Comparative study of Experimental and Simulative (COMSOL) results on Extended Heat Transfer

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Abstract
Heat transfer is an integral part of most processes and machines, whether it's cooling a machine or heating a solution. Naturally, heat flows from the highest temperature to the lowest. This driving force is defined as the temperature gradient. Heat will dissipate as it flows through the medium into the surrounding air. This study was conducted using an Extended Heat Transfer Unit. In this study, a brass rod was heated and the temperature profile observed. The experiment was simulated using COMSOL and this was compared to experimental data. The objective of this study was to compare the experimental results of an extended heat transfer pilot unit to the simulated results. The error between the simulation and the experimental results grew larger the higher the current output. There is no formal documented work on simulation of the extended heat transfer phenomenon, with an accurate simulation of extended heat transfer the model obtained could be implemented in more complex models such as fuel cells and furnaces.

Keywords
COMSOL, Simulation, Experimental, Extended Heat Transfer, Comparative Study.

1. Introduction
Heat transfer is an important aspect of all energy and science, especially in mechanical and thermodynamic processes. This driving force is defined as the temperature gradient. Heat conduct through the medium and dissipate through radiation and convection. Having a complete understanding of how heat is conducted through different mediums is a very important aspect of engineering design (Luo & Yang, 2017).

This study focusses on an extended heat transfer unit with the main objective the comparison of simulated results against the actual results. This was conducted by means of three trials where the brass rod is heated from the one end with four different power settings and allowed to reach a state as close to steady state as possible. The temperature along the rod was then observed. The system was simulated using COMSOL and results compared.

2. Literature Review
The estimation of the total heat exchange factor plays an important role while obtaining the reference trajectories on steady-state furnace operation for the reheating furnace control system in the metal industry, the metal must undergo several thermal, mechanical, or thermomechanical process before it is suitable for industrial applications. In the process chain, continuous reheating furnaces are often used for reheating or heat treatment of metal products before and after the rolling mill, as illustrated in Figure 1 (Luo & Yang, 2017).

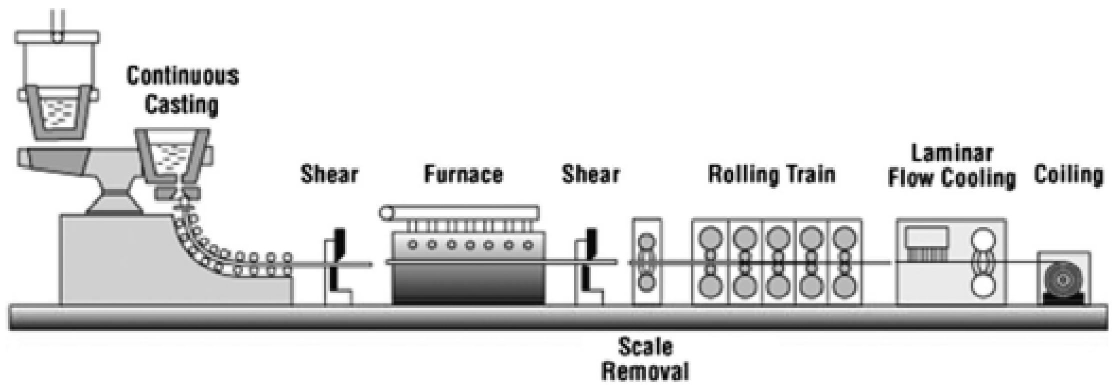

Figure 1: Metal Manufacturing Process (Luo & Yang, 2017)

In many heat transfer processes, it is necessary to transfer the flow of heat in the desired direction but block the heat flow in the opposite direction. Heat transfer devices with this feature are termed thermal diodes analogous to the electrical diodes which are commonly employed for rectification in electrical circuits. This phenomenon can appear in heat conduction, heat convection and heat radiation problems as well. (Sadat & Le Dez, 2016). The cooling of electronic devices is an important issue in the electronics industry. Although the increasing power density of electronic components leads to performance improvement, it inevitably causes significant temperature rise. Heat generated in a small-scale electronic component will damage the device if it cannot be discharged to the environment in an efficient way. A feasible and common way to cool the high-temperature device is to insert a certain number of highly conductive materials into the heat generation domain (Zhang, Zheng, Qi, Guo, Liu & Liu, 2017).

