Physics Extended Assessment

Analysing Effect of Voltage Change in Heating Performance of Tubular Electrical Coils

May 2025

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1. Research Question

What does the effect of voltage change on the performance of tubular electrical coils?

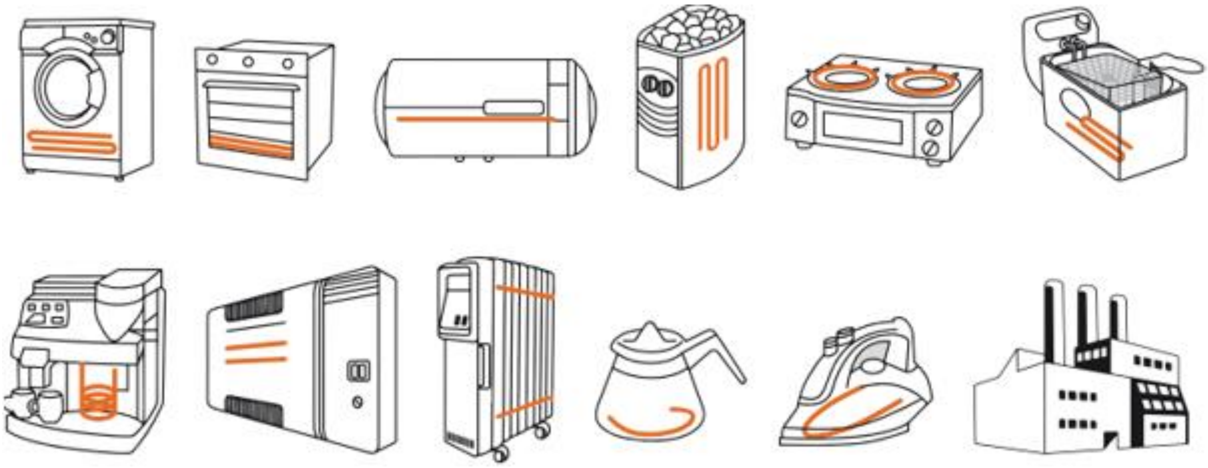
2. Introduction

While studying physics topics, I brought together two topics that showed my curiosity and realized that they were very similar. The forms of heat and electricity were very similar to each other, both when evaluated in terms of general formulas. Electricity uses the voltage difference, heat uses the temperature difference between the two environments, both try to overcome a resistance, and the magnitude of these values is reflected in the magnitude of the heat flow or electric current. While I was thinking about how I could combine these two issues in research, I thought that electric heaters could be a solution to this issue.

Electricity is also used for heating purposes in many areas of life from comfort heating to hot water supply, from household appliances such as ovens, washing machines and dishwashers to large-scale industrial ovens.

In this study, I will examine tubular electrical heating coils used in small home appliances. To examine how these heaters may be affected by electrical fluctuations in the city network, I will test the heaters. I will use different types of coils at different voltages and examine the changes in their heating capacities and surface temperatures. I will also compare theoretical heating capacities with experimental ones, so instead of saying total heating capacity I will trye to show actual daily situation.

Figure1: General applications of tubular type electrical heating coils in household appliance

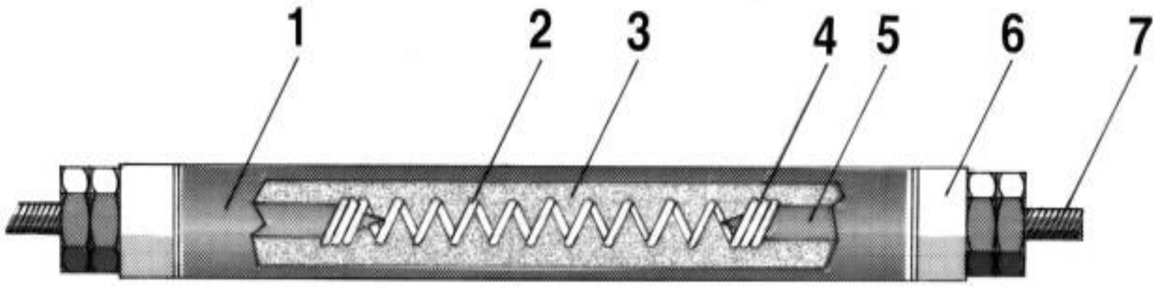


3. Background Information

3.1 Electrical Heating Coils

Today tubular heating elements can be found almost anywhere from coffee machines to cab heaters. The ability to efficiently transfer heat from an electric current makes heating elements an efficient source for heating. The technology itself is used today as a modern way of intelligent heating, but many challenges are ahead. Inside the metal tube, a resistance coil is embedded and electrically isolated in highly compressed magnesium oxide. When an electric current is applied to a heating element, a heating wire in its core heats up, and generated heat is transferred to a mantle at the element periphery through an insulation material. The insulation material should be blocking the conduction of electric current from the heating wire to the mantle while conducting heat with minimum losses. This enables efficient heating of surrounding medium, which is the main purpose of a heating element operation. (1)

Figure2: Electrical Tubular Coils and Its Heating Elements (2)



1. Steel, stainless steel, copper, or Incoloy sheathed elements.
2. Element wire situated in proximity to outside surface for maximum heat transfer and minimum internal temperature while preserving good dielectric qualities.
3. Pure magnesium oxide compressed to an optimum density for best heat transfer and electrical insulation at elevated temperatures.
4. Weld connection.
5. Cold pin.
6. Insulator.
7. Standard post terminal.

