Integration of Charcoal Kiln Waste Heat in a Thermal Water Pump System

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***Abstract*— This an innovative solution for water pumping in resource-limited settings has been presented by waste heat utilization from charcoal production. This experiment investigates a novel thermal water pump system integrated with 200-liter charcoal kilns (CK). The experimental setup consisted of a driving tank, a storage tank, an overhead tank, and a well tank. A 1-meter discharge head and 1-3 m suction heads were tested. This experiment compared pump efficiency and thermal efficiency between single and double CK, using 25 kg and 50 kg of eucalyptus wood as fuel, respectively. Data acquisition was recorded over 2-hour operations. It revealed that the pump achieved optimal performance at driving tank temperatures of 99°C, with maximum efficiency at a 3-meter suction head. The single CK delivered 155.89 L for 25 cycles, with 0.00073% pump efficiency and 2.2% thermal efficiency, while the double CK could enhance performance, pumping 274.15 L for 28 cycles at 0.000847% pump efficiency and 2.8% thermal efficiency. The double CK has higher system efficiency than a single CK due to increased thermal energy availability. However, the water pumping system still has low efficiency due to environmental heat losses. This study can verify that waste heat utilization in water pumping applications and identifies key areas for future optimization.**

Keywords—waste heat, thermal water pump, charcoal, energy conversion

I. INTRODUCTION

Nowadays, many barbecue restaurants use charcoal as fuel for grilling. The process of charcoal production produces thermal energy, which is wasted heat that is not utilized. Therefore, it could be useful to use wasted heat for a thermal water pump (TWP), which uses thermal energy for water pumping. Usually, charcoal is made in fields or open areas, which are far from a power grid, and therefore, makes it challenging to use an electric pump. Similarly, if a gasoline water pump were used, it would consume fossil fuel. The thermal water pump from charcoal production (TWPC) could partly reduce fossil fuel consumption and energy cost. Especially since it does not require a transmission line and can be mounted anywhere.

Numerous thermal water pumps have been studied and developed [1-10]. In 1996, Sumathy et al. built a solar thermal water pump. The pentane vapor from the solar collector was generated as pump power. The maximum water discharge from this pump was 10 meters [11]. These solar thermal water pumping systems were reviewed by Wong & Sumathy. The conventional and unconventional pumping techniques are the main topics of this study. While the unconventional type converts thermal energy to hydraulic work, the conventional type converts thermal energy to mechanical energy. The multiple unconventional types have advantages, being that they are simple and non-mechanical. Solar thermal water pumps for irrigation tend to improve due to technological advancements and falling costs [12]. Wong & Sumathy built a solar water pump using n-pentane and ethyl ether as working substances. The maximum pump efficiency was 0.34%. The pumped water is between 700-1400 L/day [13]. Roonprasang et al. built a solar water heater system (SWHS) that utilized a solar water pump. The operating temperature was around 70-90°C. The daily pump efficiency was 0.0014–0.0019% on average [14]. Delgado-Torres reviewed numerous methods of solar thermal water pumps [15]. Sutthivirode et al. [16] and Roonprasang et al. [17] built a solar water heating system, compared to the system developed by Roonprasang et al. [14]. Their system operates at temperatures between 70 and 90°C. The water temperature was around 60°C. This system operates automatically. Sutthivirode et al. [18] presented a waste heat water pumping model with direct contact cooling. It can pump 65-170 L of water in 2 hours. The solar water heater was enhanced efficiency by Sitranon et al. A thermal water pump built by Sutthivirod et al. [16] was used as the prototype. Their pump has daily efficiency of about 0.0012% [19]. The application of a TWP for agriculture was studied by Sitranon et al. A working fluid is air-steam. The pumping efficiency reached 0.01973% [20]. The mathematical model of the solar thermal water pump was investigated by Bandaru et al. The solar thermal energy conversion was simulated [21].

Biomass can be used as a source of energy in two ways: directly, by burning it, or indirectly, by turning it into solid, liquid, or gaseous fuels [22]. This research uses a direct method of biomass energy. Charcoal production is one method of utilizing biomass energy, which plays a vital role in global energy generation, with significant amounts produced in diverse regions, such Africa, Asia-Pacific, and Latin America [23]. Studies have shown that heat is generated during the production process [24, 25].

The goal of this research was to study the efficiency of a thermal water pump that uses waste heat from charcoal production, with 200-liter charcoal kilns. The experiment was to compare the efficiency between a system equipped with single CK, and double CK. Eucalyptus wood was used as a heat source, 25 kg and 50 kg, for single CK and double CK, respectively. A 1-meter discharge head and 1, 2 and 3 m suction heads were tested.

