PERFORMANCE ENHANCMENT OF TEMPERATURE CONTROL RESPONSE FOR EXTRUDER PLANT IN ELECTRIC CABLE MANUFACTURING

Okeke, V. N., Uju, I. and Nwabueze, C. A
Department of Electrical/Electronic Engineering, Chukwuemeka Odumegwu Ojukwu University, Uli, Anambra State.

ABSTRACT
There are many control strategies employed in electric cable manufacturing industry to produce high quality products. In order to ensure good quality product formation, one requirement is to control the temperature of an extruder plant so as to form molten plastic on a wire. The gain parameters of the proportional integral and derivative (PID) controller designed in this work were obtained using the MATLAB PID tuner. The gain parameters were then implemented in MATLAB/SIMULINK environment. The designed controller was integrated with the single screw plastic extruder dynamic model to have an efficient control loop. The efficiency provided by the designed controller shows that the system responds efficiently to a step input temperature. The improved efficient characteristics performances of the system are rise time of 0.0245s, settling time of 0.237s and overshoot of 6.92%. The designed controller can be effectively employed in a single screw extruder for efficient electric cable manufacturing.

Keywords: Extruder, Performance, PID, Temperature, Cable

1.0 INTRODUCTION
Polymer materials have been of interest for automotive, aerospace, electronic systems, medical products, civil engineering construction and chemical industries. This is due to their many attractive properties such as ease of forming into complex shapes, light-weight with high tensile/impact/tear strength, high temperature resistance, high chemical resistant, high clarity, re–process ability and low cost (Khanam and Almaadeed, 2015). Despite this success, effective thermal monitoring and control is still an issue even in electric cable manufacturing process.

Plastic extrusion has been a challenging process for many manufactures and researchers to produce products that meet production requirements at the lowest cost. The complexity of extrusion process and the enormous amount of process parameters involved makes it difficult to keep the process under control. Extrusion is a well-established technique widely used in different industries like aluminum, sheet and plastic. The extruder topically consists of a large barrel divided into several constant temperature zones, with a hopper at one end and die at another end.

Techniques of seeing that standards are maintained are the control of product quality. Put more specifically, quality control simply means the monitoring of production to maintain process control and produce goods that are fit for the intended purpose. Integral to a quality control/statistical process control system is the concept of designing quality into products, with monitoring to maintain control, and acceptance sampling as a final check (Pervidi et al, 2006).

In practice, it is a challenging task to achieve the required quality control. Most of the previous works were focused on process variable control (Fountaine, 1975 and Gardiner, 1975). It is inadequate to guarantee a good process quality since there was no quality feedback in the control loop. The definition of product quality involves two aspects: precision and accuracy. Precision is the repeatability of successive measurements under the same conditions, which is a representation of quality scattering. Accuracy depicts the difference between the measured value and the true value as a measurement of bias. From principle analysis, variation of process variables will lead to variation of output flow rate, which in turn affects product quality precision (Pervidi et al, 2006) . Therefore, control of product quality precision can be done by proper control of process variables as investigated by Jiang et al, 2012. This work proposes a process of achieving an efficient quality control for industrial extrusion in electric cable manufacturing by implementing a Three-term PID (Proportional, Integral and Derivative) temperature control system on a single screw extruder. This process generally guarantees an efficient temperature control in plastic extrusion machine that produces high quality products.

2.0 OVERVIEW OF ELECTRICAL CABLE MANUFACTURING

Typically, the manufacturer of electrical wires and power cables faces a scenario where multiple products, some with more than one feasible process plan, are to be allocated on limited number of available machines and be produced within some time limit. Furthermore, different allocation sequences of products (wires and cables) on machines require a lot of setup efforts in terms of die changes in the drawing operation, extruders' cleaning and changes of insulation material or colour for the insulation operation, parameters changes of the twisting and annealing operations, and other setup time-consuming activities (Anthony, 2014).

2.1 Methods of Processing Plastics

Polymer processing is the technology of converting raw polymers or compounds containing raw polymers and additives into such useful items as fibres, films, sheets, tubes, pipes, bottles, foams, shaped objects etc., by mechanical fabrication. The mechanical fabrication of polymers into shaped articles can be accomplished in very many ways: such as compression moulding, injection moulding, extrusion, sheet forming, bottle-blowing, calendaring, wet fabrication (fibre spinning, coatings). Polymer compounding is the mixing of raw polymer materials with additives, namely plasticizers, colorants, photo and heat stabilizers, flame retardants etc., prior to fabrication (Ogunnaike and Garge, 2010).

