

DESIGN AND THERMAL ANALYSES OF SUPERHEATED STEAM MICRO POWER PLANT

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ABSTRACT

A PKS-fired 5-10 kW micro power plant was designed to produce superheated steam for domestic and SMEs consumption. Design and thermal analyses were done on components to determine the integrity of the plant's materials. The efficiency of whole power plant was enhanced through reduction of heat losses and optimal design of components. The results showed that angular mild steel of diameter ranging 5 mm - 10 mm were adequate for the plant stand. All other parameters (stress, strain, deflection, and thermal resistance) were within the acceptable values. Plant's component material stress and strain between ambient and elevated (22- 400°C) were within the established experimental and modeling values. Heat flux (2.31 W/mm²) output was also in consonant with the target; hence, the plant is sustainable.

Keywords: *Micro steam plant, PKS, Optimal design parameters, Enhanced efficiency*

INTRODUCTION

Provision of basic infrastructure such as good roads, water, electricity and other social amenities is pre-requisite for socio-economic development of a society (Ekpo, 2005). Energy is central and life blood of engineering activities globally (Ekpo, 2012; Makoju, 2003). There is a great demand for electricity but in short supply and has affected GDP of many developing nations (Makoju, 2003). Past studies had looked into this challenge (Awosope and Okoye, 2003), yet complete solution not in sight. In order to complement those past efforts, this study designed and analyzed thermal parameters of a micro steam power plant that utilizes Palm Kernel Shell (PKS)- a renewable energy source, as fuel to generate steam for industrial application (Ajayi, 2007). PKSs have been used to generate electricity with steam turbines in place (Oladosu, 2016). PKSs are wastes that if left to decay might lead to environmental nuisance (Binstocks, 1989). PKSs formed the energy recovery goal of palm oil industry in providing steam and electricity for the mill operations (Mohammed *et al.*, 2014). Utilizing PKSs for energy purposes could help prevent global warming, emission of excessive CO₂ and other green house gases (Mohammed *et al.*, 2014). The existing micro steam generators (Astrom and Bell 2000; Yin *et al.*, 2008; Oladosu, 2016) were deficient due to inability to regulate water supply into the boiler section, release steam from the boiler's chamber to the turbine, and enable heat distribution at the heating chamber for effective heating without affecting material properties. Redesign of the steam generator is necessary to ensure provision of lagging mechanisms such that heat lost reduction is enhanced without affecting material properties under high temperature operation. In this study a 5-10 kW capacity PKS-fired micro power plant for superheated steam production was designed and thermal property of components was analyzed for domestic and SMEs consumption. The technology featured improvement on the past micro power plant (Oladosu, 2016) for enhanced thermal performance efficiency.

LITERATURE REVIEW

Grate-fired boilers could use a wide range of fuels of varying moisture contents and have a great potential in biomass combustion (Marrow, 2005). According to Jekayinfa and Bamgbose (2008), and Joller *et al.*,

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(2007), about 0.07 tons of palm shell, 0.103 tons of palm fibre and 0.012 tons of kernel were produced as solid wastes. Paper and pulp that were obtained by processing the oil palm wastes could be used in so many ways- cigarette paper and bond paper for writing (MNNA, 2001). Palm kernel shell (PKS) was used as concrete reinforcement in construction industry (Najmi *et al.*, 2007; Okpula *et al.*, 1990). PKS was included as admixture with Portland cement for concrete production (Oladosu *et al.*, 2016). PKS was mixed with activated carbon for industrial use (Adewumi and Ogedengbe, 2005). Oil palm trunks mixed with EFB to produce electrical energy (Sumanttin and Chai, 2008). The use of palm shells and palm fibres for the production of briquettes was reported by Hussain *et al.*, (2002). In all these studies, it was evident that PKS has higher calorific value. Fixed bed combustion was appropriate for biomass fuel with high moisture content, varying particle sizes and high ash content. A good and well controlled grate was designed to guarantee a homogenous distribution of fuel and residues over the whole grate surface. Grate combustion could be obtained by separating the primary and secondary combustion chamber in order to avoid back mixing of the secondary air and to separate gasification and oxidation zone (Sjaak and Jaap, 2008). The better the mixing quality between flue gas and secondary combustion air, the lower the amount of excess oxygen required for complete combustion in the power plant (Oladosu, 2016; Thomas, 2009). Fluidized bed boilers have recently been used in steam generator. In fluidized bed boilers, biomass and the additives were suspended in a combustion chamber by air blowing up through the bed. The amount of fluidization that occurred is dependent on the size of the fuel and velocity of the air moving through the bed (Sjaak and Jaap, 2008). In palm oil processing industry, biomass residues (KPS) were converted from waste pollutants to useful fuel for steam and electricity generation (Pettersson and Steenari, 2009). PKS wastes in a nation accounted for about 1.5% (930,000 metric tons) of the global output (Izah *et al.*, 2016). This huge quantity of PKS waste could be used for energy generation (Mohammed *et al.*, 2014). This outcome could trigger economic growth and increase employment for local population (Khullar, 1995). Fixed bed grate combustor has been applied in this study due to its simplicity of design and enhancement of combustion with less oxygen requirements due to better mixing quality between flue gas and secondary combustion air. Comprehensive understanding of fuel characteristics during the designing of combustion equipment and boiler plant (Aho, 2001) is necessary. PKS fuel is a good choice in firing technology due to its lower moisture and ash contents (Adeline, 2012). Grate firing system and fluidized bed combustor were technologies suitable for reduced ash (Oladosu, 2016). This study focused only on utilization of heat content of PKS fuel in term of calorific value in designing and enhancing the thermal performance of a micro power plant for producing superheated steam. There were several technologies employed that enable biomass such as PKS to be useful for generating heat energy. Relevant studies on combustion of biomass in grate and fluidized bed power plants include: Pichet and Vladimir, (2014); Oladosu (2016); Yusniati *et al.* (2018); and Oladosu *et al.* (2017). Findings from those studies showed that they concentrated more on optimizing PKS fuel efficiency with less attention to optimal performance of the plant. This is the gap this study posed to bridge. The consideration of PKS fuel in the design of micro steam power plant would lower the cost of fuelling (Kareem and Babatunde, 2018; Kareem *et al.*, 2018 a, b, c; Oladosu *et al.*, 2018; Elefe *et al.*, 2024). This study concentrated on how to enhance the thermal efficiency of whole power plant through reduction of heat losses and optimal design of components.

