Energy Saving and Techno-economic Assessment of Self Aspirated Domestic LPG Stove with Porous Radiant Burner

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Abstract. In this paper, a comparative study on energy and cost saving in a self-aspirated domestic LPG cook-stove with porous radiant burner (SAPRB) developed by Mishra et al. [1] with reference to a conventional LPG burner (CB) using Controlled Cooking Test (CCT) and Techno-economic Assessment (TEA) is presented. CCT estimates the total energy required for the preparation of typical food items, based on average daily food intake as reported in National Sample Survey [2]. In order to make a fair comparison between SAPRB and CB, the similar dishes were prepared in parallel in both the stoves. The fuel and time required for cooking of various dishes were recorded individually. Results indicated that the cook-stove with PRB is a better choice for the replacement of conventional LPG stove due to its economic and environmental superiority. On daily basis, SAPRB resulted in average saving of 50 min cooking time and 29.46% fuel consumption. SAPRB has been found to significantly reduce the emissions of CO by 84.4% and NOx by 91.3%. TEA showed annual saving of Rs. 2025 /- and the cumulative present worth of annual savings over the life of the PRB cook-stove has been found as Rs. 16572 /-, which are much higher than the capital cost of the PRB cook-stove (Rs. 990 /-). The calculated Internal Rate of Return (IRR) has been found to be 209.3% which is much higher than rate of return (8%). Similarly, the payback period has been found less than 6 month, which is very small considering the life of the cook-stove (10 years).

1. Introduction

In developing countries like India, with 1.22 billion population, cooking sector shares a larger part of total energy consumption. According to Planning Commission India, the residential cooking has a share of about 22% of the total energy use [3]. In India, approximately 71% of the urban population use LPG whereas in the rural areas only 21% of the population use LPG as the primary fuel for cooking needs. In rural area, people still use solid fuels viz. firewood & chips, cattle dung, etc. for cooking purposes. In 2016-2017 India has become the second-largest domestic LPG consumer in the world with 19.88 crore active consumers [4], which had led the nation to focus on the development of alternate fuels and energy efficient technologies to consumption of LPG. In the Financial Year 2017, government of India has earmarked Rs. 16076.13 crore for LPG subsidy and with 10% annual consumption growth, it may increase rapidly. Because of massive active consumers, a stove with new burner design with improved performance will lead to significant reduction in cooking energy consumption and associated pollution. In order to minimize the financial burden on the government and to reduce the environmental pollution, developing an energy efficient and environmental friendly technology for cooking application is a major

challenge for scientific society. In the following section, a brief review on the Porous Media Combustion (PMC) technology applied for cooking and other industrial applications are summarized.

Comprehensive review papers [5,6] published on this topic provide an overall view about the advances and various applications of PMC technology. Jugjai and co-workers [7-9] constructed different recirculation based porous radiant burner (PRRB) of power range between 1 to 63 kW, for domestic and small-scale food processing applications. For 1-5 kW power input, PRRB yielded around 10% improvement in thermal efficiency and at 11 kW the PRRB with swirling flame resulted in ~60 % efficiency against ~30 % of the conventional stove. Similarly, 23-63 kW self-aspirating porous medium burner with ~8% higher efficiency and less than 200 ppm CO and 98 ppm NOx, showed the potential for replacement with conventional counterpart.

Different material like metal balls, pebbles, metal chips, SiC and Al_2O_3 balls were used by Pantangi et al. [10,11] as porous matrix for LPG cooking stoves burners. They developed 0.8-1.8 kW, double-layered PB with SiC foam and Al_2O_3 balls and examined the thermal efficiencies of the burners at equivalence ratio of 0.3-0.7. PRB with diameter of 80 mm reported the maximum thermal efficiency of 68 % which was 3% higher than its conventional counterpart. Maximum thermal efficiency of burner was further improved to 71% at equivalence ratio of 0.68 by employing a ceramic block instead of Al_2O_3 balls in the preheating zone [12]. Further [13], the research team at IIT Guwahati have optimized the porosity of combustion zone (CZ) and found 90% porosity as optimum for 90 mm diameter burner. The maximum thermal efficiency of the burner was found to be 75% and this was observed at an equivalence ratio of 0.54 and firing rate 1.3 kW. Mishra et al. [1,14], by modification in the supply pressure of fuel, design of orifice, fuel-air mixing chamber, design of preheating zone and the casing holding the burners, developed a self-aspirated porous burner for firing rate 1-3 kW and 5-15 kW and reported 8% improvement in thermal efficiency at lower firing and 10% for higher firing rate.

