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Experimental study for improving energy efficiency of charcoal stove

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This paper describes design steps with experiments carried out for charcoal stove (SEES) to interlink efficiency and various design parameters. Important parameters affecting energy efficiency are amount of air supplied (flue gas temp.), retention time of flue gas in stove, insulation and skirt gap. Skirt gap is most important parameter for higher efficiency of SEES prototype.

Keywords: Charcoal stove, Efficiency, Heat transfer

Introduction

Traditional stoves generate large quantities of smoke and suspended particulate matter, while only a small proportion (10-40%) of released energy transfers to pot[1-3]**.** Improving combustion efficiency will not only reduce smoke and harmful emissions to human health, but also save on fuel cost by reducing fuel consumption**.** On the other hand, improving heat transfer efficiency to the pot makes a huge difference in efficiency of a cook stove. This paper describes an experimental study on design of charcoal stove, named SEES, to optimize its energy efficiency.

Experimental

Selection of Design Parameters

SEES has been designed using principles of combustion and heat transfer to improve stove efficiency[1-5]. Parameters incorporated in present design are (Fig. 1): i) Low thermal conductivity insulation (glass wool and rock wool) is applied around stove to conserve generated heat without smoke; ii) Stove is built of thin mild steel sheet for low heat absorption by stove body; iii) A gap (3 cm) is provided between bottom of stove and grate to ensure good supply of combustion air; iv) Provision of a skirt, a metal sheet envelope to surround pot to guide flue gases through gap/cavity, is made to avoid loss of generated heat energy (Fig. 2); v) Provision of two concentric circular plates[6] bolted together at center and circular holes drilled coaxially to vary air flow rate in order to maintain temperature of hot flue gases as high as possible; and vi) Reducing heat loss by convection/radiation from outer surface of stove by maintaining lower surface temperature. To reduce heat loss, metallic jacket, which can be filled with water (as water can't have temperature > 100°C at atmospheric pressure), has been constructed around the stove. Steam produced in jacket will be directed to hot burning charcoal bed. Air trapped between jackets will act as an insulator reducing outer surface temperature. Also, provision of primary/secondary air separator[7] allows secondary air to get heated and rise upward towards pot to change direction of heat flow. In this case, heat, which would have passed to outer surface of stove, will be redirected towards pot lowering losses and increasing efficiency. Primary/secondary air separator also accomplishes preheating of secondary air to burn volatile contents efficiently to ensure complete combustion.

Apparatus

Prototype SEES consists of following main components (Fig. 1): i) Two mild steel circular plates (diam, 21 cm), which are drilled coaxially, each with 6 primary air supply holes (diam, 3 cm) and 25 secondary air supply holes (diam, 0.5 cm), are fitted with an adjustable nut and bolt assembly at the center for using one plate as base and another left free to adjust relative positions of holes to vary air flow rate[8]; ii) Inner cylindrical jacket (diam, 20 cm) is welded to base plate concentrically; iii) To create water/air gap, another