MATERIALS AND METHODS

Micro Steam Generator Design Concept

The steam generator used was designed to have water tank (reservoir) called primary water feeder supported by a frame called tank stand. This primary feeder (tank) (ϕ 45 cm x 30 cm) was water fed by gravity from a reservoir tank placed on a building top (tower). Primary tank water level was controlled mechanically using floating mechanism. A metallic ladder is designed on tank stand to check primary

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tank's water level if desired. The primary tank was made to allow the flow water into secondary tank (30 cm x 15 cm) (reservoir) through half inch (½") diameter metallic pipe whose flow rate was mechanically regulated/controlled using half inch (½") diameter metallic ball gauge valve. The secondary tank is designed to have floating mechanism to regulate water level in the tank. The release of water from secondary tank into the boiler vessel, downcomer (30 cm x ϕ 30 cm) was moderated by a half inch (½") diameter metallic ball gauge valve and a half inch (½") diameter non-return valve. Water inlet orifice was located 18 cm from the 30 cm diameter base of the cylindrical vessel. A half inch diameter non-return valve was incorporated to prevent backflow of water/steam from cylindrical vessel to the secondary tank during combustion process. The vessel was firmly sealed at the top using heat resistant leather insulator and secured with six-number 19 mm bolts/nuts to prevent heat loss. A ½" orifice was made close to the base of the vessel and piped to allow evacuation of leftover water through a ½" ball gauge fixed to its end after operation. Three equal lengths (90 cm) and diameters (½") stainless helical-shaped risers were welded to balance on the top of the cylindrical vessel and made to converge at 90 cm from the cylindrical vessel's top using a small stainless cylindrical-shaped (ϕ 6 cm x 5 cm), A single stainless coiled (½" diameter) super-heater emerges from the stainless cylindrical-shaped (ϕ 6 cm x 5 cm) and terminated at a small steam tank (ϕ 6 cm x 10 cm). The steam tank had two outlets: one (incorporated with ½" ball gauge valve) for testing steam presence and for evacuating condensed water after operation; while the second outlet served as measurement window (steam pressure and temperature) and steam supply channel for powering purpose. The furnace was fuelled with PKS biomass. Furnace was insulated to prevent heat losses using combined refractory brick, fibre glass and synthetic leaders as insulators. Regulated primary and secondary air flow systems were provided for effective heating and evenly temperature distribution across the combustion chamber. The line diagram of the conceptual design is shown in Fig. 1. Assumptions made in design calculations are: steady-state operation for the boiler system; negligible heat losses and within the limit of the boiler's efficiency; properties of PKS as fuel (e.g. calorific value, moisture content) were not changed significantly during usage; specific design parameters for boiler remain constant (e.g. heat transfer area, tube diameter); and thermodynamic property data for water and steam were used and remained constant. The design focus was to obtain the required steam flow rate based on heat lost resistance; and heat transfer rate within desired temperature range (22-400 °C). Five-Ten (5-10) kW micro steam power plant was selected for this study (Oladosu *et al.*, 2018). For the design of a 10 kW superheated steam generator, operating pressure P_o range (0.45-4.5 MPa), feed water temperature T_f (34°C), palm kernel shell (PKS) of calorific value C_v 18 MJ were applied with assumed boiler efficiency (79%) and tube diameter (12.7 mm). On this basis, mechanical, physical and thermal properties of the designed plant's components were estimated (Fig. 1).