Figure 3:Different Types of Commercial Electrical Tubular Coils

3.2 General Standards Used in Capacity Calculations

Following standards are used in design of tubular heating elements.

EN 60335 Safety of household and similar electrical appliances General requirements (2)

EN 60335-2-9 Safety of household and similar electrical appliances Particular requirements for toasters, grills, boilers and similar appliances.

EN 60335-2-15 Safety of household and similar electrical appliances Particular requirements for appliances for heating liquids.

EN 60.335-2-30 Safety of household and similar electrical appliances Particular requirements for room heaters.

EN 60.335-2-73 Safety of household and similar electrical appliances Particular requirements for fixed immersion heaters.

EN 60335-1 – Electric tubular heating elements for use in household appliances EU-guideline 1907/2006/EG – REACH

3.3 General Formulas Used in Capacity Calculations

Following formulas can be used in capacity calculation of tubular electrical coils (3).

- **Power**

Formula-1

$$P = V * I \text{ or } P = \frac{V^2}{R}$$

P is the power (or capacity) in watts (W),

V is the voltage applied across the coil in volts (V),

I is the current flowing through the coil in amperes (A).

R is the resistance of the coil in ohms (Ω).

- **The surface load (or surface power density)** of a heating element refers to the power output per unit area of the heating surface. This is an important parameter in heating element design, as it impacts the efficiency and lifespan of the heater.

Formula-2

$$SURFACE\ LOAD = \frac{P}{A}$$

where,

Surface Load is in watts per square centimetre (W/cm^2)

P is the total power of the heating element in watts (W),

A is the surface area of the heating element in square centimetres (cm^2)

- **Calculating the Surface Area for a Tubular Heating Element**

For a tubular heating element with a cylindrical shape:

Formula-3

$$A = \pi * d * L$$

where,

A is the Surface Area for a Tubular Heating Element (cm^2)

d is the diameter of the tubular element (cm)

L is the length of the tubular element. (cm)

3.4 Importance of Studying the Effect of Voltage Changes in Heating Performance of Tubular Electrical Coils

With this study following items can be understood and design of coils can be improved.

- Impact on Heating Power Output
- Energy Efficiency and Cost Implication
- Thermal Stress and Longevity of Heating Elements
- Control and Precision in Temperature-Sensitive Applications
- Adaptation to Variable Power Supplies
- Safety Concern

3.5 Previous Academic Papers

Related with electrical type heaters there are several academic research s. Some of them can be given as;

- “RESEARCH PROGRESS OF WEARABLE ELECTRIC HEATING ELEMENTS” by Shuo GAO, Runjun SUN, Yan FENG and Jingxian HAO (4) They studied the research progress of electric heating elements is summarized in terms of heating element type and thermal performance evaluation. Their shortcomings are summarized, and the development trend is pointed out to provide help and direction guidance for the research of electric heating element.
- “Optimization of tubular heating elements” by Victor Almblad (1). The studies made in this project were able to provide a better understanding of how moisture affect electrical insulation of heating elements while also contributing useful knowledge regarding sealing materials.
- “Protecting Tubular Heating Elements Against Moisture” by Roland J. Knouff (5). This paper presents a method of treating tubular heating elements operating below 550°F so as to minimize the effect of moisture on the impedance between the sheath and the heater wire of the element.

4. Hypothesis

In my experiment, I will test five similar tubular type electrical heating coil with different voltages. I will record output power and surface temperature to calculate surface load. Therefore, I am expecting that increasing the voltage will increase the output power and surface load but after certain value it will be dangerous for daily use.

5. Variable Identification

5.1 Independent Variable

The electrical resistance and voltages of tubular type electrical heating coil will be tested are 41,8 , 44,1 , 69 and 70,2 ohm and 195, 200,205,210,215,220,225,230,235,240 Volt. Room temperature will be 25°C.

5.2 Dependent Variable

Output power in watt and surface temperature in °C of tubular type electrical heating coil are variable. I will measure in response to changes in the voltage.

Controlled Variables

Table1: Controlled variables

Controlled Variables	Method for Control	Reason for Control
Di-electrical test device	Same device was used	Different device will have different calibrations and affect the measured values.
Environmental Conditions	Indoor temperature, is recorded and checked	Indoor temperature can affect heat transfer from heating coil to room.
Connection cables	The same cable was used	The length and types of cables will affect the measured values.

6. Material and Equipment

Table2: Materials and Equipment list used in experiment.

Materials:	Equipment:
Tubular type electrical coils CODE: 24438 230V/1300W (3Ea) CODE:24421 230V/1200W (1Ea) CODE:22872 230V/800W (1Ea) CODE:26406 220V/700W(1Ea)	Germak Di-electrical test device
Connection cables (2 Ea)	Thermo Electra PCE-T312N Thermometer for surface temperature
	Thermometer for room temperature

7. Procedure

The following steps will be followed

Pre-test preparations

1. Di-electrical test device operator requirements: A qualified adult operator with a valid license must provide guidance during the test.
2. Preparation of tubular type electrical heating coils: 5 each coil will be ready.
3. Environmental conditions: Record the indoor temperature at the test location.
4. Safety measures: Check the emergency stop of di-electrical test device with the operator.

