DESIGN OF A CHIMNEY FOR INCREASING AIR FLOW AND ITS EFFECT ON STOVE PERFORMANCE

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ABSTRACT

This paper describes the design of a chimney to increase the air flow and hence improve the thermal heating efficiency and burning rate of stoves. For the purpose of comparing the performance of the earlier designed stoves with the new ones with a chimney, a new parameter "thermal specific fuel consumption" is introduced. Results show that the addition of a chimney stack generally improves stove performance and hence is an important design feature to consider.

INTRODUCTION

The performance of charcoal stoves is largely influenced by combustion, heat transfer and boundary layer effect (Yamba). This is further affected by the size of charcoal, control vent, and pre-heating.

Using these efficiency criteria two series of stoves were designed. The first series of stoves are biased to combustion, ie a higher heating efficiency and the second to a higher burning rate but at the expense of a lower heating efficiency. Four sets of stoves have been designed in both series biased to: i. combustion; ii. combustion and heat transfer; iii. combustion and pre-heating; and iv. combustion, pre-heating and heat-transfer. Efficiencies varied from 20-30%. The second range of stoves were similar in design, but the number of 10 mm diameter holes in the grate was increased from 78 to 130.

Eighty such stoves, ie ten of each design have been fabricated and are currently being tested in the field for their acceptability and to determine fuel saving in actual cooking situations in selected households.

A disadvantage of both existing and new designs is the insufficient air flow, resulting in turbulence in the stoves. This is caused by an insufficient air draw from natural convection into the stoves. In attempting to increase the air flow and hence affecting both thermal heating efficiency and burning rate, it was found necessary to design an appropriate chimney. The design of this chimney and its effect on stove performance are described below.

DESIGN OF THE CHIMNEY

The height of chimney required chimney (Hs) was calculated using the expression developed by Morse as follows (all notations in following equations are given in the appendix):

$$Hs^* = \frac{D_r^*}{D_{100}^*} \times 100 \qquad (1)$$

where $D^*_{100} = K(\rho^*_a - \rho^*_g) \quad - \quad 0.0148\rho^*_g \frac{(V^{*5}_g)^{\frac{1}{2}}}{Q^*_g}$ (2)

The required draft (D^*_r) in equation 1 is the sum of all chimney friction, and other losses external to the chimney which includes pressure head losses encountered by air and flue gases in passing at the point of air entry (stove air vent) through the grate air holes, fuel bed in the combustion chamber and chimney duct plus velocity head loss of the flue gases discharging from the chimney. Thus the required draft may be represented by total pressure losses head, ΔH_t, which in turn is expressed by the pressure head balance equation as shown below:

$$D_r = \Delta H_t = \Delta h_1 + \Delta h_2 + \Delta h_3 + \Delta h_4 + \Delta h_5 + \Delta h_6 \qquad (3)$$

The value of $\Delta h_1 + \Delta h_2 + \Delta h_3 + \Delta h_4 = \Delta h_s$ has been estimated (Sindano 1983) for a charcoal stove similar in dimensions to the stoves described here.

The chimney friction head, h_5, was determined using the equation:

$$h^*_5 = \frac{78.74 x f x H_s x V^2_g}{g.d_s} \qquad (4)$$

The total velocity head loss, Δh_6, according to Morse was determined as:

$$h^*_6 = 0.033\, \rho^*_g\, V^*_g \qquad (5)$$

The mass of flue gases $\dot{M}_g$ leaving per unit time was determined by the expression:

$$\dot{M}_g = \dot{M}_g x b_f \qquad (6)$$

The mass of flue gases M_g from equation 6 leaving the stove was estimated based on the modified equation required for determining the theoretical amount of air required for complete combustion per kilogram of fuel as follows.

$$M_g = \frac{1}{23}\left(\frac{8}{3}C + 8H - 0_r\right) x \alpha \qquad (7)$$

The densities of air and flue gases were determined using the perfect gas law as follows:

$$\rho_a = \frac{P_b}{RT_a} \qquad (8)$$

$$\rho_g = \frac{P_b}{RT_g} \qquad (9)$$

The preliminary diameter of the chimney was determined using the continuity equation at the pre-determined velocities of 1.5, 3 and 8 m/s which are typical values for flue gases leaving charcoal stoves.

Setting velocity values at 1.5, 3 and 8 m/s the chimney height and diameter were calculated to range from 30 to 70 mm, and 1000 to 2400 mm respectively (Table 1 and 2).

TESTING A CHARCOAL STOVE WITH A CHIMNEY

The charcoal stove used in these series of experiments is similar to the stoves shown in Figure 1 designed to be biased towards greater combustion.

To increase the fluid/wall temperature gradient, ie the rate of heat flow to the pot through increased turbulence, a variable chimney was installed to the stove as shown in Figure 2. Chimney height was adjustable within the range 0-1700mm. The diameter was constant at 75 mm to allow determination of the effect of stack height on thermal performance ie fuel burning rate, heat flow to the pot and thermal efficiency.