Design for Mechanical and Physical Properties

Standard design formulae were applied (Oladosu *et al.*, 2016; Daramola *et al.*, 2025) to estimate relevant mechanical, physical and thermal properties of plant's components' materials (Fig. 1). The mild carbon steel was the main material used for the design. The components designed for were combustion chamber and stand, refractory brick, water stand, PKS feeder and auger shaft. Other components were chamber cover, steam drum, fan, downcomer, riser, superheater, temperature, pressure and flow rate gauges and water feeder. The stress (strain) on a standard angle mild carbon steel stand of length 1m and thickness (5- 10 mm) (0.005-0.01 m) under a distributed load of 1ton (comprised mild steel and/or with refractory bricks) were computed under the following design parameters: i. The angle mild steel is a standard equal angle section (50 x 50 x 5 mm-50 x 50 x 10 mm) was used as stand/support. ii.. The distributed load of 1 ton (1000 kg or 9806.65 N was applied uniformly along the length of the angle. iii.. The angle is simply supported at both ends. iv. The material properties of mild steel used were: Young's modulus (E) taken to be 200 GPa (200,000 N/mm²) and Yield strength of 250 MPa (250 N/mm²). v. The load assumed to be

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applied perpendicular to one of the legs. Maximum Bending Moment (M) for a simply supported beam with a uniformly distributed load was estimated to be 2451750 Nmm, while the corresponding Maximum Stress (σ) and the strain (ϵ) were 559.3 N/mm² (559.3 MPa) and 0.0028 (0.28%). This yielded a factor of safety F_{os} (0.447), which indicated that the design was not safe. The Shear Stress (τ) obtained was 19.61 MPa. In order to enhance safe design, steel plate thickness was increased (10mm) which yielded a factor of safety 1.79 for the same process. Other parameter values were presented in (Table 1). The physical properties were estimated based on the given 5-10 mm thick mild steel, 60 mm thick refractory brick lagging, 50 W/m K thermal conductivity mild carbon steel and 0.5 W/m K refractory brick thermal conductivity. In calculating overall heat transfer coefficient H_{tc} , the thermal resistance of both the mild steel and the refractory brick lagging was considered. Thermal Resistance of Mild Steel R_{ms} obtained from ratio of mild steel thickness (t_{ms}) and thermal conductivity (S_{tc}) was estimated as 0.0002 m²K/W.

The corresponding heat flux q_{ms} at ambient temperature 22 °C and designed temperature of 400 °C was estimated to be 1.89 W/mm². The thermal resistance of refractory brick (R_{rb}) was estimated as the ratio of refractory brick thickness t_{rb} and that of its thermal conductivity R_{tb} as 0.12 m²K/W, while the corresponding heat flux q_{rb} with temperature change from 22 °C to 400 °C was estimated as 3,150 W/m² (0.003150 W/mm²). The Overall Thermal Resistance (R_T) was obtained from summation of R_{ms} and R_{rb} as 0.1202 m²K/W. Overall Heat Transfer Coefficient, H_{tc} was a reciprocal ($1 / R_T$) and estimated as 8.32 W/m²K. The corresponding heat flux q_T with temperature range 22 °C and 400 °C was estimated from $\partial T/R_T$ as 3,144.76 W/m² (0.003145 W/mm²).

If the mild steel thickness is 5 mm (0.005 m), then, R_{ms} is t_{ms}/S_{tc} (0.0001 m²K/W) with Overall Thermal Resistance (R_T) ($R_{ms} + R_{rb}$) estimated as 0.1201 m²K/W, and the Overall Heat Transfer Coefficient H_{tc} would be reciprocal ($1 / R_T$) 8.326 W/m² K. The corresponding heat flux q_T at temperature range of 22 °C and 400 °C was estimated as 0.003147 W/mm². The outcomes showed that refractory brick lagging significantly reduced the heat transfer rate due to its low thermal conductivity while there was no significant change in heat transfer rate reduction when mild steel plate of 5 mm and 10 mm thickness were used. Hence, the choice of mild steel plate of 5 mm thickness or less would be sustainable. In the case of downcomer, riser and superheater, stainless steel material was used. By assuming thermal conductivity k_{ss} of 16.2 W/mK (range from 16.2- 22.6 W/mK, 100°C (373K)- 500 °C (773 K)) for popular stainless steel 304 with a thickness L_{ss} of 0.003m (3 mm), heat flux q_{ss} for stainless steel heated from ambient (outside) temperature of 22 °C to design temperature of 400 °C was obtained using Fourier's law (Daramola et al., 2025) from as

$$q_{ss} (-k_{ss}\partial T/L_{ss}) (2.3112 W/mm^2)$$

The thermal resistance R_{ss} was estimated 0.000185 m²K/W, Overall Heat Transfer Coefficient H_{ss} obtained 5,405 W/m² K.

Stress σ'_{wrT} exerted on the stand by the cylinder reservoir; was obtained as the ratio of total force applied F_{wrT} and the base area A_{wrb} ; as 4,458.36 N/m²

Similarly, for the cuboids water feeding tank Stress σ'_{wcT} exerted on the stand by the cuboids; was obtained as the ratio of total force applied F_{wcT} and the base area A_{wcb} ; as 1,989.9N/m²
 Total stress on the stand σ_{crT} ; sum of both ($\sigma'_{wrT} + \sigma'_{wcT}$) as 6,448.26 N/m²

In analyzing the stress exerted by the PKS feeding hopper on its stand, PKS feeding rate (0.000703 kg/s \approx 2.5308 kg/hr) and density of PKS (350-400 kg/m³, 375 kg/m³ on average) were considered. By assuming that maximum stress was acted on the neck portion Area of the hopper (A_{hs}), then stress on the hopper stand σ_{hs} was estimated as ratio of force F_{hs} over the area A_{hs} ; 32,375 N/m².