During the test

1. Take one tubular type electrical heating coil connect to the di-electrical test device by using connection cables.
2. Open the test device and set voltage at 195 V.

3. Record output power in watt and surface temperature of coil.
4. Repeat this procedure with 200,205,210,215,220,225,230,235,240 Volts.
5. Repetition for Accuracy: Repeat the test five times with other coils to ensure consistent and reliable results.

Safety Precautions and Environmental Issues

- The operator must be authorized.
- Perform a thorough inspection of the devise before each test to ensure that all systems, are in optimal condition.
- Have a plan in place for emergencies, including emergency stops, first aid kits, and quick access to emergency services.
- Ensure that all participants are well-informed about the procedures and safety measures to follow during the experiment.

Table3: The experiment their possible threats, and safety precautions and disposal of them

Equipment	**Possible Threat**	**Safety Precautions and Disposal**
Di-electrical test device	Electrical leakage	Stop the device by using emergency stop.
Tubular type electrical coils	Overheating	Stop the device by using emergency stop.
Di-electrical test device	Excessive power consumption	Stop the devise while changing the tubular type of electrical coils.
Tubular type electrical coils	Waste Management	Properly dispose of any waste materials or damaged parts, in accordance with local environmental regulations.

8. Data

By following above procedure, data obtained in experiment were tabulated below.

8.1 Quantitative Data

8.1.1 Indoor temperature

Indoor temperature of testing area is recorded as 25°C and it remained same during the experiment.

8.1.2 Di-electrical test device & Tubular type electrical coils

Figure4: Di-electrical test device and Tubular type electrical coils used in experiment

Raw Data

Table4: 1300 W Coils output powers and surface temperatures

ITEM	CODE: 24438 230V/1300W								
OHM	41,80 OHM								
NO	VOLT	SAMPE-1		SAMPE-2		SAMPE-3		MEAN	
		WATT	TEM. °C	WATT	TEM. °C	WATT	TEM. °C	WATT	TEM. °C
1	195,0	875,0	413,0	880,0	412,0	875,0	413,0	876,7	412,7
2	200,0	920,0	415,0	915,0	415,0	925,0	418,0	920,0	416,0
3	205,0	960,0	420,0	955,0	418,0	960,0	420,0	958,3	419,3
4	210,0	1020,0	430,0	1015,0	430,0	1020,0	430,0	1018,3	430,0
5	215,0	1070,0	440,0	1070,0	440,0	1080,0	443,0	1073,3	441,0
6	220,0	1120,0	460,0	1115,0	458,0	1130,0	462,0	1121,7	460,0
7	225,0	1160,0	470,0	1190,0	474,0	1180,0	474,0	1176,7	472,7
8	230,0	1230,0	475,0	1245,0	480,0	1240,0	478,0	1238,3	477,7
9	235,0	1270,0	520,0	1295,0	525,0	1280,0	524,0	1281,7	523,0
10	240,0	1320,0	570,0	1310,0	570,0	1350,0	576,0	1326,7	572,0

Table5: 700-800-1200 W Coils output powers and surface temperatures

ITEM	VOLT	CODE:24421 230V/1200W		CODE:22872 230V/800W		CODE:26406 220V/700W	
OHM		44,10 OHM		69,0 OHM		70,20 OHM	
NO		WATT	TEM. °C	WATT	TEM. °C	WATT	TEM. °C
1	195,0	830,0	307,0	530,0	225,0	510,0	250,0
2	200,0	875,0	310,0	555,0	230,0	540,0	270,0
3	205,0	920,0	315,0	580,0	270,0	565,0	285,0
4	210,0	960,0	320,0	612,0	285,0	600,0	310,0

5	215,0	1010,0	330,0	645,0	300,0	627,0	320,0
6	220,0	1060,0	340,0	680,0	320,0	653,0	330,0
7	225,0	1100,0	360,0	705,0	340,0	685,0	340,0
8	230,0	1150,0	400,0	740,0	370,0	715,0	350,0
9	235,0	1215,0	420,0	770,0	405,0	750,0	357,0
10	240,0	1265,0	450,0	810,0	435,0	780,0	365,0

8.1.3 Observations

During the experiment following observers have been done

- Indoor room temperature did not change. However, air conditioning and ventilation system in the test area are not controlled. During the test the exhaust system which is served to hoods close to test area was started and stopped automatically this affects the indoor conditions.
- It is easy and accurate to record data from di-electric testing device.
- When voltage is increased heat dissipation from coils are increased dramatically.

Figure5: Connection of coils

9. Calculations

9.1 Power Output:

By using Formula 1, theoretical power output can be calculated as follows;

$$P = \frac{V^2}{R}$$

For coil 24438 1300W

V=195 V R=41,8 ohms (Ω).

$$P = \frac{195*195}{41,8} = 909,7$$

P= 909,7 watt

Since experimental value of P=876,7 W

$$\% efficency = \frac{\text{experimental value}}{\text{theoretical value}} = \frac{876,7}{909,7} = \%96,4$$

