INDUCTION HEATING MODEL OF CERMET FUEL ELEMENT ENVIRONMENTAL TEST (CFEET)

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ABSTRACT

Deep space missions with large payloads require high specific impulse and relatively high thrust to achieve mission goals in reasonable time frames. Nuclear Thermal Rockets (NTR) are capable of producing a high specific impulse by employing heat produced by a fission reactor to heat and therefore accelerate hydrogen through a rocket nozzle providing thrust. Fuel element temperatures are very high (up to 3000 K) and hydrogen is highly reactive with most materials at high temperatures. Data covering the effects of high-temperature hydrogen exposure on fuel elements are limited. The primary concern is the mechanical failure of fuel elements due to large thermal gradients; therefore, high-melting-point ceramics-metallic matrix composites (cermets) are one of the fuels under consideration as part of the Nuclear Cryogenic Propulsion Stage (NCPS) Advance Exploration System (AES) technology project at the Marshall Space Flight Center. The purpose of testing and analytical modeling is to determine their ability to survive and maintain thermal performance in a prototypical NTR reactor environment of exposure to hydrogen at very high temperatures and obtain data to assess the properties of the non-nuclear support materials. The fission process and the resulting heating performance are well known and do not require that active fissile material to be integrated in this testing. A small-scale test bed; Compact Fuel Element Environmental Tester (CFEET), designed to heat fuel element samples via induction heating and expose samples to hydrogen is being developed at MSFC to assist in optimal material and manufacturing process selection without utilizing fissile material. This paper details the analytical approach to help design and optimize the test bed using COMSOL Multiphysics for predicting thermal gradients induced by electromagnetic heating (Induction heating) and Thermal Desktop for radiation calculations.

INTRODUCTION

The objective for the Cermet Fuel Element Environmental Test (CFEET) simulation effort is to develop and correlate a mathematical model for induction heating of cermet samples. The primary interest is for samples to reach temperatures of 3000 K and determine their ability to survive and maintain thermal performance in an Induction heating environment. Initial test show that reaching high temperatures by induction heating has proved difficult due to large amounts of thermal energy being lost by radiation and the low energy efficiency of the inductor coil. Power and energy can be computed using text book equations for induction heating and processing, but these values are only estimations which don't take into account accurate energy losses such as radiation and electromagnetic losses. Thermal Desktop is being used to

model and improve the energy transferred to the sample in order to reach high temperatures. In addition, an Induction heating model created in Common Solution Multi Physics (COMSOL) will be used to predict the energy induced by the electromagnetic field. The analytical approach using both simulations will help design a better and more efficient test bed.

INDUCTION HEAT THEORY

Induction heating systems consist of a power supply providing an alternating current (AC), an induction coil, and the test sample which is being heated. The role of the power supply is to provide a frequency and magnitude of the AC current to the induction coil. The AC current in the coil will produce in its surroundings a time variable magnetic field that has the same frequency as the coil current. The magnetic field induces eddy currents in the test sample located inside the coil. Figure 1 illustrates the magnetic field created by the AC current in the coil. These induced currents have the same frequency as the coil current but their direction is opposite. The currents produce heat by the Joule effect. Due to several electromagnetic phenomena, the current distribution within the inductor and test sample is not uniform. This heat source variance causes a non-uniform temperature profile in the test sample.
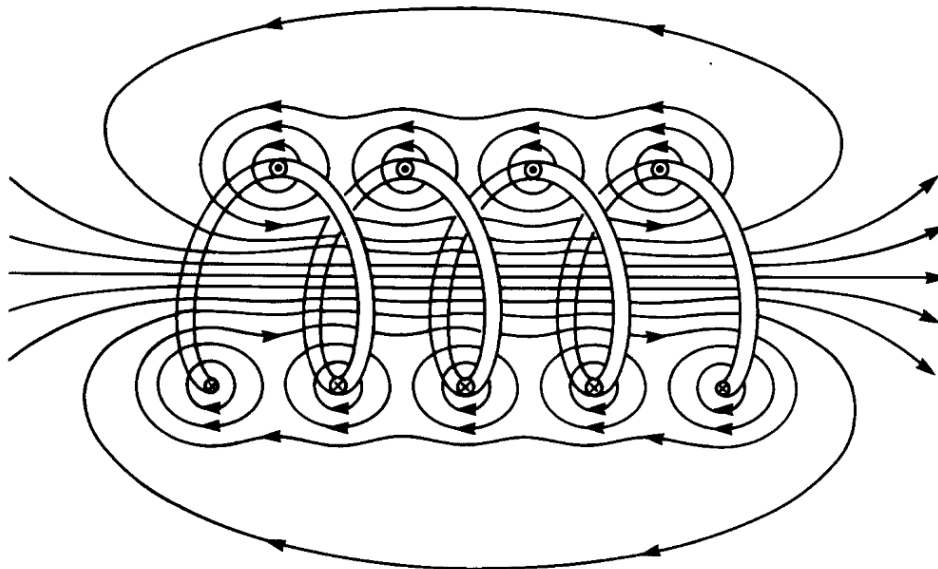

Figure 1. Induced Magnetic Field.

The non-uniform current eddy distribution is caused by the electromagnetic properties of the test sample, skin effect and the proximity effect. The ability of a material to easily conduct electric current is specified by the electrical conductivity (σ). The reciprocal of conductivity is

electrical resistivity (ρ). Electrical resistivity varies with temperature. Metals and Alloys are considered to be good conductors and have much less electrical resistance compared to other materials. Electrical resistivity is an imperative physical property since it affects practically all the important parameters of an induction heating systems.

Relative magnetic permeability (μ_r) indicates the ability of a material to conduct the magnetic flux better than vacuum or air. Magnetic permeability is also a function of temperature. This non-dimensional parameter effects coil calculation and computation of electromagnetic field distribution on the test sample.