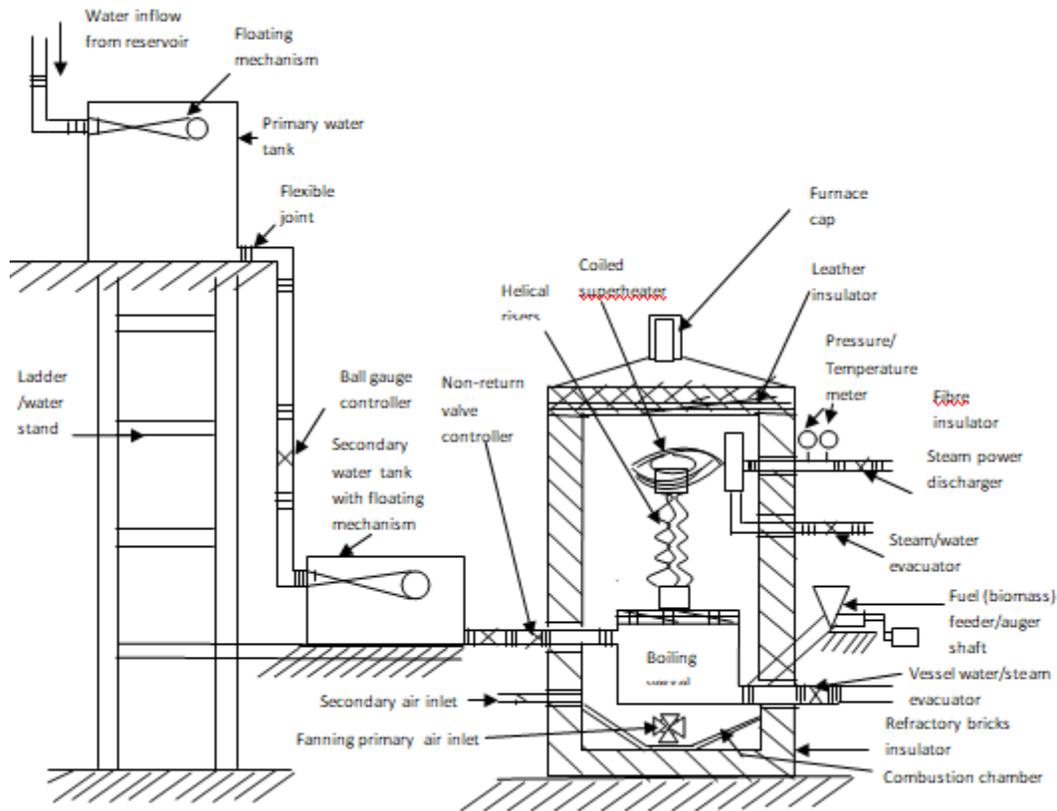


Fig. 1. Concepts of Micro Steam Power Plant

Micro Steam Plant Components Simulation

Each of the components was modeled using Solidworks CAD software and then analyzed (simulated) using Ansys^R software to determine their design integrity over temperature range 22-400°C. Isometric projection model of the designed micro power plant using Solidworks/ AutoCAD^R tools is shown in Fig. 2. Thermal (physical) and mechanical properties were analyzed to determine the behavior of the model

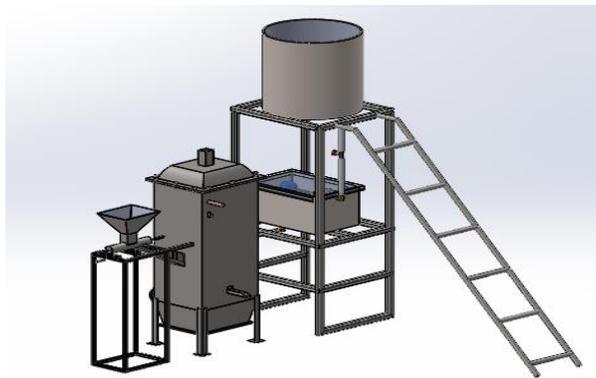


Fig. 2: Isometric view of the Steam Plant Model

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(component) with respect to the temperature differences and the load applied, respectively. First, the static structural analysis of the component was carried out based on the load capacities. Second, the total and dimensional deformation, strain, and (Von- Misses) stress equivalents were determined, and third, the thermal analysis of the steam generating furnace/chamber was carried out.

Thermal integrity of the plant's component material (carbon steel) was evaluated by comparing the stress and strain values on each of the components with those obtained from simulation, modeling and experiment under elevated temperatures, 20-400°C (Al-Khazraji et. al., 2016; Seif *et al.*, 2016).

