Design and Development of an Energy-Efficient Suki Sauce Stirrer: a Novel Concept Study

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Abstract. This study presents the design and evaluation of an energy-efficient sukiyaki sauce stirrer incorporating thermosyphon technology to reduce both heating time and fuel consumption. The conventional method requires continuous stirring for 180 minutes to reach the target temperature of 85˚C, consuming approximately 3.5 kg of LPG. To address this inefficiency, a novel thermosyphon system was developed and integrated into the stirrer pot. The apparatus comprises twelve AISI 304 stainless steel thermosyphon tubes (25.4 mm OD, 54.5 cm length) mounted on a custom-built structure. Water was used as the working fluid, filled to 50% of the evaporator volume to facilitate effective heat transfer via phase change. Experimental testing, using a mixture of water and granulated sugar to simulate sukiyaki sauce, demonstrated that the target temperature was achieved in 80 minutes, reducing heating time by over 50% and saving 0.84 kg of LPG. The findings confirm that thermosyphon-assisted heat transfer, combined with active stirring, significantly enhances thermal efficiency and shortens the processing time. Notably, microbial testing conducted in accordance with the Ministry of Public Health's standards revealed no contamination during production. This approach offers a promising, energy-conserving solution for food preparation processes, particularly in small scale or individually operated cooking applications.

1 Introduction

FOOD DE MAGICAL CO., LTD operates The Rock Shabu restaurant chain, specialising in grilling and shabu set meals. Its product range includes fresh ingredients such as meats, vegetables, and fruits, as well as processed items like black shabu soup and sukiyaki dipping sauce. As part of its commitment to continuos innovation and quality enhancement, the company participated in the Pre-Talent Mobility Project at King Mongkut's University of Technology North Bangkok (KMUTNB). The project aimed to improve production processes, extend the shelf life of sukiyaki dipping sauce, and elevate overall product standards. The company has been certified with Primary GMP (Good Manufacturing Practice) by the Ministry of Public Health, authorising the production of sukiyaki dipping sauce, soup bases, and a variety of sauces. Its prototype sukiyaki dipping sauce has also received FDA approval for commercial distribution.

In response to the expansion of its restaurant branches and ongoing business negotiations both domestically and internationally, the company is preparing to increase its production capacity. However, the existing sukiyaki sauce production method remains highly labour-intensive, relying on manual stirring in a single-layer stainless steel pot heated by an LPG gas stove. This method lacks precise control over stirring speed, exposes workers to excessive heat and physical strain, and often results in inconsistent stirring, leading to sauce burning, production losses, and quality fluctuations. To overcome these limitations, the company has proposed the development of an advanced sukiyaki sauce stirring system. The improved design will feature a double-layered pot to prevent the thick and viscous sauce from burning; a thermosyphon unit to enhance energy efficiency; and specially designed stirring blades powered by a regulated drive system.

The upgraded system will also incorporate controls for adjusting stirring speed and duration, a real-time display of sterilisation temperatures, and integrated process monitoring; however, these features are not discussed in detail within this paper. These enhancements aim to boost production capacity, ensure product uniformity, reduce waste and processing time, and lower both labour and energy costs.

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Figure 1 illustrates a two-phase closed thermosyphon (TPCT), which is a type of wickless heat pipe that facilitates heat transfer through evaporation and condensation processes. Unlike conventional heat pipes, which depend on capillary action to return condensate, the TPCT employs gravitational force for liquid return. In this system, the evaporator is strategically placed at the lowest point, allowing gravity to effectively assist in circulating the working fluid. TPCTs are known for their straightforward design, low thermal resistance, high thermal performance, and economical manufacturing. These attributes have led to their widespread adoption in multiple applications, such as waste heat recovery, electronic cooling, turbine blade temperature control, and solar thermal systems [1-3].

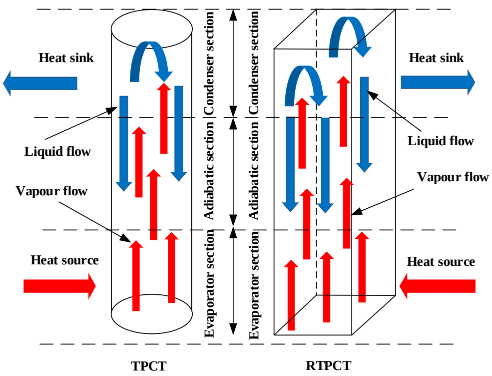

Fig. 1. Structure and functional concept of a TPCT system [1].

