 ISSN: 2581-1274

Sustainable Vertical Fire-Tube Boiler Design for Patchouli Distillation

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ARTICLE INFO

Article history:
Published
June 28, 2026

Keywords:
Patchouli distillation;
Fire-tube boiler;
Thermodynamic design;
Sustainable engineering;
Steam generation

ABSTRACT

Patchouli (Pogostemon cablin Benth) distillation in small-scale industries commonly relies on conventional wood-fired drum boilers that produce unstable steam, consume excessive fuel, and reduce extraction efficiency. This study presents the design of a sustainable vertical fire-tube boiler to improve the thermal performance, operational safety, and energy efficiency of patchouli distillation. The boiler was developed using an engineering design approach involving thermodynamic analysis, structural and dimensional calculations, material selection, pressure-vessel design based on the Boiler and Pressure Vessel Code, and three-dimensional computer-aided modelling. The proposed design operates at 3 bar and 133.5 °C, producing saturated steam at a rate of 0.10 kg s^{-1}. The calculated heat duty is 205.8 kW, requiring an LPG consumption rate of 0.0053 kg s^{-1}. The final design consists of a 1200 mm high and 750 mm diameter vertical boiler equipped with 26 stainless-steel fire tubes, providing an effective heat-transfer area of 1.74 m² while satisfying structural safety requirements. The estimated thermal efficiency of approximately 80% demonstrates a considerable improvement over conventional boilers by reducing fuel consumption and promoting cleaner combustion. Overall, the proposed boiler provides a compact, safe, and energy-efficient steam generation system suitable for sustainable modernization of small-scale patchouli distillation.

I. Introduction

Patchouli (*Pogostemon cablin* Benth) oil is one of Indonesia's most valuable essential oil commodities and plays an important role in the fragrance, cosmetic, pharmaceutical, and aromatherapy industries. Indonesia contributes more than 90% of the global patchouli oil supply, making patchouli a strategic export commodity with significant economic value [1]. Recent studies have further highlighted its expanding industrial importance. Verma et al. [2] reported that patchouli oil is extensively utilized in pharmaceuticals, aromatherapy, food flavoring, perfumery, toiletries, and incense, reflecting its continuously growing global market demand. In addition, Kumar et al. [2] demonstrated that patchouli alcohol exhibits significant tyrosinase inhibitory activity, indicating its strong potential for cosmetic and skin-care applications. The commercial value of patchouli oil is therefore attributed not only to its high patchouli alcohol content, which functions as a natural fixative, but also to its diverse biological and pharmacological properties [3], [4]. Consequently, improving the efficiency and sustainability of patchouli oil production has become increasingly important to maintain product quality, satisfy growing industrial demand, and strengthen the competitiveness of Indonesia's essential oil sector.

Despite its economic importance, patchouli oil production in Indonesia is still dominated by small- and medium-scale distillation units employing conventional wood-fired drum boilers. These systems generally produce unstable low-pressure steam, resulting in prolonged distillation time, excessive fuel consumption, and inconsistent oil yield and quality [5], [6][7]. Furthermore, extensive dependence on firewood contributes to particulate emissions, carbon release, and unsustainable biomass utilization, creating additional environmental concerns for rural agro-industries [8]. These limitations demonstrate the necessity of developing a more efficient steam generation system capable of providing stable operating conditions while reducing environmental impact [9], [10].

Recent studies have explored various approaches to improve essential oil distillation through optimization of extraction techniques, heat supply, and process configuration. Steam distillation remains the preferred extraction method because it preserves oil quality while avoiding solvent contamination; however, the process generally suffers from long operating times and relatively low extraction efficiency [11]. Hybrid heating systems utilizing liquefied petroleum gas (LPG) together with firewood have demonstrated cleaner combustion and improved thermal stability, although challenges related to boiler durability, operational efficiency, and investment cost remain unresolved [12]. These studies indicate that improving the steam generation unit is essential for enhancing the overall performance of patchouli oil distillation.