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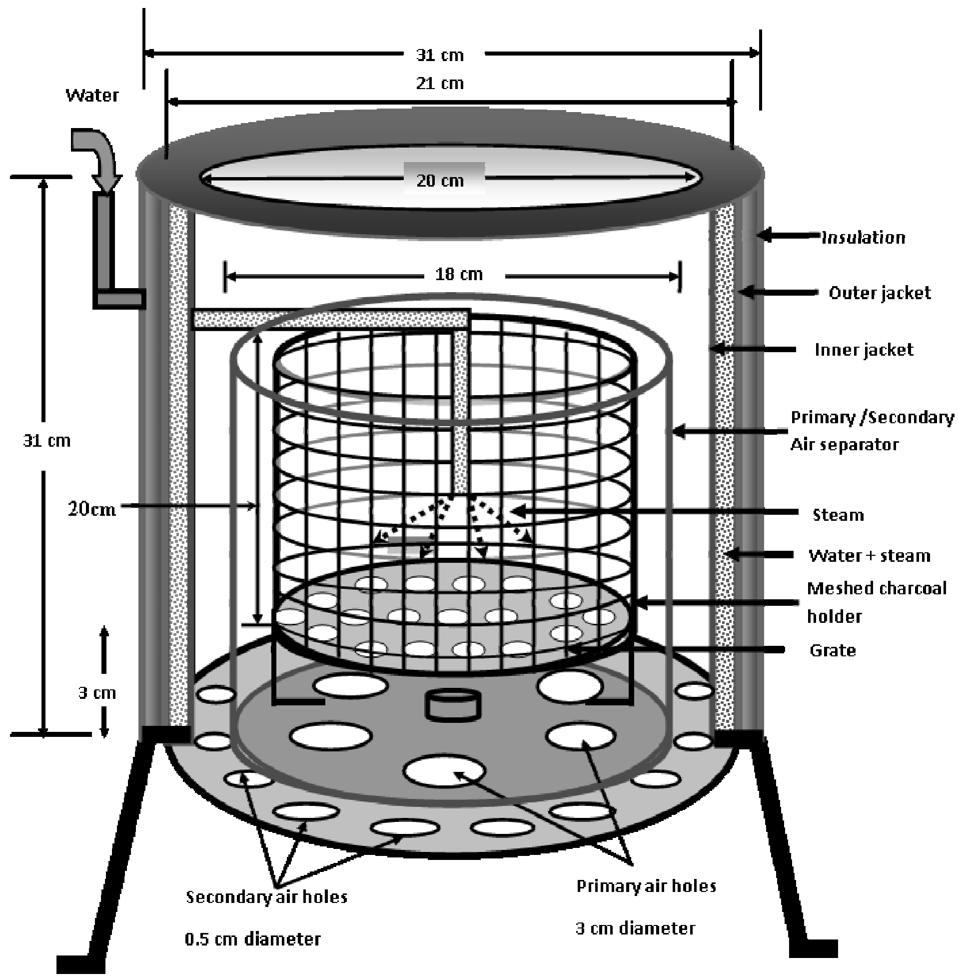

Fig. 1—Schematic diagram of SEES

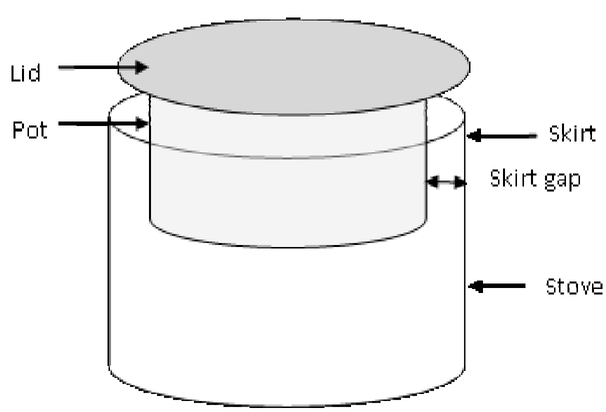

Fig. 2—Design of skirt

concentric cylinder (diam, 21 cm) is welded to the base firmly over first cylinder thus creating an annulus (inner diam, 20 cm; outer diam, 21 cm), and assembly is sealed to form cavity by welding a concentric ring at upper open end; iv) Inner cylinder is fitted with a bent pipe (90°) for introducing steam from water jacket to hot charcoal bed, and inlet for water is provided by an elbow rigidly fitted on outer cylinder; v) Another cylinder (diam, 18 cm; ht, 20 cm) is placed concentrically inside this assembly to act as primary/secondary air separator to separate flow passages of two combustion airs; vi) A meshed charcoal holder (3 cm high from bottom and 1.5 cm away from air separator) is placed inside to support charcoal burning; vii) Insulator (thickness, 5 cm) can be applied as per requirement over outer surface; viii) Stove is supported by three legs (height of each leg, 10 cm); ix) To place frying pan, three cylindrical nails (length, 5 cm; diam, 0.5 cm) are welded at top circular ring in horizontal plane at equal circumferential distance; and x) Cylindrical pot (diam, 15 cm; ht, 15 cm; rim thickness, 2 cm) is used for facilitating immersion.