RESULTS AND DISCUSSION

Design and simulation of components

The results of the mechanical, and physical (thermal) properties obtained for the furnace chamber/casing of the boiler are presented in Table 1. The results showed that angular mild steel stand of 5 mm thickness could not withstand the load due to low factor of safety (0.447). Redesign results using angular mild steel (10 mm) showed a good factor of safety (1.79), which was highly adequate to support the plant's chamber. This outcome indicated that any angular mild steel of diameter range 5 -10 mm could be adequate as plant's support (stand). All other designed parameters (stress, strain, deflection, and thermal resistance) were within the acceptable standard, this portrayed design adequacy (Fig. 2). For example, the results generated for the steam chamber for temperature analysis are presented in Fig. 3. It was revealed that designed temperature of 22- 400°C was within the acceptable range and far from maximum tolerable temperature of 1200°C. Besides, the results indicated that there was more heating effect inside the chamber. The heat loss was negligible, since the outside seemed to show a blue colour fading till about 400°C, showing that the material can withstand the thermal effect even beyond 400°C.

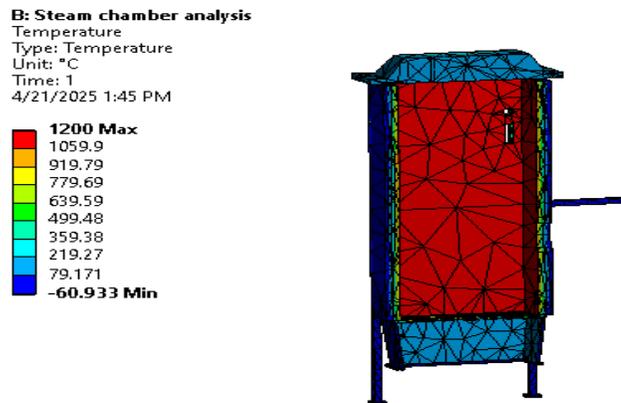


Fig. 3: Temperature difference inside the Steam Chamber

Table 1 shows the outcomes of applications of conventional and simulated design methods. It was revealed from the table that mechanical, physical (thermal) and simulation outcomes were adequate for all the parameters under consideration for the micro power plant. The application of 10 mm mild carbon steel reduced the maximum stress, stain, deflection, and shear stress, from the previous (5 mm steel) values, while the factor of safety was greatly improved (Table 1). For instance, maximum stress of 559.3 MPa was drastically reduced to 139.8 MPa while factor of safety 0.447 was highly increased to 1.79 for 10 mm steel. This improvement led to a safer and rugged design. On the same basis, thermal resistance of the plant increased from 0.0001 (under 5 mm steel) to 0.0002 for 10 mm steel plate. Combined steel and refractory insulation of the plant produced similar results, 0.1201 (5 mm steel) thermal resistance against 0.1202 (10 mm steel). Furthermore, the total heat flux of the combined material was reduced from initial

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value 0.00315 to 0.00314 due to higher thickness (10 mm) of steel component. Though change in thermal resistance (0.0001) and total heat flux (0.00001) seemed small, but necessary for consideration under sensitive applications. Simulation results also fell within the stated values. Therefore, the outcomes were good representation of the actual design values.

Table 1: Furnace Chamber designed by conventional and simulation methods

Designed Properties	Conventional: Mild steel of 5 mm thickness	Conventional: Mild steel of 10 mm thickness	Simulation: Mild steel of 10 mm thickness
Maximum Stress (σ), MPa	559.3	139.8	497
Strain (ϵ) %	0.28%	0.07%	0.0-1.69%
Factor of Safety (F_{OS})	0.447	1.79	0.6-15
Deflection (δ), mm	5.83	1.46	0.0-1.8
Shear Stress (τ). MPa	19.61	9.81	9.81
Thermal conductivity, C_T , W/m·K	50	50	50
Specific heat capacity, C_S J/kg·K	500	500	500
Thermal Resistance of Mild Steel R_{ms} , m ² K/W	0.0001	0.0002	0.0002
Thermal Resistance of refractory brick (R_{rb}), m ² K/W	0.12	0.12	0.12
Thermal Resistance of mild steel and refractory brick (R_{rb}), m ² K/W	0.1201	0.1202	0.1202
Total Heat Flux of combined mild steel and refractory bricks at ∂T (22°C-400°C (378 °C=378K)) W/mm ²	0.00315	0.00314	2.4008 x 10 ⁻¹² – 17.066

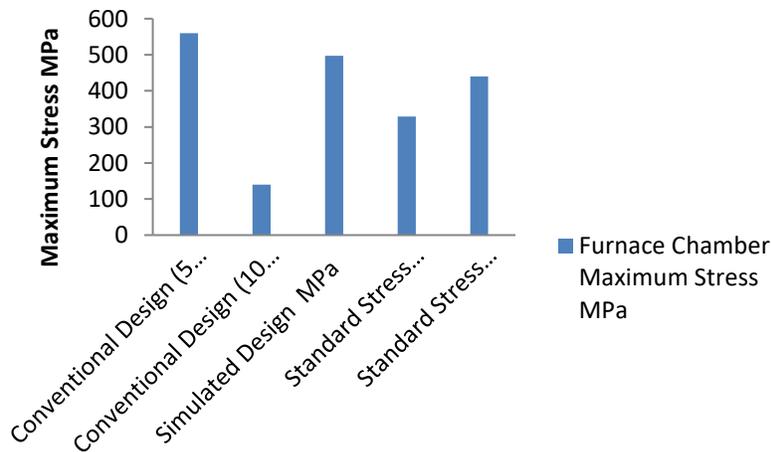


Fig. 4 Coventional, Simulated and Standard Stresses of Furnace Chamber

Fig. 4 shows clearly how maximum stress was reduced far below standard or normal stress when steel plate 5 mm was replaced with 10 mm. Fig. 5 explains how furnace and other components' temperature

