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Original Research Article

Investigation of Thermal Efficiency and Heat Flux Analysis of a Tube Boiller Used in Boiling Palm Nuts

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Abstract: Heat energy and heat energy generation become significant in manufacturing, production and processing processes. Heat management is needed to avoid wastage of human efforts, cost implication, material sources needed to generate this heat.and to minimize cost of production. Hence, this work critically investigates thermal efficiency and heat flux analysis of a tube boiler used in palm oil processing. A good comparative analysis between a boiling vessel without extended tubes and a tube boiler reveals the thermal efficiency, energy, materials and time conservation of the tube boiler over the latter of the same capacity. This provokes the investigation of the conditions that favoures its thermal efficiency ,energy , materials and time conservation .Tube boiler boils with steam ,and its heat surface area increased by the provision of tubes thus the water expose larger surface area to the heat source hence its boils within shortest possible time and change to gaseous state-steam. The residence time of palm nuts is short as possible in the steam chamber owing to the fact the heat energy possessed by steam is higher than that of boiling water. The choice of fuel used cannot be undermined, fuel with high heat value –calorific value will heat faster than that of lower calorific value. Coal, hydrocarbonfuels, dry wool is locally available. This study reveals that tube boiler is energy, time, water and fuel efficient with high thermal efficiency in boiling palm nuts to facilitate processing operations.
Keywords: increased surface area, heat flux, steam energy, thermal efficiency and modeling, palm nut tube boiler

INTRODUCTION

Palm oil processing would be a mirage without heating. Hence, it is an inevitable to investigate on the best alternative for heating, conserving useful energy and time as well as the fuel conservation. Boiling of palm nuts in the local areas especially in Nigeria is labor intensive as it involves fetching of fire-wood, regular setting of the fire, and water wastage. This waste fire wood and much of the heat energy is not conserved with large resident time in boiling palm nut in the boiling water. In most local areas both domestic and industrial places of palm oil processing, fetching of fire-wood has led to deforestation and disturbing the balance in the ecosystem. Wastage of the fire-wood can be minimized if a more efficient way of boiling palm nut is adopted. This will eliminate the drudgery in long heating and boiling of the palm nuts in the boiling water and help to achieved efficient use of resources and energy. Tube boiler exposes large heating surface area for the burning fuel in the heating stage and transfers same to the water surface area exposed by the extended heat tubes to fasting the temperature change and boiling of the water. As the temperature is above the boiling (steam) point 100^oC steam begins to liberate with high heat energy. Steam burns severely than boiling water because the latent heat of vaporization of steam is higher than specific heat capacity of water. Hence the preference to boil the palm nuts with steam that will yield faster result through a shortest resident time for the palm nuts and minimize heat and water input. Heat transfer is the area which describes the energy transport between material bodies due to a difference in temperature, and its development and applications are of fundamental importance in many branches of engineering since provides economical and efficient solutions for critical problems encountered in many engineering items of equip-ment. Among the parameters that determine the thermal behavior of a material, the thermal conductivity is especially important because it represents the ability of a material to transfer heat, and it is one of the physical quantities whose measurement is very difficult and it requires high precision in the determination of the parameters involved in its calculations [5, 6].

DESCRIPTION

Steam is extensively used for various applications such as power production, industrial processes, work interaction, heating etc. With the increasing use of steam in different engineering systems the steam generation technology has also undergone various developments starting from 100 B.C. when Hero of Alexandria invented a combined reaction turbine and boiler. Boiler, also called steam generator is the engineering device which generates steam at constant pressure. It is a closed vessel, generally made of steel in which vaporization of water takes place. Heat required for vaporization may be provided by the combustion of fuel in furnace, electricity, nuclear reactor, hot exhaust gases, solar radiations etc. Boilers are of many types. Their classification depends upon their features as follows:

The orientation/axis of the shell:

- *Vertical boiler* has its shell vertical.
- *Horizontal boiler* has its shell horizontal.
- *Inclined boiler* has its shell inclined.

Based upon utility of boiler:

- (*Stationery boiler*, such boilers are stationery and are extensively used in power plants, industrial processes, heating etc.
- (*Portable boiler*, such boilers are portable and are of small size, e.g Locomotive boiler, which are exclusively used in locomotives. Marine boiler, which are used for marine applications.

