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Design and Fabrication of a Steam Generation System for Fruit Preservation

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Abstract

Steam-based thermal processing is widely applied in fruit preservation due to its effectiveness in enzyme inactivation and microbial control. This study presents the design, fabrication, and performance evaluation of a natural circulation water-tube steam generation system developed for small- to medium-scale fruit processing. The system incorporates a steam drum (0.95 m height, 0.45 m diameter), a furnace chamber (0.80 m height, 0.13 m^3 volume), and 32 mm outer diameter riser tubes to ensure efficient steam–water circulation. An automatic control unit integrating temperature, water-level, and emission sensors enhances operational safety and stability. The design was guided by thermodynamic and heat transfer analyses, including heat duty estimation and logarithmic mean temperature difference evaluation. The measured thermal efficiency was 67 %, which indicates that the system effectively converted thermal energy from fuel combustion into useful steam energy, minimizing losses. Fabrication was carried out using locally available materials to ensure durability and food safety compliance. Performance results indicate that the developed system is energy-efficient, cost-effective, and well-suited for fruit preservation applications in resource-limited agro-processing environments.

Keywords: *Steam, boiler, fabrication, furnace, combustion, preservation.*

1.0 Introduction

Historically, steam has served as the engine of progress, driving the industrial revolution and modernising economies around the world. As Nuvolari (2019) highlights, steam has consistently provided a reliable means of converting thermal energy into mechanical work. The demand for high-quality steam generation systems has increased as industries evolved, especially those that emphasise safety, cost-effectiveness, and energy efficiency (Sathish et al., 2021). Steam (the gaseous phase of water) is typically produced by heating water to its boiling point. This simple yet powerful transformation allows it to perform essential roles such as driving turbines for power generation, enabling heat transfer in industrial processing, providing sterilisation in healthcare, and facilitating food preservation and preparation (Lin et al., 2019).

The methods used in generating steam have undergone considerable evolution over the years. Traditional techniques like fossil fuel combustion have dominated industrial steam generation for decades (Khaleel et al., 2022).Yet, as environmental awareness grows, the shift toward sustainable alternatives is accelerating (Islam et al., 2020). Sustainable industrial development emphasizes the protection of non-renewable energy resources and the implementation of energy-efficient production techniques. Declining fossil fuel availability, coupled with environmental challenges associated with greenhouse gas emissions and regulatory pressures, has driven the search for innovative industrial solutions, including advanced drying technologies (Romdhana et al., 2015). The application of superheated steam in place of hot air offers improved energy utilization by recovering latent heat from discharged steam while preventing gaseous emissions through condensation. This shift has prompted engineers, policymakers, and researchers to explore renewable energy pathways for generating steam that align with sustainable development goals.

A steam generator produces steam by transferring thermal energy to water. The evolution of steam recovery systems is largely driven by variations in capital investment, expansion of operational scale, and increasing requirements for energy efficiency and environmental compliance. These pressures have led to the adoption of superheated steam operating conditions in applications such as food processing (Babu et al., 2016). The application of superheated steam as a drying medium is increasingly preferred due to its inherent safety, absence of toxic emissions, elimination of fire hazards, and antioxidant nature, all of which make it compatible with food materials. It also demonstrates better thermophysical performance than conventional hot air (Patel & Bade, 2021). Energy consumption is reduced by recovering energy from spent steam through recirculation, while surplus steam can be utilized in auxiliary operations to further cut energy use (Hampel et al., 2019). Additionally, the specific heat capacity of superheated steam at constant pressure is nearly twice that of hot

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air, decreasing the required drying medium volume. According to Patel and Bade (2021), superheated steam shows strong potential as an alternative to hot-air drying.

