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College of Engineering

Department of Mechanical Engineering

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Senior Design Project Report

“Design of experiments to study the thermal and mechanical properties of polymers produced from 3-D printing”

In partial fulfillment of the requirements for the
Degree of Bachelor of Science in Mechanical Engineering

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Abstract

The recent increase in application of Additive Manufacturing (AM) products has resulted in new demands throughout the industry. Although FDM-based products are used in various fields, the mechanical properties of such products still tend to be weaker than that of the products manufactured through conventional manufacturing processes. Therefore, improving the mechanical properties of FDM-printed products is a key factor that can greatly contribute to the manufacturing industry.

Keywords– Dual material 3D printing, FDM, tensile strength.

Acknowledgment

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On the other hand, the efforts of the team members were tremendous. The division of work among the team members was clear, remarkable and productive too. It was a great time to work with team members. The leader of the group addresses his strongest gratitude to each of the four members of the team.

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CHAPTER 1

INTRODUCTION

1.1 PROJECT DEFINITION

1.2 PROJECT OBJECTIVES

1.1 Project Definition

In this project we are designing experiments to study the thermal and mechanical properties of the polymer produced from 3-D printing. For this design introduction about 3-D printing and some literature review done is discussed here.

1.1.1 3-D Printing

3D printing (rapid prototyping) is a new advanced manufacturing process which manufactures functional products based upon a 3D CAD (Computer Aided Design) model. This CAD model is then further processed with a slicer software, such as CURA, that converts the CAD model into set of machine G-code instructions that are used to command the motors of a 3D printing machine. The 3D printing process can be used with different types of plastic materials. This new technology is most likely going to be the future manufacturing process to save time, money and efforts within certain industries and within research and development. Recent developments in additive manufacturing (AM) or 3D printing have resulted in numerous applications toward the engineering sector and the medical sector. AM can offer the capacity to manufacture complex CAD shapes, to produce final product designs with specific chemical, physical, and mechanical properties. This has allowed the production of various medical implants and devices for medical applications.

1.1.2 How Does it Work?

The 3D printing machine (called a 3D printer) is an innovation that uses an x, y, z robotic stage combined with other deposition technologies, to print products from referenced 3D CAD models. The CAD model is created using CAD software such as Solidworks, Auto CAD, or other. This CAD model is then converted to the G-code using slicer software and sent to the 3D printer. The G-code is similar to a CNC programme which will move the printer material deposition system, to print the final product as per the instructions. The recent developments in this process can allow printing variety of materials including plastics and polymers, and in some cases metals, ceramics and non-metals.

1.1.3 Advantages

There are several advantages to 3D printing:

- No specialized tooling is needed, thus significantly reducing production time and cost.
- Small production batches are feasible and economical.
- Possibility to quickly change design.
- Easy to produce prototype products.
- Waste reduction.
- Shorter lead times for easy supply chain and lower inventories.
- Design customization.

The advantages described above also allow for personalized design of medical devices matched to individual body shapes. Hence, this technique has good application towards fabrication of spinal braces.

1.1.4 Applications

Due to the relative high cost of Additive Manufacturing (AM) technologies in comparison to injection molding, AM has limited adoption by manufacturers; however, in the engineering research and development sector, medical field, and in some construction industries they are gaining popularity. There are many new AM opportunities available in the biomedical field regarding the 3D printing of custom-shaped orthopedic, dental implants, medical equipment and tissue scaffolds. CAD/CAM-based AM technologies for plastics, metals and non-metals have established many applications in the near net shape fabrication of complex geometries with tailored mechanical properties for biomedical sectors.

1.2 Project Objectives

Following are the objectives of this project which we need to achieve at the end of the project:

- I. To study the thermal and mechanical properties of polymer produced from 3D printing.
- II. To design an experimental setup to measure the thermal and mechanical properties of polymer produced from 3-D printing.
- III. Learn to work as a team.

CHAPTER 2

LITERATURE REVIEW

2.1 PROJECT BACKGROUND

2.2 PREVIOUS WORK

2.3 COMPARATIVE STUDY

2.1 Project Background

In this section background of 3D printing technologies are discussed:

2.1.1 3D Printing Technologies

There are a variety of 3D printing techniques available in the market to fabricate plastic parts, where the most recommended and accepted are as follows: Fusion Deposition Modelling, Selective Laser Sintering, Inkjet 3D printing, Stereolithography and 3D plotting. In addition, other 3D printing technologies for printing of metals, ceramics and composites are rarer in industrial use, or are still in the process of development. Each technique has its own benefits and drawbacks during the manufacturing process. The choice and selection of the fabrication technique depends on the selection of raw materials, requirement of processing speeds and resolution, cost and performance needs for the intended application.

2.2 Previous Work

In this section all the previous work which has been done before are discussed.

2.2.1 FEA for 3D Printing

3D printing provides the possibility of low volume and cost effect production as well customized parts with extraordinary features such as multilateral fabrication, light weight hollow material and fabrication of complex structures which are not possible using traditional fabrication techniques such as CNC milling, casting or molding. Computer simulation of 3D printing process is a necessary step to make sure that the 3D printing systems work as they are supposed to, and to analyse that the 3D printed parts have the exact physical properties that the designers expect.

2.2.1 Fused Deposition Modelling (FDM)

It begins with a meshed 3D computer model that can be created by acquired image data or structures built in computer-aided design (CAD) software. A Stereolithography (STL) file is created and the mesh data will be further sliced into a build file of 2D layers and sent to the 3D printing machine where the part is printed. FDM uses preformed polymer filament that is supplied on a spool as the building material.

CHAPTER 3

SYSTEM DESIGN

3.1 DESIGN CONSTRAINTS

3.2 DESIGN METHODOLOGY

3.3 THEORETICAL CALCULATIONS & DESIGN

3.4 PRODUCT SUBSYSTEMS & COMPONENTS

3.5 MANUFACTURING & ASSEMBLY

This chapter talks about design part to conduct an experiment to test our 3D printed parts. The important part in this process was selection of material, design of components and design of experiments. All these parts are discussed in this chapter.

3.1 Material

Material of interest in this study should be 3D printable. All tensile test specimens are fabricated and prepared with these chosen materials. In this project we want to test five different types of plastic. Following 5 materials have been selected for test:

- Polypropylene
- Cellulose Acetate Butyrate
- Acrylic
- Glass-Reinforced Polyester
- Glass-Reinforced Nylon

3.2 Sample preparation with 3D printing

According to ASTM D638-14, tensile specimens are printed with the commercially available Poly jet type 3D printer. 3D CAD models are generated by Autodesk® Design. In Polyjet type 3D printing, each specimen is printed by three main processes. Firstly, in pre-processing step built-in software automatically calculates the placement of photopolymers and support materials from 3D CAD file. In printing step, the model and support materials, are jetted onto a build tray and cured immediately by the UV-light to realize 3D products. After printing step, the final samples were obtained by removal of supporting materials. Each specimen is printed individually at the center of the printing bed in order to produce all specimen as similarly as possible.

In our project there are two parts;

- Thermal Analysis
- Mechanical Analysis

For thermal part we are using small steel cylinder shape which we designed using AUTOCAD® program according to the standard instruction as shown in Figure 3.1, we will print it by 3D printing for each type of material mentioned in subsection 3.1.

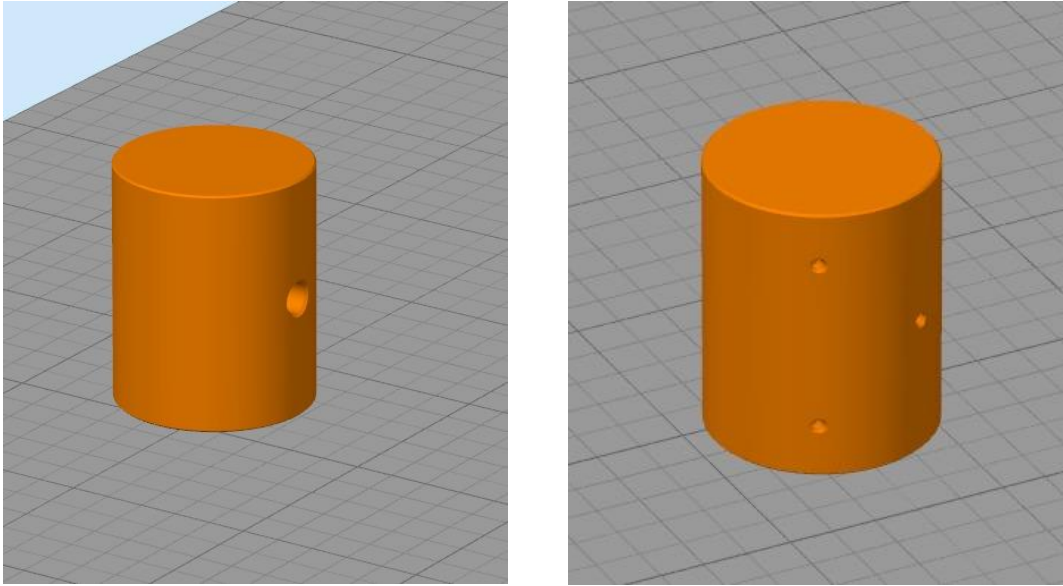


Figure 3.1: Thermal test cylinder specimen.

Another part is the Solid part which have different shape, we designed this shape in AUTOCAD® program according to standard instructions as shown in figure 3.2. We will print this shape using 3D printer for five different types of materials discussed in section 3.1. According to the Standard instruction for solid we must test each type of shape five times so we will print of each type and test it using Tensile Testing Machine.

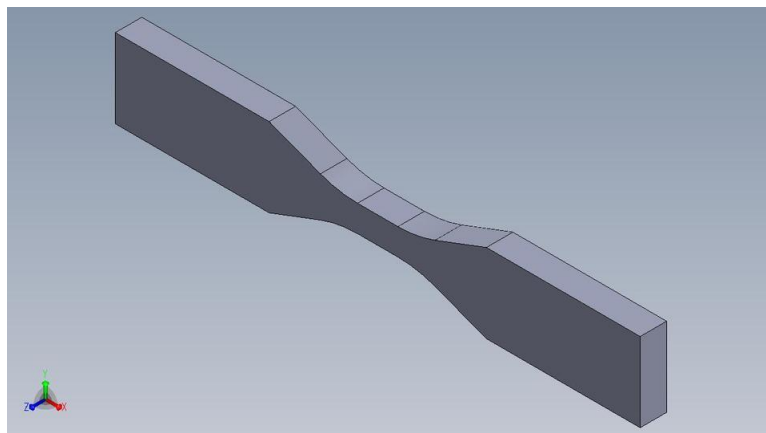


Figure 3.2: Type I ASTM D638 – 14 test specimen designed in AUTOCAD®.