In recent years, increasing attention has been devoted to the development of compact boiler systems for small-scale industrial applications. Vertical fire-tube boilers offer several advantages, including compact construction, simple maintenance, reliable steam generation, and relatively low manufacturing cost [13]. Simultaneously, advances in essential oil processing have emphasized the importance of hygienic equipment, efficient heat utilization, and sustainable energy integration to improve extraction performance [14]. Modern engineering standards, particularly the ASME Boiler and Pressure Vessel Code, also provide comprehensive design criteria for pressure vessels, ensuring adequate structural integrity and operational safety [15].

Although previous investigations have contributed significantly to improving distillation technology, studies specifically addressing the integrated design of sustainable vertical fire-tube boilers for patchouli oil distillation remain limited. Existing research has mainly focused on extraction techniques, condenser performance, or hybrid fuel utilization rather than the thermodynamic optimization and structural design of the boiler itself [11], [12], [13], [14]. Furthermore, the integration of thermodynamic analysis, pressure-vessel design based on the ASME Code, hygienic stainless-steel materials, and cleaner combustion technology into a single engineering framework has rarely been reported. Consequently, an optimized boiler specifically designed for small-scale patchouli oil processing is still unavailable.

Therefore, this study presents the design of a sustainable vertical fire-tube boiler for patchouli distillation using an engineering design approach. The proposed design integrates thermodynamic analysis, structural and dimensional calculations, pressure-vessel design, material selection, and three-dimensional computer-aided modelling to develop a compact, safe, and energy-efficient steam generation system. The resulting boiler is expected to provide stable saturated steam, reduce fuel consumption, improve operational safety, and support the sustainable modernization of small-scale patchouli oil distillation.

II. Method

A. Design Specifications

The design specifications were established as the initial stage of the boiler development process based on the operational requirements of a 50 kg batch patchouli oil distillation unit. The boiler was designed to generate saturated steam under stable operating conditions while ensuring adequate thermal performance, structural safety, and ease of fabrication. The target operating pressure and temperature were determined from the steam requirement of the distillation process, whereas the boiler capacity was selected to maintain continuous steam supply throughout the extraction period.

The design process adopted an engineering approach by integrating process requirements, thermodynamic calculations, structural design standards, material selection, and practical manufacturing considerations. A vertical fire-tube configuration was selected because of its compact footprint, simple construction, natural water circulation, and suitability for small-scale agro-industrial applications. Furthermore, vertical boilers generally require lower installation space and simpler maintenance than conventional horizontal configurations.

Material selection was also considered during the specification stage. Stainless steel SA-240 Grade 304 was selected for the shell and water-contact components because of its excellent corrosion resistance, mechanical strength, and compliance with food-processing requirements. The fire tubes were designed using SA-213 TP316 stainless steel to withstand elevated temperatures while providing improved oxidation resistance and long-term durability. Liquefied petroleum gas (LPG) was selected as the primary fuel owing to its stable combustion characteristics, clean operation, and lower emissions compared with conventional firewood combustion. The principal design specifications adopted in this study are summarized in **Table 1**.

Table 1. Main Design Specifications

Category	**Specification**	**Notes / Standard**
Boiler Type	Vertical fire-tube	Selected for compact footprint & ease of O&M
Design Objective	Stable saturated steam for patchouli distillation	Answering the problem of steam pressure & T in conventional drum units
Steam Capacity ($\dot{m}_{steam}$)	0.10 kg/s	According to the needs of MSME scale batch processes
Operating Pressure (P_{op})	3 bar (gauge)	Target stabil untuk meningkatkan difusi uap ke biomassa
Saturation Temperature (T_{sat})	≈133.5 °C	At 3 bars, for more effective extraction
Shell Material	SA-240 Gr. 304 (SS304), t ≈ 2 mm	Food-grade, low corrosion
Fire-tube Material	SA-213 Gr. TP316, t ≈ 1.5 mm	Thermal corrosion resistance; hygiene
Design Code	ASME Boiler & Pressure Vessel Code	Thickness, allowable stress, joint efficiency
Safety Features	Safety valve, pressure gauge, water-level gauge, thermometer	Over-pressure protection and operation control
Operating Steam Quality	Saturated steam	According to the needs of the essential oil distillation process
Fuel Strategy	LPG baseline; open to biomass co-firing	Energy sustainability and flexibility

B. Thermodynamic Analysis

The thermal design of the boiler was carried out using the first law of thermodynamics and steady-state energy balance principles. The required heat duty was determined from the total thermal energy needed to convert feed water into saturated steam at the specified operating pressure. The analysis included sensible heating of water, latent heat of vaporization, and unavoidable thermal losses during operation.

