

To the Graduate Council:

I am submitting herewith a thesis written by Larry Scott Spencer entitled "Temperature Control of the Online Rheological Sensor." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Chemical Engineering.

Charles Moore

Major Professor

We have read this thesis
and recommend its acceptance:

John Collier

Simioan Petrovan

Accepted for the Council:

Anne Mayhew

Vice Chancellor and
Dean of Graduate Studies

(Original signatures are on file with official student records.)

Temperature Control of the Online Rheological Sensor

A Thesis
Presented for the
Master of Science
Degree
University of Tennessee, Knoxville

Larry Scott Spencer
December 2005

Dedication

This thesis is dedicated to my father and mother, Dr. Barry Spencer and Ms. Kathy Strunk, and to my stepmother, Mrs. Joyce Spencer, and sister, Erin Spencer, and to my niece, Estella. This thesis is also dedicated to my family, friends, and to my wife, Jami.

Acknowledgements

I would like to thank all of the people and organizations that helped make this research possible. First, I would like to thank Dr. Charles F. Moore for serving as my major advisor and for all of his guidance during this project. I would also like to thank Dr. John Collier for giving me the opportunity to work on this project and for all of his encouragement throughout the course of this research. I would like to thank Dr. Simioan Petrovan for serving on my committee and for all of his help and support. I would like to thank Dr. Billie Collier for all of her support. I would like to thank MCEC and TANDEC at the University of Tennessee for their help sponsoring this research. I would also like to acknowledge the following TANDEC employees for all of their support: Dr. Allan Stahl, Mr. Jack Wyrick, Mr. James Murphy, and Mr. Shaun Stahl. I would like to give a special thank you to Mr. Chris Eash at TANDEC for all of his assistance during this research. I would like to thank Mr. Doug Fielden and Mr. Mike Neal at the University of Tennessee for all of their technical assistance. I also would like to thank the APAL lab at the University of Tennessee, which includes Dr. Duane Bruns and Mr. Alok Patel for their time and assistance. I would like to thank the following students for all of their help and time during the course of this research: Mr. Jesse Bush, Mr. Atul Dihaya, and Mr. Adam Talley.

Abstract

Rheometers are devices that can be used to measure the rheological properties of polymers. Online rheometers test for rheological properties during a polymer process. Real-time rheological data would eliminate any time delays that accompany off-line rheometers and would provide the feedback information needed for tighter polymer process control. A real-time control system would eliminate the need for an offline rheometer to analyze polymer product properties, thus saving both time and money.

The Online Rheological Sensor was used to estimate the shear and elongational viscosities of a polymer from measured variables during processing. The Online Rheological Sensor was mounted on a twin-screw extruder in order to measure polymer viscosities for a melt blowing process. The Online Rheological Sensor was equipped with process measurement devices that interfaced with National Instrument's LabVIEW. The LabVIEW program calculated and plotted the shear and elongational viscosities of a polymer, along with the process pressures and temperatures. The goal of this research was to work towards using the Online Rheological Sensor as a device to monitor and control polymer viscosities during processing.

The following paper explores methods to control the temperature of the Online Rheological Sensor block to help maintain a constant polymer viscosity. This research also outlines methods in which the Online Rheological Sensor can be used as a feedback control device for a melt blowing line during processing.

Table of Contents

1.0	Introduction & Background.....	1
1.1	Twin-Screw Extruder.....	1
1.2	Melt Blowing Process.....	2
1.2.1	Melt Blowing Operational Variables.....	3
1.2.2	Melt Blowing Offline Variables.....	4
1.3	Work Motivation & Goals.....	5
2.0	Shear and Elongational Program.....	6
2.1	Leistritz Twin-Screw Extruder.....	6
2.2	Online Rheological Sensor.....	8
2.2.1	Sensor Dies.....	8
2.2.2	Sensor Hardware.....	11
2.3	Sensor Interface.....	13
2.4	Sensor Computer Program.....	18
2.4.1	National Instrument's LabVIEW.....	18
2.4.2	Shear and Elongational Virtual Instrument.....	19
3.0	Sensor Block Temperature Models.....	24
3.1	Temperature Response Experiments.....	24
3.2	Temperature Response Models.....	25
3.2.1	Individual Run Simulink Models.....	25
3.2.2	Single Simulink Model.....	27
4.0	Shear and Elongational Version 2.0.....	36
4.1	The New Interface.....	36
4.1.1	Hardware Interface.....	36
4.1.1.1	Ethernet Card.....	37
4.1.1.2	Input Simulator.....	37
4.1.1.3	Relay Card.....	37

4.1.1.4	DC Output Card.....	39
4.1.1.5	Thermocouple Card.....	39
4.1.1.6	Analog Input Card.....	41
4.1.2	Interface Software.....	42
4.2	Shear and Elongational Version 2.0 VI.....	45
5.0	Future Work.....	53
5.1	TANDEC 6-inch MB Pilot Line.....	53
5.2	Calculations for Future Work.....	54
5.3	Shear and Elongational VI Upgrades.....	57
5.4	Expanding the Interface.....	59
	References.....	60
	Appendix.....	64
	Appendix A.....	65
A.1	Win-Tech Modbus Server Installation.....	65
A.2	Port Configuration for Win-Tech Server.....	66
A.3	DataSocket Connections.....	69
	Appendix B.....	70
	Vita.....	100

List of Tables

Table 2.1-1: Leistriz TSE Features	7
Table 3.1-1: Experimental Run Summary.....	25
Table 3.2-1: Results for Individual Run Models Using Simulink.....	28
Table 4.1-1: APT Variable Assignments.....	43

List of Figures

Figure 2.1-1: The Leistritz twin-screw extruder	6
Figure 2.2-1: Online Rheological Sensor schematic	9
Figure 2.2-2: Picture of the Online Rheological Sensor mounted on the Leistritz twin-screw extruder.....	10
Figure 2.2-3: Electric motor shafts to sensor gear pumps.....	12
Figure 2.2-4: Picture of the black control box.....	13
Figure 2.3-1: Typical half-duplex system	14
Figure 2.3-2: DB-9 connector schematic	15
Figure 2.3-3: OPC server and device information exchange diagram	16
Figure 2.3-4: Screenshot of the Win-Tech mbOPCsvr	17
Figure 2.4-1: The “edit rate” menu of the <i>shearandelongational.vi</i> program	21
Figure 2.4-2: <i>Shearandelongational.vi</i> program monitors the process pressure and plot the viscosities in the “measure” portion of the program.....	21
Figure 2.4-3: LabVIEW code for calculating elongational viscosity in the <i>shearand elongational</i> program	22
Figure 2.4-4: LabVIEW code for calculating shear viscosity in the <i>Shearandelongational</i> program	22
Figure 2.4-5: Shear viscosity of PP3854 at 230°C using the ACER and the Online Rheological Sensor	23
Figure 2.4-6: Elongational viscosity of PP3854 at 230°C using the ACER and the Online Rheological Sensor	23
Figure 3.2-1: Sensor block heater and thermocouple nomenclature	26
Figure 3.2-2: Final model structure describing the sensor block temperature response.....	31
Figure 3.2-3: The Simulink PID substructure model	31
Figure 3.2-4: The elongational side substructure containing the final model parameters	32
Figure 3.2-5: The shear side substructure containing the final model parameters	33

Figure 3.2-6: PID controlled elongational side temperature response with a step change in polymer temperature	34
Figure 3.2-7: PID controlled shear side temperature response with a step change in polymer temperature	35
Figure 4.1-1: Relay terminal block pin definitions	38
Figure 4.1-2: Pin definitions for the 2A DC Output Module	40
Figure 4.1-3: Calibration curve for the sensor block pressure transducers	42
Figure 4.1-4: CTI 505 OPC server <i>device</i> properties	44
Figure 4.1-5: Screenshot of the <i>die server Larry</i> opf CTI 505 OPC program	45
Figure 4.2-1: Screenshot of the front panel of the V2 program	46
Figure 4.2-2: Block diagram to calculate shear viscosity in V2	47
Figure 4.2-3: Block diagram to calculate elongational viscosity in V2	48
Figure 4.2-4: A 1 st Order Lag with a time constant of 15 in LabVIEW	49
Figure 4.2-5: The PID structure to control the sensor relay outputs	51
Figure 4.2-6: Sensor block response to a step change from 23°C to 220°C	52
Figure 5.1-1: The TANDEC 6-inch pilot line	54
Figure 5.2-1: Leistritz TSE RPM for a given mass using PP3155 at 220°C.....	57
Figure 5.3-1: Acquiring a viscosity set point in “automatic” mode	58
Figure 5.3-2: Acquiring a viscosity set point in “manual” mode	59
Figure A-1: The Win-Tech OPC server in the Registry Editor of the laptop	66
Figure A-2: Port availability on laptop computer after the Win-Tech OPC server is installed	67
Figure A-3: Port configuration properties to use with Win-Tech OPC server.....	68
Figure A-4: Advanced port settings to use with Win-Tech OPC server.....	68
Figure A-5: DataSocket Connection window	69
Figure B-1: Simulink block structure for the elongational side of the sensor block for Run #3.....	70
Figure B-2: Simulink block structure for the shear side of the sensor block for Run #3.....	70

Figure B-3: Simulink model of the elongational side of the sensor block for Run #3.....	71
Figure B-4: Simulink model of the shear side of the sensor block for Run #3.....	72
Figure B-5: Simulink block structure for the elongational side of the sensor block for Run #4.....	73
Figure B-6: Simulink block structure for the shear side of the sensor block for Run #4.....	73
Figure B-7: Simulink model of the elongational side of the sensor block for Run #4.....	74
Figure B-8: Simulink model of the shear side of the sensor block for Run #4.....	75
Figure B-9: Simulink block structure for the elongational side of the sensor block for Run #5.....	76
Figure B-10: Simulink block structure for the shear side of the sensor block for Run #5.....	77
Figure B-11: Simulink model of the elongational side of the sensor block for Run #5.....	78
Figure B-12: Simulink model of the shear side of the sensor block for Run #5.....	79
Figure B-13: Simulink block structure for the elongational side of the sensor block for Run #6.....	80
Figure B-14: Simulink block structure for the shear side of the sensor block for Run #6.....	81
Figure B-15: Simulink model of the elongational side of the sensor block for Run #6.....	82
Figure B-16: Simulink model of the shear side of the sensor block for Run #6.....	83
Figure B-17: Simulink block structure for the elongational side of the sensor block for Run #7.....	84
Figure B-18: Simulink block structure for the shear side of the sensor block for Run #7.....	85
Figure B-19: Simulink model of the elongational side of the sensor block for Run #7.....	86

Figure B-20: Simulink model of the shear side of the sensor block for Run #7.....	87
Figure B-21: Simulink block structure for the elongational side of the sensor block for Run #6 to determine the “cooling parameters”	88
Figure B-22: Simulink block structure for the shear side of the sensor block for Run #6 to determine the “cooling parameters”	89
Figure B-23: Simulink cooling model of the elongational side of the sensor block for Run #6.....	90
Figure B-24: Simulink cooling model of the shear side of the sensor block for Run #6.....	91
Figure B-25: Simulink block structure for the elongational side of the sensor block for Run #3 using the “combined parameters”	92
Figure B-26: Simulink block structure for the shear side of the sensor block for Run #3 using the “combined parameters”	93
Figure B-27: Simulink model for the elongational side of the sensor block for Run #3 using the “combined parameters”	94
Figure B-28: Simulink model for the shear side of the sensor block for Run #3 using the “combined parameters”	95
Figure B-29: Simulink block structure for the elongational side of the sensor block for Run #6 using the “combined parameters”	96
Figure B-30: Simulink block structure for the shear side of the sensor block for Run #6 using the “combined parameters”	97
Figure B-31: Simulink model for the elongational side of the sensor block for Run #6 using the “combined parameters”	98
Figure B-32: Simulink model for the shear side of the sensor block for Run #6 using the “combined parameters”	99

Nomenclature & Abbreviations

Nomenclature

A_{ex}	Exit Area of the Hyperbolic Die
A_o	Initial Area of the Hyperbolic Die
L	Centerline Length of the Die
P	Pressure
Q	Volumetric Flow Rate
R	Radius of Capillary Die
TC1	Controller for Top Heaters in Sensor Block
TC1%	Controller Output Percentage for Top Heaters in Sensor Block
TC2	Controller for Bottom Heaters in Sensor Block
TC2%	Controller Output Percentage for Bottom Heaters in Sensor Block
T-E/C	Temperature of the Elongational Side of the Sensor Block (Centigrade)
T-S/C	Temperature of the Shear Side of the Sensor Block (Centigrade)
v_o	Initial Velocity
$\dot{\gamma}$	Shear Rate at the Wall
$\dot{\epsilon}$	Elongational Strain Rate
ϵ_H	Henky Strain
η_e	Elongational Viscosity
η_s	Shear Viscosity
τ	Shear Stress

Abbreviations

ACER	Advanced Capillary Extrusion Rheometer
ANSI	American National Standards Institute
APT	Applied Productivity Tool
COM	Component Object Model
CPU	Central Processing Unit
CTI	Control Technology, Inc.
I/O	Input/Output

IP	Internet Protocol
LV	LabVIEW
LVM	LabVIEW Measurement File
MB	Melt Blowing
NI	National Instrument's
OLE	Objective Linking and Embedding
OPC	OLE for Process Control
PID	Proportional, Integral, and Derivative
PLC	Pro Logic Controller
PP	Polypropylene
RBC	Remote Base Controller
RPM	Revolutions Per Minute
SSE	Sum of the Squared Error
TANDEC	Textiles and Nonwovens Development Center
TSE	Twin-Screw Extruder
USB	Universal Serial Bus
VAC	Volts Alternating Current
VDC	Volts Direct Current
VI	Virtual Instrument

1.0 Introduction & Background

The extrusion process is defined as the shaping of a material by forcing it through a die (Bernhardt, 154). In the thermoplastic extrusion process, a material is first heated in order to soften it. The material is softened enough so that it may be forced down an extrusion line and through a die located at the end of that line (Goff, 1). A screw extruder is one of the devices used for extrusion (Bernhardt, 154). The number of screws used to drive the material through an extruder is often used as a means to name the extruder. Extruders containing one screw are called single-screw extruders. Extruders containing two or more screws are called multiple-screw extruders (Goff, 1).

1.1 Twin-Screw Extruder

The twin-screw extruder (TSE) is the simplest example of a multiple-screw extruder. The TSE is particularly useful in processes that have both compounding and extrusion steps (Goff, 3). The twin-screw extruder, like most extruders, contains four main part parts: (1) the hopper, (2) the feed throat, (3) the screw, and (4) the barrel (Bernhardt, 156).

The hopper is a device that is mounted on an extruder at the feeding port. The primary function of the hopper is to first hold and then feed the material that is to be extruded (Goff, 272).

The feed throat is the opening in which material enters an extruder. The cross section of the feed throat is usually a minimum of one screw diameter in length and is generally rectangular or circular in shape. The sides of the feed throat leading to the barrel and screw can either be vertical or sloped (Bernhardt, 156).

The screw or screws of an extruder are used to push a polymer melt from the hopper, down the barrel, and out through a die (Bernhardt, 157). The screws of a twin-screw extruder can either be turned in a co-rotating or counter-rotating fashion. A co-rotating screw extruder rotates the screws in the same direction, while a counter-rotating screw extruder rotates the screws in opposite directions (Goff, 3). The counter-rotation of the two screws provides positive material feed and conveying effects. Some

disadvantages of counter-rotating extrusion are air entrapment, high-pressure generation, and low rotational speeds. A co-rotating screw extruder is used primarily for material processes that require compounding. A co-rotating screw extruder allows the screws to clean, or self-wipe, one another during processing. Co-rotating screw extruders also allow for higher rotational speeds that result in better mixing and compounding (Goff, 4).

The barrel of the TSE contains three distinct regions: (1) the partially filled region, (2) the transition region, and (3) the fully filled region (Chen et al, 6824). The partially filled region of a twin-screw extruder is the portion in which the barrel is first filled with loose polymer pellets and the extrusion channel is only partially filled (Chen et al, 6824). While polymer passes through the partially filled region, the pressure within the TSE remains low and relatively constant. Some polymer pellets melt in this region primarily due to heat from the barrel. The pellets that remain in solid form flow through the barrel in a manner similar to plug flow. In the partially filled region of the barrel, a decrease followed by an increase in temperature occurs (Chen et al, 6826). The transition region of a twin-screw extruder occurs when the majority of the polymer pellets melt. At the beginning of the transition region, the barrel contains a high concentration of polymer pellets. In this region, the polymer pellets melt due to the heat transfer from the barrel and the heat produced from viscous energy dissipation. The viscous energy dissipation comes from the shearing effects on the polymer. The mechanical energy from the motor and screws contributes to the viscous energy that must be dissipated (Chen et al, 6827). At the end of the transition region, the temperature increases as the polymer melt fills the screw channels (Chen et al, 6828). The fully filled region is the portion of the TSE in which the majority of the polymer is melted. The temperature of this region steadily increases due to the heat from the barrel and the viscous energy dissipation. The pressure of the TSE increases at a constant rate until the polymer melt is unleashed from the barrel. The pressure then drops suddenly to atmospheric pressure (Chen et al, 6828).

1.2 Melt Blowing Process

Introduced in the 1950's, the melt blowing process is a method of converting polymer resins into a nonwoven mat of fibers. The melt blowing process plays a key role

in the processing of many commercial products, ranging from automobile parts to the teabag (Malkan, 46). In the melt blowing process, a polymer is melted and pressurized through a die. A hot air stream, at a high velocity, is used to attenuate the fiber while suspended in the air. The polymer fibers, ranging from 1 to 5 microns, are then collected on a mat. The mat of fibers is referred to as “nonwoven” because knitting is not required to form the mat (Marla, Shambaugh, 6993). The melt blowing process variables can be divided into two categories: (1) operational variables and (2) off-line variables (Malkan, 50).

1.2.1 Melt Blowing Operational Variables

The melt blowing process contains four operational variables that may be used to control the properties of the final polymer product. The four operational variables include: (1) air velocity at the die exit, (2) air temperature at the die exit, (3) polymer flow rate, and (4) polymer temperature at the die exit. Changing any one of these four variables has a distinct effect on the process output (Bansal, Shambaugh, 1800).

The air velocity at the die exit is a mechanism that helps determine how the polymer fiber attenuates before it is collected. A high air velocity results in an increased rate of fiber attenuation. As the attenuation rate is increased, the final polymer fiber diameter decreases. The higher air velocity also increases heat transfer to the fiber. A high air velocity decreases hot air exposure time and allows the fiber to cool faster. As the polymer fiber is cooled, the attenuation process is slowed (Bansal, Shambaugh, 1801). As the air velocity increases, strong velocity fluctuations may also occur. Strong fluctuations in the air velocity result in polymer fibers breaking off and sticking to the die face (Krutka et al, 4207).

The air temperature at the die exit may be manipulated to control the melt blowing process (Bansal, Shambaugh, 1800). The air temperature also helps determine how a polymer fiber attenuates (Krutka et al, 4207). In general, the air temperature should be set equal to or greater than the exiting polymer temperature to allow for proper fiber attenuation (Tate, Shambaugh, 5406). Higher air temperatures reduce the viscosity of a polymer fiber. A polymer with a lower viscosity allows for higher attenuation rates, which results in smaller fiber diameters (Bansal, Shambaugh, 1801).

The polymer flow rate helps determine attenuation rates and fiber diameters. Low attenuation rates occur as a result of high polymer flow rates (Marla, Shambaugh, 2793). Higher polymer flow rates also produce fibers having greater diameters because more material per unit area leads to lower attenuation rates. Polymer fibers with large diameters transfer heat to the surroundings at greater rates due to the increased surface area (Bansal, Shambaugh, 1802).

The polymer temperature affects how the polymer fiber attenuates during the melt blowing process. As the polymer temperature increases, the viscosity of the polymer decreases. A less viscous polymer will produce fibers with smaller diameters as a result of the higher attenuation rates (Bansal, Shambaugh, 1802).

1.2.2 Melt Blowing Offline Variables

Processing variables that can only be changed while a melt blowing process line is not in operation are called “offline variables”. The offline variables of a melt blowing process include: (1) die hole size and set back, (2) air gap and angle, and (3) die to collector distance (Malkan, 50).

The die hole size and set back affect the polymer fiber size. The die hole size must be large enough for the flowing polymer melts, so plugging will not occur. The polymer feed distribution type and orifice length to diameter ratio must produce enough backpressure to force a good melt distribution and a controllable polymer flow (Malkan, 50).

The exit air pressure is affected by the air gap. A proper air gap is important because it is believed that the exit air pressure directly affects the degree of fiber breakage. The nature of the airflow is controlled by the air angle (Malkan, 50). A die with a sharp angle produces higher centerline velocities. The higher centerline velocities result in faster attenuation rates. In contrast, blunt dies produce slow centerline velocities that result in slower attenuation rates (Marla, Shambaugh, 2792).

The distance from the die to the collector affects the thermal bonding and fiber layout. A shorter die to collector distance allows the fibers to lay closer to one another, reducing the openness of the fabric (Malkan, 50). Larger die to collector distances allow the fibers to spread out due to the different air velocity vectors that result from turbulent

flow. The fiber length also increases due to the longer distance the polymer fibers must travel (Yin et al., 25).

1.3 Work Motivation & Goals

Rheological properties of polymers are closely related to the processing conditions of a polymer system. The acquisition of rheological properties provides a basis for choosing the appropriate equipment and polymer processing conditions (Wang, 8).

Rheometers are devices that can be used to measure the rheological properties of polymers. Rheometers may be categorized as off-line, in-line, and online depending on the application. Off-line rheometers are used to measure rheological properties at a site remote from the polymer process. Rheological measurements taken off-line have become a standard in commercial and academic fields due to accurate and repeatable results. Off-line rheological testing may add further temperature history or strain to the material. Rheometers mounted in a polymer processing line are called in-line rheometers. Online rheometers are mounted on a processing line and usually draw a side stream off of the main polymer stream to measure rheological properties. Both in-line and offline rheometers provide real-time rheological data that is more indicative of the polymer process (Wang, 8).

Online rheometers test for rheological properties during a polymer process. Real-time rheological data could eliminate any material degradation and time delays that accompany off-line rheometers. Real-time rheological data can provide the feedback information needed for tighter polymer process control. A real-time control system could eliminate the need for an offline rheometer to analyze polymer product properties, thus saving both time and money.

The Online Rheological Sensor was used to estimate the shear and elongational viscosities of a polymer from measured variables during processing. The goal of this research was to work towards using the Online Rheological Sensor as a device to monitor and control polymer viscosities during processing.

2.0 Shear and Elongational Program

2.1 Leistritz Twin-Screw Extruder

A Leistritz twin-screw extruder (TSE) was used for the purposes of this research. The twin-screw extruder was a Leistritz model *Micro 27* with the capability of operating as either a co-rotating or a counter-rotating extruder. The Leistritz TSE 10.5 kW drive motor had a maximum speed of 2700 RPM, which produced a maximum screw speed of 500 RPM through gear reduction. The motor speed was controlled by a potentiometer that was mounted on the Leistritz control panel. The motor speed potentiometer was adjusted manually until the desired set point was read from a *Hengstler* digital indicator located on the control panel. However, Leistritz recommended that the rotational speed of the screw not exceed 300 RPM in the counter-rotating mode. The Leistritz TSE featured ten heating zones with 9.25 kW of heating power. Nine of the ten heating zones were also water-cooled zones. Each heating zone was controlled by a digital *Eurotherm* temperature controller. The Leistritz twin-screw extruder featured a maximum melt pressure of 300 BAR and a maximum melt temperature of 350 °C (Leistritz manual, 11). Figure 2.1-1 shows a photograph of the Leistritz TSE and Table 2.1-1 shows a summary of the machine data.



Figure 2.1-1: The Leistritz twin-screw extruder (photo by Larry Spencer)

Table 2.1-1 - Leistritz TSE Features

Feature	Value
Model	<i>Micro 27</i> , co- or counter-rotating
Axle base of screws	23 mm
Screw diameter	27 mm
Barrel diameter	27.2 H8
Screw Functionary Length	40D
Drive	DC-motor
Drive Power	10.5 kW
Max motor speed	2700 RPM
Max screw rotation	500 RPM
Number of heating zones	10
Heating power	9.25 kW
Number of cooling zones	9
Max melt pressure	300 bar
Max melt temperature	350 °C
Operating height	1050 mm
Approximate weight	950 kg

2.2 Online Rheological Sensor

The Online Rheological Sensor estimated the shear and elongational viscosities of a polymer from measured variables during processing. The shear and elongational viscosities were functions of die dimension, flow rate, pressure drop, and temperature. The sensor block was designed to hold a set of capillary and hyperbolic dies, as shown in Figure 2.2-1, while measuring and sending values of the process variables to an algorithm written in National Instrument's LabVIEW, where the shear and elongational viscosities were calculated. Figure 2.2-2 shows a photograph of the Online Rheological Sensor mounted on the Leistritz twin-screw extruder.

2.2.1 Sensor Dies

The equations of continuity, motion, and energy may be used to develop simple relationships for the shear rates and viscosities using a capillary die and relationships for the elongational rates and viscosities using a hyperbolic die (Wang, 36). Assuming isothermal flow of an incompressible fluid through a capillary die and applying Newton's law of viscosity results in the following equation for the shear rate at the wall of the capillary

$$\dot{\gamma} = \frac{4Q}{\pi R^3} \quad (2.2.1-1)$$

where Q is the volumetric flow rate and R is the radius of the capillary die (Wang, 39).

The elongational strain rate may be derived in the same manner as the shear rate and is shown in the following equation

$$\dot{\epsilon} = \left(\frac{v_o}{L} \right) (e^{\epsilon_H} - 1) \quad (2.2.1-2)$$

where L is the centerline length of the die, v_o is the initial velocity, and ϵ_H is the Henky strain. The Henky strain is defined as

$$\epsilon_H = \ln \left(\frac{A_0}{A_{ex}} \right) \quad (2.2.1-3)$$

where A_0 is the initial area and A_{ex} is the exit area of the hyperbolic die (Collier, 2362).