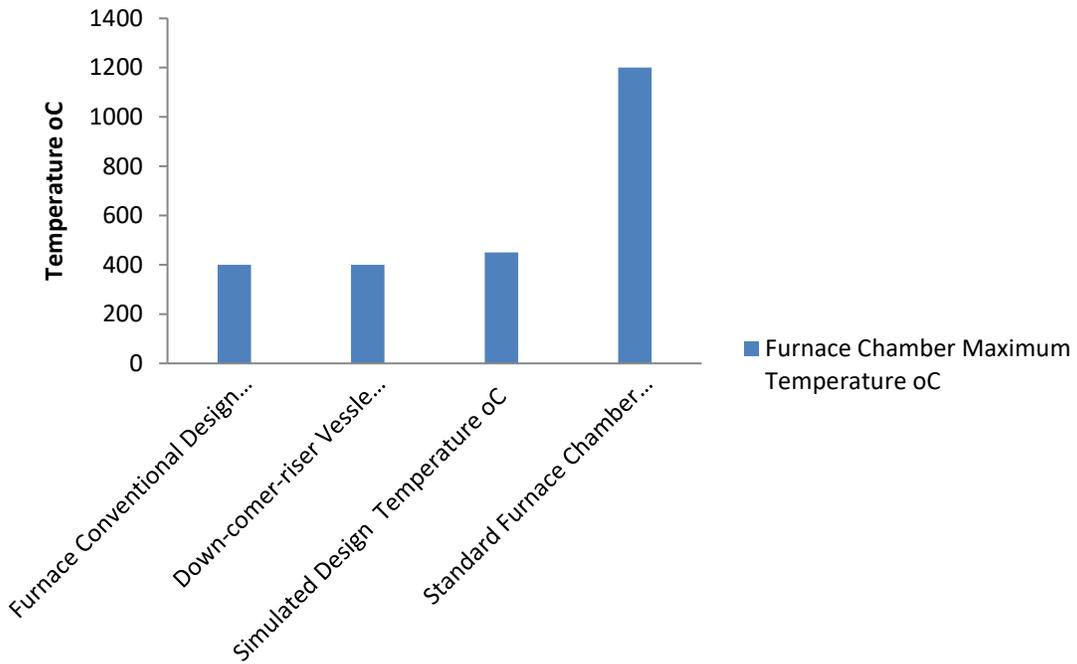


Fig. 5 Furnace Conventional, Simulated and Standard Design Temperature

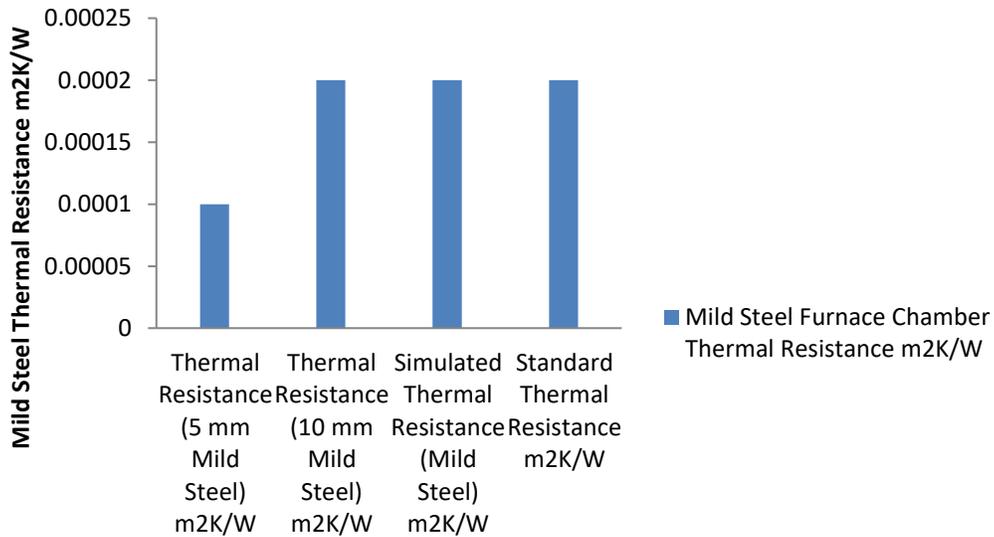


Fig. 6 Mild Steel Conventional, Simulated and Standard Thermal Resistance

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were low than the maximum design and simulation values, which indicated safe operation of the system. Fig. 6 clearly revealed that thermal resistance was improved upon close to maximum simulated and designed thermal resistance values with increased steel plate thickness from 5 mm to 10 mm, hence, safety of the plant was ensured; while Fig. 7 presents clear picture of how refractory bricks on 10 mm thick steel contributed to improved thermal resistance close to maximum simulation and design values. This trend was somewhat similar to that presented in Fig. 6.

