HEAT RECOVERY FROM COTTON STALKS

A Thesis submitted to
Ain Shams University
for the Degree of Doctor of Philosophy

by

Mohamed Refat Salem Salem
M.Sc., Ain Shams University, 1981

Department of Power
and Automotive Engineering,
Faculty of Engineering,
Ain Shams University.

1985

To my wife and my children

with all my love.

بسم الله الرحمن الرحيم

SUMMARY

The aim of this study is to determine the combustion characteristics of cotton stalk pellets and from these results design an efficient cotton stalk pellet-burning stove to be used by Egyptian Farmers.

The literature that has been reviewed in this thesis concerns the importance and annual yields of the available agricultural wastes, the pelletization of agricultural wastes, the pyrolysis of a solid fuel, the combustion of the char, the ignition of a solid fuel on a grate, the combustion of solid fuel in a fixed bed, and the technology of existing domestic cookers which use solid fuels.

The theories of solid fuel pyrolysis, together with the combustion of char and pyrolysis gases have been reviewed and the effect of the presence of ash in the cotton stalk char on its rate of burning was investigated. As a result of these studies, the theoretical instantaneous rate of burning of cotton stalk char, $\dot{M}$, was calculated using the analogy between heat and mass transfer and is given by:

$$\dot{M} = \frac{\dot{M}_{initial}}{1 + \frac{R g_{lmass}}{\rho D_{shell}} \ell n(1-f)^{-\frac{1}{2}}}$$

where $\dot{M}_{initial}$ is the initial rate of burning and $\frac{R/D_{shell}}{\rho/g_{lmass}}$ is the ratio of the ash resistance to the gas film resistance to the diffusion of oxygen to the unreacted core.

The thickness of the oxidation zone in a fixed bed of cotton stalk pellets, x_o, is related to the rate of air flowing through unit area of the grate, m', by:

$$x_o = \frac{0.00498\ m'}{K'\ F\ P'_{O_2}}$$

Thermogravimetric analysis was used to determine the combustion characteristics of single cotton stalk pellets. The asymptotic weight loss of a single pellet during pyrolysis in a nitrogen atmosphere, Δw_∞, was related to the pellet final temperature, T_f, by $\Delta w_\infty = 0.0013\ T_f - 0.326$. The heat content in the pyrolytic products of cotton stalks at 340^o C as a fraction of the calorific value are as follows: char = 0.58, tar = 0.27, and gases = 0.15.

The experimental and theoretical rate of burning of cotton stalk char were compared. Although the agreement was quite good, there was a discrepancy between these two rates due to the presence of some volatiles in the char which were initially lost.

The air drawn in by the draught of a 30.0 cm long chimney was consumed through a distance of 2.6 cm to 3.9 cm in a cotton stalk pellets bed. This result is in good agreement with the calculated thickness of the oxidation zone.

A cotton stalk pellets-burning stove to be used by the Egyptian farmers, was designed and tested. In this stove, the green pellets were pyrolyzed in a separate annular container. This pyrolysis container or gasifier enclosed the fixed bed and received heat from it. The char produced in the gasifier was saved and later burnt on the grate as a fixed bed with the combustion air and the pyrolytic products entering the bottom of the bed. The stove used a 30.0 cm long chimney to draw the required combustion air through the bed. The combustion efficiency of cotton stalk pellets in this improved stove was about 88%.

ACKNOWLEDGEMENTS

This work has been done under the co-supervision scheme between the Department of Power and Automotive Engineering, Faculty of Engineering, Ain Shams University, Egypt, and the Department of Chemical Engineering and Fuel Technology, Sheffield University, England.

The author would like to express his sincere gratitude to his supervisors, Professor J. Swithenbank, who is Head of the Chemical Engineering and Fuel Technology Department, Sheffield University, and Professor A.S. Gad El Mawla for their appreciated aid, supervision and encouragement throughout this work.

Thanks are also due to the technical staff of both University Departments for their help.