SKIN EFFECT AND EQUIVALENT POWER

When an alternating current flows through a conductor, the current distribution within the conductor is not uniform. The maximum value of the current density will always be located on the surface of the conductor. This phenomenon of non-uniform current distribution within the conductor cross section is called the skin effect (Semiatin & Zinn, 1998). Mathematical determination of eddy current distribution through the test sample is difficult especially for complicated geometries. An effective depth of a current carrying layer can be calculated using Equation 1.

$$ d = \sqrt{\frac{2*\rho}{\omega*\mu}} \qquad \text{eq. 1} $$

Where,

ρ=electrical resistivity of test sample

ω= angular frequency

μ=absolute magnetic permeability of test sample

This depth, known as the reference depth d, depends on the frequency of the alternating current through the coil and the electrical resistivity and relative magnetic permeability of the test sample. Because of the skin effect approximately 86% of the power induced will be

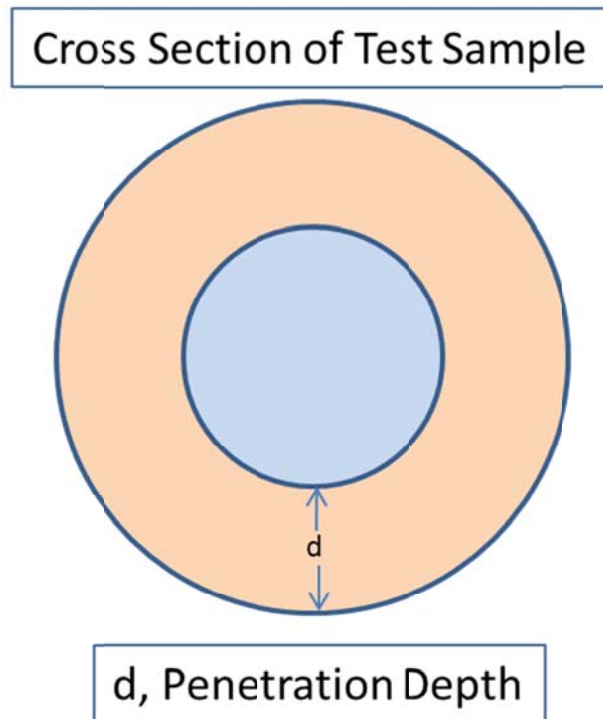concentrated in the surface layer of the test sample. Figure 2 illustrates where the penetration depth is located.

Cross Section of Test Sample

d

d, Penetration Depth

Figure 2. Induced Magnetic Field Penetration Depth .

Electrical resistivity is a function of temperature and during the heating cycle it can increase to four to five times its initial value. The behavior of relative magnetic permeability also changes as a function of temperature. As the temperature rises, μ_r starts to decrease until it reaches unity because the metal becomes nonmagnetic. As a result, the penetration depth will increase significantly during the heating cycle because of the change in electrical resistivity and relative magnetic permeability.

The variation of penetration depth during induction heating makes it difficult to predict since the electromagnetic properties are constantly changing. It's important to make realistic assumptions about all properties when making power calculations for the test sample. The reference penetration depth allows for the equivalent resistance (R_{eq}) of the test sample to be calculated. The equivalent resistance is the test sample resistance which if placed in a series circuit with the induction coil would dissipate as much heat as all the eddy currents in the actual test sample. In other words, the equivalent power (P_{eq}) to the work piece can be calculated by assuming the current of the coil to be the same at the eddy currents in the test sample. Equations 2 and 3 show the relationship between equivalent resistance and power.

$$R_{eq} = \frac{\rho * \pi * D * K_R * N^2}{d * L} \qquad \text{eq. 2}$$

$$P_{eq} = I_C^2 * R_{eq} \qquad \text{eq. 3}$$

Where,

ρ= electrical resistivity of test sample

D=bar diameter

Kr= electrical path factor

N=number of turns of coil

d=penetration depth

L=bar height

Ic= current in coil

For a solid round bar, such as the test sample, it turns out that the R_{eq} is equal to the number of turns in the coil and the resistance of the reference penetration depth d located on the surface. The dependence of R_{eq} on the number of induction coil turns N is a result of the fact that the induced voltage and eddy currents both increase linearly with N according to Faraday's Ohm's Law.

It's important to note that the power supply will not provide the full rated power directly to the test sample. There will be power losses through the circuit system of the power supply, electromagnetic losses, and losses through the induction coil (Rudnev, Loveless, Cook, & Black, 2003). The equations listed, gives a steady state approximation of the power being induced to the test sample by just knowing the coil design and the electrical current. This power was used as the main heat source on the Thermal Desktop model.

TEST SETUP

The test hardware used a very small custom-fabricated vacuum chamber 10 in diameter by 18 in. tall that was capable of vacuum levels up to 10E-6 Torr. The chamber was integrated with an induction heating system via a vacuum-rated Radio Frequency (RF) power feed-through. Figure 3 shows the vacuum chamber configuration.
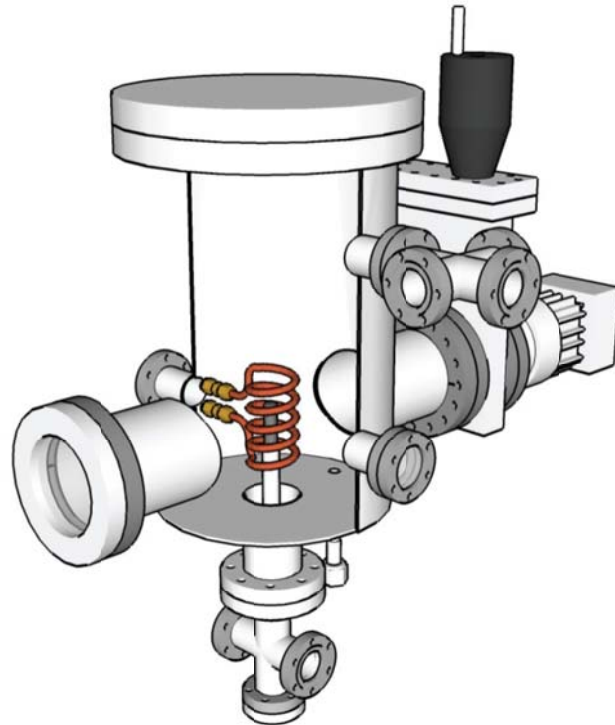

Figure 3. CFEET Vacuum Chamber Configuration.

The induction coil was located inside the vacuum chamber and was powered by a 15 kW Flexitune water-cooled RF power supply connected with copper tubing. The power supply had an output frequency of 20-60 kHz. The output power was user-adjustable. The copper tubing functioned as both the water-cooling channel and the electrical current conductor. Cooling water was circulated throughout the components within the RF power supply and also flowed through the induction coil itself. Heat was rejected from the induction coil and power supply by the building's facility cooling water.

The induction coil was manually formed from bendable refrigeration copper tubing. Figure 4 shows a 3 loop induction coil. Dimensions typically required a trade-off between induction operating frequency and enclosed fuel element dimensions.

Figure 4. Induction Coil.