Testing Procedure

Testing procedure followed during experiments is a simplified version of University of California Berkeley (UCB)/Shell Foundation revision of 1985 VITA International Standard Water Boiling Test, almost identical to that for wood burning stoves[1]. Fire is set to charcoal (initial quantity, 0.5 kg; calorific value, 21300 kJ/kg) using kerosene (5 ml), in order to allow water to boil and to get evaporated for another ½ h. Initial standard amount of water taken during each test is 1.3 kg. Parameters (quantity of water evaporated, amount of fuel burnt, time taken to boil, boiling point and initial temperature of water) are recorded. Useful heat energy efficiency of charcoal stove can be expressed as

$$\eta = \frac{M_w * C_p (T_b - T_i) + M_{we} * L_v}{M_{charcoal} * CV}$$

where, M_w, initial mass of water (1.3 kg); C_p, specific heat of water (4.2 kJ/kg); T_b, boiling temperature of water, °C; T_i, initial temperature of water, °C; M_{we}, mass of water evaporated, kg; L_v, latent heat of vaporization of water (2258 kJ/kg), $M_{charcoal}$, fuel used, kg; CV, calorific value of charcoal (21300 kJ/kg).

Results and Discussion

Test 1

Test shows lower efficiency (21.45%), because heat produced is absorbed by water in jacket itself prior to pot. It is observed that about 700 g of water is evaporated from jacket, whereas evaporation from pot is only 635 g. Water in pot even doesn't grasp energy at sufficient rate to boil and remains at 82-88°C, attributed to the presence of water in jacket. So water-jacketing is not very useful consideration from energy efficiency point of view. Also, double jacket or separate steam drum adds to extra and unnecessary cost due to manufacturing process involved such as seam welding and water and steam proofing. Extra benefit for energy efficiency is about 5%. Another advantage of water in jacket is of maintaining low temperature at outer surface of stove, which can be easily replaced with proper insulation. Finally, a poor person uses wood/charcoal stove and there is no sense in costly stoves.

Test 2

Water in pot shows rigorous boiling for first time without water in jacket and no unnecessary evaporation losses. Efficiency jumps by 6%.

Test 3

With air control and reduction in air fuel ratio, efficiency is decreased by 2.6%, due to higher surface temperature, resulting from high flue gas temperature. Also, radiation is more dominant than convection. Charcoal bed radiates heat in outward and downward direction and hence increase in temperature doesn't contribute much to heat transferred to pot but to outer and bottom surfaces.

Test 4

Insulation (glass wool) is applied to the stove. Air control is discontinued for time being. Water is added to jacket. Efficiency drops by 3% as compared to empty jacket without insulation. This clearly shows that water in jacket has no advantage from efficiency point of view. Insulation effect can be felt by comparing result with Test 1, which shows 2.5% increase in efficiency. This is not remarkable increase because with water in jacket outer surface temperature is 100°C and by putting insulation it is still near to 50°C, which is not a remarkable improvement.

Test 5

As water is removed from jacket, efficiency increases by 15%. Insulation effect for stove can be felt by comparing results with Test 2; efficiency jumps by 12% due to reduction in surface temperature.

Test 6

Test was carried out to confirm overwhelming results of last test.

Test 7

Change of insulation has shown negative effect on efficiency. New insulation by rock wool, being thinner and not bounded properly, gives decrease of 3% in efficiency as compared to glass wool. Also, thermal conductivity of rock wool (0.05 w/mk) is higher than that of glass wool (0.045 w/mk).

