Functions, Features and Performance of the 1.5 Litre Vektra Vacuum Insulated Kettle

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Introduction

The Vektra vacuum-insulated kettle uses electricity to boil water. The water then retains heat for up to four hours, according to the manufacturer, by virtue of its vacuum-insulated sides and multi-walled lid. When hot water is required often or regularly, this ability to retain heat reduces the number of times that the kettle has to be boiled, and reduces the electricity required each time the kettle is re-boiled. When heating, the kettle consumes 1.5 to 1.8kW of power when supplied with AC electrical power at between 220V and 240V.

In the context of the MECS project, the Vektra kettle provides a means of pre-heating hot water during the day, thereby storing energy as heat, and relieving the energy demanded from a battery. In the cooking diaries, a substantial number of heating events are only for hot water, and pre-heated hot water would be beneficial to reduce the cooking times of many foods (J. Leary, Scott, Numi, *et al.*, 2019; J. Leary, Scott, Sago, *et al.*, 2019; J. Leary, Scott, Serenje, *et al.*, 2019; Jon Leary *et al.*, 2019).

Vektra market vacuum kettles in sizes of 1.5 litres and 1.7 litres. The 1.5 litre model is sold in the UK for about £60 at the time of writing whereas the 1.7 litre kettle is sold for about £80. The 1.7 litre model has various features that have poorer reliability, according to online customer reviews (Amazon.co.uk, 2020; Ethical Superstore.com, 2020). Only the 1.5 litre kettle has been tested as part of the MECS project, see Figure 1.

The kettle bears the following information on the product label with CE mark:

I Grunwerg Limited	
Product Name: Vacuum Electric Kettle	
Model: VEK-1506	Capacity: 1.5L
Rated voltage: 220-240V	Frequency: 50Hz
Rated power input: 1500-1800W	
Silversteel House 29-49 Rockiingham Street	
Sheffield S1 4EA United Kingdom	

Figure 1. Vektra Vacuum Electric Kettle

1. Functions and Features

The Vektra kettle operates in the same way as any other electric jug kettle. The user opens the lid and manually fills the kettle with water, closes the lid and stands the kettle on its power base with power socket. The power base is plugged into a mains electricity socket by its power cord and BS1363 (UK three-pin) plug. The kettle is switched on by using the on/off switch above the handle. When the water has boiled, the kettle automatically switches off. The kettle will also automatically switch off if there is no water inside. The kettle is supplied with live, neutral and earth electrical connections through the power base.

The kettle has a few additional features not found in every jug kettle:

- The kettle is cordless. Power is transferred to the kettle via the socket in the power base.
- The power base is circular with a central round power socket for 360 symmetry. The kettle may therefore be placed at any angle on the power base.
- The switch illuminates to indicate that the kettle is heating.
- The spout has a push-button pouring lock to open and close the spout.
- Inside the kettle are markings to indicate 0.5, 1.0 and 1.5 litre levels with 1.5 litres being the maximum.
- The kettle has vacuum insulated sides and a multi-walled lid for reducing heat loss rate.

- Most of the kettle's body is cool to the touch, even when the water inside is hot. This is a co-benefit of the vacuum insulation.

The kettle lacks some features found in some jug kettles:

- There is no external level indicator. The only way to see the amount of water in the kettle is by opening the lid and looking inside. On the other hand, leaking water-gauge windows are a common cause of failure that has been avoided in this kettle (The Waste and Resources Action Programme (WRAP), 2020).
- There is no minimum level indicator. However, the heating element is concealed in a flat base. Even with very little water, the base is covered, and water is in good thermal contact with the element.
- There are no multiple temperature settings. The kettle only switches off when boiling.
- There is no inbuilt water filter.
- There is no keep-warm electrical function. However, the kettle keeps warm for a long time due to its vacuum insulation.

2. Safety

The Vektra kettle includes the following safety features:

- Dry boil protection in the form of two bimetallic switches: One on the live wire and another on the neutral, inside the base of the kettle, Figure 2.
- The outer walls are cool to the touch because the walls are vacuum insulated.

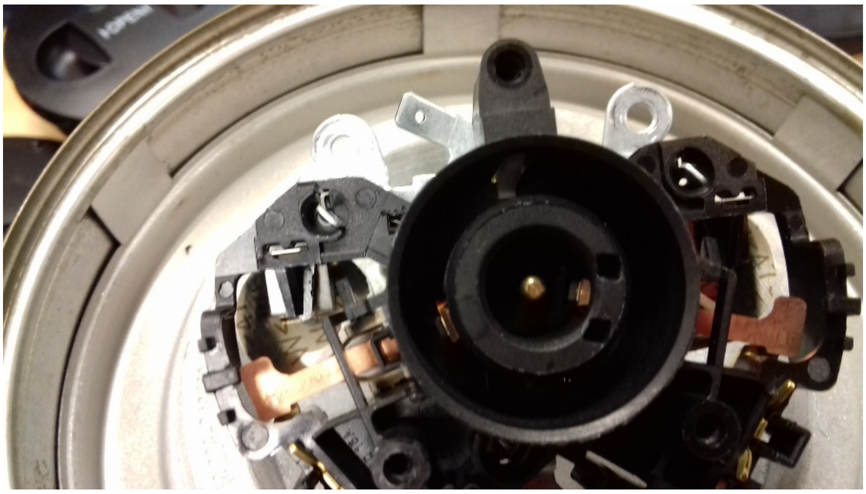


Figure 2. Central circular plug inside the base of the kettle with bimetallic switches on both the live and neutral wires

3. Examination

The circuit diagrams of the power base and kettle are shown in Figure 3 and Figure 4 respectively.

