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#5: The effect of materials selection and design features on energy consumption of electric kettles

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Abstract: Sustainable energy technologies and development have attracted the attention of researchers in recent years towards NetZero. Energy poverty and the increase in energy prices in domestic context have attracted the attention to measures that could help save energy and reduce energy bills. Boiling water is a common part of daily life, and the energy consumed can be influenced by the heating process, heat loss and consumer behaviour. This paper focuses on the materials and design features of electric kettles and the energy consumption when boiling water. As in many countries, boiling water is done via electric kettles for convenience. For this study and to examine the effect of kettle selection on energy consumption, three types of kettles are used to test the effect of materials on energy consumption: glass, steel and plastic. Furthermore, the effect of some design features is investigated such as insulation. The study reveals that energy consumption of plastic kettles is lower than the energy consumed by steel and glass kettles. Additionally, other design features, such as insulation, could lead to a lower energy consumption for boiling water. Although the reduction in energy consumed per household per day is relatively small, the accumulated energy savings are still worth paying attention to since kettles are everyday household appliances. In the UK, for example, using energy saving kettles could save about 80 GWh of electricity per annum (assuming only 1 litre of water is boiled every day in each household). This study contributes to making the process of boiling water more sustainable from a consumer perspective. Furthermore, the experimental work offers evidence that with the help of the newly designed and suggested features which include enhanced thermal insulation, boiling water could consume less energy and heated water would maintain relatively higher temperatures for longer periods.

Keywords: Energy; Netzero; Water Kettles; Thermal Conductivity; Sustainable Design; Consumer Behaviour

1. INTRODUCTION

After the tremendous volatility of the global energy crisis in 2023, some of the tensions in the energy markets subsided (IEA, 2023), however, energy poverty and global warming have made sustainable energy technologies still the focus of global research in recent years. As a result of energy poverty, the fluctuation of energy prices exposes households, especially those with lower incomes, to significant risks (Fuerst et al., 2019). Despite the continuous development of new energy technologies, the rises in energy prices are causing financial pressure and driving the need for in-depth investigation into ways to reduce energy consumption. The need to heat, cool, and light residential buildings makes the residential sector use one-fifth of the world's energy (Brounen, 2013). Additionally, the primary drivers of household energy consumption in the UK are cooking and heating (Government Property Agency, 2022). Though kitchen appliance energy efficiency is improving, less attention is given to energy poverty in social dwellings (Foster, 2023). As household appliances, kettles have become popular globally including British and Chinese households. The UK market for electric kettles is anticipated to reach US$139.90 million in sales by 2024; and with a revenue of US$1,183 million, China tops the global comparison (Statista, 2024). Various kettles on the market meet individuals' requirements for appearance and thermal insulation performance, however, most individuals do not understand the impact of different features on power consumption when they try to buy a new kettle or use one.

Therefore, this paper focuses on the material and design features of electric kettles and the energy consumption when boiling water. Glass, steel and plastic kettles are the surface materials of the three kettles used to investigate the relationship between material properties and energy consumption. Additionally, design features of kettles are investigated in an attempt to reduce energy consumption. Although kettles are not high-power appliances, this research is valuable due to kettles widespread appeal and their high frequency of usage. Additionally, researchers' choice and comprehension of modern technologies are frequently overlooked in favour of the technical focus in most studies, though the use of appliances such as kettles is a user-centred process. The research framework encompasses quantitative research methods, with the help of experiment data and data analysis to investigate the energy consumption of kettles with different features. The research makes a unique contribution by investigating the water boiling process in a sustainable way from the perspective of consumer requirements. It is important to acknowledge that the heating process, heat transfer and consumer behaviour are three factors that affect the energy consumption of the water boiling process, and this study focuses on features designed for the heat transfer (heat loss) and the related thermal insulation.

2. MATERIALS AND METHODS

This study explores the impact of different materials on the energy consumption of boiling water and designs and tests insulation covers for kettles to enhance boiling efficiency by reducing heat loss. The experimental work uses a plastic kettle (220-240V~50/60Hz, 2520-3000W), a glass kettle (220-240V~50/60Hz, 1850-2200W) and a steel kettle (220-240V~50/60Hz, 1850-2200W) (Figure 1). A plug-in power meter is used to measure time and energy consumption. A logger with a K-type thermocouple is used to measure the water temperature during heating water, and a kitchen temperature probe was used to measure water temperature.

