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ADVANCED CONTROL TECHNIQUES WITH FUZZY LOGIC

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Structural Validation Branch
Aerospace Vehicles Division

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Interim Report

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14. ABSTRACT
Research on the Fuzzy Logic control algorithm focused on improving the accuracy of applied thermal loads in structural validation programs. The algorithm allows for compensation of nonlinear thermal radiation transfer. The fuzzy logic algorithm response was compared with the response of the existing algorithm. Results showed significant thermal control accuracy improvement for metallic articles, and moderate improvement for nonmetallic (graphite) articles.

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1.0 - SUMMARY

The Structural Validation Branch (RQVV) provides facilities for researchers to perform validation of elevated temperature structures. This involves heating articles at specified rates of temperature increase, measuring article temperatures, and validating the structure's model with the experimental data. The thermal control accuracy is essential because the experimental data is used as the basis to validate the model.

This research paper focuses on the fuzzy logic control algorithm as a method to provide improved control of thermal radiation processes. The existing RQVV control algorithm is linear while the thermal radiation output of quartz lamps is non-linear, resulting in degraded control accuracy at certain areas of the temperature ramp. A fuzzy controller can be designed to provide a non-linear output to compensate for the non-linear thermal radiation process.

Experiments were performed by heating various articles at various rates and controlling the temperature of the article in separate experiments using linear and fuzzy algorithms, while recording desired temperature, actual temperature, and electrical power data. The data was analyzed and a comparison was made between the two algorithms. The comparison was based upon the temperature deviation (error) during the temperature transient, and the temperature overshoot when transitioning from a transient to a steady state temperature.

Graphical and quantitative analysis confirmed the fuzzy control algorithm provides improved control of the thermal radiation process. However, further investigation is needed for temperature control of articles that produce time lags between thermal input and temperature response. Also, adequate comfort and familiarity levels with the fuzzy algorithm need to be obtained before deploying the fuzzy control algorithm on structural validation programs.

2.0 - INTRODUCTION

2.1 BACKGROUND

The Structural Validation Branch (RQVV) provides facilities for researchers to perform experimental validation of elevated temperature structures. These structures are developed by various Air Force Research Laboratory (AFRL) and industry organizations and tested to compare the structural model to actual thermal conditions. The Advanced Control Techniques research project's purpose is to improve the accuracy of applied thermal loads, which directly aids the validation of the structure's model.

The Advanced Control Techniques (ACT) research focuses on the closed loop control algorithm used to modulate the electrical power applied to the heating elements. This periodic modulation allows the structure's temperature to follow a predetermined profile. Currently, a traditional PID (Proportional - Integral - Derivative) algorithm is used by RQVV for temperature control. The PID algorithm relies on a process to be relatively linear and uses a linear algorithm. This poses an issue when controlling non-linear processes such as radiation heat transfer whose model includes the temperature of the heating element to the fourth power (Stefan Boltzmann Law). In practice, nonlinearities are compensated for by adjusting the PID sensitivity parameters based on a tradeoff between accurate control at lower temperatures and accurate control at higher temperatures. Figure 1 shows this control accuracy tradeoff, and also the non-linear nature of heat transfer radiation.

Compensation for the non-linear nature of the radiation heat transfer and the desire to have accurate control across all temperatures drives the need to depart from traditional PID control and implement a more intelligent control algorithm. This research project attempts to implement fuzzy logic control as a replacement for the PID algorithm. Figure 2 shows the basic difference between the PID and fuzzy control algorithms.

Fuzzy logic control is a variation of set theory that provides a means of quantifying the non-linear nature of many physical processes in the real world. The term "fuzzy" refers to the fact that the logic involved is expressed as a normalized continuum between 0 and 1, instead of classical Boolean logic expressed in terms of 0 and 1. The normalized continuum is used to determine the degree of set membership, and the set membership and rule base determine the response of the control algorithm. The rule base is the mechanism that allows for the non-linear response of the control algorithm.

The fuzzy logic controller calculates the error and its integral, performs the control algorithm, and outputs a value in an attempt to reduce the error to zero. Table 1 shows the fuzzy rule base, a matrix that divides error and its integral into sets. After the input calculations, the control algorithm determines the degree of set membership, then outputs a value in proportion to the intersecting set(s) in the matrix. For example, if error is PM and its integral is PS, then the algorithm produces a PB output. Further, if error is NS and its integral is PM, then the algorithm produces a PS output. Before the experiment commences the rows, columns, and the matrix contents must be numerically defined. This is referred to as sensitivity adjustment, or tuning. By defining the rows, columns, and the matrix contents in a non-linear manner, the algorithm provides improved control of non-linear processes.

