Research Article

Energy Efficiency Comparison in Heating Water Using Gas, Electric, and Induction Cooktops and Determination of Container Emissivity Coefficient

Aas Wasri Hasanah[1]*, Adhitya Sumardi Sunarya[2], Sparisoma Viridi[3]

[1]Department of Electrical Engineering, Faculty of Electric Power and Renewable Energy, Institut Teknologi PLN, Jakarta 11750, Indonesia
[2]Department of Manufacturing Automation Engineering and Mechatronics, Politeknik Manufaktur Bandung, Bandung 40135, Indonesia
[3] Department of Physics, Faculty of Mathematics and Natural Sciences, Institut Teknologi Bandung, Bandung 40132, Indonesia

ORCID
Aas Wasri Hasanah: https://orcid.org/0009-0006-0598-8806
Adhitya Sumardi Sunarya: https://orcid.org/0000-0001-9509-0325
Sparisoma Viridi: https://orcid.org/0000-0002-7588-4539

Corresponding Author: Aas Wasri Hasanah; email: aas@itpln.ac.id

Published: 27 March 2024

Publishing services provided by Knowledge E

© Aas Wasri Hasanah et al. This article is distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use and redistribution provided that the original author and source are credited.

Selection and Peer-review under the responsibility of the ICMScE Conference Committee.

OPEN ACCESS

Abstract.
A 1.315 kg stewpan is used to boil 1 kg water using three different type of cooktops, that is, gas, electric, and induction. The power of the electric cooktop is 600 W, a gas cooktop uses the maximum setting (large burner in control knob), and the induction cooktop has maximum power of 1200 W. We have observed two different settings of power: 600 W and 1200 W. In the first setting, we compared induction and electric cooktops, while in the second induction and gas cooktops were compared. We obtained energy efficiency about 67.24% and 56.2% for the first setting and 74.03% and 38.55% for the second, which shows that induction cooktop always gives better performance compared to the other cooktops. Besides this, we also investigated the energy leak from the stewpan to the environment through radiation, which should be the same, since all four observations were using the same container to heat the water.

Keywords: energy efficiency, heating water, induction cooktops, container emissivity coefficient

1. INTRODUCTION

Investigating energy efficiency in cooking using induction and other cooktops still an interesting study nowadays, since it depends on many factors such as interaction between various types of cooktops and pans [1], size of the vessel [2], and cooking mode of the appliance [3]. Impact of the use of more efficient cooktop to environment and anual costs depend also to a country condition, e.g Indonesia [4], Vietnam [5], Korea [6], and Ethiopia [7], which should be carefully considered before turn it into policy. In this work we perform observation of three different cooktops (electric, gas, induction) in heating water from nearly room temperature 30 °C to about 90 °C at the place with elevation about 8 m above sea level, Jakarta. The difference between this work and the others [1–3] is the analysis of energy loss in the form of radiation enery to the surrounding environment using Stefan-Boltzmann law, where the formulation is sometimes mentioned but not used explicitly [7] or used to study the heat transfer inside an oven [8]. We neglect the time evolution of heating element as it powered and the the same time release the heat to the environment as the case of a single heating wire [9].

2. RESEARCH METHOD

A model is developed in this work to produce temperature T – time t relation, which contains some parameters. Then, experiments are performed to get the same relation for different type of cooktops. The model and experimental results will be plotted in the same graph to get the parameters.

2.1. Model

A cooktop has power P_{CT}, in the form of heat, indicating the energy produced every time duration Δt

$$P_{CT} = \frac{Q_{CT}}{\Delta t}$$

Where Q_{CT} is enery generated by the cooktop. This energy is intended for heat a stewpan and its content (water in this work) and rise their temperature according to

$$Q_{SP} = m_{SP} c_{ST} \Delta T$$

and

$$Q_W = m_W c_W \Delta T$$

with m_{SP} and m_W are mass of stewpan vessel and water, c_{SP} and c_W is specific heat capacity of stewpan material and water. Thermal radiation of stewpan to surrounding environment uses