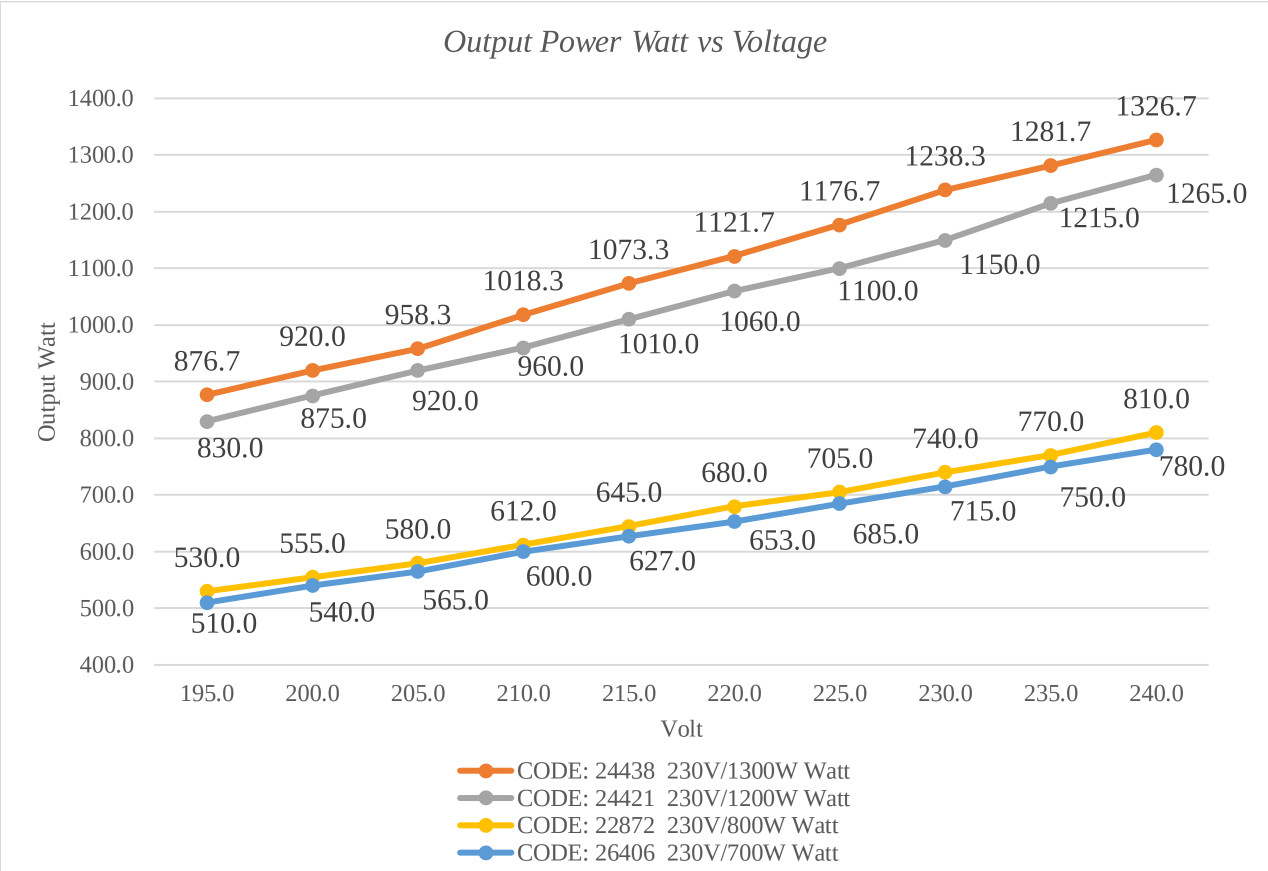
By using same method all values are tabulated in Table 6.

Table6: Comparison of Theoretical and Actual Power Output (Watt)

ITEM	VOLT	CODE: 24438 230V/1300W			CODE: 24421 230V/1200W		
OHM		41,80 OHM			44,10 OHM		
NO		Watt Mean	Watt Theoretical (V*V/R)	Efficiency %	Watt	Watt Theoretical (V*V/R)	Efficiency %
1	195,0	876,7	909,7	96,4%	830,0	862,2	96,3%
2	200,0	920,0	956,9	96,1%	875,0	907,0	96,5%
3	205,0	958,3	1005,4	95,3%	920,0	952,9	96,5%
4	210,0	1018,3	1055,0	96,5%	960,0	1000,0	96,0%
5	215,0	1073,3	1105,9	97,1%	1010,0	1048,2	96,4%
6	220,0	1121,7	1157,9	96,9%	1060,0	1097,5	96,6%
7	225,0	1176,7	1211,1	97,2%	1100,0	1148,0	95,8%
8	230,0	1238,3	1265,6	97,8%	1150,0	1199,5	95,9%
9	235,0	1281,7	1321,2	97,0%	1215,0	1252,3	97,0%
10	240,0	1326,7	1378,0	96,3%	1265,0	1306,1	96,9%
Mean				96,7%			96,4%

ITEM	VOLT	CODE: 22872 230V/800W			CODE: 26406 230V/700W		
OHM		69,00 OHM			70,20 OHM		
NO		Watt	Watt Theoretical (V*V/R)	Efficiency %	Watt	Watt Theoretical (V*V/R)	Efficiency %
1	195,0	530,0	551,1	96,2%	510,0	541,7	94,2%
2	200,0	555,0	579,7	95,7%	540,0	569,8	94,8%
3	205,0	580,0	609,1	95,2%	565,0	598,6	94,4%
4	210,0	612,0	639,1	95,8%	600,0	628,2	95,5%
5	215,0	645,0	669,9	96,3%	627,0	658,5	95,2%
6	220,0	680,0	701,4	96,9%	653,0	689,5	94,7%
7	225,0	705,0	733,7	96,1%	685,0	721,2	95,0%
8	230,0	740,0	766,7	96,5%	715,0	753,6	94,9%
9	235,0	770,0	800,4	96,2%	750,0	786,7	95,3%
10	240,0	810,0	834,8	97,0%	780,0	820,5	95,1%
Mean				96,2%			94,9%