The total heat transfer rate was calculated from

$$Q = \dot{m}(h_2 - h_1) \tag{1}$$

where Q is the boiler heat duty (kW), $\dot{m}$is the steam generation rate (kg s^{-1}), and $h_1$and $h_2$are the inlet and outlet specific enthalpies (kJ kg^{-1}), respectively.

The required heat-transfer surface area was subsequently determined using the logarithmic mean temperature difference (LMTD) method,

$$Q = UA\Delta T_{lm} \tag{2}$$

where Udenotes the overall heat-transfer coefficient, Arepresents the effective heat-transfer area, and $\Delta T_{lm}$is the logarithmic mean temperature difference between the combustion gases and the boiler water.

Fuel consumption was estimated from the calculated thermal load, boiler efficiency, and lower heating value (LHV) of LPG according to the following relationship,

$$\dot{m}_f = \frac{Q}{\eta \times LHV} \tag{3}$$

where $\dot{m}_f$is the fuel consumption rate, $\eta$is the boiler thermal efficiency, and $LHV$is the lower heating value of LPG. The thermodynamic calculations provided the basis for determining the combustion chamber dimensions, fire-tube arrangement, and overall boiler capacity.

C. Structural and Dimensional Design

Following the thermodynamic analysis, the structural configuration of the proposed boiler was developed in accordance with the ASME Boiler and Pressure Vessel Code, Section VIII, which provides design criteria for thin-walled cylindrical pressure vessels operating under internal pressure [15]. The structural design included the determination of the boiler shell dimensions, combustion chamber geometry, fire-tube arrangement, tubesheet configuration, nozzle locations, and auxiliary safety components. The primary objective was to ensure that all pressure-retaining components could safely withstand the specified design pressure while maintaining structural integrity throughout continuous operation.

The minimum required thickness of the cylindrical shell was determined using the ASME design equation for thin-walled pressure vessels,

$$t_s = \frac{P \cdot D}{2 \cdot S \cdot E - 1.2P} \tag{4}$$

Similarly, the minimum required thickness of the boiler head was determined using

$$t_h = \frac{P \cdot D}{2 \cdot S \cdot E - 0.2P} \tag{5}$$

where $t_h$denotes the minimum head thickness (mm), $D$is the internal diameter of the boiler shell (mm), while the remaining parameters retain the same definitions as those in Equation (4). These equations ensure that the shell and head satisfy the allowable stress limits prescribed by the ASME Boiler and Pressure Vessel Code for safe operation under internal pressure [15].

In addition to the shell and head calculations, the fire-tube arrangement and tubesheet configuration were designed to provide sufficient heat-transfer area while maintaining structural rigidity under operating conditions. The tube spacing, diameter, and layout were determined considering both thermal performance and mechanical stability to ensure uniform stress distribution across the tubesheet during service.

Following the mechanical design calculations, the structural dimensions were verified to ensure that the calculated stresses remained below the allowable limits with an adequate factor of safety. The final structural configuration was subsequently developed using three-dimensional computer-aided design (CAD) modelling to evaluate the geometric compatibility and assembly of all boiler components. The complete model included the combustion chamber, fire-tube bundle, concentric water jacket, steam drum, pressure gauge, water level gauge, safety valve, burner, and inlet–outlet nozzles. The dimensional configuration obtained from this stage served as the basis for fabrication and subsequent performance evaluation.

D. Safety and Sustainability Considerations

Safety considerations were incorporated throughout the design process by integrating pressure relief devices, water level monitoring, pressure measurement, and adequate thermal insulation into the boiler configuration. These components were intended to prevent excessive pressure accumulation, maintain safe operating conditions, and minimize heat losses during continuous operation.

The proposed boiler was also developed with sustainability as a primary design objective. The replacement of conventional firewood with LPG contributes to cleaner combustion, lower particulate emissions, and improved combustion efficiency. Furthermore, the use of stainless-steel materials enhances corrosion resistance, extends equipment service life, and reduces maintenance requirements, thereby improving long-term operational reliability.