II. Experimental Setups

A. *Component of thermal water pump system*

The TWPC is made up of six primary components, as indicated in Fig. 1. First, the CK, which are made of a 200-liter fuel tank with no insulation. It has three smokestacks, assembled beside the tank. The inlet for fuel and natural air convection is placed below the CK. The copper tube (CT) roll is installed in tank, to generate the vapor as pump power. Second, a driving tank (DT), which is built using a 2-mm thick stainless-steel sheet, which has good insulation. The DT body consists of two parts: a cylindrical shape, and a conical shape, both welded together. The cylinder contains 0.01 m^3 of water, and the cone has 0.005 m^3 of air. Third, an overhead tank (OT), which is made of plastic with no insulation. It is located at a higher level, above the DT. The water of the OT is controlled by a floating valve. The cooling water valve (CWV) consists of PVC reducing socket, which has a ping pong ball and rubber seal. It is included in the OT. It is utilized to regulate 300 mL of water, which is the minimum water volume, into the DT to establish a vacuum. The CWV is essential for this research. Fourth, a storage tank (ST), well tank (WT) and supply tank (SPT), they are the cylindrical tank with air vent.

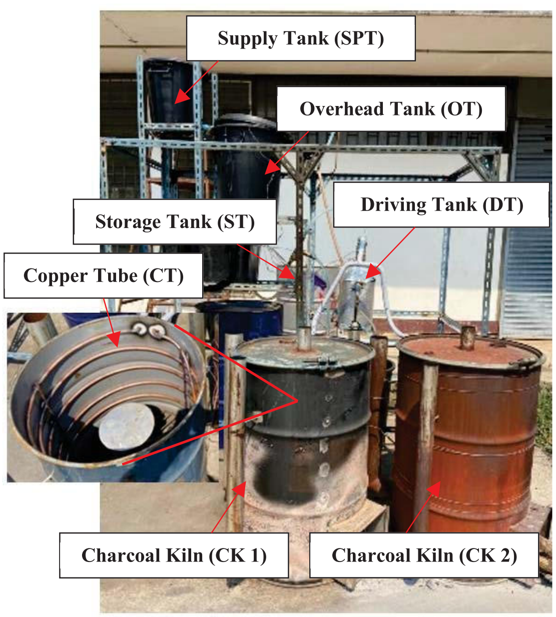


Fig. 1. The component of TWCP system

The CT-DT is connected by a 1/2-in copper tube. The ST, OT, and SPT are linked to the DT, via a 1/2-in rubber tube, where the water flow can be observed. The 1, 2, and 3-m suction heads were tested with a constant 1-m discharge head. The suction head is the difference between the DT top and the water level at WT. The discharge head is the difference between an air vent level: that is h1 in Fig.2, and DT bottom. Eucalyptus wood, which weighed 25 kg, was used as fuel, with its heating value being around 19,000 kJ/kg. The experimental data were recorded for 2 hours at the Faculty of Engineering and Technology, Rajamangala University of Technology Isan. The data entry was recorded for every 1 second per measured data.

B. *Measurement points of thermal water pump system*

The temperature of the steam, water, and surrounding air was measured by K-type thermocouples, with an accuracy of +0.5°C, connected to a data logger (Hioki LRB8431-20) which has improved accuracy of ±1.5°C. The measurement points are shown in Fig. 2. There are 7 measuring points: 1) water temperature in overhead tank, 2-4) water temperature in driving tank, 5) water temperature in storage tank, 6) water temperature in well tank, and 7) ambient temperature

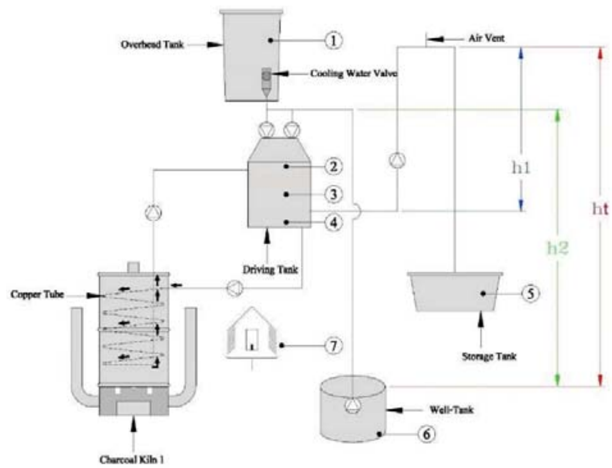


Fig. 2. Points of measurement: h1, discharge head; h2, suction head; ht, total head