Test 8

Pot immersion improves efficiency but large skirt gap (17.5 mm) reduced efficiency by 12%. Large skirt gap increases flow area around pot decreasing flue gas velocity, which decreases Reynolds Number, which in turn reduces value of heat transfer coefficient and hence heat transfer efficiency.

Table 1—Experimental results on SEES

Test No.	Mode of operation(Matter in bold represents changes made in test over previous one)	Water Temperature initial °c	Water TemperatureFinal °c	Time Taken to Boil min	Fuel Burnt g	Water Evaporated, g	Efficiency %
1	Water in jacket + no insulation.	24	88	——	390	635	21.46
2	**Empty jacket** + no insulation.	24	98	65	250	460	27.08
3	Empty jacket + no insulation + **air control.**	24	98	60	260	410	24.00
4	Water in jacket + **insulation (glass wool).**	23	98	50	240	365	24.12
5	**Empty jacket** + insulation (glass wool).	22	98	40	200	560	39.41
6	Empty jacket + insulation (glass wool).	23	98	40	180	510	40.70
7	Empty jacket + **rock wool** insulation.	22	98	45	170	410	37.01
8	Empty jacket + rock wool + **pot immersed (skirt gap 17.5 mm.)**	22	98	60	280	500	25.88
9	Empty jacket + rock wool + pot immersed (skirt gap 17.5 mm) + **no air separator.**	24	98	50	215	475	32.60
10	Empty jacket + rock wool + no air separator + pot immersed (**skirt gap 8 mm**)	20	98	30	270	715	35.52
11	Empty jacket + rock wool + no air separator + pot immersed (**skirt gap 2 mm**)	21	98	90	110	380	54.53
12	Empty jacket + rock wool + no air separator + pot immersed (skirt gap 2 mm) + **air control.**	20	98	105	100	400	62.36

Test 9

In order to increase flue gas velocity and hence heat transfer coefficient, it is decided to remove primary/ secondary air separator, which is suspected to cause remarkable pressure drop. Efficiency jumps by 7%, due to higher velocity of flue gases. But this can lead to higher stove surface temperature, as radiation now will directly travel to out skirt. But with proper insulation, one can go on safely and efficiently. Volatile content of charcoal are very less as compare to wood and hence it needs less air for combustion and needs no separate secondary air for complete combustion.

Test 10

Reducing skirt gap to half of earlier one improves efficiency by 3%. This is right combination, 30 min to boil and appreciable amount of water (715 g) being evaporated in next ½ h.

Test 11

Skirt gap is reduced to ¼th of previous one. Burning process in this test is more than 5 times slower as compared to earlier test. Slower processes are more efficient due to increase in residential time of flue gases in stove providing more time for the process of heat exchange to take place. Apart from this, slower fire always burns better giving higher combustion efficiency.

Test 12

Now with air control, same skirt gap leads to higher efficiency. Another reason can be increase in flue gas temperature due to air control. Charcoal self regulates its combustion rate by ash formation and hence there is rarely any need of excess air for its combustion. Also, volatile contents of charcoal are very less as compare to wood and hence it needs less air for combustion. In this case, burning process is 6 times slower than normal modes and efficiency is almost double.

Conclusions and Recommendations

In design of energy efficient charcoal stove, design parameters considered were amount of air supplied, retention time of flue gas in stove, insulation, and skirt gap, which emerged as the most important parameter. Skirt gap can convert same stove from an inefficient one to a highly efficient one. But skirt gap for a given stove depends upon pot size used for cooking purpose leading to the concept of design of "energy efficient cooking set". Set includes stove and pot along with energy efficient skirts. Developmental design approach to cook stove has been shifting from fuel-efficient stoves to emission efficient stoves. Conditions that lead to high efficiency (relatively low ratio of air to fuel) are conditions leading to higher pollution. Thus emission quality testing is also to be carried out for the stove.

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