Coils can be carefully designed analytically to maximize heating efficiency and compatibility with a given power supply and test sample configuration. Table 1 shows the coil configuration used for this test. The test sample was made out of 99.9% tungsten round bar: 1.5" in length and .5" diameter.

Table 1. Coil Configuration

Tube Size, in	Coil Diameter, in	Number of turns	Coil height, in	Operating Frequency, kHz
.375	1.875	4	1.75	23.4

In order to achieve maximum temperatures, radiation heat transfer from the tungsten test sample to the vacuum chamber wall had to be reduced. A Boron Nitride (BN) insulator was used to completely encapsulate the tungsten test sample. Figure 5 shows the tungsten test sample in the BN insulator. Physical contact with test parts was not practicable because of high part temperatures desired. A small port was machined to allow an optical pyrometer to measure the temperature of the test sample. The tungsten test sample and the BN insulator was placed at the center of the induction coil and positioned along its axial centerline so that a clear line-of-sight existed to pyrometers outside the vacuum chamber. Figure 6 illustrates where the pyrometer takes temperature measurements.

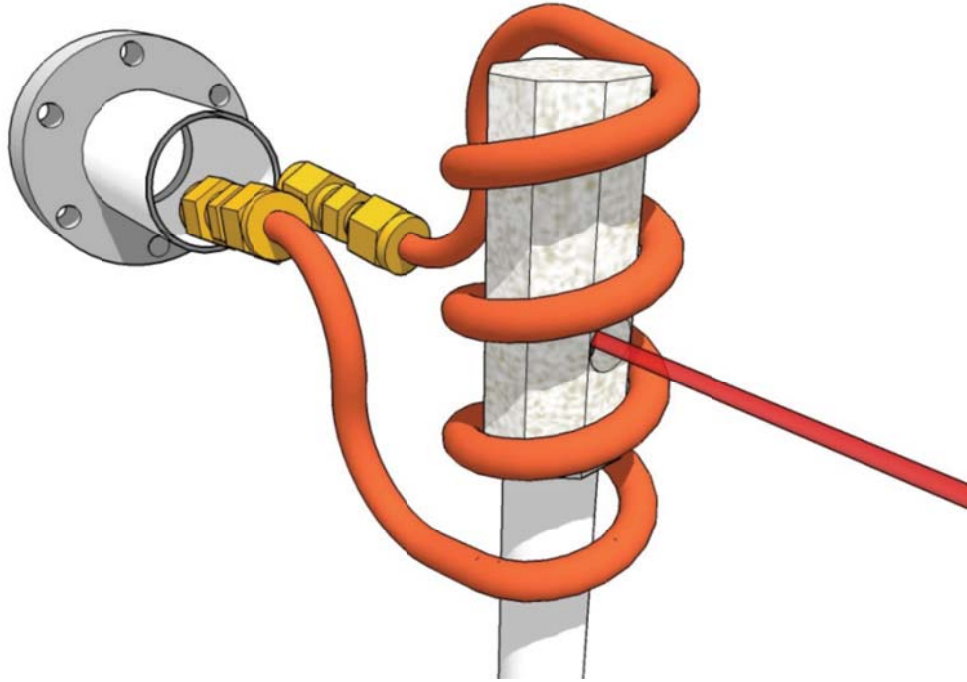**Figure 5. Test Sample and Boron Nitride Insulator.**

Figure 6. Pyrometer Temperature Measurements.

The power supply had its own instrumentation that measured power, current, voltage, and frequency. The pyrometer only measured temperature and emissivity. All tests were done in a vacuum pressure of 1E-4 Torr. The test was conducted until a steady state (SS) temperature was reached. Table 2 shows the power supply outputs and the average steady state temperature reached for this configuration.

Table 2. Coil Configuration

Power Supply power	Current in coil	Voltage	Frequency	SS Temp of Sample	Time
14.25 kW	1569 A	146.6	23.4 kHz	2500 °C	250 s

THERMAL DESKTOP MODEL

The induction heating model in Thermal Desktop was kept simple and only major parts of the test setup were modeled in 3D to keep the analysis simplistic. The tungsten test sample was represented by a TD primitive cylinder. The boron nitride insulator was imported and meshed in Thermal Desktop. The coil was created using the FlowCAD pipe function. Figure 7 shows the model with the tungsten test sample in the boron nitride.
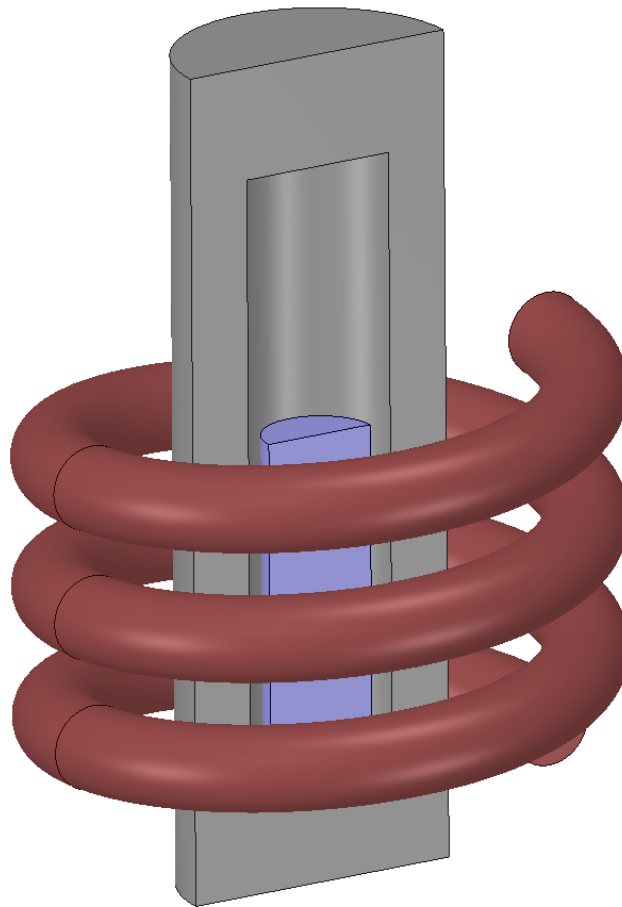

Figure 7. Thermal Desktop 3D Model with Cross Section.