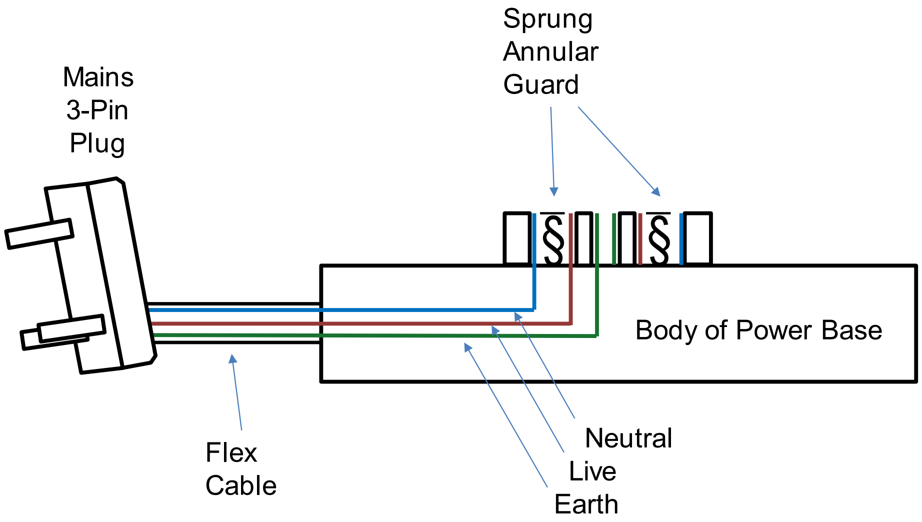


Figure 3. Circuit diagram of the powerbase

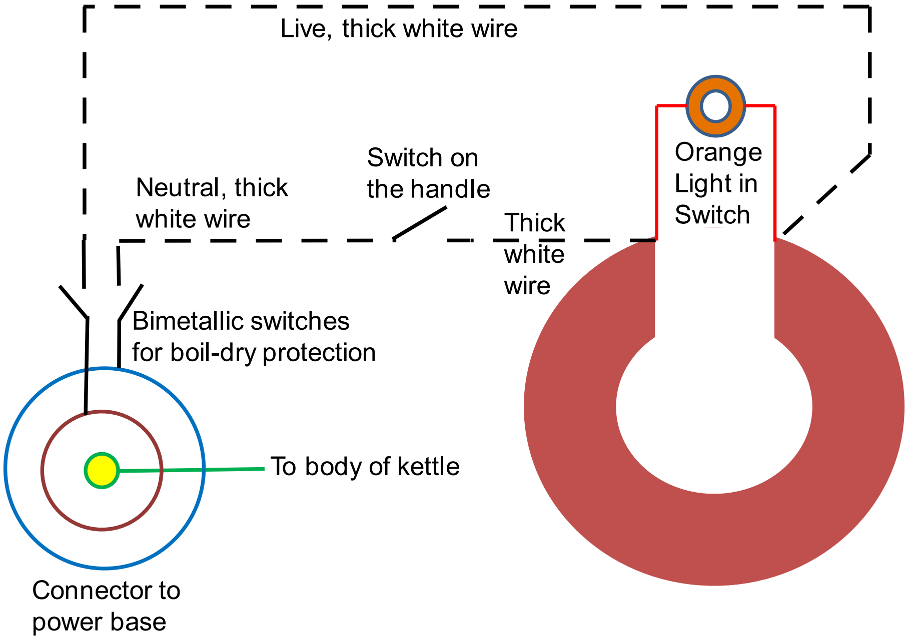


Figure 4. Circuit diagram of the kettle itself

4. Potential Problems in Normal Use

Note that the pouring lock should be closed when heating. If the pouring lock is left open, heating is still possible and boiling water can spill and spit from the spout during heating.

Pouring without the spout (with the lid removed) is not recommended as there are dangers of spillage and scalding.

5. Modifications and Testing

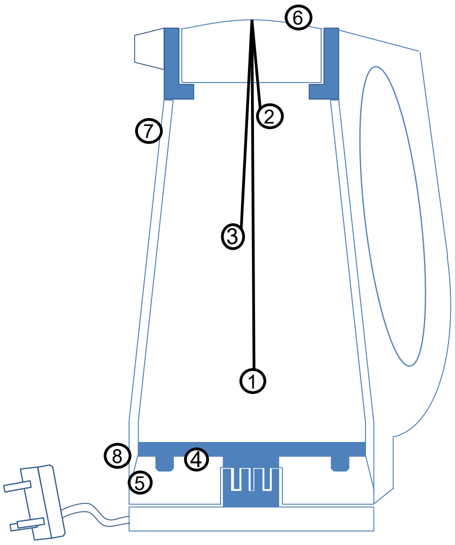
The kettle has been tested with and without additional external insulation. In each test, the kettle was boiled and then cooled whilst monitoring electrical power and temperatures.

The kettle has been tested with the specified mains voltage and at reduced voltages, both AC and low-voltage DC. AC power was supplied by direct connection to a mains socket or through a Variac auto-transformer. DC power was supplied by a benchtop power supply.

Table 1. Description of power tests

Electricity supplied	Volume of water	Added external insulation	Notes
220V to 240V AC	1500 ml	None	
220V to 240V AC	1500 ml	Top, sides and bottom	
220V to 240V AC	1000 ml	None	
220V to 240V AC	500 ml	None	
220V to 240V AC	200 ml	None	
220V to 240V AC	200 ml	Top, sides and bottom	
160V AC	1500 ml	None	
160V AC	1500 ml	Top, sides and bottom	
115V AC	1500 ml	None	
115V AC	1500 ml	Top and sides	
115V AC	200 ml	None	Spout left open
115V AC	200 ml	None	
115V AC	200 ml		
48V DC	1500 ml	None	
30V DC	1500 ml	None	
30V DC	1500 ml	Top and sides	
30V DC	200 ml	None	
30V DC	200 ml	Top and sides	
0 to 110V AC	1500 ml	None	Slowly increase voltage until kettle switches off
0 to 110V AC	1500 ml	Top and sides	Slowly increase voltage until kettle switches off
0 to 110V AC	200 ml	None	Slowly increase voltage until kettle switches off
0 to 110V AC	200 ml	Top and sides	Slowly increase voltage until kettle switches off
	200ml	Top, sides and bottom	Cool-down test

Voltages and currents were recorded using a Yokogawa signal analyser. Temperatures were measured using an 8-channel Picologger and K-type thermocouples. The positions of the thermocouples are shown in Figure 5. Some are also visible in Figure 6. Each test typically took 24 hours to complete, including a wait for the kettle to cool to near room temperature. The cooling phase was recorded in order to estimate the heat loss rate.



1. 12.5cm down inside kettle
2. 2.5cm down inside kettle
3. 7.5cm down inside kettle
4. Behind a bracket, in thermal contact with baseplate
5. Behind a clip, in thermal contact with inside of wall
6. On top of lid, near the back
7. Attached to top of stainless steel outer surface
8. Attached to bottom of stainless steel outer surface

Figure 5. Positions of thermocouples in and on the vacuum kettle

Figure 6. Photograph of the instrumented vacuum kettle showing some of the thermocouples

6. Energy Used and Thermal Model

The time-based measurements of electricity consumption and temperatures have been used to quantify the parameters of a simplified thermal model of the vacuum kettle, Figure 7.