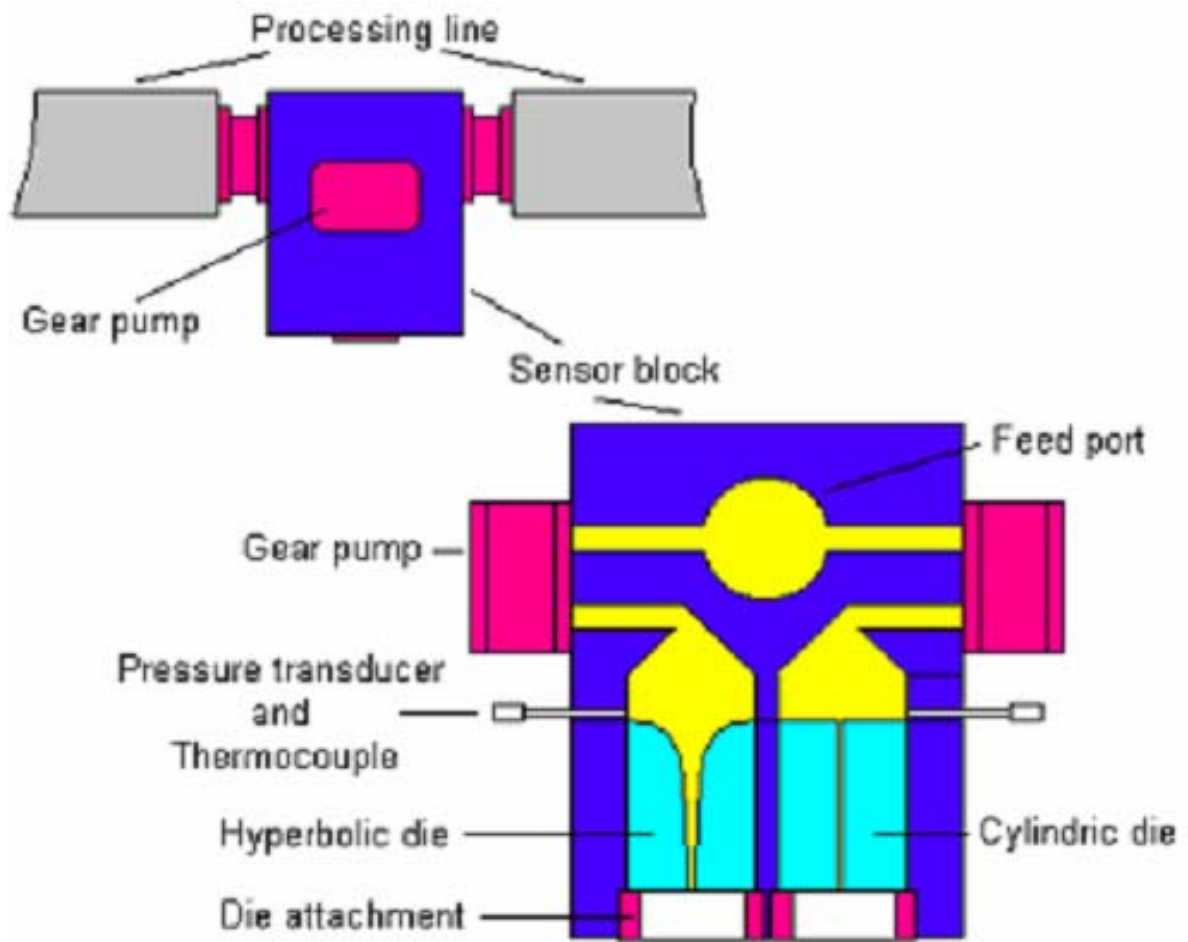


Figure 2.2-1: Online Rheological Sensor schematic (illustration by Simioan Petrovan)



Figure 2.2-2: Picture of the Online Rheological Sensor mounted on the Leistritz twin-screw extruder (photo by Larry Spencer)

The shear and elongational viscosities can be calculated from the shear and elongational strain rates, respectively. The shear viscosity may be defined as

$$\eta_s = \left(\frac{\tau}{\dot{\gamma}} \right) \quad (2.2.1-4)$$

where τ is the shear stress. The shear stress is defined as

$$\tau = \frac{R\Delta P}{2L} \quad (2.2.1-5)$$

where ΔP is the change in pressure and L is the capillary die length. The elongational viscosity equation is also listed below

$$\eta_e = \frac{\left(\frac{\Delta P}{\epsilon_H} \right)}{\dot{\epsilon}} \quad (2.2.1-6)$$

2.2.2 Sensor Hardware

The Online Rheological Sensor operated by drawing off a side stream of polymer from the main product line using a set of gear pumps. A 2.92 cc gear pump was located on each side of the sensor block in order to draw a stream through the capillary or hyperbolic dies either independently or simultaneously. The gear pumps were turned by electric motors manufactured by *Sew-Eurodrive, Inc.* The 0.5 HP electric motors were a type DFT71D4 having a maximum speed of 1700 RPM. The electric motors had an attached gear reduction device, *Sew-Eurodrive* type R17DT71D4 with a 12.98 reduction ratio. The gear reduction ratio allowed the shaft that turn the gear pumps to rotate at up to 131 RPM. The electric motors were mounted on an aluminum frame built by Mr. Doug Fielden, Instrument Maker Supervisor at the University of Tennessee, Knoxville. The aluminum frame was designed to hold both of the electric motors so that an electric motor could be used to turn each gear pump located on either side of the sensor block. The aluminum frame was designed to slide the electric motors towards or away from the sensor block. The frame had a height adjusting feature, so that the electric motors could be used with different extruder heads, such as the spinning head. Figure 2.2-3 shows how the electric motors were mounted on the aluminum frame and how the electric motor shafts insert into the gear pumps located on each side of the sensor block. The gear pump speeds were maintained and controlled by a set of *Motortronics CSD series* AC drives. The *Motortronics CSD series* was designed to interface with 0.5 to 30 HP motors operated at 200 to 460V, which made it an ideal controller for the *Sew-Eurodrive* electric motors (Motortronics, 2).

The Online Rheological Sensor had two sets of four heaters and two J-type thermocouples located on the top and bottom of the sensor block. The sensor was heated independently of the polymer process. The heating elements were 240V *Watlow Firerod* heaters. One set of 4 heating elements was a *Firerod* model 0307 11M 34A73 –J12C14 and operated at 1000W. The other set of heating elements was a *Firerod* model 0308 07 J3A112 –J12C14 and operated at 750W. The heating elements provided a uniform block temperature that was controlled by two *Omega i-Series* digital PID controllers. The *Omega i-Series* featured a RS-485 output that was addressable from 0 to 199 (Omega

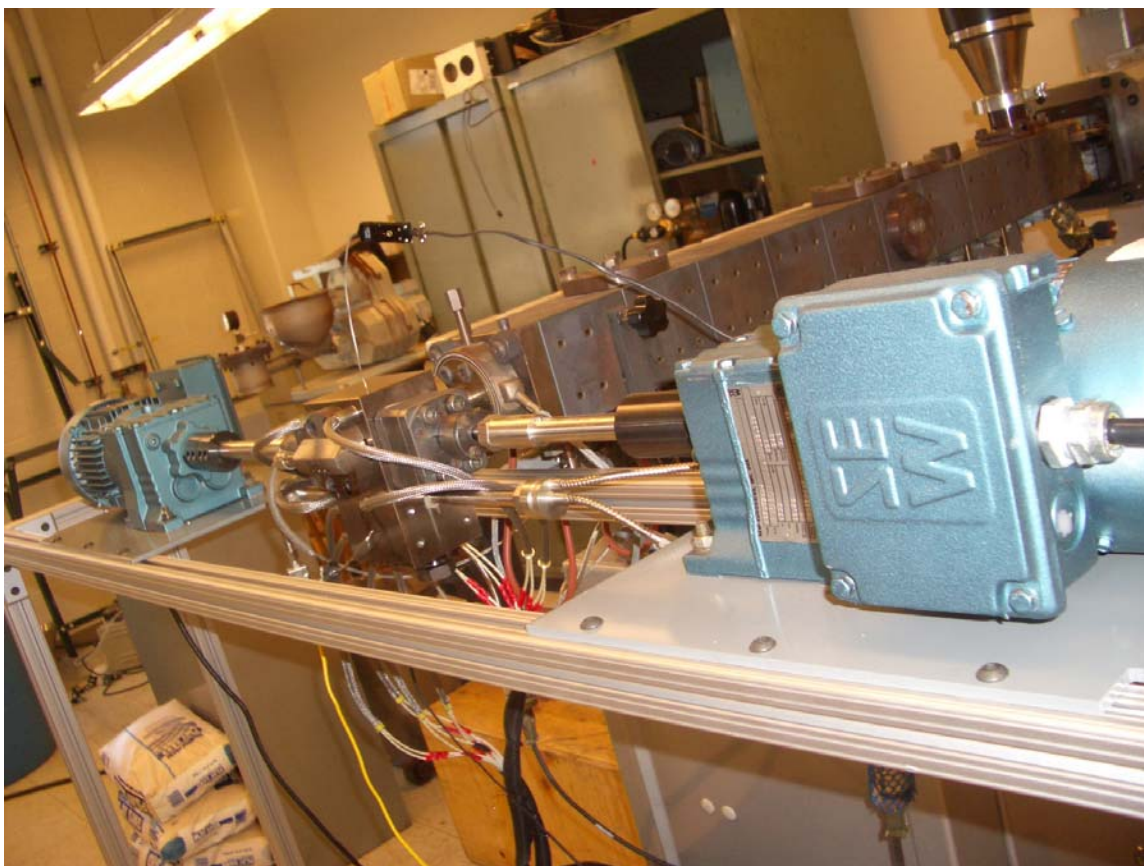


Figure 2.2-3: Electric motor shafts to sensor gear pumps (photo by Larry Spencer)

manual, 59). The *Omega i-Series* controllers sent an output voltage to a set of *Cutler-Hammer*, model C25DND330 relays. The relays turned the heating elements on or off, depending upon the *Omega i-Series* PID temperature control output. The sensor also had a J-type thermocouple and pressure transducer combination that was used to measure the temperatures and differential pressures of the shear and elongational sides of the sensor block, respectively. The thermocouple and pressure transducer combination was a *Dynisco* model TPT 463E-5M-6/18. The pressure transducer was designed to cover a 0 to 5,000 psig range and had a 10V DC input and 33.3mV output. These thermocouple and pressure transducer readings were shown on a set of *Dynisco* digital indicators, model numbers UPR700. The two *Motortronics CSD series* AC drives, the two *Omega i-Series* digital PID controllers, the *Cutler-Hammer* relays, and the *Dynisco* digital indicators were all mounted inside or on the panel of a black control box built by Mr. Mike Neal,



Figure 2.2-4: Picture of the black control box (photo by Larry Spencer)

Senior Design Technician at the University of Tennessee, Knoxville. The black control box also contained two extra *Omega* temperature controllers, models CN9000A, for heaters that were added to this system or heaters contained in other extruder heads, such as the spinning head. Figure 2.2-4 is a photograph showing the black control box and controllers.

2.3 Sensor Interface

The temperature and pressure data from the Online Rheological Sensor were transmitted to LabVIEW using a RS-485 interface. RS-485 is a two-wire system that uses multiple transmitters on the same communication line. RS-485 uses a half-duplex protocol that can communicate with up to 32 devices. The half-duplex system is a master-slave protocol by which the master sends poll packets to the slave devices. Each slave device has a unique polling address that responds only to packets addressed to the unit. RS-485

is designed to communicate with different devices using multiple drivers. The RS-485 cable may be up to 1200 meters long and can communicate with speeds of 2.5MB/s that supports most automation and control applications. Figure 2.3-1 illustrates a typical half-duplex system (Wang, 146).

A National Instruments USB to RS-485 device was used to create the interface between LabVIEW on the laptop computer through the USB port and the external controllers that communicate through the two DB-9 connector ports. Each device that communicated with LabVIEW was wired to the DB-9 connector. Figure 2.3-2 shows the functions and location of the pins for the DB-9 connector. The National Instruments USB to RS-485 device was a model number of USB-485/2 with a part number of 187660C-02. If further communication ports are needed in the future, 8 and 16 serial board buses are available through National Instruments (Wang, 129).

In order to use the USB to RS-485 interface, the drivers must first be installed on the computer. A file named *serusb11.exe* must be run to install the application drivers for the USB to RS-485 device. *Serusb11.exe* was available for download at the National Instruments website. Once the driver was installed, the USB to RS-485 interface could be plugged into the USB port of the computer. In order for the device to operate properly, the USB to RS-485 communication ports must be set correctly. Detailed instructions to properly configure the NI serial ports are located in Appendix A.2.

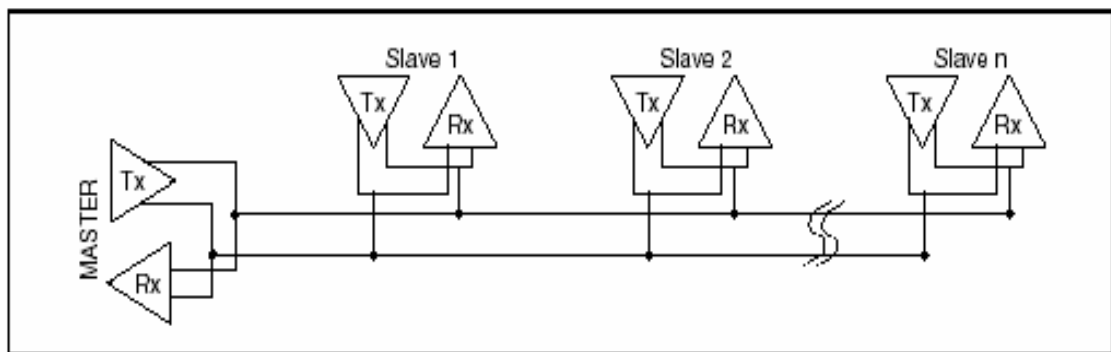


Figure 2.3-1: Typical half-duplex system (NI Serial Manual, 6-4)

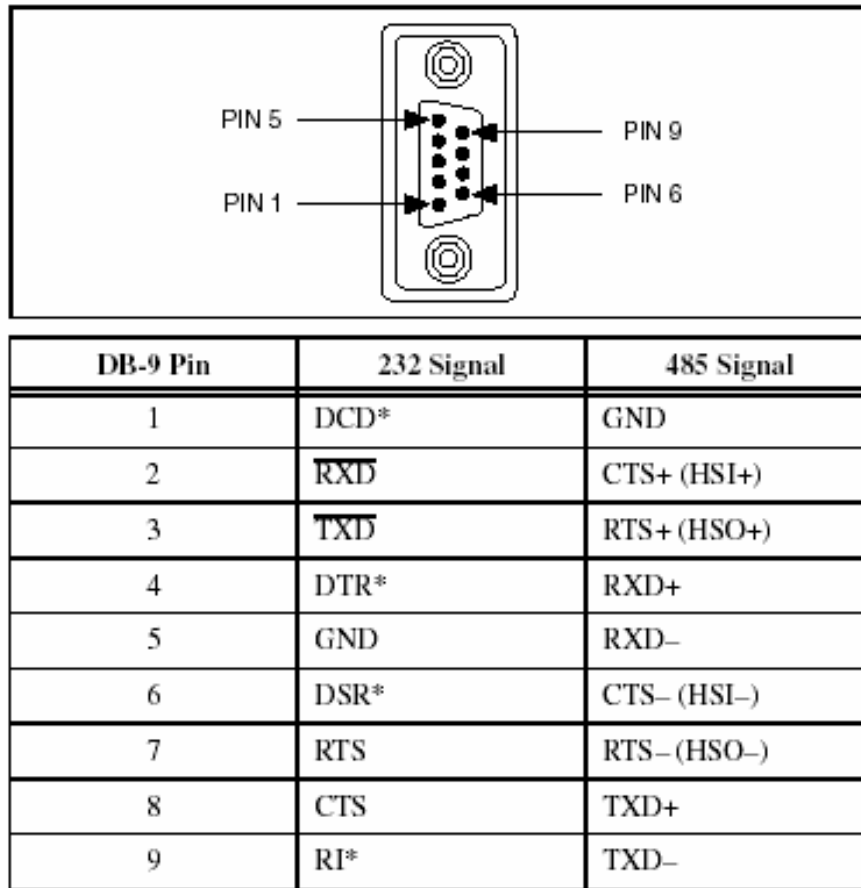


Figure 2.3-2: DB-9 connector schematic (NI Serial Manual, A-2)

A MODBUS Serial Line protocol was used to allow communication from the master to the slave nodes. In this research study, the master was the computer and the slaves were the temperature and pressure readings from the Dynisco digital indicators and the temperature set point function for the Omega controllers. The MODBUS protocol only permits one master per serial port. The master initiates communication with the slave devices in two modes: (1) unicast mode and (2) broadcast mode. In unicast mode, the master transmits a signal or polls a single slave node. Each slave node has a unique address, ranging from 1 to 247, so that each slave can be called upon independently. The slave node will not transmit a signal until the slave node receives a command from the master. In broadcast mode, the master polls all of the slave nodes at once. The slaves do not reply to the master in broadcasting mode. An address of '0' designates broadcast

mode. The Online Rheological Sensor operated in unicast mode for purposes of this research (Wang, 133).

Objective Linking and Embedding (OLE) for Process Control (OPC) was used to allow communication from Windows based programming and software to process control hardware. OPC servers provide the link necessary to acquire information from PLC, DCS, and other hardware devices. OPC servers take advantage of Microsoft's OLE technology, also known as *Component Object Model* or *COM*, to provide the user with real-time information from the hardware devices. Figure 2.3-3 depicts how data was exchanged using an OPC server (Wang, 135).

An OPC server for Modbus software called "mbOPCsrv" from Win-Tech Technology was used for this research study. The Win-Tech OPC server must be installed on the computer as a "service". A more detailed description of the software installation is shown in Appendix A.1. Once installed, applications are able to call an

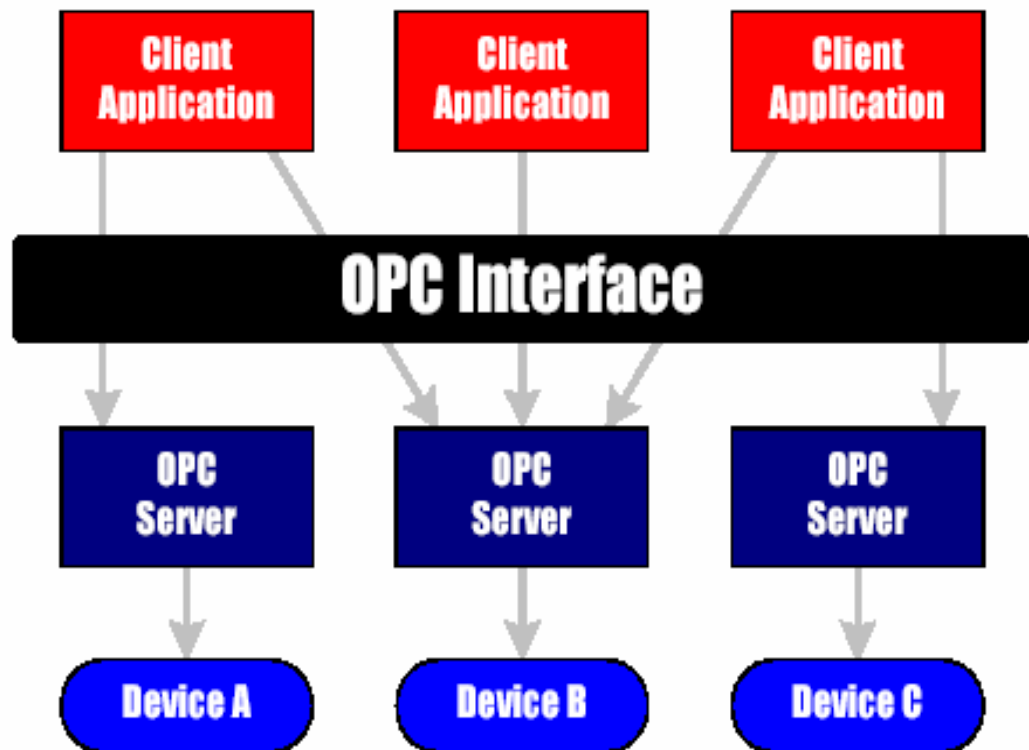


Figure 2.3-3: OPC server and device information exchange diagram (Wang, 137)

OPC server file named “mbOPCsvr.tst” to start communications with the attached devices at each specified address. When LabVIEW calls upon the Win-Tech OPC server, a window will open and show all of the available device addresses. The user must then manually open the appropriate communication ports. For this research study, communication port 4 and port 5 were used. Communication port 4 was used to read the temperature and pressure values from the two *Dynisco* UPR700 digital indicators, and route the signal as input to National Instrument’s LabVIEW. Communication port 5 was used to send the temperature set point from LabVIEW to the two *Omega i-Series* digital PID controllers. Figure 2.3-4 shows the Win-Tech Modbus server and all of the available addresses for the Online Rheological Sensor in operation (Wang, 138).

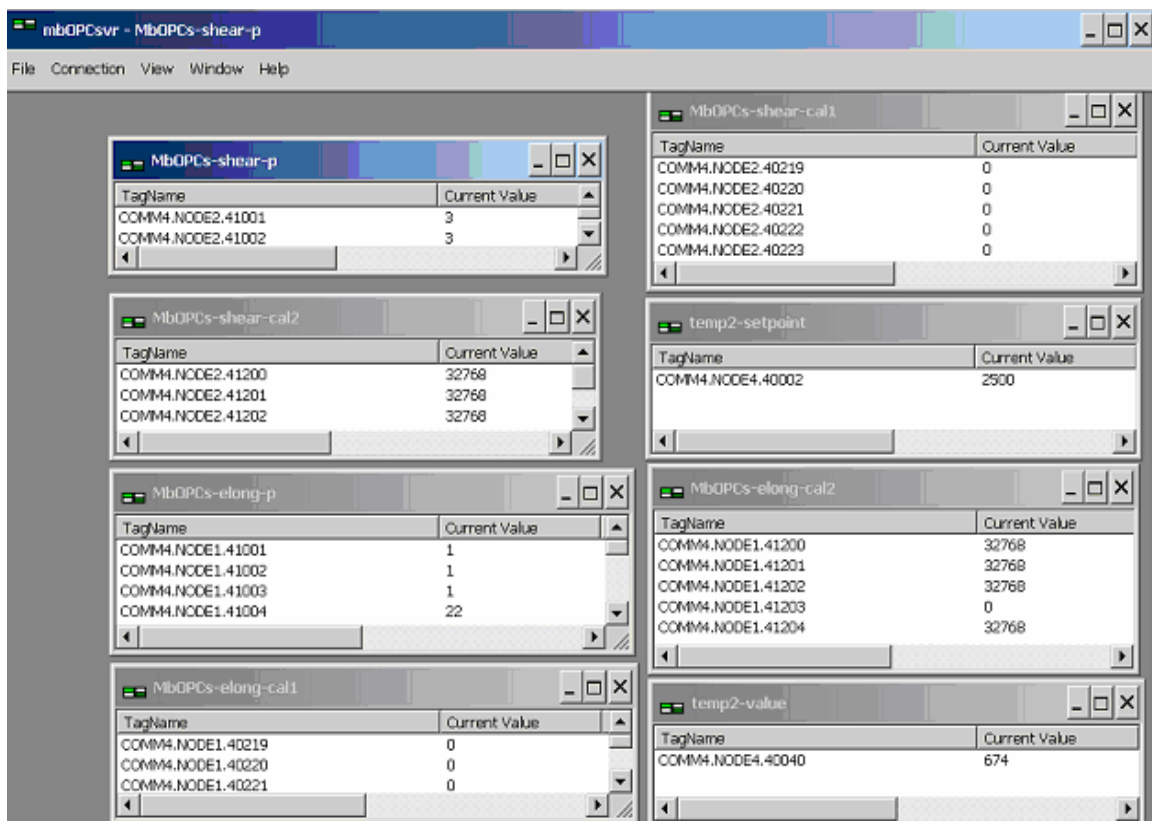


Figure 2.3-4: Screenshot of the Win-Tech mbOPCsvr (Wang, 140)

2.4 Sensor Computer Program

2.4.1 National Instrument's LabVIEW

National Instrument's LabVIEW is a programming language that can be used to monitor and control a process and its devices. LabVIEW is a graphical based language that uses icons, instead of lines of code, to create applications (LV Manual, 1-1).

LabVIEW programs are called *virtual instruments* or *VI's* (LV Manual, 1-4).

A *virtual instrument* consists of two windows: (1) the *front panel* and (2) the *block diagram*. The *front panel* of LabVIEW serves as the user interface. The front panel is a user defined, graphical representation of all the controls and indicators for a device connected to LabVIEW (Essick, 1). Front panel objects can be accessed from the *Controls palette*. The *Controls palette* contain items such as knobs, buttons, switches, charts, and graphs to monitor and control devices connected to LabVIEW (LV Manual, 3-1). The *block diagram* contains the programming source code for the *virtual instrument*. The *block diagram* uses a system of icons that are connected to one another by *wires* to perform a desired task (Esseck, 1). The icons in the *block diagram* can be either *terminals* from the items located on the *front panel* or programming functions that are located in the *Functions palette*. The *Functions palette* contains items such as arithmetic functions, strings, and formula nodes (LV Manual, 2-4).

The *Tools palette* is used to operate and modify objects on the front panel and block diagram. The *Tools palette* features a variety of cursor operators that include: an *operating tool*, *positioning tool*, *labeling tool*, and a *wiring tool*. The *Tools palette* may be placed in an *Automatic Tool Selection* mode so that LabVIEW will automatically choose the appropriate tool for a given application (LV Basics, slide9).

Virtual instruments that serve as subroutines in larger LabVIEW programs are called *sub-VI's*. A *sub-VI* is created by first designing a representation icon and then assigning the appropriate *connectors* (Basics, slide 27). An icon representing a *sub-VI* is created by right-clicking on the front panel icon and choosing a custom design (Basics, slide 28). After an icon is created, right-click the icon and choose "show connectors" (LV Basics, slide 29). The icon will change from user-defined design to a series of blocks.

The blocks on the left side of the icon represent the user inputs, while the blocks on the right side represent the program outputs. The *wiring tool* is then used to define the input and output terminals from by clicking a connector block and then clicking a corresponding control or indicator on the front panel (LV Basics, slide 30). Once saved, the *sub-VI* can be accessed or placed on the block diagram of a *Top Level VI* via the *Functions palette* (LV Basics, slide 32).

National Instrument's LabVIEW uses a *DataSocket* connection to communicate with devices on the OPC server. A *DataSocket* connection can be used to publish (or write) a command or data to a device, such as the set point for a temperature controller. A *DataSocket* connection may also be used to subscribe (or read) data from devices on an OPC server, such as thermocouple and pressure transducer real-time readings. A *DataSocket* connection is established when the user specifies a device address for the appropriate front panel or block diagram variable. A more detailed description of creating a *DataSocket* connection is located in Appendix A.3 (LabVIEW manual, 18-2).

2.4.2 Shear and Elongational Virtual Instrument

Shearandelongational.vi, written by Yizhong Wang, is a virtual instrument that calculates the shear and elongational polymer viscosities, either independently or simultaneously, from user defined variables and the Online Rheological Sensor process variables. The die geometries, process temperatures, shear rates, and elongational strain rate must all be defined by the user in the virtual instrument. The shear and elongational viscosities are then calculated from the sensor block pressures that result from the user-defined variables during processing. The shear and elongational viscosity measurements are then plotted on a chart versus shear rate or elongational strain rate, respectively.

Shearandelongational.vi prompts the user to define the types of dies used within the sensor block. The hyperbolic die used in the process is specified by the Henky number. The capillary die, used to calculate the shear viscosity, is defined from the capillary length and hole radius.

The polymer processing temperature can be divided into two categories: (1) the ten temperature zones of the Leistritz twin-screw extruder and (2) the Online Rheological Sensor block temperature. The ten zones of the Leistritz twin-screw extruder are not

currently interfaced with the laptop computer and must be set manually using the digital PID controllers on the extruder control panel. However, the temperature setpoint of the sensor block can be defined by the user in the *shearandelongational.vi* program. The temperature setpoint for the sensor block is transmitted (through channel 5 of the Win-Tech OPC server) to the two digital *Omega i-Series* PID controllers that control the top and bottom sets of heaters, respectively. However, signal interference prevents both channel 4 and channel 5 of the Win-Tech mbOPCsr to remain open; therefore, once the temperature is set on the two controllers, the user must close channel 5.

An array of shear rates and elongational strain rates must be defined by the user in the *shearandelongational.vi* program. The shear rate array and the elongational strain rate array must contain at least one value if the shear and elongational viscosities are to be measured, respectively. Each of the two arrays may hold up to thirteen rate values, as shown in Figure 2.4-1. If only one of the two viscosity types is to be measured, then only the array that corresponds to the desired viscosity is to be filled. When the program is executed, the program begins with the first rate value in each respective array. That rate value is then used to calculate the gear pump RPM required to produce a small side stream at a volumetric flow rate, through each respective die, necessary to match the specified rate. However, the shear rates and elongational strain rates do not represent the rates at the exit die of the main stream. The volumetric flow rate of the main stream must be greater than or equal to the sum of the Online Rheological Sensor flow rates. As the gear pump draws the small side stream through the die, the pressure changes inside of the die which is read by the program. When the pressure reaches a steady state value, or the slope of the pressure line equals zero, the user presses the “next step” button. The “next step” button triggers the program to save the viscosity at that point and proceeds to the next rate value in the array. The program then prompts the user to change the gear pump speed and the process continues until a value of viscosity for all of the positions in the array are calculated. Figure 2.4-2 shows the “measuring” portion of the program. The block diagrams for calculating the shear and elongational viscosities are shown in Figures 2.4-3 and Figure 2.4-4, respectively. Viscosity measurements from an offline rheometer and the Online Rheological Sensor are compared in Figure 2.4-5 and Figure 2.4-6.