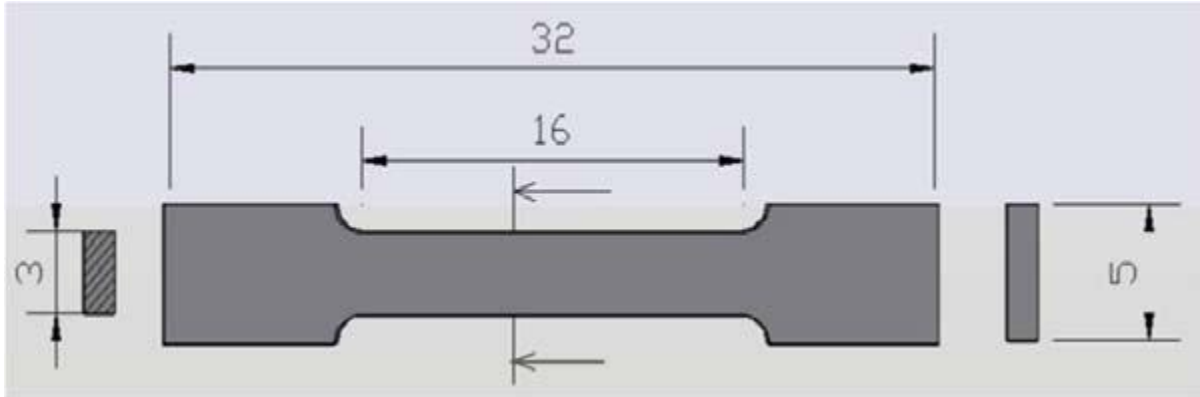


Figure 3.3: Tensile/Fatigue Specimen Dimensions[mm].

3.3 Mechanical Analysis

Above 3D-printed specimens will be used to conduct tensile, flexural and fatigue testing. The standard "dumbbell" or "dogbone" shaped specimens are used, so that the deformation is confined to the narrow center region and to reduce the possibility of fracture to occur at the ends of the specimen. Avoiding failure at the ends (where the specimen is gripped) is crucial. Moreover, grips of tensile testing machines have teeth to attain a fairly strong grip that can resist the forces required to deform the specimen longitudinally. The teeth usually cause plastic deformation of the gripped portion of the specimen. Material properties may change because of plastic deformation, but it indeed changes the specimen geometry. The stress concentrations in the gripped region is created as the specimen geometry changes. If a failure occurred at the grips in a cylindrical or bar specimen without enlarged ends, then both the changes would lead to an incorrect measurement [3]. Dog-bone shape is also crucial as it determines another property called Elongation, which is usually measured at the same time. Elongation is measured by placing a gauge on the reduced section and for the measurements to be accurate, the elongation should occur in this area [3]. Any plastic deformation resulting due to the movement of the machine grips will add to the measurement of elongation.

With reference to the size, these are controlled by standards which are universally accepted. For example, tensile testing of plastics is done by following the guidelines of the ASTM D638

standard. Since, according to the Standard instruction for solid we must test each type of shape Specimen 5 times so finally, we will test 25 specimens and minimum 5 of each material. All specimens are printed following the guidelines of the ASTM D638 standard with 100% fill density with different printing temperatures depending on the material. The tensile specimens will be printed in two different printing directions, longitudinal and transverse to the length of the tensile specimen, respectively to measure the direction properties dependence.

3.4 Thermal Analysis

Curing behaviors and glass transition temperatures (T_g) of the photopolymers prior to 3D printing are characterized with Differential Photo calorimetry (DPC) technique. After 3D printing dynamic DSC measurements are performed to determine glass transition temperature (T_g) of each sample. Finally, results are concluded to give thermal analysis of the 3D specimen.

CHAPTER 4

SYSTEM TESTING and ANALYSIS

4.1 EXPERIMENTAL SET-UP

4.2 Thermal Analysis

4.3 Mechanical Analysis

4.4 RESULTS, ANALYSIS and DISCUSSION

4.1 Experimental Set-up

This chapter covers all the experimental results for our 3D printed component. Various experiments have been performed to obtain results and final results are discussed in this chapter.

4.2 Thermal Analysis

This part discusses the result obtained for thermal analysis of the component. Heat conduction module designed by EDIBON was used to perform experiments temperatures were measured at different points as shown in figure below with the help of thermocouples installed. Temperature Vs distance graph plotted and variation of thermal conductivity with temperature is approximated using below equation for value of different heat transfer.

$$\frac{\Delta T}{\Delta x} = m = Pte$$

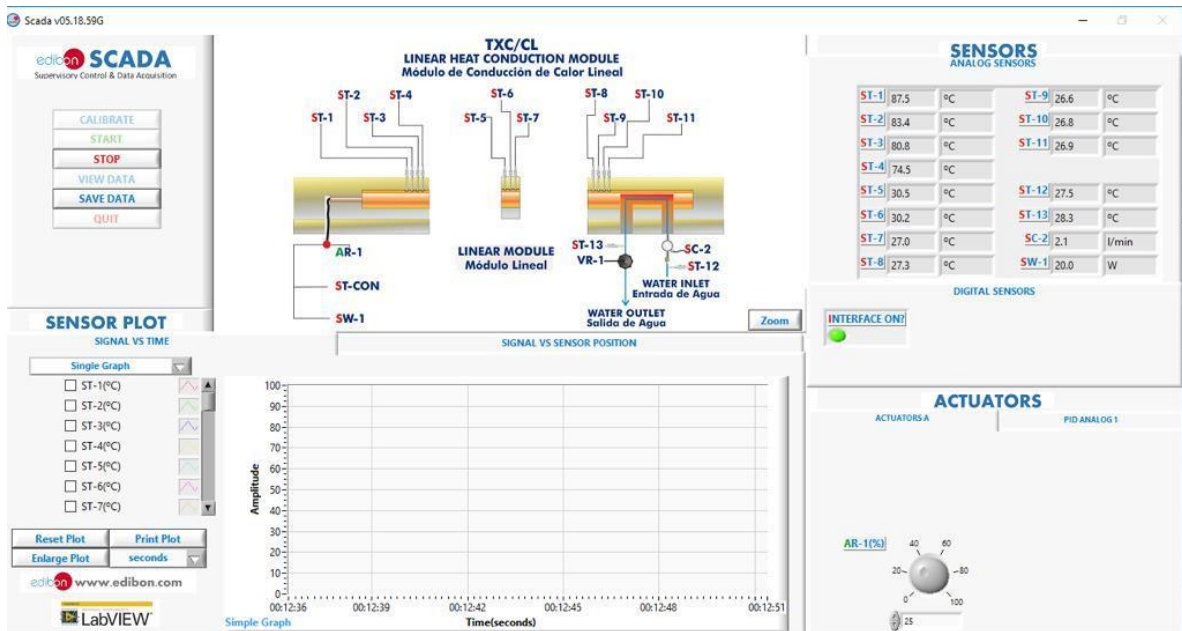


Figure 4.1: Type ABS at 20 W.

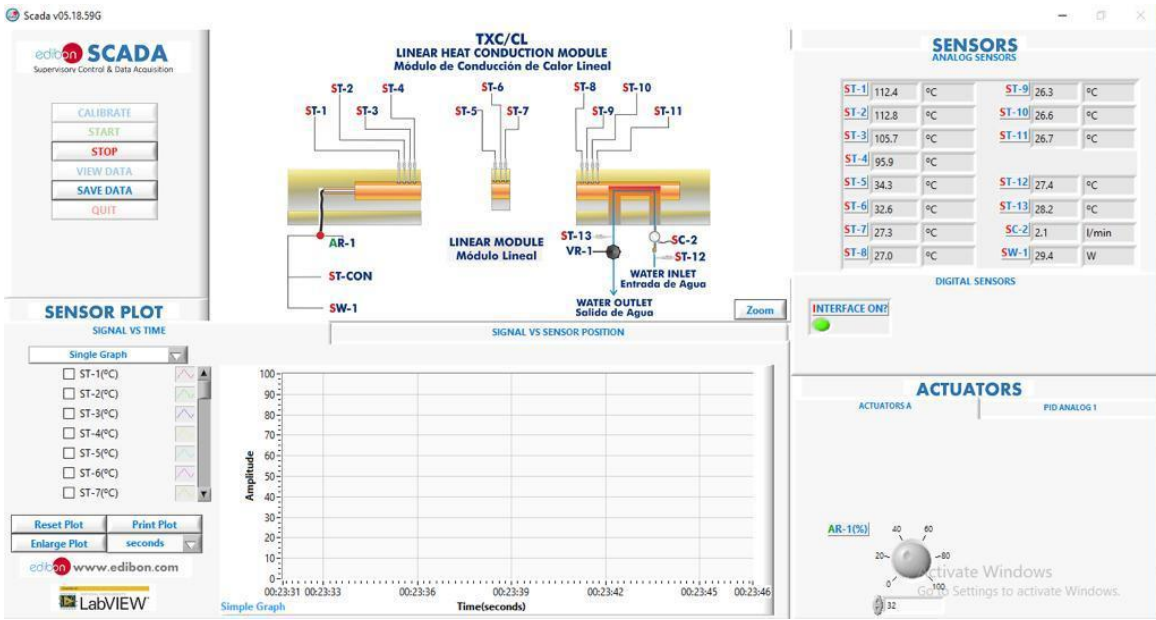


Figure 4.2: Type ABS at 30 W.