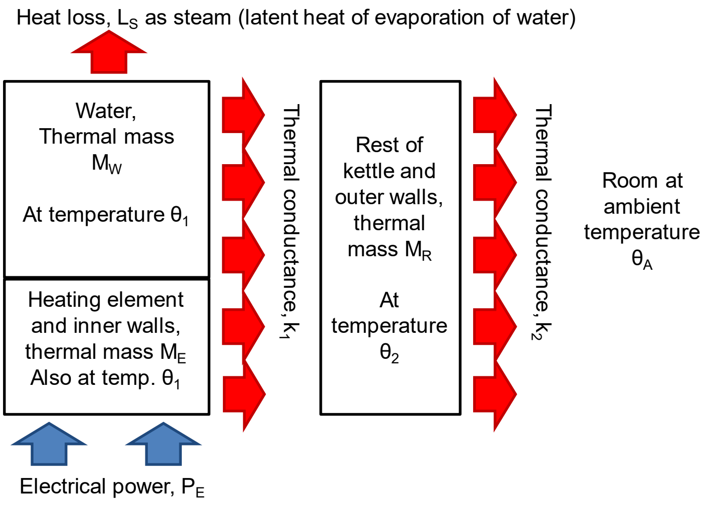


Figure 7. Thermal model of the vacuum kettle

In theory, this model can be used to calculate the following components of energy use or loss in any heating cycle:

1. Heat delivered to water
2. Heat lost to the immediate parasitic thermal mass (heating element and inner walls)
3. Heat lost to peripheral parasitic thermal masses (outer walls, remainder of kettle body and any added insulation)
4. Heat lost in escaped steam
5. Heat lost to surroundings by conduction, convection and radiation

Derivation of Model Parameters

The temperatures of the kettle are subject to the following differential equations based on conservation of energy and linear coefficients of thermal conduction (Fourier's Law in all materials and in the surrounding air):

$$(M_W + M_E)\frac{d\theta_1}{dt} = P_E - k_1(\theta_1 - \theta_2) - L_S \qquad [1]$$

$$M_R\frac{d\theta_2}{dt} = k_1(\theta_1 - \theta_2) - k_2(\theta_2 - \theta_A) \qquad [2]$$

The following assumptions and boundary conditions can be used to calculate some of the unknown parameters of equations 1 and 2:

- During the initial and middle phases of heating, and again during cooling, the rate of heat loss to steam is negligible, $L_S = 0$.
- The specific thermal mass of water is well known and published as a function of temperature. By measuring the mass of water, M_W can be calculated.
- The ambient temperature of the laboratory, θ_A is held within a narrow range by the room thermostat, usually close to 22 °C. The initial temperatures of the kettle and the water within it are stabilised at close to this temperature.

- Since the initial temperatures are all approximately equal, $\theta_1 = \theta_2 = \theta_A$, equation 1 simplifies at time t = 0 to: $$(M_W + M_E)\frac{d\theta_1}{dt} = P_E \qquad [3]$$
- The electrical power input is also measured. Hence the initial rate of temperature rise can be used to calculate the thermal mass of the inner parts of the kettle, M_E. The consequences of this simplification are that the model does not take account of the temperature differences between the water and parts of the kettle such as the heating element and the inner walls.

In theory, we could fit multiple curves to the heating up phases and cooling down phases of appliances and solve the above equations to give values for the thermal masses and thermal conductances of the model. However, this is a very difficult process.

A more promising approach is to run a numeric time-step model of the above equations. A time-step of one second was used and found to be sufficient to create smooth curves and very small temperature changes from one step to the next. Manual trial and error were used to optimise the values of the parameters M_E, M_R, k_1 and k_2 until a best fit was obtained to the measured temperature data. In practice, only the temperatures inside the kettle were of value, especially the thermocouples that were positioned below the surface of the hot water. It was generally assumed that the water was at a more homogeneous temperature than the gases above it and has better heat transfer properties to the thermocouples.

The following values gave a good fit to the data throughout most tests:

Heat capacity of heating element and inner walls, M_E = 0.17 kJ/K

Heat capacity of outer walls and remainder of kettle, M_R = 1.5 kJ/K

Internal thermal conductivity, k_1 = 0.34 W/K

External thermal conductivity, k_2 = 0.5 W/K with no external insulation

External thermal conductivity, k_2 = 0.35 W/K with added insulation

Example measured and modelled water temperature data show good agreement in the following four graphs, Figure 8 to Figure 11.

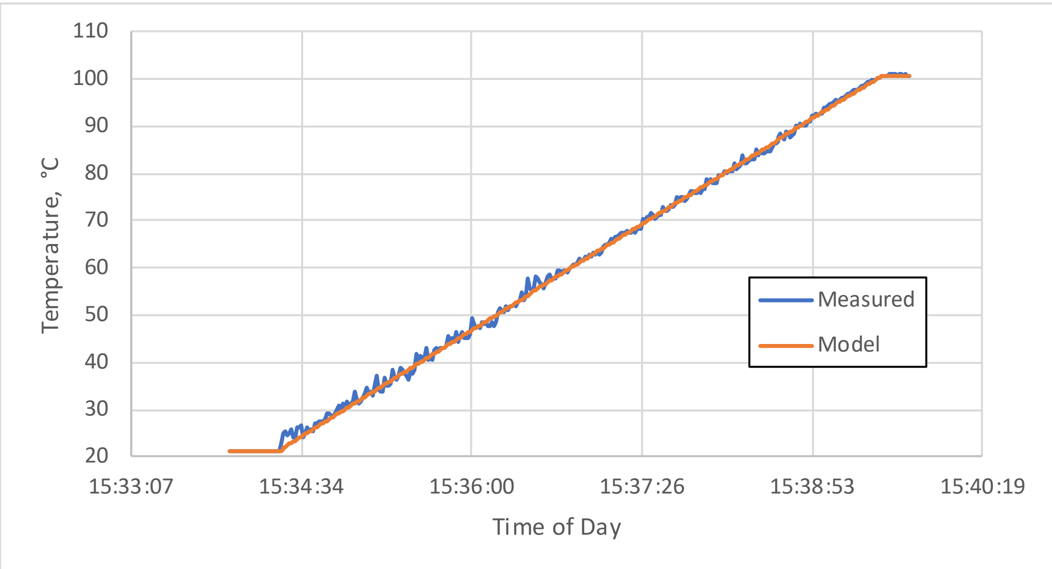


Figure 8. Measured and modelled temperatures while heating 1.5 litres of water using 230V AC electricity in the unmodified vacuum kettle.