In all the burners, the performance analysis has been carried out by conducting a standard water boiling test (WBT). But, this test does not reflect the actual cooking condition. Whereas, the controlled cooking test (CCT) provides a true picture of the cooking energy requirement, and help to gain insight into which cooking stove has the potential of meeting particular energy needs. From literature, it is found that no work on CCT and Techno-economic Assessment (TEA) associated to PRB has been done. Thus, the present work analyzes and compares the average daily cooking heat energy requirement of Indian households by employing LPG operated conventional domestic stove and newly developed state-of-the art Self-Aspirated Porous Radiant Burner (SAPRB) [1] by CCT method. Comparison has been also done for fuel and time saving and emission mitigation between both the cooking stoves.

2. Experimental setup and procedure for Controlled Combustion Test (CCT)

Conventional burner (CB), of "supreme" make and the SAPRB [1] were used in the present investigation for estimating the average daily heat energy required by a household. A 14.2 kg LPG domestic cylinder was connected to a pressure regulator and then with a Coriolis flow meter (accuracy± 0.001 g). The fuel flow rate was monitored using a suitable flow control valve. LPG, after passing through the flow meter reached the burner head, after getting mixed with air in the mixing chamber. Using an igniter, the combustion was initiated and appropriate cooking vessel was placed over it to conduct the cooking experiments. As mentioned in Table 1, ingredients were measured using a weighing balance (WB) and beaker. Time required for cooking of each item was recorded by using a stop watch and at the same time, the LPG consumption for each item was noted. Based on the average daily intake of food type and quantity reported by [2], different dishes were cooked in both the cooking stoves simultaneously. Two menus (A & B) were prepared after conducting a small query in the families of rural and urban household. Average value of fuel consumed by menu A&B gives the daily heat energy requirement per household. Emissions from cooking stoves were calculated based on Eq. 1.

$$E_i = P_i \times C_i \times 10^{-6} \times Yearly\ operating\ hours \qquad (1)$$

Where, E_i = emission of pollutant i, C_i = pollutant concentration (mg/kWh), P_i = Input power (kW).

Table 1. Menus for estimating the average heat energy requirement

Dish	Menu A	Menu B
Dish 1	Rice (875 g + 3 kg water), boiled, open vessel	Khichdi' (rice 500 g + pulse 130 g + 3 kg water), boiled, cooker
Dish 2	Pulse 'dal' (130 g + 676 g water), boiled, cooker	Vegetables 'Mix veg' (1073 g + 40 g oil), fried, open vessel
Dish 3	Vegetables 'Cabbage' (1073 g + 30 g oil), fried, open vessel	Kheer' (milk 636 ml + 375 g rice), boiled, open vessel
Dish 4	Chicken (965 g + 85 g oil), fried, open vessel	Fish (965 g + 75 g oil), fried, open vessel
Dish 5	Leaf bread 'chapatis' (665 g wheat), hot plate cooking	Fried Leaf bread 'Chapatis' (665 g wheat), hot plate cooking
Dish 6	Milk 636 ml, boiled, open vessel	Tea-5 cups (14 g + 75 g sugar + 100 ml milk), boiled, open vessel
Dish 7	Tea-5 cups (14 g + 75 g sugar + 100 ml milk), boiled, open vessel	

3. Techno-economic Assessment (TEA)

Economic analysis includes capital cost, life cycle cost and annual saving. Present worth of annual saving is expressed as a function of time, internal rate of return, and payback period. The parameters and equations used for monetary cost estimation are summarized as follows:

(A) Capital Cost (C); capital needed to purchase a stove.

(B) Annual operating cost (C_{OP}): where C_M is maintenance cost, m_f is daily fuel requirement and C_F is fuel cost.

$$C_{OP} = C_F + C_M \tag{2}$$

$$C_F = m_f \times C_f \times yeraly\ operating\ day \tag{3}$$

(C) Cook-stove emission cost ($C_{emission}$): for its calculation, unit environmental loading unit (ELU) for emissions was used [15].