Different studies have been done on steam generators and their applications. Notably, Ehtiwesh et al. (2023) implemented a transient dynamic model of a direct steam generation solar power system with steam storage, enabling load-following operation for a hospital in Libya with power demands varying between 50 and 200 kW. The performability of a coal-fired power plant's steam generation unit was investigated by Malik et al. (2022) through Markov modelling, with results indicating that enhancements in the economiser subsystem led to the highest availability gain, rising from 0.7640 to 0.8827. Hampel et al. (2019) developed a time-dependent macroscopic framework to investigate the coupled heat and moisture transfer mechanisms within an individual rice kernel subjected to superheated steam drying. Using a superheated steam fluidized bed drying system, Kozanoglu et al. (2013) analyzed paddy drying under varying pressures (40–67 kPa), temperatures (98–118°C), steam velocities (2.9–4.0 m/s), and mass flow conditions. The study revealed temperature as the dominant factor controlling drying kinetics, while pressure and steam velocity played comparatively insignificant roles. In their study, Malaikritsanachalee et al. (2020) applied superheated steam–based dehydration at a low operating pressure of 6.0 kPa to ripe mangoes, contrasting it with hot-air drying at 70 °C and 2.0 m/s. Different heating and tempering intervals ratios of 10:1, 20:1, and 30:1 min were assessed. The intermittent 20:1 min treatment resulted in the most porous dried mangoes with superior rehydration performance. Different studies have been done on steam generators and their applications.

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The generation of steam remains a critical process with wide-ranging applications across numerous sectors, including energy, healthcare, manufacturing, agriculture, and food processing (Ostovan et al., 2022). Innovations in heat recovery, such as combined heat and power systems and waste heat recovery boilers, have introduced new efficiencies in the simultaneous generation of steam and electricity. By capturing and reusing thermal energy that would otherwise be lost, these systems reduce fuel consumption, lower operational costs, and minimise environmental impact (Ononogbo et al., 2023). Steam sterilisation remains the standard for decontaminating medical instruments, surgical tools, and laboratory equipment in health sectors. It ensures the elimination of pathogens and protects patients from hospital-acquired infections (Lim et al., 2024). In the agricultural and food sectors, steam is extensively used for blanching, pasteurisation, cooking, and sterilisation processes. In the preservation of perishable crops like fruits and vegetables, steam treatment can deactivate spoilage organisms, reduce enzymatic activity, and extend shelf life without the need for chemical preservatives (Raza et al., 2023).

However, the efficient preservation of perishable agricultural produce remains a persistent challenge in tropical regions where climatic conditions accelerate spoilage. Perishable products are susceptible to rapid deterioration due to microbial activity, high respiration rates, and moisture loss. In many developing countries, especially in rural and peri-urban areas, inadequate post-harvest handling and preservation infrastructure result in significant losses of mangoes shortly after harvest. These losses not only impact food security but also reduce farmers' income and limit export opportunities.

The novelty of this study lies in the design and fabrication of a compact biomass-powered steam generation system specifically developed for fruit preservation applications. Unlike conventional steam generators that rely on fossil fuels and large-scale industrial infrastructure, the developed system utilizes locally available biomass as a sustainable energy source and integrates a natural circulation water-tube configuration for efficient heat transfer and steam production. In addition, the system is designed using locally sourced materials, making it cost-effective, environmentally friendly, and suitable for small- and medium-scale agro-processing operations, particularly in resource-limited regions.

This study aimed to design and developed a novel biomass-powered steam generation and control system for agro-processing and preservation. This project contributes to cleaner energy technologies, advances in thermal engineering, and aligns with Sustainable Development Goals (SDGs) 7, 9, and 13, addressing local energy challenges.