Graphic 1: Change of Actual Power Output (Watt)with Voltage Change

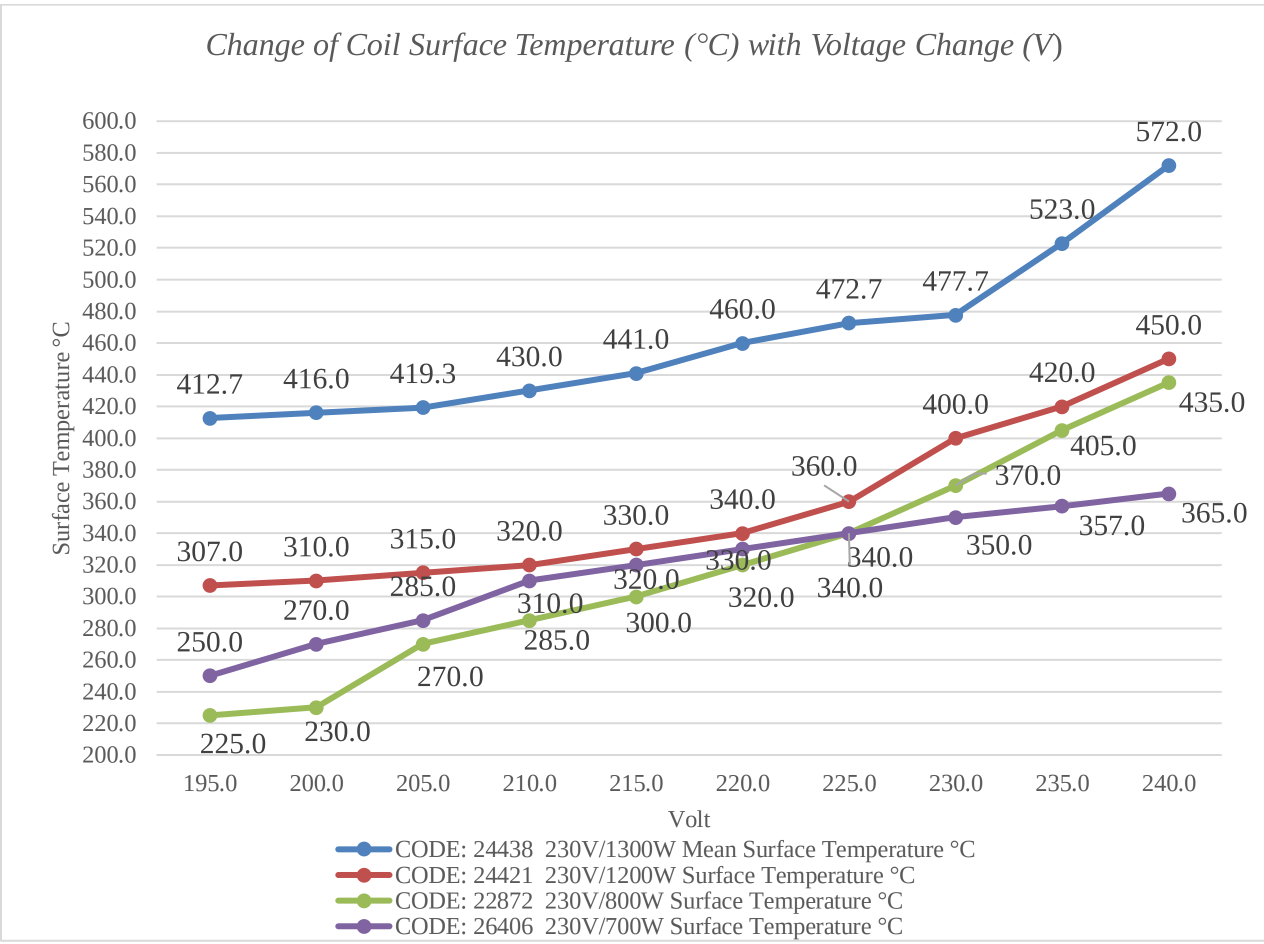


9.2 Surface Temperatures:

Table7: Comparison of Coil Surface Temperature (°C) with Voltage (V)

VOLT	CODE: 24438 230V/1300W Mean Surface Temperature °C	CODE: 24421 230V/1200W Surface Temperature °C	CODE: 22872 230V/800W Surface Temperature °C	CODE: 26406 230V/700W Surface Temperature °C
195,0	412,7	307,0	225,0	250,0
200,0	416,0	310,0	230,0	270,0
205,0	419,3	315,0	270,0	285,0
210,0	430,0	320,0	285,0	310,0
215,0	441,0	330,0	300,0	320,0
220,0	460,0	340,0	320,0	330,0
225,0	472,7	360,0	340,0	340,0
230,0	477,7	400,0	370,0	350,0
235,0	523,0	420,0	405,0	357,0
240,0	572,0	450,0	435,0	365,0

Graphic 2: Change of Coil Surface Temperature (°C) with Voltage Change (V)