$$\frac{P_{RAD}}{A_{SP}} = \sigma \epsilon_{SP} (T_{SP}^4 - T_{EV}^4)$$

with P_{RAD}, A_{SP}, ϵ_{SP}, T_{SP} are power of thermal radiation, surface area, emissivity, and temperature of stewpan, while T_{EV} is temperature of surrounding environment. Similar to (1) we can have

$$Q_{RAD} = \sigma \epsilon_{SP} (T_{SP}^4 - T_{EV}^4) A_{SP} \Delta t$$

from (4), where (4) is known as Stefan-Boltzmann law. Conservation law of energy and the use of (1)-(3) and (5) will give

$$Q_{CT} = Q_{SP} + Q_W + Q_{RAD} + Q_{LOSS}$$

while the last term Q_{LOSS} is the energy that cannot be quantified due to other factor such as heat convection and absorption in the space between heating element and bottom of the stewpan vessel (in electric and gas cooktops). We assume that the use of induction cooktop and induction stewpan will have heat loss in only due to thermal radiation Q_{RAD} from stewpan vessel to surrounding environment. In other works [1-3] normally the heat loss count for both Q_{LOSS} and Q_{RAD} in this work.

It is required to define temperature of stewpan T_{SP} at two different time, namely t and at $t + \Delta t$, that turns (2) and (3) into

$$Q_{SP} = m_{SP} c_{SP} [T_{SP}(t + \Delta t) - T_{SP}(t)]$$

$$Q_W = m_W c_W [T_{SP}(t + \Delta t) - T_{SP}(t)]$$

since we assume that

$$T_{SP} = T_W$$

by neglecting thermal conduction in stewpan vessel wall and thermal convection in water inside the pan.

Then, substitution of (1), (5), (7) and (8) into (6) will produce

$$P_{CT} \Delta t = m_{SP} c_{SP} [T_{SP}(t + \Delta t) - T_{SP}(t)] + m_W c_W [T_{SP}(t + \Delta t) - T_{SP}(t)]$$

$$+ \sigma \epsilon_{SP} [T_{SP}^4(t) - T_{EV}^4] A_{SP} \Delta t + Q_{LOSS}$$

than can be simplified as

$$T(t + \Delta t) = T(t) + c_1 P_{CT} \Delta t - c_2 [T^4(t) - T_{EV}^4] - c_1 Q_{LOSS}$$

by dropping the indeks SP since we consider only stewpan temperature, with

$$c_1 = \frac{1}{m_{SP} c_{SP} + m_W c_W}$$

$$c_2 = c_1 \sigma \epsilon_{SP} A_{SP}$$

DOI 10.18502/kls.v8i1.15624

We can label for each type of cooktop, e.g. ELE ≡ electric, GAS ≡ gas and IND ≡ induction, and present (11) in the form of

$$T_{XXX}(t+\Delta t) = T_{IND}(t) + c_1 P_{CT}\Delta t - c_2[T^4_{XXX}(t) - T^4_{EV}] - c_1 Q_{LOSS}$$

with XXX ≡ IND, ELE, GAS. Finally, we can have c_1, c_2 and Q_{LOSS} from (14)-(15).

2.2. Experiment

A stewpan with diameter and height about 20 cm with mass of 1.315 kg filled with 1 kg of water is used in the experiment. The pan is heated using three different type of cooktops as shown in Figure 1.

Figure 1: Type of cooktops: ele (left), gas (center), ind (right).

A thermometer is attached on the stewpan for measuring the temperature. Time t is recorder at each increase of temperature about 10 °C. For electric cooktop current I and voltage V are measured using clamp meter. There are four types of experiment performed in this work: electric cooktop 600 W (ELE), gas cooktop full flame (GAS), induction cooktop 600 W (IND1), and induction cooktop 1200 W (IND2). For gas cooktop mass of the 12 kg gas cylinder mGC is measured every time the time t for temperature T is recorded. The difference between two succeded observation time, t and t + Δt, will give mass of mGAS the gas used during the time interval Δt. Each experiment (ELE, GAS, IND1, IND2) is repeated five times. Related to this field the five times repetion and observation of time t for each increase of temperature T about 10 °C are already a common practice [3].