TABLE OF CONTENTS

		Page No.
	Summary.	i.
	Acknowledgements.	iii.
	Table of Contents.	iv.
	Nomenclature.	vi.
CHAPTER 1:	INTRODUCTION.	1.
CHAPTER 2:	LITERATURE SURVEY.	4.
2.1	World Energy.	4.
2.2	Agricultural Wastes.	5.
2.3	Densification of Agricultural Wastes.	7.
2.4	Combustion of Solid Fuel.	11.
2.4.1	Pyrolysis of Solid Fuel.	12.
2.4.2	The Combustion of Char.	18.
2.5	Ignition of Solid Fuel on a Grate.	19.
2.6	Gas Composition through Fixed Beds.	25.
2.7	Fuel Consumption in Fixed Beds.	31.
2.8	Heat Released through a Fixed Bed.	31.
2.9	Temperature Attained in a Fixed Bed.	32.
2.10	Technology of Existing Domestic Cookers which use Solid Fuel.	33.
CHAPTER 3:	THEORETICAL WORK.	41.
3.1	Introduction.	41.
3.2	Theory of Pyrolysis of Solid Fuel.	41.
3.3	Theory of Combustion of Char and Pyrolysis Gases.	43.
3.4	Theory of Stove Design.	50.
3.4.1	The Egyptian Traditional Stove.	50.
3.4.2	Theory of the New Stove.	52.
CHAPTER 4:	APPARATUS AND EXPERIMENT.	67.
4.1	Experiments on a Single Pellet System.	67.
4.1.1	The Assessment of the Energy Consumed in Briquetting a Single Cotton Stalk Pellet.	67.
4.1.2	Determination of the Combustion Characteristics of a Single Cotton Stalk Pellet.	68.
4.1.2.1	Determination of the Composition of Pyrolytic Products.	69.
4.1.2.2	Thermogravimetric Analysis of Cotton Stalk Pellets.	70.
4.2	Experiments on Multi-pellet System.	76.
4.2.1	Improved Stove Design.	77.
4.2.2	Temperature Measurements.	78.
4.2.3	Air Flow Measurements.	80.
4.2.4	Pressure Measurements.	80.
4.2.5	Gas Sampling and Gas Analysis.	81.

Page No.

	4.2.6	Experiments to Determine the Thickness of the Oxidation Zone in a Fixed Bed of Cotton Stalk Pellets.	81.
	4.2.7	Test of the Improved Stove.	82.
CHAPTER 5:		RESULTS AND DISCUSSION.	84.
	5.1	Results of Experiments on Single Pellets.	84.
	5.1.1	Energy Requirements for Briquetting Cotton Stalk Powder.	84.
	5.1.2	Combustion Characteristics of Cotton Stalk Pellets.	85.
	5.2	Results of Experiments on a Multi-pellet system.	93.
	5.2.1	Ignition of a Fixed Bed of Cotton Stalk Pellets.	93.
	5.2.2	Thickness of the Oxidation Zone in a Bed of Cotton Stalk Pellets.	94.
	5.2.3	Alternative Method of burning Cotton Stalk Pellets.	96.
	5.2.4	Underfeed and Overfeed Combustion.	97.
	5.2.5	Results and Observations of the Stove Test.	98.
	5.2.6	Interpretation of the Experimental Investigation of both the Pyrolysis and the Char Combustion of a Single Cotton Stalk Pellet.	100.
CHAPTER 6:		COMPARISON OF THE ENERGY COST FOR COTTON STALK PELLETS, AS-HARVESTED COTTON STALKS, AND ANTHRACITE COAL.	105.
CHAPTER 7:		CONCLUSIONS AND SUGGESTIONS FOR FURTHER WORK.	107.
		REFERENCES.	112.

NOMENCLATURE

A	Cross-section area of the pellet, m^2.
A_I	Inner surface area of the stove gasifier, m^2.
A_o	Outer surface area of the stove gasifer, m^2.
A_t	Outer surface area of the stove insulation, m^2.
A_T	Thermocouple surface area, m^2.
$\frac{a}{m_s}$	Ratio of the surface area to mass of the solid fuel, m^2/kg.
B	Driving force of mass transfer, dimensionless.
B_s	Fraction of gases striking unit axial length through the fixed bed, m^{-1}
b	Constant from the reaction (fluid)+b(solid) $\rightarrow$ fluid and solid products
C_s	Specific heat at constant pressure, J/kg.k.
C'	Depreciation of knife mill and densifier, \$/tonne.
C_{O_2}	Concentration of oxygen in combustion air, $kmol/m^3$.
$(C.V.)_1$	Lower calorific value of cotton stalks, kJ/kg.
$(C.V.)_c$	Lower calorific value of coal, kJ/kg.
D	Diffusion coefficient, m^2/sec.
D_b	Fixed bed diameter.
D_e	Effective diffusion coefficient of oxygen in the ash layer, m^2/sec.
D_K	Knudsen diffusion coefficient, $\frac{4}{3}(8RT/\pi M)^{\frac{1}{2}} K_o$, m/sec.
D_o	Outer diameter of the stove gasifier, m.
D_{shell}	Diffusion coefficient through the ash shell, m^2/sec.
d	Diameter of the pores in the ash shell, μm.
d_p	Pellet diameter, m.
$\bar{d}_p$	Average pellet diameter, defined as the diameter of a sphere of the same volume as the pellet, m.
F	Factor defined by $1/[1+6.7\ \ln(1-f)^{-\frac{1}{3}}]$, dimensionless.
f	Fractional conversion of the pellet, dimensionless.
f_m	Friction factor, dimensionless.

g' Acceleration gravity, 9.8 m/sec².

g Reynolds flux, kg/m².sec.

g_{heat} Reynolds flux for heat transfer from ambience to the core of the cotton stalk char, kg/m².sec.

g_{1heat} Reynolds flux for convection to the outside surface of the cotton stalk, kg/m².sec.

g_{mass} Reynolds flux for mass transfer, kg/m².sec.

g_{1mass} Reynolds flux for mass transfer at the beginning of the char combustion, kg/m².sec.