9.3 The surface load (or surface power density):

In standard EN 60335 maximum surface load for dry application is given by 7 watt/cm^2 (2) and when high operating temperatures are needed, watt density must be limited in order not to exceed the maximum sheath temperature. Watt density is given in the specifications for each tubular heater (6). Therefore, by using Formula 2&3 the surface load can be calculated as follows.

$$SURFACE\ LOAD = \frac{P}{\pi * d * L}$$

where Coil Code : 24438 230V/1300W d:6,4 mm L: 1800 mm
Coil Code : 24421 230V/1200W d:6,4 mm L: 1750 mm
Coil Code : 22872 230V/800W d:6,4 mm L: 1200 mm
Coil Code : 26406 230V/700W d:6,4 mm L: 1000 mm

For coil CODE: 24438 230V/1300W at 195V mean power output is 876,7 watt therefore,

$$SURFACE\ LOAD = \frac{P}{\pi * d * L}$$

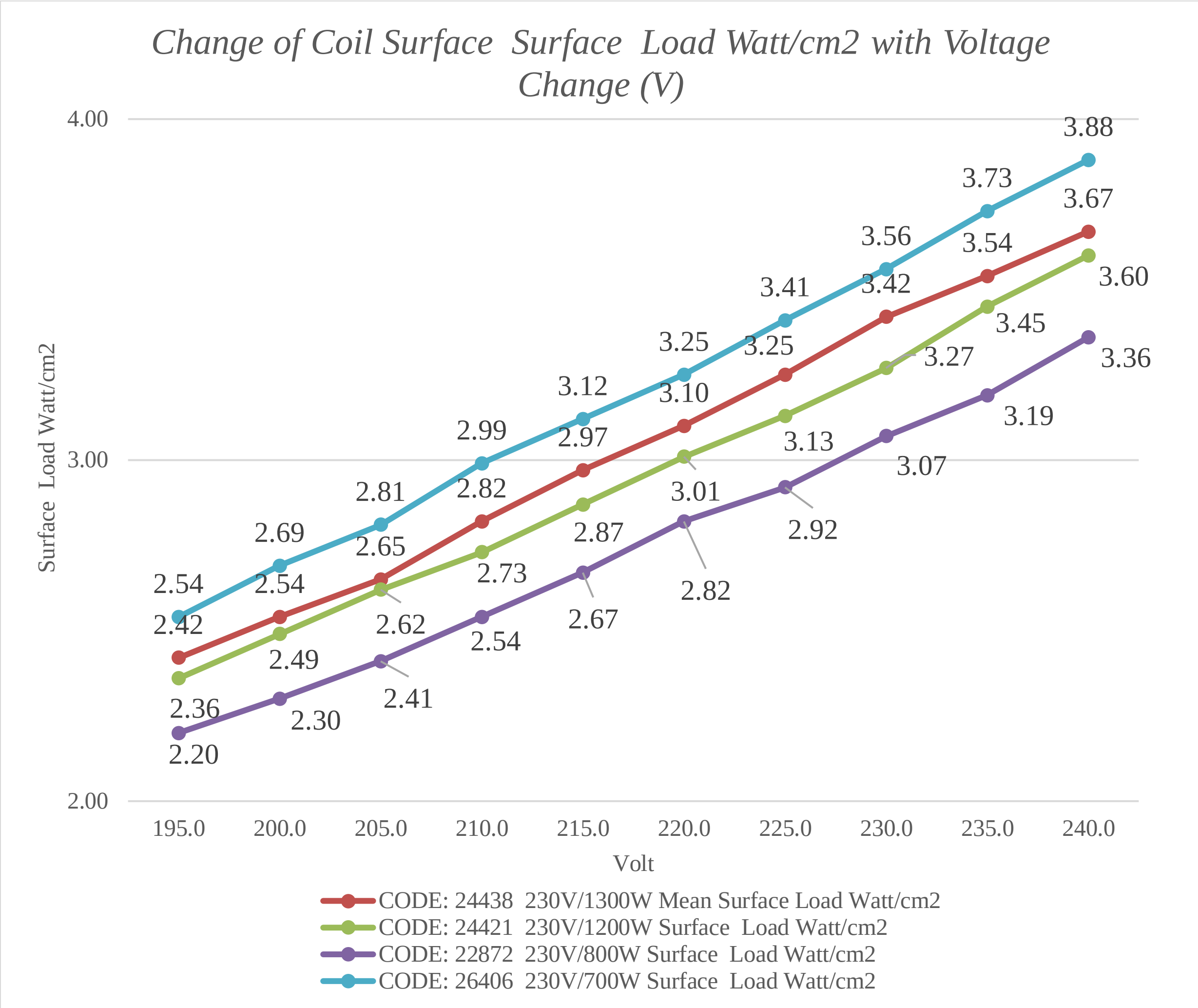
$$SURFACE\ LOAD = \frac{876{,}7}{\pi * 0{,}64 * 180} = 2{,}42\ watt/cm2$$

Which is less than 7 watt/cm^2. By using same method all values are tabulated in Table 8.