This is primarily a radiation exchange model with some fluid heat transfer. The model was set to solve in steady state. Test data and hand calculations were used to set up the appropriate boundary conditions to reflect the radiation losses. The power calculated from Equation 3 was set on the surface of the tungsten test sample. Radiation was set on the surface of the tungsten test sample, boron nitride, and coil. This mimicked the energy interaction between the tungsten and boron nitride insulator in order to maintain and keep maximum temperatures on the surface. A contact resistance of 500 W/m^2/°C was used on the base of the tungsten test sample that touched the bottom of the boron nitride since some energy was being lost by conduction. The outside surface of the coil and boron nitride radiated to a chamber sink temperature of 25 °C, which was the temperature measured of the inside surface of the vacuum chamber. Figure 8 shows how the radiation was set in the model.
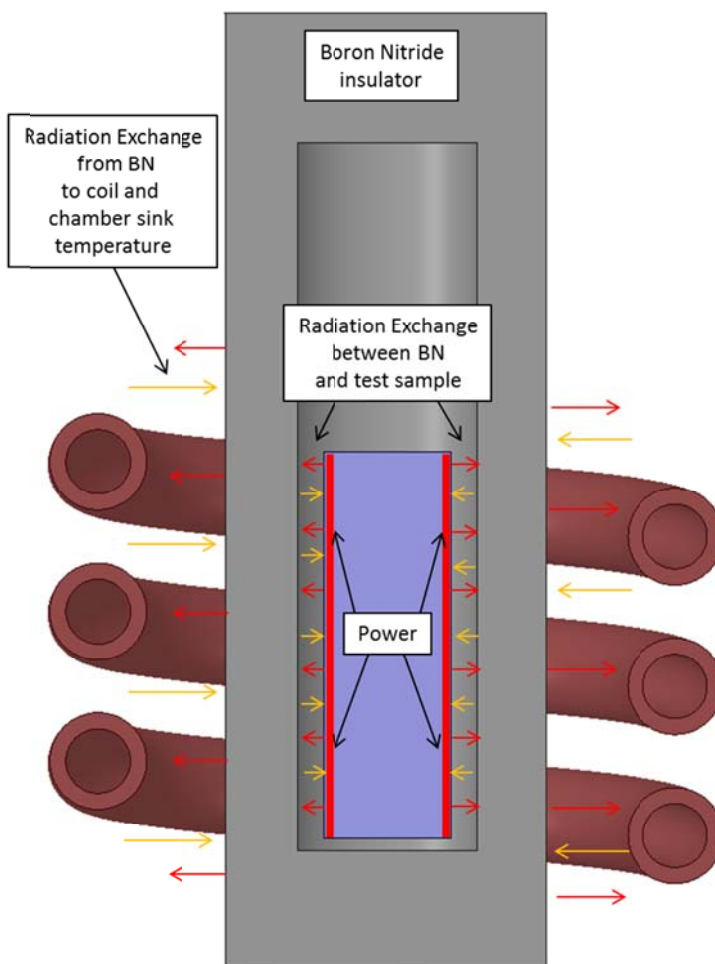

Figure 8. Thermal Desktop Radiation Exchange.

The coil was modeled using a FlowCad Pipe. The pipe consisted of mesh surfaces, fluid lumps and flow paths. Water was selected as the main fluid for the flow paths. The inlet temperature of the flow was set at 20 °C. The flow paths were connected to the surface of the pipe which allowed heat to be removed. The heat removed in coil came from the radiation from the boron nitride and heat produced by the current in the coil. The current being conducted through the coil produces heat in a form of Joule heating. Since the current travels mostly through the surface of the coil, a power was calculated by simply knowing the coil dimension and electrical resistivity. A power of 2000 Watts was applied to the surface of the pipe.

COMSOL MODEL

The induction heating model in COMSOL was kept simple by creating a 2D axisymmetric model. Figure 9 illustrates each individual component in the 2D axisymmetric model. The Multi-Physics module combined with the Induction heating module was used. Domains were created that represented the tungsten test sample coil, and free space.
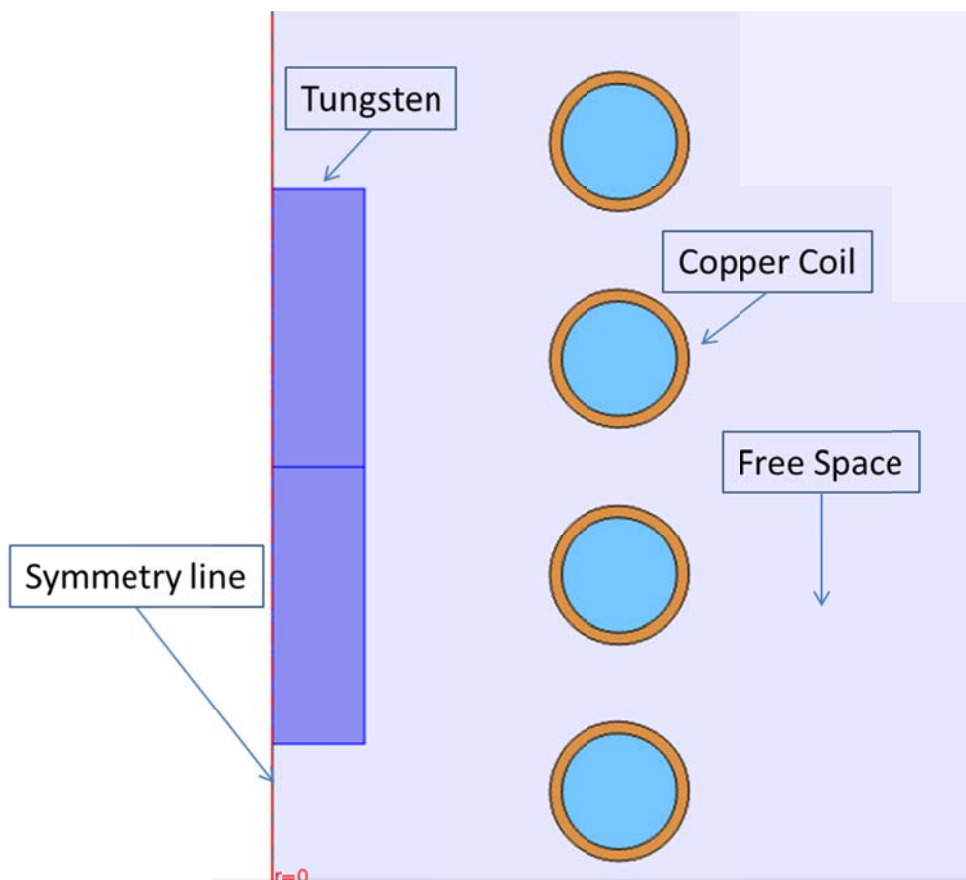

Figure 9. COMSOL Axisymmetric Model.

