REDESIGN OF COMMONLY USED TOBACCO CURING BARNS IN ZIMBABWE FOR INCREASED ENERGY EFFICIENCY

SPECIAL MUSONI[1]
Department of Soil Science and Agricultural Engineering,
University of Zimbabwe, MP 167
Mt Pleasant, Harare, Zimbabwe
smusoni3@gmail.com

RAYMOND NAZARE[2]
Department of Soil Science and Agricultural Engineering,
University of Zimbabwe, MP 167
Mt Pleasant, Harare, Zimbabwe
nazare2003@yahoo.com,

EMMANUEL MANZUNGU[3]
Department of Soil Science and Agricultural Engineering,
University of Zimbabwe, MP 167
Mt Pleasant, Harare, Zimbabwe.
manzungu@iwayafrica.co.zw

BRIGHTON CHEKENYA[4]
Department of Soil Science and Agricultural Engineering,
University of Zimbabwe, MP 167
Mt Pleasant, Harare, Zimbabwe.

Abstract

In Zimbabwe two types of barns are commonly used for tobacco curing, namely the traditional and Rocket barns. The traditional barn and the Rocket Barn loose 98.5% and 55.6% of the energy supplied respectively. The latter is 43.6% more thermally efficient than the traditional barn. There is, however, potential of increasing the energy efficiency of both barns. In this study, a design that incorporates structural changes to reduce heat loss as well as recovery of heat was developed. The design is a combination of commercially available components, and allows for ventilation heat re-use and increased heat transfer from furnace ducts to the drying chamber. The structure was found to be 54.7% more thermally efficient than the Rocket barn and 74.2% more efficient than the traditional barn. The new design needs to be field-tested so that it can be adopted by tobacco farmers.

Key words: Tobacco, energy efficiency, traditional barn, Rocket barn thermal energy.

1. Introduction

Zimbabwe is the largest producer of flue-cured tobacco in Africa and the world's fourth-largest after China, Brazil and the United States of America (FAO 2011). The crop is quite important to the Zimbabwean economy. It normally accounts for more than 50 % of the country's agricultural exports, 35 % of total exports and nearly 10 % of Gross Domestic Product (GDP) and 43% of agricultural GDP (Diao *et.al* ,2006)

Successful tobacco production involves an energy intensive curing process, which determines the final quality of the tobacco leaf and ultimately the selling price of the leaf. In Zimbabwe, the majority of farmers use the traditional barn. The barn uses a high amount of energy due to heat losses that are incurred through various structural elements such as walls, floors, roofs, exhaust chimney and the fireplace. The high energy consumption causes environmental degradation. This is because many tobacco farmers, especially smallholder ones, rely on wood fuel for tobacco curing.

Smallholder farmers use approximately 43m^3 of fuelwood (approximately 15 000kg)/yr to produce an average of 1 400kg of cured tobacco. This translates to a Specific Fuel Consumption (SFC) of 10.7kg/kg of tobacco (Scott, 2006), which is approximately a third of the farmers' income (Scott, 2006). This indicates a loss of 98.5% of energy lost during curing as a result of inefficient curing barns that are currently in use. As already implied this has negative consequences on the country 's forest resources. In the last three years it is estimated that more than 300,000 hectares of indigenous forests were destroyed annually mostly by new small-scale tobacco farmers

(CFUZ, 2011). Forest degradation has wider environmental consequences such as soil erosion and the destruction of the natural carbon sink, which results in the build up of greenhouse gases.