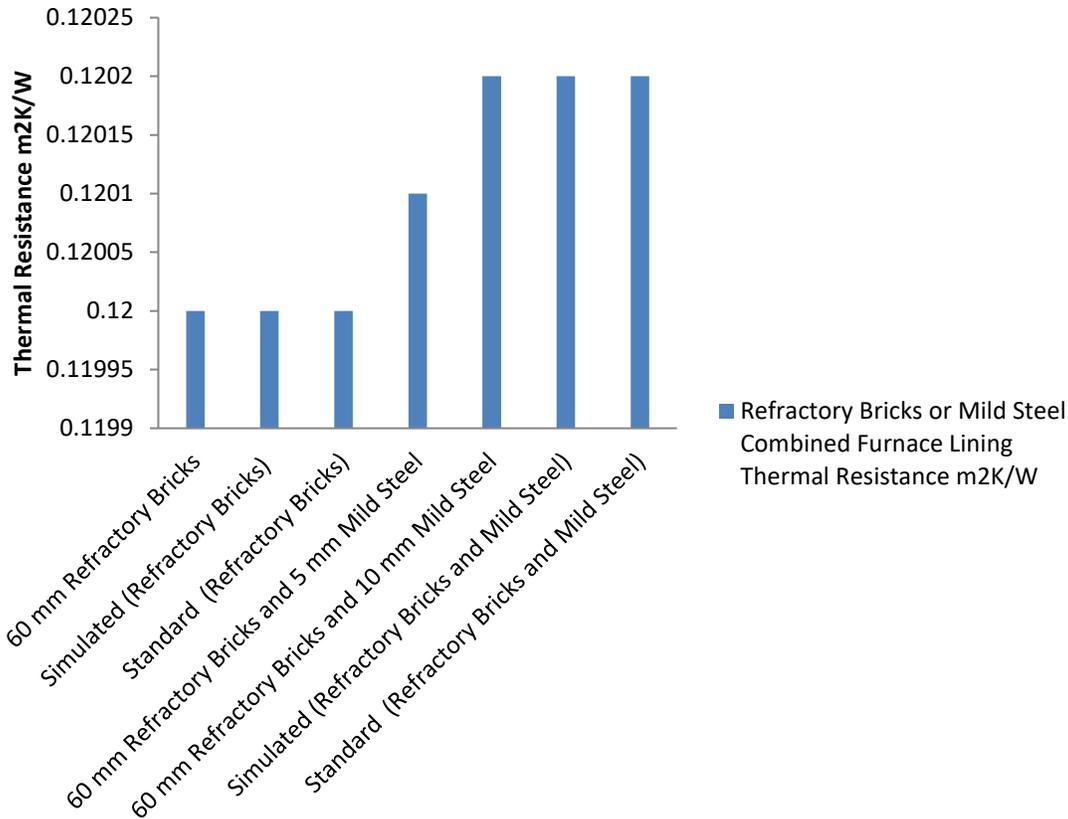


Fig. 7 Mild Steel-Refractory Bricks Lining Thermal Resistance

The design results of other supporting components are respectively presented in Table 2. From the results obtained for supporting components, it was observed that water tank stand, PKS fuel feeder and feeder auger/shaft were within the acceptable maximum stress, strain, factor of safety and deflection values when compared with the simulation results. For instance, water tank maximum stress (≈ 0.00645 MPa) was conveniently below simulation value (0.370-3.491 MPa). Stresses on PKS feeder and feeder auger/shaft followed the same trend. The factor of safety outcomes (1.78, 1.78, and 1.5) respectively for water tank stand, PKS feeder and feeder auger/shaft indicated that the design was safe (Table 2). These factors were also in agreement with the value (0.6-15) obtained by simulation. Total heat flux values obtained by conventional and simulated design for steam steam chamber, boiler vessel, downcomer, and risers were also in agreement. For example, total heat flux for vessel/down-comer/risers (2.31 W/mm^2) fell within the simulated value ($1.9971 \times 10^{-15} - 56.653 \text{ W/mm}^2$). Same for steam chamber total heat flux (0.00315 W/mm^2) as against ($2.4008 \times 10^{-12} - 17.066 \text{ W/mm}^2$) simulated value (Table 2).

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Table 2. Supporting Components designed by conventional and simulation methods

Design Parameters	Conventional 5mm thickness mild steel	Conventional 3mm stainless steel (304)	Simulation
Water tanks (feeding /reservoir) support/stand			
Maximum Stress (σ), kPa	6.44826	-	370-3490.7
Strain (ϵ) %	0.07	-	0.0-1.69
Factor of Safety (F_{OS})	1.78	-	0.6-15
Deflection (δ), mm	1.45	-	0.0-1.8
PKS Fuel feeding hopper support/stand			
Deformation	0.0	-	0-0.001343
Elastic strain	0.0	-	0-0.00002384
Maximum stress kPa	32.375	-	81.92-4970.9
Factor of Safety (F_{OS})	1.78	-	0.-15
Hopper Auger /Shaft			
Deformation (mm)	0	-	0-0.00025118
Elastic strain	0	-	0.0-0.0024396
Factor of safety	1.5	-	0.65-15.0
Maximum Stress, kPa	32.375	-	0-4970.90
Thermal analysis of the furnace chamber components			
Steam Chamber analysis: Heating effect and retention, °C	400	-	0-1200
Steam Chamber Total heat flux, W/mm ²	0.00315	-	2.4008 x 10 ⁻¹² - 17.066
Boiling vessel/ down-comer under thermal loading, °C	-	450	450-1403.2
Total heat flux vessel/down-comer/risers, W/mm ²	-	2.31	1.9971 x 10 ⁻¹⁵ - 56.653
Thermal Resistance of Stainless Steel R_{ms} , m ² K/W	-	0.000185	-