Plastic Steel Glass

Figure 1: The used glass, plastic and steel kettles.

The experimental work first tests the use of the three materials: plastic, metal and glass, as research objects to study the impact of materials on the energy consumption of kettles in a lab environment similar to a home kitchen. Room temperature, the initial water temperature, the initial surface temperature of the kettle, the surface temperature of the kettle at after boiling watr, energy consumption and the time for water to boil are recorded during the experimental process, see Table 1. The experiment of each kettle was repeated 7 times. The water boiled in each experiment was 1 Liter of tap water. Also, the infrared camera and thermocouple data logger are used to help measure temperatures and thermal profile during the experimental work.

To compare between the three kettles in normal home scenarios, room temperature, water temperature and energy are measured in the boiling process. A relative measurement of energy factor term (KEF) is developed based on equation 1 below:

$$Kettle\ Energy\ Factor\ KEF = \frac{Energy\ consumed\ in\ boiling\ one\ later\ of\ water}{(100 - initial\ water\ temperature)} x1000 \quad Wh/oC \qquad (1)$$

Table 1: Energy consumption of boiling 1L water

Test #	Material of the Kettle	Volume (L)	Room Temperature (°C)	Initial Water Temperature (°C)	Energy (kWh)	Time (minute)
1	Plastic	1	27.0	24.1	0.103	2’06
2	Plastic	1	25.5	23.0	0.107	2’08
3	Plastic	1	25.9	23.3	0.108	2’10
4	Plastic	1	27.0	26.2	0.106	2’12
5	Plastic	1	26.2	21.7	0.109	2’14
6	Plastic	1	27.8	27.0	0.100	2’04
7	Plastic	1	26.9	26.7	0.097	2’02
8	Steel	1	27.3	23.5	0.116	3’18
9	Steel	1	26.6	26.4	0.109	3’08
10	Steel	1	25.7	22.0	0.117	3’22
11	Steel	1	25.8	24.0	0.112	3’14
12	Steel	1	28.5	26.4	0.107	3’06
13	Steel	1	24.7	28.3	0.108	3’10
14	Steel	1	25.8	26.3	0.107	3’15
15	Glass	1	27.1	26.4	0.111	3’06
16	Glass	1	24.7	22.4	0.115	3’11
17	Glass	1	25.9	21.9	0.113	3’14
18	Glass	1	27.2	26.2	0.108	3’02
19	Glass	1	26.3	20.1	0.118	3’09
20	Glass	1	27.7	26.8	0.107	3’03
21	Glass	1	26.9	26.0	0.105	3’01

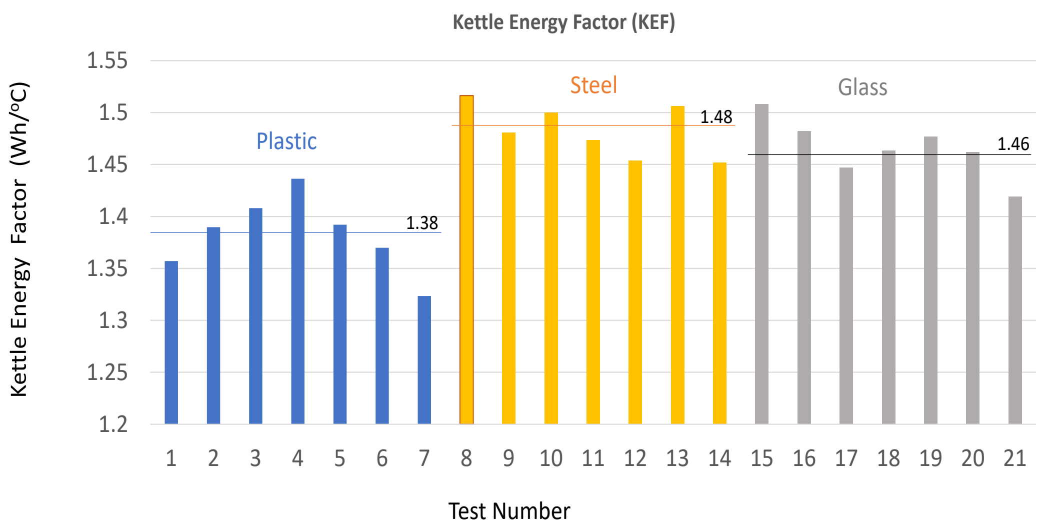

Figure 2: Energy consumption (Wh) of boiling 1L water per °C.