The methods for processing plastics are based on polymer ability to acquire plasticity and fluidity when they are treated with temperature and pressure, and then to retain the shape that they have been given in ordinary conditions (Ogbuagu, and Ogburubi, 2000).

The basic steps for processing of manufactured plastics into useful articles are as follows:
Compression, Injection, Extrusion, Sheet forming.

2.2 Conceptual Framework

Two types of extruders are used in industries: Single screw extruders and twin–screw extruders. The single-screw extruders are the most common extruders (Steel et al, 2011).In this context single- screw extruder is considered. The motion of material in single screw extruder is straightforward. From the feed hopper, raw material enters and flows by gravity into the extruder barrel. As raw material falls, friction between materials and screw surface and barrel is produced. It is the friction that pushes materials to be transported forward. While moving forward, raw material is heated up and melted. As melted polymer reaches the die, its shape is adopted.

A typical standard single-screw extruder layout is shown in figure 1. Here, the heater bands which surround the barrel allow setting of the axial temperature profile. One end of the barrel is coupled to the die, while the raw material is fed by a lateral hole at the opposite end, on top of which a hopper is fixed (the hopper usually consists of a vertical column with straight and inclined sections). The screw as shown has a constant pitch which has variable channel depth, thereby generating three distinct geometrical zones. One can identify a feed zone (with constant channel depth) form hopper to die, a compression zone (with decreasing channel depth) and where the screw is shallower (melting zone). Given the same screw diameter, D and axial length, L, the length of each zone may vary, as well as the maximum and minimum channel depths, which give rise to different screw profiles. From this, together with the possibility of changing the set temperatures and the screw speed, may produce quitted distinct thermo mechanical environments inside the machine, such that local heat conduction, heat dissipation, velocity profile and residence time may differ substantially (Covas and Cumba, 2011).

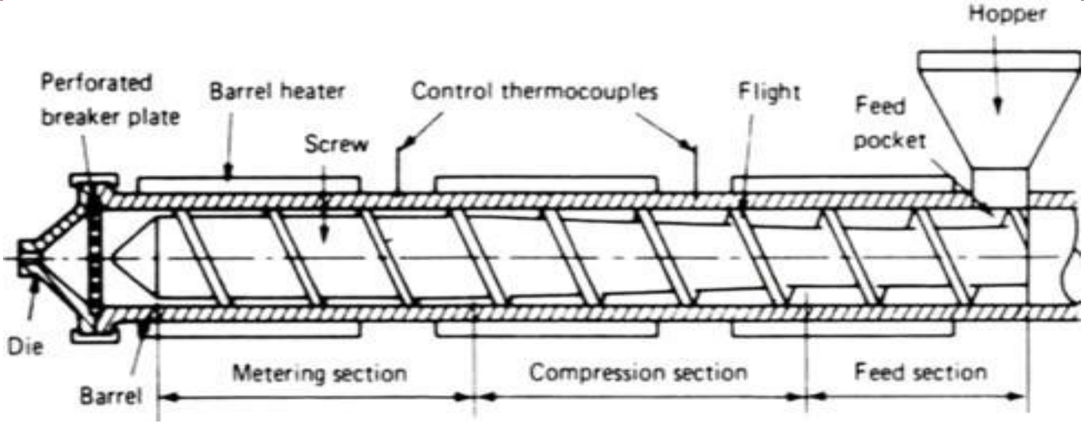

Figure 1: Pictorial diagram of an extrusion machine (Covas and Cumha, 2011)

2.3 PID Heat Transfer/Temperature Control Mechanisms

Tuning a control loop is the adjustment of its control parameters (proportional band/gain, integral gain/reset, derivative gain/rate) to the optimum values for the desired control response. Stability being a basic requirement denotes that different systems have different behavior, different applications have different requirements, and requirements may conflict with one another. PID tuning is a difficult problem, even though there are only three parameters and in principle is simple to describe, because it must satisfy complex criteria within the limitations of PID control. There are various methods for loop tuning (Intro: PID Controller, 2007).