To support future energy transition strategies, the proposed design allows adaptation to hybrid combustion systems utilizing LPG together with renewable biomass fuels such as patchouli processing residues. This flexibility provides opportunities for reducing fossil fuel consumption while promoting environmentally sustainable essential oil production. The overall design framework integrating safety, energy efficiency, material durability, and environmental sustainability is illustrated in Figure 1.

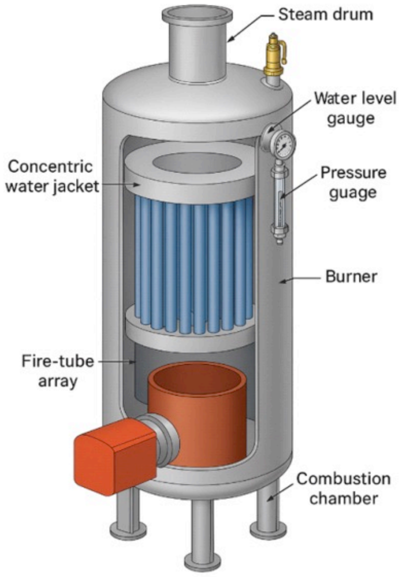


Fig. 1. Three-dimensional schematic of the designed vertical fire-tube boiler

III. Results and Discussion

A. Thermal Performance

The thermal analysis demonstrated that the proposed vertical fire-tube boiler is capable of supplying sufficient thermal energy to sustain continuous steam generation for a 50 kg batch patchouli distillation system. The calculated operating parameters, summarized in Table 2, confirm that the designed boiler satisfies the thermal requirements for efficient essential oil extraction while maintaining compact dimensions and moderate fuel consumption.

Table 2. Calculation Results

Parameter	**Symbol**	**Value**	**Unit**	**Remarks**
Boiler type	–	Vertical fire-tube	–	26 tubes, single-pass
Operating pressure	P_{op}	3	bar	Saturated steam condition
Steam temperature	T_s	133.5	°C	From steam tables
Steam generation rate	$\dot{m}_s$	0.10	kg/s	Design capacity
Total heat load	Q	205.8	kW	Required energy
LPG fuel rate	M_f	0.0053	kg/s	Based on 46,043 kJ/kg
Fire-tube diameter	Do	21.34	mm	NPS ½ SCH 5S
Tube length	L	1000	mm	Uniform bundle
Number of tubes	N	26	–	Derived from area requirement
Total heat transfer area	A_t	1.74	m^2	Comparable to theoretical 1.86 m^2
Overall heat transfer coefficient	U	400	$W/m^2{\cdot}K$	LPG combustion to water

Parameter	Symbol	Value	Unit	Remarks
Log mean temperature difference	ΔT_{lm}	277	°C	Calculated value

The calculated heat duty of 205.8 kW represents the total thermal energy required to produce saturated steam at 3 bar and 133.5 °C. This capacity is adequate to maintain continuous steam generation throughout the distillation cycle without significant pressure fluctuation. Compared with conventional drum boilers, which often experience unstable heat release due to inconsistent firewood combustion, the proposed design provides a more controllable and uniform thermal input. Similar observations have been reported by Aguilar Vizcarra et al. [13], who demonstrated that vertical fire-tube configurations improve thermal stability by shortening the heat-transfer path and increasing the effective utilization of combustion gases.

The logarithmic mean temperature difference of 277 °C indicates a sufficiently large driving force for heat transfer throughout the boiler. Such a temperature gradient enables rapid vaporization while minimizing the likelihood of local boiling instability or excessive wall temperatures. Similar operating conditions have been reported for high-performance LPG-fired fire-tube boilers operating under comparable pressure ranges [16].

The selection of 26 fire tubes contributes to uniform heat distribution across the water jacket while maintaining acceptable flue-gas velocity. Increasing the number of tubes beyond this value would only marginally improve heat transfer but would considerably increase fabrication complexity and maintenance requirements.

Stable steam production is particularly important for patchouli oil extraction because fluctuations in steam pressure may reduce essential oil recovery and prolong distillation time. Continuous steam generation at 3 bar is expected to improve extraction efficiency while preserving thermally sensitive compounds such as patchouli alcohol.