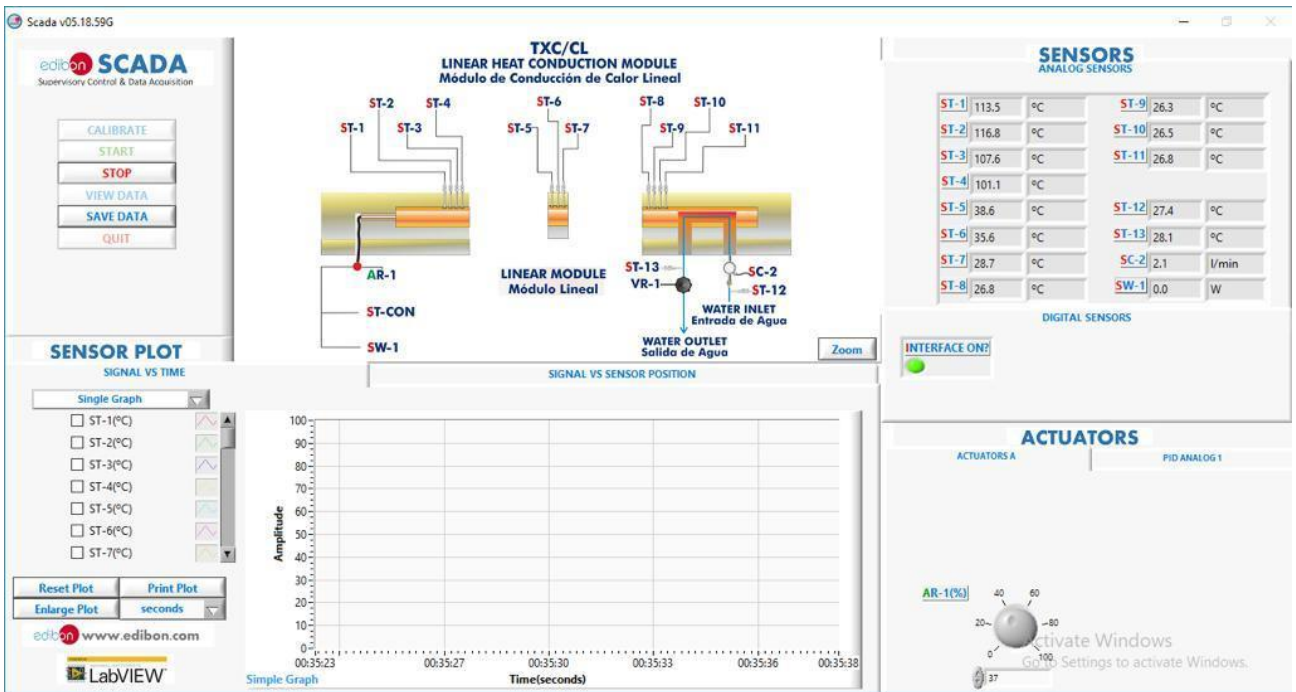


Figure 4.3: Type ABS at 40 W.

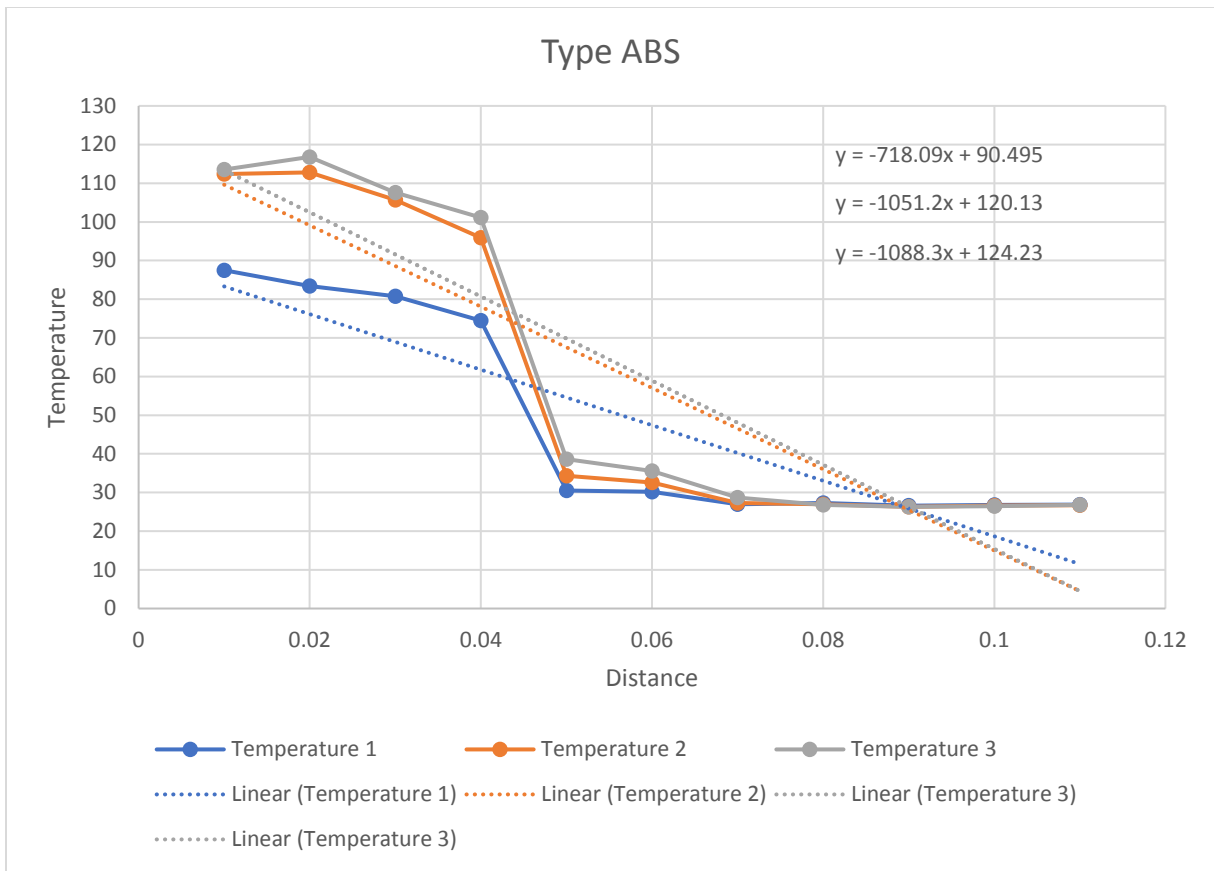


Figure 4.4: Temperature Vs Distance plot for type ABS.

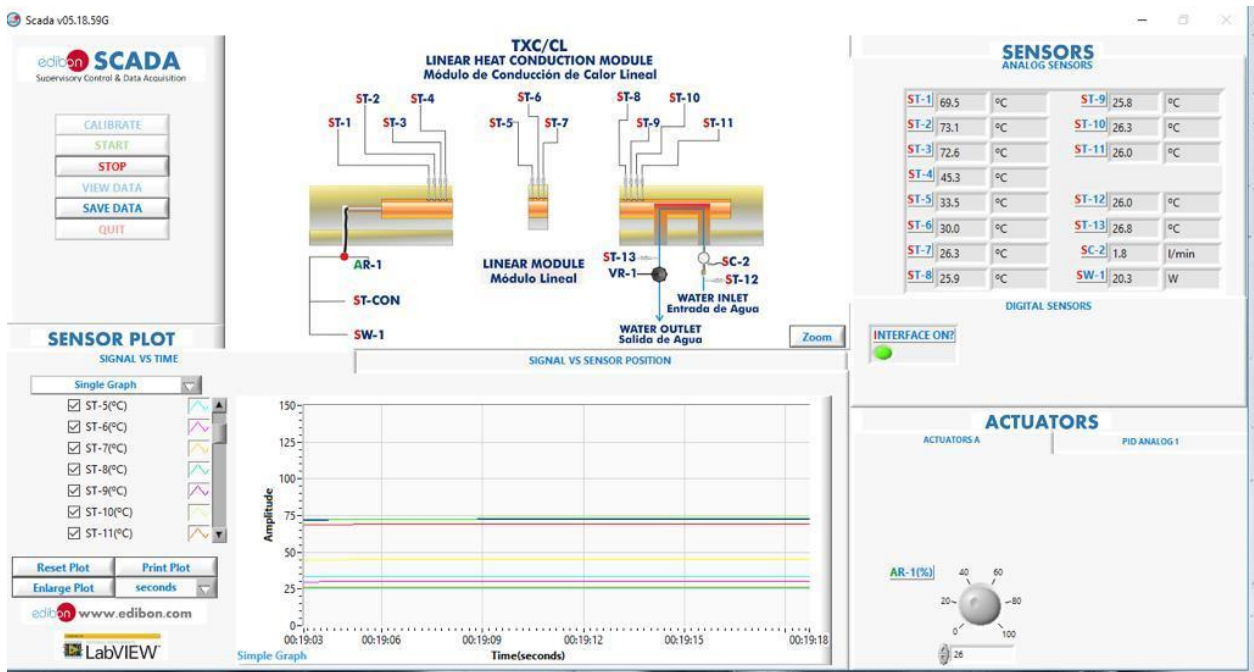


Figure 4.5: Type PLA at 20 W.

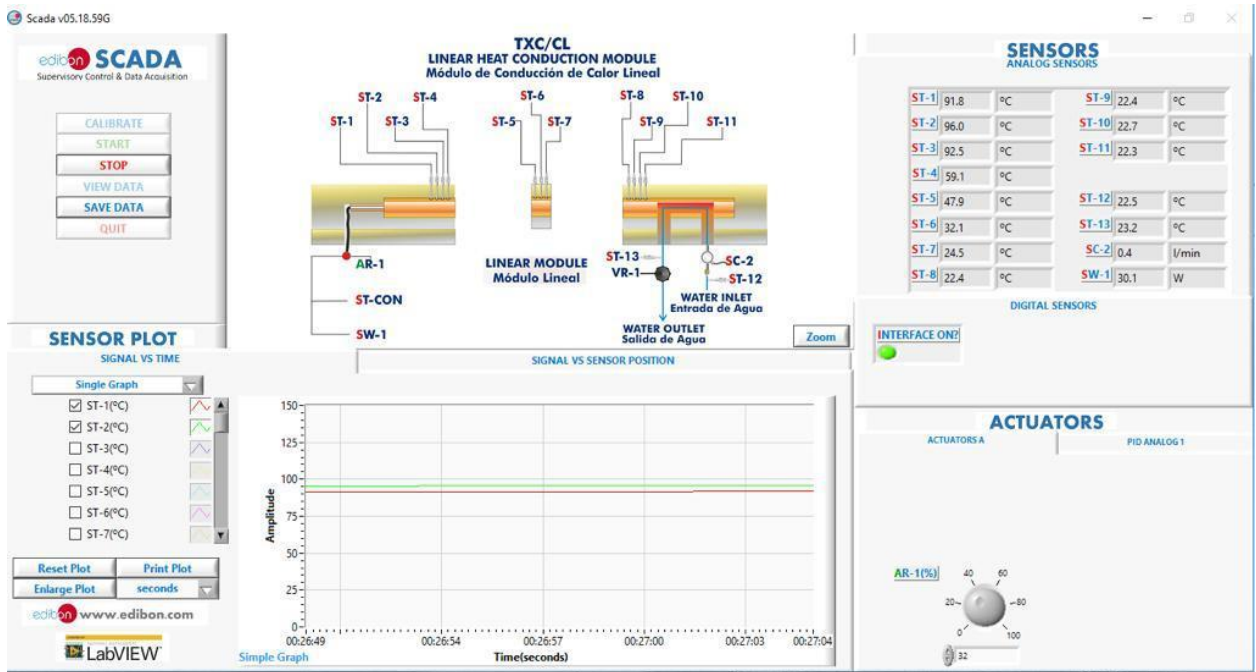


Figure 4.6: Type PLA at 30 W.