(D) Life cycle cost (C_{LS}): which is the sum of the actual capital cost (C/L_s), the operating cost (C_{OP}), and $C_{emission}$ cook-stove emission cost.

$$C_{LS} = \frac{C}{L_s} + C_{OP} + C_{emission} \tag{4}$$

The above equations were used to calculate the cost of individual stove and later the cost parameters of the PRB and CB stoves were compared with the help of the following equations.

(E) Annual saving (S): which is the life cycle cost difference between stove with PRB and CB.

$$S = (C_{LS})_{Stove\ with\ PRB} - (C_{LS})_{conventional\ Stove} \tag{5}$$

(F) Net Present Value (NPV): It is used to analyses an investment decision, and positive NPV is used as the base to accept a proposed investment. NPV with consideration of interest and inflation rate are calculated by using following equations: Where, i = interest rate, P_a = Present worth, F_a = future worth, f = inflation rate, N life of cook-stove and n is a positive integer.

$$P_a = \frac{F_a}{(1+f)^n} \times \frac{1}{(1+i)^n} \tag{6}$$

$$\mathbf{NPV} = \sum_{n=0}^{N} P_a \qquad (7)$$

(G) Internal Rate of Return (IRR): it is a used for measuring the profitability of potential investments. IRR is a discount rate that makes the net present value (NPV) of all cash flows from a particular project equal to zero.

(H) Payback method: Payback period (N_{PB}) is the ratio of amount of initial investment and estimated annual net cash flow. While operating the stove, when Running Total (RT) is zero it gives the number of year required to recover all the invested money. The payback period is expressed in year and computed using the following formula:

$$RT = C - S \times N_{PB} \qquad (8)$$

4. Result and Discussion

4.1. *Energy and Time saving, and Emission Mitigation from cooking*

For preparing menu-A, given in Table 1, the CB consumed 296.76 g of LPG whereas PRB utilized only 203.49 g. Fuel savings is approximately 93.27 g per day per household. Similarly, for menu-B, fuel consumed by CB and PRB were 311.11 g and 222.71 g, respectively, with a fuel saving of 88.4 g by the PRB. The average heat energy requirement per household for daily cooking activities is estimated as 3208 kcal and 2249 kcal for stoves with CB and PRB, respectively. It can be clearly seen that PRB complies with the heat energy requirement values (1515~2271 kcal) as suggested by Planning Commission of India, but stove incorporated with CB requires 3208 kcal, which is higher than the recommended limit. On using PRB cook stove, yearly fuel saving estimated on average value from menu-A and menu-B shows 33.2 kg of LPG.

Table 2. Cooking time and LPG required to prepare various dishes, menu A&B.

Dish	PRB				CB			
	Time (min)		LPG (g)		Time (min)		LPG (g)	
	Menu A	Menu B	Menu A	Menu B	Menu A	Menu B	Menu A	Menu B
1	22	17	42.29	33.78	29	22	55.78	43.69
2	8	21	16.37	34.95	13	28	26.58	46.63
3	14	29	25.23	56.98	25	40	44.78	78.56
4	26	18	43.46	34.25	34	27	59.61	51.35
5	33	31	54.98	51.4	44	42	72.98	70.12
6	7	6	11.86	11.35	12	11	20.34	20.76
7	5	-	9.3	-	9	-	16.69	-
Total	**115**	**122**	**203.49**	**222.71**	**166**	**170**	**296.76**	**311.11**

In present study, the time taken by two different stoves to cook the meal given in Table 1, has been measured. Result shows (Table 2) that time required to cook in PRB is lesser than in CB. Time taken for complete cooking by stove with CB are 166 min and 170 min for menu-A and Menu-B respectively. On the other hand, PRB incorporated stove required only 115 min and 122 min for menu-A and Menu-B, respectively. Average time saving is approximately 50 min and this reveals the extent to which time budgets can be affected by newly developed PRB stove. From Eq. 1, the average daily emissions of CO and NOx during food preparation (menu A and menu B) were found to be 176.5 mg/day and 6.284 mg/day, respectively for PRB stoves and 1131.5 mg/day and 72.25 mg/day respectively for CB stoves. The percentage pollution reduction on daily basis of PRB cook stove, as compared to the conventional one is 84.4% and 91.3% respectively for CO and NOx emission.