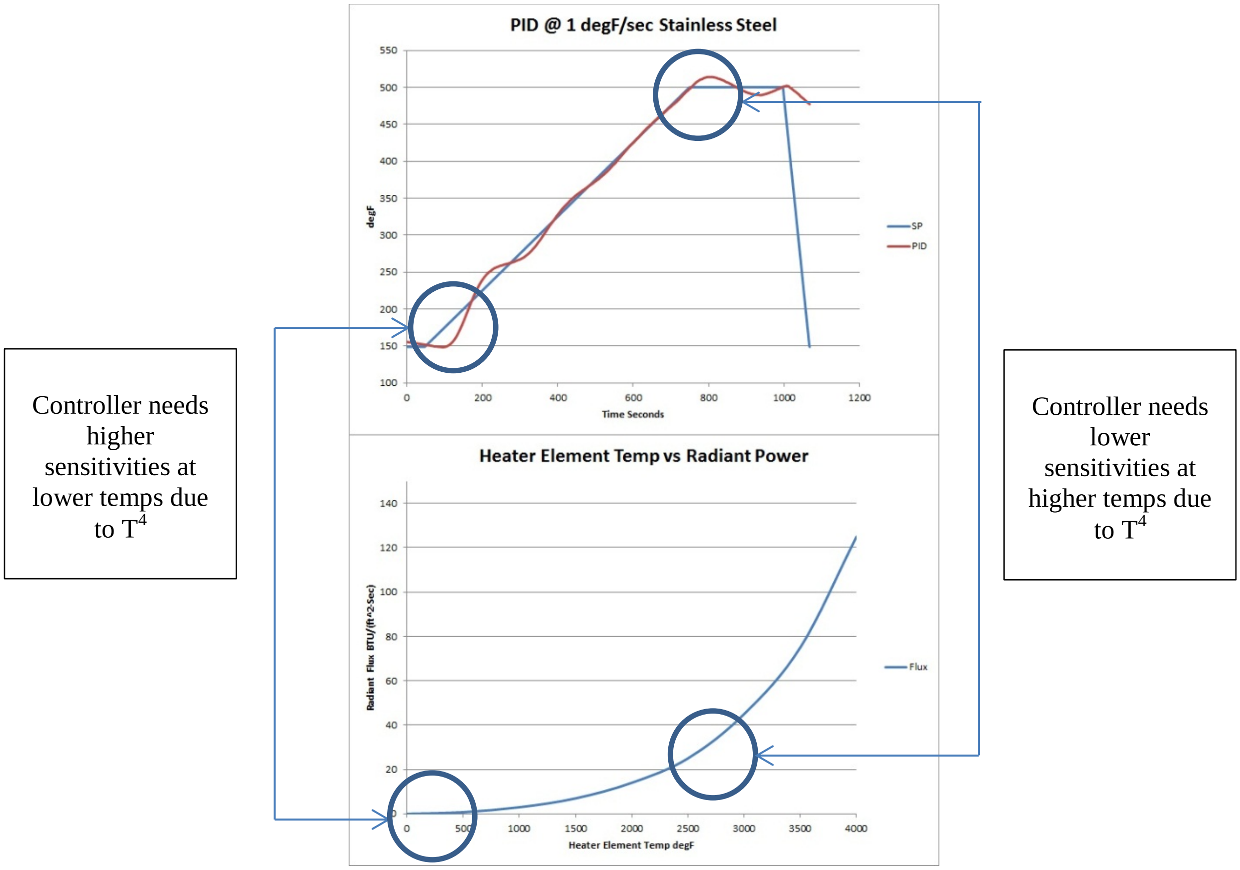
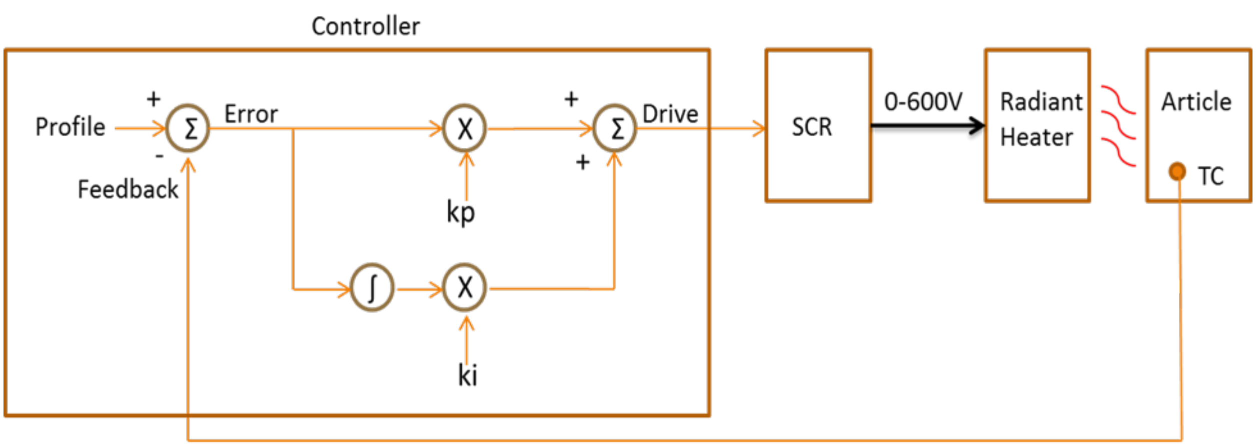


Figure 1 Controller Sensitivity Parameters and Non-Linear Radiation Heat Transfer



PID – kp and ki are constant

Fuzzy – kp and ki are continuously variable, based on instantaneous value of error

Figure 2 Difference Between PID and Fuzzy Algorithms

Fuzzy Rule Base

Integral of Error \ Error	NB	NM	NS	Z0	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	Z0
NM	NB	NB	NB	NM	NS	Z0	PS
NS	NB	NB	NM	NS	Z0	PS	PM
Z0	NB	NM	NS	Z0	PS	PM	PB
PS	NM	NS	Z0	PS	PM	PB	PB
PM	NS	Z0	PS	PM	PB	PB	PB
PB	Z0	PS	PM	PB	PB	PB	PB

Table 1 Fuzzy Rule Base

Linguistic variables
NB = Negative Big, NM = Negative Medium, NS = Negative Small
Z0 = Zero
PS = Positive Small, PM = Positive Medium, PB = Positive Big
Error = Difference between desired temperature and actual temperature

2.2 SCOPE

This project involved heating 4 different test articles with quartz lamps, utilizing the PID and Fuzzy algorithms for temperature control, and measuring temperature responses for the quantitative analysis.