3. RESULTS AND DISCUSSION

Experiments are performed in a lab Physics Laboratory, Department of Electrical Engineering, Institut Teknologi PLN, Jakarta, Indonesia with ambient conditions pinitial =

pfinal = 759 mmHg and Tinitial = Tfinal = 29 °C. The constant temperature is maintained using a common air conditioner.

3.1. Water Temperature Measurement

At t = 0 s the initial temperature is recorded and at each increase of temperature about 10 °C the time t is recorded, where the results for different type of cooktops is given in Figure 2.

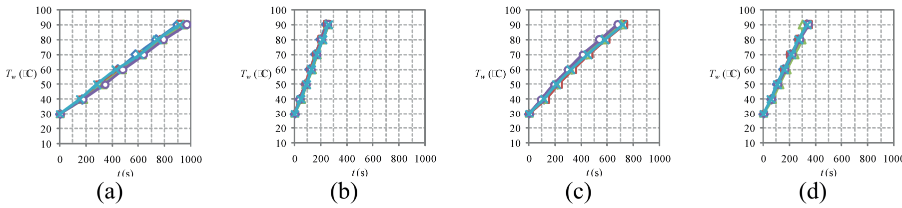

Figure 2: Water temperature T_w as function of time *t* for different type of cooktops:(a) ELE, (b) GAS, (c) IND1 and (d) IND2.

Even we know tha from Figure 1 that gas cooktop heat the water in shortest time but it does not tell it has the highest efficiency among the four experiments (ELE, GAS, IND1, IND2) observed in this work.

3.2. Parameters

Following parameters are used in fitting the model with experimental results

1. Area of the stewpan consists of circular top surface A_1 and curved surface A_2. From given parameters of diameter D = 0.2 m and height H = 0.2 m, it can be obtained A_1 = 3.1416×10^{--2} m^2, A_2 = 1.2566×10^{--1} m^2, $A_{SP} = A_1 + A_2$ = 1.5708×10^{--1} m^2.
2. Spesific heat capacity for water c_W = 4.1480×10^3 J/kg·K and stewpan c_{SP} = 4.5628×10^2 J/kg·K.
3. Stefan-Boltzmann constant σ = 5.6704×10^{--4} J/m^2·K^4.
4. Mass percentage χ of C_3H_8 and C_4H_{10} in LPG (liquefied petroleum gas) are 0.3 and 0.7 with $\Delta H(C_3H_8)$ = –2.2217×10^3 kJ/mol, $\Delta H(C_4H_{10})$ = –2.8786×10^3 kJ/mol, MR(C_3H_8) = 4.4097×10^1 kg/kmol, MR(C_4H_{10}) = 5.8124×10^1 kg/kmol.
5. Ambient temperature T_{EV} = 29 °C = 302 K.
6. For the model c_1 = 2.1432×10^{--4} K/J and c_2 = 1.9090×10^{--12} ϵ_{SP} K^{--3}.

To fit the data time step Δt will be adjusted and also ϵ_{SP}.

3.3. Gas Mass and Produced Energy

In the experiment using as cooktop time t and mass of gas cylinder and its content mGAS+C are recorded at every increase of water temperature T of 10 °C, where the results are given in Figure 3 Left. There are five repetitions.

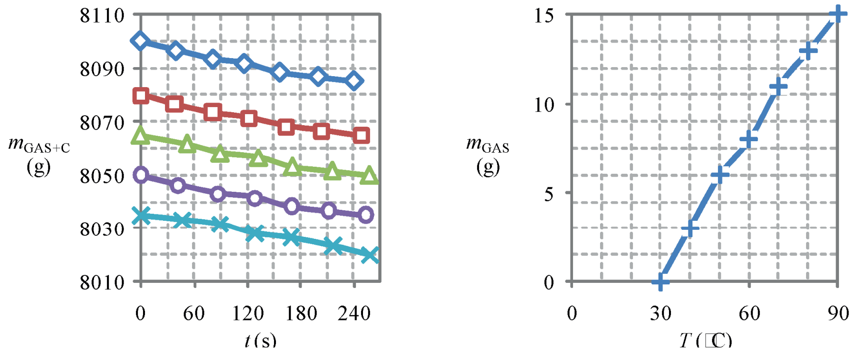

Figure 3: Left: Mass of LPG gas cylinder m_{GAS+C} and its content as function of time t. Right: Mass of gas m_{GAS} used to achieve certain temperature T.