The COMSOL model uses an expanded version of the energy equation that combines features from magnetic fields in the time harmonic formulation with heat transfer for modeling induction and eddy current heating. The model was set as transient. The primary purpose of this model was to predict the total power being induced to the tungsten test sample by the magnetic field created by the coil design. This power was then compared to the hand calculations to demonstrate its accuracy.

The thermal physical and electrical properties were assigned to each domain that was being affected by induction. All properties used were based on the highest temperature reached during testing. Since the boron nitride insulator has no electrical resistance and a magnetic permeability equal to free space, it was completely ignored and does not affect the analysis. The only inputs required in COMSOL were current, frequency and time. These inputs are listed in Table 2 from the test data recorded. A current of 1569 Amps and a frequency 23.4 kHz were used. Since the model can only be set as transient, a time of 3000 seconds was used to achieve steady state conditions.

THERMAL DESKTOP RESULTS

The measured data and coil design parameters were used to calculate the amount of power induced to the tungsten test sample using equations 1, 2 and 3. Since these equations assume a steady state case, the electrical and material properties used were based on the highest temperature reached by the tungsten test sample. The absolute magnetic permeability of tungsten drops but not enough to make a significant change in the power induced. The calculated induced power was 1738 watts.
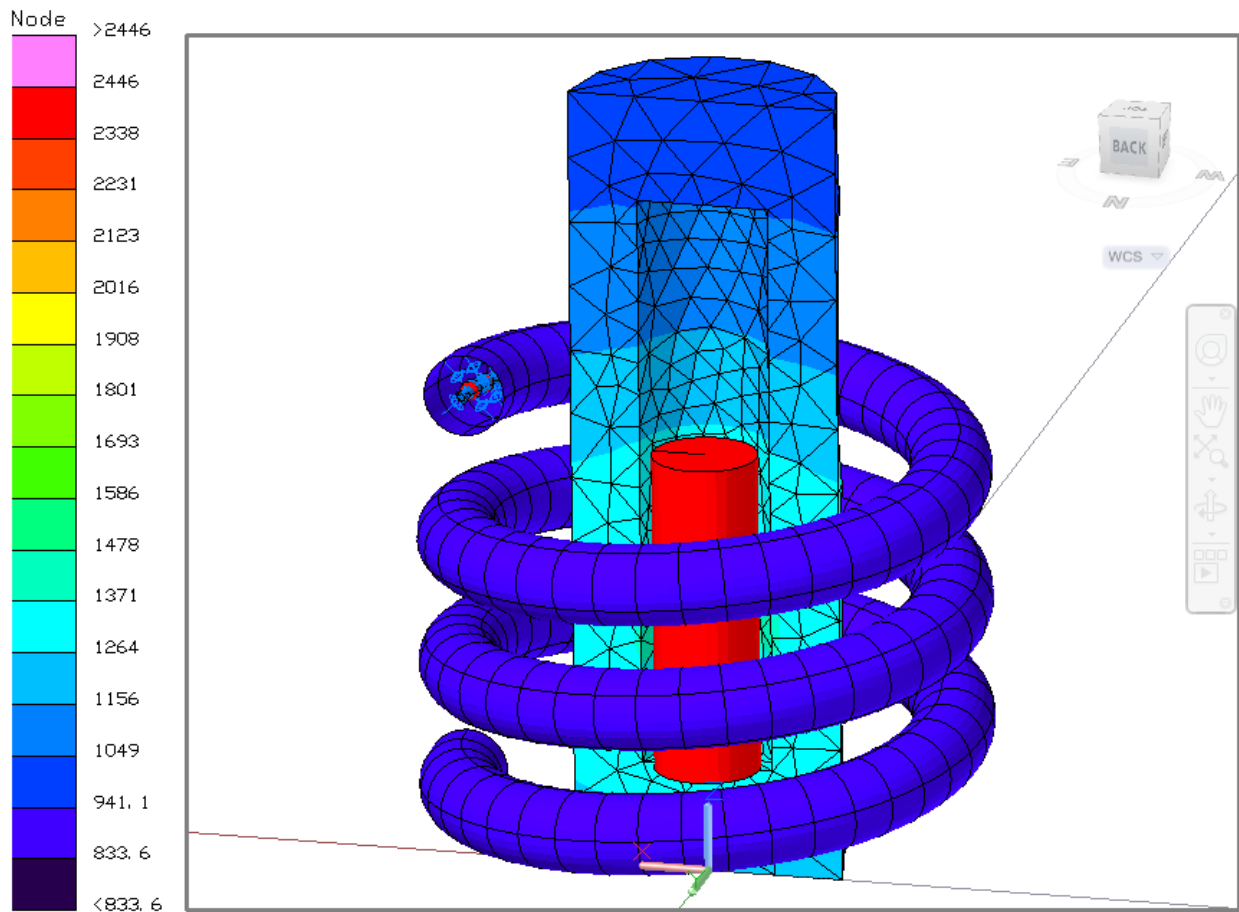

Figure 10. Steady State Temperature Profile.

Figure 10 shows the tungsten test sample reaching a steady state temperature of 2446 °C, which matches test data. The boron nitride insulator reaches higher temperatures near the bottom since most of that surface area is exposed to the radiation from the tungsten test sample. The copper coil only reaches temperatures of 830 °C, which is a temperature well below the melting point of copper.

