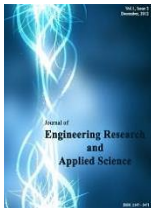
Journal of Engineering Research and Applied Science
Available at www.journaleras.com
Volume 15 (1), June 2026, pp 120-129
ISSN 2147-3471 © 2026



Optimization of Operational Design Parameters of Superheated Steam Micro Power Plant

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Accepted 07 June 2026

Abstract

High cost of maintaining power plants has hindered the sustenance of small scale businesses; hence, there is the need to optimize plant's operational parameters to enhance energy delivery efficiency for domestic and SMEs consumption. This study applied strategies of reduction of heat losses through optimal design for micro power plant operational parameters. For the 5-10 kW plant at PKS fuel feeding rates of 0.000703 kg/s and 0.000352 kg/s, temperatures (pressures) of 220ºC (0.38 MPa), and 235ºC (0.35MPa), optimal steam mass flow rate of 0.00357 kg/s and 0.00178 kg/s were respectively established. For safety and economy of operation, running at the lowest possible temperatures (pressures) of 235 ºC (0.35 MPa) would be sufficient in both plants (5-10 kW) for generating optimum steam flow velocities (14.87 m/s, 7.43 m/s). This outcome outperformed the known micro power plants by at least 12%.

Keywords: *Micro steam plant, Operational parameters, PKS, Safety, Economy*

1. Introduction

Socio-economic development of any nation depends on how well sufficient energy is provided to power basic infrastructure such as good roads, water, and other amenities [1]. This made energy a life blood of any engineering activity [2, 3]. The energy is in short supply [4] that it has affected the GDP of many nations due to low accessibility [3]. This challenge had been noticed [5], but more efforts were still in sight.

This study adds to this effort by optimizing operational design parameters of a PKS-fired 5-10 kW micro steam power plant. Palm Kernel Shell (PKS) is a renewable energy source or palm fruit residues (wastes) usable as fuel [6]. If these residues were abandoned would have led to environmental nuisance [7]. PKS has been used to generate electricity with steam turbines in place [8]. PKS has been used to power oil palm mills [9]. Utilizing PKS from oil palm for energy purposes has prevented global warming from escalation [9].

Energy production from micro steam generators [8, 10, 11] were deficient of inability to optimize operational design parameters by establishing best PKS feeding rate, temperature and pressure that would result to efficient mass flow rate and steam velocity that would enable safe and maintainable operation of the plant.

2. Literature Review

PKS combustion has been applied in grate and fluidized-bed boilers to generate steam energy [12-14]. Besides, PKS was applied in the processing of paper and pulp [15]. PKS was used as concrete reinforcement in construction industry [16-18]. PKS was mixed with activated carbon for industrial use [19]. PKS derivatives were applied to produce electrical energy [20]. PKS was a principal ingredient for production of briquettes [21]. In all these studies, PKS was applied due to its higher calorific value. Utilization of PKS in this study would lead to efficient combustion with minimum possible feeding rate.

In grate combustion, there is the need to separate primary and secondary air flow in order to avoid back mixing [22]. 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 [8, 23, 24]. On this basis PKS residues would be effectively utilized during grate combustion [9, 25]. Hence, realization of

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optimum operational design parameters of the plant is possible.

Fixed bed grate combustor was applied due to its simplicity of design and enhancement of combustion with less oxygen requirement due to better mixing quality between flue gas and secondary combustion air [26]. PKS fuel was used because of its low moisture and ash contents, and high calorific value [27]. PKS ash challenge has been tackled previously [8]. This study focused only on utilization of heat content of PKS fuel in term of calorific value in designing and enhancing operational parameters of a micro steam power plant.

Selected relevant studies on combustion of biomass on grate and fluidized bed power plants are [8, 28-35]. Findings from those studies showed that they concentrated more on optimizing PKS biomass performance but neglected operational design parameters optimization to enhance safety and sustainable operation. This is the gap this study would address.