Based on type of firing employed

- Externally fired boilers, in which heat addition is done externally i.e. furnace is outside the boiler unit. Such as Lanchashire boiler, Locomotive boiler etc.
- Internally fired boilers, in which heat addition is done internally i.e. furnace is within the boiler unit. Such as Cochran boiler, Bobcock Wilcox boiler etc.

Based upon the tube content

- *Fire tube boilers*, such boilers have the hot gases inside the tube and water is outside surrounding them. Examples for these boilers are Cornish boiler, Cochran boiler, Lancashire boiler, Locomotive boiler etc.
- *Water tube boilers*, such boilers have water flowing inside the tubes and hot gases surround them. Examples for such boilers are Babcock-Wilcox boiler, Stirling boiler, La-Mont boiler, Benson boiler etc.

Based on type of fuel used

- *Solid fuel fired boilers*, such as coal fired boilers etc.
- *Liquid fuel fired boilers*, such as oil fired boilers etc.
- *Gas fired boilers*, such as natural gas fired boilers etc.

Based on circulation

- *Natural circulation boilers*, in which the circulation of water/steam is caused by the density difference which is due to the temperature variation.
- *Forced circulation boilers*, in which the circulation of water/steam is caused by a pump i.e. externally, assisted circulation.

Based on extent of firing

- *Fired boilers*, in which heat is provided by fuel firing.
- *Unfired boilers*, in which heat is provided by some other source except fuel firing such as hot flue gases etc.
- *Supplementary fired boilers*, in which a portion of heat is provided by fuel firing and remaining by some other source [1].

SCOPE

This tube boiler under analysis is designed and fabricated to facilitate boiling of palm nuts for palm oil processing aim at improving, conserving both cost and material as well as energy and time. It comprises the steam chamber that houses the nuts and a tilted perforated metal sheet that separate the boiling water compartment. The heat tube are extended bodies that houses the water are vertically down at the base of the boiler that receives direct heat from the burning fuel.it has ash plate ,stand and a ladder for feeding the boiler of the palm nuts with air tight lock for both hopper and the discharge chute. A water inlet pipe with a tap is provided and the design provides means of maintenance for the aluminum tubes. Local fabrication is done minding material selection in a view to boosting agricultural productivity via palm oil processing.

Aims and Objective

Investigating heat flux distribution analysis and thermal efficiency of a tube boiler fabricated to boil palm nuts, the followings were had in mind;

- To know the thermal efficiency of tube boiler over the local boiling drum.
- To know the important and application of extended bodies like these tube for heat transfer.
- That the heat tube increase the surface area of the heating base thereby exposing the water surface area to heating.
- To x-ray temperature distribution in the cylindrical tubes through CAE Heat flux analysis.
- To utilize steam energy latent heat of vaporization of steam to heat palm nuts since it is higher than specific heat capacity of water for reasources, energy, fuel and time conservation.

Statement of the Problem

There had been energy and time wastage involved in the drudgery in the boiling of palm nuts during palm oil processing. This involves waste of fire-wood and water, creating high demand on fire –wood thus leading to deforestation on local and industrial demands. As fire –wood become the most readily available source of domestic fuel and the likes of Hydrocarbon fuels and coal in Nigeria, it becomes imperative to design an efficient boiler that would give a lasting solution to these problems. Hence, the investigation of heat fluxes distribution and thermal efficiency of a tube boiler in boiling of palm nuts.

Significant Of Study

This work is done to show the use of steam energy to heat palm nuts with shortest possible resident time with efficient use of fuel, water, human effort and time. Heat content of steam is found greater than the heat content of boiling water.

DESIGN

Methodology

The cross sectional area of a boiler drum base is determine with or without tubes. Temperature and heat flux distributions are analysed through conduction and convection in the tubes. The model is analyzed with solid works 2014 and Ansys.

Assumptions

The following assumptions were made;

- The tubes are made of pure aluminium with 3mm wall thickness, an external diameter 40mm, 450mm long for its high thermal conductivity and diffusivity and considered infinite tubes.
- Pure water is considered.
- Adiabatic flame burner condition hence no cross flow of air through the burners that can conduct heat away.
- A liquid fossil fuel –diesel is used
- Heat conduction and temperature distributions are uniform and steady state.