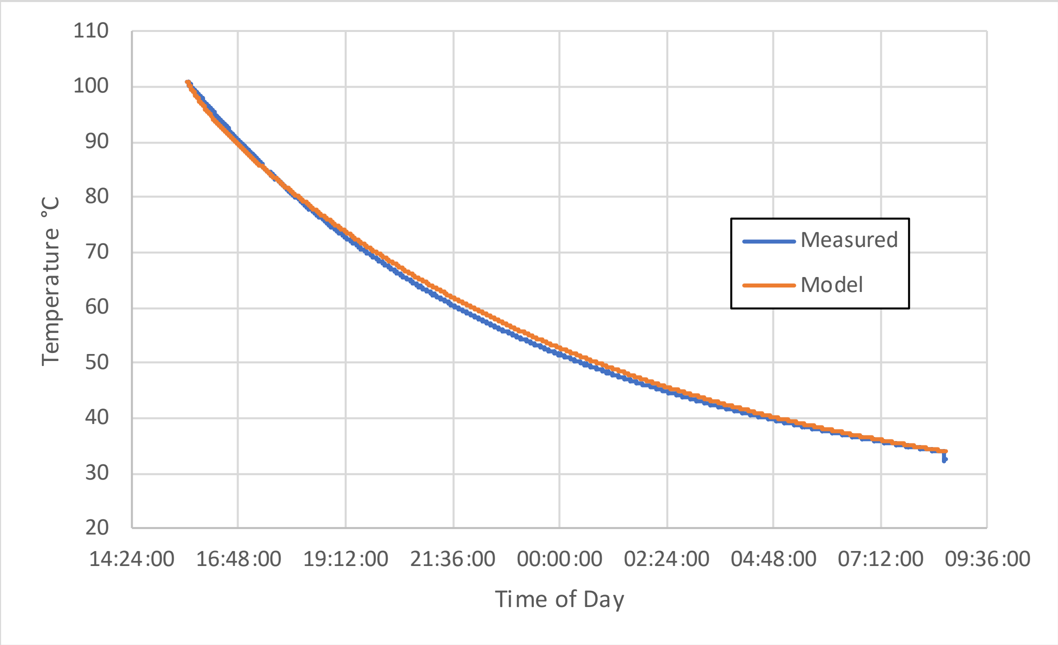


Figure 9. Measured and modelled temperature of 1.5 litres of water as it cools from boiling towards ambient temperature in the unmodified vacuum kettle.

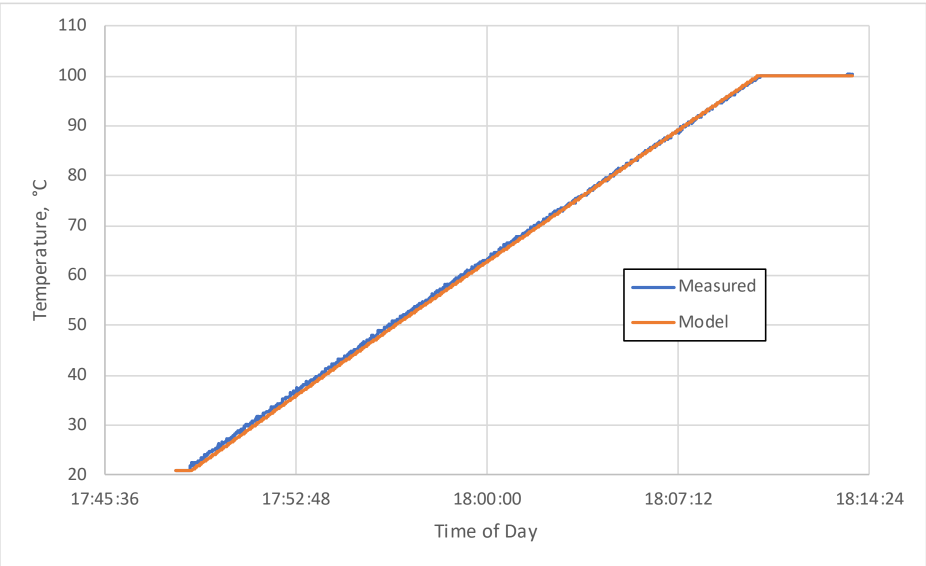


Figure 10. Measured and modelled temperatures while heating 1.5 litres of water using 115V AC electricity with extra insulation added.

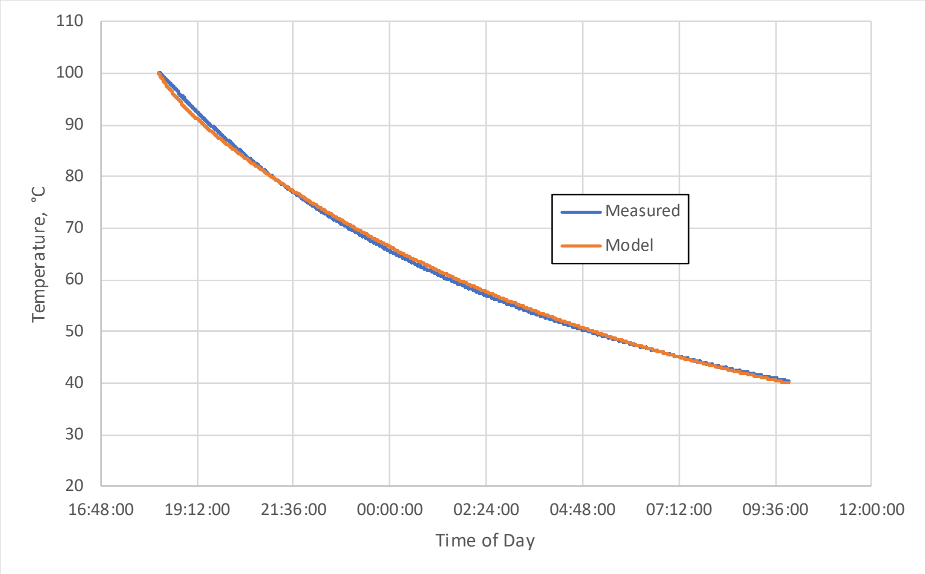


Figure 11. Measured and modelled temperatures of 1.5 litres of water cooling from boiling towards ambient with extra insulation added.

Limitations of the Model

The model works well with large amounts of water in the kettle and fast heating times. The reduced heat loss coefficient, k2, models the benefit of added insulation very well. However, some behaviour is not so well modelled.

Firstly, when the amount of water in the kettle is very small, 0.2 litres or 0.5 litres, the measured temperature lags behind the modelled temperature during the heating phase, Figure 12.