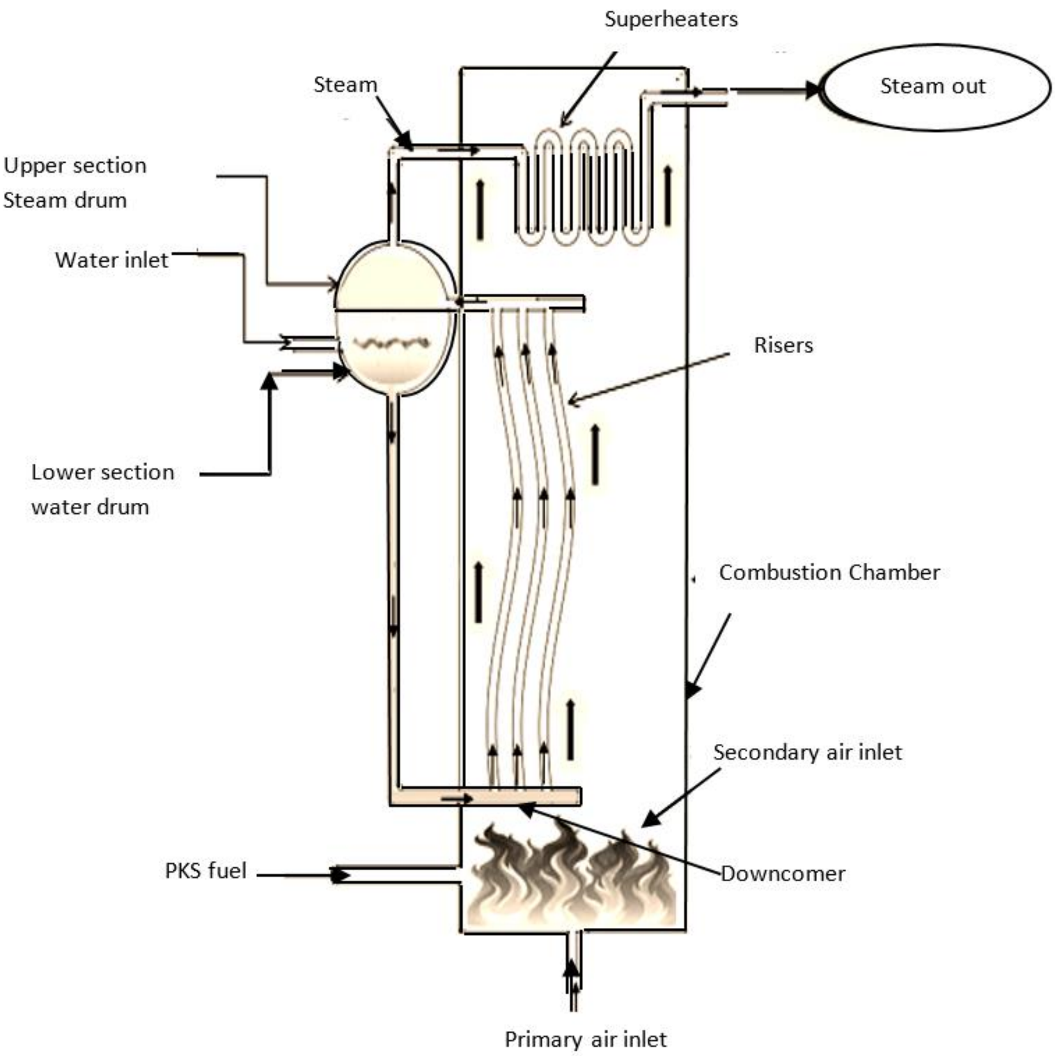

Figure 1. Line Diagram Simplifying 5-10 kW Micro Steam Power Plant

3. Materials and Methods

3.1. Micro Steam Generator Design Concept

The line diagram of the design concept of a 5-10 kW micro steam power plant for this study is shown in Fig. 1. The steam generator was designed to have water tank (reservoir) called primary water/feeder supported by a frame called tank stand. This primary feeder (tank) water was fed by gravity into secondary tank. Water from the secondary tank into the downcomer was passed through half inch (12.7 mm) diameter metallic ball gauge value and a half inch (12.7 mm) diameter non-return valve. A half inch diameter non-return value was incorporated to prevent backflow of water/steam from the downcomer during combustion process. Three equal lengths (900 mm) and diameters (12.7 mm) stainless helical-shaped risers were welded to balance on the top of the downcomer and made to converge at 90 mm to a steam cylinder (60 mm dia x 100 mm) on top of the risers. Three coils of stainless (12.7 mm diameter) called superheater emerged from the steam tank. The steam tank had two outlets: one for steam regulator (incorporated with 12.7 mm ball gauge value) and the other was instrumented to enable measurement of steam pressure, steam temperature, steam mass flow rate, and steam flow velocity. The furnace was fired with PKS fuel. Furnace was well insulated to prevent heat losses using combination of refractory brick, fibre glass and synthetic leaders. Primary and secondary air flow into the combustion chamber was regulated and was made evenly distributed using fan mechanism to enhance complete combustion of PKS for effective heating (Fig. 1).

3.2. Design Calculations

3.2.1. Steam Power Plant/Boiler System Design and Operation

The steam power plant/boiler has the following design and operation conditions: water-tube/steam generator-type; operating pressure range; superheated steam quality; feed water at room temperature; palm kernel shell (PKS) fuelled with calorific value 18MJ/kg; and boiler efficiency 79% [36]. Assumptions made in design modeling are: steady-state operation for the boiler system; negligible heat losses and within the limit of the boiler's efficiency; properties of PKS 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); thermodynamic property data for water and steam from steam tables were applied.