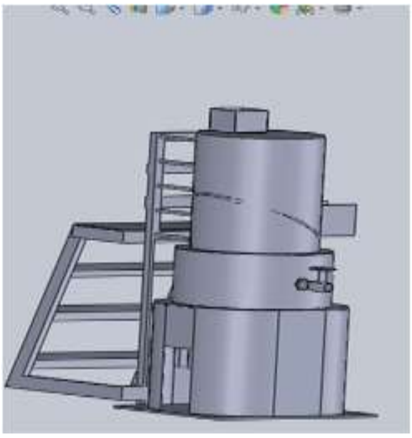

Fig-1: Solid view of the palm fruit tube boiler

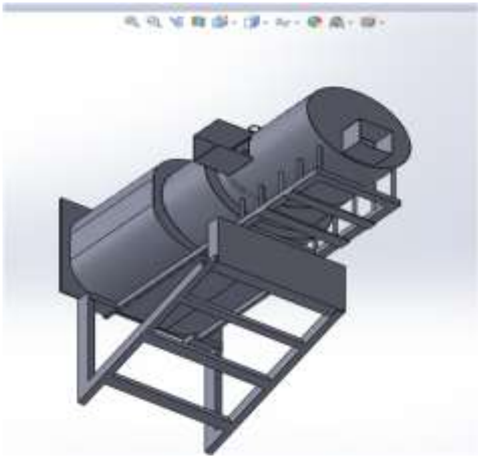

Fig-2: View of the palm nut tube boiler with ladder for feeding

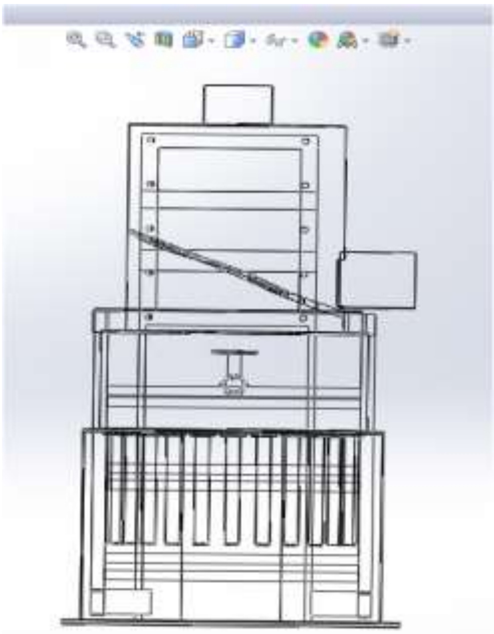

Fig-3: wire frame of the palm fruit tube boiler

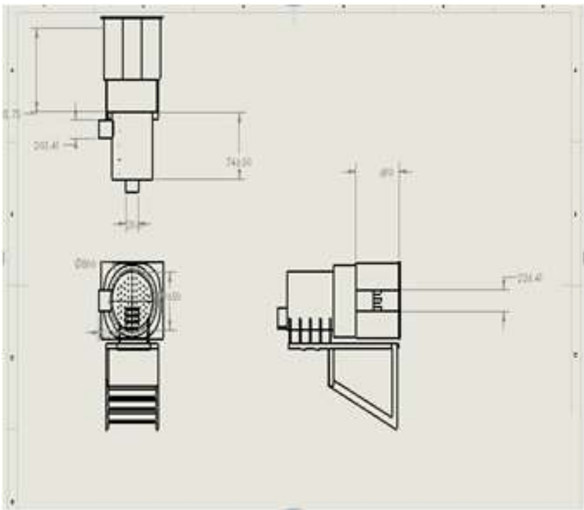

Fig-4: Othographic view of the palm fruit tube boiler

Analysis

Heat required to raise a unit mass (m) of water at room temperature to steam.

$q_w = C_w \Delta T + \dot{L}$ (1)

$m = \rho_w V$ (2)

$Q_w = mC_w \Delta T + m\dot{L}$ (3)

The quantity of heat required to cause change of state of the mass of water to steam in the boiling tubes is the heat equivalent that should be generated from the burning fuel assume uniform and steady heat generation without heat lost. Considering the heat analysis for the heat generation of the liquid fuel is idealized through combustion equation.

$C_xH_{y\,l} + \left(\frac{4x+y}{4}\right) O_{2\,g} \rightarrow xCO_{2\,g} + \frac{y}{2} H_2O + Heat\ Energy$ (4)

Heat energy is the heat dissipation due to combustion as a function of the calorific value of the fuel and assumed to be equal to the heat required to change the mass of water to steam.