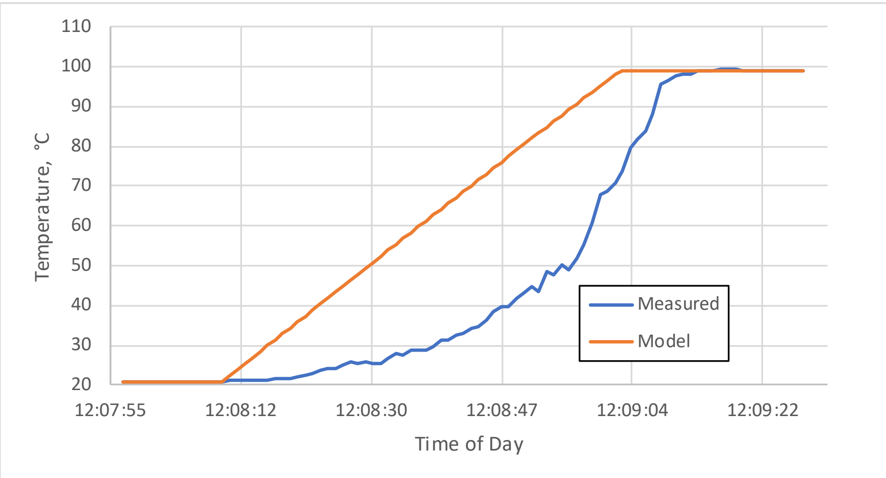


Figure 12. Measured and modelled temperatures while heating 0.2 litres of water using 230V AC electricity in the unmodified vacuum kettle.

The temperature lag in Figure 12 may be because none of the thermocouples reached down below the water level, and because the air above the water was cooler.

Secondly, when the heating power is low, the water takes longer than expected to reach boiling point, see Figure 13. The rate of temperature rise slows significantly as the water approaches boiling point. This effect is particularly strong with low voltage and power and only a small amount of water in the kettle,

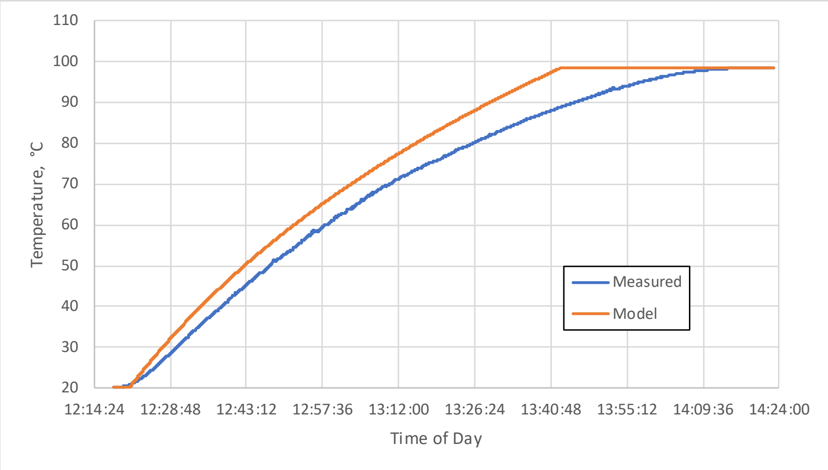


Figure 13. Measured and modelled temperatures while heating 0.2 litres of water using 30V DC electricity with extra insulation added.

Energy Use and Losses

Using the measured data, the energy used to boil water has been calculated. The electrical energy input was measured up to the point of boiling. Boiling point was determined either by the automatic switch off of the kettle's own switch, or the time at which the water temperature stabilised if automatic switch-off did not occur.

The thermal model has been used to estimate the energy losses by thermal conduction and parasitic heating of the inner and outer portions of the kettle. Additional heat losses occur due to apparent additional conduction and/or evaporation, both before and after boiling point or switch off.

Performance

The data is summarised in Figure 14, Figure 15 and Figure 16.

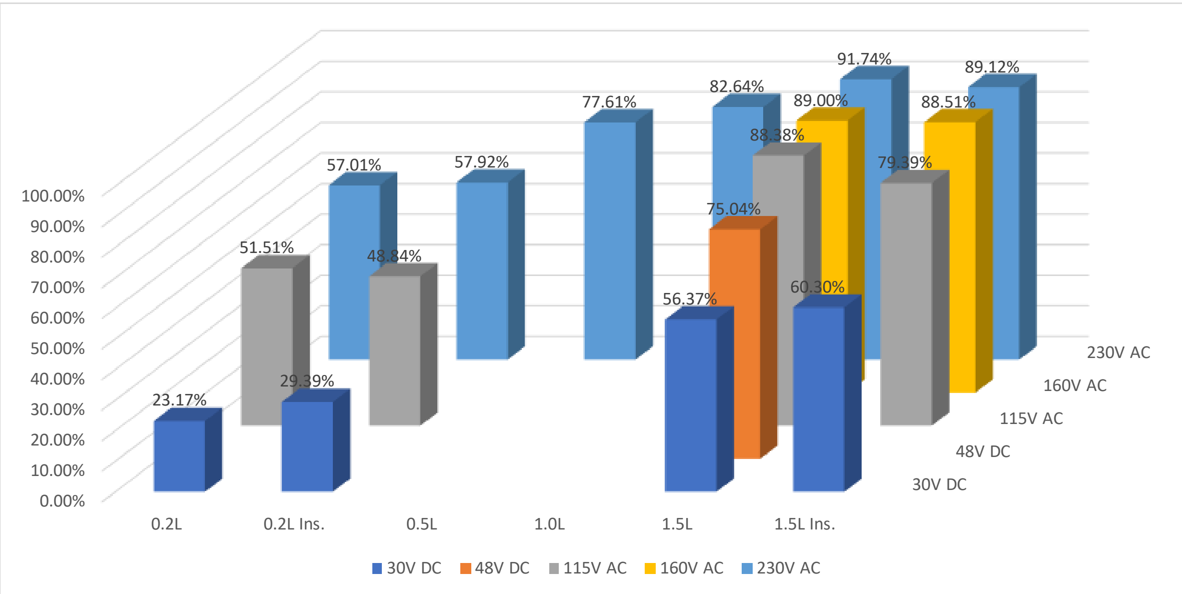


Figure 14. Percentage of electrical energy going to heat water, up to boiling point.

The percentage of energy that usefully heats water in the kettle depends strongly on the amount of water in the kettle, and on the applied voltage, Figure 14. When the amount of water is small, the parasitic thermal mass of the kettle becomes significant, especially when the kettle has less than 0.5

litres (less than 1/3 full). Low voltages also result in low efficiency, as the longer heating time allows more heat to flow into the outer body of the kettle and into the environment.

During the heating phase, no significant benefit is seen from adding extra insulation, labelled 'Ins' on Figure 14. The insulation might reduce heat flow rate from the kettle, but also adds parasitic thermal mass.

The heat losses during the boiling phase appear to be strongly linked to the time taken to boil the kettle, Figure 15 (Monk, 2020). Again, there appears to be no significant benefit from adding extra external insulation to the kettle while boiling.