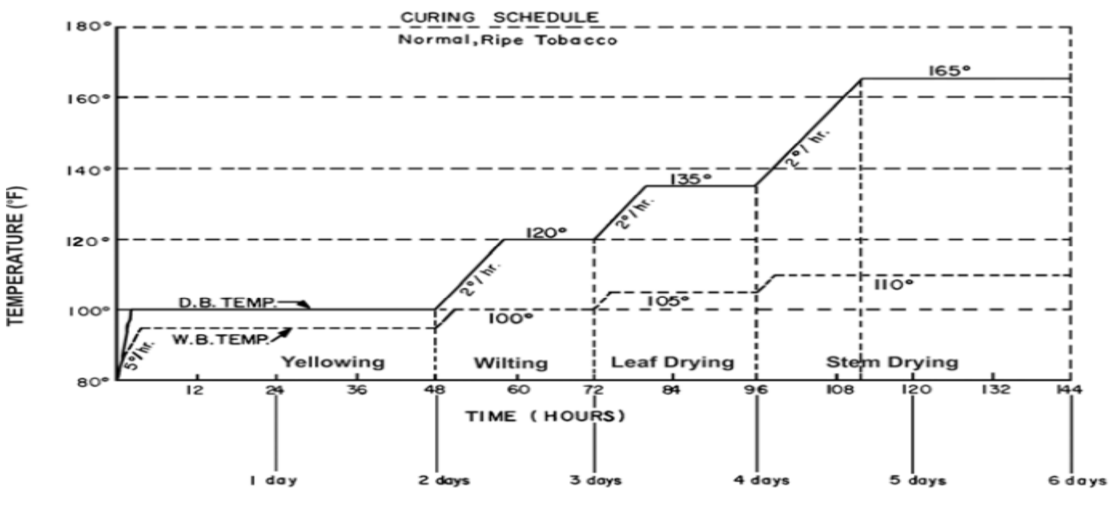
The rising number of smallholder farmers venturing into tobacco production in the aftermath of the land reform programme means that environmental degradation is likely to worsen. Various proposals have been put forward in order to contain the problems of deforestation. . For example the Forestry Commission of Zimbabwe launched the Tobacco Wood Energy Programme. The programme encouraged farmers to plant fast growing tree species such as eucalyptus for tobacco curing. It takes an average of five years from planting to harvest a mature eucalyptus tree in the subtropical climate and over 15 years to harvest an indigenous tree.(Du Toit *et al*. 1998) and in the process farmers cut down indigenous trees for fuel. An equivalent of about 26.5 million indigenous trees are cut to provide fuel wood for curing before potentially using newly grown trees.

From the above it is clear that there is a need to reduce energy consumption that is a consequence of tobacco curing through the identification of opportunities of energy-improving technologies. Possible areas of intervention include improving heat generation, transfer and distribution. High rates of wood use can be considerably reduced if investment is done in furnace technology, barn construction and efficient loading (Geist 1997)The objective of the study was to redesign the curing system in most commonly used tobacco curing barns.

2. The curing process

The redesign of the tobacco barns should be based on a proper understanding of the curing process. The overall aim of curing is to ensure that the harvested tobacco undergoes through a process that positively affects the quality of the leaf, which ultimately determines the final selling price of the crop. As such the conditions that obtain in the barn should closely approximate the conditions that are required during the various curing phases.

Tobacco curing is both a chemical and a physical process. It involves controlling the temperature and humidity in the barn, which is mainly achieved by controlling ventilation (Fig 1). Correct temperature and humidity are important in allowing the chemical reactions. During the first stage of curing, known as the yellowing stage, chemical conversions of starches to sugars take place (Tso, 1990) at a high relative humidity of approximately 85% or higher and a temperature of 38^0C (North Carolina Cooperative Extension Service, 2010). The second stage is drying of leaf by rapid removal of moisture. This is achieved by increasing the ventilation in the barn. The temperature is gradually raised from 38 ˚C to 57 ˚C. If the leaf temperature gets too high too quickly, scalding may occur which damages the leaf. The last stage is mid rib drying where it is dried by gradually raising the barn temperature from 57 ˚C(135^{o}F) to 74 ˚C (165^{0}F). Over-ventilating during these three stages wastes heat. Once completely dried to zero percent moisture, a small amount of moisture is added back to the cured leaf (the "conditioning" process). This allows the leaf to be handled for market preparation.