III. System Operation

The system operation of this study is similar to several previous studies [18, 26] except for the heat source. The system operation is shown in Fig. 3. The process of TWPC comprises five stages:

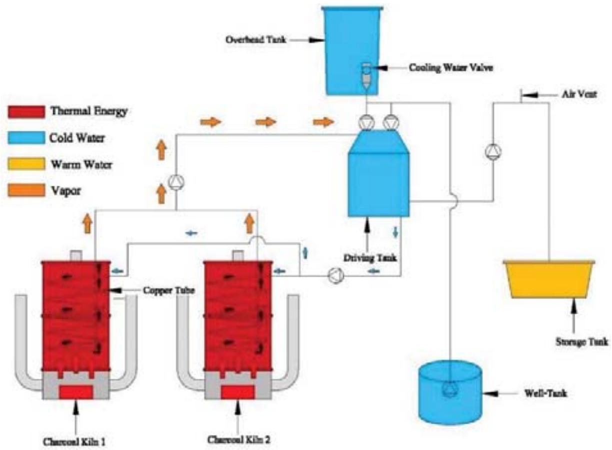
Heating stage: initially, the CT contains water in a full tube. Thermal energy in charcoal production process transfers to the CT. The water in the CT is heated to boiling temperature, and then it vaporizes and flows to the DT. Because of this, the pressure and temperature of the water and air in the DT slightly rise. The heating stage continues until the DT's pressure is sufficient to transport hot water from the DT to the ST.

Pumping stage: when the DT pressure is higher than the discharge head pressure, the water in the DT is pushed to the ST until the water is gone.

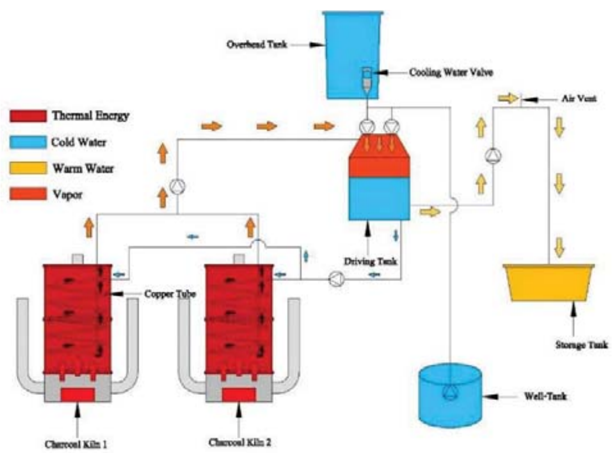
Vapor flow stage: the vapor from the CT can flow to the air vent after the last drop. The vapor flow process continues until the DT pressure reaches one atmosphere.

Cooling stage: the 300 mL of water in the OT automatically moves downward by gravitational force, into the DT, and the CWV is closed promptly temporarily.

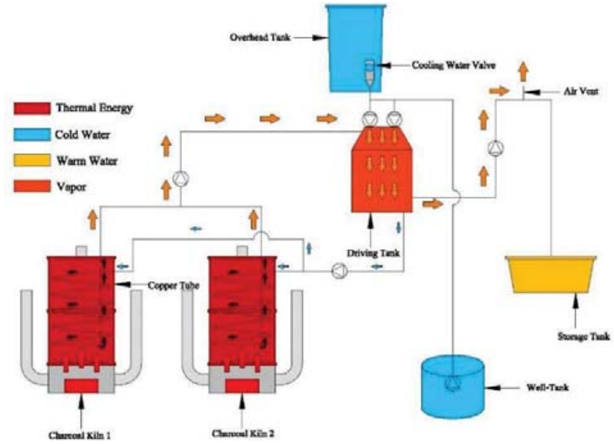
Suction stage: the vacuum is generated owing to steam condensation, and then the water from the WT is sucked into the DT. The sucked water is estimated to be 0.01 m^3, which is not the full capacity of the DT. The remaining space is for air. Some part of sucked water fills up the CT to continually produce steam. One cycle of the self-pumping process is accomplished, and the pumping action is then prepared for the next cycle.