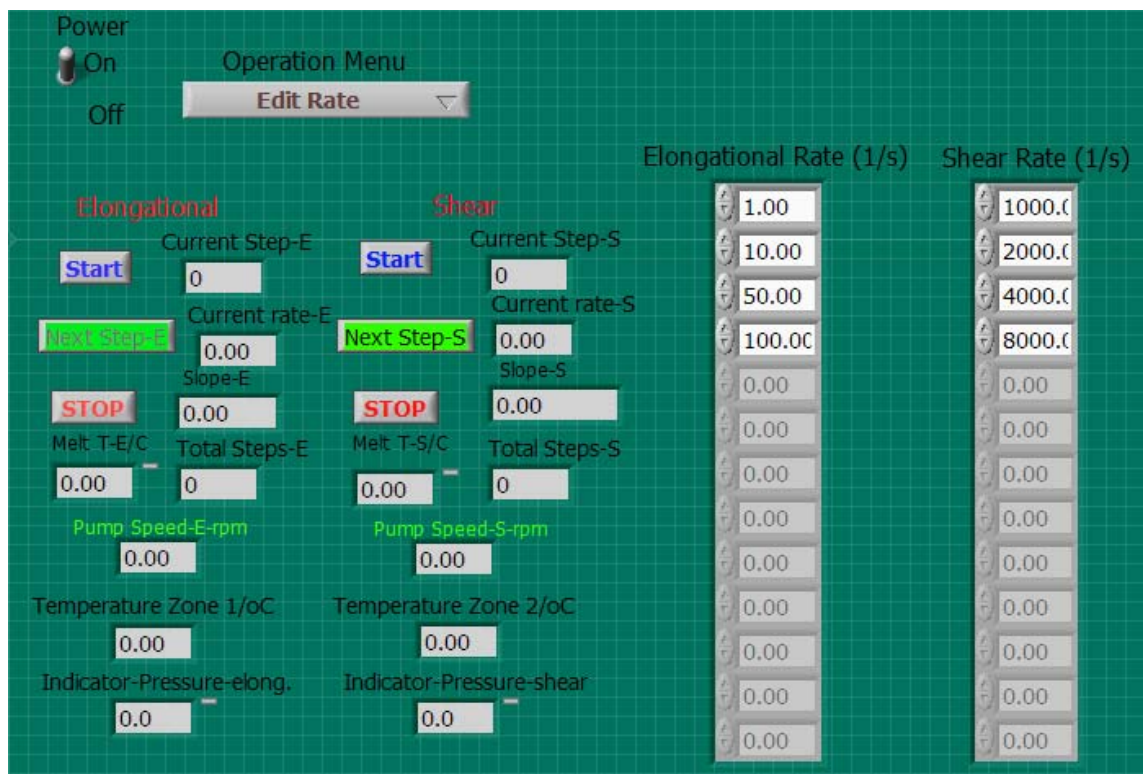


Figure 2.4-1: The “edit rate” menu of the *shearandelongational.vi* program (by Y. Wang)

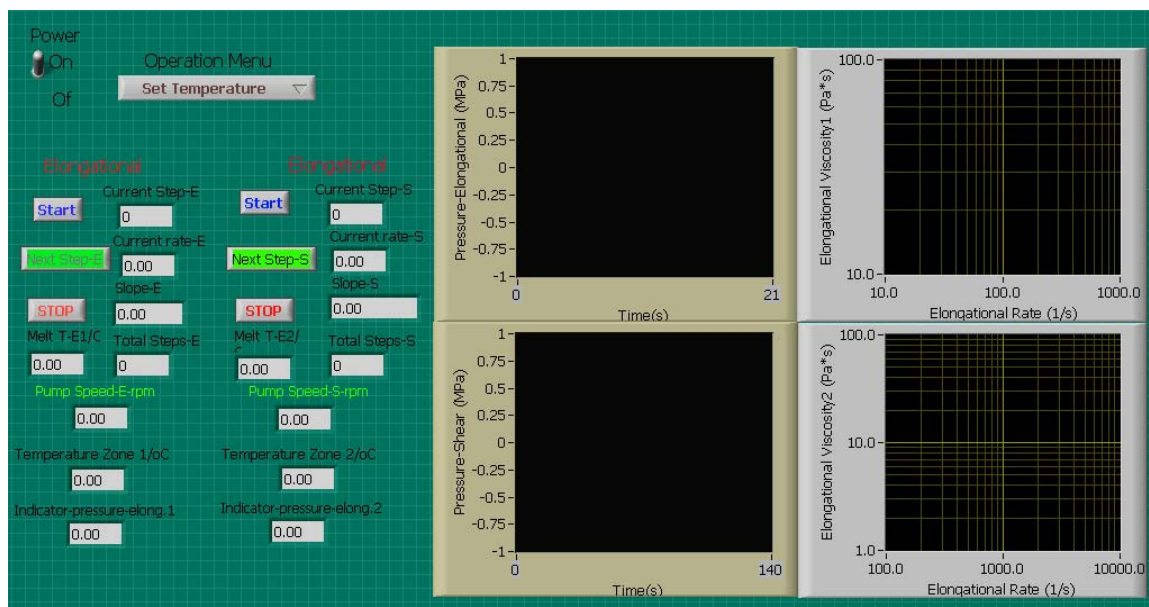


Figure 2.4-2: *Shearandelongational.vi* program monitors the process pressure and plot the viscosities in the “measure” portion of the program (Wang, 143)

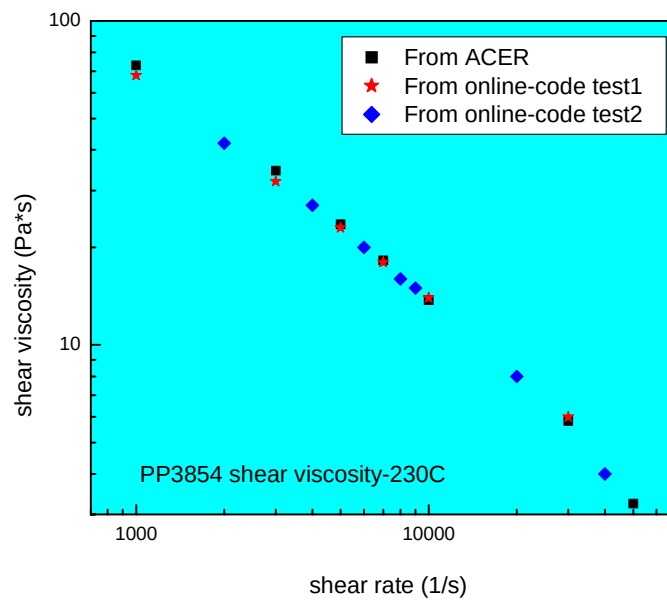


Figure 2.4-5: Shear viscosity of PP3854 at 230°C using the ACER (offline rheometer) and the Online Rheological Sensor (Wang, 155)

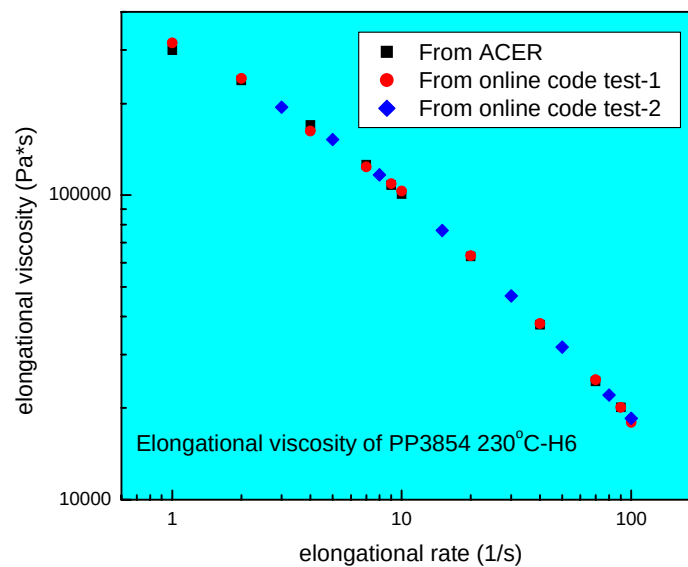


Figure 2.4-6: Elongational viscosity of PP3854 at 230°C using the ACER (offline rheometer) and the Online Rheological Sensor (Wang, 155)

3.0 Sensor Block Temperature Models

The main objective of this research was to work towards using the Online Rheological Sensor to monitor and control the shear and elongational viscosities of a polymer during processing. In order to maintain a constant viscosity or adjust to a change in viscosity, the sensor block temperature should be controlled. Experimental data describing the temperature response of the sensor block was used to create a mathematical model that was used in PID control simulations. A computer simulation was used to help determine the proper PID tuning parameters for the sensor block.

3.1 Temperature Response Experiments

Several experiments were conducted to collect time-temperature response data of the sensor block under different heating conditions. In the first experiment or “Run”, the temperature of the sensor block was recorded while the Leistritz twin-screw extruder was heated from 23°C (room temperature) to an operating temperature of 220°C. During Run #1, the sensor heaters remained OFF. In Run #2, the sensor heaters were turned ON and the time-temperature response of the block was recorded while it was heated to 220°C. The Run #1 and #2 data sets were not used in the mathematical model of the sensor block.

The time-temperature response of the sensor block was collected in Runs #3 through #7 for different heater control outputs under processing conditions, as shown in Table 3.1. Exxon Mobil PP3155 (polypropylene) was extruded through the sensor and out of the three-hole melt blowing die at 220°C. A temperature response data point was taken once every 0.1 seconds until each experiment concluded. For each experimental run, one heater remained ON at different control output percentages, while its counterpart remained OFF. For each set of heater controller outputs, the temperature set point changed from an initial 220°C to 260°C and then was changed back to 220°C when the actual temperature of the block reached 240°C. The change in temperature set points ensured that the heater was turned fully ON until a temperature of 240°C was reached

Table 3.1 - Experimental Run Summary

RUN	TC1%	TC2%
3	OFF	50%
4	OFF	25%
5	99%	OFF
6	80%	OFF
7	60%	OFF

and turned fully OFF thereafter. However, later studies showed this was not the case. The temperature set points were changed manually using the *Omega* temperature controllers, which resulted in different temperature ranges for each run.

The data for each experimental run was collected and saved in a LabVIEW measurement file (LVM) containing a column of time values and a corresponding column of temperature values. An elongational side (T-E/C) LVM file and a shear side (T-S/C) LVM file were both created for an individual run.

3.2 Temperature Response Models

A model that described the heating characteristics of the Online Rheological Sensor was created by performing an energy balance. The experimental data, as described in Section 3.1, was used to develop individual run models, and later a single mathematical model, describing the heating effects of the sensor block. The single model describing the temperature response of the Online Rheological Sensor was then used to conduct a computer simulated PID control study.

3.2.1 Individual Run Simulink Models

Matlab Simulink block diagrams were created that described the experimental data for Run #3 through Run #7 as the first step towards building a single mathematical

model to describe the temperature effects of the Online Rheological Sensor. Simulink models were created for both the shear and elongational sides of the sensor block for each experimental run. The shear and elongational sides of the sensor block were treated independently. The Simulink models contained three main components that contributed to the overall temperature of the sensor block: (1) the sensor block heaters, (2) the polymer throughput, (3) and the cooling effects of ambient air.

The sensor block contained two sets of four heating elements. The top set of heating elements were controlled by the top *Omega* temperature controller (TC1) on the black control box. In contrast, the bottom heating elements were controlled by the bottom *Omega* temperature controller (TC2). For the model describing the temperature response of the sensor block, the top and bottom heaters located closest to the T-E/C and T-S/C thermocouples were assumed to have a first order lag effect. The top and bottom sets of heaters located furthest from the T-E/C and T-S/C thermocouples were assumed to have a second order lag effect. A first order lag was assumed for each of the actual heater controllers, resulting in overall second and third order lag effects. Figure 3.2-1 shows the location and nomenclature of the sensor hardware.

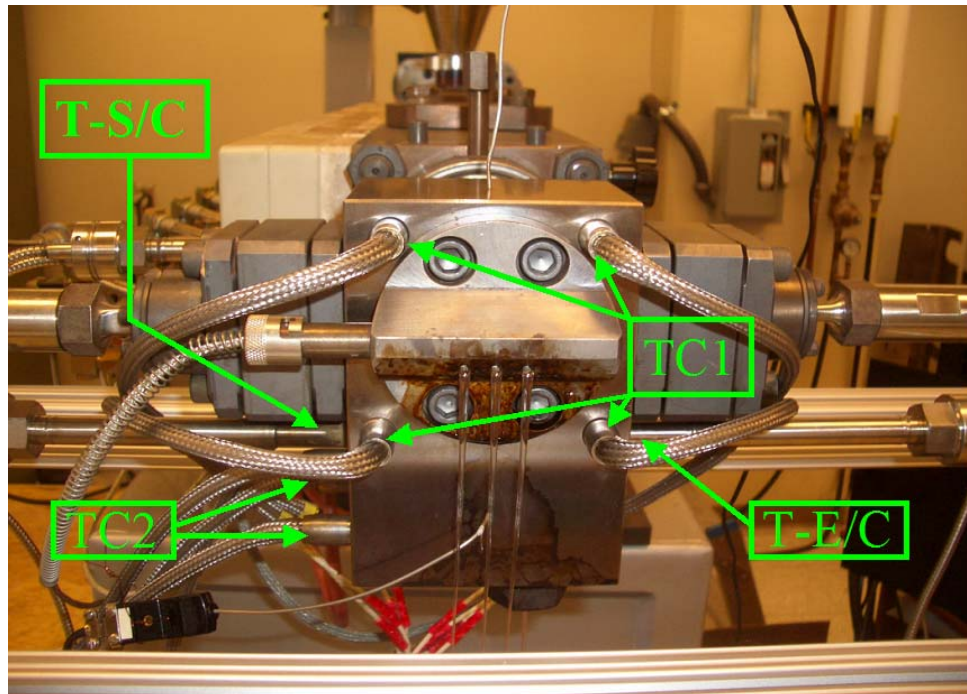


Figure 3.2-1: Sensor block heater and thermocouple nomenclature (photo by L. Spencer)

The polymer throughput had a cooling effect on the Online Rheological Sensor block. During each experimental procedure, the sensor was heated from 220°C to 240°C and then cooled to 220°C, while the Leistritz twin-screw maintained a constant temperature of 220°C. Therefore, the polymer also would have had a temperature of 220°C upon enter the sensor block. Since the polymer temperature was lower than the sensor block temperature throughout each run, the polymer throughput produced a slight cooling effect on the sensor block.

The ambient air temperature also had a cooling effect on the Online Rheological Sensor. The ambient air temperature (23°C) was considerably less than the processing temperature. Natural convection to ambient air provided the main cooling mechanism for the sensor block, since the Online Rheological Sensor does not contain any type of water cooling system or cooling fans.

The models for each experimental run were developed by adjusting the gain constants and time constants in each Simulink block diagram until the model fit the experimental data. In addition, the model parameters, that describe the effects of the polymer and the air on the temperature of the block, were changed from being a constant gain value (as used in Run #3 and Run #4) to a value containing a second-order lag for Runs #5 to #7 to better fit the experimental data. The Simulink programs and results for all five runs are shown in Appendix B. A summary of the results for this study is shown in Table 3.2-1.

3.2.2 Single Simulink Model

A single model describing the temperature response of the Online Rheological Sensor was needed in order to find the proper PID values for temperature control. The single or combined model needed to contain one set of cooling parameters, time-constants, and gains that describe the temperature response of the elongational and shear sides of the sensor block, simultaneously.

A single set of parameters was found to adequately describe the cooling effects on the sensor block in the combined model. The cooling parameters for the model were the polymer and ambient air time-constants and lags. Only one set of cooling parameters

Table 3.2-1 - Results for Individual Run Models Using Simulink

Parameters	3E	3S	4E	4S	5E	5S	6E	6S	7E	7S
Top (%)	0	0	0	0	99	99	80	80	60	60
Bottom (%)	50	50	25	25	0	0	0	0	0	0
Tau 1	0	0	0	0	1	13.39	7.38	10.63	10.22	11.82
Tau 2	0	0	0	0	1	1	1	1	1	1
Tau 3	1	1	59.3	62.3	0	0	0	0	0	0
Tau 4	1	1	1	1	0	0	0	0	0	0
K1	0	0	0	0	20.88	0.5	0.5	0.5	3.15	2.25
K2	0	0	0	0	0.5	0.5	0.5	0.5	0.5	0.5
K3	0.5	0.5	0.5	0.5	0	0	0	0	0	0
K4	0.5	0.5	0.5	0.5	0	0	0	0	0	0
K top heater	0	0	0	0	1E-04	2E-04	0.714	0.602	0.043	0.068
Tau top heater	0	0	0	0	5	15	10	12	10	15
K btm heater	0.541	0.49	0.935	0.781	0	0	0	0	0	0
Tau btm heater	16.69	28.4	2.94	6.23	0	0	0	0	0	0
K polymer	0.002	0	0.004	0.004	0.006	0.005	0.006	0.005	0.006	0.006
Tau Polymer	0	0	0	0	20	20	10	10	20	20
K air	4E-04	0	6E-04	5E-04	5E-04	5E-04	6E-04	6E-04	7E-04	7E-04
Tau Air	0	0	0	0	10	10	10	10	10	10

should exist because the air and polymer temperature remained constant in all of the experiments. The cooling parameters were found by comparing the models for Run #3 and Run #6. The cooling portion of the time-temperature response curve for Run #3 appeared to behave slightly more linear compared to the exponential behavior of the cooling portion of the curve for Run #6. One explanation for the different cooling behaviors is that the TC2 controller never turned fully OFF during Run #3. In contrast, the TC1 controller did turn fully OFF during Run #6. The cooling parameters for Run #6 are more representative of the cooling effects of the sensor block and were used in the combined model.

The experimental data set for each run was reduced to an experimental data subset that only contained the cooling response of the elongational and shears sides. To this point, all of the models treated the elongational and shear sides of the sensor block independently. A new model parameter was added to the combined model to show the temperature interactions between the shear and elongational sides of the sensor block. Only the cooling parameters were changed in each model and the results were compared to the cooling data subset. This process continued until a set of cooling parameters for Run #6 was found. The results of this simulation are shown in Appendix B.2.

The model parameters from all of the individual runs were averaged to create a single set of time-constants and gains. The time-constant and gain parameters for the two models describing Run #5 were not used in the average, due to the very different model parameters. The averaged set of time-constants and gain were used in conjunction with the combined cooling parameters found for Run #6. Time-constants that had values of 1 were changed to have a new value of 5 in the model. The temperature controller gains and the block interaction terms were adjusted until each model fit the respective data set. The combined model values found for Run #3 represent the model parameters for the sensor block when only the bottom heater, TC2, was used. In contrast, the Run #6 combined model values represent the model parameters for the Online Rheological Sensor when only the top heater, TC1, was used. The models using the combined values for Run #3 and Run #6 are shown in Appendix B.3.

The models for TC1 and TC2 were combined into a single model, as shown in Figure 3.2-2. The model used Simulink block substructures to describe the time-temperature response of the Online Rheological Sensor when both temperature controllers were used. The final elongational and shear sensor block models were then placed in a Simulink control loop simulation containing a top and bottom PID controller. The PID control loop simulation was set at a constant 220°C and the initial conditions for the model parameters were adjusted until the initial output of the model was zero. The PID simulations were run, each time changing the control bias values, until the temperature value maintained a relatively steady value of 220°C. A control bias of 0.1303 for the top controller and a bias of 0.0 for the bottom controller were found from the model. The PID Simulink block structure is shown in Figure 3.2-3. The elongational and shear side sensor block models are shown in Figure 3.2-4 and Figure 3.2-5.

A step change in polymer temperature from 220°C to 240°C was implemented in the model simulation. The control bias values found for the model were used and remained constant. For this simulation, the derivative term was set to zero, while the proportional and integral values for the PID controllers were adjusted until the change in polymer temperature was correctly controlled, as shown in Figure 3.2-6 and Figure 3.2-7.

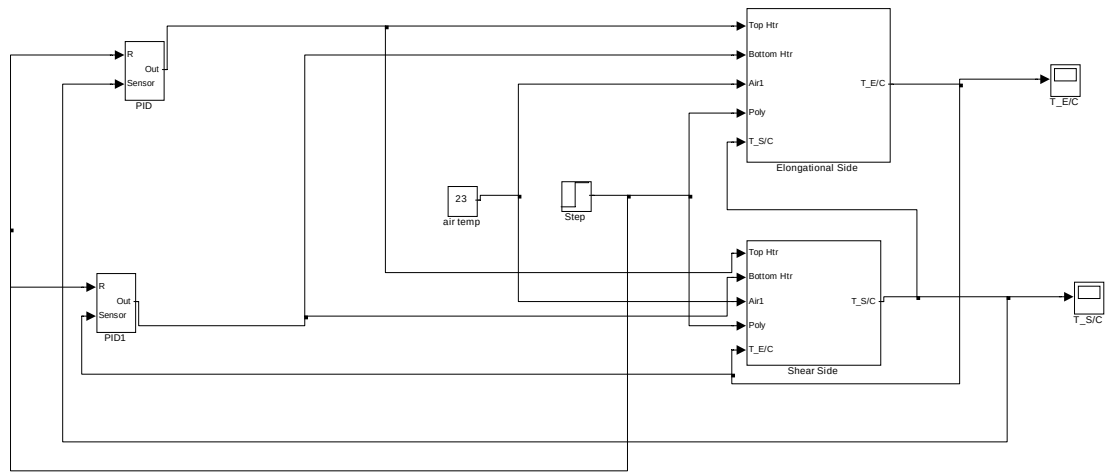


Figure 3.2-2: Final model structure describing the sensor block temperature response

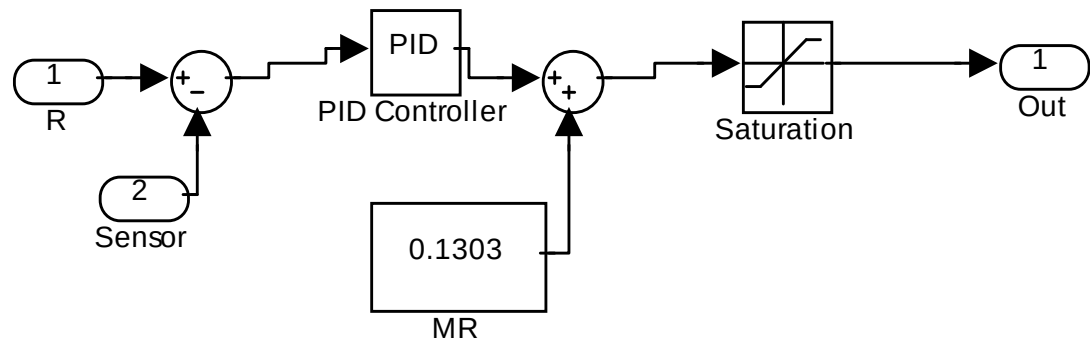


Figure 3.2-3: The Simulink PID substructure model

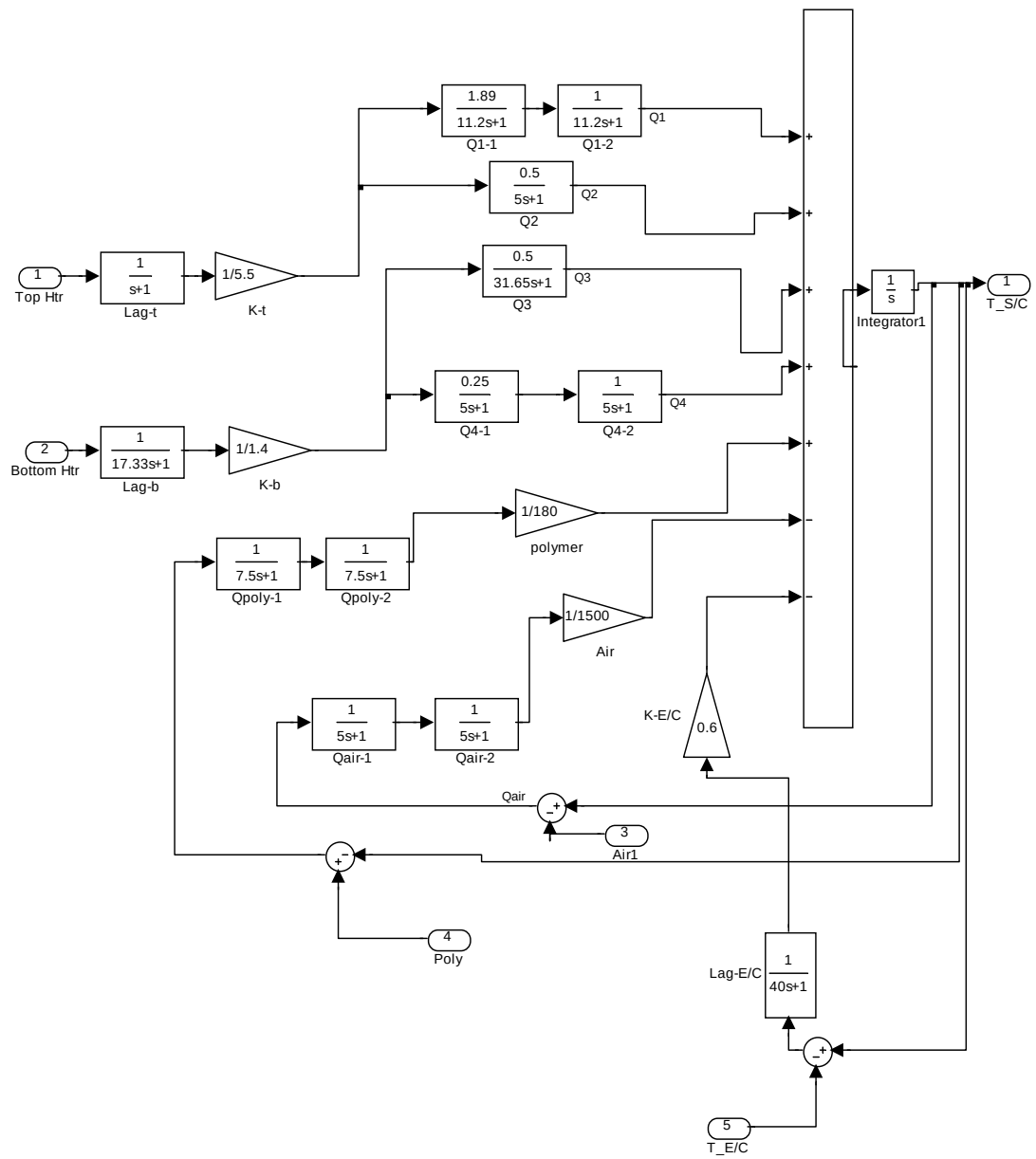


Figure 3.2-5: The shear side substructure containing the final model parameters

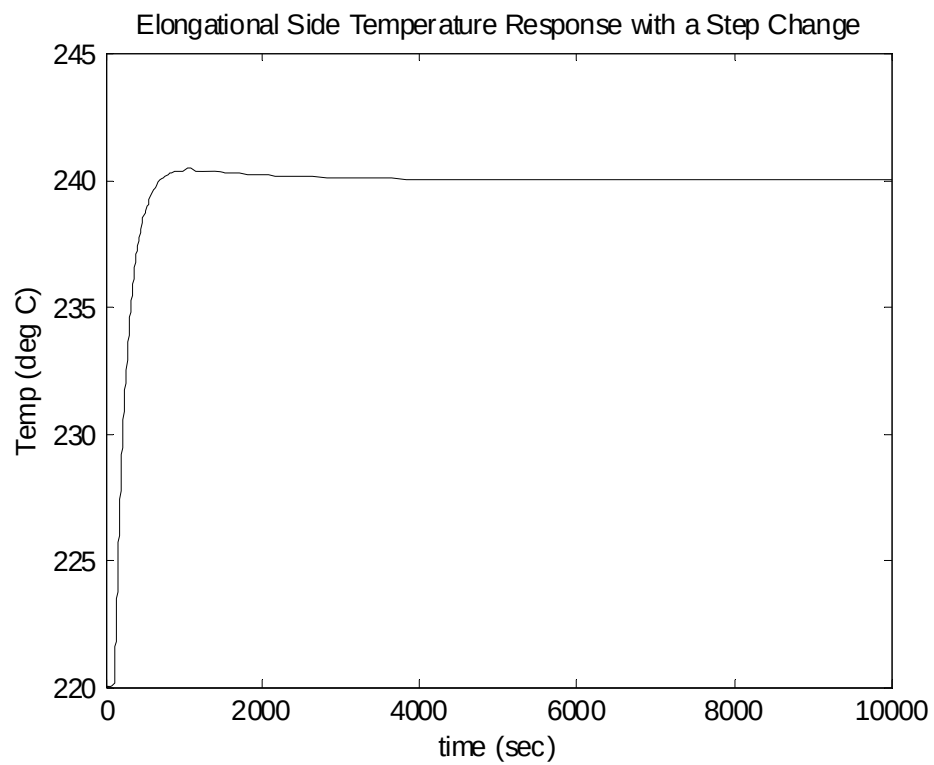


Figure 3.2-6: PID controlled elongational side temperature response with a step change in polymer temperature

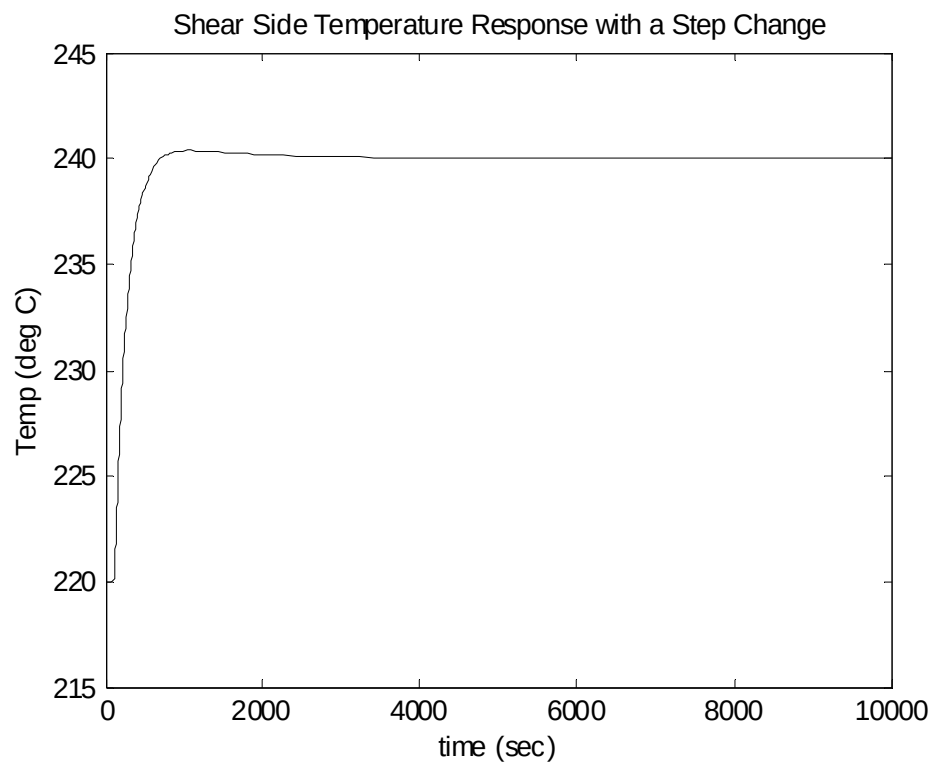


Figure 3.2-7: PID controlled shear side temperature response with a step change in polymer temperature

4.0 Shear and Elongational Version 2.0

The goal of this research was to use the Online Rheological Sensor to monitor and control the shear and elongational viscosities of a melt blowing process. A new interface was created to read and write commands to both the Online Rheological Sensor and the processing line. The *shearandelongational.vi* program was also modified in order to control the temperature of the sensor block.

