be reliable because a considerable amount of kerosene has been finally used and the P_{br} and hence P_{eff} might not have remained constant, as fuel has been burned towards latter part of cooking.

Using our method the total heat required is 567 kJ for cooking 1 kg of dry rice with 1.6 kg of water. To date this (567 kJ per kg of dry rice) is the reported lowest amount of heat that was delivered to the pot so far in cooking 1 kg of dry rice. The conventional method of using pressure cooker time (as per Table I) required 821.7 kJ of energy Q_N delivered to the pot and 22.37 min of on-stove-time. The net energy used in conventional method of using pressure cooker is found to be 1.620 MJ (Table II). Our experiments shows that the conventional method of cooking rice without pressure cooker (as done by most of the households in African countries with fire wood) requires roughly $Q_N = 1.64$ MJ of heat to be delivered to the pot with a corresponding fuel burning energy of 2.79 MJ (Table II). One thing that is quite clear from our experiments is that a considerable saving of energy (and thus fuel) can then be achieved when rice is cooked with the new method (technique I) presented here using a simple insulation box (Fig. 1 in Ref. 8) in comparison to the energy used in conventional method of cooking with or without pressure cooker. This technique translates to raising the temperature of all the food ingredients to about 15 °C higher than the boiling point (100 °C) of water and transfer the whole sealed container to an insulating box, where the food is cooked by the internal heat for about 30 min. Thus saving energy and on-stove time in domestic cooking using our new method (technique I) is expected to reach the level unattained by any other means of cooking so far, if the insulation box is quite good and the stove's heat transfer ratio is close to unity. In our separate papers, we provide our research data on cooking of meat, yam, etc., following the same procedure.

If h_s is determined for different food items, then it can be of help in making a new electric pressure cooker with the design as was shown in our earlier work[8] to cook food items with lowest amount of energy. Here the heating current in the coil could be adjusted so that the total energy delivered inside the pot is just 5%–8% more than the sensible heat required for cooking, h_s. It may also be switched off when the temperature inside the pot reaches the maximum value ~115 °C. The cooking pot (Fig. 4 in Ref. 8) will be highly energy efficient if the space in between the two metal walls (Fig. 4 in Ref. 8) could be made vacuum and highly reflecting instead of putting the metal foil and white paper sandwiches as done in the cooking box (Fig. 1 of Ref. 8). This, however, would make the pressure cooker pot costly.

It should be noted that there is further room for research. Based on the above findings, one can still design a cooking vessel that can cook rice with lesser energy (heat) and shorter on-stove time or with electric timer. For example, if a pressure cooker with a new design[8] (see Fig. 4) has a heating coil of 1 kW, then the net heating time for cooking 1 kg of rice using the above calculated sensible heat h_s, will just be around 520 s, with 10% excess heat supply. In further research, determination of h_s can also be more refined by using a stove whose power is electronically controlled and determining the pot's external surface temperature using an infra red laser thermometer (that is accurate to ±0.1 °C).

In this work, the highly reflecting internal surfaces (which were made Fabry-Perot type) of the cooking box conserved the radiant heat of the pot to continue rest of the cooking. It has been observed that the pot's outside wall temperature when kept inside the box after a period of an hour was recorded to be 79 °C, while the temperature of the center of the cooked food was 90 °C. This is an indication that the box maintained temperature close to boiling point. It thus enables the partially cooked food to be completely done inside the box. Without the box, the corresponding readings under the same conditions have been found to be 41 °C and 52 °C, respectively. The analysis of the reflection and transmission of heat rays from smooth aluminum foils and transmission and absorption by white paper sheets shows that with about four layers (of smooth aluminum foil and white sheet of paper) the reflected part of heat back to the space of food container is more than the part transmitted to the walls of the insulating box, allowing heat conservation inside the box containing the food material. The heat insulation property of the reflecting surface has been found to be ineffective if the foil surface is not smooth and shiny. Such materials can find applications in between sheet rocks in buildings as insulating materials to conserve energy and thus reduce energy bills of buildings in cold countries. The insulation property of the box can be further improved by using Styrofoam materials on the outside walls of the box. The higher the insulation of the box the better and faster the food can be cooked once it is transferred to the box after raising the temperature of the food to around 115 °C.

The results of this investigation can find many applications in restaurants and kitchen, especially for saving energy and on-stove cooking time. If the findings of this research are utilized in developing countries for cooking along with highly energy efficient wood stove[13] rapid deforestation due to fire-wood collection can be prevented and this can help protection of our environment.