Nevertheless, additional investigation is necessary to thoroughly evaluate the feasibility and applicability of these approaches within real-world engineering contexts. This study focuses on the development of an energy-efficient sukiyaki sauce stirrer, introducing a novel TPCT-based design [4]. This system incorporates a uniquely engineered TPCT that relies solely on water as the working fluid to transport heat from the evaporator to the condenser, eliminating the need for any external power input. The primary objective is to evaluate the system's effectiveness and its ability to maintain optimal temperature regulation during the sauce preparation process.

2 Development Concept and Experimental Configuration

2.1 Design of Thermosyphon System and Stirring Device

The thermosyphon kit used in this study, developed in accordance with ESDU 80013 [5] , has a total length of 545 mm, comprising both the evaporator and condenser sections. An adiabatic section was omitted, as the design is tailored to align with the optimised tank length for this specific application. The thermosyphon is constructed from AISI 304 stainless steel tubing with an internal diameter of 25.4 mm. A total of twelve tubes are employed, with deionised (DI) water serving as the working fluid. The thermosyphons are evenly distributed along the inner circumference of the pot, with a center-to-center distance of 10 cm. The pot is constructed from AISI 304 stainless steel, with an internal diameter of 650 mm, an external diameter of 680 mm, and a height of 800 mm, resulting in a total volume of 100 liters.

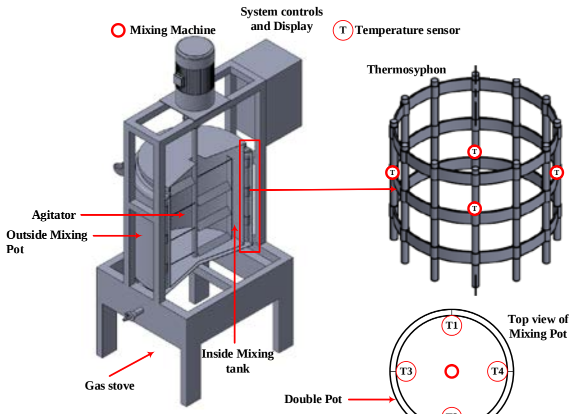

Fig. **2**. Process and experimental setup.

Figure 2 shows the positioning of the experimental setup adjacent to the suki sauce stirrer machine. For each trial, 100 litres of Suki Sauce were used in the mixing process. The system schematic shown in Figure 2 includes a gas stove (LPG) heater as the primary heat source. To monitor thermal performance, seven type-K thermocouples (± 0.1°C accuracy) were installed and connected to a Yokogawa DX200 data acquisition system, which supports up to 20 input channels and measures temperatures ranging from −200°C to 1100°C. The thermocouples were strategically positioned throughout the system to capture the temperature distribution and facilitate effective process control and display.

The heat transfer rate Q_{Pot} and heat flux q_{Pot} at the evaporator section of the TPCT can be determined using Equations (1) and (2), respectively [3, 4], [6]:

$$Q_{POT} = m_{LPG} LHV_{LPG} \left(T_{Company} - T_{start} \right) \tag{1}$$

$$q_{Pot} = \frac{Q_{Pot}}{A_{eap,TPCT}} \tag{2}$$

The heat transfer rate of the sukiyaki sauce (SS) within the storage tank was determined at the condenser section, based on Equations (3) and (4) [3, 4], [6]:

$$Q_{SS} = mc_{p,SS} \left(T_{SS,\,final} - T_{SS,\,first} \right) / \, t \tag{3}$$

$$q_{CB} = \frac{Q_{CB}}{A_{CB\ \mathrm{tank}}} \tag{4}$$

The effectiveness (ε) of HE-TPCT was determined by comparing the actual heat flux to the maximum heat flux obtained through TPCT, which can be calculated using equation (5) [3, 4], [6].

$$\varepsilon_{HETPCT} = \frac{Q_{actual}}{Q_{max}} = \frac{Q_{SS}}{C_{\min}(T_e - T_{Pot})} \quad (5)$$

2.2 Design Concept and Thermosyphon Selection

The primary production process employed by the company involves stirring and boiling sukiyaki sauce until it reaches a temperature of 85°C. Once this target temperature is achieved, the sauce is held at boiling for an additional 30 minutes to effectively eliminate pathogens such as Staphylococcus aureus and Salmonella spp. To optimise this process, a thermosyphon system was integrated into the boiling pot, and combined with mechanical stirring., This integration enhances heat transfer efficiency from the bottom to the top of the vessel and improves overall temperature distribution. Upon reaching 85 °C, the thermosyphon assists in maintaining a stable temperature and retaining heat throughout the process. The underlying design concept is shown in Figure 3.