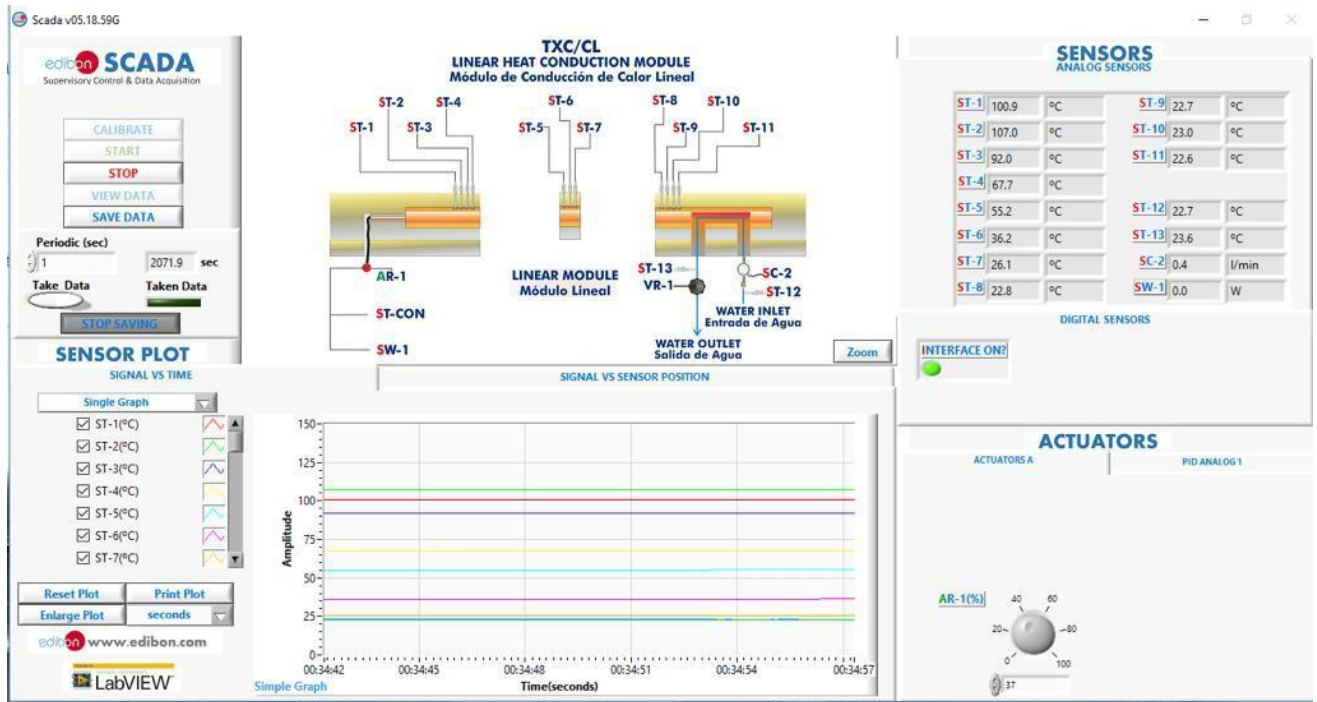


Figure 4.7: Type PLA at 40 W.

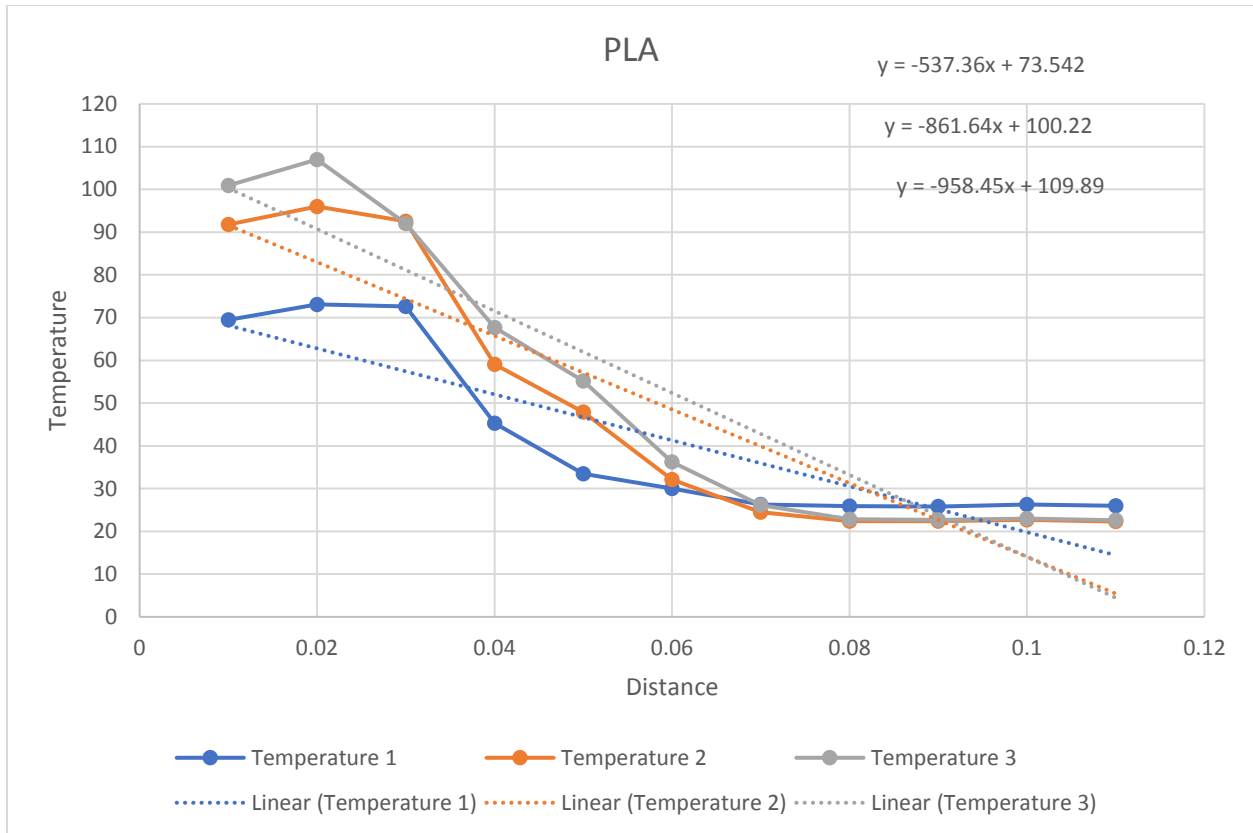


Figure 4.8: Temperature Vs Distance plot for type PLA.

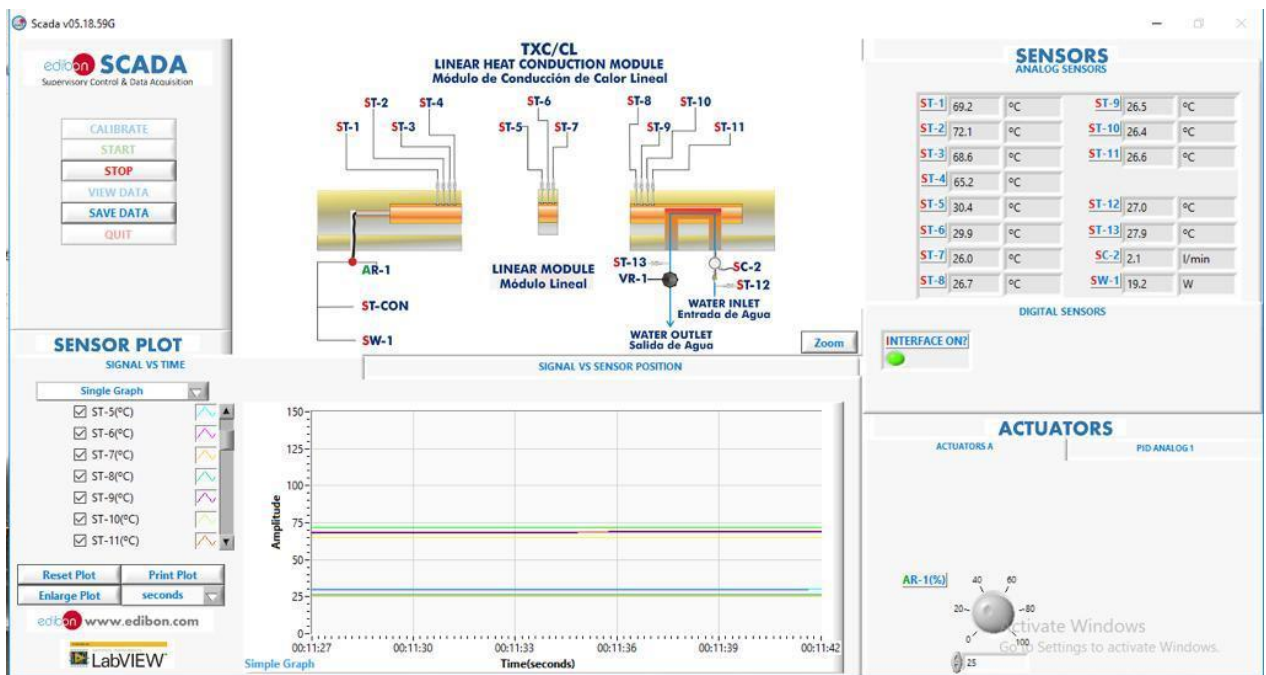


Figure 4.9: Type PETG at 20 W.