Test data had water flowing through the coil with a temperature rise of 4 °C at 2 gal/min. The FlowCad model of the coil showed a temperature rise of 3.7 °C at the same flow rate. The temperature rise in the water almost matched test data by just knowing the current and the electrical properties of the coil. Figure 11 shows the FlowCad lump temperature rise.
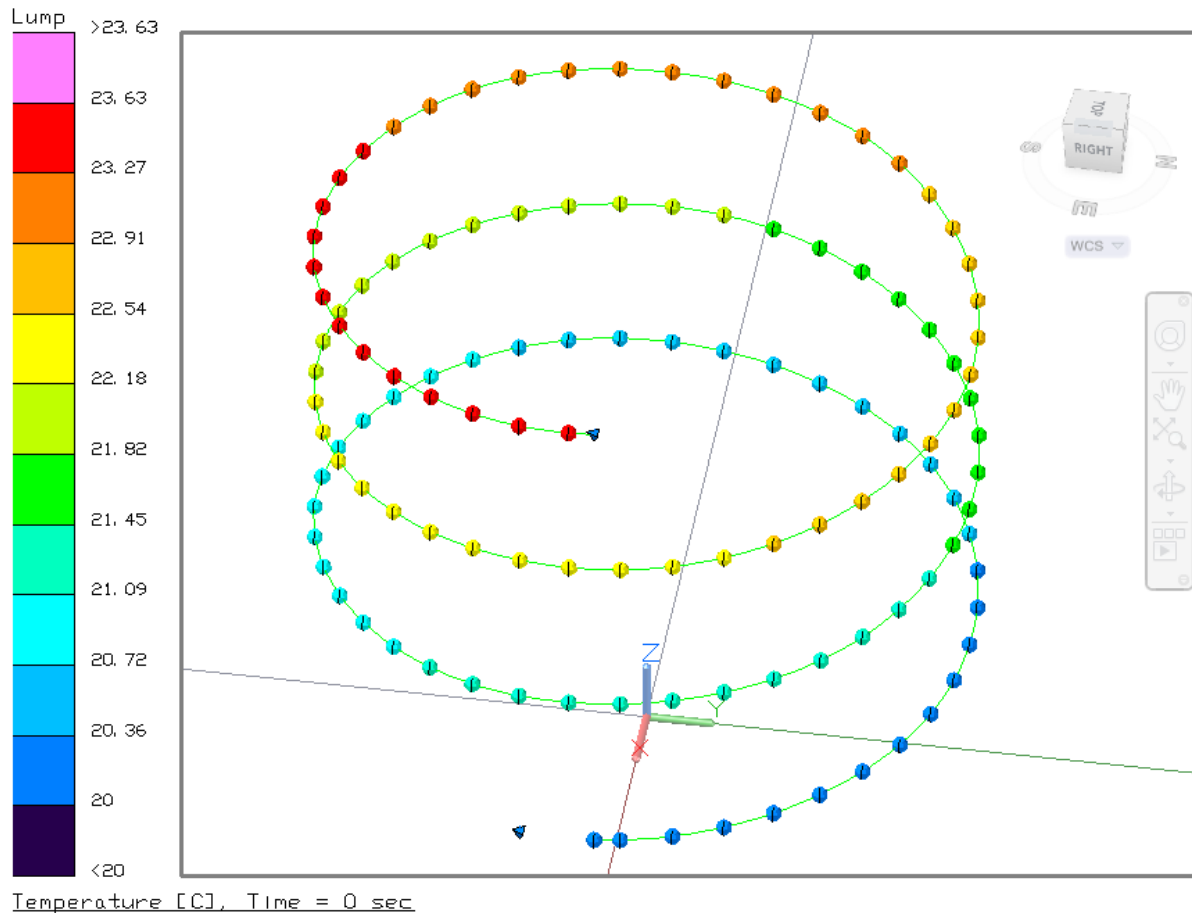

Figure 11. FlowCad Coil Coolant Temperature .

COMSOL RESULTS

In the COMSOL induction heating model, the magnetic field induces electrical currents in the tungsten test sample. The magnetic field lines form around the coil but are stronger and more intense toward the center. Figure 11 shows how the magnetic field lines are distorted and stronger toward the center axisymmetric line where the tungsten test sample is located.
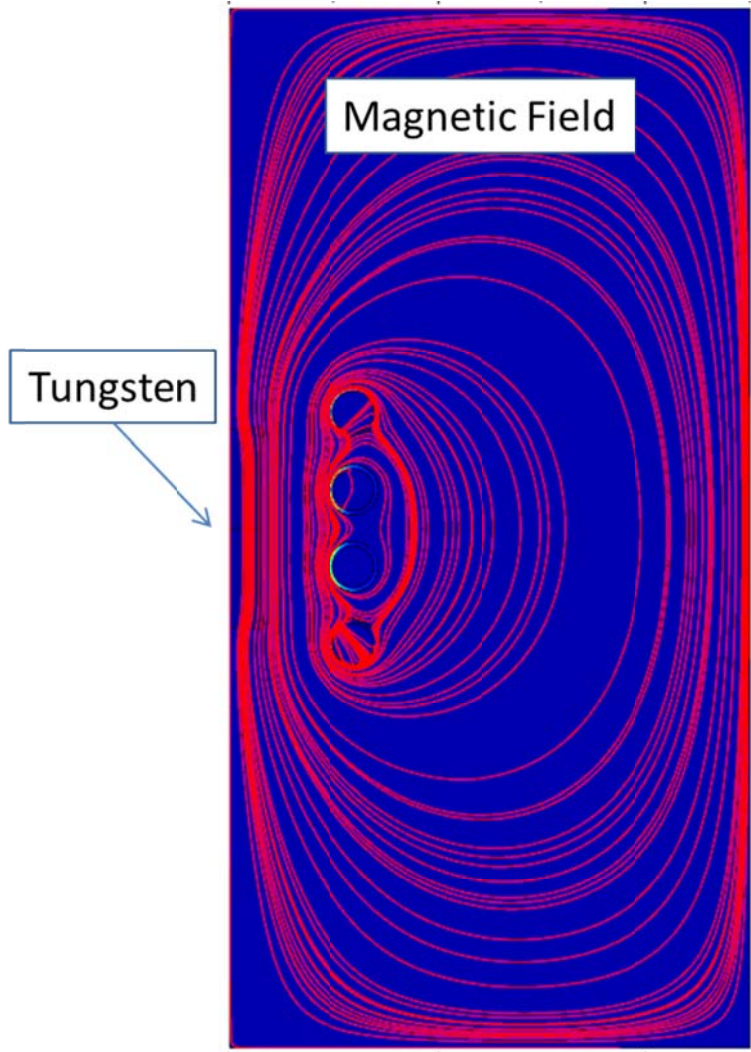
Figure 12. COMSOL Magnetic Field .