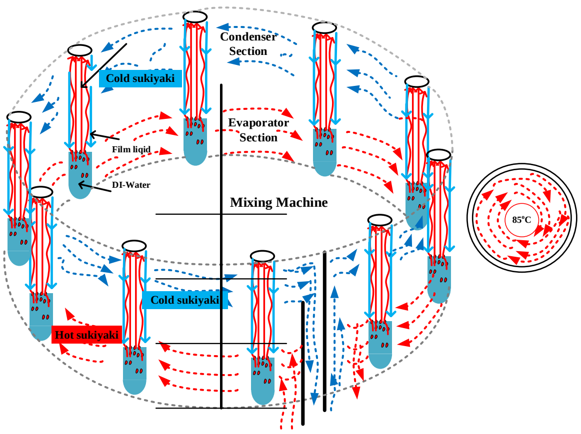

Fig 3. Design Concept and Thermosyphon Selection.

2.3 Microbiological Quality Analysis of the Sukiyaki Sauce Products

Sukiyaki sauce samples were sterilised by heating at 85°C for 30 minutes using a kettle equipped with a thermosyphon to ensure even temperature distribution. Achieving the specified temperature and time parameters during sterilisation is critical for eliminating spoilage microorganisms as well as pathogenic microbes that pose health risks to consumers.

The microbiological quality of the sukiyaki sauce was assessed according to standard analytical methods. This included the determination of total plate count, and the detection of yeasts and moulds using the BAM method (2001) [7], Bacillus cereus (BAM, 2020) [8], Clostridium perfringens (BAM, 2001) [9], Staphylococcus aureus (BAM, 2016) [10], Escherichia coli via the Most Probable Number (MPN) method (BAM, 2020) [11], and Salmonella spp. (BAM, 2022) [12]. These analyses were conducted in accordance with the Community Product Standard TISI 466/2547 for sukiyaki sauce, as well as the Ministry of Public Health Notification No. 201 B.E. 2543 (Under Thailand government) governing specific types of sauces.

3 Results and Discussion

3.1 Investigation into the Reduction of Stirring Time in a Sukiyaki Sauce Pot with and without Thermosyphon Integration

Figure 4 presents the experimental results obtained from trials involving the heating of 100 litres of sukiyaki sauce initially at ambient room temperature. The findings revealed a significant reduction in the time required to reach the target temperature when a thermosyphon was integrated into the system. Without the thermosyphon, the sukiyaki sauce required 100 minutes to reach 88°C. However, when the thermosyphon was employed, the same temperature was achieved in just 80 minutes. This represents a 30-minute reduction in heating time, equivalent to a 20% improvement in thermal response. These results clearly demonstrate that incorporating a thermosyphon into the heating system substantially enhances heat transfer efficiency and significantly reduces overall processing time [13, 14].

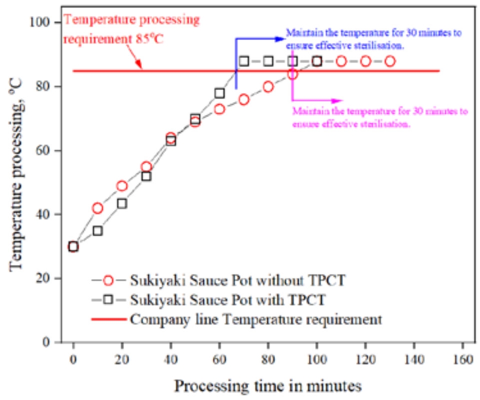

Fig 4. Temperature profiles of sukiyaki sauce with and without TPCT during thermal processing.

3.2 Distribution temperature

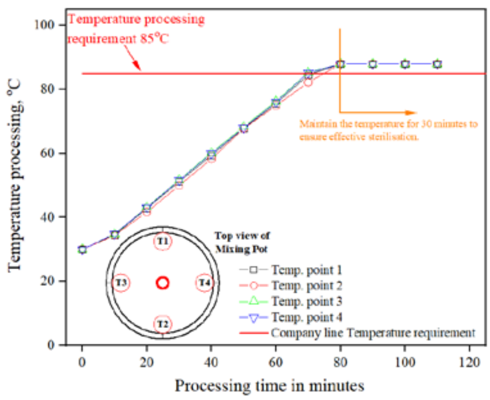

Fig 5. Temperature distribution at four measurement points during the heating of sukiyaki sauce using a TPCT-integrated system.

Figure 5 presents the temperature distribution of a plain water and sukiyaki sauce mixture processed using a system integrated with a thermosyphon. The results demonstrate a high degree of thermal uniformity across all four measurement points. Compared to the vendor's conventional sauce-stirring method, this configuration achieved the target temperature of 85°C more rapidly. During the heating process, the temperature variation at any given time remained within ±5°C. Notably, after 80 minutes, all measurement points consistently exceeded 85°C. These findings support the results shown in Figure 4, confirming that the integration of a thermosyphon, combined with mechanical stirring, substantially enhances heat distribution [13, 15]. This improvement is attributed to the thermosyphon's ability to efficiently transfer heat from the bottom to the top of the vessel, thereby ensuring consistent temperature control and meeting the thermal requirements specified by the company.