The design objective was to obtain the following performance parameters: minimum PKS fuel feed rate that would produce best operation temperature and pressure for safe and maintainable steam mass flow rate and steam velocity.

3.2.2. Design of 5-10 kW Micro Steam Power Plant/Generator

Micro steam power plant considered was within the range of 5-45 kW [37, 38]. For a superheated steam generator of 5-10 kW, with operating pressure P_o range of 0.45-4.5 MPa, feed water temperature T_f of 34ºC under atmospheric pressure, palm kernel shell (PKS) of calorific value C_v 18 MJ, boiler efficiency of 79%, and tube diameter of 12.7 mm, the steam flow rate, heat transfer rate, boiler outlet steam temperature and pressure, steam flow velocity through the tube (risers) were estimated for 5-10 kW capacity steam generator as follows.

Superheated steam generator given design parameters are:
Boiler capacity, G_c= 10 kW
Operating pressure P_o range= 0.45-4.5 MPa
Feed water temperature, T_f = 34°C
Calorific value of palm kernel shell, C_v = 18 MJ/kg
Boiler efficiency, B_e= 79%
Diameter of the tube (pipe), D_t =12.7 mm
Energy input required E_i by the steam generator was obtained from:

$$E_i = G_c/B_e \tag{1}$$

Where, the parameters are as defined above
= 10 kW / 0.79
= 12.66 kW
In computing the mass flow rate of Steam m_s, the enthalpy change Δh between the feed-water and the superheated steam must be obtained first.
By using a balanced operating pressure P_o of 2.5 MPa, and enthalpy of feed-water at 34°C (approximately 142.4 kJ/kg), and superheated steam at 250°C (approximately 2945.7 kJ/kg);
Then, the enthalpy change Δh was obtained from:

$$\Delta h = h_s - h_f \tag{2}$$

Where, h_s is the enthalpy for superheated steam and h_f is the enthalpy for feed water
= 2945.7 kJ/kg - 142.4 kJ/kg
= 2803.3 kJ/kg
This Δh was used to compute mass flow rate of steam m_s as

$$m_s = E_i/\Delta h \tag{3}$$

= 12.66 kW / 2803.3 kJ/kg
= 0.00452 kg/s
Heat transfer rate H_t was also obtained from

$$H_t = m_s \Delta h \tag{4}$$

= 0.00452 kg/s x 2803.3 kJ/kg
= 12.66 kW= E_i
PKS fuel Consumption rate m_f was obtained from;

$$m_f = \frac{E_i}{C_v} \tag{5}$$

Where the parameters are as defined before.
m_f =12.66 kW/ 18000 kJ/kg
m_f= 0.000703 kg/s
Cross sectional area of the tube A_c was obtained for a given tube diameter 12.7 mm (0.0127 m) from;

$$A_c = \pi (D_t/2)^2 \tag{6}$$

A_c=3.142 (0.0127 m /2)^2
A_c≈0.0001267 m^2
In calculating steam density, the specific volume of superheated steam was first obtained. The specific volume V_s of superheated steam at 2.5 MPa and 250ºC, obtained on the basis of steam tables was approximately 0.1155 m^3/kg, then density of superheated steam, ρ was obtained from:

$$\rho = 1/V_s \quad (7)$$

ρ≈ 8.66 kg/m^3

Hence, steam velocity, v_s was obtained from:

$$v_s = m_s/(\rho A_c) \quad (8)$$

v_s= 0.00452 kg/s /(8.66 kg/m^3 x 0.0001267 m^2)

v_s≈ 4.12 m/s

The calculations were repeated at varying temperatures and pressures on the basis of past data [8, 32, 38]. The performance operational parameters obtained for superheated steam generator of 10 kW were compared with that of 5 kW [8, 32].

4. Results and Discussion

Design results for the 5-10 kW micro steam power plant operational parameters are presented in Table 1. It was revealed that temperature range of 220-400 ºC effectively enhanced the performances of the plants. Temperatures (pressures) of 220ºC (0.38 MPa), and 235ºC (0.35 MPa) resulted in best possible steam mass flow rate of 0.00357 kg/s and 0.00178 kg/s respectively for the 5-10 kW steam power plants at PKS feed rates of 0.000352 and 0.000703 kg/s, respectively. It was further showed that for the best steam flow velocities (7.43, 14.87 m/s) temperatures (pressures) should be maintained at 235 ºC (0.35 MPa) or 220ºC (0.38 MPa) respectively. In terms of operational economy and safety, running at the lowest possible temperatures (pressures) of 235 ºC (0.35 MPa) and 235 ºC (0.35 MPa) would be sufficient for 5-10 kW plants, and resulted to acceptable steam mass flow rates (0.00357 kg/s, 0.00178) and steam flow velocities (14.87 m/s, 7.43 m/s), respectively. Though, highest velocities (15.5, 16.5 m/s) were obtained at temperature (pressure) 400ºC (0.45MPa) and 250ºC (2.5 MPa) but their operational safety and maintainability were doubtful.