Therefore, for normalised initial water temperature of 21 degrees (assumed room temperature), the average electricity consumption of plastic, steel, and glass kettles is found to be 0.109kWh, 0.117kWh and 0.115kWh respectively. Based on the collected data, the plastic kettle consumes the least energy during the boiling process. Figure 2 illustrates that the electricity consumption of the plastic kettle is significantly lower than the other two, assuming the same water temperature reference point despite the variation in room temperature during the tests. Through the surface temperature of the three kettles after the boiling process, the heat transfer and heat capacity properties of the three materials are found to play an important role in heat losses. For accurate measurement of temperature using infrared thermography, a matt black tape is used to unify the emissivity and produce consistent measurements, see Figure 3. The highest temperature is found to be for the steel kettle, followed by the glass kettle which also has higher thermal capacity, followed by the plastic kettle.

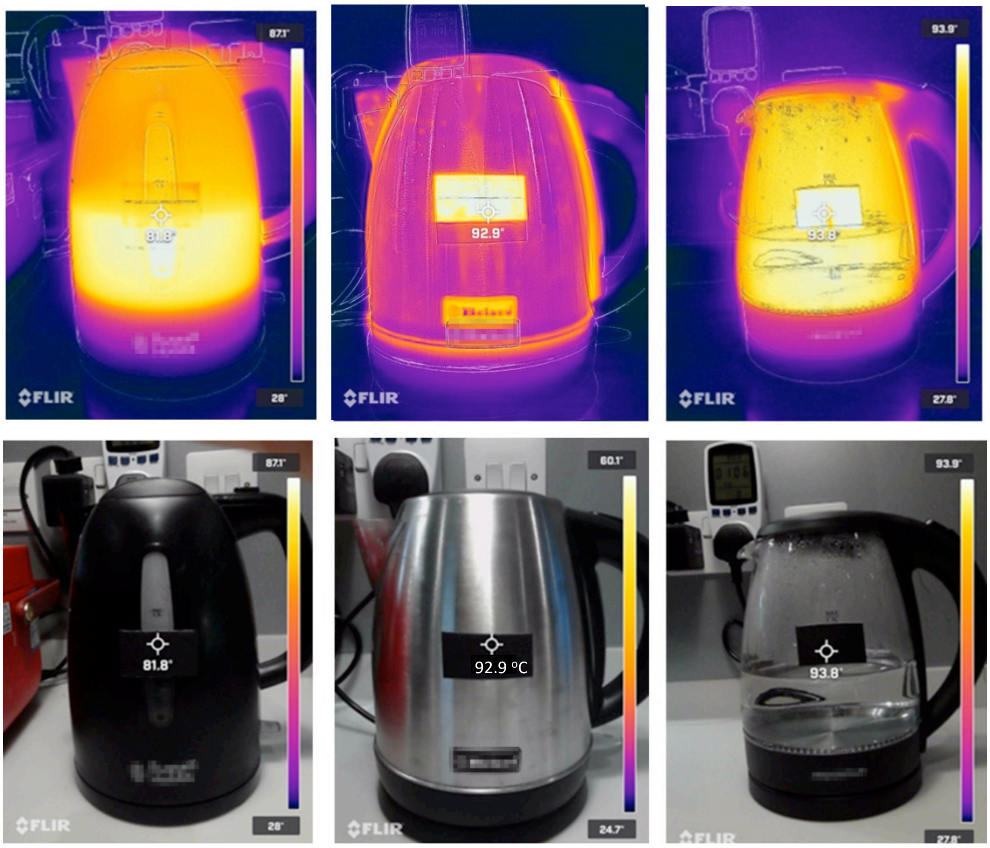

Figure 3: Surface temperature of plastic, steel and steel kettle using infrared thermography after 15 seconds of switching the kettle off.