From these results we can have gass mass mGAS that is used to heat the water and rise the temperature every 10 °C as shown in Figure 3 Right, which is the average of five repetition. From this we can have the energi produced by the gas cooktop $Q_{CT} \equiv Q_{GAS}$ which is given in Figure 4. Figure 4 Left and Figure 4 Right show similar trend since the relation between total gass mass m_{GAS} and total energy produced by gas cooktop Q_{GAS} is as follow

$$Q_{GAS} = \frac{m_{GAS} \cdot \chi(C_3H_8)}{MR(C_3H_8)} \Delta H(C_3H_8) + \frac{m_{GAS} \cdot \chi(C_4H_{10})}{MR(C_4H_{10})} \Delta H(C_4H_{10})$$

which is simple a number and does not depend on the temperature T.

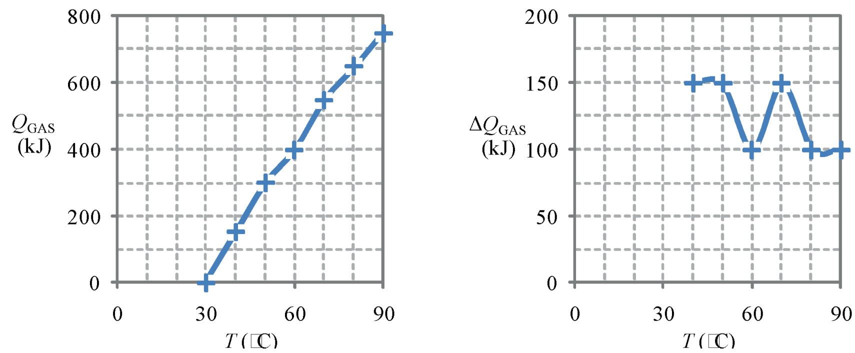

Figure 4: Total energy (left) and energy difference (right) produced by gas cooktop at temperature T.

The energy difference ΔQ_{GAS} at temperature T in Figure 3 left is

$$\Delta Q_{GAS}(T) = Q_{GAS}(T) - Q_{GAS}(T - \Delta T)$$

where the ΔT = 30 °C, which shows that at time range Δt that the temperature increases about ΔT the energy produced by gas cooktop is not constant, but fluctuated between 100 – 150 kJ.

3.4. Cooktops Power and Produced Energy

For electric and induction cooktops, they have already information of power PCT delivered by the appliances, which is assumed to be true. Their delivered energy will use (1).

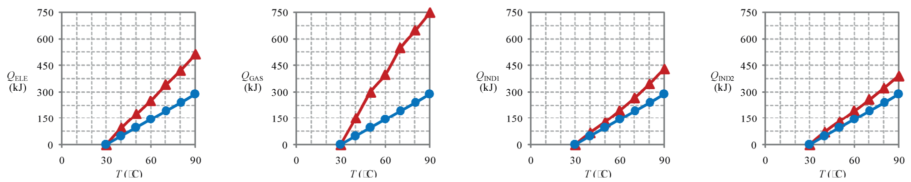

Figure 5: Total energy Q at certain temperature T produced by cooktops (▲) and received by water (⊠) for different cooktops: Q_{ELE}, Q_{GAS}, Q_{IND1}, Q_{IND2}.

From Figure 5 we can have the energy efficiency for every cooktops and mode that are used in this work as given in Table 1.

TABLE 1: Energy efficiency of the cooktops.