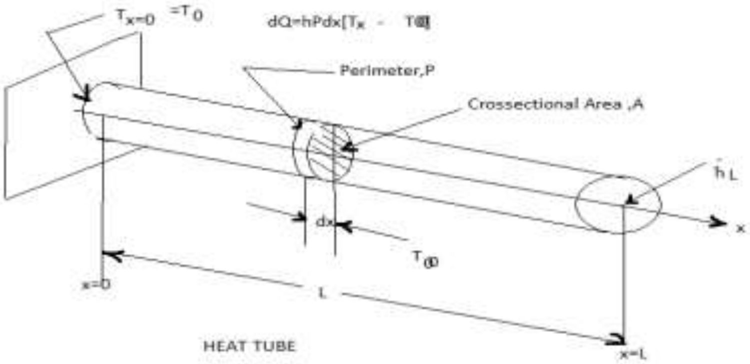

Fig-5: one dimensional heat analysis in a cylindrical tube fin

The base area of the drum without tube is considered A_{wt} ;

$A_{wt} = \frac{\pi D^2}{4}$ (5)

The tubes with crossectional area. A_{tc};

$A_{tc} = \frac{\pi {D_e}^2}{4}$ (6)

$Total\ surface\ area\ of\ the\ of\ the\ tube = curved\ surface\ area\ of\ the\ cylinder + base\ area\ of\ the\ cylinder$

This is given as

Total surface area of the cylindrical tube A_T;

$A_T = 2\pi r_e(r_e + l)$ (7)

For n number of extended tubes, the total area for available for heating is given A_H;
$A_H = A_{wt} - A_{tc} + n * A_T$ (8)

This gives a larger surface area than a boiler drum without boiling tubes, hence it has more area expose to heat than the drum of the same based area without tube thereby exposing more of the water to heat. The tubes are Aluminum for its thermal conductivity and diffusivity.

Heat Conduction

Heat absorbed from the furnace is conducted through the piping of the water walls. Conduction is governed by the Fourier relation, which for a cylindrical pipe wall principally yields

$\dot{Q} = \frac{\lambda 2\pi l(T_0 - T_i)}{In\frac{r_0}{r_i}}$ (9)

The radiactive, conductive and convective heat transfer forms the basis for the design. Fourier's law of heat conduction is applied to analyze heat conduction through the uniform wall of the aluminium tube. Heat per unit area conducted is q_c

$q_c = Q/A_T$ (10)

$q_c = -K\frac{dT}{dx}$ (11)

In a three dimensions

$q_c = -K\left[\frac{\partial T}{\partial x} + \frac{\partial T}{\partial y} + \frac{\partial T}{\partial y}\right]$ (12)

Hence heat equation is given as

$\frac{1}{r}\frac{d}{dr}\left(r\frac{dT}{dr}\right) + \frac{q}{K} = 0$ (13)

For a uniform heat generation

$\frac{r\,dT}{dr} = -\frac{q}{2K}r^2 + C_1$ (14)

From general solution

$T(r) = -\frac{\dot{q}}{4K}r^2 + C_1 Inr + C_2$ (15)

Hence uniform distribution

$T_{0(r_o)} = T_{s(r_s)} \equiv T_{i\,(r_i)} = T_{e\,(r_e)}$ (16)

$C_2 = T_e + \frac{\dot{q}}{4K}r_1{}^2$ (17)

The temperature distribution in the tube

$T_{(r_i)} = \frac{q r_e{}^2}{4K}\left(1 - \left(\frac{r_i}{r_e}\right)^2\right) + T_e$ (17)

The dimensionless temperature distribution form is given

$\frac{T_{ri} - T_e}{T_o - T_e} = 1 - \left(\frac{r_i}{r_e}\right)^2$ (18)

Heat rate balance

$\dot{q}A_i = \dot{q}A_e$ (19)

$-h(2\pi r_e L)(T_e - T_\infty) + \dot{q}(\pi r_e{}^2) = 0$ (20)

$T_e = T_\infty + \frac{\dot{q}r_e}{2h}$ (21)

In the free stream T_∞ from the surface T_s we employ fluid mechanics in this regard the reverse of Newton's law of cooling takes place when heating the tubes. the convective heat transfer process

$q_{cv} = \varepsilon h_c A(T_s - T_\infty)$ (22)

The convective heat transfer coefficient(ε) depends on the conditions in the boundary layer which is influenced by surface geometry, nature of the fluid in motion and thermodynamics and transport properties. A tube has a total convective mode of heat transfer as

$q_{cv} = \varepsilon h_c A_T (T_s - T_\infty)$ (23)

$q_{cv} = \varepsilon h_c 2\pi r_e (r_e + l)(T_s - T_\infty)$ (24)

The choice of material for the tubes is governed by the material thermal conductivity (K) and thermal diffusivity (α) which is the ability of a material to conduct heat energy in relation to its ability to its ability to store.