Figure 4.10: Type PETG at 30 W.

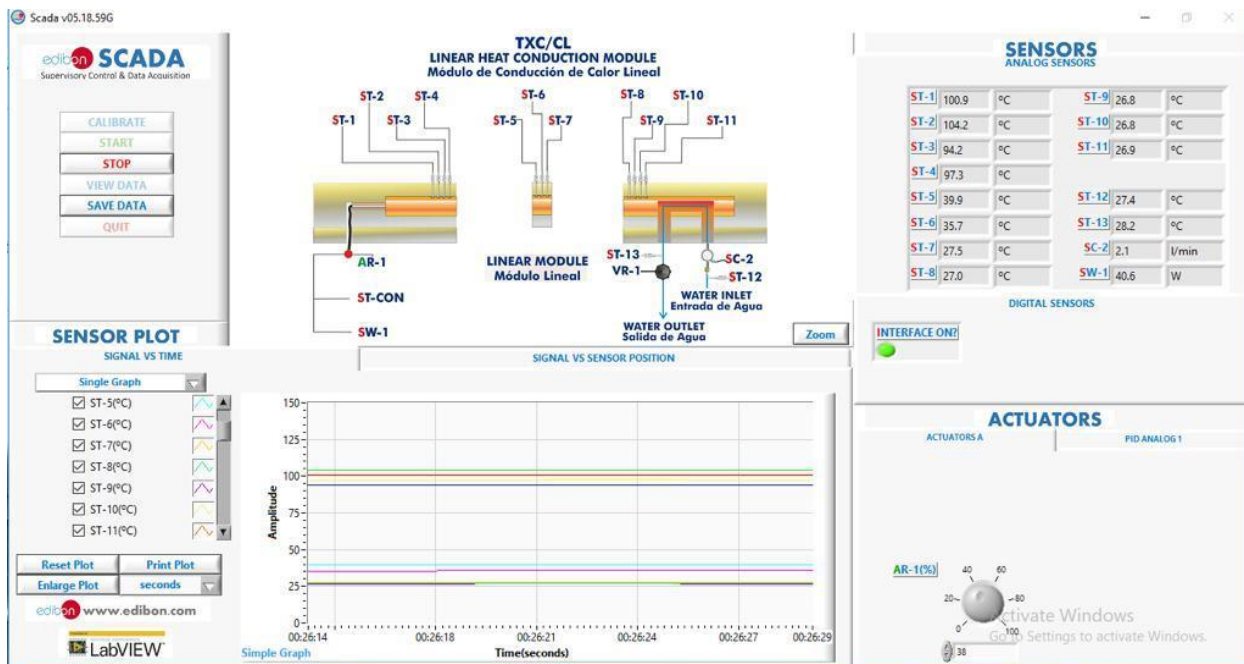


Figure 4.11: Type PETG at 40 W.

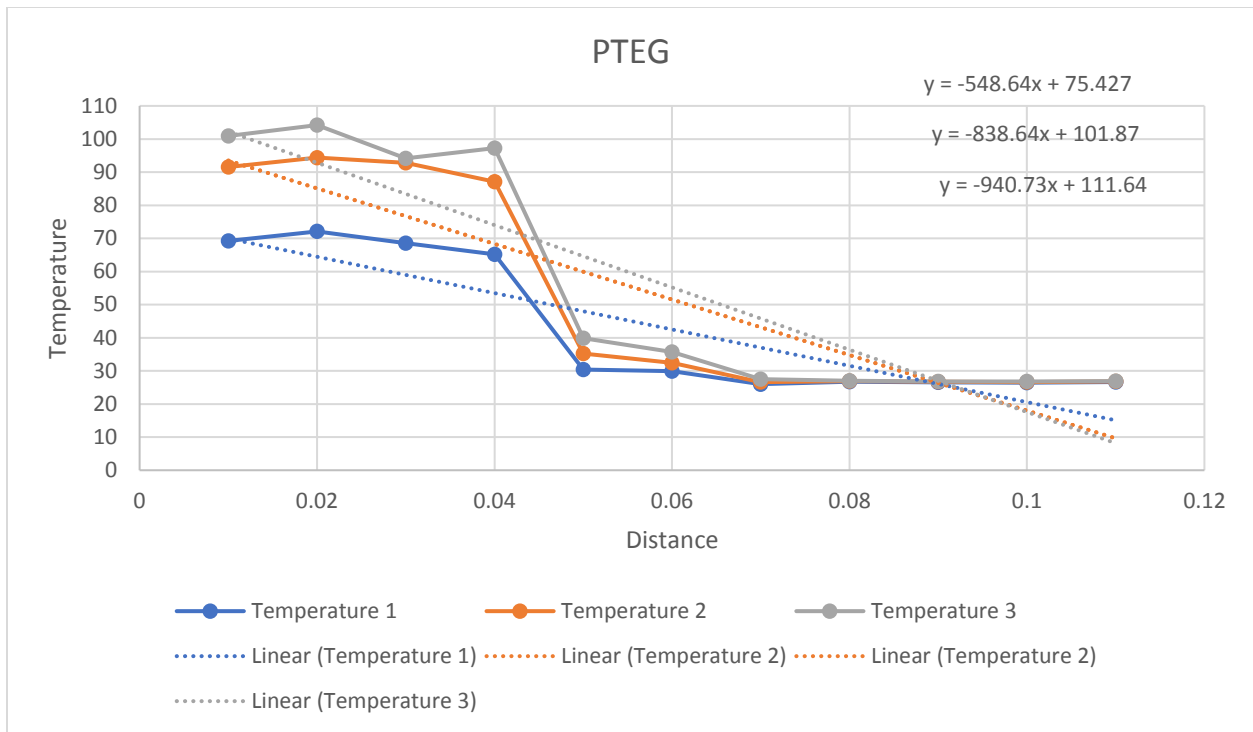


Figure 4.12: Temperature Vs Distance plot for type PETG.

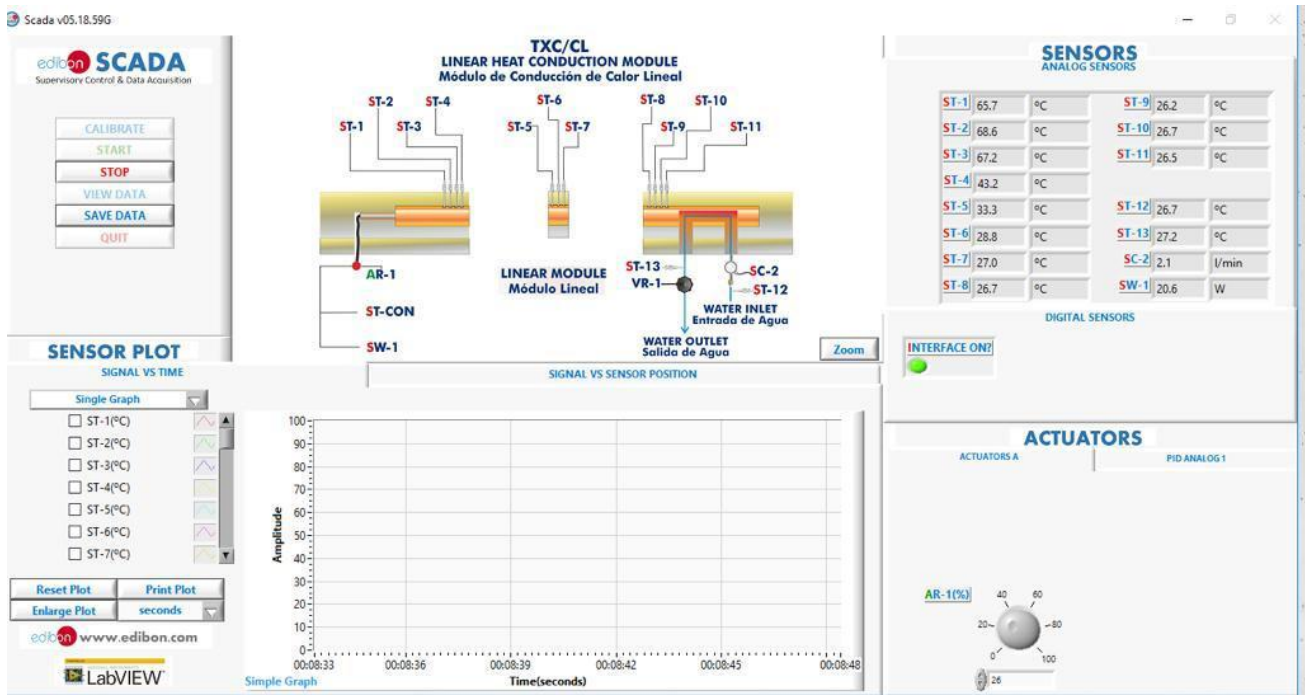


Figure 4.13: Type Polycarbonate at 20 W.