In addition to the above parameters of thermal efficiency, a new indicator "Thermal Specific Fuel Consumption" (TSFC) is introduced. This is defined as the ratio of the rate of fuel consumption to the heat flow into the pot as follows:

$$TSFC = \frac{b_f}{Q_p} \text{ kg fuel/kWh} \qquad (10)$$

This indicator is independent of the calorific value of the fuel and gives a complete picture of the behaviour of the amount of fuel used per unit heat flow for a specified period of time. The lower the value of TSFC the more efficiently and economically the system is performing.

Results showing the effect of heating efficiency, burning rate, useful heat flow to the pot and TSFC against stack height are shown in Figures 3-6 respectively. The performance of the two stoves was compared with or without a chimney.

To determine the values of thermal heating efficiency, burning rate, heat flow into the pot and TSFC against chimney height, various parameters such as amount of water heater, rise in water temperature, amount of fuel used, flue gas velocity, burning fuel temperature and flue gases temperature were measured during the experiments.

DISCUSSION OF RESULTS

It can be seen from Figure 3 that heating efficiency increased with an increase in stack height until about 1500mm stack height. Useful heat into the pot (Figure 5) follows the same trend but peaks at 1100mm. TSFC also improves with stack height until 1500 mm.. The theoretical optimum stack height was calculated at 1100 mm at a flue gases velocity of 1.5 m/s which is typical of charcoal stoves. This conforms well with experimental findings of an optimum between 1100 and 1500mm. Thus this equation may be useful for determining theoretical optimum heights for different configurations of charcoal stoves including stack diameter.

With a chimney in place thermal heating efficiency ranged from 23.5 to 26% and burning rate and hence useful heat ranged from 0.40 to 0.48 Kg/hr. In the absence of a chimney thernal heating efficiency peaked at 24% and burning rates ranged from 0.30 to 0.35 Kg/hr. Thus, the chimney improves performance, in particular of TSFC. This is indicated by low TSFC values for the stove with chimney while other values of thermal heating efficiency are quite similar in both systems.

Improved efficiency of the chimney can be attributed to an increase in air and flue gas turbulence which probably improved air/fuel contact and pot wall/flue heat transfer coefficient. Improved air/fuel contact is essential for efficient combustion. A further advantage of the permanent chimney is the time saved during priming of the stoves without a chimney.

CONCLUSION

The addition of a chimney has been shown to have an important role in improving performance of charcoal stoves. To optimise the design, further work is needed to determine the effect of performance as a function of stack diameter, control vent area, heat transfer and possibly pre-heating.

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NOTATION

b_f	Burning fuel rate Kg/hr
C	Carbon content %
D_r	Required draft N/m^2
D_r^*	Required draft inches of H_20
D_{100}	Available draft N/m^2
D_{100}^*	Available height per 100 feet of chimney height
d_s	Chimney diameter mm
f	Friction wall coefficient
ΔH_t	Total pressure head loss N/m^2
Δh_1	Pressure head loss due to resistance at the stove air vent N/m^2
Δh_2	Pressure head loss through grate air holes N/m^2
Δh_3	Pressure head loss through fuel bed N/m^2
Δh_4	Pressure head loss friction resistance on pot and hood walls N/m^2
Δh_5	Pressure head loss friction resistance on chimney walls N/m^2
Δh_s^*	Pressure head loss chimney walls inches of water
Δh_6	Pressure head loss total velocity head of flue gases at chimney exit temperature N/m^2
Δh_6^*	Pressure head loss total velocity head of flue gases at chimney exit temperature inches of water
H_s	Chimney height mm
H	Hydrogen content %
K	chimney height constant
M_g	Mass of flue gases Kg
M_g^*	Mass flow rate of flue gases Kg/s
ΔP_S	Summation of pressure head loss due to resistance at the stove air vent, through grate air holes and fuel bed, and due to friction resistance on chimney holes N/m^2 ie $h_1 + h_2 + h_3 + h_4$.
ΔP_5	Chimney friction head N/m^2
ΔP_6	Total velocity head loss N/m^2

P_b	Barometric pressure N/m^2
T_a	ambient air temperature K(Kelvin)
T_g	Flue gas temperature K(Kelvin)
R	Gas constant Kg/KJ K
Q_g	Volumetric flue gas flow rate m^3/s
Q_p	Heat flow rate kW
Q_g^*	Volumetric flue gas flow rate (ft^3/s)
V_g	Flue gas velocity m/s
V_g^*	Flue gas velocity ft/s
α	Excess air coefficient
ρ_a	Density of air Kg/m^3
ρ_a^*	Density of air lb/ft^3
ρ_g	Density of flue gases Kg/m^3
ρ_g^*	Density of flue gases lb/ft^3

TABLE 1: Given values for determination of chimney diameter and height

T_a (K)	T_g (K)	P_b (mmHg)	b_f (kg/hr)		f	C (%)	H (%)	P_s (N/m²)
298	623	660	0.45	2.0	.011	80	10	2.0

TABLE 2: Calculated chimney height and diameter at three pre-determined flue gases velocities