$\alpha = \frac{K}{\rho C}$ (25)

Materials with large thermal diffusivity respond quickly to changes in their thermal environment than those with small thermal diffusivity. For a transient conduction with volumetric energy generation

$\frac{\partial}{\partial x}\left(K \frac{\partial T}{\partial x}\right) + \dot{q} = \rho C \frac{\partial T}{\partial t}$ (26)

where

T =f(x,t)

$volumetric\ heat\ capacity = \rho C$ (27)

Convective Heat Transfer inside Tubes

Heat transfer inside tubes is for single-phase fluids. An equation which may be applied over a large range of flow characteristics

$Nu = \frac{\alpha}{\lambda D} = \frac{\frac{f}{8}(Re - 1000)\,Pr}{1 + 12.7\sqrt{\frac{f}{8}}(Pr^{2/3} - 1)}$ (28)

$f = (0.79 InRe - 1.64)^{-2}$ (29)

Friction factor for smooth walled pipe

The Nusselt number for steam and for liquid water may be calculated. Also water at supercritical pressure has been calculated by this equation. Fluid properties should be taken as the mean of inlet and outlet values for pressure and temperature. Specific volume and viscosity should be evaluated according to the mean pressure and the mean temperature to have consistent values

Pressure Loss in Tubes

For flow inside boiler tubes pressure loss will because by friction, gravity and changes in specific volume.

$\Delta p = \Delta pf + \Delta pg + \Delta pa$ (30)

The frictional pressure loss is

$\Delta pf = 4f \frac{l}{d}\frac{\rho\omega^2}{2}$ (31)

For turbulent flow, i.e., *Re* >2300, the friction factor is determined by

$f = (0.79 InRe - 1.64)^{-2}$ (32)

Gravitational pressure loss can be found as

$\Delta pg = \rho g \Delta H$ (33)

Pressure loss due to change in flow velocity is

$\Delta pa = \rho_i {\omega_i}^2 - \rho_0 {\omega_0}^2$ (34)

It must be noted that pressure loss is determined by the length of pipe

$\dot{Q} = \frac{\lambda 2\pi l (T_0 - T_i)}{In\frac{r_0}{r_i}}$ (35)

$\dot{Q} = F_{cf}\, UA\Delta T_{lm}$ (36)

$$U = \frac{1}{r_A} \frac{1}{\frac{1}{r_0(\alpha_g - \alpha_r)} + \frac{1}{\lambda_\omega} ln \frac{r_0}{r_i} + \frac{1}{\alpha_s r_i}} \quad (37)$$

The heat transfer coefficient is found as a combined coefficient for radiative and convective transfer on the wet gas side.

Stresses in Tube

Hoop stress in pipe is defined as:

$$\sigma_h = \frac{PD_{mean}}{2t} \quad (38)$$

Where Pis the pressure in MPa, D_{mean} is the mean diameter in mm and t is the thickness in *mm*.

The resulting stress using equation (2) represents only the stress due to internal pressure. However, additional stress could result from the transient temperature gradient across the pipethe flow regime mustbe determined, and therefore Reynold's number (*Re*) is calculated as:

$$Re_D = \frac{\rho V D}{\mu} \quad (39)$$

At a temperature of 300C, steam density (ρ) = 90.5 *kg/m3* [2] and viscosity (μ) = 3e-5 *Pa.s*(Steam). *Dmean*= 0.05 *m*, the pipe cross sectional area is as A, Therefore, the velocity (*V*) = 18.2 *m/s* and *Re* as Reynolds number. However the temperature for this palm nuts tube boiler cannot be so high because at local level wet steam is used to heat the palm nuts.The calculated stresses include von-Mises and maximum shear stress. Von-Mises failure criterion is defined as [3]:

$$(\delta_1 - \delta_2)^2 + (\delta_2 - \delta_3)^2 + (\delta_1 - \delta_3)^2 \leq 2\delta_y{}^2 \quad (40)$$

Where

δ_1, δ_2 *and* δ_3 are the principal stresses, and $\delta_y$is the yield stress for the ductile material.