Combined radiation and conduction heat transfer problems have wide applications and academic value. The energy equation describing these problems is a highly nonlinear partial differential-integral equation. Due to its mathematical complexity, it is almost impossible to obtain exact analytical solutions (Sun, Zhang & Howell, 2017).

Alloyed materials are frequently used in different branches of industries. This wide area of applications originates from their unique properties including a high ratio of strength and stiffness to density, high thermal conductivity and high corrosion resistance. Because of these features, they are used in piping, heat exchangers, cooling systems, latent heat thermal energy storage systems, aerospace components, fluid reservoirs, pressure vessels, sport and medical equipment and so on. Solutions of heat conduction in these materials provide beneficial knowledge for preventing thermal fracture, analyzing fibre placement in the production process and controlling the directional heat transfer in the structure (Gao & Cui, 2017; Norouzi & Rahmani, 2017).

The classical heat conduction is described by Fourier's law. It assumes that heat flux and temperature gradient generate at the same time instant, which implies the heat disturbance propagates at an infinite speed. Although this assumption is physically unacceptable, Fourier's law provides accurate results for most engineering problems at classical length and time scale (Kang, Zhu, Gui & Wang, 2017; Li & Cao, 2016).
Equation 1: Fourier's Law (Kang, Zhu, Gui & Wang, 2017; Li & Cao, 2016)

$$q=-\lambda\Delta T$$

Where q is the heat flux, λ is the thermal conductivity and T is the temperature. In statistical mechanics, Fourier's law has been derived approximately through several given theoretical assumptions, which also implies its possible restrictions, i.e., near-equilibrium region. Especially in Nanoscale heat transport, the effects of far-from-equilibrium can play an important role because the characteristic size can be comparable to the mean free path of heat carriers (Kang, Zhu, Gui & Wang, 2017; Li & Cao, 2016).

COMSOL Multiphysics is a general-purpose software platform, based on advanced numerical methods, for modelling and simulating physics-based problems (COMSOL). COMSOL uses multiple mathematical models to simulate in this case heat conduction through a solid.

3. Experimental

3.1. Apparatus

Figure 2: Extended Heat Transfer Pilot Unit

a. Denotes the Voltage control unit and b. denotes where the Voltage, Amperage and Resistance are displayed. c. Denotes the thermocouple inputs into the control system, d. denotes where the temperature readings are displayed and e. denotes the quartz heater. Finally f. denotes the brass rod with thermocouples.

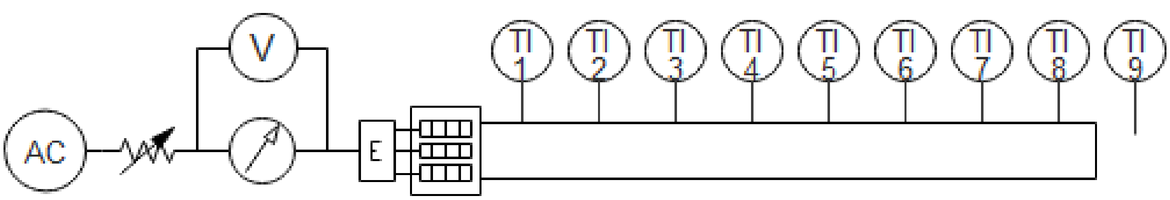

Figure 3: P&ID Extended Heat Transfer Pilot Unit

Extended Heat Transfer unit was used. The system consists of an alternating current (AC) power input which is controlled by a variable transistor after the variable transistor the Ampage and Voltage of the incoming electricity are measured. The power flows to an electrical heater which in turn heats a rod. The rod is made of brass and 360mm long with 350mm outside the heating element with a diameter of 10mm. It has Temperature probes connected to its surface (TI1 to TI8) which are 50mm apart finally Temperature probe TI9 measures ambient temperature and resides at the farthest end of the rod not touching said rod.