H_c Chimney height, m.

h_c Convection heat transfer coefficient, w/m².K.

hc Hectar, 10,000 m².

h_r Radiation heat transfer coefficient, w/m².K.

h_m Mass transfer coefficient between gas and char, m/sec.

h_T Total heat transfer coefficient $h_c + h_r$, w/m².K.

k Thermal conductivity, w/m.k.

K_e Effective thermal conductivity of the cotton stalk pellets in the stove gasifier, w/m.K.

K'' Defined by $K'' = F\,K'$.

K_o $K_o = \varepsilon(d/4)$, m.

K_s Thermal conductivity of the cotton stalks, w/m.K.

K' Defined by equation $N_A = K'\,\Delta P_A$.

K_t Temperature rate coefficient, min^{-1}

L_1 Height of the green charge in the gasifier, m.

$\bar{L}$ Particle size, m.

L' Labour cost, \$/tonne.

L_f Flame length, m.

ℓ Height of the pellet, m.

M	Molecular weight, kg/kmol.
M_a	Molecular weight of air, kg.kmol.
$\dot{M}$	Instantaneous rate of burning of char from one cotton stalk pellet, kg/sec.
M'	The price of as-harvested cotton stalks, \$/tonne.
M_c	Weight of stalk charg, kg.
M_g	Molecular weight of flue products,kg/kmol.
$\dot{M}_{initial}$	Initial rate of burning of char from one cotton stalk pellet,kg/sec.
$\bar{M}$	Total weight of wheat per hectar per year, tonne/ha.year.
m	Mass flow rate of air entering the bed per unit cross sectional area of the grate in $kg/m^2.sec$.
$m_{O_2,G}$	Mass fraction of oxygen in the main stream, dimensionless.
m_p	Mass flow rage of the pyrolysis gases and tar through the grate, $kg/m^2.sec$.
m'	Mass flow rate of air (after the deduction of air required for burning the pyrolysis gases and tar) per unit area of the grate, $kg/m^2.sec$.
$\dot{m}''$	Rate of burning of solid particle per unit surface area,$kg/m^2.sec$.
N_A	Number of kgram mole of any species diffusing across the laminar boundary layer from the core between the particles in the fixed bed to the particle surface in one second and unit volume of the bed $kmol/m^3.sec$.
N'_{Re}	Modified Reynolds number $\frac{\bar{d}p\ m}{\mu}$
n'	defined by $\eta_I = n'\eta_t$.
P	Barometric pressure, N/m^2.
P_{CO_2}	Partial pressure of carbon dioxide through the fixed bed.
P_d	Applied pressure on the pellet during densification, N/m^2.

P_N	Partial pressure of the non-transparent gases through the gas film, dimensionless.
P_{O_2}	Partial pressure of oxygen.
P_{O_2}'	Partial pressure of oxygen in the combustion air after the burning of pyrolysis gases and tar only.
P_s	Stove perimeter, m.
$\bar{P}$	$(1-2\,\eta_p)/(1-\eta_p)$
P'	Cost of consumed energy in briquetting cotton stalks, $/tonne.
Q	Heat transfer rate, w.
Q_c/w_c	Heat released through the fixed bed per unit weight of air kJ/kg air.
q	Heat of reaction during pyrolysis, kJ/kg.
R	Char initial radius, m.
R_a	Gas constant of air, 288 J/kg.K.
R'	Repair and maintenance costs, $/tonne.
R_1	Thermal resistance for radiation between the two sides of the stove gasifier, K/w.
R_2	Thermal resistance for conduction through the green cotton stalk charge in the stove gasifier, K/w.
R_3	Thermal resistance for radiation and convection between the outer surface of the stove and atmosphere, K/w.
$\bar{R}$	Universal gas constant, 8314.3 J/(kmol.K).
R_c/w_c	Amount of consumed carbon through the fixed bed per unit weight of air, kg carbon/kg air.
r	Defined by 1 kg carbon + r kg oxygen $\rightarrow$ (1+r) kg product.
r_c	Unreacted core radius, m.
Sh	Sherwood number, $h_m \times dp/D_e$
S'	Selling price of coal, $/tonne.
T_c	Average chimney temperature, K.
T_f	Final pyrolysis temperature, K.