A. Energy efficiency of the present method of cooking and comparison with conventional methods of cooking

Ideally the efficiency, η, of a cooking method should be defined by the equation: $\eta_{cm} = 100 \times h_s/Q_N$. Where as defined earlier, h_s = minimum or sensible heat required to cook 1 kg of a food material, i.e., to transform 1 kg of raw food with required ingredients into a completely cooked food product and Q_N = Total amount heat supplied by the stove for the cooking process. While values of Q_N have been determined by several workers, knowledge of h_s is not available for all types of food materials. The energy efficiency of cooking rice with the technique I (present method) is calculated to be 82% while with the conventional method of using pressure cooker it is found to be 56%. The efficiency of cooking technique III is 28%. If we consider the data of Refs. 12 and 13 and assume a linearity relation with mass of rice, the efficiencies of their cooking methods will be much less than 28%.

Actual energy efficiencies of all cooking methods should be calculated using the values of sensible heat, h_s, of the food item and the actual value, Q_N, of heat delivered to the pot in the cooking process. We recommend some further works on determinations of energy efficiencies of cooking methods using the idea mentioned above. h_s is an important parameter found in this work. Normal cooking so far used heat energy far in excess of h_s. Overall energy savings and contribution to the CDM potential (please see below) now depend on the product of h_s/Q_N and P_{eff}/P_{br}. For total minimization of emission (hence environmental protection) due to cooking, we need to have this product as close to unity as possible.

B. Contributions to the CDM potentials

Obviously, if the results of the present research are applied world-wide to cooking, it will give rise to a significant savings of energy and thus carbon emission. It thus will reduce environmental pollution significantly. In other words, it has CDM potential. To quantify precisely, the CDM potential of the present research when applied to cooking world-wide is beyond the scope of the work. However, we have approximately estimated the minimum CDM potential as follows.

1. Minimum CDM potential

In India,[14] approximately 2.5 l of kerosene is used per person per month. Emissions from kerosene stove (with blue flame) is lower by a factor of 3 when compared to biomass.[15] To estimate the minimum CDM potential, we assume that globally everybody is using kerosene for cooking at the rate of 3.0 l per person per month (assuming six persons per family). The total annual usage of kerosene for cooking = 7×10^9 (global population) $\times 3.0 \times 12 = 4.3 \times 10^{11}$ l. The carbon factor[16,17] for 1 l of kerosene is 2.331 kg of CO_2 emission. Thus the total minimum annual global carbon emission from cooking (if kerosene is used) = $2.331 \times 4.3 \times 10^{11} = 1.0 \times 10^{12}$ kg.

If our method is used for cooking globally, at least 75% of the energy will be saved. Thus the total minimum CDM potential = $0.75 \times 1.0 \times 10^{12} = 7.5 \times 10^{11}$ kg. Thus globally minimum 7.5×10^{11} kg CO_2 emissions could be saved if our method is used in cooking.

2. Estimation for CDM potential of the new method for rice cooking

Using the data of Refs. 11 and 12 and our method, the energy savings in cooking rice can be taken roughly as (2.6–0.56) MJ/kg = 2.04 MJ/kg. If our method is applied only for cooking rice, then assuming global consumption of rice stands around 400×10^6 tons annually, then total energy savings in cooking rice with our methods is $= 400 \times 10^9$ kg rice $\times (2.6 - 0.56) \times 10^6$ J/kg $= 8.16 \times 10^{17}$ J. 1 kW h of energy has carbon factors ranging from 0.53 to 0.18 depending on source of energy.[18] On the average, we can take 1 kW h to have a carbon factor 0.25 kg. Thus the total CDM potential of rice cooking $= 8.16 \times 10^{17} \times 0.25$ kg/3.6×10^6 J $= 45.3 \times 10^9$ kg $= 5.7 \times 10^{10}$ kg of CO_2.

A lot of research works have been carried out on improving efficiency of stoves using renewable energy sources[18–23] giving thermal efficiency close to 35% in some improved wood stoves. Thus if our energy efficient cooking methods are applied along with efficient stoves as mentioned above, the emissions of carbon dioxide and toxic gases from cooking would become minimum globally and cooking can be done with minimum use of energy. Thus, a huge amount of energy can be saved globally in cooking, which can be diverted to other useful works apart from cooking. This will contribute significantly not only to reduction of environmental pollution but also to the reduction of global warming,[24] saving thus our environments and atmosphere. The η_{stove} ($100P_{eff}/P_{br}$) of a typical kerosene stove is determined[12(b)] to be around 49%.

3. Applications of our findings in designing new solar cooker

The main reasons why solar cooker has not been popular in the world specially, in Africa where sunshine is abundant are

It takes from 3.5 to 5 h to cook 1 kg of beans when sunshine is intense and abundant.