4.1 The New Interface

The control scheme using the Online Rheological Sensor required that the interface between the laptop computer and the sensor be revamped. The original RS-485 to USB interface had significant signal interference while the laptop computer tried to simultaneously send information to and receive data from the process equipment. The original RS-485 to USB interface also proved to be inadequate due to its inability to communicate with the RS-485 incompatible, 6-inch pilot line equipment. A new interface with the ability to communicate with both the Online Rheological Sensor and the 6-inch melt blowing pilot line was created.

4.1.1 Hardware Interface

A Siemens Series 505 Pro Logic Controller (PLC) was used to communicate with the Online Rheological Sensor and the 6-inch melt blowing line equipment. The Siemens Series 505 base assembly included a CPU or remote base controller (RBC) unit and 16 open slots to hold additional input/output (I/O) modules. Input simulator, relay, and thermocouple cards are all examples of modules used by the Siemens PLC to read and send data from a computer to a processing line. A RS-232 serial port on the RBC was used to download programs (see section 4.2.2) that specify the modules attached to the Siemens Series 505 PLC. An independent address was assigned to each of the module ports. In this research, a Siemens Simatic TI545 (model number of 545-1101) was used as the RBC (TI545/TI555 System Manual, 1-6).

4.1.1.1 Ethernet Card

An Ethernet Transmission Control Protocol/Internet Protocol (TCP/IP) I/O module (model number 505-CP2572) was used to bridge the communications gap between the Siemens Series 505 PLC and the computer. The computer connected to the Ethernet TCP/IP module using a crossover cable that plugged into each respective Ethernet port. The Ethernet TCP/IP card had an assigned IP address, 128.169.100.112, which the computer used to communicate with the Siemens Series 505 PLC (Ethernet TCP/IP Manual, 1-2).

4.1.1.2 Input Simulator

An Input Simulator (model number 505-6010) was used to test the communication line between the Siemens Series 505 PLC and the computer. The Input Simulator had a series of two position toggle switches that could be flipped either ON or OFF. When an Input Simulator channel was switched to the ON position, an indicator lit up on the Input Simulator card and a value of “TRUE” was read by the computer.

4.1.1.3 Relay Card

A Relay Output module (model number 505-4916) was used to control the output of the 6-inch die heaters. The Relay Output module was designed to send the voltage required to trip a set of external relays. The Relay Output module was equipped with four 20 to 250 VAC commons that supply the output voltage for the 16 relay output terminals. A 24 VDC power supply was also required to power the relays within the Relay Output module. A relay output terminal diagram is shown in Figure 4.1-1. A relay module output terminal was connected to each of the five Watlow mercury displacement relays (models LD30-1000-0V00) inside of the 6-inch melt blowing line control box. The five Watlow mercury displacement relays controlled the 5 die zones of the 6-inch die. Each of the top die zones (zones 9, 10, and 11) contained two 300 W Watlow Firerod heating elements (models 043511M E385A) that operate at 240 VAC. The bottom die zone (zone 8) had two 1000 W Watlow Firerod heating elements (model 051110KG12847) that operated at 240 VAC. Zone 7 of the 6-inch MB line was a heating clamp, mounted on a connector

User Connection	LED	User Connection	LED
AR = Common for 1–4	–	AC = Common for 5–8	–
A1 = N/O* 1	A1	A5 = N/O 5	B1
A2 = N/O 2	A2	A6 = N/O 6	B2
A3 = N/O 3	A3	A7 = N/O 7	B3
A4 = N/O 4	A4	A8 = N/O 8	B4
BR = Not Used	–	BC = Not Used	–
B1 = Not Used	–	B5 = Not Used	–
B2 = Not Used	–	B6 = Not Used	–
B3 = Not Used	–	B7 = Not Used	–
B4 = N/O 9	C1	B8 = N/O 13	D1
CR = N/O 10	C2	CC = N/O 14	D2
C1 = N/O 11	C3	C5 = N/O 15	D3
C2 = N/O 12	C4	C6 = N/O 16	D4
C3 = Not Used	–	C7 = Not Used	–
C4 = Not Used	–	C8 = Not Used	–
DR = Not Used	–	DC = Not Used	–
D1 = Not Used	–	D5 = Not Used	–
D2 = Common for 9–12	–	D6 = Common for 13–16	–
D3 = Not Used	–	D7 = Not Used	–
D4 = User Coil Power (+)	–	D8 = User Coil Power (–)	–

Figure 4.1-1: Relay terminal block pin definitions (Relay Manual, 3-16).

piece, that allowed the end of the extruder to connect to the 6-inch die. A Hewlett Packard 6218A external power supply was wired to the output module and it provided the 24 VDC required for the output card relays. A 120 VAC common was also connected from a power terminal within the 6-inch line control box to the relay module. The relay modules supplied a 120 VAC current to the Watlow mercury displacement relays inside of the 6-inch melt blowing line control box to turn on the Watlow Firerod die heaters. In contrast, the relay modules remain closed and do not send a signal the Watlow mercury displacement relays when the die does not require heating (Simatic 505 Input/Output Modules Manual, 1-2).

4.1.1.4 DC Output Card

A 2A DC Output module (model number 505-4716) was used to control the output of the 3-32 VDC Omega solid state relays (model SSRL24ODC25) that operate the heating elements for the Online Rheological Sensor. The 2A DC Output module operated in the same manner as the Relay Output module (model 505-4916). The 2A DC Output module was equipped with four 6 to 24 VDC commons that supply the output voltage for the 16 DC output terminals. However, the 2A DC Output module did not require any additional hookups to power the module internal relays. A 2A DC Output module output terminal diagram is shown in Figure 4.1-2. For this research, the Hewlett Packard 6218A power supply generated the 24 VDC power for the first common of the 2A DC Output module. The 2A DC Output module sends a 24 VDC signal to the Omega solid state relays inside of the black control box when the Siemens Series 505 PLC receives a value of “TRUE” from the laptop computer. When the 24VDC signal trips an Omega relay, power is supplied to the Online Rheological Sensor heating elements and the block begins to heat (Simatic 505 Input/Output Modules Manual, A-13).

4.1.1.5 Thermocouple Card

A Thermocouple Input module (model number 505-7028) was used to read the temperatures of the five temperature zones of the 6-inch melt blowing die and the four temperature zones of the Online Rheological Sensor. The Thermocouple Input module

User Connection	User Connection
AR = User-Power (-)	AC = User-Power (+)
A1 = Output 1	A5 = Not Used
A2 = Output 2	A6 = Not Used
A3 = Output 3	A7 = Not Used
A4 = Output 4	A8 = Not Used
BR = User-Power (-)	BC = User-Power (+)
B1 = Output 5	B5 = Not Used
B2 = Output 6	B6 = Not Used
B3 = Output 7	B7 = Not Used
B4 = Output 8	B8 = Not Used
CR = User-Power (-)	CC = User-Power (+)
C1 = Output 9	C5 = Not Used
C2 = Output 10	C6 = Not Used
C3 = Output 11	C7 = Not Used
C4 = Output 12	C8 = Not Used
DR = User-Power (-)	DC = User-Power (+)
D1 = Output 13	D5 = Not Used
D2 = Output 14	D6 = Not Used
D3 = Output 15	D7 = Not Used
D4 = Output 16	D8 = Not Used

Figure 4.1-2: Pin definitions for the 2A DC Output Module (Simatic 505 Input/Output Modules Manual, A-13)

had 8 input ports designed to read one of the American National Standards Institute (ANSI) defined thermocouple types (J, K, T, E, R, and N). The thermocouple card can read temperature data in either engineering units ($^{\circ}\text{F}$ or $^{\circ}\text{C}$) or scaled data integer formats at a 250-millisecond update rate (Thermocouple Input Module Manual, 1-2). The J-type thermocouples located in the five temperature zones (zones 7 through 11) of the melt blowing die were connected to the first five ports of the first Thermocouple Input module. The four temperature zones (top, bottom, left, and right) of the Online Rheological Sensor were connected to the first four ports of a second Thermocouple Input module. All of the raw thermocouple data was read into the computer and then divided by a factor of ten to properly scale the values in degrees Centigrade (Thermocouple Input Module Manual, 2-5).

4.1.1.6 Analog Input Card

An Analog Input module (model 505-6208A) was used to read the pressures from the pressure transducers located on the left and right sides of the sensor block. The Analog Input module was designed to read a 0-10 VDC or 0-20 mA signal (Analog I/O Manual, B-4). The Analog Input module read the pressure from the two pressure transducers directly from the UPR700 digital indicator on the black control box. The UPR700 sent a voltage signal from an auxiliary output to the ports of the Analog Input module. The Analog Input module read this signal as a number between 0 and 32,765. The number read by the Analog Input module needed to be scaled properly in order to read the pressure from the sensor block. The readings were scaled by connecting a Dynisco pressure transducer calibrator to each of the pressure transducers and applying set pressures to each of them. Each of the set pressures was recorded along with the corresponding value between 0 and 32,765 on the OPC server. The set pressures were plotted versus the OPC values and a linear regression was performed to create a conversion function that was used in LabVIEW to calculate the sensor block pressures. The pressure transducer calibration curves for the left and right sides of the Online Rheological Sensor are shown in Figure 4.1-3.

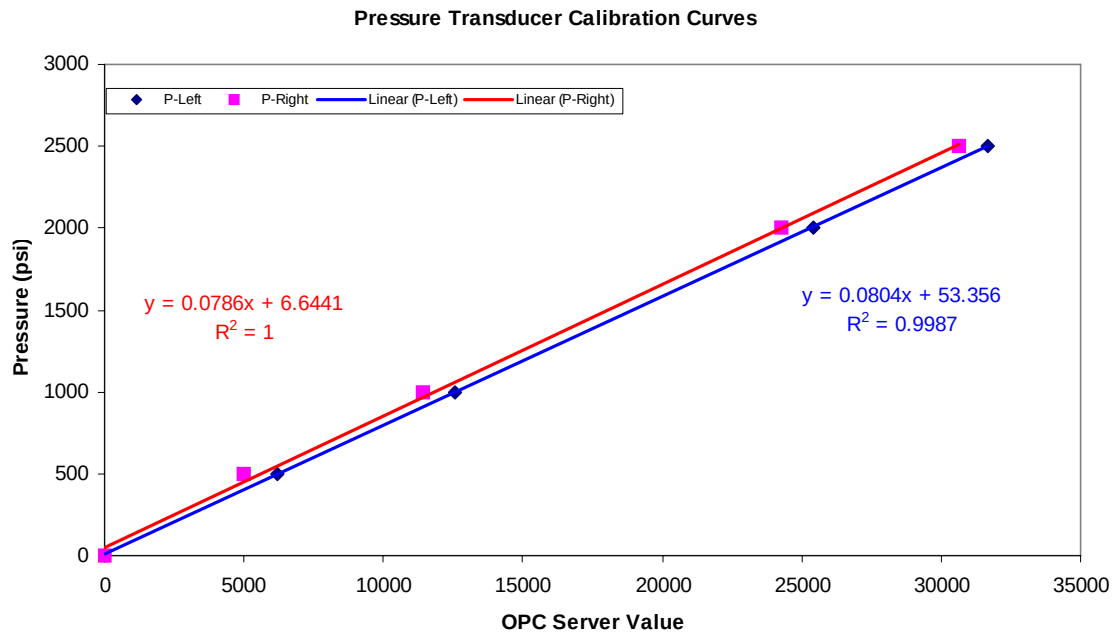


Figure 4.1-3: Calibration curve for the sensor block pressure transducers

4.1.2 Interface Software

The Application Productivity Tool (APT) is a software package designed by Siemens that was used to program the Series 505 PLC. Once APT had been successfully installed on the host computer, programs indicating the slot locations of the different I/O modules on the PLC were constructed. Each I/O module port or channel was assigned a unique address that the computer used to communicate with the attached hardware devices, such as the thermocouples or relays. Once the program was written, APT needed to first “compile” the program and then it was “downloaded” to the Siemens Series 505 PLC using a cable connecting the RS-232 port of the host computer to the RS-232 port of the RBC. An APT program called *Larry* was created for this research. A summary of the devices and the corresponding APT addresses are shown in Table 4.1-1.

Control Technology, Inc. (CTI) produces an OPC server that is designed to communicate with a Siemens Series 505 PLC. The CTI OPC server is similar to the

Table 4.1-1 - APT Variable Assignments

APT Variable	Address	Description
BOTBOXRELAY	Y0122	Relay for bottom sensor heaters
TOPBOXRELAY	Y0121	Relay for top sensor heaters
PTOPLEFT	WX0010	Left-side sensor pressure transducer
PBOTRIGHT	WX0009	Right-side sensor pressure transducer
BOTTOMTEMP	WX0116	Bottom sensor thermocouple
TOPTEMP	WX0115	Top sensor thermocouple
RIGHTTEMP	WX0114	Right-side sensor thermocouple
LEFTTEMP	WX0113	Left-side sensor thermocouple
THERMO7	WX0105	Zone 7 thermocouple for six-inch die
THERMO8	WX0106	Zone 8 thermocouple for six-inch die
THERMO9	WX0107	Zone 9 thermocouple for six-inch die
THERMO10	WX0108	Zone 10 thermocouple for six-inch die
THERMO11	WX0109	Zone 11 thermocouple for six-inch die
RELAY7	Y0089	Zone 7 heater relay
RELAY8	Y0090	Zone 8 heater relay
RELAY9	Y0091	Zone 9 heater relay
RELAY10	Y0092	Zone 10 heater relay
RELAY11	Y0093	Zone 11 heater relay
LIGHT1	X0025	Input Simulator 1
LIGHT2	X0026	Input Simulator 2

original Win-Tech Modbus server in the respect that each program was installed as a “service” on the laptop computer. Once installed, National Instruments LabVIEW used the *DataSocket Connection* to communicate with all of the devices connected to the Siemens Series 505 PLC. An *opf* file was created in order for the CTI OPC server to communicate with the PLC. An *opf* file consists of three main components: (1) a *channel*, (2) a *device*, and (3) *tags*. A *channel* represents the communication line that the computer uses to send and receive data from external device or devices. A *device* is defined as the PLC that an OPC server uses to communicate with the external devices. The Ethernet address under the *device* properties must be set to match the address assigned to the Ethernet port on the laptop computer in order for the OPC server to operate. The Ethernet port address was set as 128.169.100.111 for this research. Figure 4.1-4 shows the *device properties* window and the settings used to communicate through the Ethernet port. *Tags* are all of the device addresses assigned within the PLC (CTI 505 Server Help). Once an *opf* file is created, the user may open the CTI 505 OPC server *quick client* to view all of the values transmitted to the laptop computer from the process equipment. An *opf* file named *die server Larry*, as shown in Figure 4.1-5, was created for this research in order to communicate with the Online Rheological Sensor and the TANDEC 6-inch line components.

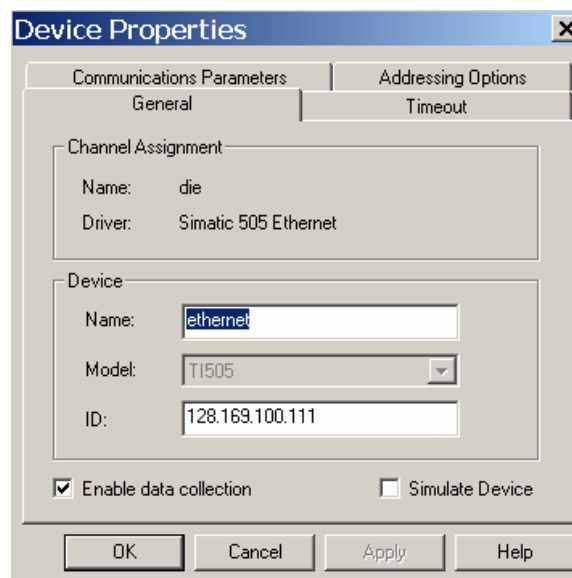
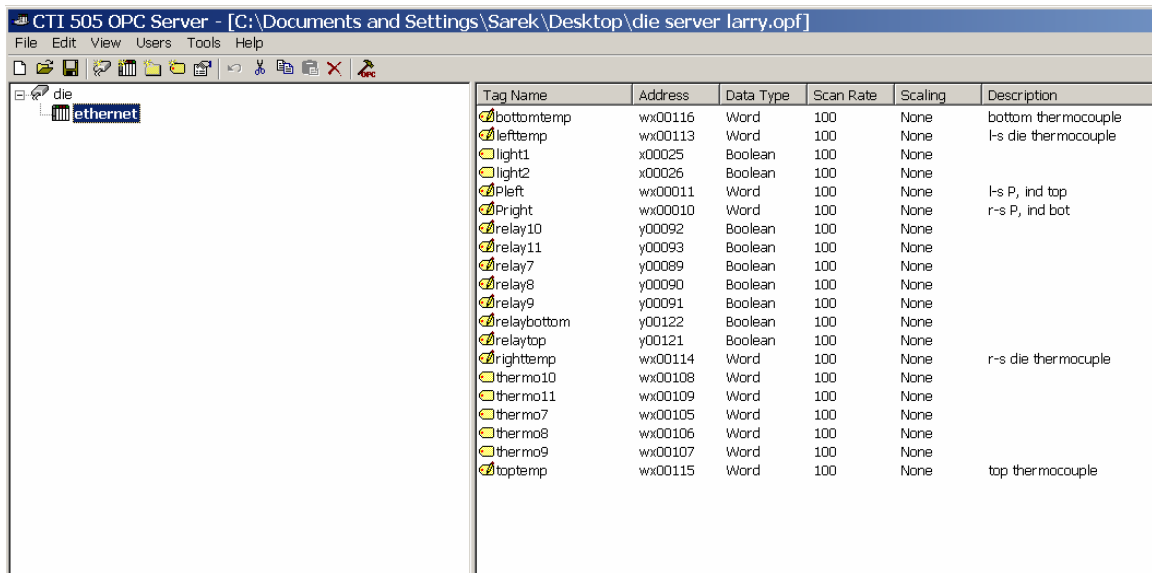


Figure 4.1-4: CTI 505 OPC server *device* properties



Tag Name	Address	Data Type	Scan Rate	Scaling	Description
bottomtemp	wx00116	Word	100	None	bottom thermocouple
lefttemp	wx00113	Word	100	None	l-s die thermocouple
light1	x00025	Boolean	100	None	
light2	x00026	Boolean	100	None	
Plleft	wx00011	Word	100	None	l-s P, ind top
Pright	wx00010	Word	100	None	r-s P, ind bot
relay10	y00092	Boolean	100	None	
relay11	y00093	Boolean	100	None	
relay7	y00089	Boolean	100	None	
relay8	y00090	Boolean	100	None	
relay9	y00091	Boolean	100	None	
relaybottom	y00122	Boolean	100	None	
relaytop	y00121	Boolean	100	None	
righttemp	wx00114	Word	100	None	r-s die thermocouple
thermo10	wx00108	Word	100	None	
thermo11	wx00109	Word	100	None	
thermo7	wx00105	Word	100	None	
thermo8	wx00106	Word	100	None	
thermo9	wx00107	Word	100	None	
toptemp	wx00115	Word	100	None	top thermocouple

Figure 4.1-5: Screenshot of the *die server Larry opf* CTI 505 OPC program

4.2 Shear and Elongational Version 2.0 VI

The shear and elongational version number 2.0 program (V2), *shearandelongationalv2.vi*, builds upon the previous version written by Yizhong Wang. The V2 program utilized the new the hardware interface and OPC server to send and receive variables from the Online Rheological sensor. This allowed V2 to monitor all of the Online Rheological Sensor variables, calculate the shear and elongational viscosities, and control the temperature of the sensor block. The V2 program was also used to communicate with 6-inch melt blowing process line equipment.

Specifying which dies are being used in the Online Rheological Sensor in the V2 virtual instrument is similar to the original *shearandelongational.vi* program. The shear and elongational dies being used within the sensor block are defined by specifying the die geometries on the *front panel*.

The shear rates and elongational strain rates are also defined by the user on the *front panel*. The *shearandelongational.vi* program uses an array of shear rates and elongational strain rates to create viscosity curves plotted against the corresponding shear or elongational rates. However, only one shear rate and one elongational strain rate was

used in the V2 program. Only one shear rate and elongational strain rate was used because only one shear rate or elongational strain rate would exist, based upon the exit die geometry, during a melt blowing process at a constant throughput. This is further discussed in Chapter 5 of this document.

The gear pump speeds for the shear and elongational sides of the Online Rheological Sensor are calculated in the V2 program using the *sub-vi*'s, written by Yizhong Wang,. *Calculate pump speed-E.vi* calculates the gear pump speed for the elongational side of the sensor block based upon the elongational strain rate and Henky number of the hyperbolic die. *Calculate pump speed-S.vi* calculates the gear pump speed for the shear side of the Online Rheological Sensor based upon the shear rate and capillary die length and radius. Each *sub-vi* calculates the RPM set point for the gear pumps by first calculating the volumetric flow rate of a polymer through the die and then dividing the volumetric flow rate by the gear pump displacement. The resulting value for the electric motor RPM is then displayed on the *front panel*, as shown in Figure 4.2-1. The RPM value can then be set on the Motortronics electric motor controller.



Figure 4.2-1: Screenshot of the front panel of the V2 program

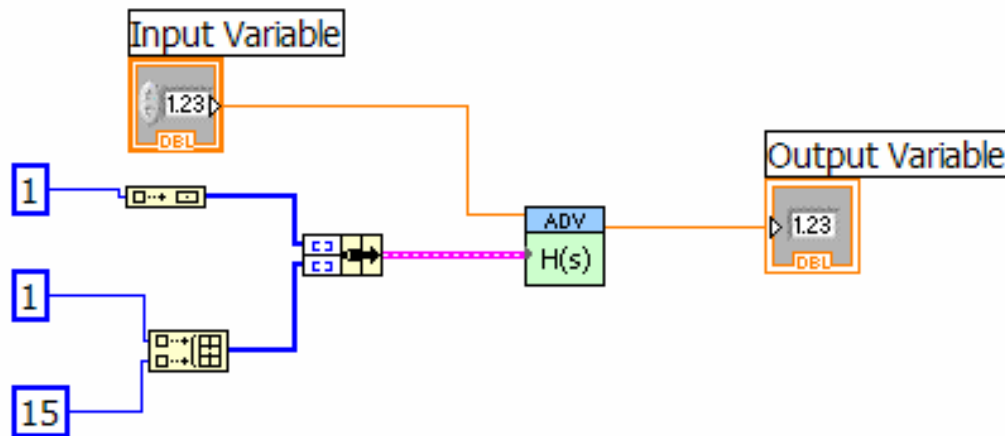


Figure 4.2-4: A 1st Order Lag with a time constant of 15 in LabVIEW

Using an average block temperature allows the heating elements to be controlled with one PID controller. The advantage of using a single PID controller is it treats the system as a single entity and eliminates the interactions associated with multiple controller interference, as seen in the results for the sensor block temperature models in Chapter 3. Ideally, the average temperature would approximately be equal to all of the temperature zones of the sensor block. However, the bottom heating elements are 1000 W heaters and heat the sensor block much faster than the 750 W top heaters. If the PID controller allowed both heaters to heat at the same rate, the bottom of the sensor block would be much hotter than the top and would transfer heat to the top zone, even after the average temperature reached the set point. In order to use a single PID controller with the two different sets of heating elements, the bottom heating elements would need to operate at a fraction of the output that the top heaters operated. Using a trial and error method, the bottom heaters would need to operate at 50% of the top heater output. However, as the top heater outputs approached 10%, the bottom and top heaters would begin to heat at approximately the same rates due to the resolution of the relay output card. The resolution problems associated with the relay output card were countered in two ways. First, the PID output was rounded to the nearest 5% (0, 5, 10,...,45, 50). Second, a logic

statement was added to the bottom heater portion of the control loop that did not allow the bottom heating elements to heat if the top heater output was below 10%. Rounding the output of the PID and not allowing the bottom heaters to heat below a set percentage allowed the control system to oscillate about the temperature set point (plus or minus 1°C). If tighter temperature control is desired, a system with a better resolution will be needed.

The output range for the PID controller was set to be between 0 and 50%. The output range represents a duty cycle percentage with a maximum heating value of 50%. The maximum heater output was regulated due to the fast temperature response of the sensor block. The output of the PID controller was connected to the duty cycle input of the *squarewaveform.vi* function. The *squarewaveform.vi* converts the duty cycle percent into a percentage of 1's in a cycle of 1's and -1's. For example, a 40% duty cycle would translate to [1 1 -1 -1 -1] using the *squarewaveform.vi* function. The *squarewaveform.vi* function outputs a 2-D array that is based upon sample time and the number of elements. Using a set of *for loops*, the individual elements, 1's or -1's, in the array can be read before the next cycle begins. In V2, the PID controller and *squarewaveform.vi* were set up to operate once every second and the *squarewaveform.vi* was set up to write 5 elements per second. The individual elements of the array controlled the output of the heaters relays. A value of 1 translates into a Boolean value of "TRUE", which turns the heater relays ON. In contrast, a value of -1 translates into a Boolean value of "FALSE", which turns the heater relays OFF.

The V2 program can also be used to control the 6-inch melt blowing die at TANDEC (see Chapter 5) at the University of Tennessee. The PID controllers for the 5 heating zones are located within the *block diagram* of the V2 program. The thermocouple readings from the 5 temperature zones are interfaced with the V2 program and are shown on the *front panel* using digital indicators and a chart. The V2 program can use the thermocouple data and a temperature set point to control the Watlow mercury displacement relays that control the heating elements for the 6-inch die. The control set-up for the 6-inch die is a prototype design and needs to be adjusted and properly tuned.

The PID controller in the V2 program, as shown in Figure 4.2-5, was tuned by trial and error using a step change from approximately 23°C to 220°C. The temperature set point was defined on the *front panel* of the V2 program. The average temperature response was monitored and the proportional, integral, and derivative values were adjusted until the response was controlled. The derivative term was added to the tuning of the sensor block, even though it was omitted in the response modeling in Chapter 3. The derivative parameter of the PID controller helped limit the temperature overshoot of the sensor block by adding a “braking” action. A proportional gain (K_c) of 5.0, an integral time (T_i) of 5.0 minutes, and a derivative time (T_d) of 0.75 minutes was used to tune the sensor block. Figure 4.2-6 shows the controlled response of a step change in sensor block temperature.