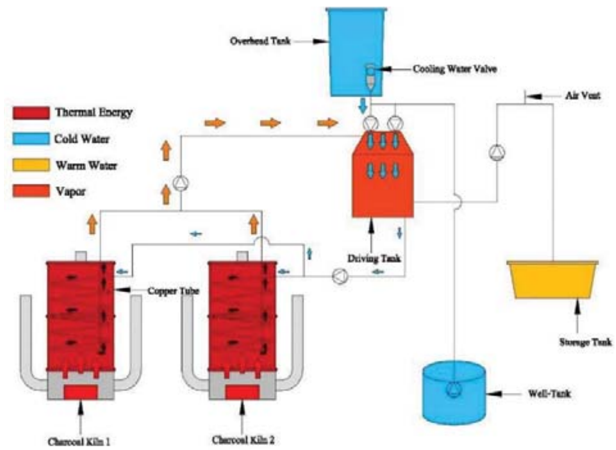
(a) Heating stage



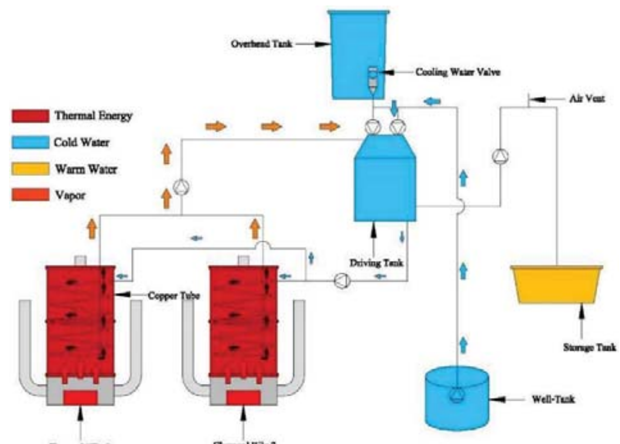
(b) Pumping stage



(c) Vapor flow stage



(d) Cooling stage



(e) Suction stage

Fig. 3. Five-stage operation of TWCP system

IV. SYSTEM ANALYSIS

Pump efficiency is expressed as a percentage, using the following formula by [1]:

$$\eta_p = NW_h / Q_{input} \quad (1)$$

Where N is the number of water circulating cycles per 2 hr W_h, being the required hydraulic energy for each cycle, which is expressed by:

$$W_h = V_w \rho g h_t \quad (2)$$

Where V_w is the amount of pumped water per cycle, including 300 ml of the cooling water, ρ is density of water, g is the acceleration of gravity, and h_t is the overall head of system.

The thermal energy of water in the ST can be calculated, as in (3)

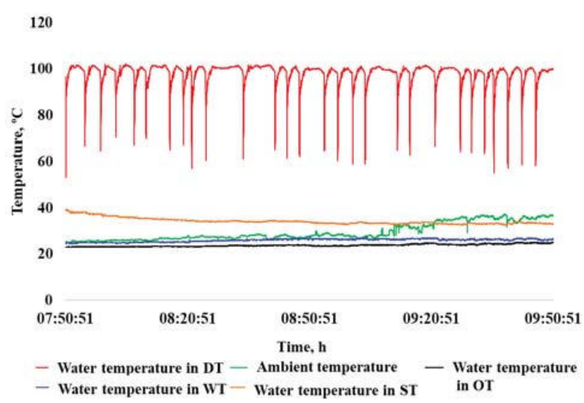
$$Q_s = m_{w,s} c_p \Delta T_s \quad (3)$$

Where $m_{w,s}$ is the water quantity in the ST, c_p is the specific heat of water, and ΔT_s is the water temperature increase in the ST. The thermal efficiency is defined as the ratio of the thermal energy of water in the ST, compared to the total energy from eucalyptus wood, as in (4)

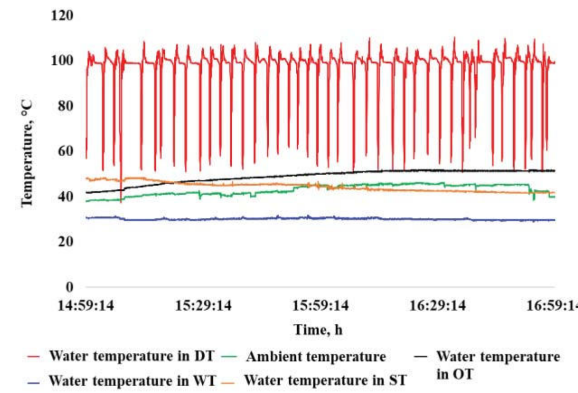
$$\eta_t = (Q_s / Q_{input}) \times 100\% \quad (4)$$