Key: D.B –dry bulb temperature, WB-wet bulb temperature,

Fig 1. Stages in tobacco curing

3. Tobacco barns in Zimbabwe

3.1 Traditional barn

The traditional barn has one course wall built with a furnace outside (Fig. 2). The roofing material is usually corrugated iron or 2.5mm grass thatch. There are vents on the walls near the floor and near the roof for ventilation. The chimney allows for ventilation of air that has passed through the brick conduits directly from the furnace. The heat exchanger consists of conduits made of 110mm farm brick. Brick has low thermal conductivity of 5,88W/m^2K, thus allowing low heat transfer. The brick conduit also acts as a heat store releasing energy slowly due to its heat capacity. There is very little residence time of hot air as the conduit length (4m) and heat transfer area(1.2m^2) are both too small to allow high heat transfer to the drying chamber.. This leads to the exhaustion of hot air from the chimney to the atmosphere with unused energy. Laminar flow of hot air in conduits leads to low dissipation of heat energy from the conduit air. Consequently, air leaves the barn through the chimney at temperatures equal to barn temperatures at thermal equilibrium points of the three phases of curing.

Heat is also lost from the barn through conductive heat losses that occur through the surfaces of the barn. At each stage of curing, the temperature (see Fig 1) is raised and more heat is lost through the floor which subsequently losses heat by conduction to the ground. Heat is also lost through radiation at night because the barn is warmer than the night air. The furnace is outside the barn structure leading to heat losses by both convection and radiation.

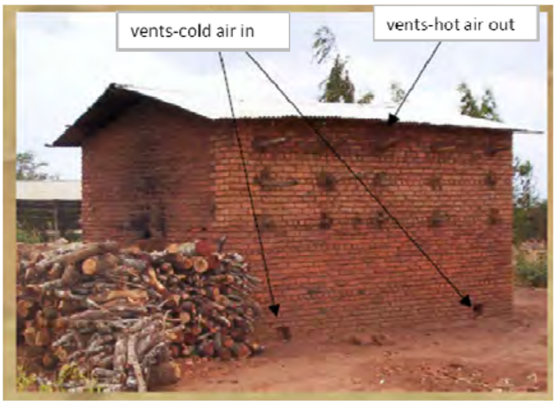


Fig 2. Traditional barn in Zimbabwe

Such heat losses affect the curing schedule of the tobacco leaf in the barn. To improve energy use in curing, the Rocket Barn was developed.

3.2 The Rocket Barn

A Rocket Barn was developed by Peter Scott at Tobacco Research Board (TRB) in an effort to reduce energy consumption in traditional barn, (Geist, 1999). The Rocket Barn was found to reduce wood consumption by 54.3% (Scott, 1997). However this system operates at low efficiencies as heat is lost through various elements of the structure. Air exhausted from the conduit pipes is slightly below ambient barn air temperature before the two mediums reach equilibrium. Once equilibrium temperature is reached (depending on the drying phase of tobacco) the former air medium leaves the barn at slightly the same temperature as barn temperature. This is because there is little heat transfer as the conduit length (13m) and surface area of heat transfer (3.9$m^{2)}$ are both too low to allow sufficient residence time of hot air in the heat exchanger. Although this area is 225% more than that of the traditional barn there is potential to increase it to improve on residence time hot air in heat exchanger hence and heat transfer. Useful heat is subsequently exhausted out of the curing system. The concrete floor is uninsulated and losses heat to the ground by conduction. The research recommended a more holistic approach that involves integrated measures to reduce deforestation caused by wood use in curing (Scott, 1997).

Fig 3: Rocket Barn Heat Exchanger

From the above it can be seen that the building elements which make up the tobacco curing structures need to be redesigned for both the traditional and rocket barn so as to improve on thermal efficiency. The floor, walls, roofing, furnace and exhaust systems are possible areas that require redesigning to improve thermal efficiency of curing barns. Table 1 summarises the main points of possible intervention.