Table 1. Operational Design Parameters for 5-10 kW Plant

T_f oC, Temperature	**P_o, MPa, Pressure**	**M_s kg/s, Mass flow rate**	**E_i kW, Energy input**	**m_f kg/s, PKS feed rate**	**v_s m/s Velocity**	**C_{spp} kW, Energy output**
220	0.38	0.00362	12.66	0.000703	1.88	10
400	0.45	0.00319	12.66	0.000703	15.5	10
235	0.35	0.00357	12.66	0.000703	14.87	10
400	4.2	0.00326	12.66	0.000703	1.88	10
250	2.5	0.00452	12.66	0.000703	4.12	10
220	0.38	0.00181	6.33	0.000352	6.97	5
400	0.45	0.00159	6.33	0.000352	7.75	5
235	0.35	0.00178	6.33	0.000352	7.43	5
400	4.2	0.00163	6.33	0.000352	0.94	5
250	2.5	0.00181	6.33	0.000352	16.5	5

Fig. 2 shows interplay among temperature, pressure, flow rate and flow velocity parameters for the 10 kW plant. From this figure, it was clear that temperature 220ºC and pressure 0.38 MPa produced mass flow rate (0.00362) at lowest steam velocity (1.88 m/s). In the case of 5 kW plant highest mass flow rate (0.00181 kg/s) and velocity (6.97 m/s) were estimated. This revealed that 5 kW would be recommended in terms of energy saving and usage economy (Fig. 5).

Fig. 3 shows the opportunity of the 10 kW plant operating at low pressure and temperature to attain good energy delivery at a lowest risk. It was clear from Fig. 4 that operating at a mass flow rate (velocity) of 0.00362 kg/s (1.88 m/s) or 0.00357 kg/s (14.87 m/s) would be safer due to moderate operating temperature (220, 235ºC) and pressure (0.38, 0.35 MPa).

Once the temperatures (400, 250ºC) and pressures (2.5, 4.2 MPa) that produced highest mass flow rate and velocity could be unsafe and unsustainable (Fig. 4), hence, the best optimum performance was achievable for 10 kW plant at temperature 235ºC and pressure 0.35 MPa with optimum mass flow rate (0.00357 kg/s) and velocity (14.87 m/s), while mass flow rate (0.00178 kg/s) and velocity (7.43 m/s) were obtained for 5 kW plant. Fig. 6 revealed similar trend in which optimum mass flow rates were (0.00181, 0.00178 kg/s) at temperatures (220, 235ºC) and pressures (0.38, 0.35 MPa). Fig. 7 showed that steam velocities (6.97, 7.43 m/s) were obtained at lowest possible temperatures (220, 235ºC) and pressures (0.38, 0.35 MPa). It was realized that (Figs. 8 and 9) 10 kW plant produced best steam mass flow rate and velocity (0.00357 kg/s, 14.87 m/s) at optimum temperature (235ºC) and pressure (0.35 MPa), while

5 kW plant had steam mass flow rate and velocity (0.00178 kg/s, 7.43 m/s) as the best. These outcomes, generally established that temperature (pressure) 235ºC (0.35 MPa) were the best design parameters for optimum realization of best steam mass flow rate and steam velocity to enhance steam energy delivery at a minimum possible PKS feeding rate (0.000703 kg/s).