Although the difference in total energy consumption may not be considered significant, the high frequency use of kettles and overall electricity consumption differences over lengthy periods of time are still worth paying attention to. Assuming one household has an electric kettle and boils water once a day (1L), a family will consume per annum circa 38.87kWh, 41.7 kWh and 41.2 kWh for plastic, steel and glass kettles respectively. Given that there are about 28.2 million households in the UK in 2022 (Clark, 2023), using a plastic kettle will save about circa 80 GWh of electricity in one year when compared to using a steel kettle; and 65.8GWh of savings when compared the plastic kettle with the glass kettle. The research does not aim to encourage individuals to throw away their existing steel or glass kettles and buy a plastic one, but to provide an informed choice to individuals when buying a kettle.

Based on the results, it is assumed that insulating the steel kettle would reduce energy consumption by reducing heat loses. To further verify this point and explore ways to make the process of boiling water more sustainable and save energy bills for consumers, experiments to improve the insulation performance and working efficiency of a steel kettle is conducted. As we know, an electric kettle will automatically switch off power when the appropriate heating point is reached via a thermostat (Appliance Experts, 2024). Therefore, reducing heat loss during the heating process to help the water temperature rise faster will theoretically increase the working efficiency. To reduce heat loss during the heating process, three different heat insulation materials are proposed to cover the surface of the steel kettle, see Figure 4. The first cover is a cosy made of a kitchen foil and bubble foam sheet. A foil is generally used to keep food warm in domestic kitchens. Food remains warm since the foil retains the heat within and as a result of aluminium's low emissivity, the heat emitted by the food is reflected inwards (Haomei Aluminum, 2023). Besides, bubble warp is an insulator due to the tiny air pockets (Ganesh Kumar et al., 2019). The air bubble functions as a thermal barrier, retaining heat and impeding the transmission of heat through conduction and convention (Amit, 2024). The second designed cover is an ABS 3D printed plastic model. The plastic model has two layers with 3mm thickness for each and 10mm clearance in between. The model is designed and built to fit the surface of the kettle to reduce heat losses during the heating process. After testing this air -insulation design, expending foam is injected into the air gap of the model to form the third insulation type, see Figure 4. Expanding foam can cover a gap quickly to effectively to create thermal insulation (Liu et al., 2022). Energy consumed for the three types of insulation, in additional to the standard steel kettle, can be seen in Figure 5.

Figure 4: The steel kettle with foil and bubble foam sheet cover (a), with ABS cover with air gap (b), with ABS and expending foam cover (c).