Table 1: Summary of new barn design

BUILDING ELEMENT/SYSTEM	REDESIGN
Floor	The floor is insulated by polystyrene imbedded between 75mm layer of bricks below the barn and a 10cm concrete surface on the inside of the barn. This eliminates heat loss by conduction vertically down to the ground
Walls	Walls are insulated with 4 centimetres polystyrene (Styrofoam) of thermal conductivity 0.033-0.04(w/mk) on the inside. It is supported by a mesh wire to the wall. The wall is constructed form a single course of 10cm wide farm bricks. Heat loss by both conduction on wall surface and radiation is reduced.
Roofing	Material for roofing needs to be changed from corrugated iron to straw. Straw has a thermal resistance of $23.81m^0$ K/W while that of sheet metal that is commonly used is 0.11 m^0 K/W The straw profile will be 10cm thick. The straw is supported by gum poles underneath.
Exhaust Gasses	Exhausted heat can be used to pre-heat furnace feed air. This is achieved through recovering and recycling all or part of the heat. Exhaust heat from the heat exchanger is constricted into a flue pipe which is discharges into an air-air exchanger above the roof mad by laying corrugated sheets parallel to each other. Corrugated sheets allow for turbulent flow. The air-air exchanger is embedded in the fibre glass roof.
Furnace	A pressure fan was introduced as part of the furnace to ensure sufficient oxygen supply. The volume of the furnace is made sufficiently long to ensure air residence time of at least two seconds. The cross sectional area above the grate is $0.4\times0.6m^2$ and is 1.5m long. The furnace is built inside the barn to ensure that if any heat leaks, it leaks into the drying chamber, thus there is no need for insulation. The furnace is also raised from the floor, there is an air gap between the base of the furnace and the floor to ensure that there is no heat loss through conduction to the floor and the ground. Heat transferred through the metal base of the furnace heats up the chamber air and thus is not wasted. Complete combustion of wood produces only Carbon, Dioxide (CO_2) and Water (H_2O).

When these changes have been made to the current designs, the new barn design will be as shown in Fig 5 below. Thermal efficiency is expected to improve as indicated in Table 3