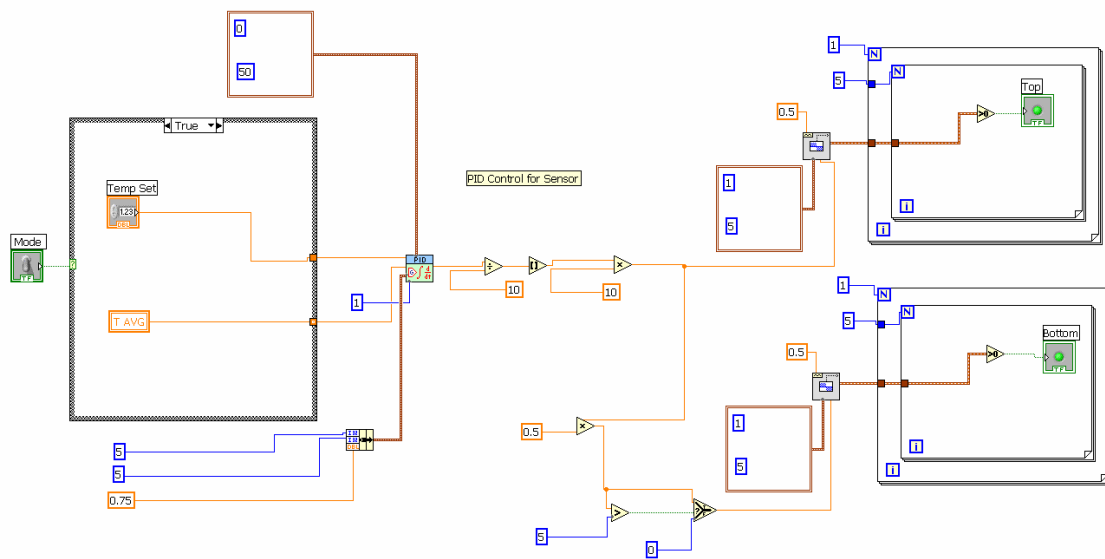


Figure 4.2-5: The PID structure to control the sensor relay outputs

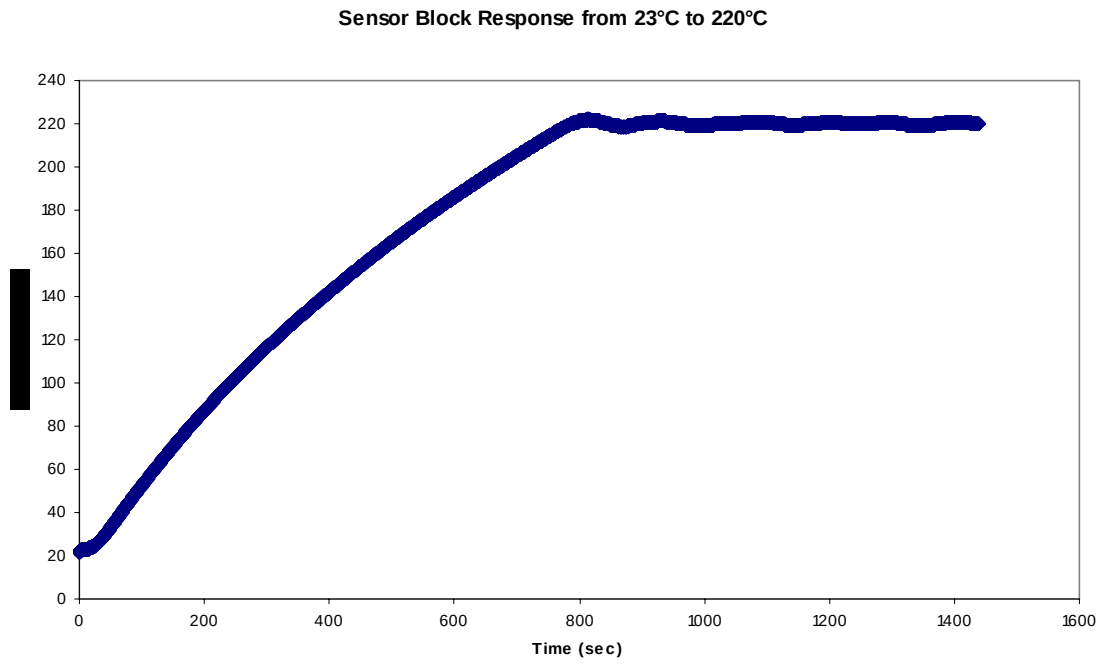


Figure 4.2-6: Sensor block response to a step change from 23°C to 220°C

5.0 Future Work

The goal of this research and for future research was to use the Online Rheological Sensor to monitor and control the shear and elongational viscosities of a polymer processing line. In order for the Online Rheological Sensor to be used to monitor a polymer processing line for feedback control, the sensor and the processing line must operate under the same polymer processing conditions. If the Online Rheological Sensor has the exact processing conditions as a main polymer process line, then the sensor would become a “clone” of that main line, meaning the polymer viscosities calculated by the sensor and the polymer viscosities exiting the main line would be equal. The TANDEC 6-inch MB line was an ideal choice to continue this research. The *shearandelongationalv2.vi* program already takes steps toward achieving that goal by its ability to communicate with portions of the TANDEC 6-inch MB line process equipment.

5.1 TANDEC 6-inch MB Pilot Line

The Textiles and Nonwovens Development Center (TANDEC) at the University of Tennessee provides pilot lines and testing facilities for polymer research, process improvement, and applications development for advancements in nonwoven technologies. TANDEC currently provides the following pilot lines to academic, industrial, and government organizations: (1) 1-meter wide Reicofil Spunbond Pilot Line, (2) 20-inch wide Accurate Products Melt Blowing Pilot Line, (3) 500mm Reifenhäuser Melt Blowing Pilot Line with Bicomponent Fiber Technology, and (4) 6-inch Melt blowing Pilot Lines (<http://tandec.utk.edu>).

The 6-inch melt blowing pilot line located at TANDEC, as shown in Figure 5.1-1, was used to test the new Online Rheological Sensor control scheme. The 6-inch melt blowing pilot line can process polymers at a maximum air temperature of 400°C and a maximum melt temperature of 425°C at the die. The 6-inch line can be used to collect the nonwoven polymer product at a maximum rate of 45 meters per minute. The 6-inch melt blowing pilot line TANDEC currently provides six different dies and eight different air knives for the 6-inch melt blowing line (<http://tandec.utk.edu>).



Figure 5.1-1: The TANDEC 6-inch pilot line (photo by Chris Eash)

5.2 Calculations for Future Work

The Online Rheological Sensor could be used to calculate the viscosity of a polymer exiting a processing line. The Online Rheological Sensor could be mounted at the end of the Leistritz twin-screw extruder and the other face of the sensor could attach to the TANDEC 6-inch MB pilot line die. If the physical and processing conditions of the Online Rheological Sensor were equal to the conditions within the 6-inch die, the sensor would then become a “clone” of the 6-inch die. Therefore, the polymer viscosity produced by the Online Rheological Sensor would match the polymer viscosity of the 6-inch die.

In order for the Online Rheological Sensor to become a “clone” of the 6-inch MB die, the ratio of the online and offline variables must be equal. The holes of the 6-inch die

are cylindrical in shape, so the capillary die would be used in the Online Rheological Sensor to match the two shear viscosities. The shear viscosity of the sensor and the 6-inch die are derived from equation 2.2.1-4 and are shown equation 5.2-1 and equation 5.2-2

$$\eta_{ss} = \frac{\tau_s}{\dot{\gamma}_s} \quad (5.2-1)$$

$$\eta_{sd} = \frac{\tau_d}{\dot{\gamma}_d} \quad (5.2-2)$$

where the subscript *s* indicates the sensor and the subscript *d* indicates the 6-inch die. The goal is for the shear viscosity of the sensor and the shear viscosity of the 6-inch die to be equal, therefore equation 5.2-1 and equation 5.2-2 can be set equal to one another

$$\frac{\tau_s}{\dot{\gamma}_s} = \frac{\tau_d}{\dot{\gamma}_d} \quad (5.2-3)$$

One method to set up the sensor and the 6-inch die so that equation 5.2-3 would apply is to first manipulate the two shear rates so that they are equal to one another and then manipulate the two shear stresses so that they are equal. The shear rate for the sensor and the 6-inch die are derived from equation 1 and are shown in equation 5.2-4 and equation 5.2-5

$$\dot{\gamma}_s = \frac{4Q_s}{\pi R_s^3} \quad (5.2-4)$$

$$\dot{\gamma}_d = \frac{4Q_d}{\pi R_d^3} \quad (5.2-5)$$

where Q_d would be the volumetric flow rate per hole. A set production rate for the 6-inch MB pilot line and the geometry for the 6-inch die define the shear rate for the 6-inch die. The polymer shear rate at the 6-inch die would be equal to the shear rate at the sensor by selecting a capillary die with any radius and adjusting the gear pump speed to produce the appropriate volumetric flow rate.

A mass balance and a calibration relating screw rotational speed to mass flowrate (for the Leistritz twin-screw extruder) could be used to establish a set production rate. A mass balance about the extrusion line is shown in equation 5.2-6

$$Total\ Mass = Mass\ Out\ of\ 6-Inch\ Die + Mass\ Out\ of\ Sensor\ Die . \quad (5.2-6)$$

For a set production rate, the mass and volumetric flow rate of polymer exiting the 6-inch die is fixed. Based upon having equal shear rates for a given cylindrical die, the mass or volumetric flow rate for the sensor is set. Knowing the total mass, the Leistritz TSE RPM can be set using an rotational speed to mass flow rate calibration curve, as shown in Figure 5.2-1.

If the shear rate at the sensor and the shear rate at the 6-inch die are equal, then the shear viscosity of the polymer at both locations would be equal if the shear stresses were the same. The shear stress for the sensor and the 6-inch die are derived from equation 5 and are shown in equation 5.2-7 and equation 5.2-8

$$\tau_s = \frac{R_s \Delta P_s}{2L_s} \quad (5.2-7)$$

$$\tau_d = \frac{R_d \Delta P_d}{2L_d} . \quad (5.2-8)$$

Similar to the shear rate calculations, the two shear stresses are set to equal one another. Then, the change in pressure at the 6-inch die can be solved for by rearranging the two equations, as shown in equation 5.2-9

$$\left(\frac{R_s}{R_d} \right) \left(\frac{L_d}{L_s} \right) \Delta P_s = \Delta P_d . \quad (5.2-9)$$

Currently, the pressure at the 6-inch die is not known. If a pressure transducer was added to the 6-inch die, it could be used to verify if the change in pressure at the 6-inch die matched the change in pressure calculated from equation 5.2-9. However, if the change in pressure at the 6-inch die did not match the calculated value, a capillary die with a different geometry could be used to ensure the shear stresses matched. The geometry of the capillary die to use in the sensor could be determined by rearranging equation 5.2-9 to form equation 5.2-10

$$\left(\frac{R_s}{R_d} \right) \left(\frac{\Delta P_s}{\Delta P_d} \right) L_d = L_s . \quad (5.2-10)$$

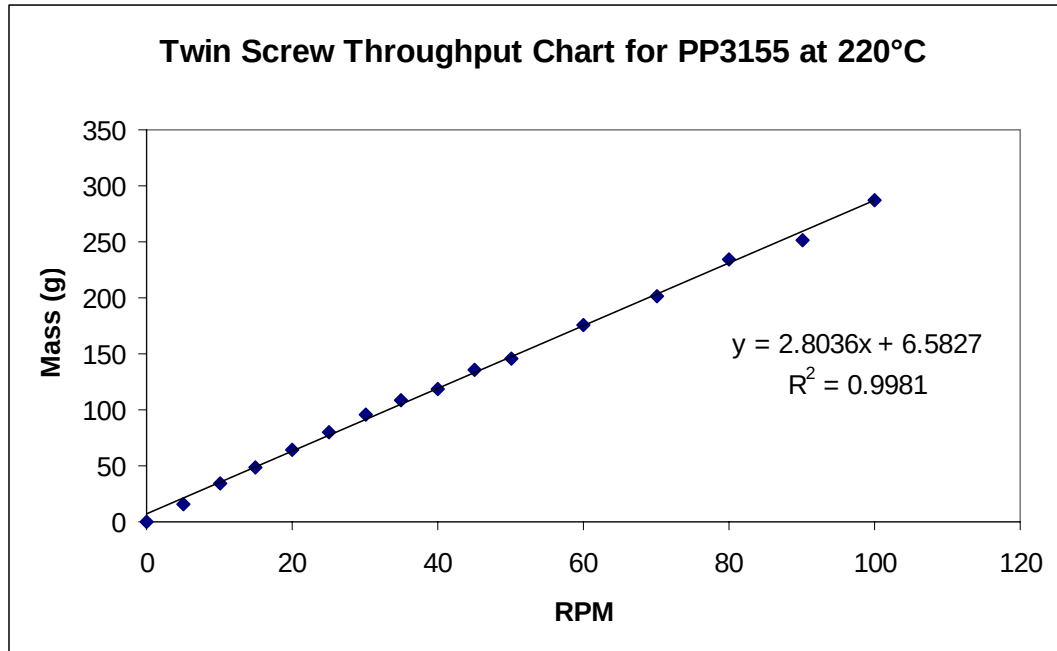


Figure 5.2-1: Leistritz TSE RPM for a given mass using PP3155 at 220°C

Equation 5.2-10 represents one method of changing the capillary die geometry to allow the shear stress at the sensor and the 6-inch die to match. Any combination of changing the die geometries and maintaining the appropriate shear stress would be valid. However, if the radius of the capillary die were to change, the volumetric flow rate through the sensor would also need to change in order to maintain equal shear rates (see eqn 2.2.1-1).

5.3 Shear and Elongational VI Upgrades

The *shearandelongationalv2.vi* program was designed to handle a number of changes that would be needed for future work. The V2 program has several switches located on the *front panel* (see Figure 4.2-1), with corresponding *block diagram* structures, that were not used in this research, but could be integrated into future work.

The first upgrade for the V2 program would be the ability to switch “modes” during program usage. The V2 program is currently written to monitor the shear and elongational viscosities of the Online Rheological Sensor, while maintaining a temperature set point. The “mode” switch could be used to acquire a steady state shear or elongational viscosity and use that value as a viscosity set point for a cascade control

loop. Under the “Acquire SS Value” mode, the V2 program would monitor the shear viscosity and elongational viscosities, while maintaining a temperature set point defined by the user. In this mode, the calculation of the shear and elongational portions of the V2 program have a *S-Vis* and *E-Vis* variable, as shown in Figure 4.2-2 and Figure 4.2-3. At steady state, the user would flip the “mode” switch over to the “control” setting. The “control” setting would allow the program to calculate the shear and elongational viscosities, but the *S-Vis* and *E-Vis* variables would no longer be calculated. The *S-Vis* or the *E-Vis* variable then would become the viscosity set point for a cascade control loop. The cascade control loop would then consist of a viscosity control outer loop and a temperature control inner loop. Now the V2 program would be able to adjust the sensor block temperature, based upon viscosity feedback, to maintain a constant viscosity.

A second upgrade for the V2 program would be the ability to switch the “viscosity control mode” from “automatic” to “manual” for the cascade control loop. In “automatic” mode, the set point for the viscosity portion of the cascade control loop would be the value from the “Acquire SS Value” mode. In “manual” mode, the user would be able to change the viscosity set point for the control loop on the *front panel*, instead of using the value for the “Acquire SS Value” mode. Figure 5.3-1 and Figure 5.3-2 show the *block diagram* structures that would allow the user to choose which method is used to define the viscosity set point.

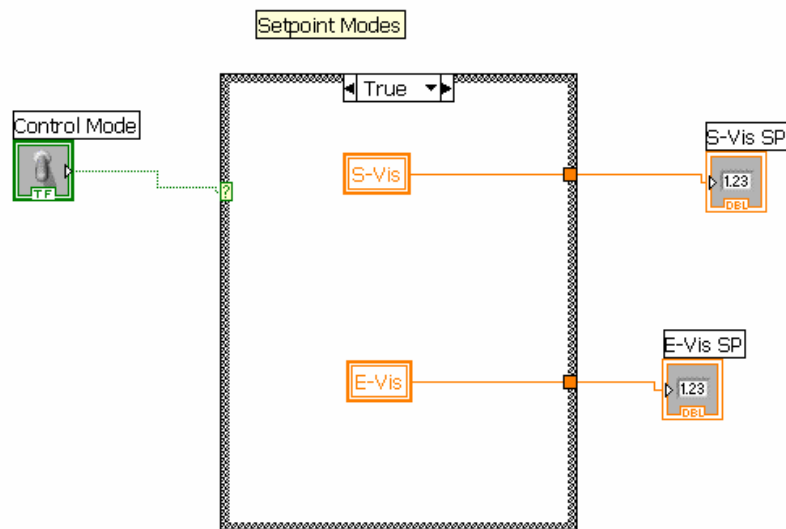


Figure 5.3-1: Acquiring a viscosity set point in “automatic” mode

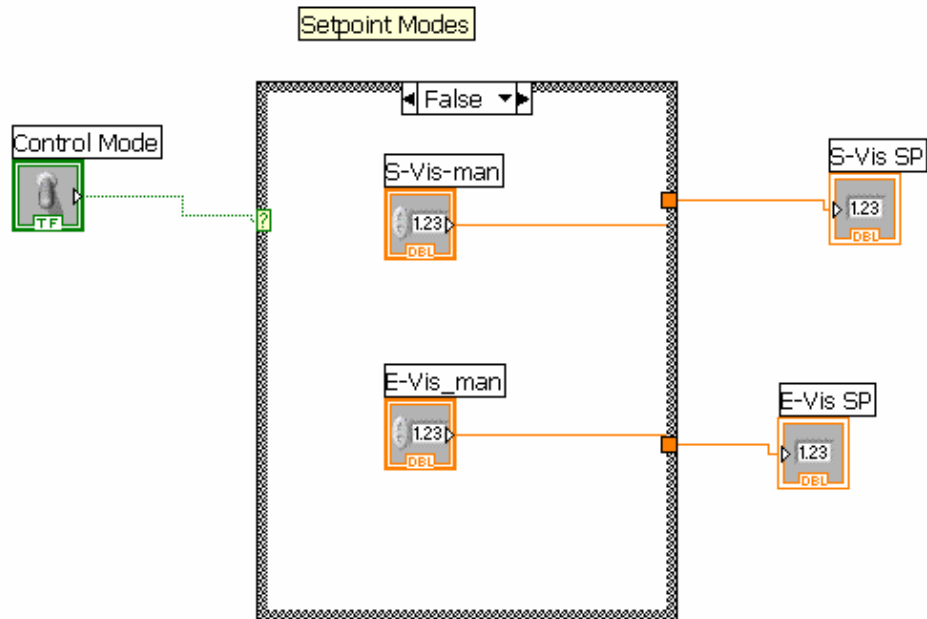


Figure 5.3-2: Acquiring a viscosity set point in “manual” mode

5.4 Expanding the Interface

The ultimate goal of this research is to be able to control and possibly automate a MB processing line using the Online Rheological Sensor. The V2 program is currently interfaced to control the temperatures of the 6-inch die. The V2 program could be used to change the temperature of the 6-inch die based upon temperature changes of the Online Rheological Sensor. The Siemens Series 505 PLC and CTI OPC server could also be used to communicate with the other processing line equipment as well. LabVIEW subroutines could be written that would utilize the Siemens PLC to control the electronic motors that turn the gear pumps on the sensor, control the extruder screw speed, and read pressures from the 6-inch die.

References

References

- Bansal, Vishal; Shambaugh, Robert L. On-line Determination of Diameter and Temperature during Melt Blowing of Polypropylene. *Ind. Eng. Chem. Res.* **1998**. 37, 1799-1806.
- Bernhardt, Ernest C. *Processing of Thermoplastic Materials*. Robert E. Krieger Publishing Company, **1959**.
- Chen, Hongbing; Sundararaj, Uttandaraman; Nandakumar, K. Investigation of the Melting Mechanism in a Twin-Screw Extruder Using a Pulse Method and Online Measurement. *Ind. Eng. Chem. Res.* **2004**. 43, 6822-6831.
- Collier, John R.; Romanoschi, Ovidiu; Petrovan, Simioan. Elongational Rheology of Polymer Melts and Solutions. *Journal of Applied Science*. **1998**. 69, 2357-2367.
- Control Technology, Inc. *CTI 505 OPC Server Help Files*.
- Essick, John. *Advanced LabVIEW Labs*. Prentice-Hall, Inc. **1999**.
- Goff, John; Whelan, Tony. *The Dynisco Extrusion Processors Handbook*. 2nd Ed.
- <http://tandec.utk.edu>, Textiles and Nonwovens Development Center at the University of Tennessee, **2005**.
- Krutka, Holly M.; Shambaugh, Robert L.; Papavassiliou, Dimitrios V. Effects of Temperature and Geometry on the Flow Field of the Melt Blowing Process. *Ind. Eng. Chem. Res.* **2004**. 43, 4199-4210.
- Leistritz Extruder *Micro 27 User's Manual*.

Malkan, Sanjiv R.; Wadsworth, Larry C. A Review on Melt Blowing Technology
Part 1. *INB Nonwovens*. **1991**. 2/91, 46-52.

Marla, Vishnu T.; Shambaugh, Robert L. Modeling of the Melt Blowing Performance
Slot Dies. *Ind. Eng. Chem. Res.* **2004**. 43, 2789-2797.

Marla, Vishnu T.; Shambaugh, Robert L. Three-Dimensional Model of the Melt Blowing
Process. *Ind. Eng. Chem. Res.* **2003**. 42, 6993-7005.

Motortronics, *The Ideal AC Drive*. Motortronics. AC Drive Datasheet.

National Instruments, *LabVIEW Introduction Three Hour Version 7 Slides*. **2003**.

National Instruments, *LabVIEW User Manual*. **2003**.

National Instruments, *NI-Serial User Manual*. **2003**.

Omega, *i-Series Temperature & Process Controller Manual*.

Siemens Simatic 505 *Analog I/O Modules User Manual*. **1998**.

Siemens Simatic 505 *Ethernet TCP/IP Communication Processor User Manual*. **1996**.

Siemens Simatic 505 *Input/Output Modules User Manual*. **1994**.

Siemens Simatic TI505 *Thermocouple Input Module User Manual*. **1994**.

Siemens Simatic TI545/TI555 *System Manual*.

Tate, Brian D.; Shambaugh, Robert L. Temperature Fields below Melt-Blowing Dies of Various Geometries. *Ind. Eng. Chem. Res.* **2004**. 43, 5405-5410.

Wang, Yizhong. Application of Polymer Rheology in Melt Blowing Process and Online Rheological Sensor. Ph. D dissertation, University of Tennessee, **2004**.

Yin, Hong; Yan, Zanyao; Ko, Wen-Chien; Bresee, Randall. Fundamental Description of the Melt Blowing Process. *Industrial Nonwovens Journal*. **2000**. Winter 25-28.

Appendix

Appendix A

A.1 Win-Tech Modbus Server Installation

The following is a summary of the mbOPCsvr *Help* file explaining how to install mbOPCsvr on a Windows 2000 machine:

1. Check the PC's SYSTEM32 directory for the two files *opccomm_ps.dll* and *opcproxy.dll*. If the two files are present, proceed to step 2. If the two files are not present, download *OPC Core Components 2.0 Redistributable 2.20*. The download is free from the OPC foundation website, www.opcfoundation.org.
2. Once *opccomm_ps.dll* and *opcproxy.dll* are in the SYSTEM32 directory, click the *START* button and highlight *RUN*. Type "REGSVR32 opccomm_ps.dll" and click OK. Now type "REGSVR opcproxy.dll".
3. Check the computer for a file called *actxprxy.dll*. If this file is not present, download *APRXDIST.EXE* and run the application.
4. Download the *OPCENUM.zip* file. Unzip the file and copy *OPCENUM.EXE* to the Windows Directory. Type "OPCENUM /RegServer" on the *RUN* window command line.
5. On the *RUN* window command line, type "mbOPCsvr /RegServer" to register the mbOPCsvr application.
6. Now, type "mbOPCsvr /Service" on the command line.
7. Copy *SRVANY.EXE* to the PC and install the as a service by typing "INSTSRV WinTECH.Modbus_OPC_Server **file name**\svrany.exe". **File name** represents the folder in which *SRVANY.EXE* is installed. From experience, it is easier to place all of the Win-Tech OPC server files and *SRVANY.EXE* in the same directory. An example of a good **file name** containing all of the server files is "c:\tools\".
8. Type "REGEDIT32.EXE" to run the computer *Registry Editor*. Goto the Win-Tech Modbus server file under "HKEY_LOCAL_MACHINE\SYSTEM\CurrentControlSet\Services". Create a *parameters* key. Type REG_SZ **file name**\mbOPCsvr.exe.

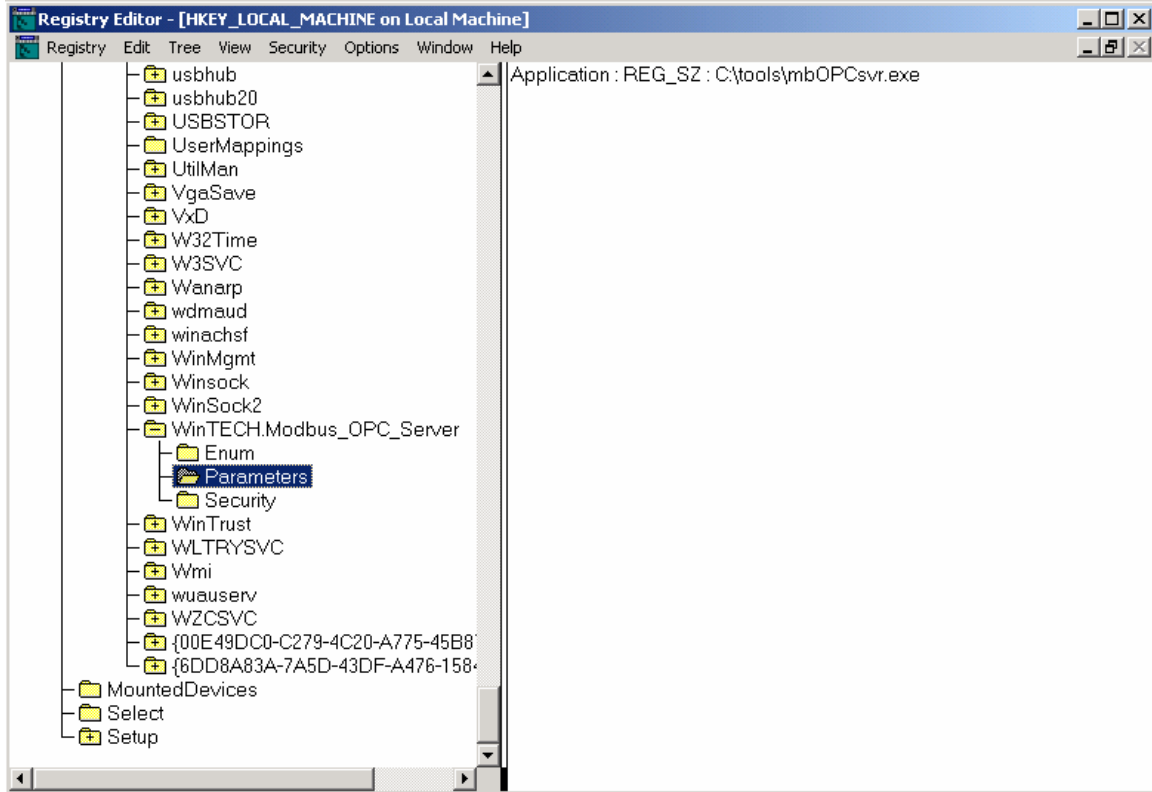


Figure A-1: The Win-Tech OPC server in the Registry Editor of the laptop

A.2 Port Configuration for Win-Tech Server

The National Instruments USB to RS-485 communication port properties must be set properly in order for the device to operate correctly. The following are instructions to properly configure the NI serial ports for a Windows 2000 machine (NI Serial Manual, 4-3):

1. Plug in the USB to RS-485 via the USB port.
2. Goto the computer's *control panel*. Click the *system* icon. Got the *Hardware* tab and open the *device manager*.
3. Click the plus sign on the *Ports (COM & LPT1)* tab. This shows the available communication ports. If the NI USB to RS-485 is not shown, try reinstalling the drivers and replugging in the device. Figure A-2 shows an example of the port availability.

4. Right-click one of the NI USB to RS-485 ports and click on *properties*. The baud rate, data bits, parity, stop bits, and flow control must be properly set. Figure A-3 shows the proper setting for the sensor for this research.
5. Click the *Advanced* button. The *COM* port number and transceiver mode can be set in this window. Figure A-4 shows the proper setting for the sensor for this research.