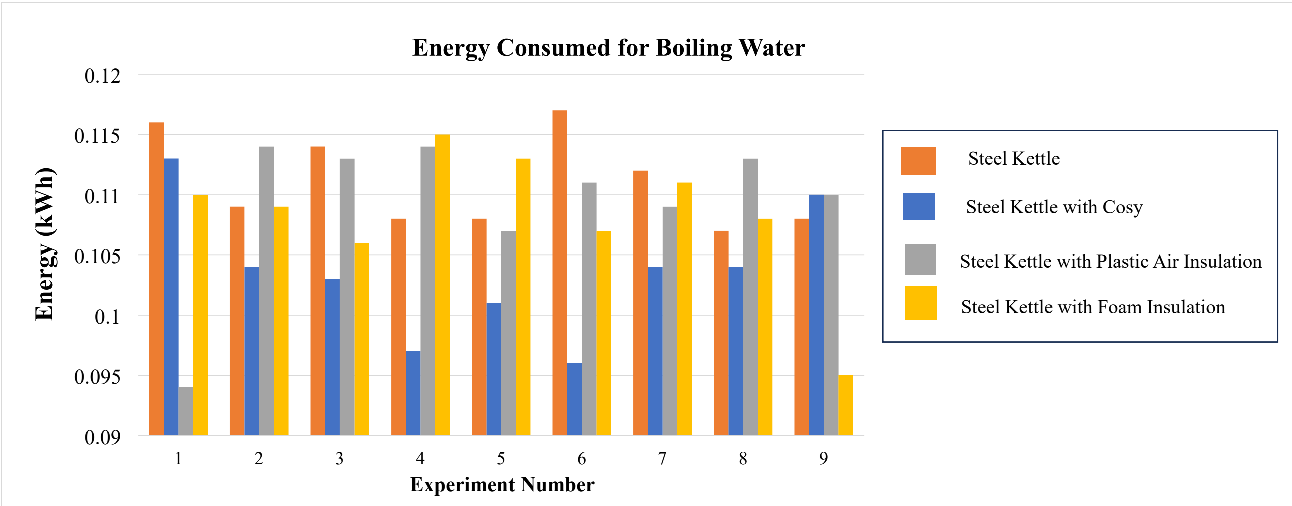

Figure 5: Energy consumption of boiling 1L water.

The average energy consumption of the steel kettle, kettle with cosy, kettle with air insulation, and kettle with foam insulation is circa 0.111 kWh, 0.1043 kWh, 0.1098 kWh and 0.1086 kWh respectively, see Figure 6. Based Figure 6, the foil and bubble warp cover (cosy) has the maximum energy savings. Figure 7 shows the water temperature of the kettle during the heating process. The focus of energy efficiency can be noticed when temperature is above 70 oC, where the kettles with insulation have a higher slope (increase per second).

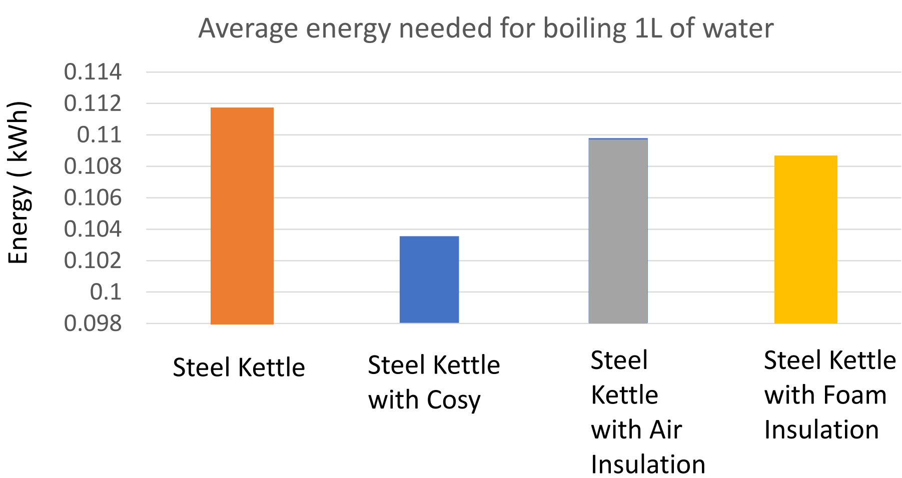

Figure 6: Average Energy consumption of boiling 1L water.

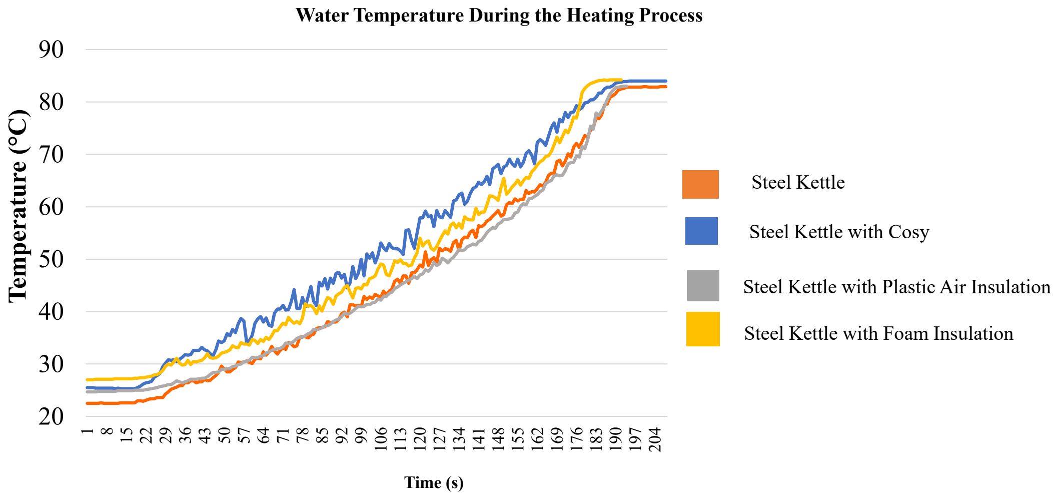

Figure 7: Water temperature during the water heating process.