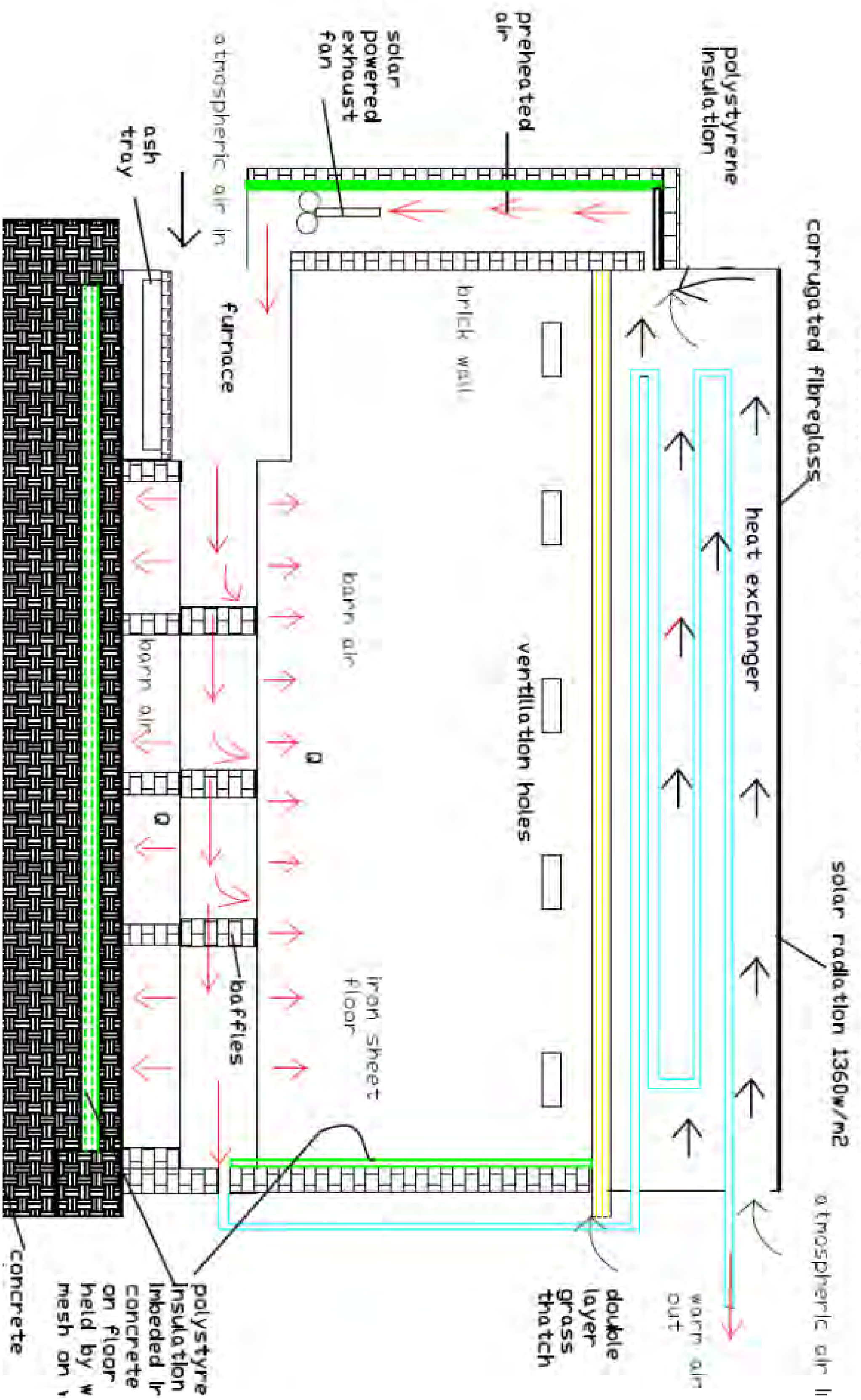


Fig 4. New barn design

The differences in design elements of the traditional barn, Rocket Barn and the new design are as summarised in Table 2.

4.2 Table 2: Summary of the main features of the barns

Building Element	**Traditional barn**	**Rocket barn**	**New barn**
SFC	11Kg/Kg	4.5 kg/kg	2.06kg/kg based on calculations in table
walls	Common farm brick wall (200mm thick), single course	Common farm brick wall(200mm thick), single course	Common farm brick wall with polystyrene insulation 40mm thick inside, supported with mesh wire or cheaply thatch grass 10mm thick supported by wooden chipboard
roof	Corrugated iron or asbestos roof	Grass straw thatch	Double grass straw thatch 100mm thick
floor	Concrete floor	Concrete floor	Concrete floor with polystyrene insulation 40mm thick underneath
furnace	Farm brick furnace with no feed chamber and insulation Furnace outside barn	Combustion chamber made with high -fired, locally produced, insulative ceramic bricks with30 by 30 cm feed chamber Furnace inside the barn	Furnace inside the barn, raised from the floor with feeding chamber made from locally highly fired insulative clay bricks
chimney	Exhaust air outlets below roof , no energy recycling	Double chimney made from galvanized iron sheets which allows preheating of incoming air into the barn but no energy recycling	Chimney with Heat exchanger to preheat air entering the furnace
conduits	Common brick conduits Length= 4m Surface area=0.36m^2	Metal conduits Length 13m, Surface area=1.17m^2	Flat iron sheet raised from the floor with baffles and screened on top Length 13m Surface area =18m^2 (whole floor space is used as heat exchanger surface, 1 438% more than the rocket barn)

Notes

(i) Dimensions for the conventional barn are given below:

4.5m length by 4m width with a flat roof 3.75m high on the highest side and 3.3m on the lower side, a furnace 2.5m long, 1.2m wide and 1.2m high, chimney 2.7m long and 0.8 m square section, These dimensions are the same for both the traditional barn and the rocket barn. The improved barn will assume the same dimensions. Traditional barn conduit pipe: 4m length and 0.3m width and 0.3m height, Rocket barn: 500 stick with conduit pipe 0.3m height, 0.3m width and 13m length