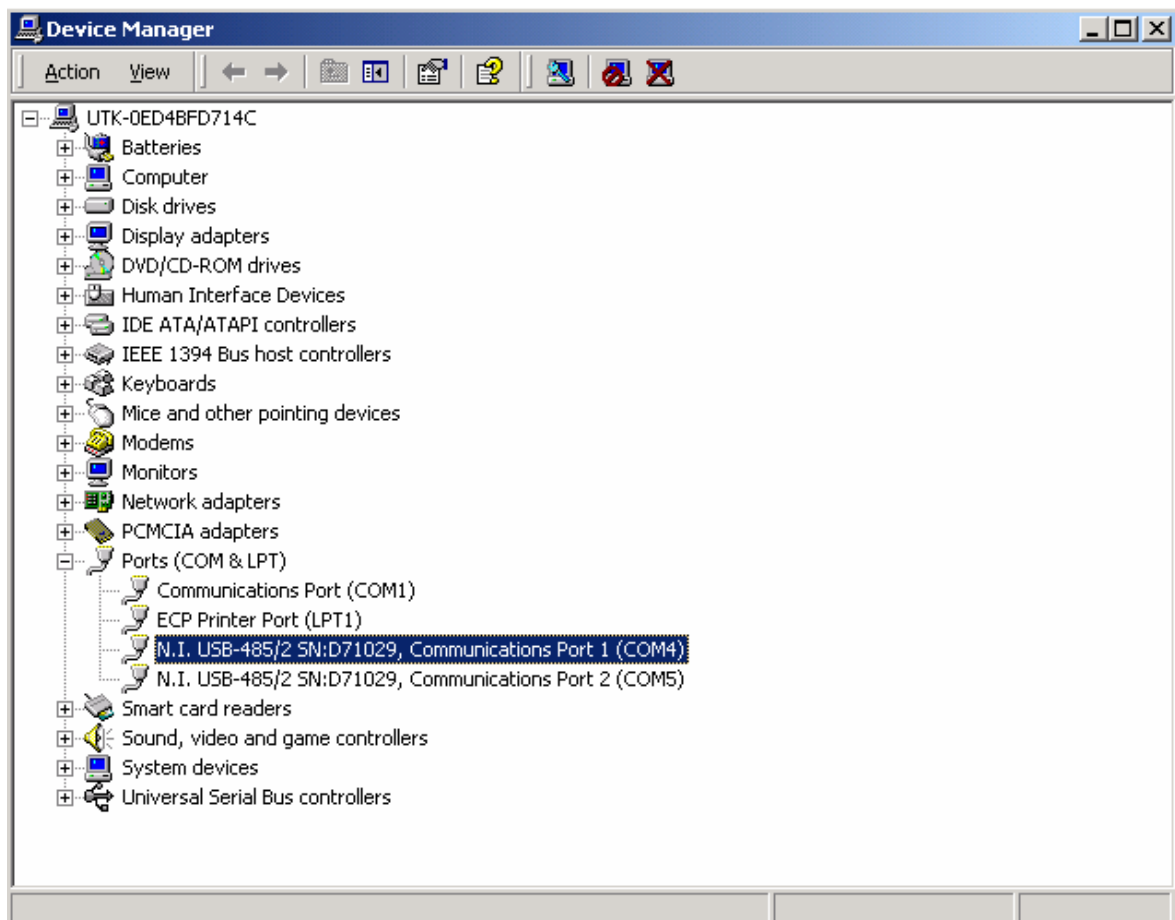


Figure A-2: Port availability on laptop computer after the Win-Tech OPC server is Installed

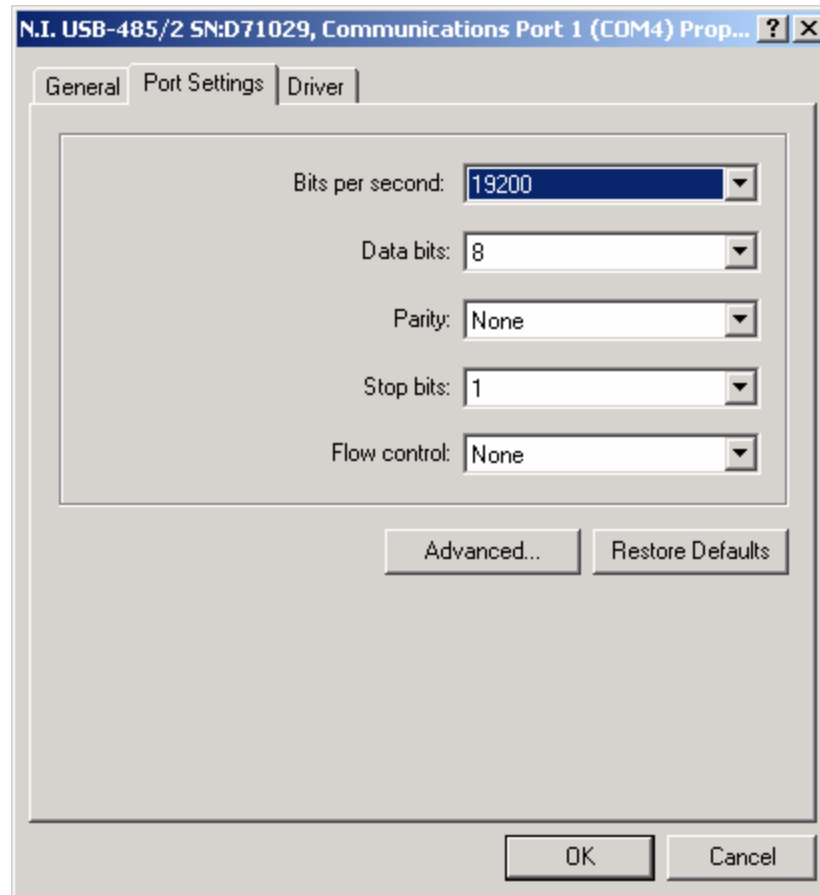


Figure A-3: Port configuration properties to use with Win-Tech OPC server

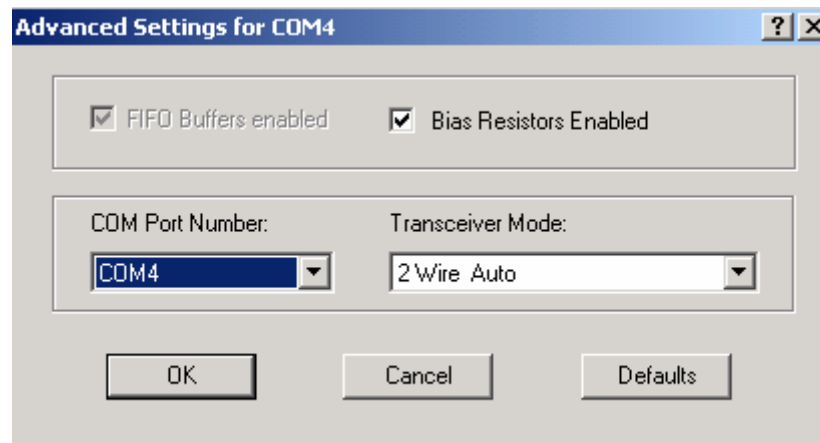


Figure A-4: Advanced port settings to use with Win-Tech OPC server

A.3 DataSocket Connections

National Instrument's LabVIEW uses a *DataSocket* connection to write or read data from devices on an OPC server. *DataSocket* connections can easily be created in LabVIEW after all of the devices are connected and an OPC server has been installed. The following are instructions explaining how to create a *DataSocket* connection in LabVIEW:

1. Open the LabVIEW VI that will be used to communicate with the attached devices.
2. Locate the control or indicator that will be used to publish or subscribe data, respectively. The control or indicator icon can either be located on the front panel or block diagram.
3. Right-click the icon and place the mouse cursor over *Data Operations*. Now move the cursor over *DataSocket Connection* and click on it.
4. A *DataSocket Connection* window will open. In the window, the connection type can be specified as publish (write), subscribe (read), or both.
5. Type the device connection address in the *DataSocket Connection* window. If the connection address is not known, click the *Browse* button. Highlight and click *Browse Measurement data*.
6. A window will appear showing all of the available servers on the computer. The "WinTECH.Modbus_OPC_Server" was one of the servers used for this research. Click on the *plus* icon to view all of the available addresses for the Win-Tech server. Now click on the appropriate address.

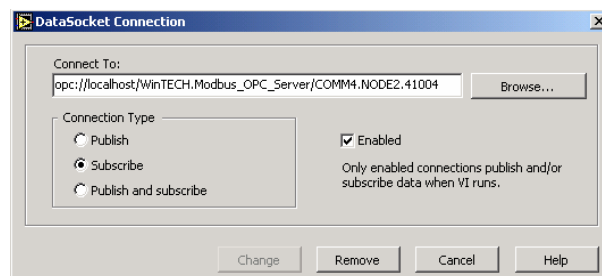


Figure A-5: DataSocket Connection window

Appendix B

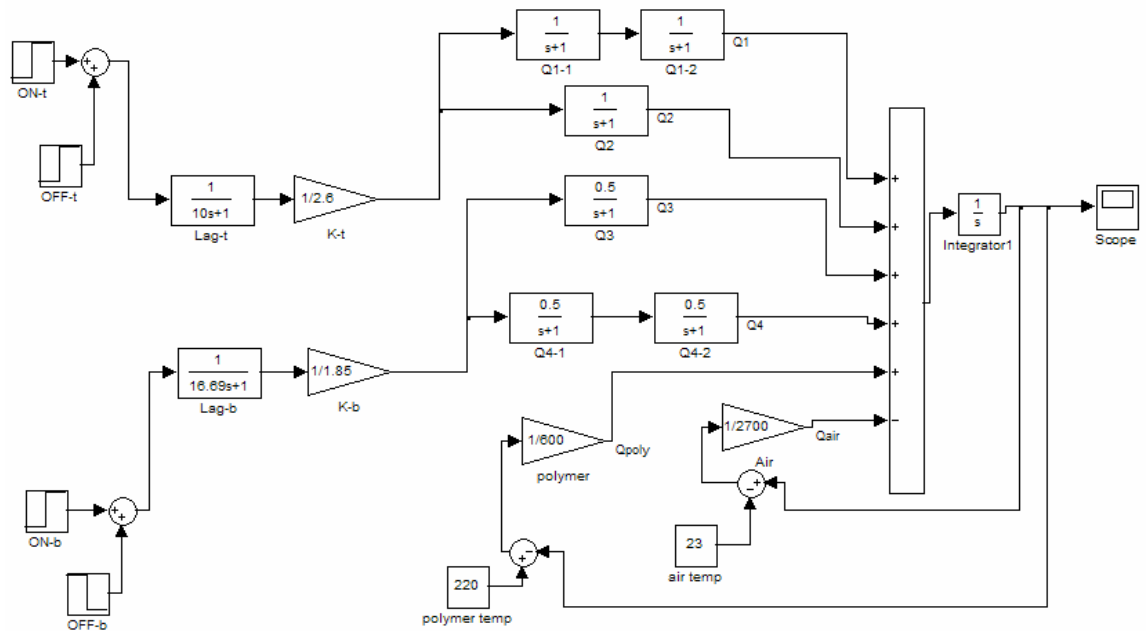


Figure B-1: Simulink block structure for the elongational side of the sensor block for Run #3

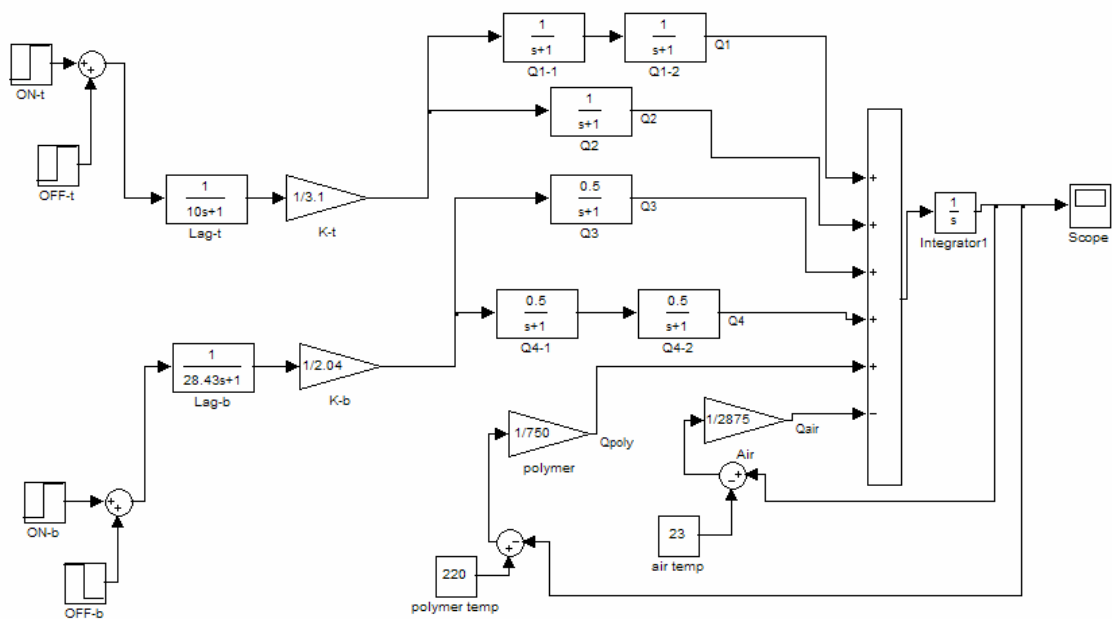


Figure B-2: Simulink block structure for the shear side of the sensor block for Run #3

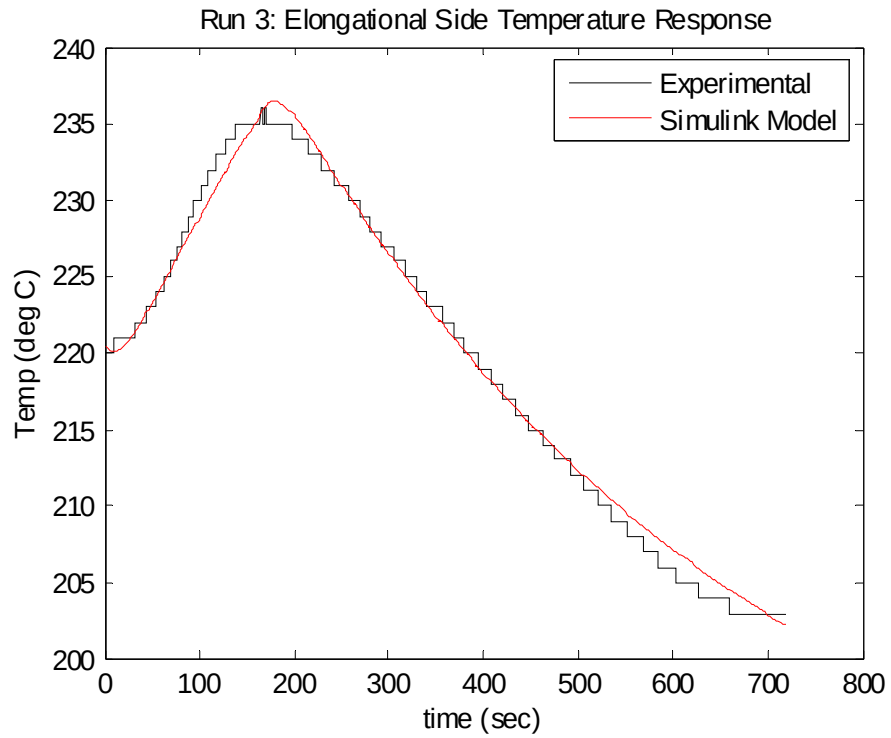


Figure B-3: Simulink model of the elongational side of the sensor block for Run #3

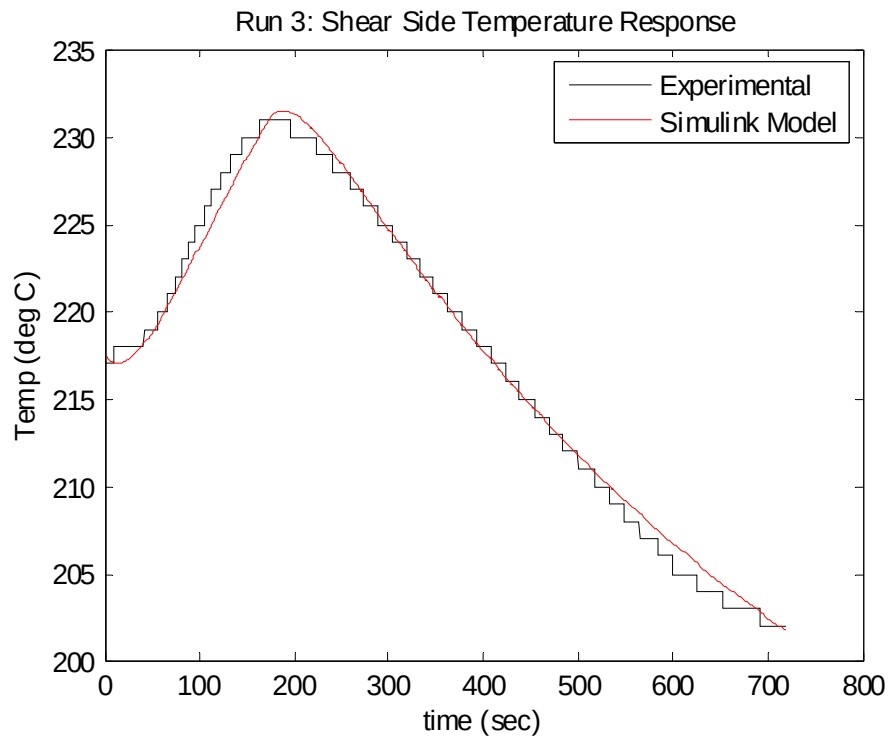


Figure B-4: Simulink model of the shear side of the sensor block for Run #3

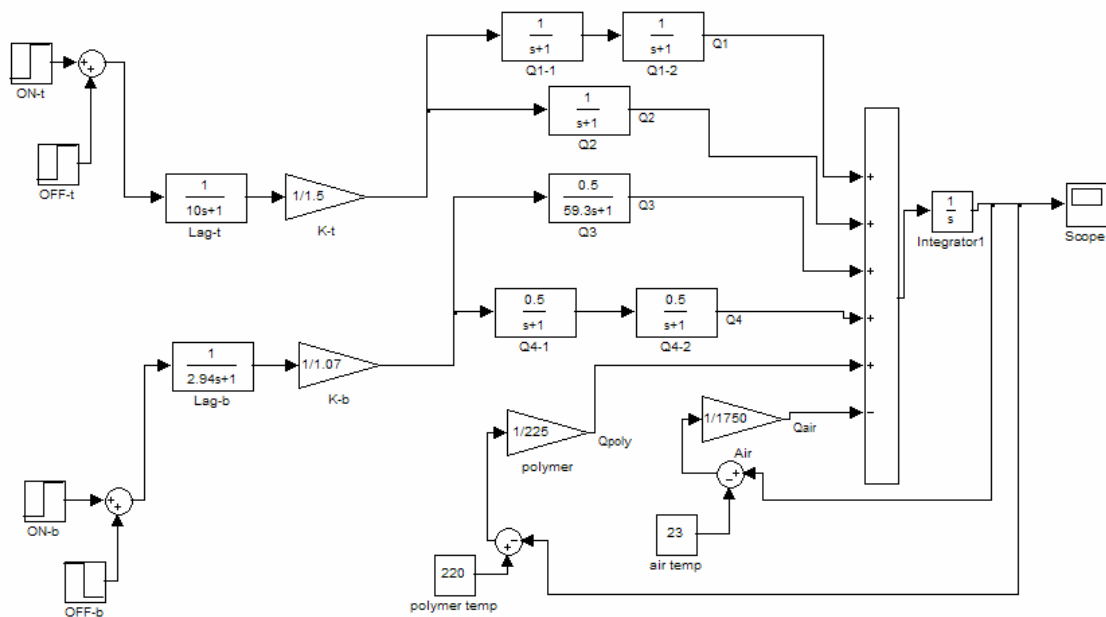


Figure B-5: Simulink block structure for the elongational side of the sensor block for Run #4

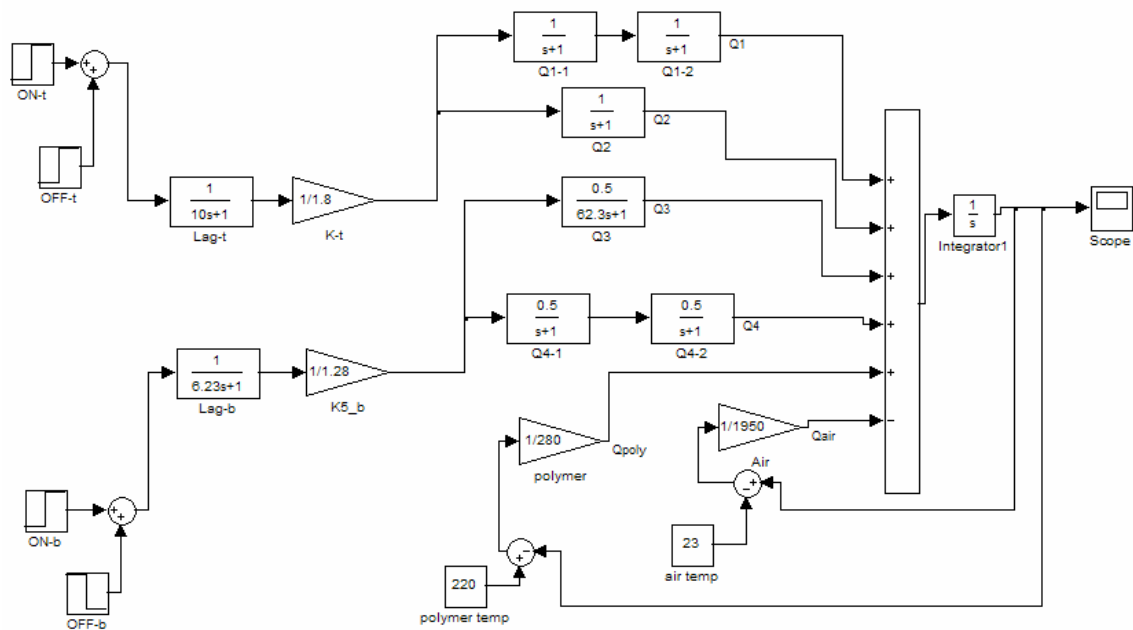


Figure B-6: Simulink block structure for the shear side of the sensor block for Run #4

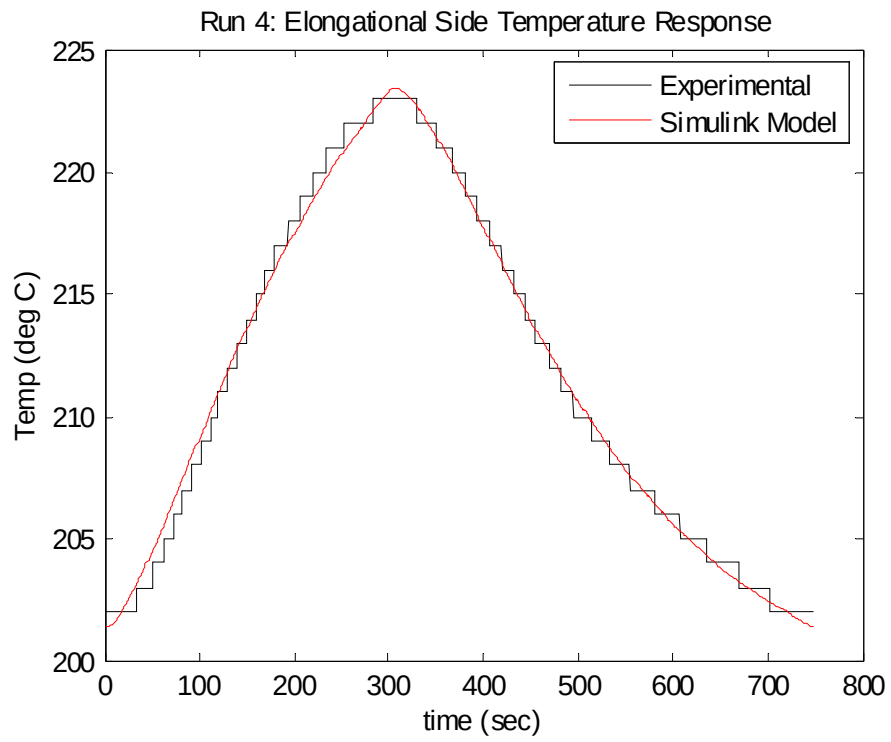


Figure B-7: Simulink model of the elongational side of the sensor block for Run #4

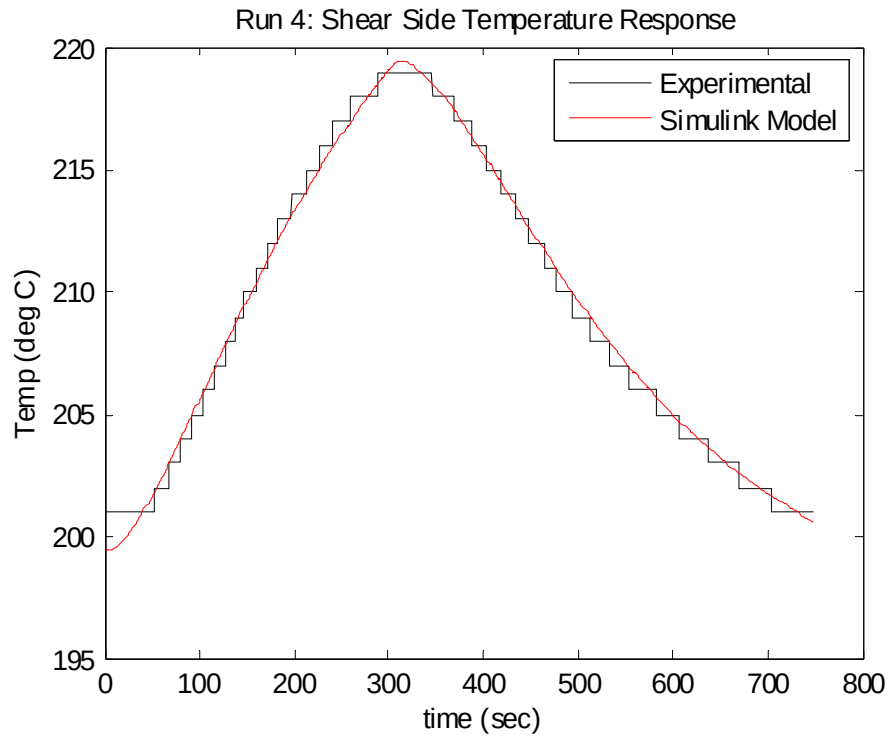


Figure B-8: Simulink model of the shear side of the sensor block for Run #4

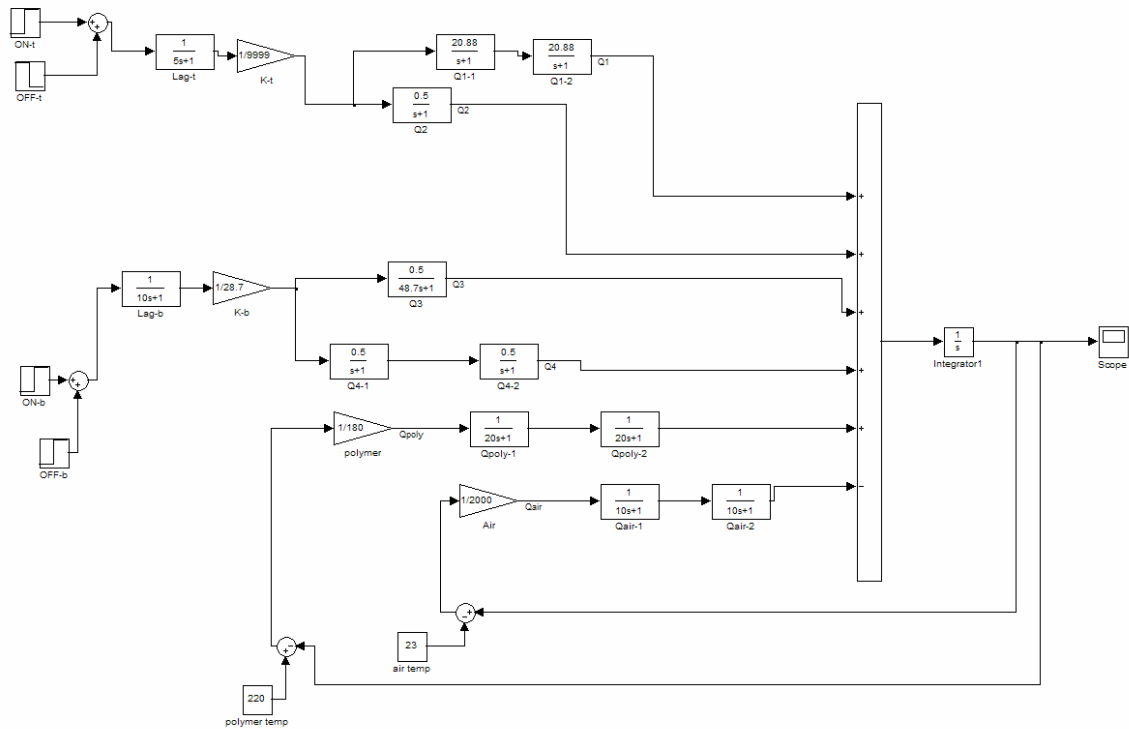


Figure B-9: Simulink block structure for the elongational side of the sensor block for Run #5