This magnetic intensity can also be called the magnetic flux density, in where it would be denser at the inner diameter of the coil since the coil is conducting the main current supplied. The tungsten test sample is then affected by the magnetic flux density since it produces the induced current. Figure 13 shows the magnetic flux density and how it weakens when it approaches the tungsten test sample. Figure 13 also illustrates how energy is lost due to resistive losses and magnetic losses.
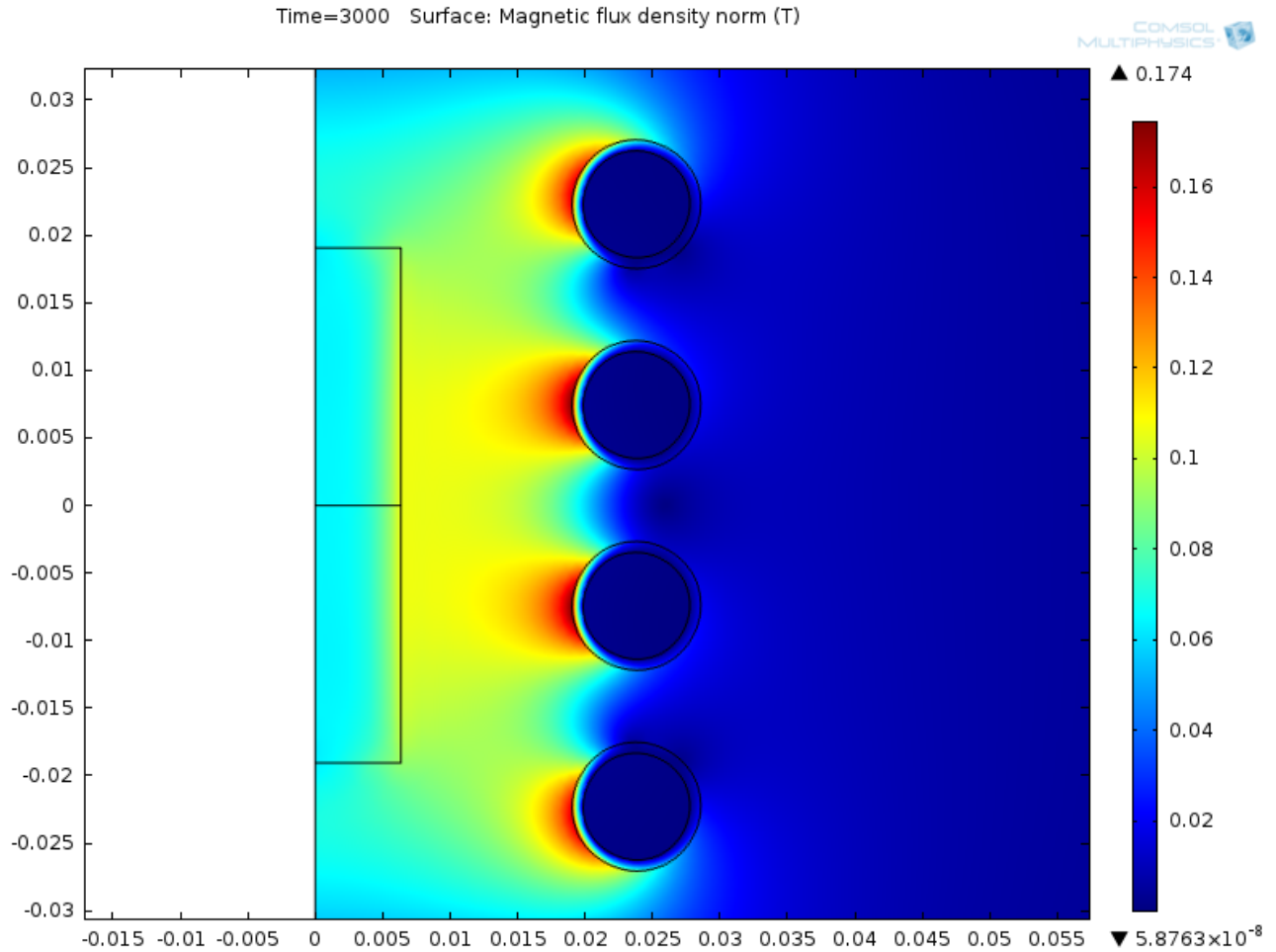
Figure 13. COMSOL Magnetic Flux Density.

The goal was to see what power COMSOL computed by just modeling the coil and entering a current and a frequency. Power varies throughout the surface of the test sample due to coil pitch, copper tube thickness, and the proximity of the coil to the tungsten test sample. The average power induce to the tungsten test sample was 1567 Watts. Figure 14 shows where the line where the average power was taken from.
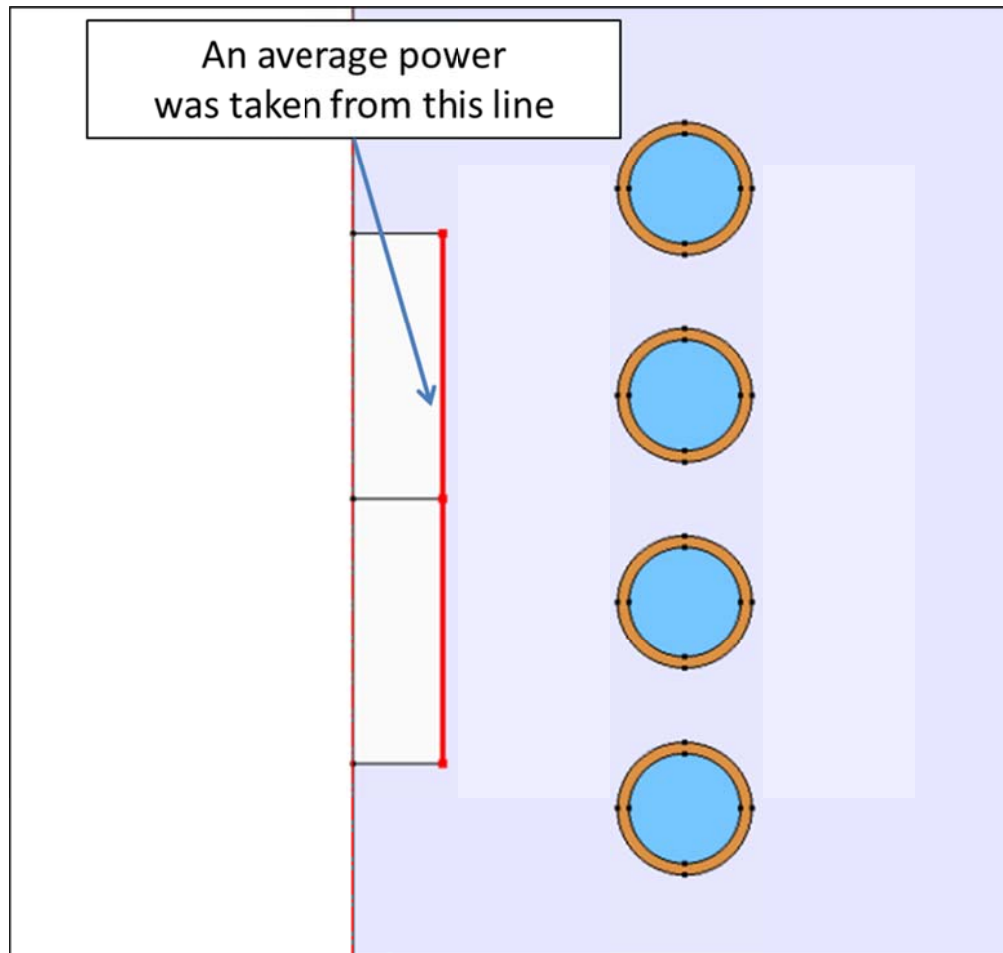
An average power was taken from this line

Figure 14. COMSOL Average Power Location.