Thermal stress $\delta_{thermal}$is generally expressed in the form [NEA, 1998]

$$\delta_{thermal} = C.E\alpha\Delta T \quad (41)$$

The factors that affect thermal stress are *E* which is Modulus of Elasticity (*MPa*), α which is coefficient of thermal expansion (°C^{-1}), ΔT which is temperature gradient (°*C*) and *c* which is a constant of proportionality. The constant depends on the condition of mechanical constraint, temperature distribution, and Poisson's ratio. Thermal stress analysis is based on transient analysis rather than steady-state, because the latter usually underestimates its value [4].

Simulation

Heat Transfer Coefficients

The heat flux at a wall boundary is implicitly specified using an external heat transfer coefficient, *h*c, and an outside or external boundary temperature, T_0. This boundary condition can be used to model thermal resistance outside the computational domain. The heat flux at the Heat Transfer Coefficient wall is calculated using:

$$q_w = h_c(T_0 - T_W) = q_{conduction} \quad (42)$$

where q_w is the total heat flux at wall boundary in W/m2, *h*c is the heat transfer coefficient in *W/m2.°C*, T_0 is the specified outside boundary temperature in *°C*, T_w is the temperature at the wall (edge of the domain) in *°C* and $q_{conduction}$ is the total heat flux from conduction in *W/m2*. For turbulent flows of the fire flames, T_w iscalculated from a surface energy balance, and for laminar flows, it is the boundary temperature field calculated by the solver

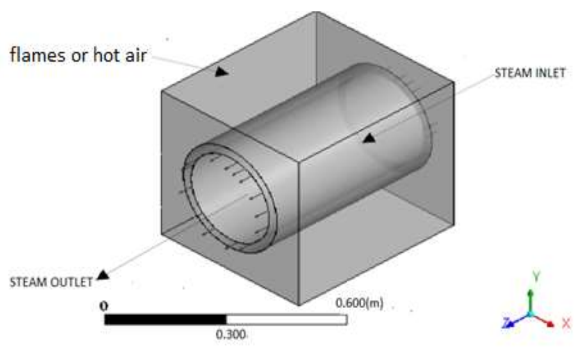

Fig-6: Boundary Conditions on the CFD Model of the tube of the boiler using ANSYS

Using solid work the model of one tube is simulated to view heat flow and temperature across the thickness.

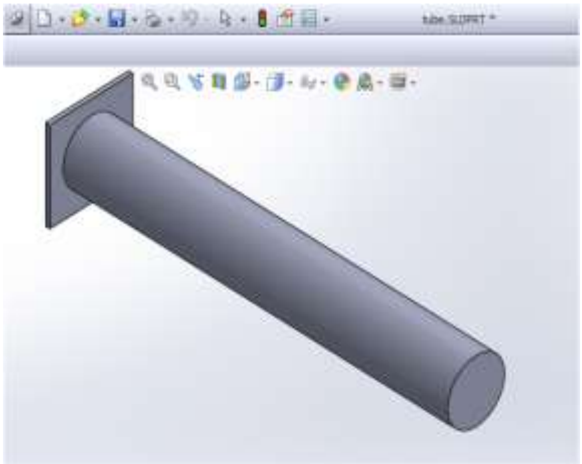

Fig-7: 3-D model of a tube

Table-1: MESH PROPERTIES

Total Nodes	Aspect Ratio	Jacobian Points
15295	6.4607	4 Points
Total Elements	Mesh Type	Element Size
7629	Solid Mesh	9.13874 mm