3.2. Procedure

Connected plant to the main power supply and switched on the plant. Using the voltage control the power input was set to 8V, the system was allowed to reach steady state for 10 minutes so that temperatures to stabilized and the temperature readings were recorded. Power output was then set to 10V and left 15 minutes to reach steady state, temperature readings were then recorded. Power output was then set to 12V and left for 20 minutes to reach steady state, temperature readings were then recorded. Finally, power output was set to 14V and left 20minutes to reach steady state, the final temperature readings of the trial were then recorded. Three Trials where conducted for consistency and accuracy. The mean between the readings of the trials was used for the comparative study.

Using COMSOL (steady state simulation), the thermal study was conducted. First, the geometry was set up using the specified dimensions of the brass rod. Then the physical characteristics of the medium were set to that of brass. The power input of heat was set to be at the origin of the rod so that heat flows from the defined vector of zero, zero, zero to that of the end of the rod. Power output was set to the product of recorded Amps and Voltages. Finally, a fine physics controlled mesh was used to simulate the heat transfer and the simulation was executed. The results obtained was tabulated by COMSOL and used for the comparative study.

4. Results and Discussion

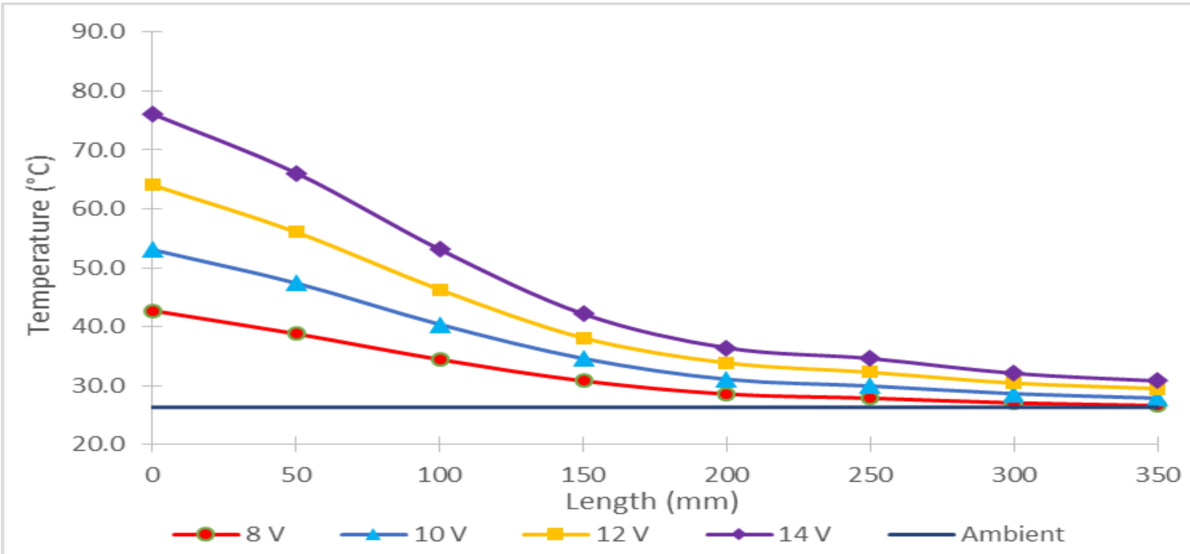

Figure 4: Actual Temperature Profile along the Rod

Figure 4 shows the actual temperature profile as measured along the length of the rod. The initial length protruding, as expected, is the highest temperature. As heat is conducted through the rod and some are lost to the atmosphere the temperature declines as it moves through the rod. At the end of the rod, the temperature is an ambient room temperature of 26 °C. The shape of the curve represents an inverse logarithmic curve with a steep initial decline which then evens out to almost plateau as it nears ambient temperature. The four power settings, defined by voltage setting, show that the more heat in, terms of power, is introduced into the rod the higher the initial temperature. The curves don't correlate at any stage along the set length but would have if the rod was longer.