CONCLUSION

From test data alone it was difficult to know what the actual amount of power was being induced to the tungsten test sample just by temperature measurements. The Thermal Desktop model required a power input that test alone could not measure. It was necessary to use the classical induction heating power calculation from equations 2 and 3. These equations gave a power approximation based on the electrical properties of the tungsten test sample, coil design, measured current, and frequency. At high temperatures the resistivity of the tungsten test sample increases but the magnetic permeability of tungsten does not change significantly to affect the model. A power can be predicted using the temperature from test data to correlate with the Thermal Desktop model and the induction heating equations

The COMSOL induction model was used to predict an induced power using more complex physics that combined electromagnetics and heat transfer. The only inputs required in the

model were current and frequency. The same approach was taken from what was learned in the Thermal Desktop model: the electrical resistivity of tungsten was increased while magnetic permeability was kept the same. The COMSOL model gave different power values that varied by the surface location of the tungsten test sample. This was due to the high magnetic flux densities based on coil loop, pitch and location. An average power was taken from the surface of the tungsten test sample and compared to the hand calculation.

The hand calculation had 1738 Watts while the COMSOL model had an average of 1567 Watts. The COMSOL average power was used as an input in the Thermal Desktop model to see what temperature the tungsten test sample reached. Figure 15 shows the steady state temperature with the new power. The steady state temperature measured in the test was 2500 °C. Table 3 shows the power and steady state temperature compared to test data.

Table 3. Power and Temperature

	Power Calculated	TD Steady State Temperature
Hand-Calculated Power Case	1738 Watts	2446 °C
COMSOL Predicted Power Case	1567 Watts	2371 °C

Both the hand calculation and COMSOL average power approaches are both acceptable for predicting induced power. However, the hand calculation has its limitations since it only works for a solid round bar. The COMSOL modeling approach can be used for predicting induced power on more complex geometry's.

The Thermal Desktop and COMSOL model will be used when correlating future models and to make improvements to coil design. It also gives a starting point and a better understanding on how to model induction heating.
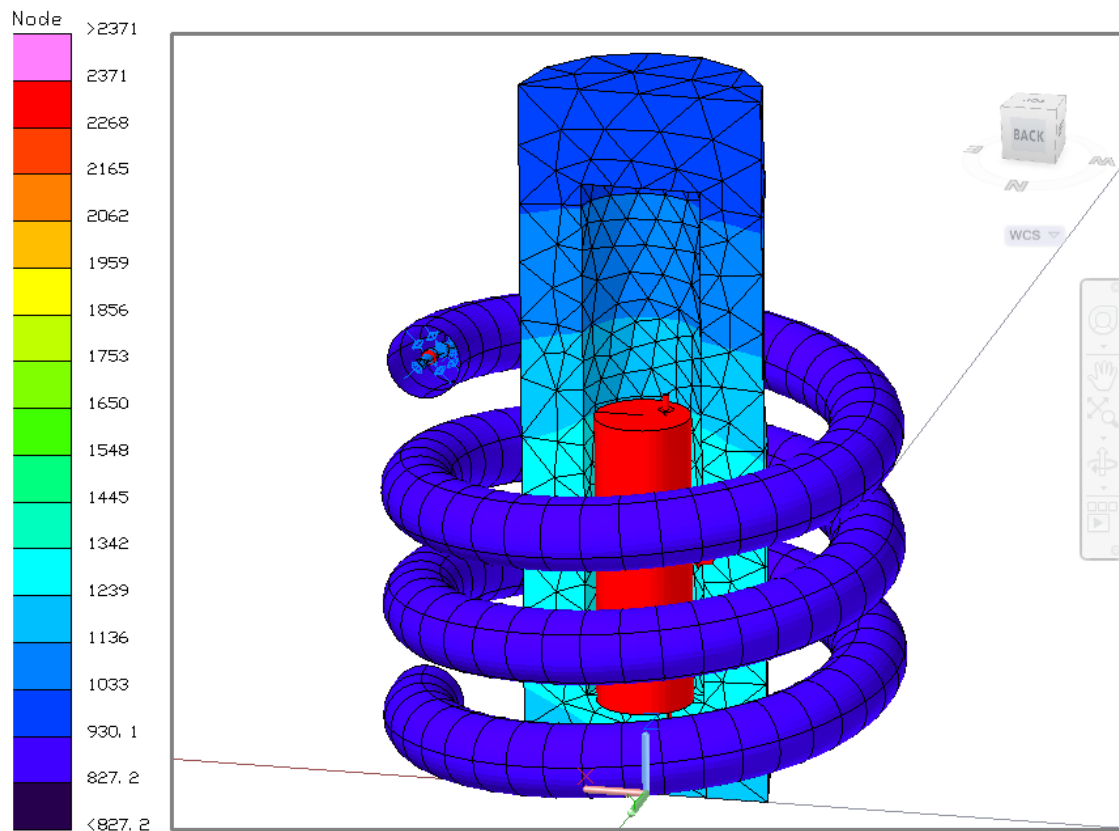
Figure 15. Thermal Desktop Model with COMSOL Average Power.

NOMENCLATURE

σ,   electrical conductivity

ρ,   electrical resistivity

μ_r,   relative magnetic permeability

μ,   absolute magnetic permeability

ω,   angular frequency

d,   penetration depth

D,   bar diameter

L,   bar length

Kr,   electrical path factor

N,   number of turns of coil

R_{eq},   equivalent resistance of work piece

Ic,   current in coil

P_{eq},   Power equivalent on work piece

AC,   alternating current

SS,   steady state

BN,   boron Nitride

TD,   thermal desktop

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Rudnev, V., Loveless, D., Cook, R., & Black, M. (2003). *Handbook of Induction Heating.* Marcel Dekker.