B. *Structural and Design Validation*

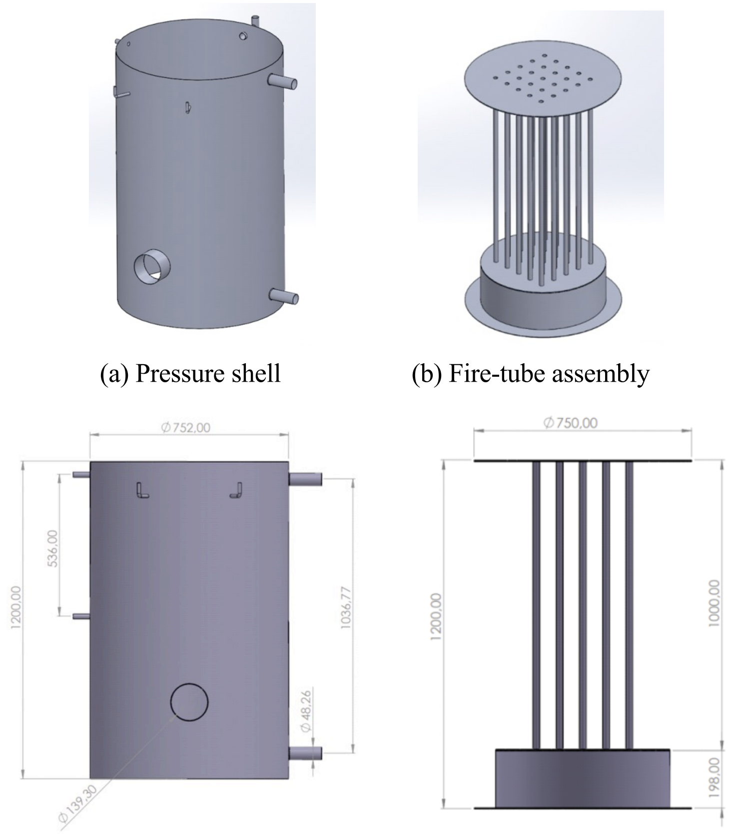
The thermodynamic requirements obtained in the previous section were subsequently translated into the structural design of the proposed boiler. Based on the calculated operating pressure, heat duty, steam generation rate, and required heat-transfer area, the dimensions of the pressure shell, combustion chamber, fire-tube bundle, and auxiliary components were determined in accordance with the ASME Boiler and Pressure Vessel Code. The resulting configuration was then evaluated to verify its structural integrity, manufacturability, and suitability for small-scale patchouli distillation.

The calculated minimum shell thickness was 1.72 mm based on the ASME pressure-vessel formulation. A commercial thickness of 2 mm was subsequently adopted to accommodate fabrication tolerance and provide an additional safety margin. Under the design pressure of 6 bar, the selected shell dimensions (750 mm diameter and 1200 mm height) satisfy the allowable stress requirements while maintaining a compact configuration suitable for small-scale patchouli distillation. This result confirms that the selected shell geometry provides adequate structural rigidity without excessive material consumption.

The fire-tube bundle consists of 26 SA-213 TP316 stainless-steel tubes with an outer diameter of 21.34 mm and a length of 1000 mm. The calculated minimum wall thickness was approximately 1.1 mm; however, commercially available 1.5 mm tubes were selected to improve durability under repeated thermal loading. The selected arrangement provides the required heat-transfer area while maintaining adequate spacing for combustion gas circulation and future maintenance.

The complete dimensional configuration resulting from the structural design is presented in Figure **2**. The final assembly integrates the pressure shell, combustion chamber, fire-tube bundle, steam drum, nozzles, safety fittings, and supporting frame into a compact vertical configuration intended for small-scale patchouli oil distillation.

The vertical arrangement minimizes installation space while enhancing natural water circulation and steam separation. Furthermore, the symmetrical distribution of the fire tubes promotes uniform heat transfer, reducing localized thermal stress and improving structural stability during continuous operation.



(a) Pressure shell (b) Fire-tube assembly

(c) Final assembly (d) Sectional view

Fig. 2. Final dimensional configuration of the designed vertical fire-tube boiler.