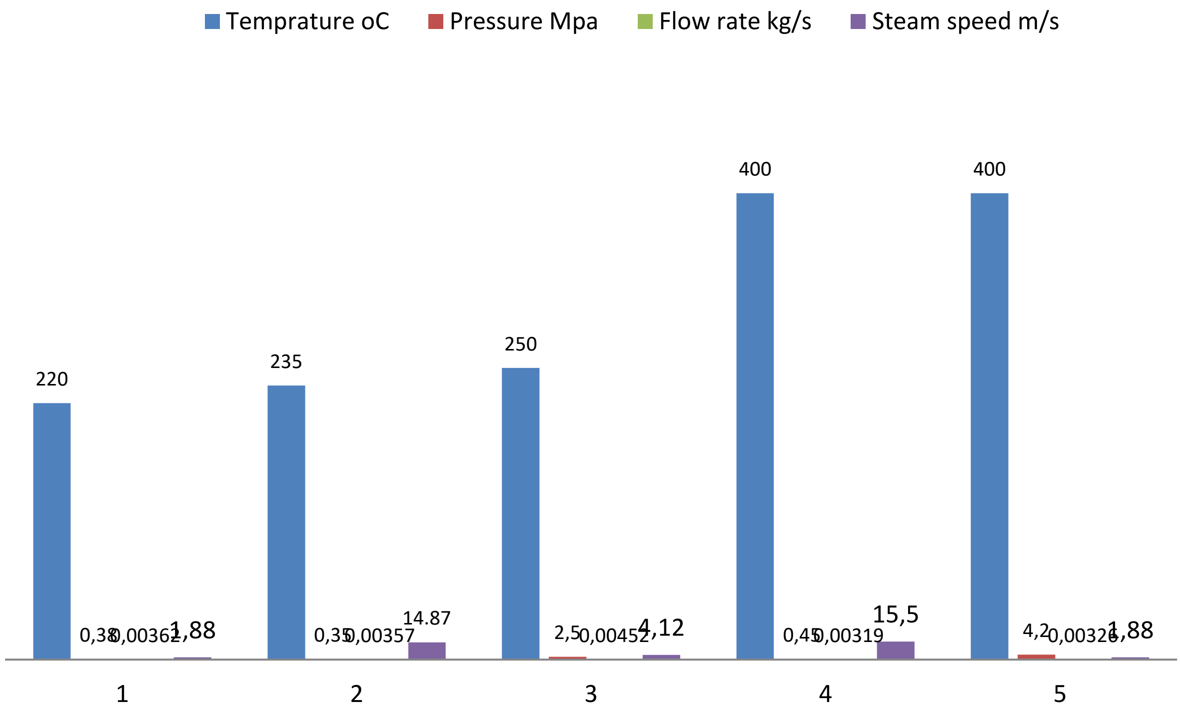

Figure 2. Interplay between Temp, Press, Flow rate and Steam Velocity for 10 kW Plant

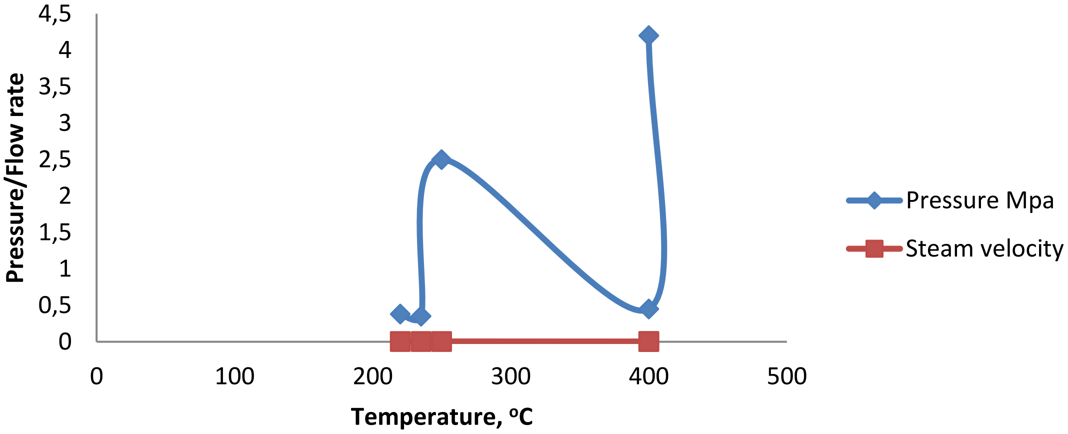

Figure 3. Interplay between Temp., Press., and Flow rate (10 kW)

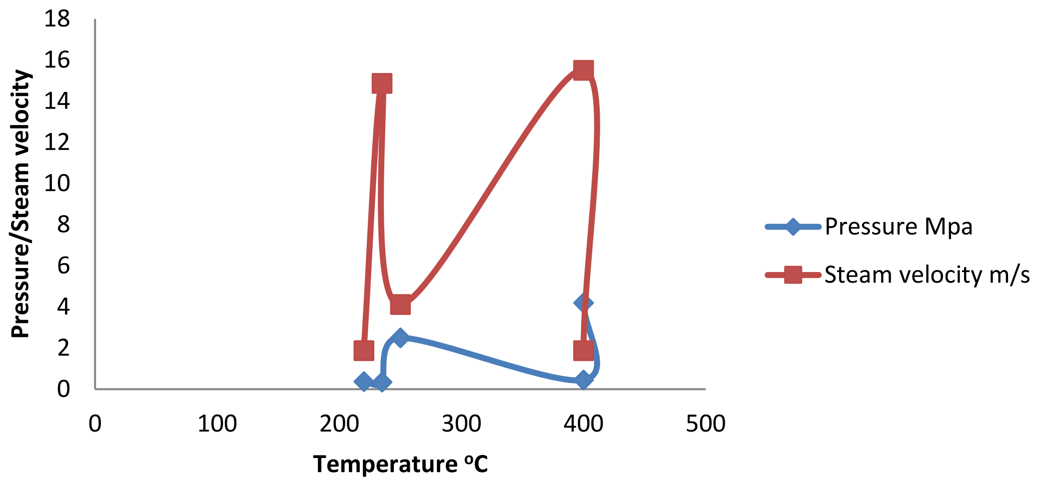

Figure 4. Interplay between Temp., Press., and Steam Velocity (10 kW)