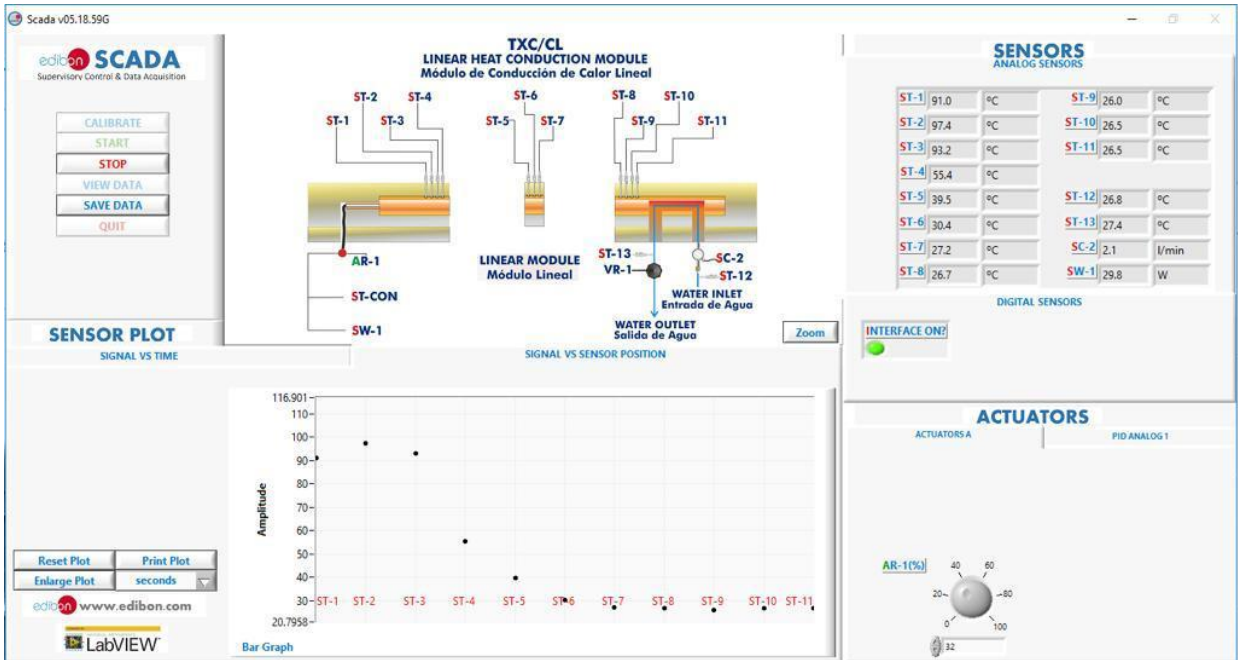


Figure 4.14: Type Polycarbonate at 30 W.

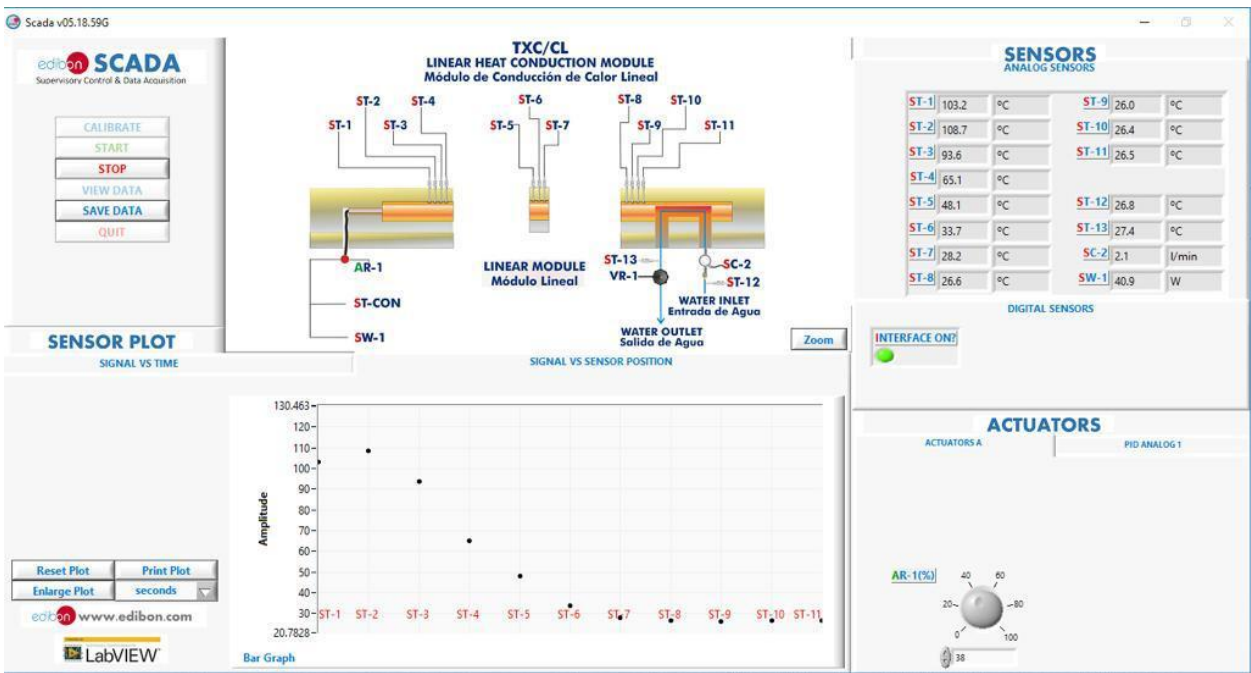


Figure 4.15: Type Polycarbonate at 40 W.

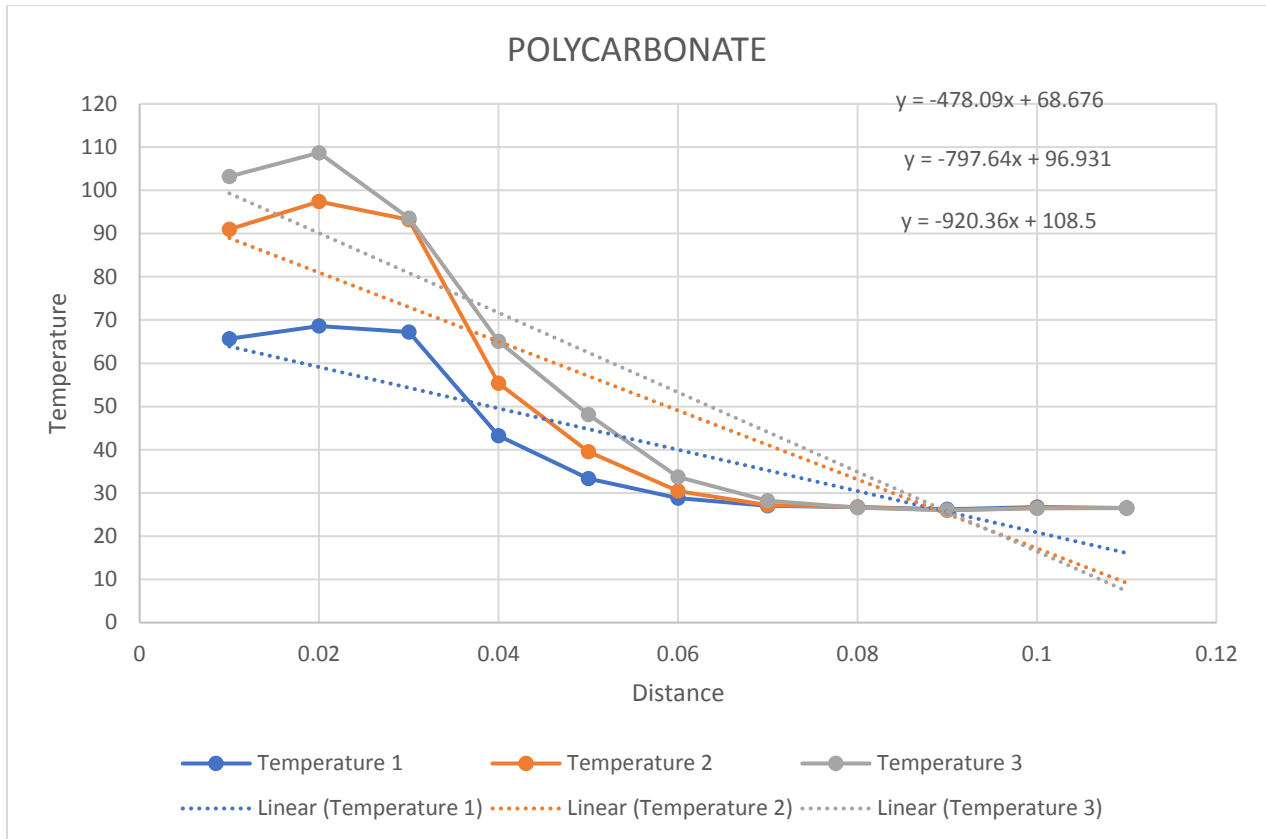


Figure 4.16: Temperature Vs Distance plot for type Polycarbonate.

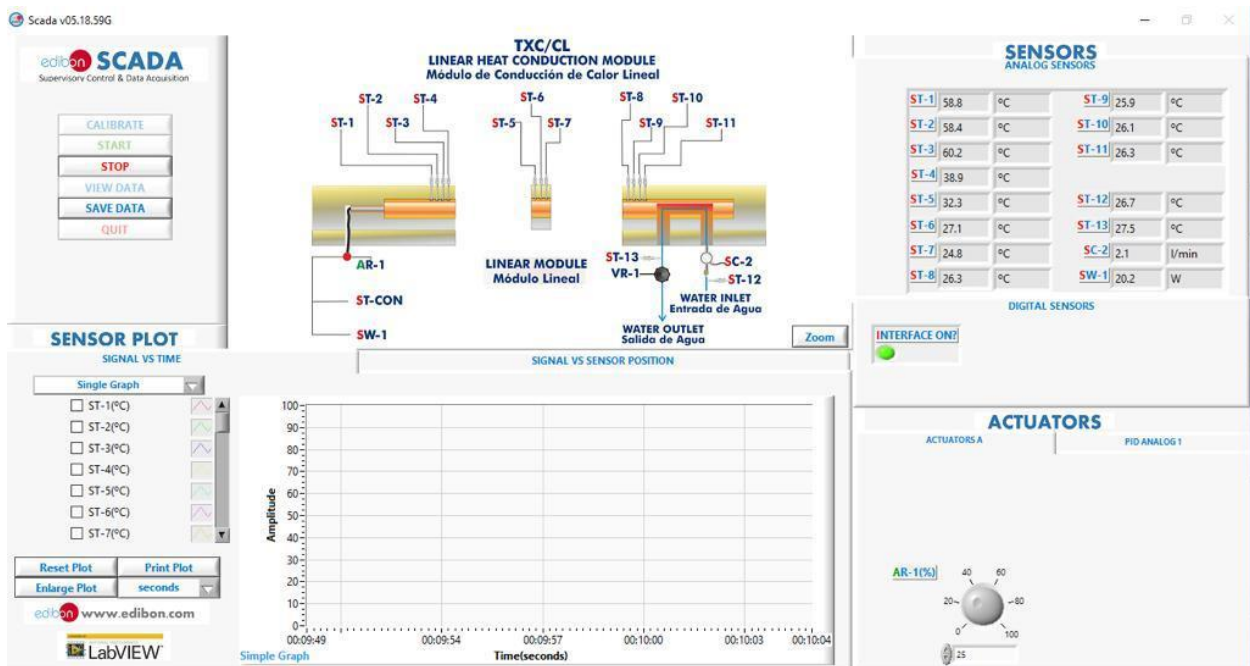


Figure 4.17: Type ABS Polycarbonate at 20 W.