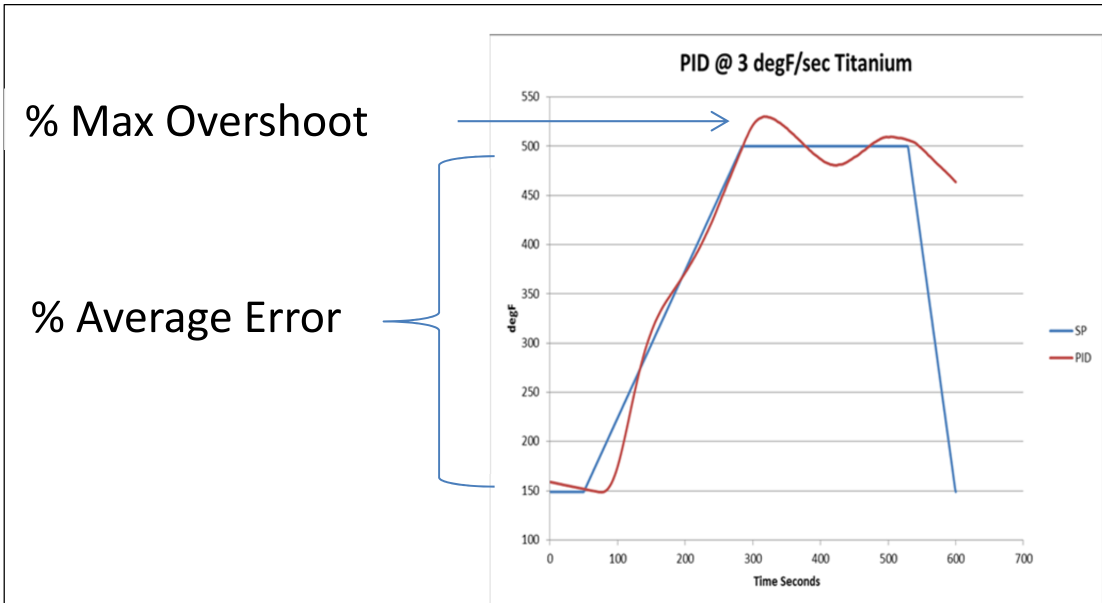
Test articles were chosen to provide various responses to radiant heat input, and included stainless steel, titanium, carbon steel, and graphite. These materials have various emissivity, density, and thermal conductivity properties, which allowed observation of PID/Fuzzy controller responses under different conditions.

Quartz lamps were configured in three pyrometric heater modules, with five 6000W lamps in each. Due to limitation of the electrical power feed, the power output of the three pyrometric modules was bounded at 90kW. In turn, this boundary resulted in a 5 ºF/sec maximum temperature rise rate.

2.3 TEST OBJECTIVE

The experiment will compare the PID and Fuzzy algorithms under identical conditions to evaluate if control accuracy can be improved with the Fuzzy algorithm. The metrics used in the comparison were Percent Average Error and Percent Max Overshoot. Figure 4 shows the metrics in graphical form. Percent Average Error demonstrates how well the algorithm performs during the temperature transients, and Percent Max Overshoot demonstrates how well the algorithm performs when transitioning from a transient to a steady state temperature. The Lower percent Average Error and Percent Max Overshoot metrics aid in the evaluation of the structure's model.

Two Key Performance Parameters were chosen. The Fuzzy algorithm must provide a 200% improvement in Percent Average Error and Percent Max Overshoot for further investigation to proceed. Practically speaking, this means if the PID algorithm produces a 10% average error, then the Fuzzy algorithm must produce a 5% average error. Likewise, if the PID algorithm produces a 20% max overshoot, then the Fuzzy algorithm must produce a 10% max overshoot. If these metrics are not obtained, then further investigation of the Fuzzy algorithm is not warranted.



$$Percent\ Error\ at\ each\ data\ point = Absolute\ Value\left(\frac{Desired\ temp - Actual\ temp}{Desired\ temp}\right)$$

$$Percent\ Average\ Error = \frac{\sum Percent\ Error\ at\ each\ data\ point}{Number\ of\ data\ points}$$

$$Percent\ Max\ Overshoot = \frac{Max\ temp\ after\ transition\ to\ steady\ state - Desired\ steady\ state\ temp}{Desired\ steady\ state\ temp}$$

Figure 3 Quantitative Metrics

3.0 - TEST HARDWARE

Test hardware required to perform the experiments include a programmable controller, modulated electrical power source, heater elements/fixturing, test articles, and a data acquisition system.

3.1 CONTROLLER

Modicon Quantum 65150 PLC (Programmable Logic Controller) processor with analog input/output, and digital input/output. Figure 4 shows the PLC integrated into an industrial enclosure along with DC power supplies, an electrical disconnect, and force guided relays. The PLC is programmed with IEC61131 languages, specifically Structured Text (ST) and Function Block Diagram (FBD). The ST language is used for repetitive calculations, and the FBD language is used for Boolean logic and graphical style programming.

Figure 4 PLC panel

3.2 SCR ELECTRICAL POWER SOURCE

The quartz lamp electrical power source is a Control Concepts brand Silicon Controlled Rectifier (SCR) Model 1029C, which is rated at 480V/500A. Figure 5 shows 3 single phase SCRs integrated into an industrial enclosure with voltage, current, and power transducers. . The Model 1029C SCR is configured in phase angle control, where the 480VAC waveform is applied to the lamps for partial AC cycles in proportion to the drive signal from the PLC. The SCR is analogous to a light dimmer, but on a much larger scale.

Figure 5 SCR Panel

3.3 QUARTZ LAMP BANK

Figure 6 shows quartz lamps configured in three pyrometric heater modules, with five 6000W lamps in each. The 15 lamps were wired electrically in parallel. Each 6000W lamp draws 12.5A at the SCR maximum output of 480VAC. Figure 7 shows the quartz lamp bank mounted on a fixture that allows easy test article installation.

Figure 6 Quartz Lamp Bank

Figure 7 Quartz Lamp Fixture

3.4 TEST ARTICLES

Test articles consist of stainless steel (unpolished), carbon steel, titanium, and graphite panels. Each panel is 12"x12"x1/4" with K type thermocouples on the back surface (away from lamps). Each panel has a different emissivity (ability to absorb thermal energy) and a different thermal conductivity (ability to conduct thermal energy to the back surface). Articles with various emissivities and thermal conductivities were chosen to provide different physical responses to thermal radiation, in order to evaluate the PID and fuzzy control algorithms. Figure 8 shows the back surface of a representative test article with thermocouples installed.