Flue gases velocity					Chimney dimensions		
(m/s)	P_5 (N/m²) Hs	P_6 (N/m²)	D_{100} (N/m²)	D_r (N/m²)	diameter (mm)	height (mm)	
1.5	0.343	0.84	113.36	or 3.4	or	66	821
			139.7	4.55			1095
3.0	1.326	3.34	51.6 or	9.79		45	2359
			201.6				
8.0	5.773	27.78	988.79	7.74		29	1864

FIGURE 1: Charcoal stoves used in experiments to determine optimum chimney height

FIGURE 2: Arrangement of test stove showing the stack and hood

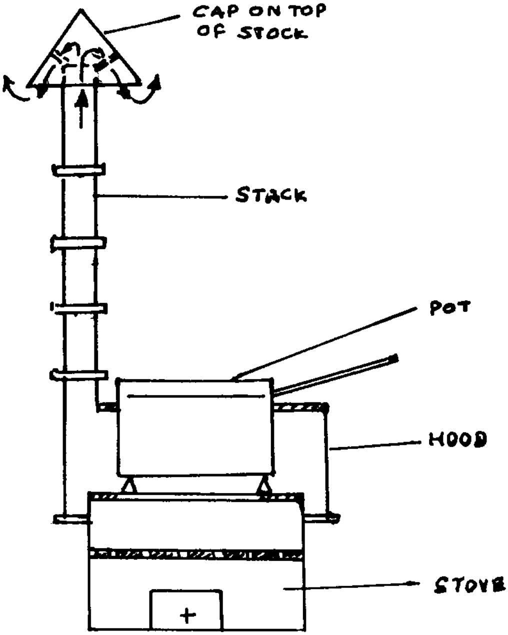

FIGURE 3: Thermal heating efficiency against stack height

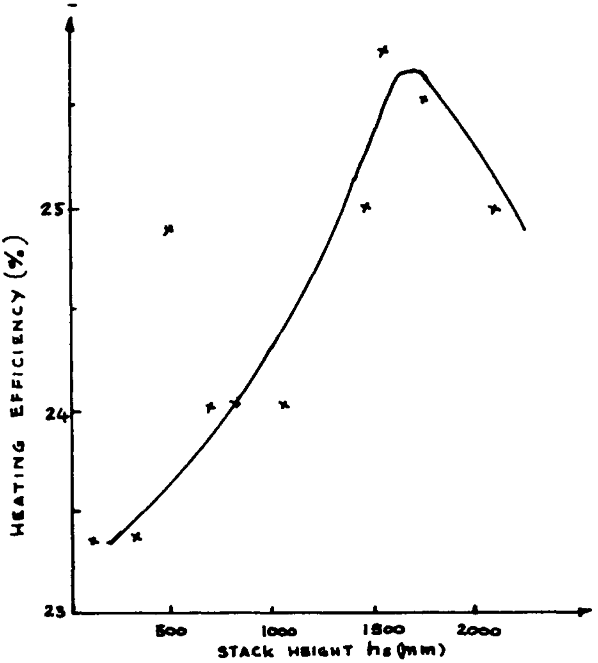

FIGURE 4: Fuel burning rate against stack height

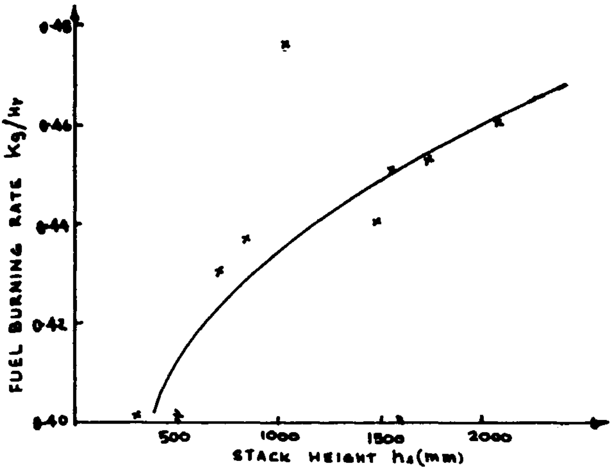

FIGURE 5: Useful heat flow to pot against stack height

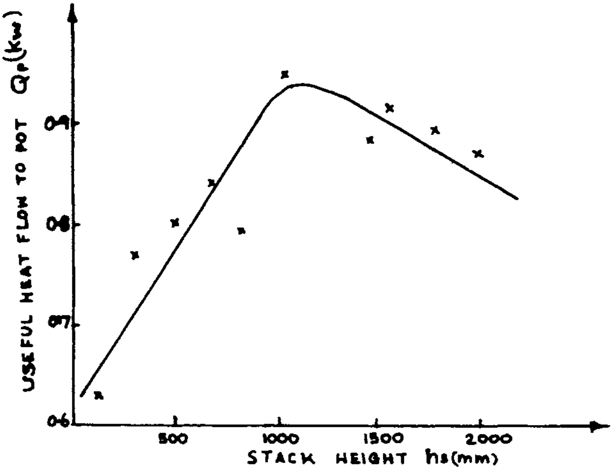

FIGURE 6: Thermal specific fuel consumption against height