Cooktop	Mode	η (%)
Electric	600 W	56.08
Gas	Full flame	38.48
Induction	600 W	66.99
Induction	1200 W	73.75

3.5. Stewpan Emissivity

Using (14) we can have a model of water temperature T as function of time t, where the results are given in Figure 6.

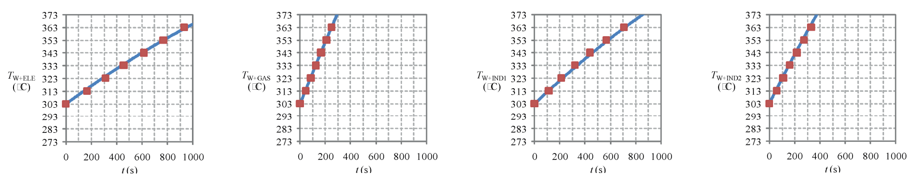

Figure 6: Water temperature T as function of time t as observed (⊠) and modeled (⊠) for different cooktops: T_{W+ELE}, T_{W+GAS}, T_{W+IND1}, T_{W+IND2}.

Area of stewpan ASP should be quadruple from measured dimension and emissivity of polished stainless steel ϵ, which about 0.16 [10], should 0.3 to fit the data. Time step Δt is chosen to 1 s. Every cooktop has different value of QLOSS, which are 250 J (ELE), 9950 J (GAS), 150 J (IND1), and 250 J (IND2). We could address this loss to other factor, e.g. air convection from surrounding. In the future work we plan to prevent the air convection by putting the system inside an insulation chamber as described in future plan subsection.

Parameters energy loss QLOSS and dan emissivity ϵ play different role in changing the curve. The former parameter will change the gradient, while the latter control the saturation of temperature. Influence of both parameters are given in Figure 7.

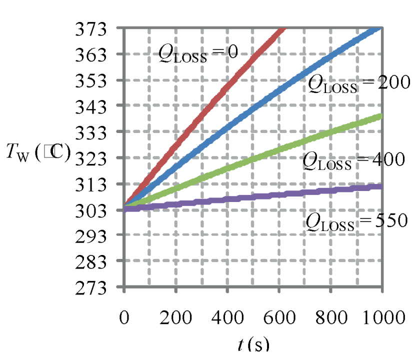

Figure 7: Influene of Q_{LOSS} and ϵ in changing function of water temperature $T_W(t)$.

Figure 7 (left) use ϵ = 0.3 and Figure 7 (right) use QLOSS = 200, while the other parameters are kept constant.

3.6. Future Plan

In the next work we will plan to design a better experimental setup to measure stewpan vessel emissivity in order to decrease energy loss due to thermal radiation. The design will be as shown in Figure 8.

Experiment setup to measure stewpan vessel emissivity consist of thermocouple-1 (1), thermocouple-2 (2), thermometer (3), stewpan vessel chamber (4), asbestos blanket insulation (5), induction cooker (6), watt meter (7) and alternating current source (8). Thermocouple-1 and thermocouple-2 have functioned to detect the temperature of the stewpan vessel chamber and the stewpan vessel wall. All of these temperatures read on the thermometer. The asbestos blanket insulation isolated the stewpan to reduce

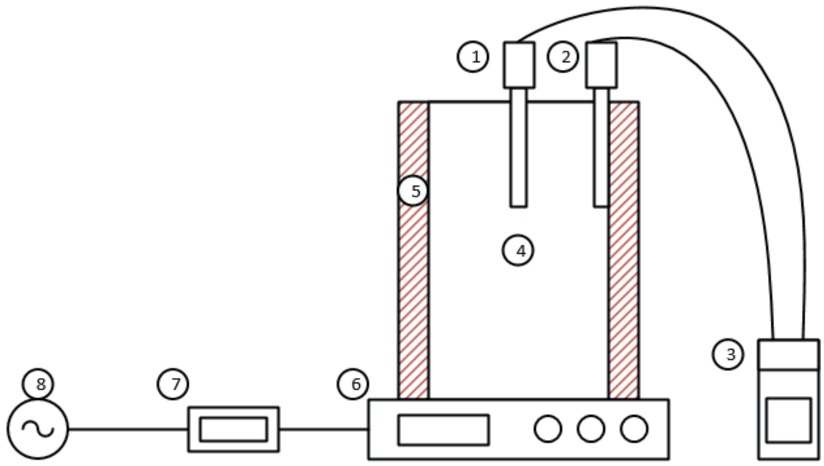

Figure 8: Future plan for experiment setup to measure stewpan vessel emissivity.