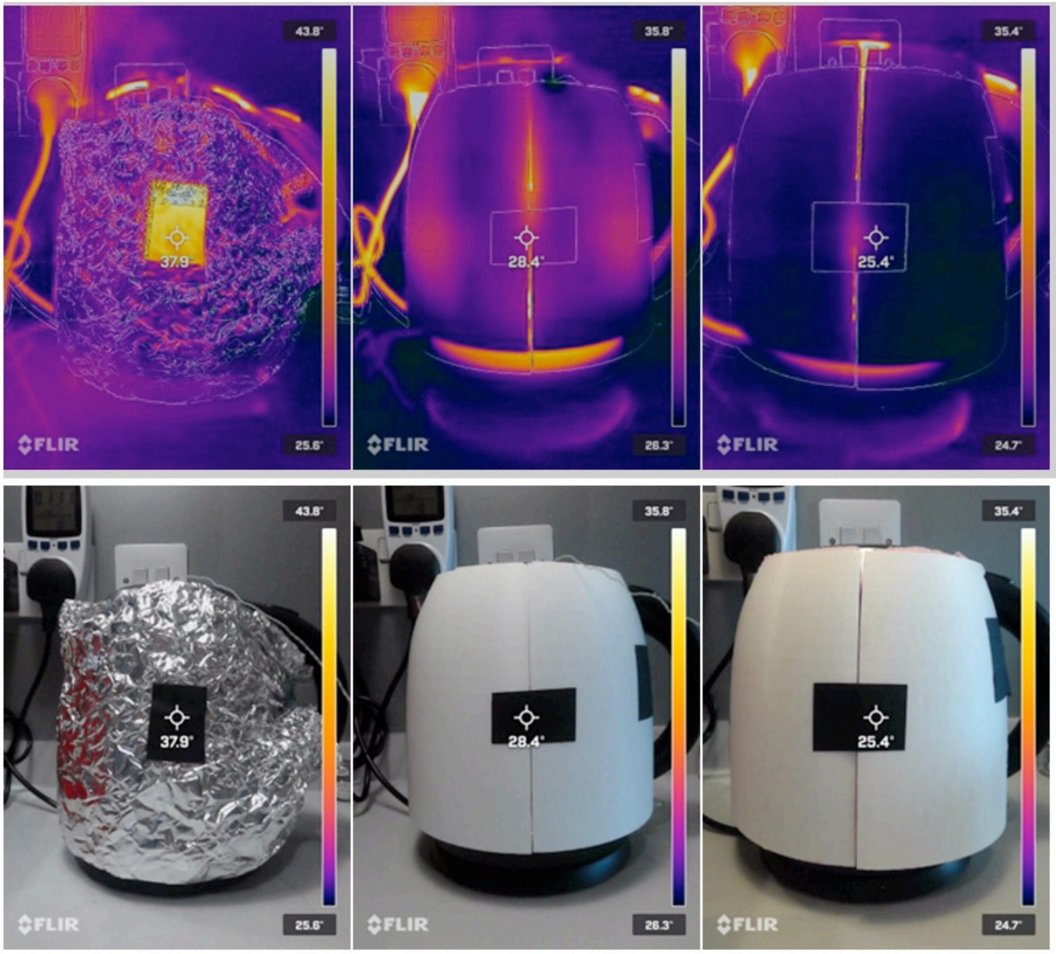

Figure 8: Surface temperature using infrared thermography of the kettle with the cosy (a), air insulation (b) and foam insulation (c).