2.0 Materials and Methods

2.1 Materials Used for Fabrication

The materials used for the fabrication of the biomass-powered steam generation system were selected based on their thermal resistance, mechanical strength, corrosion resistance, availability, and cost-effectiveness. The main structural components of the system were fabricated using mild steel due to its good weldability, high mechanical strength, and ability to withstand the thermal stresses generated during biomass combustion. Steel pipes with an outer diameter of 32 mm and wall thickness of approximately 3 mm were used for the water-tube section of the steam generator. These pipes were selected because of their excellent heat transfer characteristics and capacity to withstand internal pressure during steam generation. The combustion chamber casing was constructed using mild steel plates of about 3 mm thickness, which provide adequate structural rigidity and durability under high-temperature operating conditions. The superheater section was fabricated from stainless steel (grade 310S) due to its excellent resistance to high-temperature oxidation and corrosion when exposed to hot flue gases. Stainless steel was also used for the water storage tank and steam drum to prevent corrosion and ensure durability under pressurized steam conditions. To minimize heat loss and improve thermal efficiency, glass wool insulation (thickness of approximately 50 mm) was installed around the combustion chamber. A 0.5 hp water pump was used to transfer water from the storage reservoir to the heating drum. In addition, locally sourced biomass fuel was used as the primary energy source due to its renewability, low cost, and environmental sustainability compared to conventional fossil fuels. The use of locally available materials and components also ensures that the system can be easily fabricated, maintained, and adopted in small- and medium-scale agro-processing operations.

2.2 Furnace Design

The typical volumetric heat release rate (q_v) for biomass combustion was reported as 0.176 MW/m^3 by Yin et al. (2008). Many package boilers are designed with a cylindrical furnace incorporating a truncated conical section, with an exterior cone angle ranging from 50° to 55°. The furnace volume (V), grate area, and furnace height (h) are calculated using Equations (1–3). where q_f is the heat released.

$$V = \frac{q_f}{q_v} \tag{1}$$

$$A = \frac{\pi d^2}{4} \tag{2}$$

$$h = \frac{V}{A} \tag{3}$$

2.3 Superheater design

A superheater is a thermal device designed to raise the temperature of steam by exchanging heat with hot flue gases. The governing energy balance for the superheater can be written as:

$$q_{sp} = m_s C_{pm}\left(T_{sp1} - T_s\right) \tag{4}$$

where q_{sp} is the superheater heat requirement, T_{sp1} is the superheated steam temperature, and T_s is the saturated steam temperature at the boiler outlet. Similarly, the energy balance for the riser tube is described by:

$$q_b = m_s C_p (T_s - T_a) + x_s m_s L \tag{5}$$

Assuming saturated conditions in the downcomer and riser ($T_a = T_s = 100\ °C$), the sensible heat term becomes negligible, resulting in:

$$q_b = x_s m_s L \tag{6}$$

In these expressions, q_b corresponds to the riser tube heat duty, L denotes the specific latent heat of vaporization, and x_s represents the steam dryness fraction. The rate of heat generation from the fuel $\left(q_f\right)$ is given by:

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$$q_f = m_{fuel} \times LHV \tag{7}$$

Where m_{fuel} is the mass flow rate of fuel. The associated air mass flow rate is estimated as:

$$m_{air} = (air - fuel\ ratio) \times m_{fuel} \tag{8}$$

The thermal load required by the riser tube can be determined using:

$$q_b = UA\Delta T_{LM} \tag{9}$$

Here, ΔT_{LM} is the logarithmic mean temperature difference (LMTD) and the overall heat transfer coefficient U, referenced to the external surface area of the riser tube, is estimated from:

$$\frac{1}{U} = \frac{1}{h_g} + \frac{t_r}{k_w} + \frac{1}{h_{b1}} \tag{10}$$

In this relation, h_g denotes the flue gas heat transfer coefficient, t_r is the tube wall thickness, k_w is the thermal conductivity of stainless steel (304), and h_{b1} is the boiling-side heat transfer coefficient (Oladosu et al., 2017).