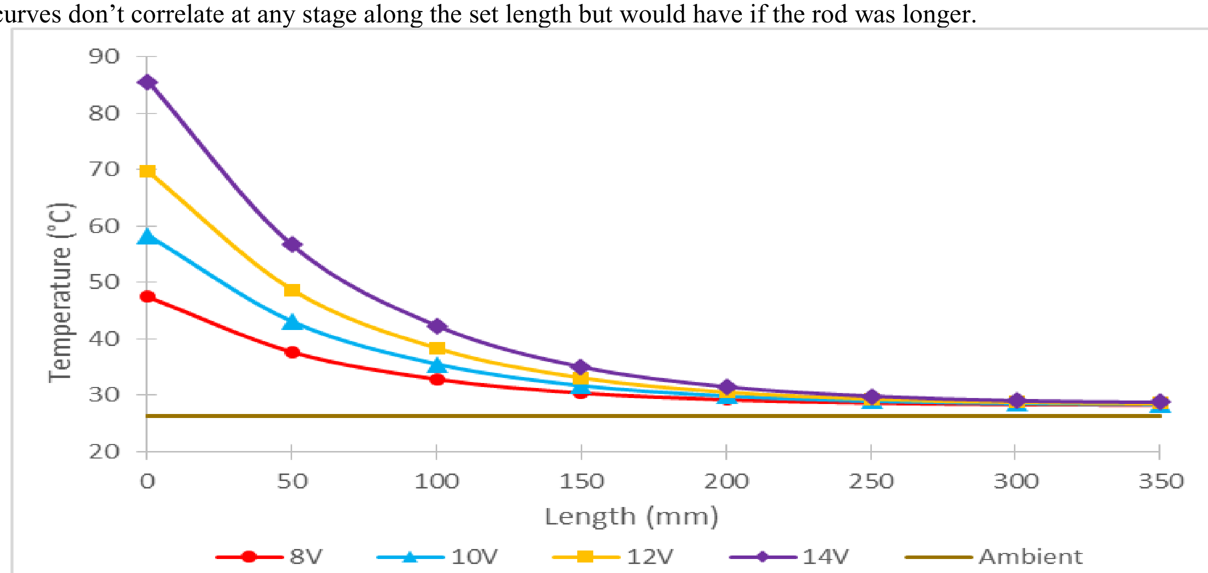

Figure 5: Simulated Temperature Profile along the Rod

Figure 5 shows the simulated temperature profile as calculated by COMSOL along the length of the rod. The initial decline in temperature, compared to Figure 4, Figure 5 is much steeper and initial values overall are higher. Furthermore wherein Figure 4 the temperatures do not correlate between the four different power settings, in Figure 5 from 200mm onwards the four curves with respective power settings merge into a single line. This indicates that the temperatures between power settings are the same at those points. This shows that in simulation heat was dissipated more into the atmosphere and the resistance to heat conduction of the rod was higher compared to actual experimental data.