V. Results and discussion

A pumping capacity of the TWPC was 6-9 L of water per cycle. The ST maintained an average temperature range between 32-46°C. Improved insulation of the ST could potentially lead to raised temperatures. The system-initiated water pumping when the DT temperature exceeded 99°C. The integration of double CK enhanced thermal energy input to the TWPC, resulting in increased pumping cycle frequency as in Fig. 4. This improvement is probably the reason that the system has more pump power to overcome friction loss and gravitational forces. Experimental results indicated that configurations with single and double CK achieved 25-29 and 28-41 pumping cycles, respectively, corresponding to total pumped water volumes of 156-175 L and 274-400 L. Furthermore, the vapor temperature in DT with double CK exceeded that of the single CK by approximately 8°C.



(a) Single CK, 1 m suction head



(b) double CK, 1 m suction head

Fig. 4. Comparison of pumping frequency with different heat input

A. *Effect of the suction head on thermal efficiency*

A comparison of thermal efficiency is shown in Fig. 5 revealed that the thermal efficiency decreases as suction head increases. This phenomenon can be explained by steam energy requirements is varied on suction head height. The conversion of thermal energy to mechanical energy for water pumping is not 100% efficient due to thermal energy losses that lead to decreasing thermal efficiency. As shown in Table I, the pumping frequency is decreased (fewer cycle), resulting in water circulation through the system is also decreased. Therefore, heat transfer of thermal energy to system is decreased. This reduction in heat transfer ultimately results in lower thermal efficiency values.

TABLE I. Pumping Cycle and Pumped Water at Different Suction Head

No. of CK	Suction head (m)	Pumping Cycle	Pumped water [a] (L)	Pumped water rate (L/cycle)
1	1	27	175	6.48
	2	29	172	5.93
	3	25	156	6.24
2	1	41	400	9.76
	2	39	378	9.69
	3	28	274	9.79

a. Including 300 ml of the cooling water

A comparison of thermal efficiency in case of one and double CK revealed that double CK have more thermal efficiency because the system can produce more steam, which increases thermal energy. However, there is no significant difference when the discharge head is 3 m. The system has the best thermal efficiency of 2.8% at the suction head of 1 m., and this is in accordance with the study of [16]. This can be expressed by the Darcy-Weisbach equation. In the suction process, the suction pipe, which is made of rubber tubes, can flatten due to suction pressure. The pumped water is obstructed. The selection of PVC spring hoses as the suction tube may reduce this problem.

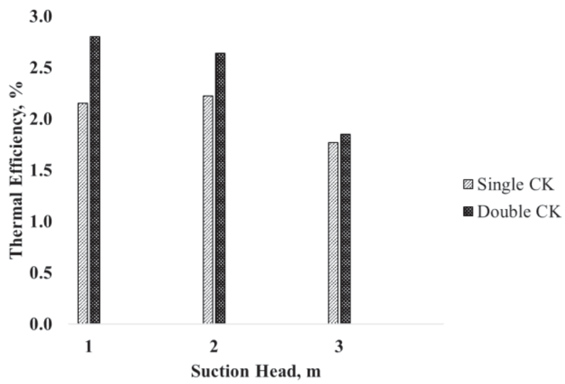


Fig. 5. Effect of different suction head on thermal efficiency

B. *Effect of the suction head on pump efficiency*

The relationship between suction head height and pumping efficiency was investigated through comparative analysis of single and double CK configurations as in Fig. 6. The pump efficiency has varied across suction heads to 1, 2, and 3 m with single and double CK. Pump efficiency using double CK is 0.000412%, 0.000778%, and 0.000847%, whereas the single CK is 0.00036%, 0.000709%, and 0.000763% at respective suction heads of 1, 2, and 3 m. Analysis revealed that pump efficiency shows a positive correlation with increasing suction head value, denoted as h2 in Fig. 2, As the suction head increases, the pump must generate increased suction force to overcome gravitational forces, necessitating higher energy input per pumping cycle. This increased energy requirement results in a reduction of both pumping cycles and total water volume output. Despite the pumped water being decreased, the elevated pressure generation capability leads to a marginal improvement in pump efficiency. However, it should be noted that the pump operates below optimal efficiency due to the additional energy required to overcome the increased suction head resistance. This relationship indicated that the suction head parameter has a greater impact on pump efficiency than the other factors specified in (2).