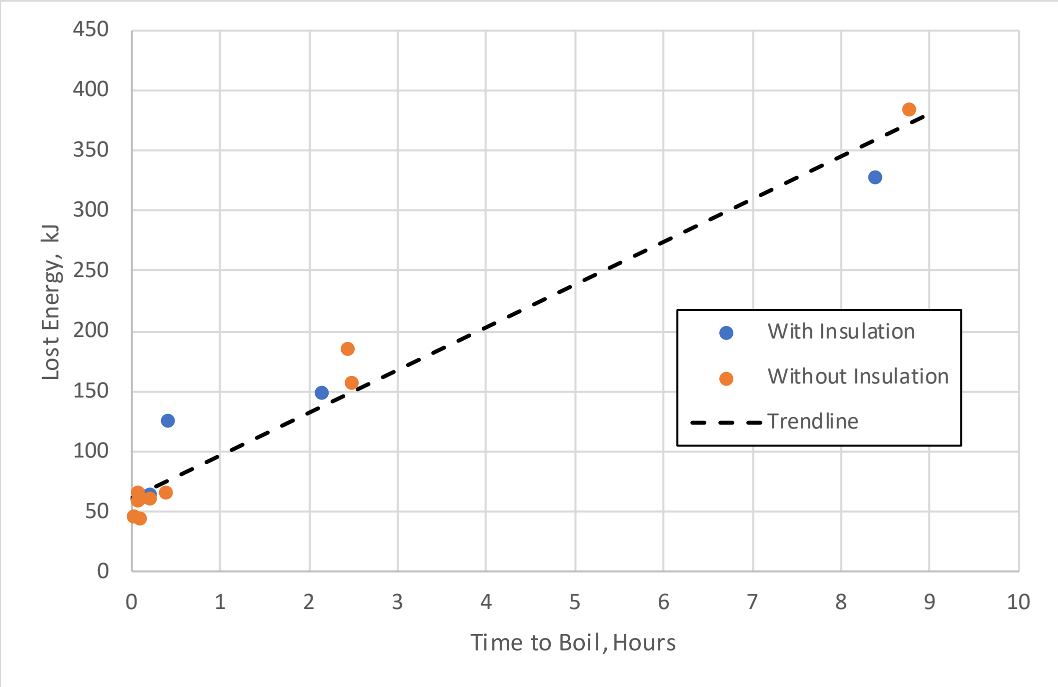


Figure 15. Energy lost to thermal conduction and parasitic thermal mass whilst heating to boiling point

The thermal model fits the cooling down phase less well and less consistently. An objective measure of the cooling rate was the time taken to cool from 99°C to 94°C, as measured by a thermocouple positioned in the water, provided it was giving stable readings. This was usually the one 12.5cm down inside the kettle, but occasionally the one 7.5cm down.

We do not know for certain the temperature of the outer parts of the kettle, nor do we accurately know the thermal mass of those outer parts. Therefore, we cannot know the thermal energy (sensible heat) contained in the outer parts of the kettle, and the true heat flow rate. However, by comparing similar tests with and without added insulation, we can see the benefit of that insulation as a percentage reduction in heat loss rate. We can also calculate the heat loss rate from the water itself, Figure 16.

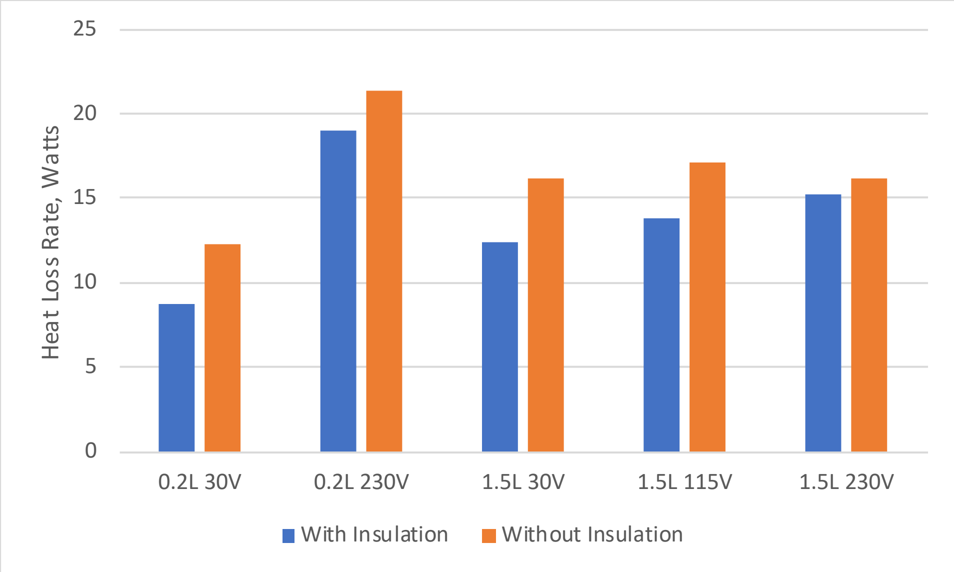


Figure 16. Heat loss rate from water in the kettle as the water cools from 99°C to 94°C, with and without added external insulation

The percentage reduction in water heat loss rate provided by the added insulation varies greatly, from 6% to 29% depending on the test. In longer tests, there was plenty of time for heat to soak into the outer parts of the kettle, whereas in shorter tests the outer parts could still be quite cool. The quality of insulation fitting was also variable, as was the amount of insulation. In some tests, the kettle base was insulated, but not in all, Table 1. Description of power tests, Table 1.

Although a definite reduction in heat loss rate is seen, that reduction may not be worth the cost and inconvenience of adding insulation. Typical heat loss rate without insulation is about 17 watts and typical heat loss rate with insulation is about 14 watts. The vacuum kettle is already very well insulated in its manufactured state.

Switch-off Reliability

The above results prove that the kettle will heat up and boil at a range of voltages down to 30 V, but the kettle does not turn itself off at the lower voltages and resulting lower power levels. Like most kettles, the Vektra vacuum kettle relies on a jet of steam released through the top of the kettle to activate the automatic switch off.

The minimum voltage and power were therefore measured with the minimum and maximum water level, with and without added insulation as described in Table 1. The kettle was first boiled and then re-boiled by stepping up the voltage until it turned off. The results are summarised in Table 2:

Table 2. Results of the turn-off tests with increasing voltages

Volume of water	Added insulation	Turn-Off Voltage (Volts)	Turn-Off Power (Watts)
1500 ml	None	98	296
1500 ml	Top and sides	96	282
200 ml	None	106	346
200 ml	Top and sides	102	320

The added insulation appears to make the kettle turn off at a slightly lower power, but the effect is small. The amount of water in the kettle has a larger effect on minimum turn-off voltage.