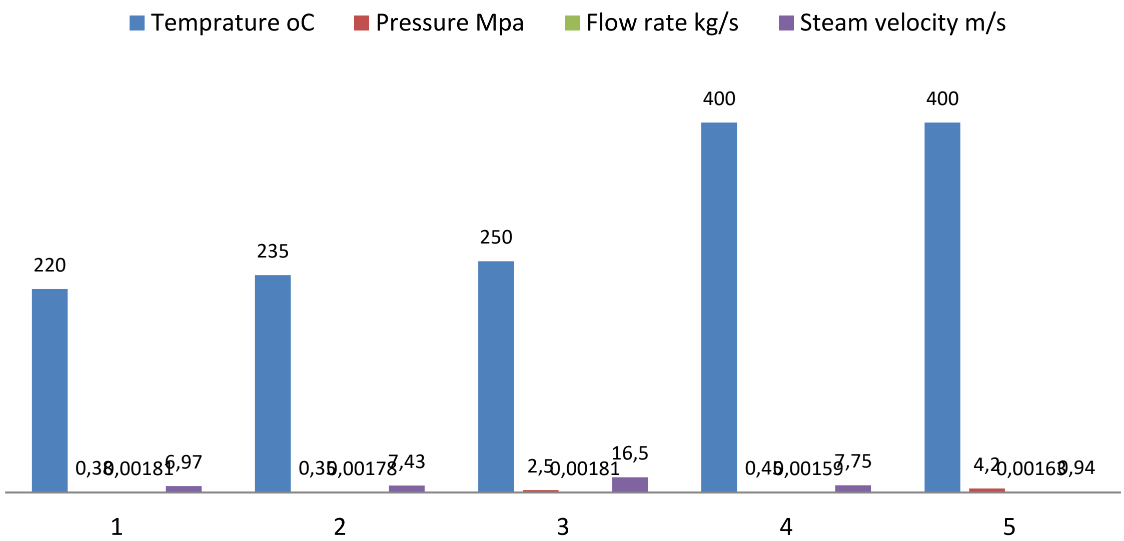

Figure 5. Interplay for Temp., Press, Flow rate and Steam Velocity for 5 kW Plant