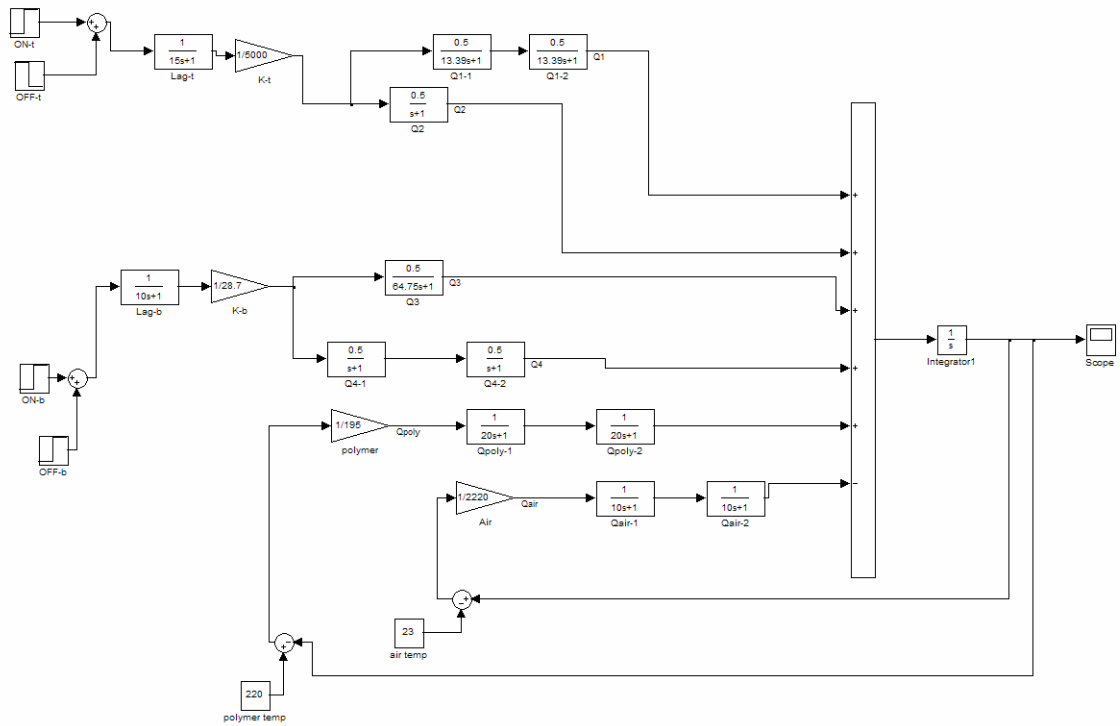


Figure B-10: Simulink block structure for the shear side of the sensor block for Run #5

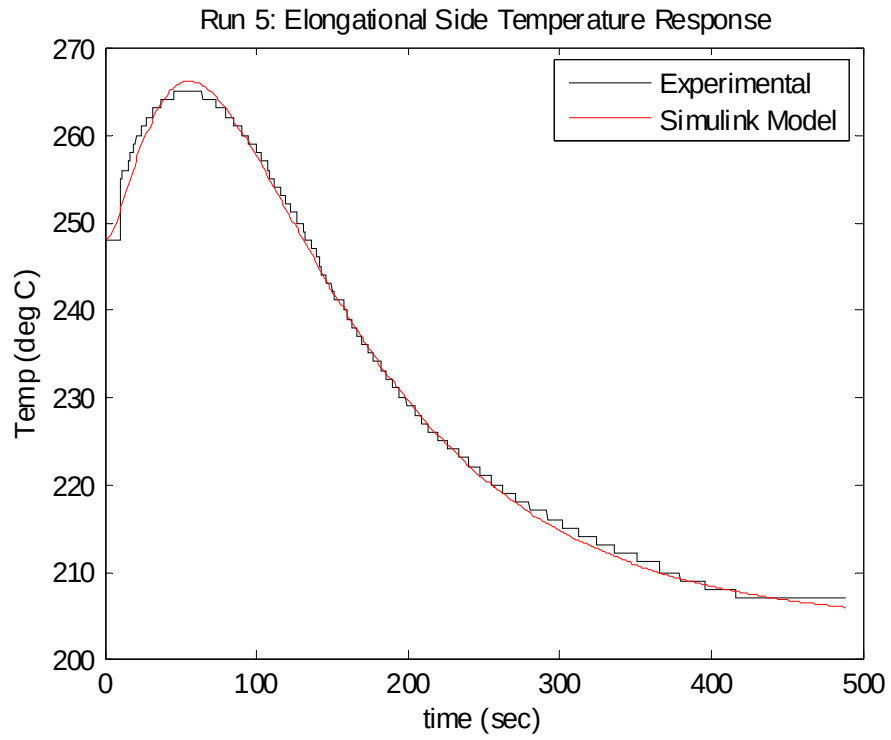


Figure B-11: Simulink model of the elongational side of the sensor block for Run #5

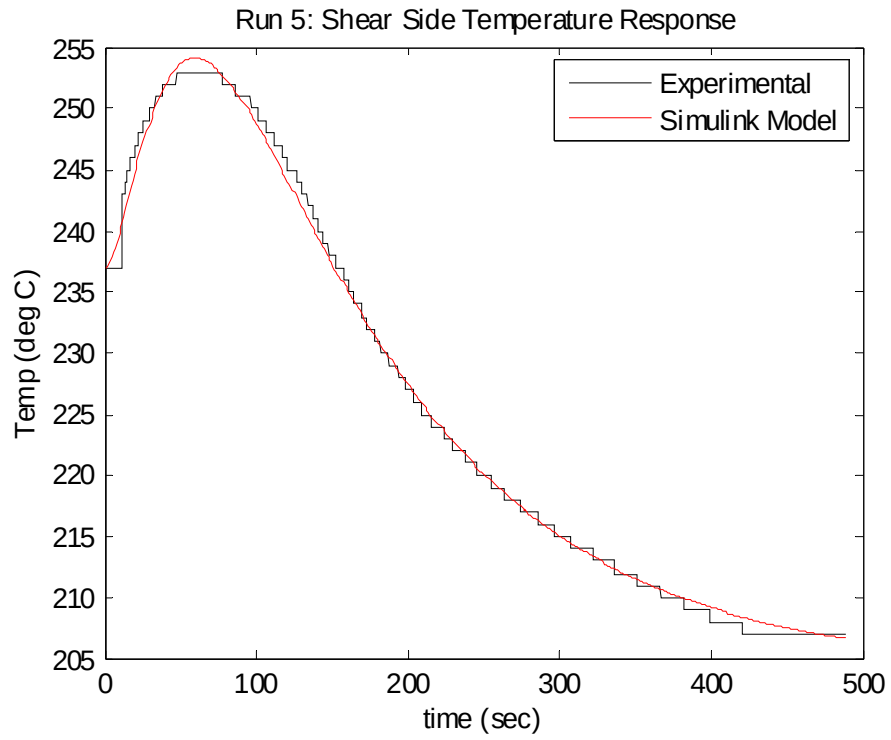


Figure B-12: Simulink model of the shear side of the sensor block for Run #5

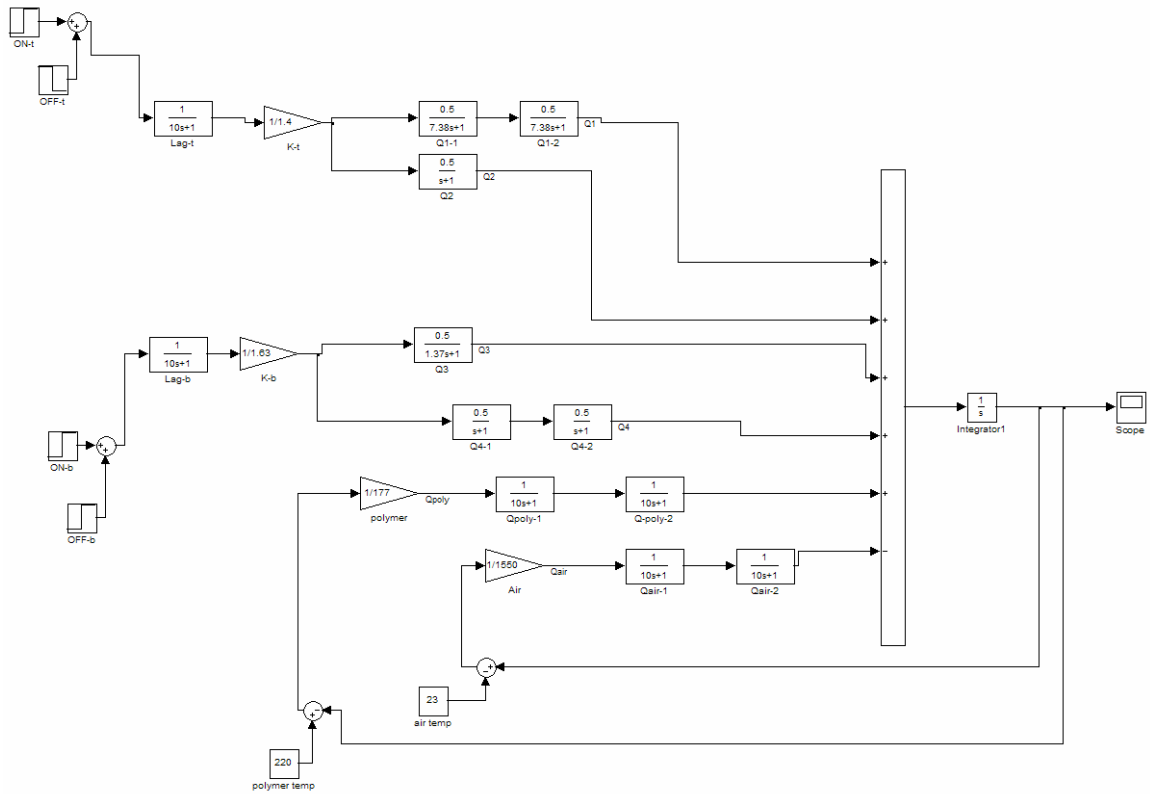


Figure B-13: Simulink block structure for the elongational side of the sensor block for Run #6

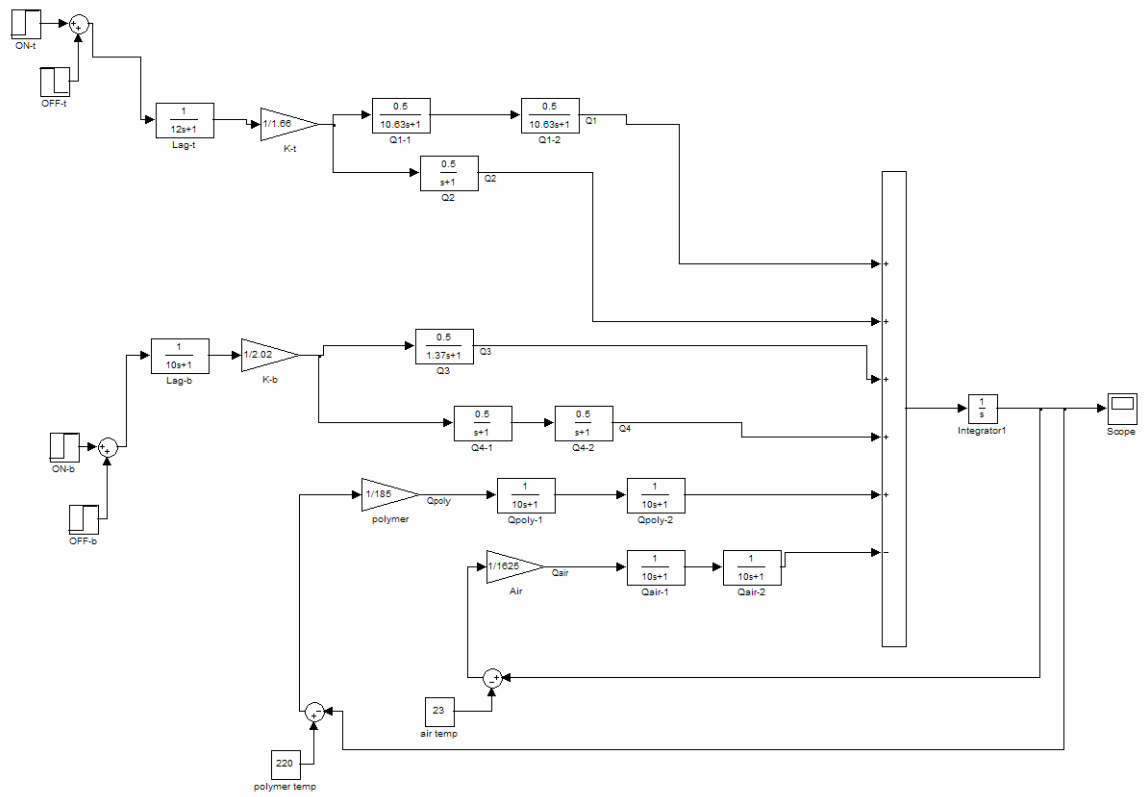


Figure B-14: Simulink block structure for the shear side of the sensor block for Run #6

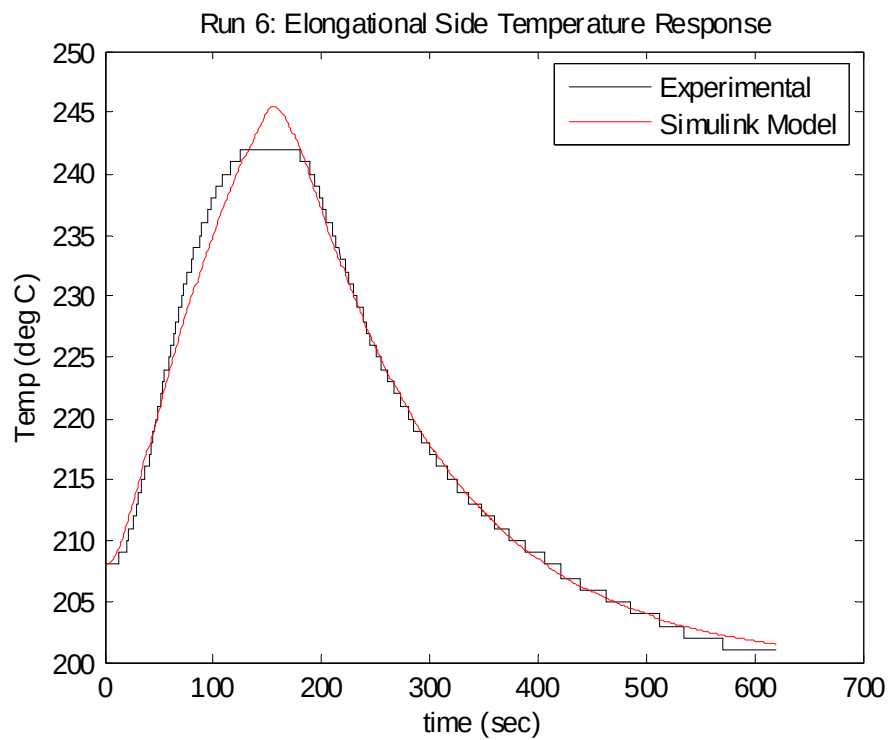


Figure B-15: Simulink model of the elongational side of the sensor block for Run #6

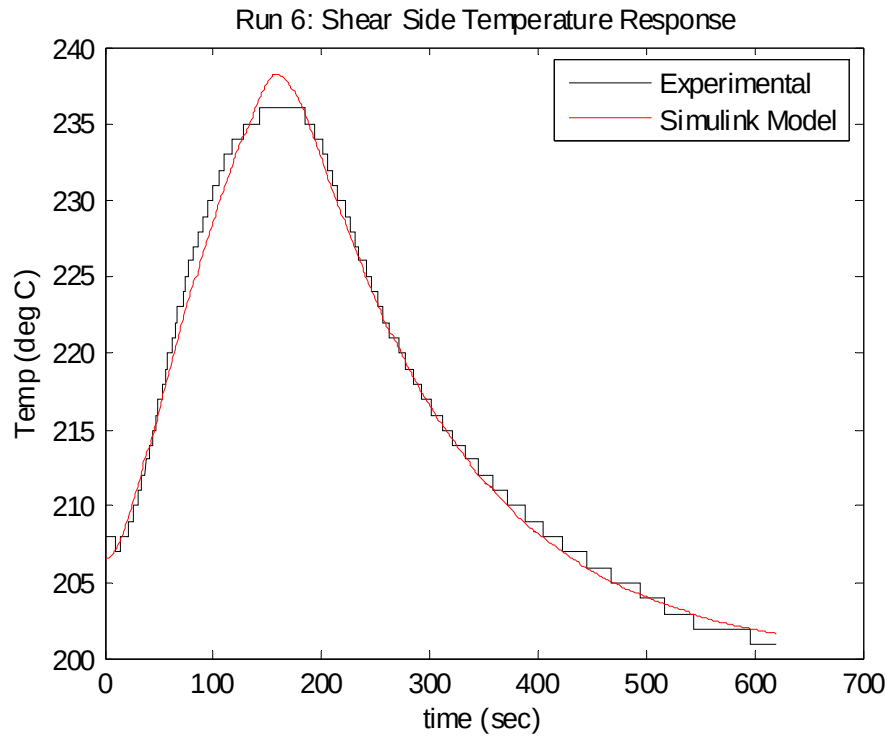


Figure B-16: Simulink model of the shear side of the sensor block for Run #6

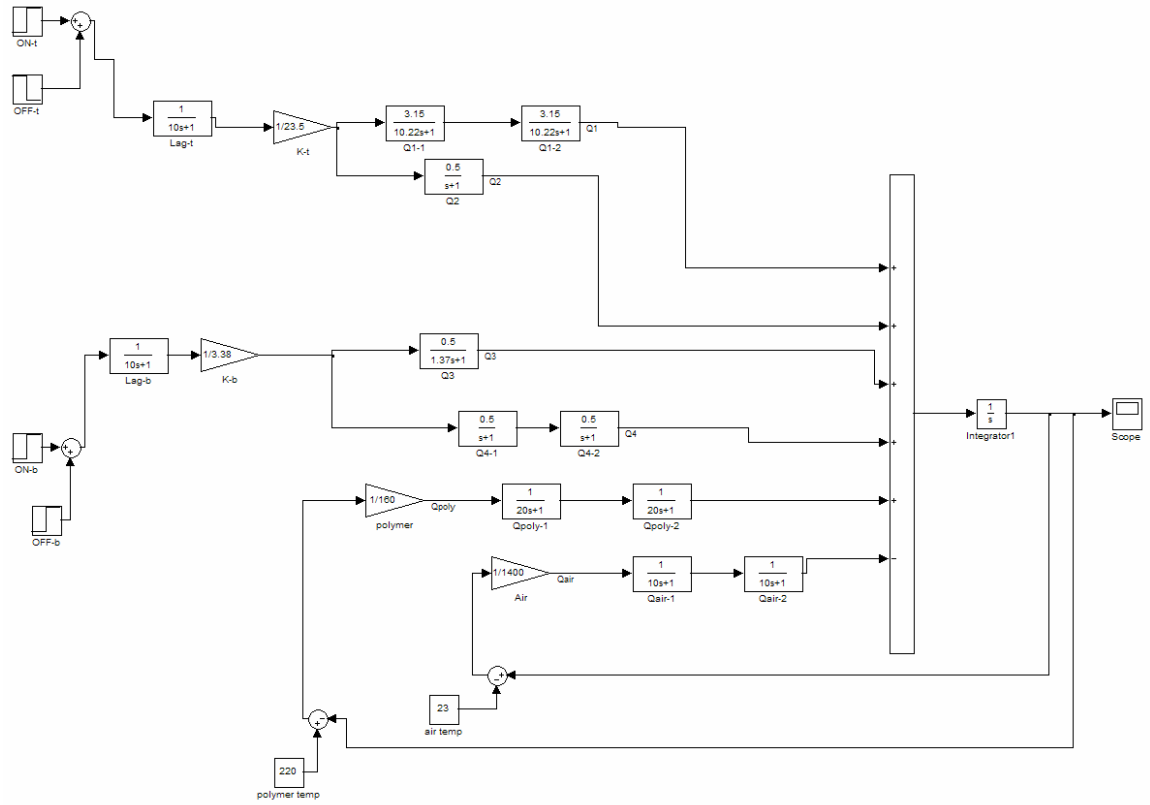


Figure B-17: Simulink block structure for the elongational side of the sensor block for Run #7

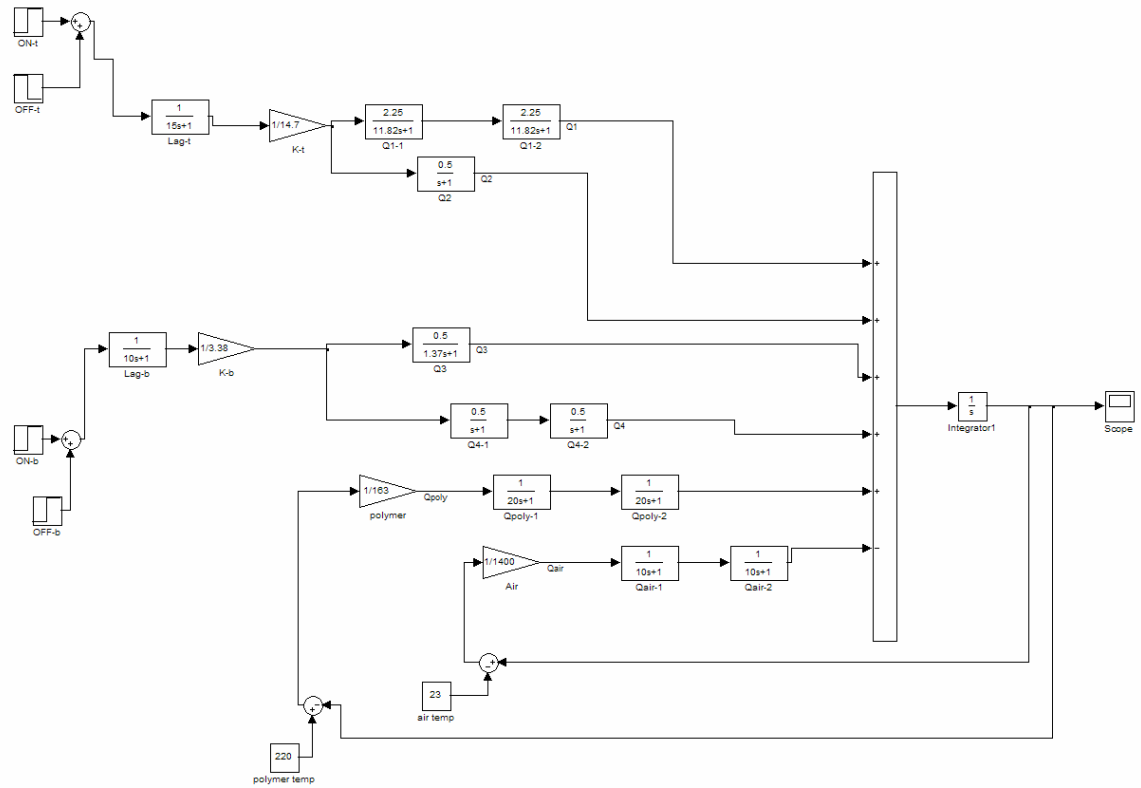


Figure B-18: Simulink block structure for the shear side of the sensor block for Run #7

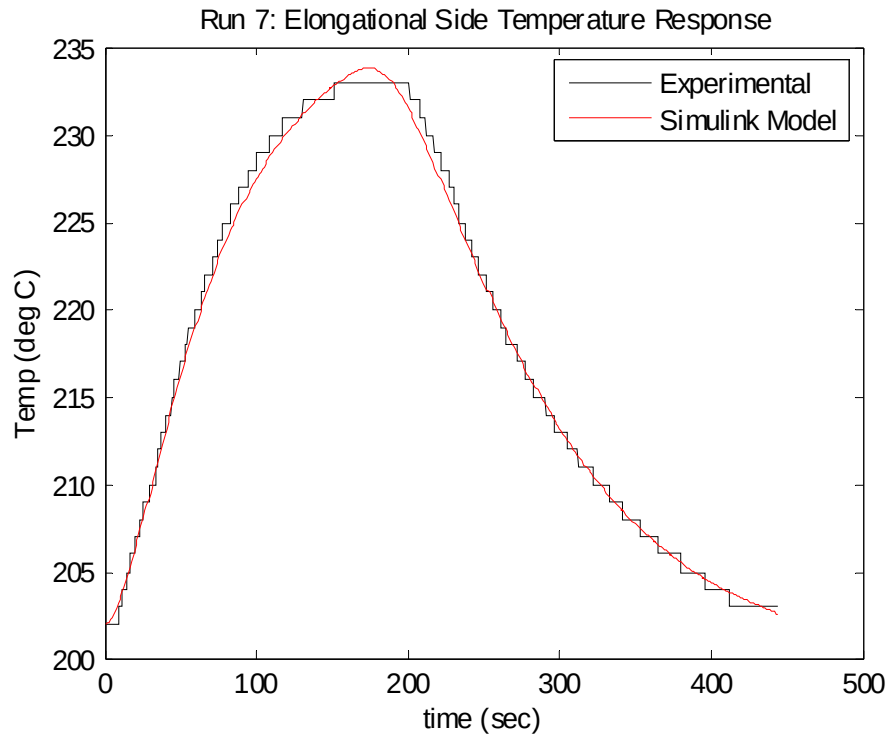


Figure B-19: Simulink model of the elongational side of the sensor block for Run #7