The turn-off tests also give a measurement of the kettle's electrical resistance as a function of voltage, Figure 17. In all cases, the electrical resistance was found to be very consistent, with values between 32.45 Ω and 32.87 Ω.

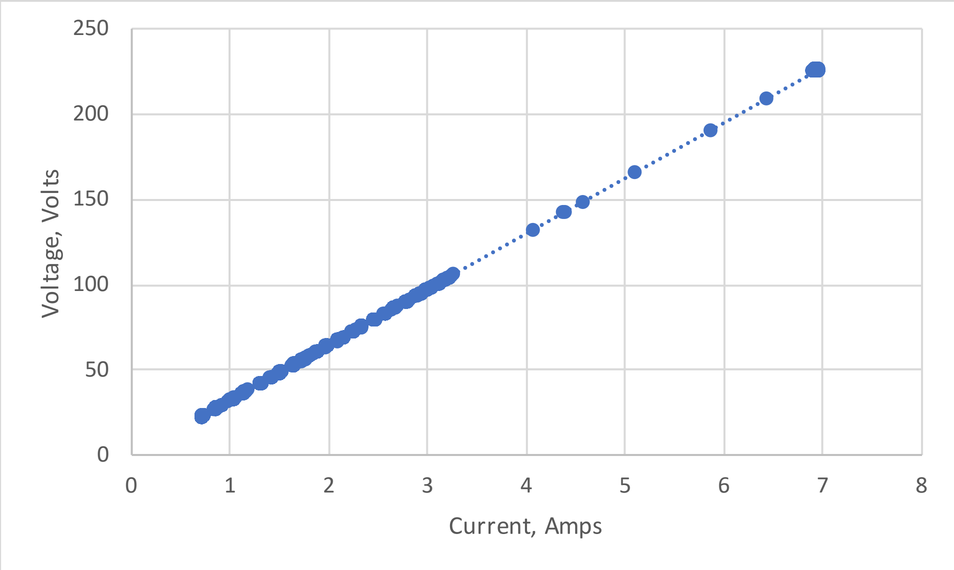


Figure 17. Voltage as a function of current with 200g of water and no added insulation. Test results measured during the turn-off test.

7. Discussion and Conclusions

The Vektra vacuum kettle looks promising for pre-heating water and thereby reducing the energy demand from batteries. This pre-heating is recommended as a use of surplus solar PV power.

At its design voltage range of 220V to 240V, the power level of the Vektra kettle is confirmed to be between 1470 W and 1750 W.

The kettle could be run at lower voltage and lower power in order to consume part of the output of one or two 300 W solar PV modules. If continuous boiling is tolerated, then the voltage supplied to the kettle could be as low as 30 V, resulting in a power input rate of 28 W and a boiling time of over 9 hours. This operation of the kettle could be achieved by using a diverter switch to use only surplus PV power. Alternatively, the kettle could be connected directly to PV modules, upstream of a battery charge controller but that would probably distort the maximum power point tracking (MPPT) of the charge controller.

If, on the other hand, the kettle is required to switch itself off when boiled, the minimum voltage is at least 110 V, and should be 120 V to be more safely reliable in switching off as shown in Table 2. North American inverters supply power at voltages between 110V and 120V, and one of these could be used to boil the kettle more slowly. The power consumption of the kettle at 120 V is about 440 W.

The thermal energy stored in the Vektra kettle by increasing the water temperature of 1.5 litres of water from e.g. 20°C to 100°C is 504 kJ or 0.14 kWh. The purchase cost of the kettle is £60 in the UK at the time of writing and therefore the cost of thermal energy storage is just over £400/kWh. This is a similar price to battery energy storage, but the kettle is expected to last longer than a battery, performing more heating cycles.

The estimated heat loss rate from the water is 17 W as shown in Figure 16, and this represents a self-discharge rate of thermal energy storage of 12% per hour. If left to cool down for 4 hours, e.g. from 5pm to 9pm, the temperature of 1.5 litres of water will drop to 70°C. If left to cool down overnight, for example 14 hours from 5pm to 7am, then 1.5 litres of water will cool to about 40°C when the ambient temperature is 22°C. In practice, the water is still warm enough for washing, and the previous day's boiling will have killed pathogens if the water is required for drinking.

In conclusion, the Vektra vacuum kettle could be used as an affordable solar powered water heater, as an addition to a solar home system that enables electric cooking. The pros and cons are listed below:

Advantages

- Affordable price comparable to the cost of one solar PV module
- Keeps water hot for 4 hours
- Makes water safe to drink
- Pre-heated hot water can reduce cooking times
- A durable form of energy storage with long cycle life

Disadvantages

- Cannot keep water hot overnight – as a form of energy storage it has a high self-discharge rate and added insulation cannot change that fact
- As a form of energy storage, it is not much cheaper than a battery
- A power diverter is needed to use only surplus solar power
- Alternatively, direct connection to PV modules would reduce the effectiveness of MPPT tracking if placed in parallel to battery charging.

8. References

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9. Appendix: More Test Results