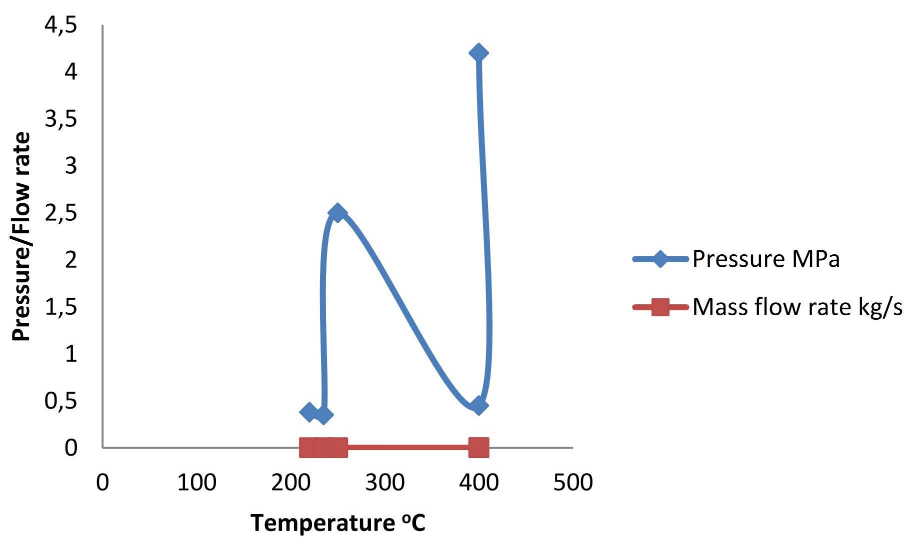

Figure 6. Interplay of Temp., Press, and Flow Rate for 5 kW Plant

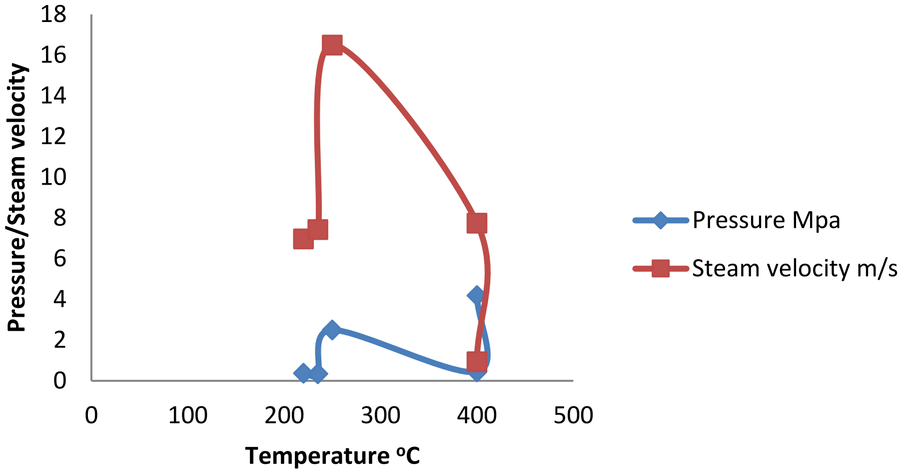

Figure 7. Interplay of Temp., Press. and Steam Velocity for 5 kW Plant

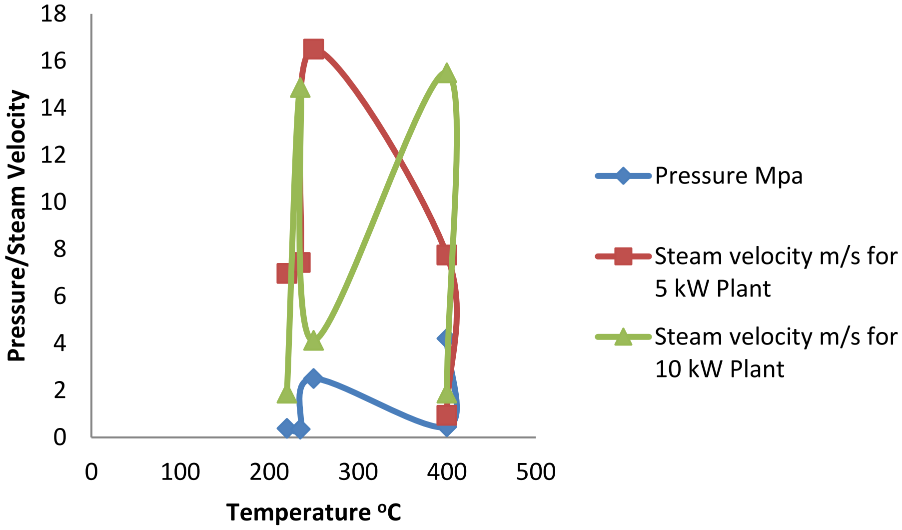

Figure 8. Interplay of Temp., Press. and Steam Velocity for 5 kW/10 kW Plant

Table 2. Performance evaluation and comparison

Parameter / Plant capacity	Elefe (2024)	Oladosu (2016)	Standard design V-FLO (2025)	This study (2026)
Temperature, ºC	234	220	400	235
Pressure, MPa	0.399	0.38	0.45-4.2	0.35
Mass flow rate, kg/s (5 kW)	-	0.023	-	0.00178
Mass flow rate, kg/s (10 kW)	-	-	-	0.00357
Steam velocity (m/s) (5 kW)	-	-	-	7.43
Steam velocity (m/s) (10 kW)	-	-	-	14.87
PKS fuel feed rate (kg/s) (5 kW)	0.0475	0.05	-	0.000352
PKS fuel feed rate (kg/s) (10 kW)	-	-	-	0.000703
Plant efficiency (%)	67	65	85	79 (At least 12 % improvement)