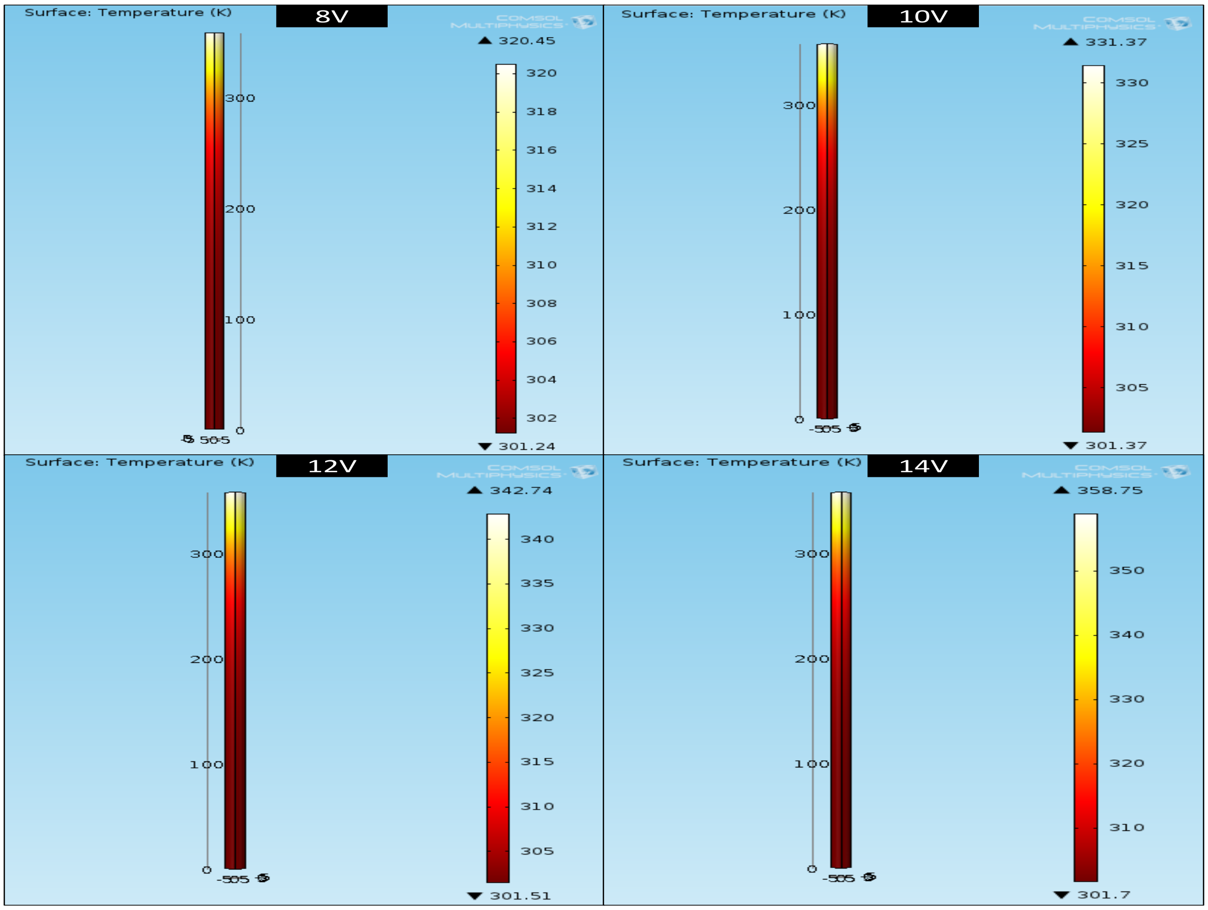

Figure 6: Visual Representation of Simulation from COMSOL

Figure 6 shows a visual representation of the rod produced by COMSOL simulation. On the right of each simulation is a scale showing the colour compared to temperature and on the left is the simulated rod with the colour indicating the heat of the rod's surface temperature in Kelvin (K). With a higher power setting, represented by higher volts, it is clear that the temperatures are higher and temperature decline much steeper.

Table 1: Summarized results of the Experimental study on extended heat transfer

	8V	10V	12V	14V
Length (mm)	Temperature (°C)	Temperature (°C)	Temperature (°C)	Temperature (°C)
350	26.6	27.9	29.5	30.8
300	27.1	28.6	30.4	32.1
251	27.9	29.9	32.3	34.6
200	28.6	31.1	33.9	36.4
150	30.8	34.6	38.1	42.2
100	34.4	40.4	46.3	53.1
50	38.8	47.4	56.1	66.1
0	42.7	53.1	64.1	76.1

Table 2: Summarized results of the Simulative (COMSOL) study on extended heat transfer