For the purposes of this research project, the emissivity and thermal conductivity values of the test articles are evaluated relative to each other and are the following:

Stainless steel, emissivity = 0.4, thermal conductivity = 16.2W/m-K
Absorbs thermal radiation poorly, and conducts thermal energy efficiently

Carbon steel, emissivity = 0.7, thermal conductivity = 19W/m-K
Absorbs thermal radiation efficiently, and conducts thermal energy efficiently

Titanium, emissivity = 0.55, thermal conductivity = 12W/m-K
Absorbs thermal radiation moderately, conducts thermal energy moderately

Graphite, emissivity = .8, thermal conductivity = 7W/m-K
Absorbs thermal radiation efficiently, conducts thermal energy poorly

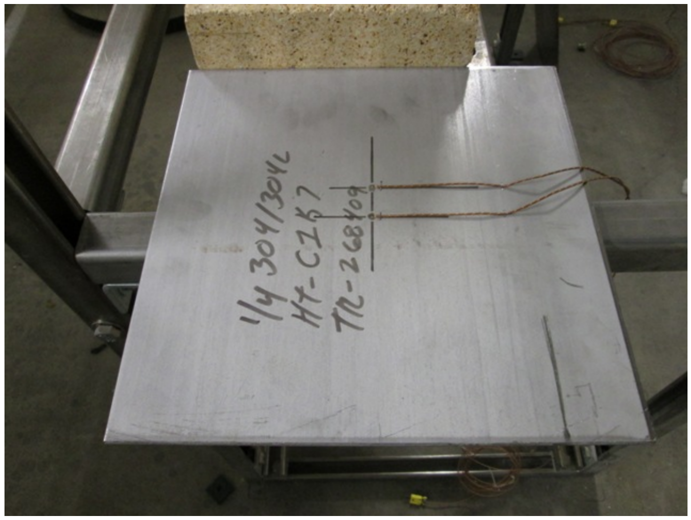


Figure 8 Representative Test Article

3.5 DATA ACQUISITION SYSTEM

An HBM brand data acquisition system was used to collect the article temperature, temperature profile ramp, and electrical power data. An HBM MGC Plus chassis populated with thermocouple input cards is shown in Figure 9. A PC with HBM software queries the MGC chassis at a 2 Hz rate, shows data plots, and records the temperature data to an Excel compatible file. The software also queries the PLC controller and records the temperature profile and electrical power data.

Figure 9 Data Acquisition System

4.0 - TEST PREPARATION

4.1 SAFETY

This experiment was covered under the Building 65, 2nd Floor ET, Yellow Cage safety permit RB 65-051, expiration date 29 Mar 2014. Identified hazards associated with this test program did not fall outside those covered by this permit.

4.2 TEST HARDWARE

The test area was configured with the PLC panel, SCR panel, data acquisition system, and lamp bank mounted on a fixture prepared to accept the test articles. The test articles were obtained and instrumented with K type thermocouples.

4.3 SOFTWARE

The controller software program was written to implement the temperature profile ramp and both control algorithms.

4.4 CONTROL ALGORITHM SENSITIVITY ADJUSTMENT

PID and Fuzzy algorithm sensitivities were adjusted (or tuned). The goal is to minimize error on the temperature transient and minimize overshoot at the transition to steady state. Tuning involves changing the sensitivity parameters, running the temperature ramp, observing the temperature response, and repeating. This iterative process can take extensive periods of time. Tradeoff between lower and higher temperature performance are subjective judgments. Also, there are multiple combinations of sensitivities that produce similar temperature responses.

5.0 - TEST EXECUTION

Each test article was heated at 1, 3, and 5 ºF/sec to 500 ºF. For each rise rate and test article, the temperature was controlled with the PID and Fuzzy algorithms in separate experiments, and data was recorded for each. Twelve sets of data were acquired for the PID/Fuzzy algorithm comparison. Data recorded included the profile (rise rate), article temperature, and electrical power applied to the lamp bank at a 2 Hz sample rate.

6.0 - TEST RESULTS

6.1 GRAPHICAL ANALYSIS

The graphical analysis allows a visual comparison between the algorithms.