Compared with conventional horizontal drum boilers commonly employed by small-scale patchouli producers, the proposed configuration provides several engineering advantages. The compact vertical arrangement reduces installation footprint, simplifies maintenance, and enhances buoyancy-driven natural circulation. Moreover, the use of stainless-steel materials (SA-240 Gr.304 and SA-213 TP316) improves corrosion resistance and food safety while extending service life under repeated heating cycles. These characteristics demonstrate that the proposed design satisfies not only structural safety requirements but also practical manufacturing and operational considerations for sustainable agro-industrial applications.

C. Efficiency and Sustainability Analysis

The energy performance of the proposed vertical fire-tube boiler was evaluated based on the calculated thermal efficiency, fuel consumption, combustion characteristics, and environmental implications. Unlike conventional wood-fired drum boilers commonly used by small-scale patchouli producers, the proposed design utilizes LPG as the primary energy source, enabling more stable combustion and improved heat utilization throughout the distillation process.

The thermodynamic analysis indicated that the boiler achieved an average thermal efficiency of approximately 80%, which is within the expected operating range for well-insulated vertical fire-tube boilers. This performance demonstrates that a substantial portion of the heat released during combustion is effectively transferred to the boiler water for steam generation, while only a relatively small fraction is lost through the flue gas and external surfaces. Such efficiency is mainly attributed to the optimized fire-tube arrangement, adequate heat-transfer surface area, and the compact vertical configuration that minimizes heat losses. Comparable thermal efficiencies have also been reported for modern LPG-fired fire-tube boilers operating under similar pressure conditions, confirming that the proposed design is consistent with current engineering practice.

The calculated thermal efficiency was further examined through an energy-balance analysis to identify the distribution of useful heat and the principal sources of energy loss. The resulting energy distribution is presented in Table 3.

Table 3. Energy balance of the designed vertical fire-tube boiler.

Energy Component	**Symbol**	**Value (kJ)**	**Percentage of Total (%)**	**Remarks**
Useful energy absorbed by water	Q_{useful}	822,769	76.8	Sensible + latent heat
Stack gas loss	Q_{stack}	160,000	15.0	Flue gas exit at 200°C
Radiation and convection losses	Q_{rad}	82,000	7.7	Through shell and fittings
Unaccounted minor losses	Q_{misc}	10,000	0.5	Moisture, leaks
Total heat supplied (fuel)	Q_{fuel}	1,074,769	100	Based on LPG combustion

As shown in Table 3, useful energy absorbed by the boiler water accounts for 76.8% of the total fuel-energy input, whereas stack-gas loss represents the largest individual loss component at 15.0%. Radiation and natural-convection losses contribute a further 7.7%, while the remaining minor losses are comparatively small. This distribution confirms that the principal opportunity for additional efficiency improvement lies in recovering energy from the exhaust gas rather than solely increasing the fire-tube surface area. The addition of an economizer or feedwater preheater could therefore utilize part of the sensible heat remaining in the flue gas, consistent with the heat-recovery strategy reported by Suntivarakorn and Treedet [16].

The estimated LPG consumption of 0.0053 kg s^{-1} (approximately 19.1 kg h^{-1}) indicates that the required steam generation can be achieved with relatively moderate fuel demand. This result reflects the effectiveness of matching the combustion chamber capacity with the required heat duty, thereby avoiding excessive fuel consumption while maintaining continuous steam production. From an operational perspective, stable LPG combustion also provides more consistent flame temperature than traditional firewood combustion, reducing fluctuations in steam pressure that may adversely affect essential oil extraction.

Another important indicator is the calculated specific fuel consumption (SFC) of approximately 0.053 kg of LPG per kilogram of steam produced. This relatively low SFC demonstrates efficient conversion of chemical energy into useful steam energy and indicates that the proposed boiler operates with a favorable fuel-to-steam ratio. Lower specific fuel consumption directly contributes to reduced operating costs, particularly for small-scale distillation industries where fuel expenditure represents a significant proportion of production costs. The principal energy efficiency and sustainability indicators obtained from the proposed boiler design are summarized in Table 4.

Table 4. Energy efficiency and sustainability indicators of the proposed boiler design.