The solar cooker is bulky, costly, and not easily transportable. Many designs are not durable.

The solar cooker is ineffective with low sunshine.

All these factors can be eliminated in the new design of solar cooker that uses the above findings and the following additional ideas:

Transparent Fresnel sheets (TFS) can be used both on the top face ABCD (Fig. 3) and the side facing the sun to focus sun light in solar cooker of trapezoidal structure on to blackened absorbing base metal plate GFHK (Fig. 3) [area of GFKH is about 1/8th of the top area ABCD] on which the cooking pots can be placed once the temperature T rises to above 250 °C (523 K). [This temperature T can be roughly estimated using the relation: $cI_s = \sigma(T^4 - T_a{}^4)$ where $c = 8$ and I_s = normal solar insolation]. Now if there is a heat reservoir containing blackened stone chips beneath the hot metal base plate heat will be stored there at temperature around 250 °C. If the pressure cooker pot containing 1 kg of dry beans (with 1.2 kg of water and other ingredients) is placed inside such a solar oven, the time to reach temperature of 120 °C inside the pot will be around 40 min with a constant solar insolation of 450 W/m^2. The temperature of the hot plate can be higher if I_s is higher. Muller[25] achieved temperature 278.6 °C with Fresnel sheets in Dec. 2012. The inner sides of the solar cooker are suitably lined with reflectors so as to reflect lights mostly on to the base. Based on our above findings, the pot then can be removed and transferred to a well insulated pot for the food to be cooked by the internal heat. The temperature can be reduced by adjusting the Fresnel sheets on the top face. Because of much higher temperature inside, such a solar cooker the heat transfer (to the pot) efficiency will be higher resulting in very time efficient cooking system. The temperature of the pot's surface can be sensed by using infra red thermometer from the top. Once the pot's external temperature stays close to 115 °C for about 10 min, the pot is removed and fresh pot of raw food can be placed inside the solar cooker. Detailed research on such new solar cooker will be reported separately.

Cooking is a unidirectional process in which heat absorbed by the system from a high temperature source and released partly to the surroundings only at the end when we are ready to consume. It would be interesting to find out ways how to utilize this heat that is released at the end. An engine runs on a cyclic process in which heat Q_1 is absorbed from a heat source, partly converted to work, W, and the rest $Q_2 = Q_1 - W$ is released to the environment (sink). The Carnot efficiency depends on the temperatures of the source and the sink. There is no known way to utilize or conserve this heat Q_2 to further useful work at a finite surrounding

Designs of new fast solar cooker/oven based on our findings.

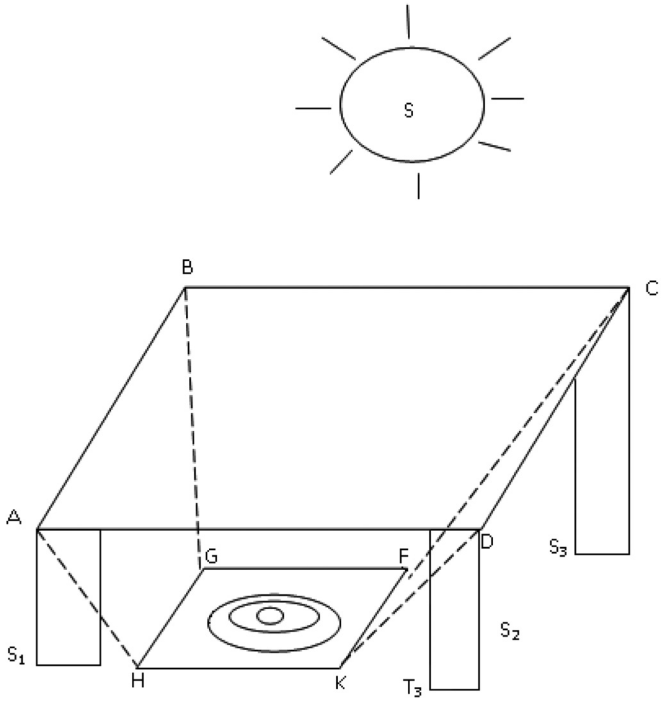

FIG. 3. New design of solar cooker using Converging Fresnel sheets.

temperature. In cooking, there is no cyclic process, yet a lot of heat is wasted during the cooking process, which thermodynamically could be zero. The heat wastages could be minimized by utilizing the idea of h_s and making both the stove and the cooking method efficient, using an insulation box as shown in this present work and the earlier work.[8]

ABCD, the top face consists of two thin layers of glass sheets (GSs) as shown below (Fig. 4). Dimension $-1.1\,\text{m} \times 1.1\,\text{m}$

TFS converging lens sheet. Thin GS of 2–4 mm thick separated by spacers; GFKH—blackened metal plate $\sim 0.4\,\text{m} \times 0.4\,\text{m}$; Below GFKH—metal plate with insulations on top of GFKH lies one heat absorbing plate of similar design materials used in electric cooker/oven. GFKH is blackened. ABGH—consists of metal sheet with half of the area blackened. The outside surface CFKD is fully insulated.