2.4 Determination of LMTD

The thermal energy gained by the riser corresponds to the heat lost by the flue gas, given by:

$$q_b = m_g C_{pg}\left(T_{g,in} - T_{g,out}\right) \tag{11}$$

According to Oladosu et al. (2017), the logarithmic mean temperature difference for a crossflow heat exchanger is evaluated using:

$$\Delta T_{LM} = \frac{\Delta T_1 - \Delta T_2}{ln\left(\frac{\Delta T_1}{\Delta T_2}\right)} \tag{12}$$

where $\Delta T_1 = T_{g,in} - T_{s,out}$ and $\Delta T_2 = T_{g,out} - T_{s,in}$

In these expressions, $T_{g,in}$ refers to the flue gas inlet temperature (°C) and $T_{g,out}$ corresponds to the flue gas outlet temperature (°C). Similarly, $T_{s,out}$ and $T_{s,in}$ indicate the saturated steam outlet and inlet temperatures (°C), respectively.

2.5 Fabrication Procedure

The fabrication of the steam generation system was carried out using conventional metalworking processes. The structural components, including the furnace chamber, steam drum, and supporting frame, were constructed from steel materials and assembled using cutting, welding, and mechanical fastening techniques. The riser tubes were installed within the furnace chamber to maximize heat transfer from the combustion gases. After assembly, the system components were inspected to ensure proper alignment, sealing, and structural stability.

2.6 Instrumentation and Control System

A control system was incorporated into the steam generation unit to monitor operating conditions and enhance safety. Temperature measurements were obtained using a K-type thermocouple connected to a MAX6675 sensor module, which provides digital temperature readings. The MQ-135 gas sensor was used to monitor emissions generated during biomass combustion, allowing evaluation of the environmental performance of the system. Electrical switching and control of system components were achieved using an SRD-12VDC-SL-C relay module integrated into the monitoring circuit. The instrumentation system enables real-time monitoring of key operating parameters, ensuring stable and safe operation of the biomass-powered steam generation system during fruit preservation.

3.0 Results and Discussion

3.1 Design, Fabrication, and Assembly of the Steam Boiler Unit

The steam boiler was successfully designed and fabricated as a natural circulation, water-tube steam-generating system suitable for fruit preservation applications. The fabricated unit (as shown in Figure 2) consists of a cylindrical steam drum, downcomer, riser tubes, furnace chamber, and superheater section. Table 1 summarizes the key design and fabricated dimensions. The deviation between design and fabricated dimensions was within ±3%, indicating good fabrication accuracy and validating the adopted design methodology. Figure 1 illustrates a 3D view of the steam boiler unit and provides the parts inventory.

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Table 1: Key design and fabricated dimensions of steam generating system

Parameter	Design Value	Fabricated Value
Steam drum height	0.95 m	0.93 m
Steam drum diameter	0.45 m	0.44 m
Furnace height	0.80 m	0.82 m
Furnace volume	0.13 m^3	0.135 m^3
Riser tube outer diameter	32 mm	32 mm
Riser tube length	0.75 m	0.74 m
Wall thickness	3 mm	3 mm

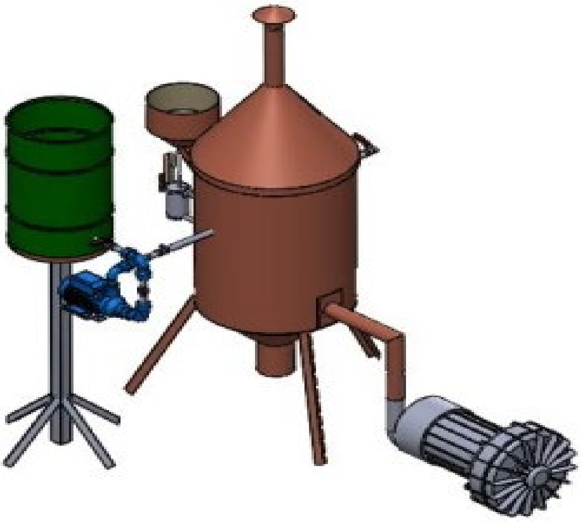

Figure 1: A 3D view of the steam boiler unit

The manufacturing processes involved in the fabrication of the boiler components in order to achieve the required geometry and tolerances were cutting, bending, rolling, and welding processes. Welding was the primary method for assembling the boiler, with specialized techniques such as TIG welding used for high-temperature components like the superheater (Ogbonna et al., 2019).