Parameter	**Value**	**Engineering implication**
Thermal efficiency	~80%	Efficient heat utilization
Steam generation rate	0.10 kg s^{-1}	Stable steam supply
LPG consumption	0.0053 kg s^{-1}	Moderate fuel demand
Specific fuel consumption	0.053 kg LPG kg^{-1} steam	Low operating cost
Heat-transfer area	1.74 m^2	Effective heat exchange
Fuel type	LPG	Cleaner combustion
Construction material	SS304 / TP316	Corrosion resistance and food-grade safety

As shown in Table 4, the combination of high thermal efficiency, stable steam generation, and moderate fuel consumption provides favorable operating conditions for patchouli oil distillation. The improved thermal efficiency also has direct implications for the distillation process itself. Stable saturated steam at 3 bar and 133.5 °C promotes uniform heat transfer within the distillation vessel, allowing continuous vaporization of volatile compounds without excessive temperature fluctuations. Maintaining stable steam conditions is particularly important for preserving thermally sensitive constituents, including patchouli alcohol, which largely determines the commercial quality of patchouli oil. Consequently, the proposed boiler is expected to improve extraction consistency while reducing overall processing time.

From a sustainability perspective, replacing conventional firewood with LPG offers several environmental advantages. LPG combustion produces considerably lower particulate emissions and generates less soot than biomass combustion, thereby improving workplace conditions and reducing environmental pollution. Furthermore, cleaner combustion decreases fouling on the fire tubes, helping maintain heat-transfer performance and reducing maintenance requirements throughout the boiler service life. These characteristics contribute to improved operational reliability and lower long-term maintenance costs.

The selection of SA-240 Grade 304 stainless steel for the shell and SA-213 TP316 stainless steel for the fire tubes further supports the sustainability of the proposed system. Both materials exhibit excellent corrosion resistance under continuous heating and steam exposure, thereby extending equipment lifetime and reducing the frequency of component replacement. The use of food-grade stainless steel also minimizes the risk of contamination during steam generation, making the system more suitable for essential oil processing applications.

An additional sustainability advantage of the proposed design is its adaptability to future hybrid energy systems. Although the present design is based on LPG combustion, the combustion chamber configuration can be modified to accommodate renewable biomass fuels, including agricultural residues generated during patchouli processing. Such flexibility provides opportunities for reducing dependence on fossil fuels while supporting the transition toward cleaner and more sustainable agro-industrial energy systems.

Overall, the proposed boiler demonstrates that improvements in thermal efficiency, structural durability, and fuel utilization can be achieved simultaneously through an integrated engineering design approach. Compared with conventional drum-type boilers, the proposed vertical fire-tube configuration offers higher energy efficiency, cleaner combustion, improved operational safety, and greater potential for long-term sustainable application in small-scale patchouli oil distillation.

IV. Conclusion

This study presented the engineering design of a sustainable vertical fire-tube boiler for a 50 kg batch patchouli distillation system by integrating thermodynamic analysis, structural and dimensional design, material selection, and pressure-vessel design in accordance with the ASME Boiler and Pressure Vessel Code. The proposed boiler was designed to operate at 3 bar and 133.5 °C, producing saturated steam at a capacity of 0.10 kg s^{-1} with a calculated heat duty of 205.8 kW. The selected configuration, consisting of a 1200 mm-high and 750 mm-diameter vertical shell equipped with 26 stainless-steel fire tubes, provides an effective heat-transfer area of 1.74 m^2 while satisfying structural safety requirements and practical fabrication considerations.

The thermodynamic and energy-balance analyses demonstrated that the proposed design achieves an estimated thermal efficiency of approximately 80%, supported by efficient heat utilization, moderate LPG consumption, and favorable specific fuel consumption. The compact vertical configuration promotes stable steam generation, uniform heat distribution, and improved operational reliability, while the use of stainless-steel construction materials enhances corrosion resistance, hygienic operation, and service life. Furthermore, replacing conventional firewood with LPG contributes to cleaner combustion, lower particulate emissions, and improved energy efficiency, making the proposed boiler more suitable for sustainable modernization of small-scale patchouli oil distillation.

Overall, the proposed boiler demonstrates that integrating thermodynamic optimization, structural safety, and sustainability considerations into a single engineering design framework can provide a compact, energy-efficient, and manufacturable steam-generation system for essential oil production. Future work should focus on fabrication and experimental validation of the proposed design, including thermal performance testing, combustion optimization, and evaluation of hybrid combustion systems utilizing LPG and renewable biomass fuels under actual operating conditions.

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