Table8: Comparison of Coil Surface Load Watt/cm^2 with Voltage (V)

VOLT	**CODE: 24438 230V/1300W Mean Surface Load Watt/cm2**	**CODE: 24421 230V/1200W Surface Load Watt/cm2**	**CODE: 22872 230V/800W Surface Load Watt/cm2**	**CODE: 26406 230V/700W Surface Load Watt/cm2**
195,0	2,42	2,36	2,20	2,54
200,0	2,54	2,49	2,30	2,69
205,0	2,65	2,62	2,41	2,81
210,0	2,82	2,73	2,54	2,99
215,0	2,97	2,87	2,67	3,12
220,0	3,10	3,01	2,82	3,25
225,0	3,25	3,13	2,92	3,41
230,0	3,42	3,27	3,07	3,56
235,0	3,54	3,45	3,19	3,73
240,0	3,67	3,60	3,36	3,88

Graphic 3: Changes of Coil Surface Load Watt/cm^{2}with Voltage (V)



9.4 Error Calculations

In the experiment I set voltage at “GEMAK di-electric testing device” and read power output watt and by using “Thermo Electra PCE-T312N Thermometer” I read surface temperature also therefore,

Error Calculation in the Di-electric testing device:
Accuracy of Scale: +/- 0,1 volt., +/- 0,1 watt.,
Error Percentage (E1) = 0,1/ (Measured Voltage) %
Error Percentage (E2) = 0,1/ (Measured Watt) %

Formula-4

Formula Total Error = $\sqrt{(E1)^2 + (E2)^2}$ %

Calculation of Error in Surface Temperature:
Thermo Electra PCE-T312N Thermometer: +/- 0,1 °C.
Error Percentage (E2) = 0,1/ (Measured Temperature) % By using these formulas total error can be calculated as follows.

Table9: Error calculations for output power (watt)

VOLT	Error Percentage (E1) = 0,1/ (Measured Voltage) %	CODE: 24438 230V/1300W Watt			CODE: 24421 230V/1200W Watt		
		Watt	Error Percentage (E2) = 0,1/ (Measured Watt) %	Formula 4 Total Error %	Watt	Error Percentage (E2) = 0,1/ (Measured Watt) %	Formula 4 Total Error %
195,0	0,051%	876,7	0,011%	0,053%	830,0	0,012%	0,053%
200,0	0,050%	920,0	0,011%	0,051%	875,0	0,011%	0,052%
205,0	0,049%	958,3	0,010%	0,050%	920,0	0,011%	0,051%
210,0	0,048%	1018,3	0,010%	0,049%	960,0	0,010%	0,049%
215,0	0,047%	1073,3	0,009%	0,047%	1010,0	0,010%	0,048%
220,0	0,045%	1121,7	0,009%	0,046%	1060,0	0,009%	0,047%
225,0	0,044%	1176,7	0,008%	0,045%	1100,0	0,009%	0,046%
230,0	0,043%	1238,3	0,008%	0,044%	1150,0	0,009%	0,045%
235,0	0,043%	1281,7	0,008%	0,043%	1215,0	0,008%	0,044%
240,0	0,042%	1326,7	0,008%	0,042%	1265,0	0,008%	0,043%
			Mean	0,047%		Mean	0,048%

VOLT	Error Percentage (E1) = 0,1/ (Measured Voltage) %	CODE: 22872 230V/800W Watt			CODE: 26406 230V/700W Watt		
		Watt	Error Percentage (E2) = 0,1/ (Measured Watt) %	Formula 4 Total Error %	Watt	Error Percentage (E2) = 0,1/ (Measured Watt) %	Formula 4 Total Error %
195,0	0,051%	530,0	0,019%	0,055%	510,0	0,020%	0,056%
200,0	0,050%	555,0	0,018%	0,053%	540,0	0,019%	0,055%
205,0	0,049%	580,0	0,017%	0,052%	565,0	0,018%	0,053%
210,0	0,048%	612,0	0,016%	0,050%	600,0	0,017%	0,052%
215,0	0,047%	645,0	0,016%	0,049%	627,0	0,016%	0,050%
220,0	0,045%	680,0	0,015%	0,048%	653,0	0,015%	0,049%
225,0	0,044%	705,0	0,014%	0,047%	685,0	0,015%	0,048%
230,0	0,043%	740,0	0,014%	0,046%	715,0	0,014%	0,047%
235,0	0,043%	770,0	0,013%	0,044%	750,0	0,013%	0,046%
240,0	0,042%	810,0	0,012%	0,043%	780,0	0,013%	0,044%
			Mean	0,049%		Mean	0,050%

Mean error in calculation of output power is 0,048%.

Table9: Error calculations for surface temperature (°C)

CODE: 24438 230V/1300W		CODE: 24421 230V/1200W		CODE: 22872 230V/800W		CODE: 26406 230V/700W	
Mean Surface Temperature °C	**% Error**	**Surface Temperature °C**	**% Error**	**Surface Temperature °C**	**% Error**	**Surface Temperature °C**	**% Error**
412,7	0,024%	307,0	0,033%	225,0	0,044%	250,0	0,040%
416,0	0,024%	310,0	0,032%	230,0	0,043%	270,0	0,037%
419,3	0,024%	315,0	0,032%	270,0	0,037%	285,0	0,035%
430,0	0,023%	320,0	0,031%	285,0	0,035%	310,0	0,032%
441,0	0,023%	330,0	0,030%	300,0	0,033%	320,0	0,031%
460,0	0,022%	340,0	0,029%	320,0	0,031%	330,0	0,030%
472,7	0,021%	360,0	0,028%	340,0	0,029%	340,0	0,029%
477,7	0,021%	400,0	0,025%	370,0	0,027%	350,0	0,029%
523,0	0,019%	420,0	0,024%	405,0	0,025%	357,0	0,028%
572,0	0,017%	450,0	0,022%	435,0	0,023%	365,0	0,027%
Mean	0,022%		0,029%		0,033%		0,032%

Mean error in calculation of output power is 0,029%.