Performance Evaluation

The stress (strain) results obtained under ambient temperature of 22°C for plant’s water stand, feeding hopper, auger/shaft and combustion chamber (in MPa, %) were approximately 0.0065 (0.07), 0.0324 (0.07), 0.0524 (0.07) and 139.8 (0.28), respectively. Simulation results using Ansys^R under 22°C -400°C on mild (carbon) steel revealed a stress (strain) outputs (in MPa, %) of 3490.8 -370 (0-0.155), 4970.9-81.92 (0-0.0024), 4970.9-81.92 (0-0024) and 5593-497 (0-1.69), respectively. Modeling and experimental studies on similar carbon steel material at temperature ranges 20 -400°C and 25 - 400°C yielded a stress, MPa (strain, %) outcomes 400-320 (0-0.030) (experimental) and 550-350 (0-0.03) (modeling) (Table 3). Also, maximum stresses in all cases were below the established yield stress limit (250-200MPa) (Al-Khazraji et. al. 2016).

It was evident as seen in table 3 that the plant’s components could survive under high temperature, 400°C and beyond, since the stress (strain) values obtained for plant’s components were far less than those obtained from simulation, modeling and experiment (Al- Khazraji et al., 2016; Seif et al., 2016). It showed that the plant could be operated for long hours at higher temperatures beyond 400°C without any material failure. This ruggedness is an added advantage that would promote patronage in the developing economy, characterized by poor maintenance culture due to low capital outlay.

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Table 3: Performance Evaluation

Design Parameters/ Plant's Components	Conventional (22°C) (stress/strain). (MPa / %)	Simulation (22-400°C) stress/strain) (MPa / %)	Modeling (20-400°C) (stress/strain) (MPa / %)	Experimental (25-400°C) (stress/strain) (MPa / %)	Experimental Yield stress of carbon steel (25-400°C) (MPa)
Water Stands	0.00645/ 0.07	0-3.491/0- 0.07	550-420/0- 0.03*	400-320/0- 0.03*	250-200*
PKS feeding hopper	0.0324/0	0.0-4.971/0- 0.002384		580-275/0- 0.155**	
Feeding Auger/shaft	0.0324/0	0.0-4.971/0- 0.002384			
Combustion chamber	139.8/0.07	0-250/0-0.07			

*Seif et al. (2016), ** Al-Khazjari et al. (2016)

CONCLUSION

A PKS-fired 10 kW micro power plant has been designed to produce superheated steam for domestic and SMEs consumption. The objectives set were achieved by designing and modeling each component of the plant. The design outcomes were validated with those obtained from simulation, and plant's components material integrity was validated using the carbon steel material stress (strain) modeling and experimental outcomes of the past studies. The design focused on enhanced efficiency of whole power plant through reduction of heat losses by incorporation of effective insulation and heat resistor to enable maximum heat flux in the system for enhanced operational efficiency. From the design outcomes, the following conclusion could be made:

Angular mild steel stand of 5 mm thickness could not withstand the load due to low factor of safety (0.447), while that of 10 mm with factor of safety (1.79) was highly excessive to support the plant, hence range 5 -10 mm would be adequate.

All other designed parameters (stress, strain, deflection, and thermal resistance) were within the acceptable values as they were in agreement with simulation, modeling and experimental values.

There was more heating effect inside the chamber as the heat loss was very negligible even at maximum temperature 400°C, due to heat resistance nature of the material, capable of withstanding the thermal effect beyond 400°C.

Application of 10 mm mild carbon steel reduced the maximum stress, stain, deflection, and shear stress, from the previous (5 mm steel) values, while the factor of safety was greatly improved. This improvement led to a safer and rugged design, in terms of reduction in heat flux and increment in thermal resistance.

Other supporting components- water tank stand, PKS fuel feeder and feeder auger/shaft were within the acceptable maximum stress, strain, and factor of safety and deflection values when compared with the simulation results. These values were also in agreement with the value obtained by simulation. Total heat flux values obtained by conventional and simulated design for steam steam chamber, boiler vessel, downcomer, and risers were also in agreement.

Modeling and experimental studies on similar carbon steel material at temperature ranges 20 -400°C and 25 - 400°C yielded a maximum stress; yield stress and strain values that were readily in agreement with the conventional and simulation design results.

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The plant's components could survive under high temperature, 400°C and beyond, since the stress (strain) values obtained on components were far less than those of simulation, modeling and experiment values. Hence, the plant could operate for long hours at higher temperatures without any material failure, and therefore would promote maintenance economy.

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