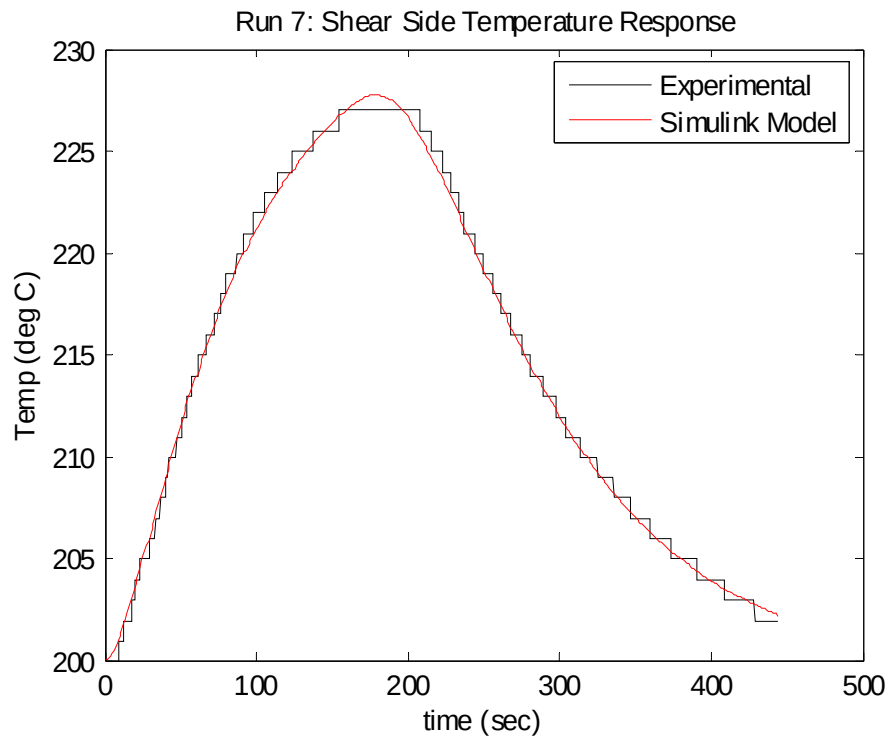


Figure B-20: Simulink model of the shear side of the sensor block for Run #7

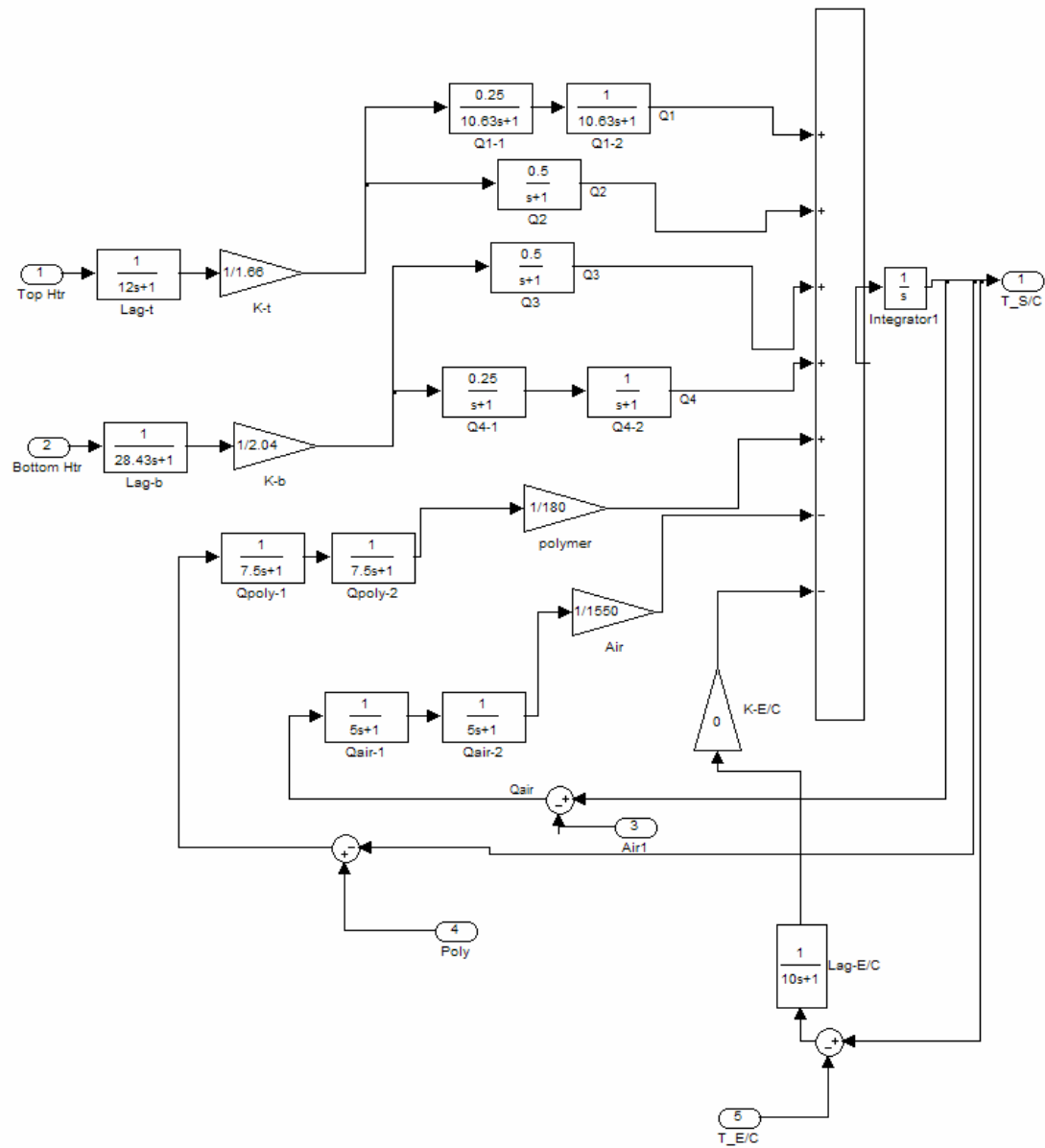


Figure B-22: Simulink block structure for the shear side of the sensor block for Run #6 to determine the “cooling parameters”

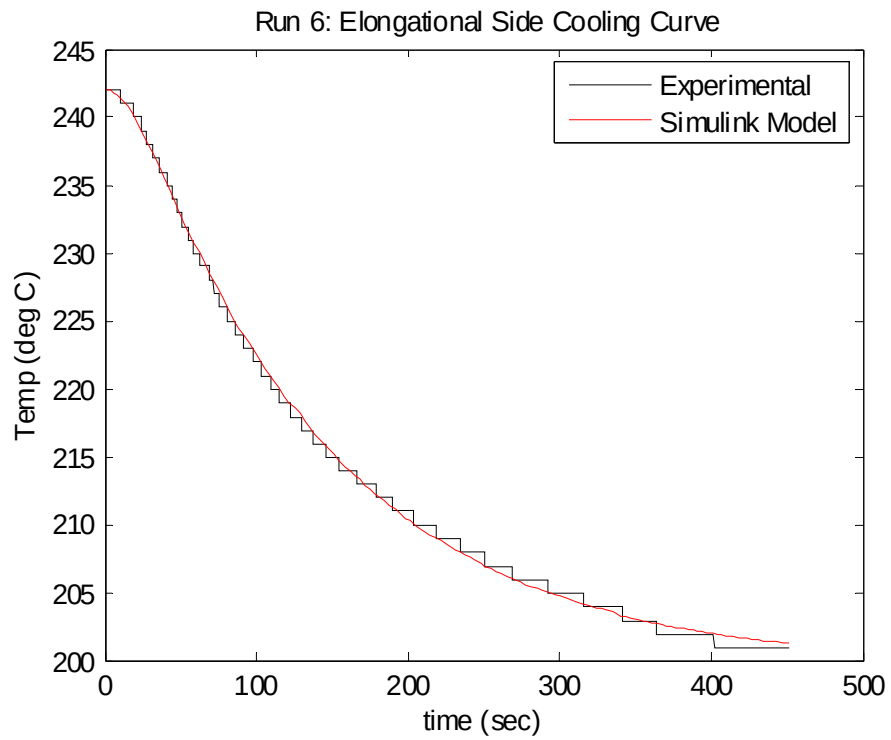


Figure B-23: Simulink cooling model of the elongational side of the sensor block for Run #6

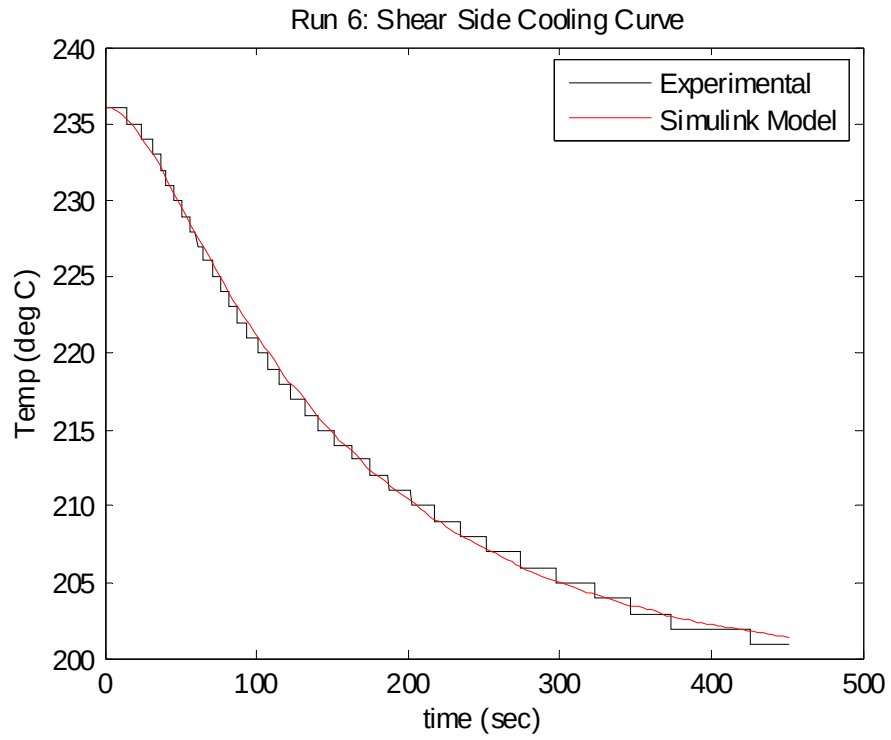


Figure B-24: Simulink cooling model of the shear side of the sensor block for Run #6

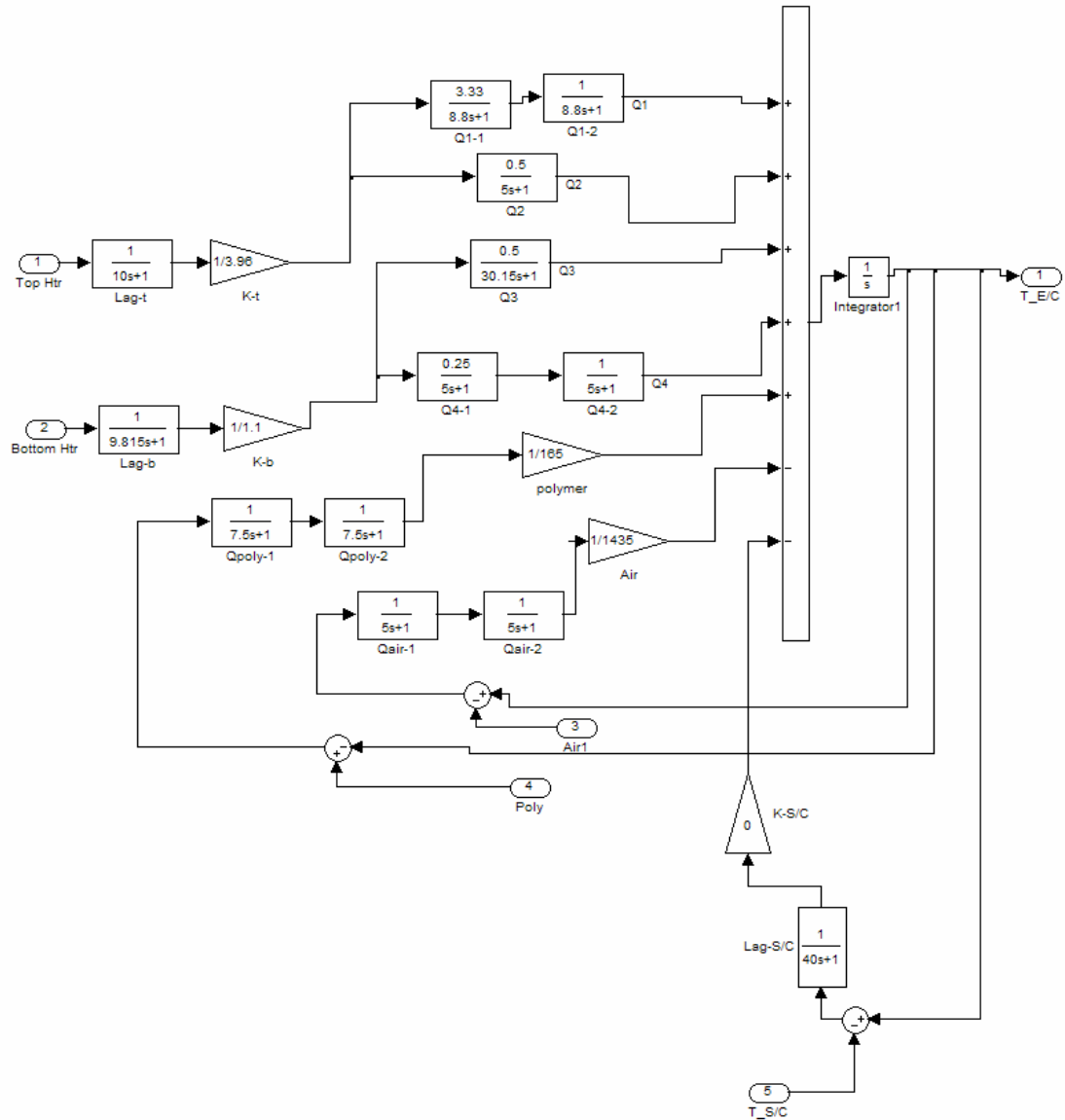


Figure B-25: Simulink block structure for the elongational side of the sensor block for Run #3 using the “combined parameters”

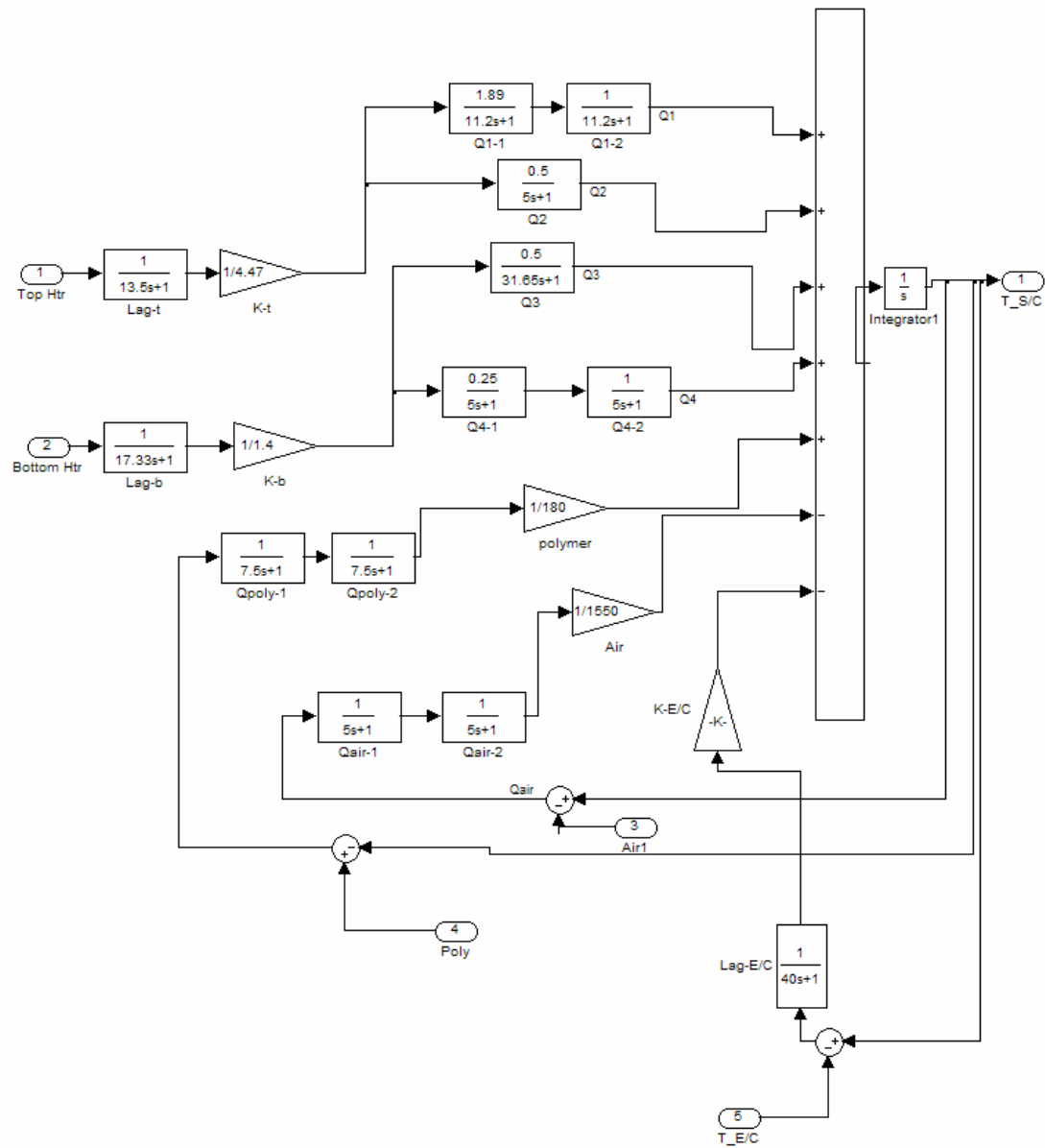


Figure B-26: Simulink block structure for the shear side of the sensor block for Run #3 using the “combined parameters”

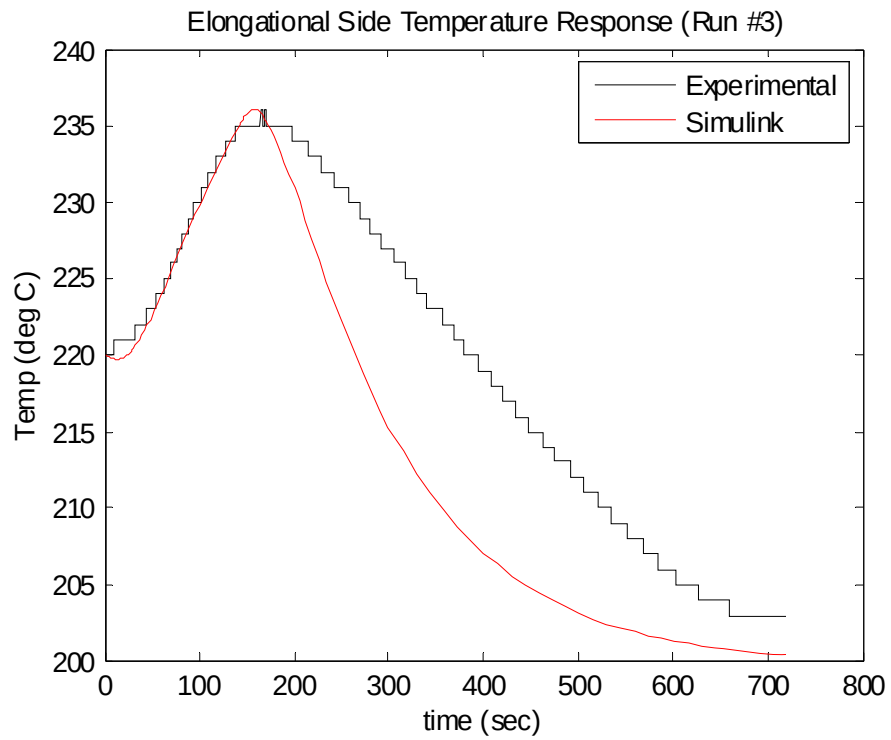


Figure B-27: Simulink model for the elongational side of the sensor block for Run #3 using the “combined parameters”

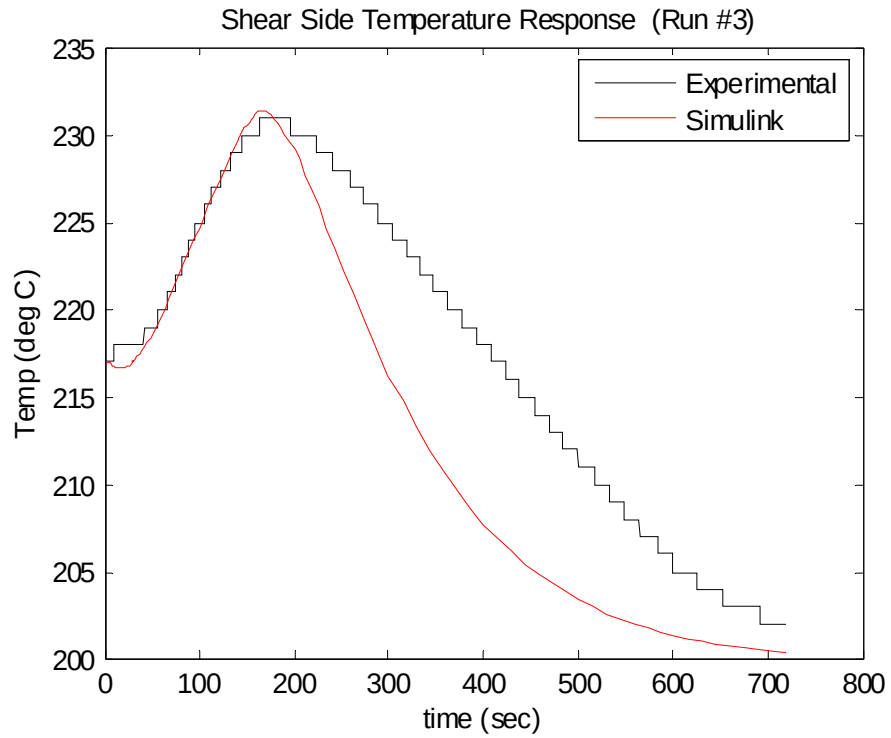


Figure B-28: Simulink model for the shear side of the sensor block for Run #3 using the “combined parameters”

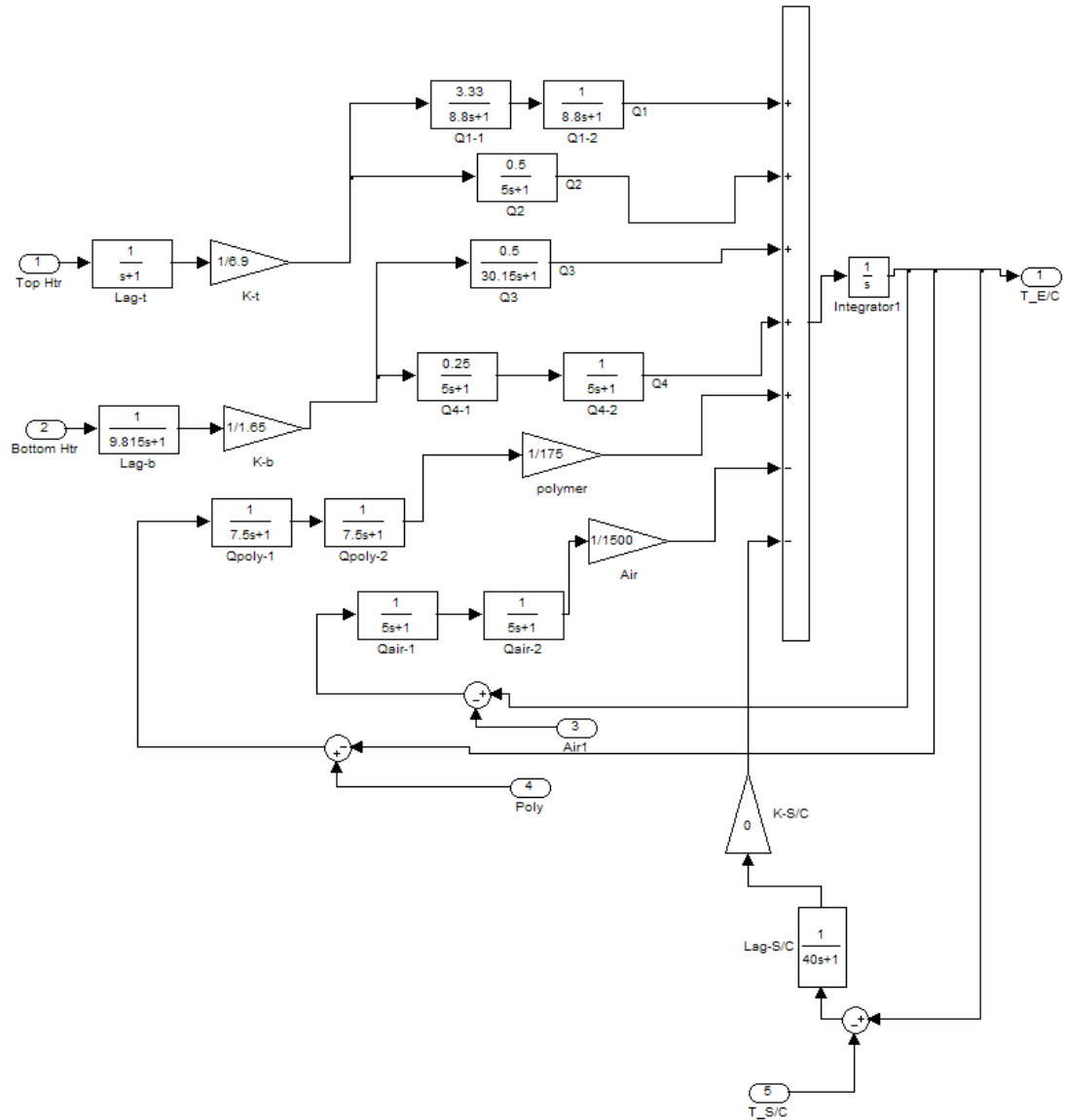


Figure B-29: Simulink block structure for the elongational side of the sensor block for Run #6 using the “combined parameters”

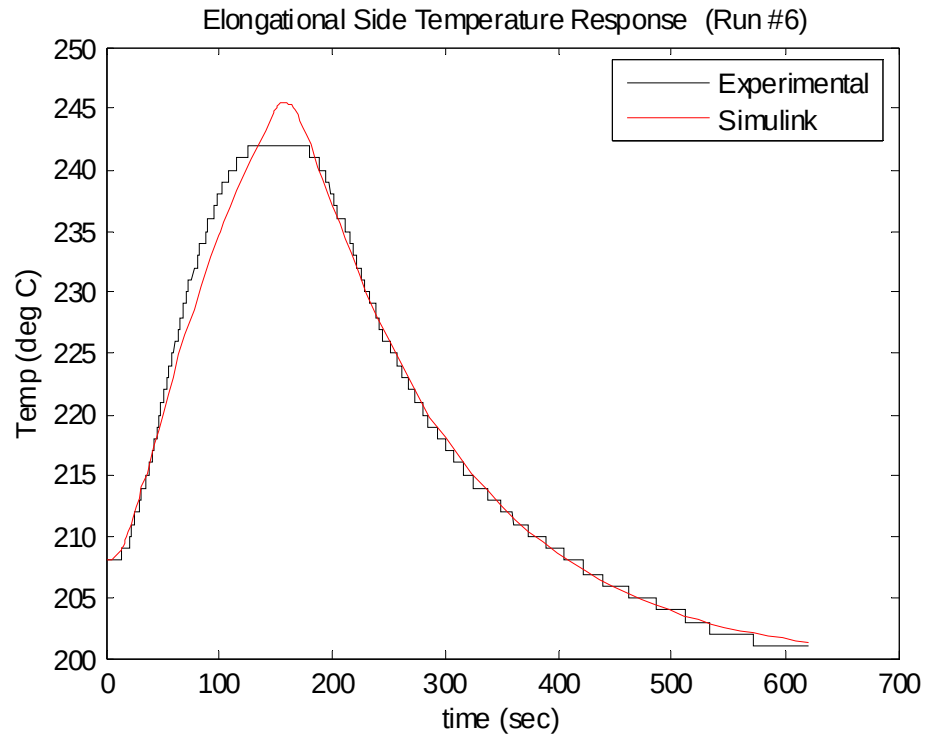


Figure B-31: Simulink model for the elongational side of the sensor block for Run #6 using the “combined parameters”

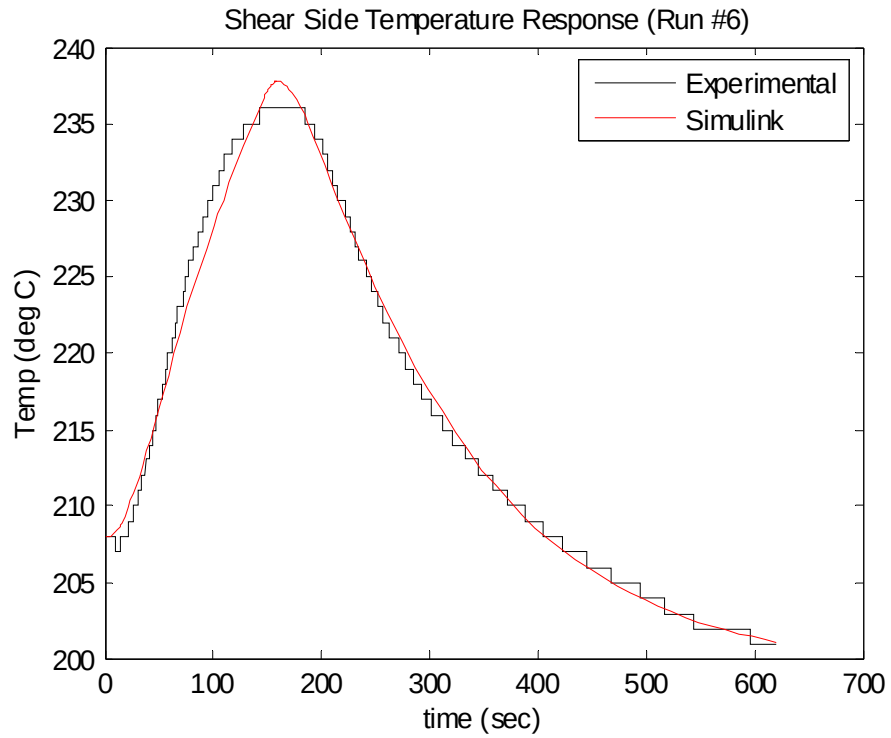


Figure B-32: Simulink model for the shear side of the sensor block for Run #6 using the “combined parameters”

Vita

Larry Scott Spencer was born in Oak Ridge, Tennessee in 1977. He attended Karns High School in Knoxville, Tennessee and graduated in 1995. He then attended Pellissippi State Technical Community College where he received an A.S. degree in 2000. Larry enrolled in the University of Tennessee at Knoxville where he was awarded a Bachelor of Science degree in Chemical Engineering in 2003 and a Master of Science degree in Chemical Engineering in 2005. Larry was married in 2005. Larry currently works in the Technology Development Division at BWXT-Y12 in Oak Ridge, Tennessee.