T_G	Temperature of the reaction zone, K.
T_g	Temperature in the main body of the gas, K.
T_I	Temperature at the inner surface of the stove gasifier, K.
T_{OI}	Temperature at the outer surface of the insulation, K.
T_{OS}	Temperature at the outer surface of the stove gasifier, K.
T_{tru}	True temperature, K.
T_s	Temperature of the surface of the particle, K.
T_t	Pellet temperature during the pyrolysis, K.
T_{th}	Reading of the thermocouple, K.
T_∞	Ambient temperature, K.
t_b	Burning time of char from radius R to r_c.
t_p	Time at which the surface of the pellet starts to pyrolyze.
t_c	Time at which the surface of the pellet starts to char.
t_{ps}	Time at which the pyrolysis front reaches the centre of the pellet.
t_{cs}	Time at which the char front reaches the centre of the pellet.
t'	Pyrolysis time, min.
th	Insulation thickness, m.
u	Defined by B_s x, dimensionless.
W'	Energy consumed in densification, J/pellet.
x	Distance, m.
x_o	Thickness of the oxidation zone, m.
Y'	Cost of cotton stalk pellets, $/tonne.

Greek Symbols

α	Proportion of oxygen molecules that react with carbon and produce carbon monoxide only, dimensionless.
$\alpha_{g,I}$	Absorptivity of the gas at the inner surface temperature of the stove.
μ	Dynamic viscosity, kg/m.sec.

η_p	Thermal efficiency of the fuel bed.
η_I	Thermal efficiency of the improved stove.
η_t	Thermal efficiency of the traditional stove.
η_c	Thermal efficiency of coal burning stove.
ε_a	Porosity of ash, dimensionless.
ε_b	Fractional voidage in the bed, dimensionless.
ε_c	Emissivity of the outer surface of the stove insulation.
ε_{CO_2}	Emissivity of carbon dioxide at gas temperature.
$\varepsilon_{CO_2,I}$	Emissivity of carbon dioxide at the inner surface temperature of the stove.
ε_g	Emissivity of gas at the gas temperature.
ε_{H_2O}	Emissivity of water vapour at the gas temperature.
$\varepsilon_{H_2O,I}$	Emissivity of water vapour at the inner surface temperature of the stove.
ε_I	Emissivity of the inner surface of the stove gasifier.
ε_o	Emissivity of the outer surface of the stove gasifier.
ε	Emissivity of the thermocouple.
ϕ_s	Shape factor of the solids in the bed defined as the quotient of the area of a sphere equivalent to the volume of the pellet divided by the actual surface area, dimensionless.
ρ	Density, kg/m^3.
ρ_c	Molar density of the char, $kmol/m^3$.
τ_f	Time required for complete burning of the char, sec.
ΔH	Heat of reaction, kJ/mol.
ΔP	Difference between the partial pressures of species A at the core and at the partial surface, dimensionless.
Δw	Fractional weight loss of a single pellet during pyrolysis up to time t
Δw_∞	Asymptotic fractional weight loss of a single pellet during pyrolysis.
σ	Stefan-Boltzman constant, 5.67×10^{-8} $w/m^2.K^4$.

CHAPTER 1.

INTRODUCTION

1.1 The General Problem.

The fossil fuels upon which our current civilization is largely based are non-renewable and limits to their availability are clearly seen. It is for this reason that so much attention is now being given to the search for alternative and supplementary fuel supplies which have the advantage of being renewable,(1).

The renewable alternatives of fuel supplies include wind and wave power, solar energy, animal wastes and agricultural wastes.

1.2 The Specific Problem.

Cotton is the main crop in Egypt and the weight of its harvested stalks is estimated to be nearly 5.0 million tonnes per year (2.6 million tonnes per year coal equivalent),(7). These cotton stalks are used as a domestic fuel in the Egyptian villages.

Many difficulties face the use of cotton stalks at the present time. Among these difficulties are, low density and low volumetric energy content of the as-harvested cotton stalks which increase the volume of the stove and consequently the percentage of heat lost by radiation and convection. The traditional stove is an open fire enclosed by three walls and these types of stoves have very low thermal efficiencies due to the heat loss from the fire to the environment. Additional problems come from the storage of the fuel, on the roofs of the houses where it is not only a serious fire risk but also plays a part in the life-cycle of cotton insect pests which hibernate in the harvested material and re-infest future crops.

The study has therefore aimed to develop an easy and attractive way of burning the cotton stalks and to provide an alternative to the Egyptian government to solve the problem of the use of the cheap government subsidised liquid and gaseous fuels currently in use in the villages.