10. Conclusion

This experiment was performed with a view to studying the impact of voltage variation on the performance in heating of tubular electrical coils. The investigation proposed a quantitative relation between voltage and generated heat through theoretical laws of physics. The experimental observations confirm that an increase in voltage yields an increased performance in heating for the coil, supporting direct proportionality between voltage and power loss.

The experiments, through orderly collection and analysis of data, effectively confirmed that generated heat in a coil varies with the square of voltage, in agreement with the expression. That is, small voltage increases can cause considerable increased output in heat, an important consideration in many engineering applications of electrical resistive heating.

The experimental values, nevertheless, showed deviation with theoretical values, predominantly through loss of heat, fluctuations in resistances, and instrumentation factors.

The observations in this investigation have engineering implications in terms of maximizing performance in heating coils for a range of applications, including manufacturing, domestic use, and laboratory apparatuses. In addition, an understanding of efficiency in electrical resistive heating can have a bearing in future improvements in conservation of energy and materials science.

Although in agreement with theoretical prediction, some factors of constraint and sources of inaccuracy have been determined, and refinements in experimental arrangement and techniques will have to be addressed in future improvements in experiments.

11. Discussion and Evaluations

Problems occurred during experiment

During the execution of the experiment, several challenges and limitations affected the accuracy and reliability of the results. These issues can be broadly categorized into environmental factors, instrumental constraints, and procedural errors. A detailed analysis of these problems is provided below:

1. Heat Loss to the Environment: Heat loss to the environment was one of the greatest sources of error. To curtail its impact, insulation materials were utilized, but loss through convection and radiation generated discrepancies between calculated and measured temperatures. Ideal calculation, assuming a perfectly insulated system, therefore, introduced a systematic source of error in experimental observations.

2. Non-Uniform Heating of the Coil: Warming of the heating device did not occur uniformly over its length. Resistance, airflow, and loss through external heat sources produced temperature inhomogeneities. Higher temperatures developed in certain parts of the coil at a faster rate compared to others, impacting accuracy in mean temperature observations.

4. Resistance Alteration with Temperature Fluctuation: Resistance in the electrical path through the coil increased with an increase in temperature, and therefore, changed actual current through the circuit. Temperature coefficient of resistance describes such an impact, in which most conductive materials have a rise in resistance with temperature. As theoretical calculation considered constant resistance, such variation impacted predicted performance in heating.

5. Human and Procedural Error: Insignificant inaccuracies in experimental performance, for instance, incorrect positioning of a thermocouple, variation in voltage application, and discrepancies in recordation, added to uncertainty in observations, too.

Improvements if experiment will be done again

To improve accuracy and dependability in the results, several improvements can be incorporated in future repetitions of this experiment. These improvements seek to address critical weaknesses in the first experiment and work towards enhancing the methodology, in turn, producing more reliable and repeatable results. The suggested improvements include the following:

1. Increased Thermal Insulation: Application of high-performance insulative materials surrounding the coil could significantly reduce thermal loss to the environment. In addition, housing the device in a temperature-controlled chamber would even out external interference in terms of airflow and ambient temperature fluctuations.

2 Use of Several Temperature Sensors: Positioning several thermocouples at specific locations in the coil could allow for temperature fluctuations to be captured, providing a truer picture of the pattern of heating. After that, a data-smoothing technique could then be utilized to remove localized discrepancies.

4 Automated Measuring and Analysis: Implementation of a computerized logging system that continues to record voltage, current, and temperature values could remove observer errors involved in taking readings and ensure uniformed readings. In addition, real-time observation and increased visualization of trends in heating could be facilitated through this arrangement.

5 Performance of the Experiment under a Controllable Environment: Performance of the experiment in a temperature-regulated room could significantly reduce external heat exchange, producing uniform and repeatable results. In addition, such an arrangement could restrict the variation produced through changing humidity and airflow.

6. Accounting for Resistance Variability: Future experiments must include techniques for measuring real-time coil resistance and compensating in computations when needed. This could involve utilizing a four-wire resistive measurement technique or taking readings of the coil's resistivity at a range of temperatures and including these fluctuations in theoretical models.

7. Broadening the Number of Trials and Observational Points: Having several trials and an extended range of voltage values for testing would yield a larger dataset, allowing for better statistical analysis. Undertaking such actions will make the conclusion more reliable and less susceptible to the impact of arbitrary errors.

8. Considering Alternative Materials for the Coil: Considering a range of alternative coil materials with specific resistivity and thermal properties could produce useful information for maximising thermal performance through optimized heating. Carrying out experiments with a range of wire gauging and compositions will extend the study's relevance even further.

9. Comparison with Established Heat Transfer Formulas: Experimental results could be compared with theoretical heat-transfer models such as conduction, convection, and radiation, and even with computational simulations, to build a more complex theoretical model for predicting thermal performance under a range of scenarios.

By taking these improvements into practice, future experiments will yield even more reliable and accurate information, and a deeper understanding of voltage's impact on thermal performance in tubular electrical coils will follow, benefiting engineering and real-life engineering and industrial heating system design with direct, applicable improvements in efficiency and performance maximization.

12. References

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