heat lost to the environment so emissivity could be measured accurately.The insulating effect of the asbestos blanket, changes (5) to

$$Q_{RAD} = \sigma T_{SP}^4 A_{SP} \Delta t$$

$$m_{air\_ch} c_{air\_ch} \Delta T_{air\_ch} = \sigma T_{SP}^4 A_{SP} \Delta t$$

with mair_ch, csp_ch and ΔTch_air are mass of air in stewpan chamber, specific heat capacity of air in stewpan chamber and temperature difference in stewpan chamber. Finally, emissivity could be calculate used formula

$$\epsilon_{SP} = \frac{\sigma T_{SP}^4 A_{SP} \Delta t}{m_{air\_ch} c_{air\_ch} \Delta T_{air\_ch}}$$

4. CONCLUSION

For 600 W induction and electric cooktops we have energy efficiency about 67.24 % and 56.29 %, where each requires 708 s and 932 s to heat 1 kg water from 30 °C to 90 °C. while for 1200 W induction and full flame gas cooktops the efficiency are 74.03 % and 38.55 % with required time are 332.4 s and 250.8 s to heat the water. Emissivity coefficient can be obtained about 0.3 but has not yet been consistent with literature.

Acknowledgments

Authors wishing to acknowledge encouragement from colleagues and support by technical staff from Physics Laboratory, Department of Electrical Engineering, Institut Teknologi PLN, Jakarta, Indonesia.

References

[1] Karunanithy C, Shafer K. Heat transfer characteristics and cooking efficiency of different sauce pans on various cooktops. Appl Therm Eng. 2016;93:1202–15.

[2] Dols J, Fortenbery B, Sweeney M, Sharp F. Efficient motor-driven appliances using embedded adjustable-speed drives. ACEEE Summer Study on Energy Efficiency in Buildings. 2014;9:90–9.

[3] S. Aisyah, M. Triani, and R. Rasgianti, "Energy efficency analysis for various type of electric cooker.," Journal of Physics: Conference Series. vol. 1869, no. 1, p. 2021. https://doi.org/10.1088/1742-6596/1869/1/012175.

[4] Tiandho Y, Indriawati A, Putri AK, Afriani F. Induction stoves: an option for clean and efficient cooking in Indonesia. IOP Conf Series Mater Sci Eng. 2021;1034(1):012068.

[5] Nguyen ST, Ho-Tran NA. "An investigation on energy efficiency of infrared and induction cooktops.," Proceedings of 2020 Applying New Technology in Green Buildings. ATiGB. 2021;2020(March):115–9.

[6] Im H, Kim Y. "The electrification of cooking methods in korea - impact on energy use and greenhouse gas emissions.," Energies. vol. 13, no. 3, p. 2020. https://doi.org/10.3390/en13030680.

[7] Hailu Kebede M. Home appliances efficiency improvements for energy conservation in Debre Berhan city, Ethiopia. American Journal of Energy Engineering. 2018;6(2):10.

[8] Cernela J, Heyd B, Broyart B. Evaluation of heating performances and associated variability of domestic cooking appliances (oven-baking and pan-frying). Appl Therm Eng. 2014;62(2):758–65.

[9] Lubis NF, Widartiningsih PM, Viridi S. Numerical and experimental study of thermal response of an electrified nickel wire. J Phys Conf Ser. 2019;1397(1):1–8.

[10] Transmetra – Messtechnik mit KnowHow. "Table of emissivity of various surfaces," http://www.czlazio.com/tecnica/Tabella delle Emissività.pdf.