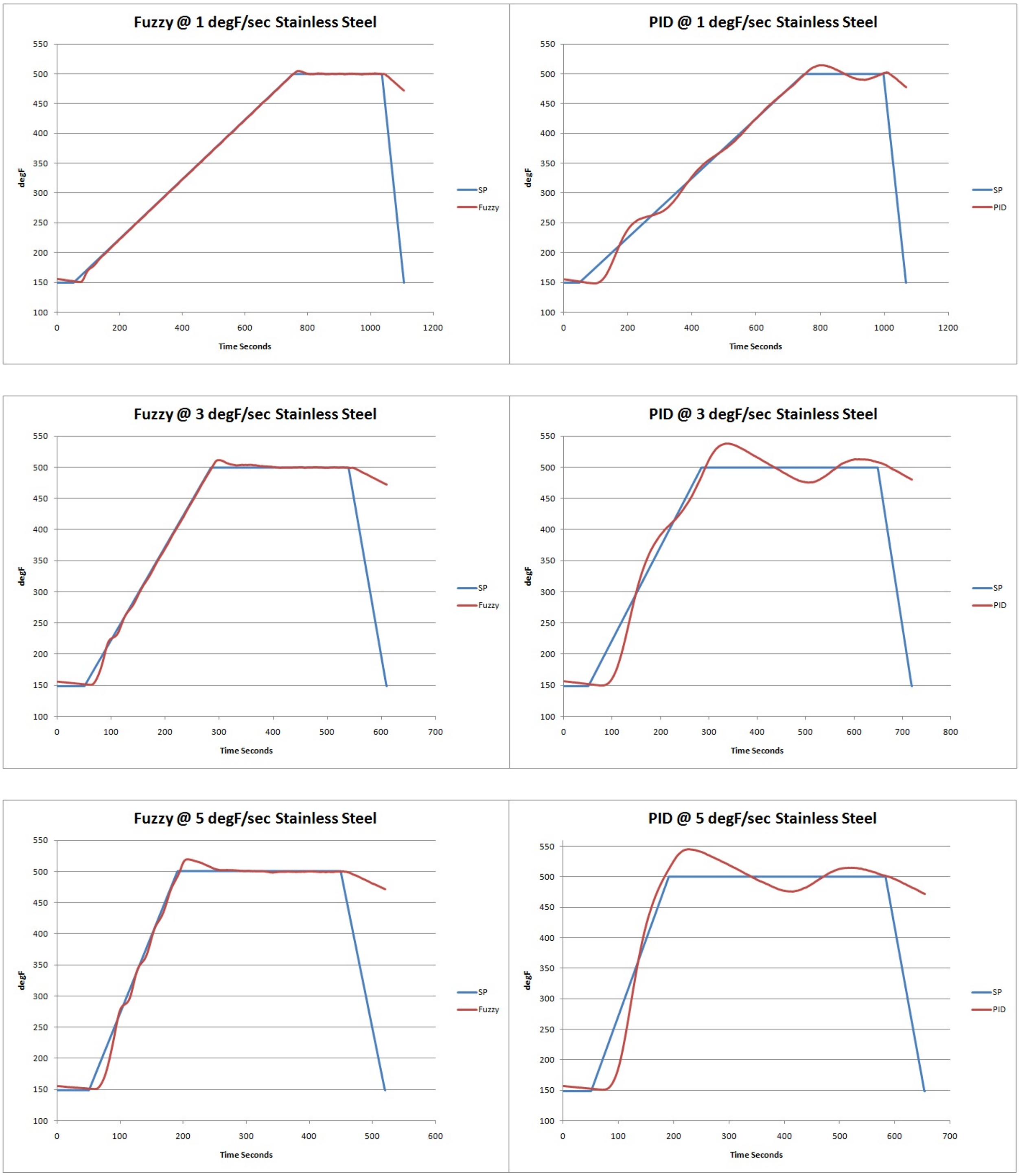


Figure 10 Stainless Steel Panel Graphical Response

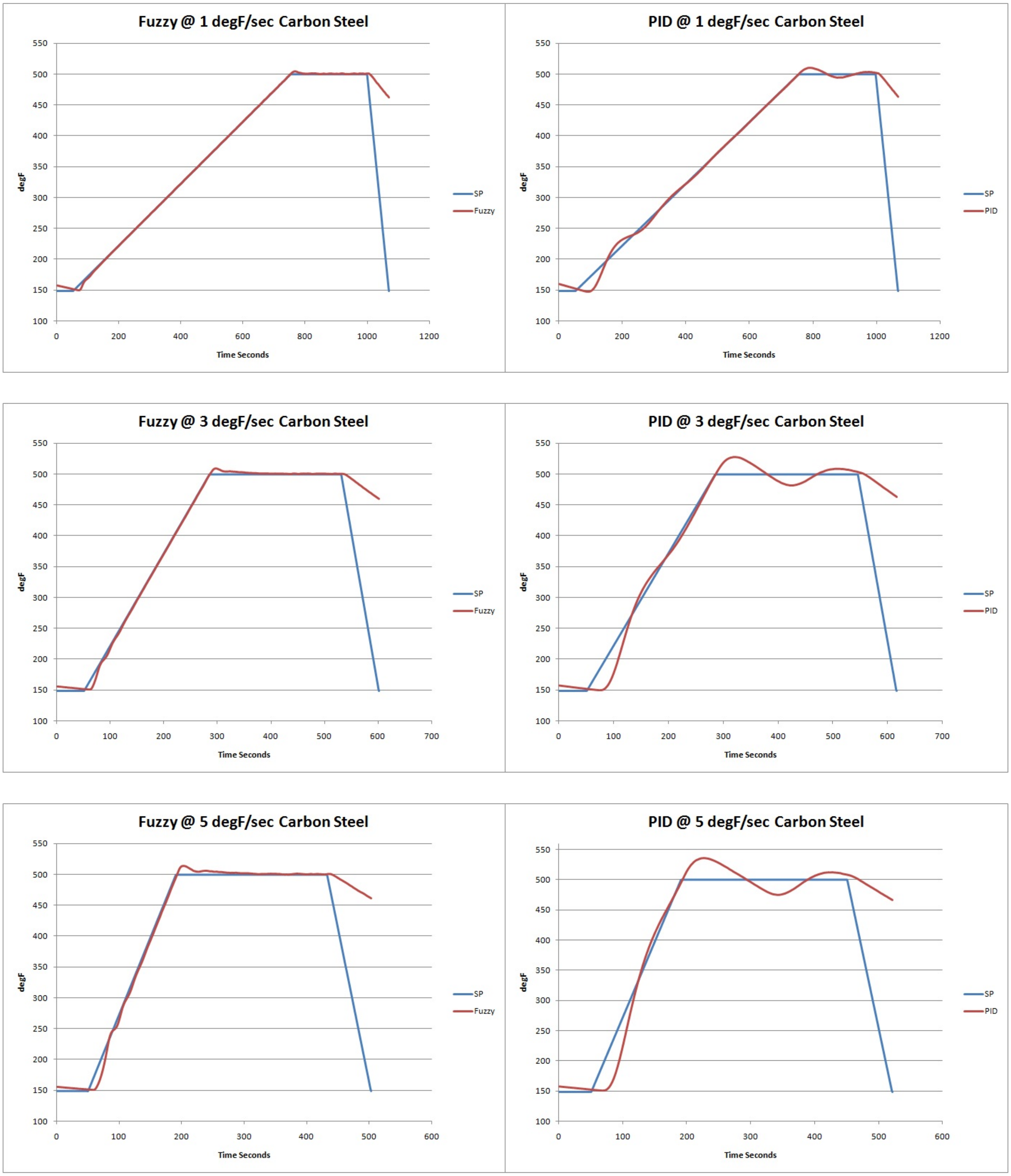


Figure 11 Carbon Steel Panel Graphical Response

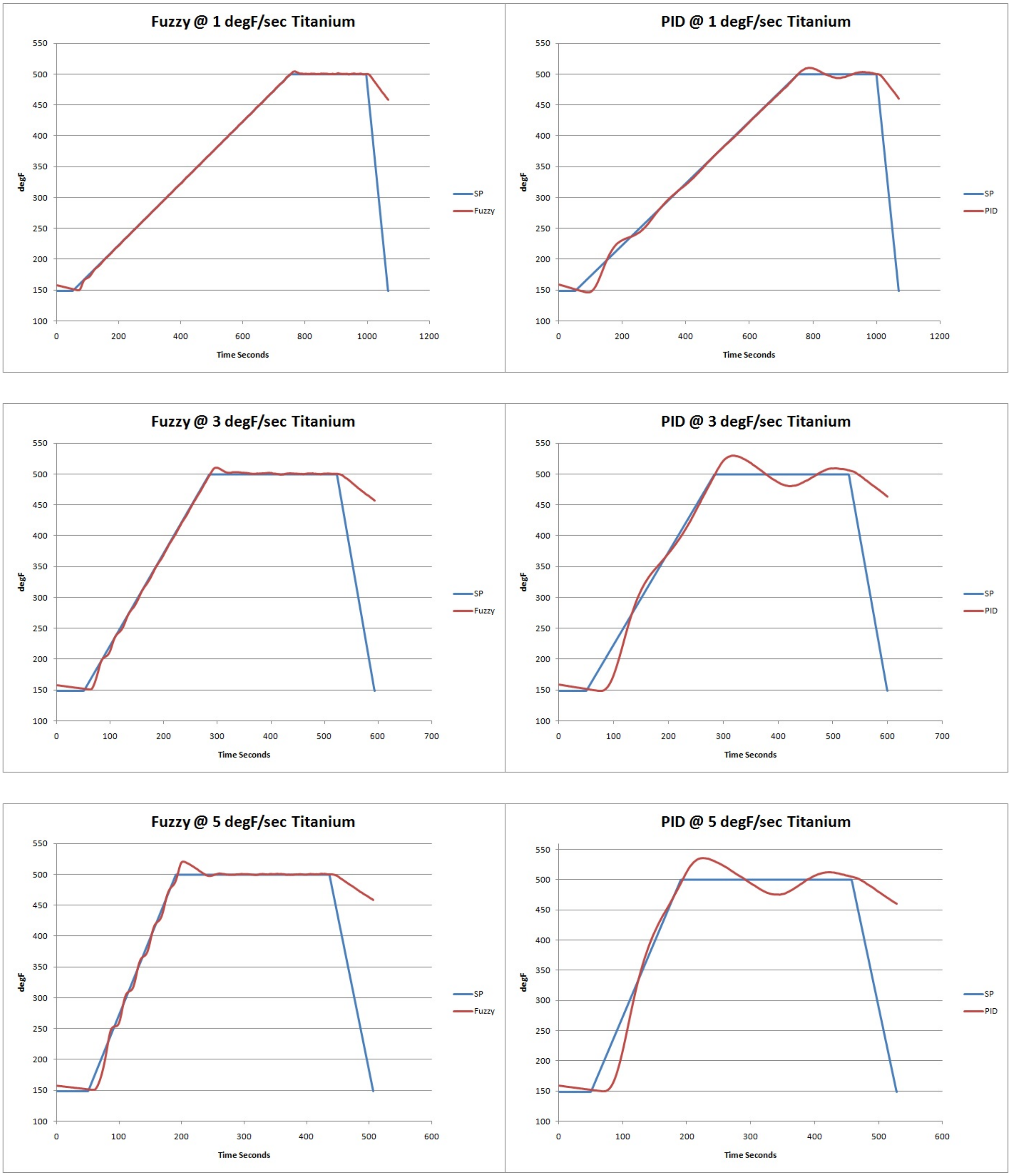


Figure 12 Titanium Panel Graphical Response

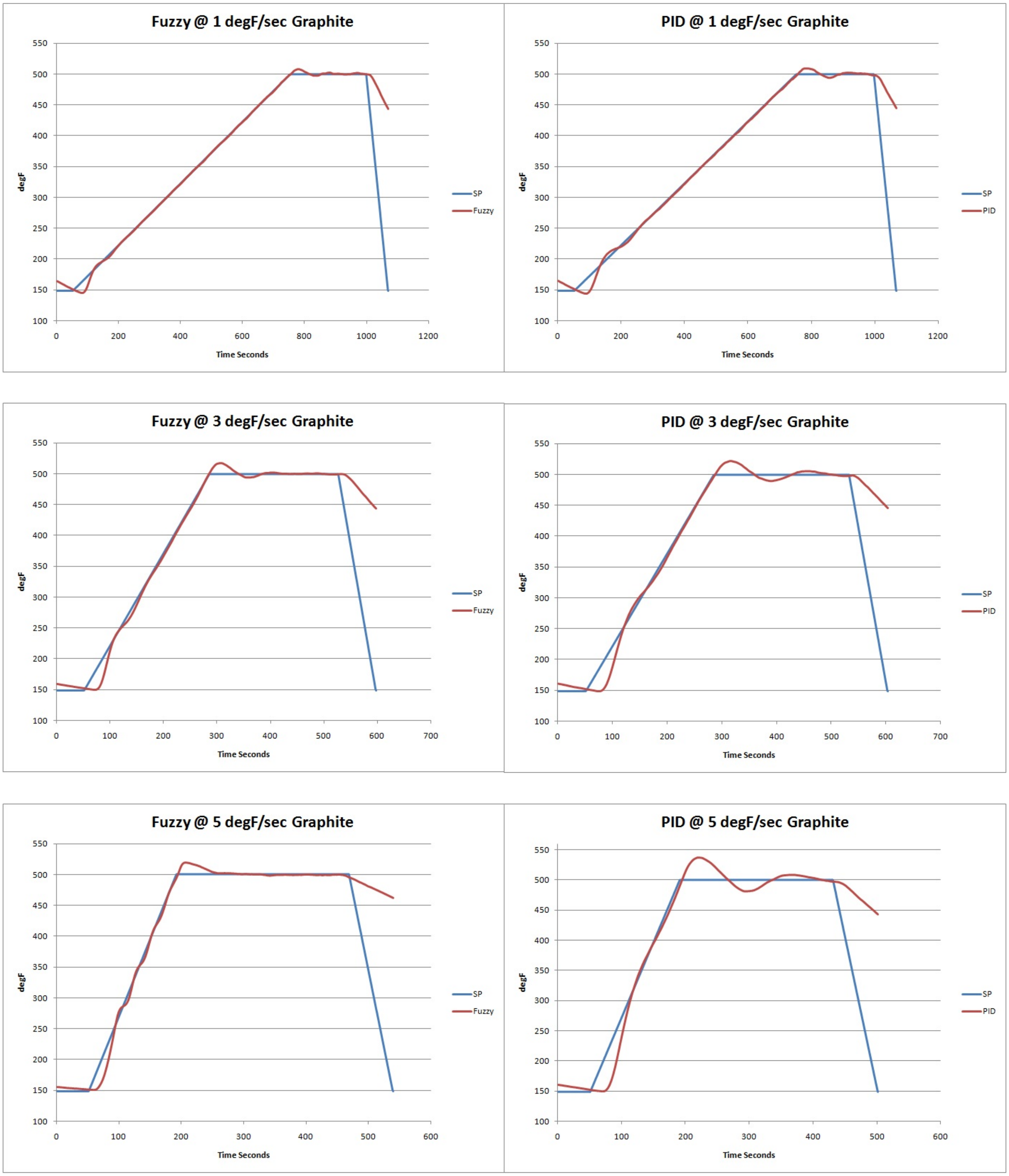


Figure 13 Graphite Panel Graphical Response

6.2 QUANTITATIVE ANALYSIS

The quantitative results of the experiment are shown in the following tables.

Stainless	PID	PID	Fuzzy	Fuzzy	Improvement	Improvement
	% Avg Error	% Max Overshoot	% Avg Error	% Max Overshoot	%Avg Error	%Max Overshoot
1 degF/sec	3.03	2.80	0.50	0.96	602.5	292.2
3 degF/sec	9.06	7.66	2.04	2.36	444.0	324.9
5 degF/sec	14.39	9.00	4.88	3.99	295.1	225.7

Table 2 Stainless Steel Panel Metrics

Steel	PID	PID	Fuzzy	Fuzzy	Improvement	Improvement
	% Avg Error	% Max Overshoot	% Avg Error	% Max Overshoot	%Avg Error	%Max Overshoot
1 degF/sec	1.90	2.02	0.44	0.78	426.9	257.3
3 degF/sec	5.80	5.55	1.42	1.73	409.8	321.7
5 degF/sec	9.45	7.11	3.39	2.64	278.7	269.8

Table 3 Carbon Steel Panel Metrics

Titanium	PID	PID	Fuzzy	Fuzzy	Improvement	Improvement
	% Avg Error	% Max Overshoot	% Avg Error	% Max Overshoot	%Avg Error	%Max Overshoot
1 degF/sec	1.96	2.08	0.43	0.83	454.8	251.6