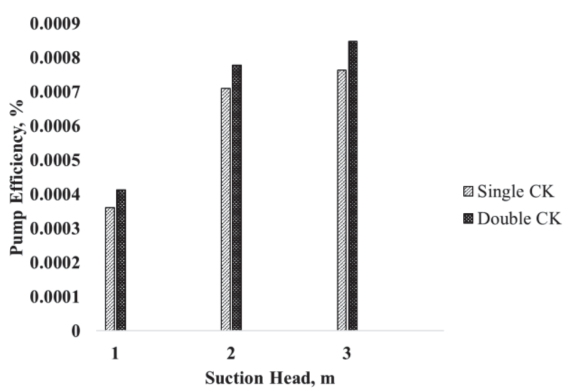


Fig. 6. Effect of different suction head on pump efficiency

VI. Conclusions

TWPC could pump when the DT temperature exceeded 99°C. As suction head increases, it affects the system's efficiency, explained by pump efficiency and thermal efficiency. Pump efficiency increases slightly due to increased energy consumption per cycle, despite the reduction in total pumped water volume. Pump efficiency is between 0.00036% and 0.000763% for single CK. While, 0.000412% and 0.000847% for double CK. The system used for this study had lower pump efficiency than previous studies [18-19], due to significant heat loss at the CK surface. Increasing the driving steam pressure, implementing flow resistance reduction mechanisms, or thermal insulation enhancement to minimize energy losses should be considered for improving pump efficiency. Meanwhile, thermal efficiency decreases because higher steam energy is required to overcome gravitational force, but energy cannot convert from thermal to mechanical work with full efficiency. Experimental trends indicate that minimizing the suction head should be a focus for increasing thermal efficiency. However, the advantage of this system is that the waste heat can be used for functions, such as pumping water and heating water. The pumped water volume with single and double CK is 156-175 L and 274-400 L, respectively. Nonetheless, the water temperature in the ST is sufficiently hot for domestic use. The pump efficiency is dependent on the suction head and ambient temperature. The thermal pump efficiency is about 1.77-2.22% for single CK and 1.85-2.80% for double CK. The overall energy losses may be decreased by minimization for the suction head and optimization of water flow rates using large water tubes at every stage, as well as good insulation. Finally, systems operating with lower suction head values demonstrate optimal steam energy utilization efficiency.

When examining the environmental impact of charcoal kilns using eucalyptus wood as combustion fuel, the emission factors were found to be CO_2 ~ 1400±101 g/kg, CO ~ 50±13 g/kg, and CH_4 ~ 3.2±0.5 g/kg [27]. Consequently, for single and double charcoal kilns utilizing 25 kg and 50 kg of eucalyptus wood, respectively, the maximum greenhouse gas emissions equate to 232 g/L and 265.18 g/L, respectively. Considering only the maximum CO_2 emissions, these amount to 224.36 g/L and 255.47 g/L, respectively. In comparison, water pumping using electric pumps at a total head of 5 meters, consuming 0.37 kW of electricity at comparable water pumping volumes, produces maximum CO_2 emissions of only 0.079 g/L and 0.102 g/L, respectively. This calculation is based on Thailand's carbon dioxide emission per electricity generation data, reported at 0.399 kg/kWh in 2024 [28]. While electric water pumps evidently release less CO_2 than eucalyptus wood fuel, the constraints of areas lacking electricity access and cost considerations make water pumping using waste heat from charcoal kilns a potentially viable alternative. The additional pollution control technologies could be implemented for solving pollution concerns, such as wet scrubber installations. Notably, wet scrubbers integrated into kilns have demonstrated removal efficiencies of 97.8% for hydrocarbons, 98.5% for CO_2, and 99% for CO, respectively [29].

When examining an economic feasibility perspective, the water pumping system powered by waste heat from charcoal kilns demonstrates potential to reduce energy costs by approximately 30% compared to conventional electric water pumps. The system has a payback period of 7.6 years. Furthermore, the system can be designed to achieve increased water pumping rates and enhanced suction and delivery distances according to the available waste heat and pressure vessel size. As the system is scaled up with increased pumping capacity, the payback period decreases proportionally. This technology is particularly suitable for agricultural applications with sufficient biomass resources for irrigation purposes.

The system presents a sustainable solution for regions with limited access to electrical infrastructure.

VII. Suggestion

The optimization techniques are proposed to improve system performance as findings:

1) The suction head should be minimized as much as possible in order to lower pump load.

2) Improvement of thermal insulation to maintain heat and energy loss reduction.

3) Increasing the water circulation rate to optimize the water flow rate for supporting efficient heat transfer within the system.

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