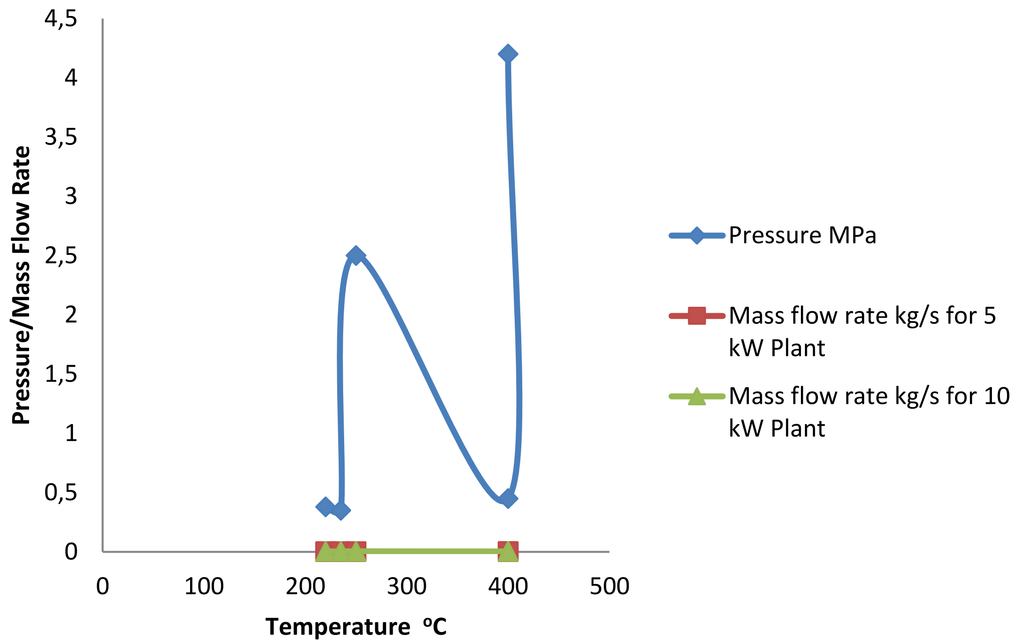

Figure 9. Interplay of Temp., Press. and Mass Flow Rate for 5/10 kW Plant

Performance evaluation results with that of other plants are presented in Table 2. Performance results comparison indicated that all outcomes from the studies [8, 32] including this study were not overshot the standard design values given by V-FLO [38]. It revealed that all the studies met design criteria. However, higher temperature output (235°C) with reduction in pressure, PKS feed rate and mass flow rate of this study made it uniquely enhanced its efficiency (79 %) as compared with other studies (67 %, 65 %). This performance analysis revealed that new plant would be safer and more sustaining than the existing ones [8, 32], with at least 12 % improvement in efficiency.

5. Conclusions

This study applied strategies of reduction of heat losses through optimal design of the micro power plant's operational parameters (PKS feeding rate, steam temperature, pressure, mass flow rate, and flow velocity) to enhance energy delivery efficiency with low maintenance for domestic and SMEs consumption. Design results for the 5-10 kW micro steam power plant operational parameters revealed that:

i. Temperature range of 220-400 °C has effectively enhanced the performances of the plants. Temperatures (pressures) of 220°C (0.38 MPa), and 235°C (0.35 MPa) resulted in best possible steam mass flow rate of 0.00357 kg/s and 0.00178 kg/s for the plants at PKS feed rates of 0.000352 and 0.000703 kg/s, respectively.

ii. The best steam flow velocities (7.43, 14.87 m/s) temperatures (pressures) should be maintained at 235 °C (0.35 MPa) or 220°C (0.38 MPa) for optimum delivery of steam power.

iii. Temperature (pressure) 220 °C (0.38 MPa) and 235 °C (0.35 MPa) would be sufficient for 5-10 kW plants in terms of operational economy and safety. This would bring acceptable steam mass flow rates (0.00357 kg/s, 0.00178) and steam flow velocities (14.87 m/s, 7.43 m/s), respectively.

iv. Highest velocities (15.5, 16.5 m/s) were obtained at temperature (pressure) 400°C (0.45MPa) and 250°C (2.5 MPa) but their operational safety and maintainability were doubtful.

v. Temperature 220°C and pressure 0.38 MPa produced mass flow rate (0.00362) at lowest steam velocity (1.88 m/s), while 5 kW plant gave highest mass flow rate (0.00181 kg/s) and velocity (6.97 m/s), hence 5 kW plant would be recommended in terms of energy saving and usage economy.

vi. Operating at a mass flow rate (velocity) of 0.00362 kg/s (1.88 m/s) or 0.00357 kg/s (14.87 m/s) would be safer due to moderated temperature (220, 235°C) and pressure (0.38, 0.35 MPa), while operating at temperatures (400, 250°C) and pressures (2.5, 4.2 MPa) though produced highest mass flow rate and velocity could be unsafe and unsustainable.

vii. Optimum performance was achievable in 10 kW plant at temperature 235ºC and pressure 0.35 MPa with best mass flow rate (0.00357 kg/s) and velocity (14.87 m/s), while for 5 kW plant mass flow rate (0.00178 kg/s) and velocity (7.43 m/s) were the best.

viii. Temperature (pressure) 235ºC (0.35 MPa) were the best design parameters for optimum realization of the best steam mass flow rate, steam velocity and enhance best steam energy delivery.

Acknowledgement
The management of the Federal University of Technology Akure is acknowledged for providing facilities to actualize this study.

Funding
Authors received no funding from any funding agency for this study

Competing Interest
The authors declare that they have no competing interest.

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