(ii) Temperatures in the barn are uniformly distributed

(iii) Ambient outside temperature is 25^0C, density of air=1.2kg/m^3, specific heat capacity of air =1.005 KJ/kg^{0}K
(iv) Natural ventilation occurs through the furnace ant the chimney through the stack effect. It is assumed that the most efficient form of natural ventilation occurs in the rocket barn and the traditional barn.
(v) Equilibrium temperatures of curing phases are taken, i.e. yellowing phase=30^0C (96hrs), leaf drying=50^0C(48hrs), mid rib drying=74^0C (48hrs)
(vi) . The barn is composed of major areas like walls, floor, roof, chimney, conduit and furnace. Heat losses will be analysed on this components using thermodynamic heat transfer equations and thermal properties of the materials that make up the barn.
(vii) The barn used carries 200kg of cured tobacco

The following heat loss equations were used:

(i) Heat lost by conduction through the walls, floors and roof is calculated using the formula:

$Q_c = UA\Delta T$

(ii) Where: Q=heat lost, U=thermal conductance, ΔT=temperature difference between barn and outside air. Thermal conductivities of the materials are shown in the appendix.

(iii) Furnace of traditional barn is outside the structure so there are radiation (Q_r) and conduction losses(Q_c)

$\sum$heat loss from furnace $=Q_c+Q_r$

$$=UA\Delta T+ \varepsilon\sigma A T^4$$

Where ε= brick emissivity=0.9, σ= Boltsman's Constant=5.67310^{-8}, A= cross sectional area, T=temperature in Kelvin

(iv) Heat losses through the chimney is through both conduction and ventilation (Q_V)

$(Q_V)= mc\Delta\theta$
$= (\rho_{air}/V)\, c\Delta\theta$

Where m=mass flow rate of air, c=specific heat capacity of air=1.005kj/kg^{0}K, Δθ=temperature gradient between exhaust air and outside air, ρ_{air}=density of air (1.2kg/m^3), V=ventilation rate (m^3/s)

Table 3: Summary of heat losses through five major structural elements on three barn types

Element	**Time Duration (hrs)**								
	traditional			**rocket**			**New design**		
	96	48	48	96	48	48	96	48	48
Walls (Kwh)	16.8	14.1	25	16.8	14.12	25.4	3.02	2.52	4.6
Roof (Kwh)	1.14	0.95	1.7	0.53	0.46	0.32	0.53	0.46	0.32
Floor (Kwh)	20.7	17.2	31	20.7	17.28	31.1	3.7	3.11	5.6
Chimney (Kwh)	17.3	14.5	37	8.6	7.2	26	31.8	14.5	22
Furnace (Kwh)	31.2	29.4	88.	20.7	17.28	62.2	4.46	3.7	13.5
Total (Kwh)	90.7	76.2	183	67.3	56.34	123	43.51	24.29	46
Total (Kwh)	**438.1**			**247**			**113**		

3 Discussion

Traditional barn energy losses through the roof contributes 10% to the total structural losses. However compared to roof losses for the other two barns which make use of thatch, the roof is inefficient by a factor of at least 30.The roof losses for the new design are the same as those of the rocket barn and have insignificant contribution to the total losses. Thatch grass used for roofing is readily available, sometimes at zero cost.

Wall energy losses for both the traditional and Rocket Barn are the same because they are all made from farm brick. Insulation of the walls using polystyrene reduces heat losses through walls by 67.4%. Insulating the floor with polystyrene on the new design reduced energy losses by by 82% as compared to the traditional barn and Rocket Barn

Rocket barn reduced the radiation loss component by placing the furnace inside the barn. On the new barn the furnace was placed inside the barn and raised above the floor. Therefore energy losses were reduced considerably by 78% from the rocket barn and by 84.6% from the traditional barn. Heat below the furnace in the new design is used to directly heat barn air and not dissipated to the ground.

Air exhausted through the chimney is at the same temperature as barn air temperature in both the rocket barn and the traditional barn. Hoewever the new barn uses this exhaust air to preheat incoming air through a heat exchanger on the roof which can be fed into the furnace at a higher temperature thereby reducing the amount of energy needed to raise air temperature.

The total energy for curing is highest on the traditional barn, followed by Rocket barn and lowest on the new barn. The new barn reduced heat losses by 74.5% from the traditional barn and by 54% compared to the Rocket barn because of the intervention measures.