In addition, the surface temperature of the kettle with different covers when the boiling process is completed is observed, see Figure 8. Compared with the steel kettle without a surface cover, both three covers played a role in reducing heat losses. Although the surface temperature of ABS with expending foam (foam insulation) was the lowest during the heating process of the kettle, the results found that the cosy (foil and bubble foam sheet cover) helped to save the most energy. The reason could be that the cosy not only forms a good insulation, but also has a better air tightness. Although the 3D printed plastic around the kettle has been built based on the surface dimension of the kettle, the ABS is a thermoplastic material and can be affected by higher temperatures. Therefore, the high surface temperature of the steel kettle caused slight deformation of the inner layer of the 3D printed plastic, which made the model unable to fit perfectly with the kettle surface. It means that heat has been lost between the surface of the kettle and the plastic cover. The thermal insulation performance of the expanding foam partially mitigated the consequences of heat loss caused by plastic deformation. However, the air insulation did not achieve the desired effect. Additionally, the deformation could be the reason that the internal temperature rising of steel kettle and kettle with ABS cover has no significant difference during the heating process, see Figure7.

Based on the experiment, both the cosy insulation (foil and bubble foam sheet cover), and foam insulation cover helped to improved the energy efficiency of the kettle. Thermal insulation performance and adhesion to the kettle surface to reduce heat loss are key points of the enhanced design. Even though a insulation cover helps to save a bit of electricity, the total amount saved over time is worth paying attention to. With 28.2 million households in the UK (Clark, 2023), 24.7032 GWh of electricity could be saved based on heating 1 L per day by enhancing the insulation of the steel kettle.

Furthermore, one hour after boiling the water, the average temperature of the steel kettle, kettle with cosy, kettle with air insulation , and kettle with foam insulation is found to be 60.56°C, 66.93°C, 64.22°C and 65.31°C respectively (Table 2). The insulated kettle achieves better insulation performance, and with a water temperature about 5°C higher than that of a regular steel kettle. Since tea is a favourite drink in many countries globally including the UK and China, Table 3 shows the best tea brewing temperatures of different types of tea. Therefore, after boiling the water for an hour, individuals can still enjoy a fresh cup of white tea with the help of the insulated steel kettle that is kept in a domestic kitchen environment.

Table 2: Water temperature after boiling during time passing every 10 minutes.

	10min	20min	30min	40min	50min	60min
Steel Kettle	87.99°C	80.07°C	73.87°C	68.59°C	64.34°C	60.56°C
Steel Kettle with Cosy	89.07°C	82.60°C	77.70°C	73.63°C	70.11°C	66.93°C
Steel Kettle with Air Insulation	88.34°C	81.54°C	75.88°C	71.41°C	67.35°C	64.22
Steel Kettle with Foam Insulation	89.28°C	82.12°C	76.41°C	72.16°C	68.35°C	65.31°C

Table 3: Tea brewing temperature [based on Bethany, 2017].

Type of Tea	Best Brewing Temperature
Herbal Tea	100°C
Black Tea	100°C
Oolong Tea	80-85°C
Green Tea	75-80°C
White Tea	65-70°C

3. DISCUSSION AND CONCLUSION

This research work has shown that the efficient design of domestic appliances could contribute to energy savings. When plastic, steel and glass kettles are compared, it was found due to heat transfer and thermal capacity that plastic kettles save more energy while steel kettles waste more energy due to high heat transfer to the surroundings. However, many people prefer to use glass or steel kettles due to assumed health or aesthetic benefits. Being the worse in case of energy use, the efficiency of the steel kettle was enhanced by testing three types of insulation. The results indicate that reducing heat losses via adding an effective insulation layer could help to improve the heating efficiency and hence reduce energy consumption. These findings have broader implications for domestic appliances design, and offer new avenues for further research in energy savings and sustainable consumption from the consumer perspective. However, this study is not without limitations. For instance, the deformation of the plastic cover made the energy-saving effect not as efficient as expected. Further studies are needed to enhance the material selection process. Thermal insulation performance and surface adhesion should be considered during the material selection process. Additionally, material price and production cost should be taken into consideration since consumers unlikely to pay for a product with a price that exceeds the financial savings from energy reduction. This study demonstrates that energy consumption in household appliances in daily life is worth paying attention to. The key findings of this study has found that a simple improvement in kettle insulation or selecting the most suitable material for the kettle could save significant energy; and on national level this small improvement could achieve energy savings, depending on the selected scenario, between 24 Gwh and 80 Gwh per annum in the case of the UK.

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