	8V	10V	12V	14V
Length (mm)	Temperature (°C)	Temperature (°C)	Temperature (°C)	Temperature (°C)
350	28.2	28.4	28.5	28.7
300	28.3	28.5	28.7	29.0
251	28.6	28.9	29.3	29.8
200	29.2	29.8	30.5	31.5
150	30.4	31.7	33.1	35.0
100	32.8	35.5	38.3	42.2
50	37.7	43.1	48.7	56.7
0	47.4	58.3	69.7	85.7

Table 1 and 2 show the summarized results from the Experimental and Simulative studies respectively. There is a clear difference between the two data sets for each respective set and to analyze whether the difference is significant an error percentage analysis was done.

Table 3: Error Percentage between Actual and COMSOL Simulated results along the length of the rod

	Error Percentage (%)			
Length (mm)	8V	10V	12V	14V
350	5.8	1.8	3.5	7.3
300	4.5	0.4	6.0	10.6
251	2.6	3.4	10.1	16.1
200	2.1	4.2	11.0	15.6
150	1.4	9.1	15.2	20.3
100	5.0	13.9	20.9	25.8
50	3.0	10.0	15.1	16.6
0	9.9	9.0	8.1	11.1
Mean	**4.3**	**6.5**	**11.2**	**15.4**

Table 3 shows the error percentage between that of the experimental trial and the simulation. The error is calculated by taking the absolute residual between the two values for each point divided by the actual measured value multiplied hundred. The mean error of 8V power setting is within a degree of error (5%) but its maximum error is not. Furthermore, the 8V power setting has the lowest maximum error as well as the lowest mean error. This shows that the simulation was inaccurate with the highest error being 26% and highest mean error 15%. For the real world perspective, the current simulation model requires greater accuracy before it can be used. Errors of 25% and a mean error of 15.4% are too great for industrial application. This may be resultant from the extended heat transfer plant being different from the input variables obtained from the equipment manual.

5. Conclusion

The simulation places had up to 26% error. The simulation initial temperatures were too high and the temperature profile declined to quickly. This shows that in simulation the brass rod would rather dissipate its heat into the atmosphere than conducting it through the length, which was not the case in experimental trials. This may be due to an insulation of some kind present which was not taken into account. The objectives of the study have been met with some consideration, while the extended heat transfer phenomenon was successfully simulated and compared with the actual experimental results the models have too great an error to be utilized at this stage. Future research will be directed at lowering the error between simulated and experimental results and testing the simulated model in more complex systems, an accurate model can be utilized in the simulation of heat transfer in fuel cells; nuclear reactor control rods and metal casting equipment to name a few. This research will be to investigate the extended heat transfer pilot plant further to validate the input variables of the brass rod obtained from the equipment manual is accurate. Then the study will be repeated using other substances like iron.

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Biographies

Douw Gerbrand Faurie is a National Diploma (N-Dip.) in Chemical Engineering 2017 graduate from the Tshwane University of Technology and currently studying his Baccalaureus Technologiae (B-Tech.) in Chemical Engineering, graduating 2018. Douw Faurie completed his Work Integrated Learning (WIL) with the Tshwane University of Technology Chemical Engineering laboratories and is currently volunteering as a mentor for the WIL students as well as doing his industrial project towards his B-Tech. there supervised by Mr M.J. Mosesane. Douw Faurie has a passion for innovation and the advancement of technology with a strong work ethic. The topic of the mentioned industrial project is green energy from waste. Douw Faurie wishes to commence his Masters (Chemical Engineering) in 2019 after completing his B-Tech.

Molelekoa James Mosesane holds a Master’s Degree in Chemical Engineering and a B-Tech Project Management Degree. He is currently employed by Tshwane University of Technology and studying towards a Master’s of Business Administration (MBA). He lectures laboratory classes and design experiments for undergraduates; supervise WIL (P1 and P2), B-Tech and Masters chemical engineering, students. His expertise includes, project management, laboratory management and maintenance, commissioning of pilot plants, liaising with industry, research collaborations and working on different projects for his students.