3 degF/sec	6.43	6.04	1.91	1.94	337.4	310.6
5 degF/sec	10.41	7.25	3.49	4.08	298.0	177.8

Table 4 Titanium Panel Metrics

Graphite	PID	PID	Fuzzy	Fuzzy	Improvement	Improvement
	% Avg Error	% Max Overshoot	% Avg Error	% Max Overshoot	%Avg Error	%Max Overshoot
1 degF/sec	1.50	1.84	1.00	1.52	149.7	121.4
3 degF/sec	4.70	4.37	3.46	3.51	135.9	124.5
5 degF/sec	8.25	7.32	4.28	3.99	193.0	183.5

Table 5 Graphite Panel Metrics

The quantitative metrics are Percent Average Error and Percent Max Overshoot. Percent Average Error demonstrates how well the algorithm performs during the temperature transients, and Percent Max Overshoot demonstrates how well the algorithm performs when transitioning from a transient to a steady state temperature.

In the quantitative analysis, the fuzzy logic algorithm demonstrated various degrees of improved performance over the PID algorithm. The tables show a range of 135% to 602% improvement in the error metric, and a 121% to 321% improvement in the overshoot metric.

Trends in the data show that the fuzzy algorithm was most improved at the lower temperature rise rates, and less improved at the higher temperature rise rates. While both algorithms' response degraded at the temperature transient rate increased, the PID algorithm response degraded more. This correlates with the graphical analysis.

Trends in the data demonstrated a correlation between metric improvement and the thermal conductivity of the article. For a higher article thermal conductivity, the fuzzy algorithm demonstrated a higher metric improvement. For a lower article thermal conductivity, the fuzzy algorithm demonstrated a lower metric improvement.

Four different test article materials were chosen to give different thermal responses to the control algorithms. Section 3.4 noted the emissivities and thermal conductivities for each article type. Stainless and carbon steel articles have similar thermal conductivities, and their metrics are similar. Titanium has ~66% of the thermal conductivity of stainless and carbon steel, and the improvement of the fuzzy over the PID algorithm is slightly reduced. Graphite has ~40% of the thermal conductivity of stainless and carbon steel, and the improvement of the fuzzy over the PID algorithm is significantly reduced.

These results suggest that the fuzzy control algorithm is satisfactory for higher thermal conductivity articles. However further investigation is needed for fuzzy algorithm temperature control of articles with lower thermal conductivities.