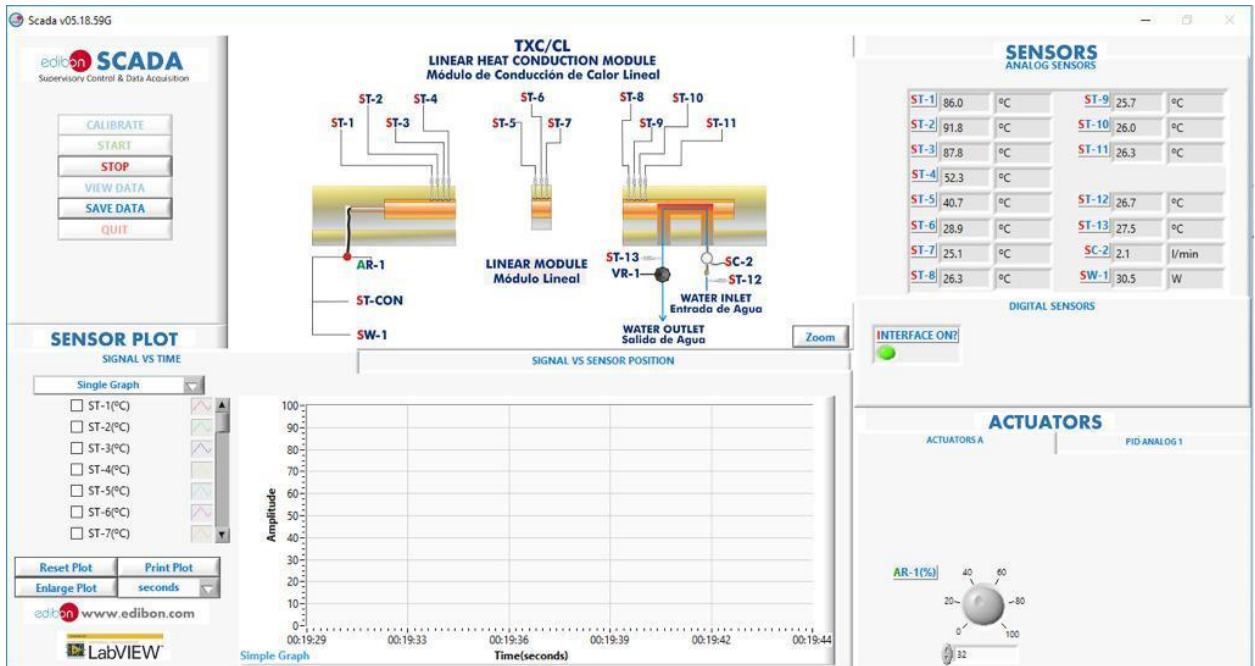


Figure 4.18: Type ABS Polycarbonate at 30 W.

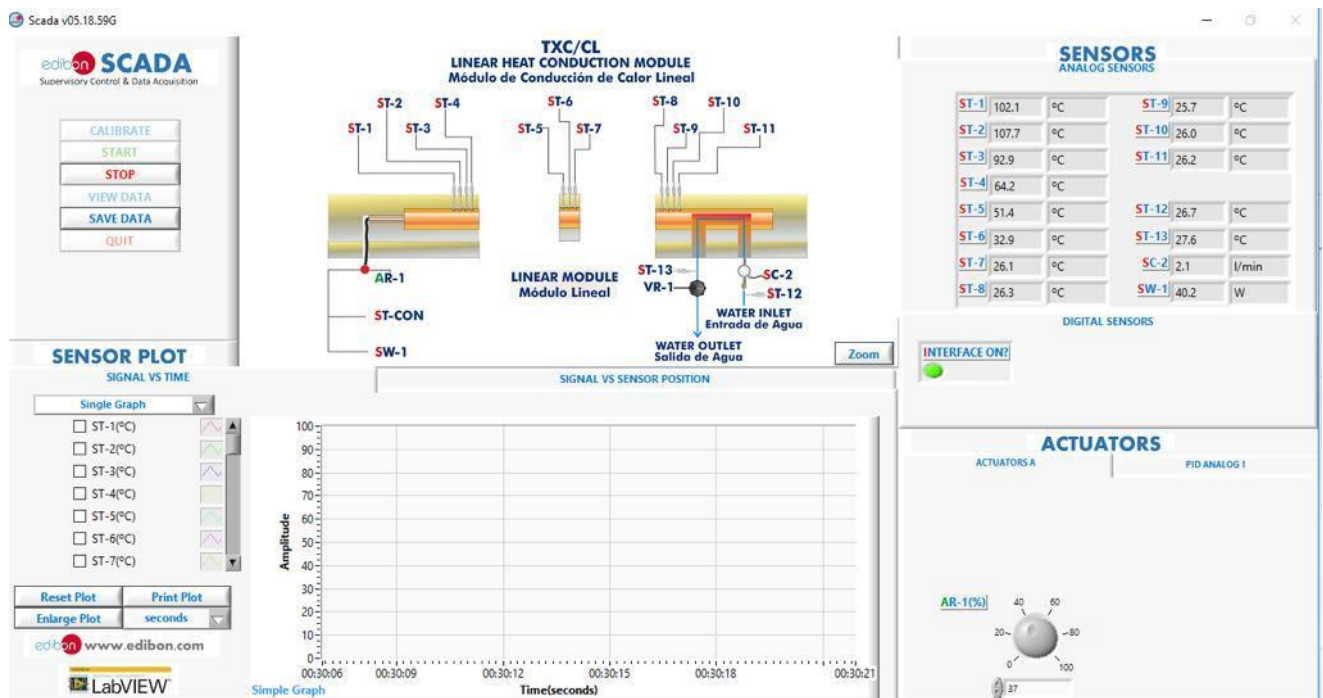


Figure 4.19: Type ABS Polycarbonate at 40 W.

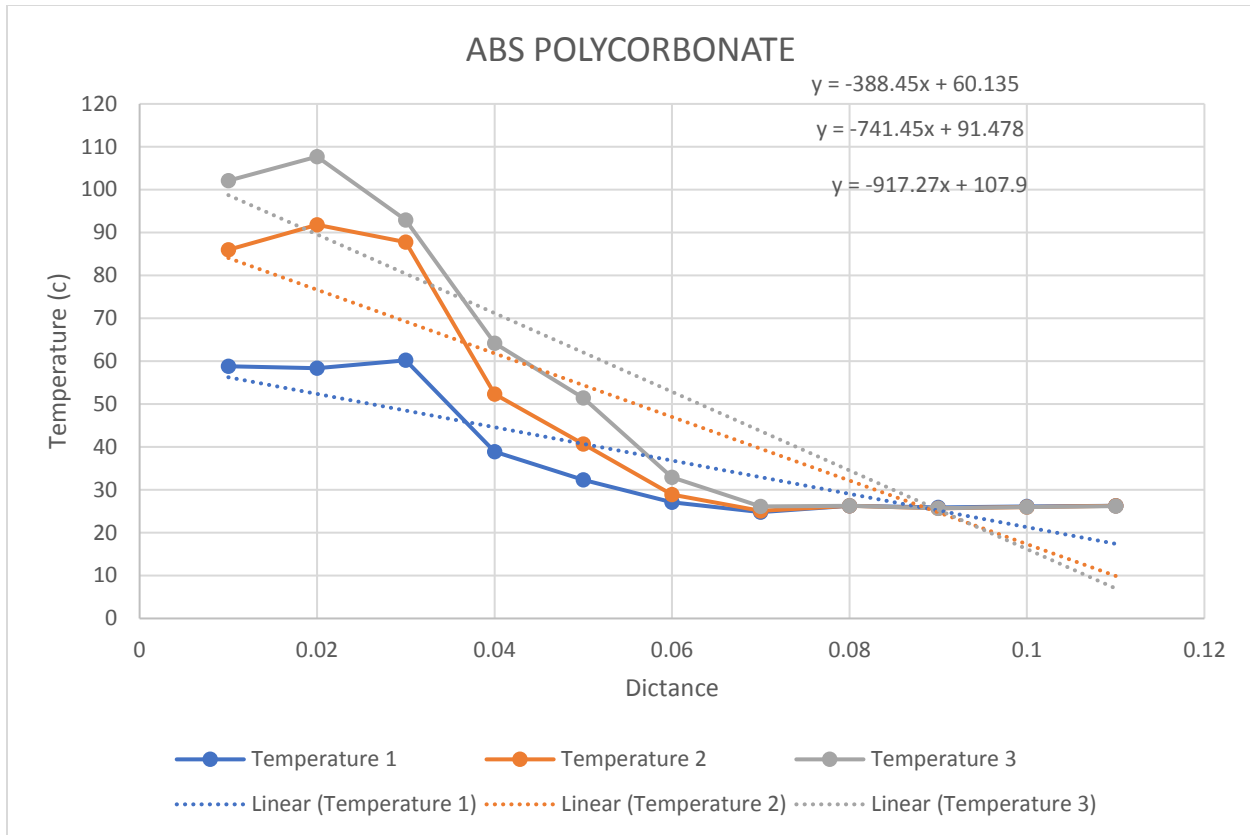


Figure 4.20: Temperature Vs Distance plot for type ABS Polycarbonate.

4.3 Mechanical Analysis

Tensile property testing was conducted on all material filament and specimens that were 3d-printed as discussed in previous chapter. Each specimen was individually measured (thickness and width) at several locations throughout the test section. According to the ASTMs, the smallest cross-sectional area (or cross-sectional area at the center of the beam for flexural testing) was used to determine appropriate stress values. MTS universal loading machines were used to conduct the tensile and fatigue testing. The results of the tensile tests for the 3D printed materials are summarized in Table 4.1-4.5 respectively.

Table 4.1: Type PLA Tensile Test Result.