Low Voltage Turn-Off Tests

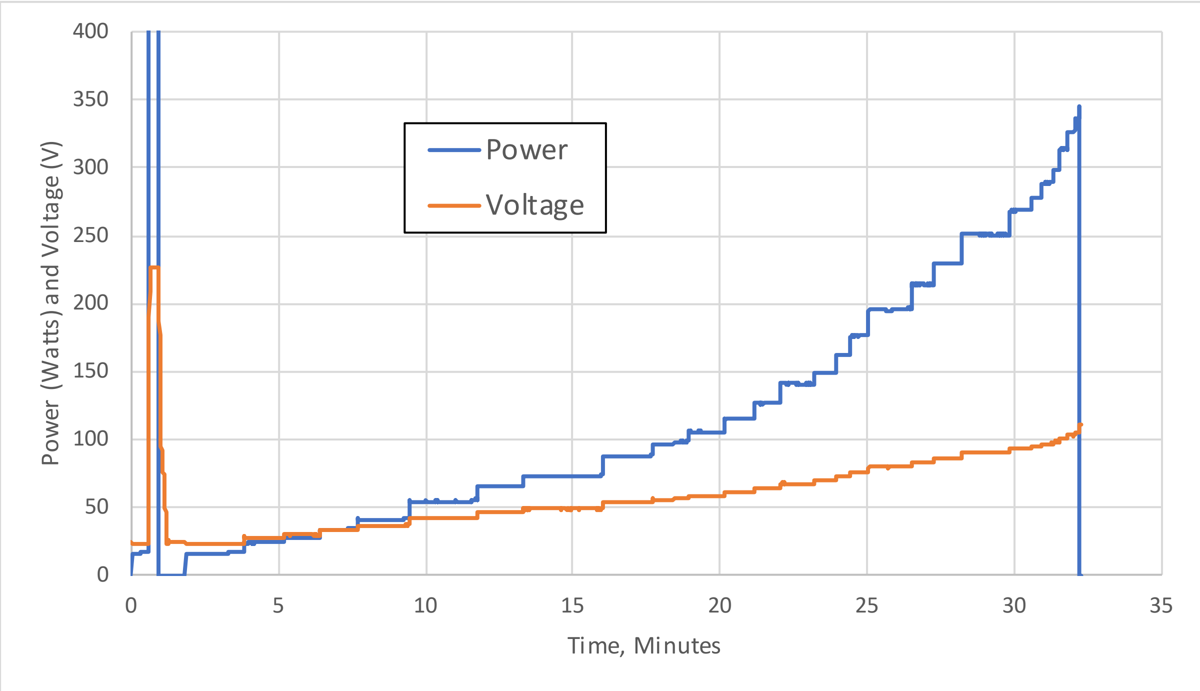

Figure 18. Turn-off test with 200g of water, no added insulation

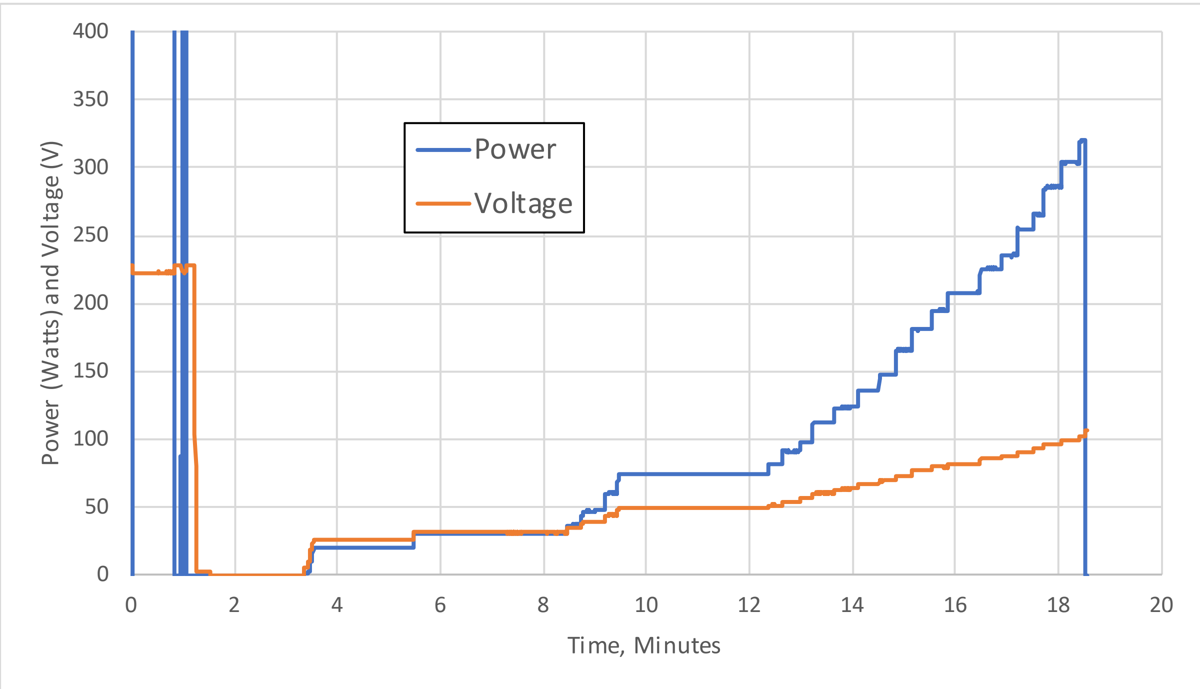

Figure 19. Turn-off test with 200g of water, with added insulation

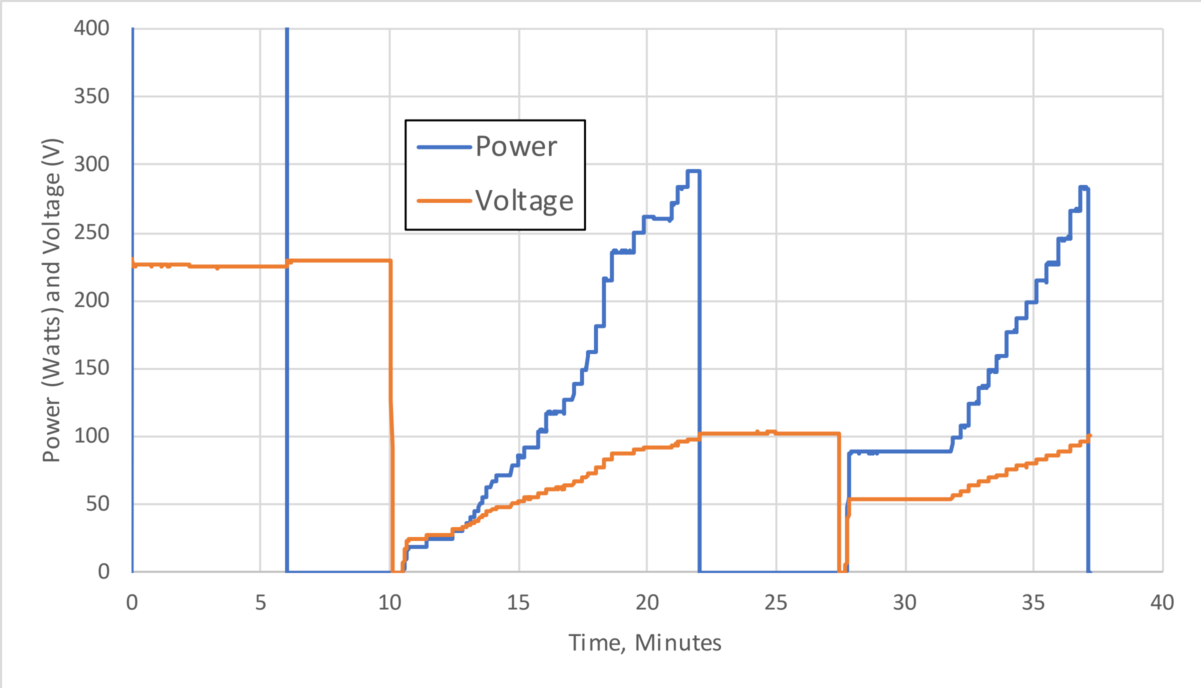

Figure 20. Turn-off test with 1500g of water, without and then with added insulation