7.0 - LESSONS LEARNED AND OBSERVATIONS

7.1 LESSONS LEARNED

Improved performance of the fuzzy algorithm comes at a cost of more sensitivity adjustments. PID control has two sensitivity adjustments, while Fuzzy control has fourteen. However, a lesson learned is that in practice, the fuzzy algorithm has four sensitivity adjustments that are significant. The fourteen adjustments were reduced to eight because the Fuzzy algorithm is based on normalized parameters, where max/min outputs are +1/-1 and includes a zero. The eight adjustments were reduced to four because the optimal Fuzzy algorithm response was obtained when there was symmetry between positive and negative error polarities. This significantly reduced the sensitivity adjustment effort, which in turn decreased test setup time and decreased the danger of having improper settings at test initiation.

Fuzzy Sensitivities

		kp	ki		
Error	NB	-1.00	-1.00	Min = -1	
	NM	-0.40	-0.40		
	NS	-0.02	-0.20		
	0	0.00	0.00	Zero	Symmetric
	PS	0.02	0.20		
	PM	0.40	0.40		
	PB	1.00	1.00	Max = 1	

Table 6 Fuzzy Parameter Adjustment

7.2 OBSERVATIONS

Section 6.1, Graphical Analysis, demonstrates the issues associated with a linear PID algorithm controlling a non-linear process (radiation heat transfer). From every graphical response chart (Figures 10 - 13), one can observe the temperature lag due to linear PID control at the beginning of the temperature ramp. The PID algorithm outputs the same drive signal for a specific temperature error at both lower and higher temperatures (linear), even though the radiation output of the lamps is proportional to the temperature of the heating element to the fourth power (non-linear).

Section 6.1, Graphical Analysis, demonstrates improved thermal control with the fuzzy control algorithm. The graphical response charts show a reduced lag at lower temperatures versus the PID algorithm. The reduced temperature lag is due to the non-linear response of the fuzzy control algorithm.

The two observations above are significant because the data RQVV produces is used in model validation. It is important to match the conditions under which the model was created, which infers the temperature ramp should be followed as closely as possible. At high rise rates (>25 ºF/sec), the controller may not be able to recover from the temperature lag at the beginning of the ramp before the steady state plateau is reached. An example of this is shown in Figure 14.

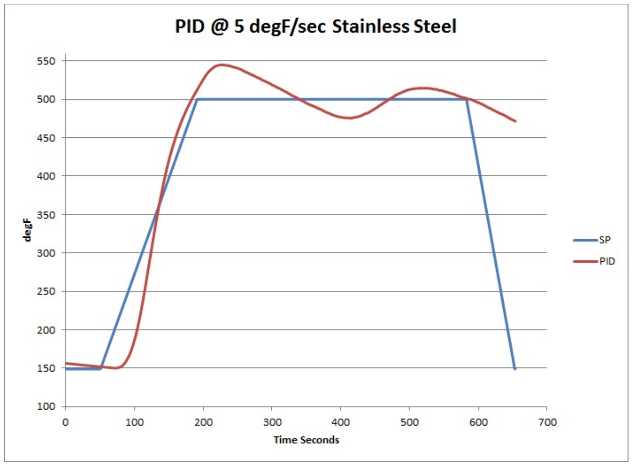


Figure 14 Lag at the beginning of a temperature ramp

8.0 - CONCLUSIONS AND RECOMMENDATIONS

8.1 CONCLUSIONS

The Fuzzy control algorithm demonstrated improved control for all articles tested in this project. Improved control is defined as lower Percent Average Error and lower Percent Max Overshoot. The nonlinear response of the fuzzy algorithm provided improved control of non-linear radiation heat transfer, demonstrated with a decreased lag at lower temperatures and a decreased overshoot at higher temperatures. The improved control is seen visually in both the graphical and quantitative analyses.

The test results suggest that the fuzzy control algorithm is satisfactory for higher thermal conductivity articles. However further investigation is needed for fuzzy algorithm temperature control of articles with lower thermal conductivities. Also, further investigation is needed in order to develop adequate comfort and familiarity levels before deploying the fuzzy control algorithm on structural validation programs.

This project was the beginning of the fuzzy control algorithm investigation. While the research project's results were positive, it still remains to be seen if the fuzzy algorithm provides positive cost/benefit results to the organization.

8.2 RECOMMENDATIONS

Further research of the fuzzy control algorithm should address the limitations of this experiment. Maximum temperatures were constrained by the limitation of the electrical power infrastructure in the experimental area. Having one temperature zone prevented algorithm evaluation for a test configuration of multiple temperature zones with a temperature gradient across the article. Addressing these two items will involve moving the experiment to a location with a higher electrical infrastructure capability and obtaining a more complex structure. A possible solution would be to piggyback off an existing test, performing experiments with existing infrastructure/articles after formal tests are complete. These experiments would be confidence builders in the replacement of the PID algorithm with the fuzzy algorithm.

Investigation into temperature control of articles with substantial mass or low thermal conductivity would be a reasonable extension of this research. These articles produce significant time lags between thermal input and temperature response. One possible low cost opportunity for this investigation is the liquid nitrogen vaporizer. The vaporizer converts liquid nitrogen to gaseous nitrogen. Liquid nitrogen flows into a large (~500lb) aluminum block, while embedded heaters provide the energy to vaporize the liquid. The temperature of the gas exiting the block is the control parameter. Currently the best performance obtained with the PID algorithm is +/- 8 ºF temperature swings around the desired nitrogen gas temperature, over two minute intervals. The magnitude of the temperature swings is marginally acceptable, and improved control (+/-2 ºF) could possibly be obtained by implementing the fuzzy control algorithm.

Finally, the experiments in this project could be repeated with a fuzzy control algorithm designed as a PD (Proportional - Derivative) controller, instead of a PI (Proportional - Integral) controller. A fuzzy PD controller output is based upon the present error and its derivative (a prediction of future error), while the fuzzy PI controller output is based upon the present error and its integral (an accumulation of past errors). The predictive nature of the PD controller could further improve control of temperature via thermal radiation.