Fig-8: 3-D meshed tube model

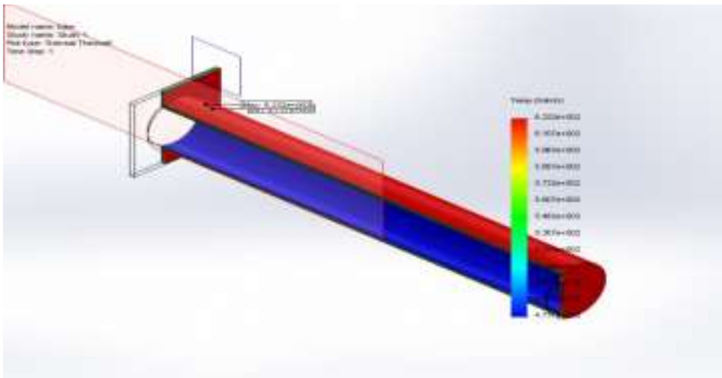

Fig-9: crossection of the simulated tube

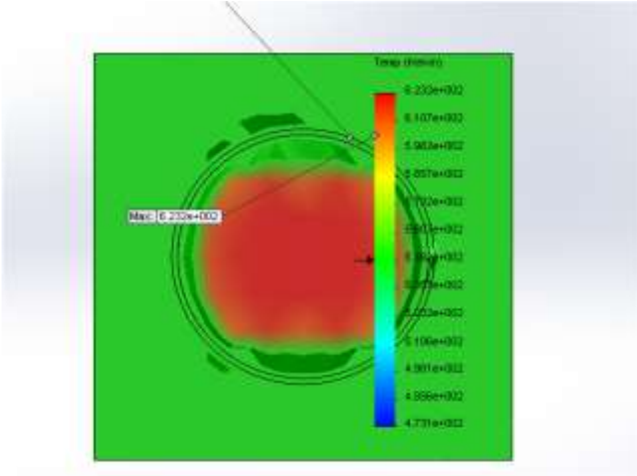

Fig-10: Top view of the simulated model

Graphs
These graphs were generated by the solidworks

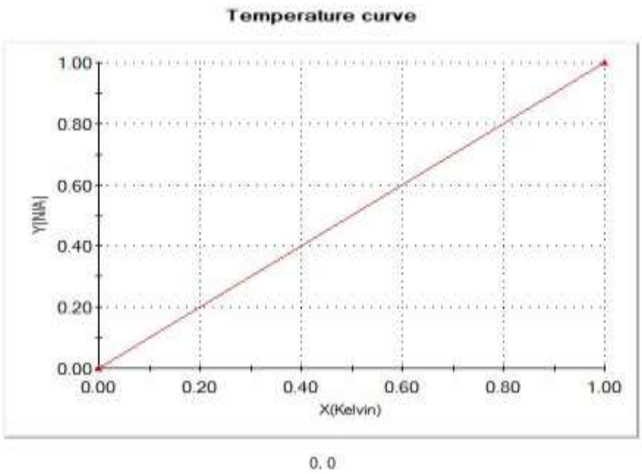

Fig-11: Wall thickness ratio versus increase in temperature

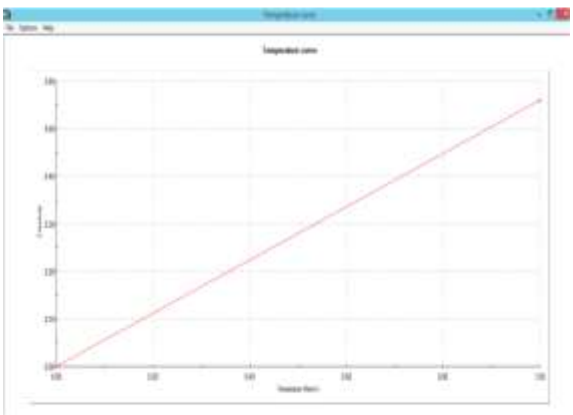

Fig-12: Emissivity versus increase in temperature

DISCUSSION

The results shows the heating by the flames at the external surface which increase the temperature gradient across the wall thickness and transfer the heat energy to the water . The tubes are not filled up so they allow room for radiation and convection especially during the boiling of the water. Radiation and the convection increase as the temperature measures. Emissivity is a function of temperature, hence, the severe temperatures favoures evaporation and increases the dryness of steam. However, the steam is wet but real dried steam is difficult to achieve not favorable to boiling the palm nuts rather it will burn them so fairly wet steam will help to achieve this result

CONCLUSION

Tube boiler used to heat palm nuts for oil palm processing reveals the high energy value of latent heat of vaporization of steam .the steam therefore possess high energy than the boiling water hence it boils the palm nut faster and it is energy saving, time ,and cost saving. The fabrication of local tube boiler should be embraced in helping the oil palm processing business.

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