S_1, S_2, S_3, etc., are standing support for the solar oven. ABCD and BGFC are facing the sun, consisting of demountable glass windows and FS sheets (Fig. 4). The outside of the three other faces (ABGH, CFKD, and ADKH) together with the base are covered with heat insulation materials: Al foil—paper layers, Styrofoam, saw dust, etc. Inside of these there faces are metal aluminum sheets, lower half of which are blackened. This ensures reflection of solar rays from top towards the bottom and absorption of those rays. Preliminary analysis shows that internal base temperature of 250 °C can be reached with solar insolation of $450\,\text{W/m}^2$ after one and half hr. of exposure to the sun. If the pressure cooker pot containing food is kept at the base, within 30 min the first whistle is expected to be heard. The pressure cooker can then be transferred to

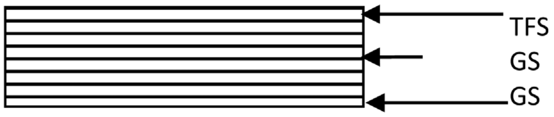

FIG. 4. Composition of the sides of the solar cooker facing the sun and the top.

an insulating box (as mentioned above) for the rest of the cooking to be completed. The detailed theoretical analysis of energy efficiency and performance evaluation studies of such a solar cooker-insulating box system will be reported later.

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APPENDIX: DEFINITION OF SYMBOLS USED IN THE TEXT

A_v	area of the nozzle's valve: $\pi r^2 = 1.135 \times 10^{-5}$ m^2
A_p	area of the pot $= 2\pi rh = 0.088$ m^2
c_p	specific heat capacity of the pot (896 J/kg K)
c_w	specific heat capacity of water (4200 J/kg K)
d	thickness of the pot (3 mm)
ε_{AL}	emissivity of the aluminum surface of the pressure cooker pot
g	acceleration due to gravity (10 m/s^2)
h	height of the pot (14 cm)
h_s	minimum or sensible heat required to cook 1 kg of dry rice
K_{AL}	thermal conductivity of the aluminum in pressure cooker pot
L_v	latent heat of vaporization (2.26×10^6 J/kg or 540 cal/kg)
m_f	mass of rice plus water and all ingredients plus the pressure cooker with lid closed at the time after time t_1 of cooking
m_i	initial mass of rice plus water and all ingredients plus the pressure cooker with lid closed at the time of putting on the stove
m_p	mass of the pot with cover (1.45 kg) and without cover (0.85 kg)
m_w	mass of water used
m_h	mass of the head of pressure limit valve (71.1 g)
Δm	amount of water lost by evaporation $= m_f - m_i$
P_o	atmospheric pressure (101 325 Pa)
P_{in}	pressure inside the pressure cooker at the time of whistling $= P_o + \frac{W_h}{A_v} = 163\,992$ Pa
P_{eff}	power of stove = 626 W (Ref. 8).
Q_{rh}	total radiation heat loss
Q_N	heat supplied by the stove to cook 1 kg of dry rice $= P_s t_1$
r	radius of the pot (10 cm)
r_n	nozzle's valve radius (0.19 cm)
t_i	total on-stove time
T_p	pot's external temperature (°C)
T_a	initial temperature of the pot (°C) = ambient temperature
T_i	pot's internal wall temperature after on-stove time (°C)
T_i	temperature of the pot's wall inside
T_i	is taken as equal to T_p (see above)
T_s	mean steam temperature
$T_i^{/}$	the mean internal temperature, which is equal to average sum of T_i, and steam temperature $T_i^{/} = \frac{(T_i+T_s)}{2}$ (Eq. (4))
T_p	temperature of pot's external wall (measured)
$T_p^{/}$	the mean wall (Aluminum pot) tempt: $T_p^{/} = \frac{(T_i^{/}+T_p)}{2}$ (Eq. (5))
V_k	volume of kerosene used in cooking

W_h weight of the head of pressure limit valve: $mg = 0.711\,N$ (Eq. (2))

σ Stefan-Boltzmann constant (5.67×10^{-8} W/m^{2}K)

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