Figure 2: The fabricated steam generation system

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A dye-penetrant inspection was used to ensure the structural integrity of welded joints and critical components. The ash exhaust was incorporated with the boiler to facilitate the removal of residual ash produced from the burning chamber, maintaining combustion efficiency. The chimney was designed to safely carry combustion gases and smoke away from the burning chamber to the atmosphere.

The fabricated steam generator was evaluated under controlled operating conditions to determine its efficiency and suitability for mango preservation. Based on the operational parameters, the following performance indicators were considered: steam temperature, steam flow rate, thermal efficiency, and energy consumption. For optimal fruit preservation, a steam temperature of 95–100 °C, a flow rate of 2–3 kg/h, and a thermal efficiency of 65–70 % were targeted. These values were determined considering the heat requirement for effective microbial inactivation and moisture retention in mangoes, without causing thermal damage. Experimental results showed that the steam generator achieved a mean steam temperature of 97 °C, which aligns closely with the recommended range for hot steam treatment of tropical fruits (Jacobi et al., 2001). The average steam flow rate was 2.5 kg/h, ensuring uniform steam distribution within the preservation chamber. The measured thermal efficiency was 67 %, which indicates that the system effectively converted thermal energy from fuel combustion into useful steam energy, minimizing losses. Energy consumption for continuous operation over a 4-hour preservation cycle was recorded at 3.2 kWh, which is competitive with similar biomass-based steam systems (Angasu et al., 2014; Leneveu-Jenvrin et al., 2021).

The performance metrics demonstrate that the fabricated system is capable of producing consistent and sufficient steam for fruit preservation, with efficiency values comparable to or exceeding those reported in previous studies. For instance, Liu et al. (2022) reported a thermal efficiency of 60–65 % for a small-scale biomass steam generator used for fruit dehydration, while Angasu et al. (2014) observed efficiencies of 55–68 % in hot steam treatment of mangoes.

The fabricated system demonstrates potential for small-scale commercial and household mango preservation, with operational parameters that are practical and energy-efficient. Its performance metrics indicate suitability for other tropical fruits with similar thermal sensitivity. Compared to conventional hot water or chemical treatments, the system offers advantages in terms of reduced water usage, improved energy efficiency, and minimal post-treatment weight loss, supporting sustainable post-harvest management.

With rapid advancements in sensor technology and automation, future developments in steam preservation systems are expected to enhance efficiency and scalability. Integrating artificial intelligence (AI) with automated steam generation systems can improve real-time monitoring and predictive maintenance. Additionally, recent innovations in energy-efficient steam boilers, as explored by Liu et al. (2022), indicate that modern steam generation systems can significantly reduce fuel consumption while maintaining high preservation standards.

4.0 Conclusions

This research successfully designed, fabricated, and evaluated a small-scale steam-generating boiler intended for fruit preservation applications. The boiler was developed using a natural circulation, water-tube configuration, which ensured stable operation, compact size, and ease of integration into agro-processing environments. Fabrication outcomes closely matched the design specifications, with dimensional deviations within ±3%, confirming the reliability of the adopted design and manufacturing approach. The measured thermal efficiency was 67 %, which indicates that the system effectively converted thermal energy from fuel combustion into useful steam energy, minimizing losses. The use of locally available materials and straightforward fabrication techniques enhances the economic feasibility and promotes local manufacturing capacity, particularly in developing agro-industrial contexts. Overall, the developed steam boiler provides a technically viable, energy-efficient, and cost-effective solution for small and medium-scale fruit preservation systems. Future work should focus on detailed emission analysis, long-term durability assessment, and optimization of fuel–air mixing to further improve efficiency and environmental performance.

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