4 Conclusions

High energy demand in tobacco curing is as a result of the use of inefficient barns. There is a potential to reduce total heat losses in curing barns through the redesign of building elements. Calculations have shown that the rocket barn is 43.6% more thermally efficient than the traditional barn. Total heat losses in the traditional ban amounted to 438.1KWH whilst that of the rocket barn was 247KWH throughout the curing 216hr period. Energy efficiency is improved by reducing energy losses that occur through structural elements of the barn and recovering the heat. The modified barn that incorporates structural changes to reduce heat loss is 54% more thermally efficient than the rocket barn and 74.5% more efficient than the traditional barn.

5. APPENDIX

Properties of materials proposed in the new barn design

	Thermal conductivity
Farm brick	5,88W/m^{2}K,
Polystyrene (40mm)	0.033-0.04
Thatch	0.26
Iron sheets roof	3.03
Concrete (floor)	0.179
Wire mesh	N/A(support material)
Gum poles(50-75mm)	N/A(support material)

6. References

[1] Bengtsson L.P, Whitaker J.H, (1988) Farm Structures in Tropical Climates, United Nations, Food and Agricultural Organisation

[2] Biomass Energy Centre, (2011). Typical Calorific Values of fuels. http://www.biomassenergycentre.org.uk/portal/page?_pageid=75,20041&_dad=portal&_schema=PORTAL (22 November 2012)

[3] Commercial Farmers Union of Zimbabwe, (2011), Tobacco Farming Negatively Impacts Zimbabwe's Indigenous Forests

[4] Curkeet R, PE. Wood Combustion Basics, EPA Workshop March 2, 2011 www.intertek.com, (20 November 2012)

[5] Diao X, Robinson S, Wobst T.P.M.(2006). Assessing Impacts of Declines in the World Price of Tobacco on China, Malawi, Turkey and Zimbabwe http://www.cgiar.org/ifpri/divs/tmd/dp.htm

[6] Elington G. Harvesting and curing flue cured tobacco. Can also be accesed at: http://www.cropsci.ncsu.edu/personnel/Fisher_Loren/class/CS%20062-495%20Lecture%206%20HarvestingandCuring.pdf? (10 October 2012)

[7] FAO Corporate Document Repository, (1997) Forestry Department Title: Estimating biomass and biomass change in tropical forests Appendix 1 - List of wood densities for tree species from tropical America, Africa, and Asia. Can also be accessed at : http://www.fao.org/docrep/w4095e/w4095e0c.htm, (17 October 2012)

[8] Geist H, 1997. How tobacco farming contributes to tropical deforestation. http://www.psychologie.uni-freiburg.de/umwelt-spp/proj2/geist.html, (16 October 2012)

[9] North Carolina Cooperative Extension Service. (2010). Flue-Cured Tobacco Guide. Prepared by North Carolina State University, Raleigh, N.C.

[10] Scott P.(2006). Development of Tobacco Rocket Barn for Small Holder Farmers in Malawi

[11] Can also be accessed at: http://www.google.co.zw/url?sa=t&rct=j&q=Tobacco+curing+Scott&source=web&cd=3&cad=rja&ved=0CCkQFjAC&url=http%3A%2F%2Fwww.aprovecho.org%2Flab%2Fpubs%2Frl%2Fstove-design%2Fdoc%2F17%2Fraw&ei=yIRRUNuwEKzb4QST-YHQDw&usg=AFQjCNFDKEH4g48MI0By-lOcAe2Yq_pBJg, (16 October 2012)
[12] Tso, T.C.(1990). Production, Physiology, and Biochemistry of Tobacco Plant. Beltsville: Ideals, Inc., 1990. http://www.engineeringtoolbox.com/wood-biomass-combustion-heat-d_440.html
[13] Watkins, R.W., and Johnson W.H . (1980). Guide for bulk curing tobacco. North Carolina Agricultural Extension Service, AG- (16 October 2012) Can also be accesed at: 101http://www.caes.uga.edu/applications/publications/files/pdf/RB%20439_2.PDF