4.2. *Techno-economic Assessment (TEA) Results*

Monetary costs through TEA have been calculated based on Eqs.2-8, and the results presented in Tab. 3.

Table 3. TEA of PRB and conventional stove.

Parameters	Conventional stove	Stove with PRB
C_m	Rs. 1200 /-	990 /-
L_s	10 Year	10 Year
Annual financial appraisal		
C_F	Rs. 6878.05 /-	Rs. 4822.45/-
C_M	Rs. 60 /-	Rs. 20 /-
C_{OP}	Rs. 6938.05 /-	Rs. 4842.45 /-
$C_{emission}$	Rs. 15 /-	Rs. 2 /-
C_{LS}	Rs. 6943.45 /-	Rs. 4943.45 /-
S	-	Rs. 2025 /-
IRR	-	209.3%
N_{PB}	-	< 6 month

Table 4. Present worth of the annual saving and the cumulative present worth of the annual saving of LPG cooking stove with PRB

Year	Annual savings (Rs.)	Present worth of annual saving (Rs.)	Present worth of cumulative saving (Rs.)
1	2025	1875	1875
2	2126.25	1822.92	3697.92
3	2232.56	1772.28	5470.2
4	2344.19	1723.05	7193.25
5	2461.4	1675.19	8868.44
6	2584.47	1628.66	10497.09
7	2713.69	1583.42	12080.5
8	2849.38	1539.43	13619.93
9	2991.85	1496.67	15116.6
10	3141.45	1455.09	16571.7

From the capital cost of stoves, it is seen that stove with PRB is cheaper with a unit capital cost of Rs. 990/-, than the conventional stove which costs around Rs. 1,200 /-. This is due to lower manufacturing and burner and its associated parts. In comparison with the CB, it can be observed that PRB attains an indirect cost saving (by minimizing the emissions) of approximately 86.67% which is due to the lower emissions of PRB as compared to CB. Replacement of stove with PRB results an annual saving of about Rs. 2025/-. Table 4 shows the calculated value of the annual saving, the present worth of the annual saving and the cumulative present worth of the annual saving for each year of life of the LPG cook-stove with PRB. With 5% inflation rate and 8% interest rate, the cumulative present worth of the annual savings for PRB stove over the life has been found as Rs. 16571.69 /- and the investment for the PRB stove is only just Rs. 990/-. It means that by investing Rs. 990 /- to procure a cook-stove today, one can save about Rs. 16571.69 /- over the life of the stove.

IRR is the interest rate at which the present value of all the cash flows from a proposed investment becomes zero. According to this method, the rate of return is worked out by arriving at the percentage ratio of the net gain over the initial anticipated investment of the project. The IRR of PRB stove has a high value of 209.3%, as the initial investment and average total annual cost saving for PRB stove are Rs. 990 /- and Rs. 2025 /- respectively. With an IRR of 209.3%, the PRB stove, expected to earn Rs. 2.1 /- out of each Rs. 1 /- invested (yearly). The payback period of less than six months shows recoupment of the original capital invested

Conclusions

Cooking is one of the most important need of mankind and therefore it has a great impact on the health and economy of every household. A comparative scientific investigation has been carried out by using CCT and TEA, in order to compare the energy saving and economic impact of the newly developed LPG cooking stove with PRB with its counterpart CB. Study concludes that PRB shows better performance as compared to CB at all three fronts of energy saving, emissions and overall cost. The CCT analysis gives a closer estimation of the performance of a cook stove as it is based on the realistic consideration of cooking environment. Owning to higher thermal efficiency, the yearly fuel saving of the stove with PRB was found to be 33.15 kg. On daily basis, this results in 29.88 % saving of fuel, 29.46% saving in time and 84.4% and 91.3% reduction in CO and NOx emission, respectively. The life cycle cost of the LPG cooking stove with PRB can be reduced to a great extent with an annual saving of Rs. 2025 /-. The cumulative present worth of annual savings over the life of the PRB cook-stove has been estimated to be Rs. 16572 /-, which is much higher than the capital cost of the PRB cook-stove (Rs. 990 /-). The calculated payback period is less than 6 month, which is very small considering the life of the cook-stove (10 years). PRB operated domestic cook stoves can be a favorable alternate for the currently used conventional one.

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