	1	2	3	4	5	ave
F (N)	210	140	150	170	160	166
A (m ²)	1.6×10^{-5}	1.6×10^{-5}	1.6×10^{-5}	1.6×10^{-5}	1.6×10^{-5}	1.6×10^{-5}
σ (pa)	13125000	8750000	9375000	10625000	10000000	10375000
L (m)	116	116.2	115.85	116	116.2	116.05
L0 (m)	116.2	116.5	116.2	116.4	116.4	116.34
ε	-1.7211×10^{-3}	-2.5751	-3.012	-3.4364	-1.71821×10^{-3}	-1.805387
E (pa)	-7625936901	-3397926.294	-3112549.801	-3091898.498	-5820000000	-2691107855

Table 4.2: Type ABS Tensile Test Result.

	1	2	3	4	5	ave
F (N)	210	140	150	170	160	139
A (m ²)	1.6×10^{-5}	1.6×10^{-5}	1.6×10^{-5}	1.6×10^{-5}	1.6×10^{-5}	1.6×10^{-5}
σ (pa)	13125000	8750000	9375000	10625000	10000000	10375000
L (m)	115.5	115.4	115.9	115.5	115.6	115.58
L0 (m)	116	115.6	116	115.8	115.9	115.86
ε	-4.3103	-1.7301×10^{-3}	-8.6206×10^{-4}	-2.5906×10^{-3}	-2.58844×10^{-3}	-0.8636142
E (pa)	-3045031.668	-5057511.127	1.0875×10^{10}	4101366479	-3863333333	2220986121

Table 4.3: Type PETG Tensile Test Result.

	1	2	3	4	5	ave
F (N)	720	800	950	420	250	628
A (m ²)	1.6×10^{-5}	1.6×10^{-5}	1.6×10^{-5}	1.6×10^{-5}	1.6×10^{-5}	1.6×10^{-5}
σ (pa)	45000000	50000000	59375000	26250000	15625000	39250000
L (m)	115	115.5	115.333	115.85	116	115.5366
L0 (m)	115.21	115.9	115.85	116	116.2	115.832
ε	-1.823×10^{-3}	-3.451×10^{-3}	-4.462×10^{-3}	-1.293×10^{-3}	-1.721×10^{-3}	-2.55×10^{-3}
E (pa)	-2.468×10^{10}	-1.448×10^{10}	-1.285×10^{10}	-2.0301×10^{10}	-9.079×10^9	-1.6278×10^{10}

Table 4.4: Type Polycarbonate Tensile Test Result.

	1	2	3	4	5	ave
F (N)	150	140				
A (m ²)	1.6×10^{-5}	1.6×10^{-5}				
σ (pa)	9375000	8750000				
L (m)	115.5	115.85				
L0 (m)	115.9	116				
ε	-3.451×10^{-3}	-1.293×10^{-3}				
E (pa)	-2716603883	-6767208043				

Table 4.5: Type ABS Polycarbonate Tensile Test Result.

	1	2	3	4	5	ave
F (N)	170	60	80	110	120	108
A (m ²)	1.6×10^{-5}	1.6×10^{-5}	1.6×10^{-5}	1.6×10^{-5}	1.6×10^{-5}	1.6×10^{-5}
σ (pa)	10625000	3750000	5000000	6875000	7500000	6750000
L (m)	116	116	116.1	116.2	116	116.06
L0 (m)	116.01	116.3	116.4	116.4	116.2	116.262
ε	-8.62×10^{-5}	-2.58×10^{-3}	-2.57732×10^{-3}	-1.718×10^{-3}	-1.7212×10^{-3}	-1.73654×10^{-3}
E (pa)	-1.232×10^{11}	-1453488372	-1940000000	-4001746217	-4357500000	-2.69905×10^{10}

CHAPTER 5
PROJECT MANAGEMENT

5.1 PROJECT PLAN

**5.2 CONTRIBUTION of TEAM
MEMBER**

**5.3 PROJECT EXECUTION
MONITORING**

5.4 CHALLENGES and DECISION MAKING

5.1 Project Plan

We worked as one team in this project. To be run with the time for the course, our leader suggested to divide the team to two groups as experimental work group and writing and research group. Every group was working by all member advices. Every group used to exchange the ideas and information to support other group and work as team in the same time. This management was successful to finish the project on time successfully.

5.2 Contribution of Team Member

All the members were effective. We shared ideas, exchange ideas and opinions. All of the team members have participated in the project in accordance with the Gantt chart and the agreed working plan. Below is the table showing the main tasks that have been done with the timing of each task.

Table 5.1: List of tasks and the team member assigned with time duration of each task.

	Tasks	Subtasks	Due date of the Tasks	Duration (Days)	Start Date	Finished Date
Initiation	Kick off meeting	Identifying the project, Group formation and Gantt chart	Week 2 (10 of January)	4	1/7/2019	1/11/2019
Introduction (Chapter 1 & Chapter 2)	Project allocation + introduction	Project Definition,	Week 5 (7 of February)	5	1/12/2019	1/17/2019
		Project Objectives		5		
		Project Specifications		5		
		Applications		5		
	Literature Review	Project background		14	1/18/2019	2/1/2019
		Previous Work				
Comparative Study						
System Design (Chapter 3)	Design	Design Constraints and Design Methodology	Week 7 (21 of February)	6	2/2/2019	2/8/2019
	Equipment and material selection (3.4)	selected the appropriate items		4	2/9/2019	2/13/2019
	Theory and Theoretical Calculations	main calculations required detailed calculations to your design.		5	2/14/2019	2/19/2019

	Prototype assemble	System integration, describe , procedures and Implementation		5	2/14/2019	2/19/2019	
System Testing and Analysis (Chapter 4)	Testing and analyses	Experimental Setup, Sensors and data acquisition system	Week 13 (4 of April)	7	2/20/2019	2/27/2019	
		Results, Analysis and Discussion					
Project Management and Project Analysis (Chapter 5)	Project Management	Project Plan		12	2/28/2019	3/12/2019	
		Contribution of Team Members					
		Project Execution Monitoring					
		Challenges and Decision Making					
		Project Bill of Materials and Budget					
	Project Analysis	Life-long Learning		14	3/13/2019	3/27/2019	
		Impact of Engineering Solutions					
Contemporary Issues Addressed							
Report submission	Final Report	Writing all chapters		Week 14 (14 of April)	3	3/28/2019	3/31/2019
	Presentation preparation	Making Slides					
	Presentation practice	A dry run presentation					
	Booklet	Print the report					
	Banner	Follow rubric					
	Brochure	Follow rubric					
	Final Presentation	Present our presentation					
Monthly progress report	1st progress report	Monthly	3	1/6/2019	1/31/2019		
	2nd progress report			2/1/2019	2/28/2019		
	3rd progress report			3/1/2019	3/31/2019		

5.3 Project Execution Monitoring

The team meet twice every week to discuss the updated progress. Our team leader manages all the meetings. All meeting was to review the previous work and planning for next part. All meetings were helpful for each member because every member tried to exchange his own idea

with others. Field group and writing group were try to work smoothly together not just focusing on their part. Every group support the other. When we face any problem, we try our best solution to ask our advisor about it. The advisor was successful to help us and find the solution by ourselves.

Below is the table for our meetings:

Table 5.2: Project Execution Monitoring Activities.

Activity	Time
Member's meeting	Two times a week
Advisor meeting	One times every two weeks, and anytime if needed.
Class meetings	Once every two weeks
Design testing meeting	2 times at a pre-testing phase 3 times at final testing phase

5.4 Challenges and Decision Making

The main challenge we got in this project while doing experiments. It was very tough to perform an experiment because of the class schedule and availability of all group member.

Material availability in the local market was biggest challenge. We face difficulties for providing our needed material from the local market, since we needed to have unordinary material. For example, nanoparticles size and specification. Assembly of the setup was also one of the tough tasks which we did with the help of coordination between our team members.

Writing and documenting the progress of the project was also challenging because of a very limited time. We found that we need to provide more efforts to have this project done. We decided to have one of us every time to go over the work we do and review it, part by part, so we can have good quality report.

CHAPTER 6
PROJECT ANALYSIS

6.1 LIFE LONG LEARNING

**1.2 IMPACT of ENGINEERING
SOLUTION**

6.3 CONCLUSION

6.4 FUTURE RECOMENDATION

6.1 Life Long Learning

This project experience we got as a team helped us to compute our skills and knowledge gained in our undergrad study. We got to know about team work to solve any difficulty we might face. What makes our implementation of the competencies special is that we had a project required a lot of teamwork, leadership, and technical communication skills. Time and cost management also plays a significant factor as well in this project because it required necessary equipment with high quality and ensure its functionality and efficiency within the cost. With all that, we as the team successfully done this iconic project within time and cost limitations. In this project, we went to some journals and other expertise on the web that related to this type of project, and we get to know some ideas and ways to increase efficiency of Heat Exchangers.

6.1.1 Improve our Skills in Some Software Tools

The technical skills are one thing of each project and the other thing is software skills. We applied and used the software tools used in this project like 3- Dimensional Computer Aided Design (3D CAD) which we used for designing heat exchanger model and Microsoft word, Excel for preparing project documents and reports. These software tools were played very important role in this project and we have learned many things which gave us very good experience. All technical skills used in this project, which provided the best result because of the well knowledge of software tools and regularly using in professional way.

6.1.2 Time Management Skill

Effective planning of time was the most important part of this project. In this project we learnt about the time management skills which are required to give the best result to your efforts. We also include buffer time because most of the time things will not go as planned. We also developed the ability to manage time effectively and it was very helpful for all of us.

After all the planning and estimation for each task, we made a project schedule graph, which includes all tasks and their duration. We made Gantt charts which was really a staple of project management that helped in schedule activities and assign resources.

6.1.3 Problem Solving

The problem-Solving skills are very important to solve industrial challenges. It makes person capable to deal with issues and problems with an easy approach. This problem-solving skill we got to learnt in this project which helped us to gain knowledge and technical ideas while we faced the problems in our project. It is a simple, systematic way to approach a problem with clearly defined steps so that an individual or team doesn't get bogged down in, "WHAT DO WE DO NEXT?". This skill set we used in this project and we have taken decisions. While doing project we faced many problems that we solved eventually.

6.2 Impact of Engineering Solution

When it come to the impacts from our project, We have achieved the great impact from this project on the society, environment, and economy.

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