3.3 Fuel Consumption and Economic Viability

Table 1. Comparison of fuel consumption during sukiyaki sauce heating with and without thermosyphon integration.

Description of Test	Fuel Consumption (kg)	Fuel Saved (%)
Fuel consumption by vendor during traditional sukiyaki sauce heating	3.5 kg	
Fuel consumption during heating of water mixed with Sukiyaki Sauce and thermosyphon	2.66 kg	24.00%

The data presented in the table 1 indicate that the integration of a thermosyphon into the sukiyaki sauce stirring system led to a notable reduction in fuel consumption. Specifically, fuel usage decreased by 0.84 kilograms per session, representing a 24% reduction. This outcome demonstrates that the thermosyphon, when employed as a heat transfer enhancement device within the sauce pot, effectively contributes to lowering production costs by reducing both heating time and energy consumption [13]. The overall efficiency of the system with the thermosyphon installed was calculated to be 27%.

3.4 Microbiological Quality Analysis of Sukiyaki Sauce Products

Table 2. shows that the sukiyaki sauce sample exhibited a pH value below 4.6, thereby classifying it as a low-acid food in accordance with the Ministry of Public Health Announcement No. 144, B.E. 2535 (Under Thailand government). Microbiological analysis of the product, which was processed using a sukiyaki sauce pot equipped with a thermosyphon system, demonstrated that the total viable microbial count was below 10,000 CFU/g. Yeast and mould counts were less than 10 CFU/g, *Bacillus cereus* and *Clostridium perfringens* were each detected at levels below 10 CFU/g, and *Staphylococcus aureus* did not exceed 100 CFU/g.

Table 2. Microorganism counts detected in sukiyaki sauce samples.

Properties	Quality criteria	Microbial count of the sample
Total plate count (CFU/g)	$<1.0 \times 10^4$	$<1.0 \times 10$
Yeast and Mold (CFU/g)	$<1.0 \times 10^2$	$<1.0 \times 10$
Bacillus cereus (CFU/g)	$<1.0 \times 10^2$	$<1.0 \times 10$
Clostridium perfringens (CFU/g)	$<1.0 \times 10^3$	$<1.0 \times 10$
Staphylococcus aureus (CFU/g)	$<1.0 \times 10^2$	$<1.0 \times 10$
Escherichia coli (MPN/mL)	<3.0	<3.0
Salmonella spp. (in 25 g)	Not Detected	Not Detected

Escherichia coli, determined using the Most Probable Number (MPN) method, was found to be less than 3 MPN/mL, while *Salmonella spp*. were not detected. These findings confirm that the sukiyaki sauce product complies with the microbial quality standards stipulated in the Community Product Standard (TISI 466/2547) for sukiyaki sauce, as well as the Ministry of Public Health Announcement No. 201, B.E. 2543 (Under Thailand government), which governs specific types of sauces.

4 .Conclusion

This project successfully transitioned sukiyaki sauce production from a labour-intensive manual process to a machine-assisted system. This shift has effectively addressed key challenges previously encountered in the manual stirring process, such as the inability to maintain consistent quality, operator fatigue due to high ambient temperatures, and the increasing viscosity of the sauce, which often led to burning and production losses. A double-layered stirring pot was designed and developed to prevent the thick sauce from burning, complemented by the integration of a thermosyphon system to ensure uniform, rapid, and energy-efficient heat distribution. These enhancements have led to notable improvements in product quality, increased production capacity, reduced material waste, minimised production time, operational costs, and labour as well as energy consumption. As a result, the prototype suki sauce stirring machine was produced, yielding standardised products that have achieved FDA registration. The project has also fostered the development of additional products for future expansion and facilitated knowledge transfer through collaborative activities with business and industrial sectors.

The installation of a thermosyphon within a standard packaging stirrer pot often introduces internal obstructions that may compromise the efficiency of

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cooking, stirring, and mixing operations. Moreover, the materials employed in the construction of the thermosyphon may pose a potential risk of food contamination. To mitigate these issues, it is critical to carefully evaluate the thermosyphon's design, fabrication methods, and installation procedures to ensure efficient heat dissipation while maintaining hygienic conditions. The results of this study confirm the feasibility of such an implementation and demonstrate its effectiveness in preserving product cleanliness and minimizing the risk of contamination. Nevertheless, minor limitations persist, particularly concerning the interference observed during product loading and unloading processes, which may necessitate further optimization of the system's spatial configuration.

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