Designing and tuning a PID controller is generally intuitive if multiple objectives such as short transient and high stability are to be achieved. PID controllers are known to provide acceptable control using default tunings. Arguably, performance can generally be improved by careful tuning and performance may be unacceptable with poor tuning. Initial designs need to be adjusted repeatedly through computer simulations until the optimal performance of the desired closed-loop system is achieved. Some processes may have some degree of nonlinearity and so parameters that work well at full-load conditions may not work when the process is starting up from no-load; consequently, this can be corrected by gain scheduling (using different parameters in different operating regions) as stated accordingly (Bechhoefer, 2005).

2.3.1 Stability

If the PID controller parameters (the gains of the proportional, integral and derivative terms) are chosen incorrectly, the controlled process input can be unstable, i.e., its output diverges, with or without oscillation, and is limited only by saturation or mechanical breakage. Instability is caused by *excess* gain, particularly in the presence of significant lag. Generally speaking, stabilization of response is required and the process must not oscillate for any combination of process conditions and set-points, though sometimes marginal stability (bounded oscillation) is acceptable or desired (Bechhoefer, 2005).
Mathematically, the origins of instability can be seen in the Laplace domain.
The total loop transfer function is:

$$Hs = \frac{K(s)G(s)}{1+K(s)G(s)} \qquad (1)$$

where
K(s): PID transfer function
G(s): Plant transfer function

The system is called unstable where the closed loop transfer function diverges for some s. This happens for situations where K(s)G(s) = 1. Typically, this happens when $|K(s)G(s)| = 1$ with a 180 degree phase shift. Stability is guaranteed when K(s)G(s) ‹ 1 for frequencies that suffer high phase shifts (Bechhoefer, 2005).

3.0 OVERVIEW OF TUNING METHODS

Tuning a PID loop has various approaches. One of the most effective approaches involves development of a process model, then choosing the P, I, and D based on the dynamic model parameters. Generally, tuning manually is very time consuming, particularly for systems with long loop times. The choice of method will depend largely on whether or not the loop can be taken "offline" for tuning as well as on the response time of the system. If the system can be taken offline, the best tuning method often involves subjecting the system to a step change in input, measuring the output as a function of time and using this response to determine the control parameters (Atherton, 2014).

3.1 Manual tuning

If the system must remain online, one tuning method is to first set K_i and K_d values to zero. Increase the K_p until the output of the loop oscillates, then the K_p should be set to approximately half of that value for a - quarter amplitude decay, type response. Then increase K_i until any offset is corrected in sufficient time for the process. Invariably, too much K_d will cause instability. Increase, if necessary will be done until the loop is acceptably quick to reach its reference after a load disturbance. It should be noted that too much will cause excessive response and overshoot. It should be noted that fast PID loop tuning generally, overshoots slightly to reach the set-point more quickly; however, some systems cannot accept overshoot, in which case an over damped closed-loop system is required, which will require a K_p setting significantly less than half that of the K_p setting that was causing oscillation (Kiam et al, 2005). Table 1 shows the effect of increasing a parameter independently.

Table 1: Effect of Increasing a Parameter Independently (Kiam et al, 2005).

Parameter	Rise Time	Overshoot	Setting Time	Steady-State Error	Stability
Kp	Decrease	Increase	Small Change	Decrease	Degrade
Ki	Decrease	Increase	Increase	Eliminate	Degrade
Kd	Minor Change	Decrease	Decrease	No effect in Theory	Improve if Kd small

3.2 Ziegler–Nichols Method

Another heuristic tuning method is formally known as the Ziegler–Nichols method which was introduced by John G. Ziegler and Nathaniel B. Nichols in the 1940s. As in the method above, the K_i and K_d gains are first set to zero. The proportional gain is increased until it reaches the ultimate K_u gain, at which the output of the loop starts to oscillate. K_u and the oscillation period T_u are used to set the gains as shown in table 2 (Wikipedia: PID Controller):

Table 2: Ziegler-Nichols Method

Control Type	K_p	K_i	K_d
P	0.50Ku	--	--
PI	0.45Ku	0.54Ku/Tu	--
PID	0.60Ku	1.2Ku/Tu	-3KuTu/40

These gains apply to the ideal, parallel form of the PID controller. When applied to the standard PID form, only the integral and derivative time parameters T_i and T_d are dependent on the oscillation period T_u. The ideal, parallel form of the PID Controller is shown in figure 2.

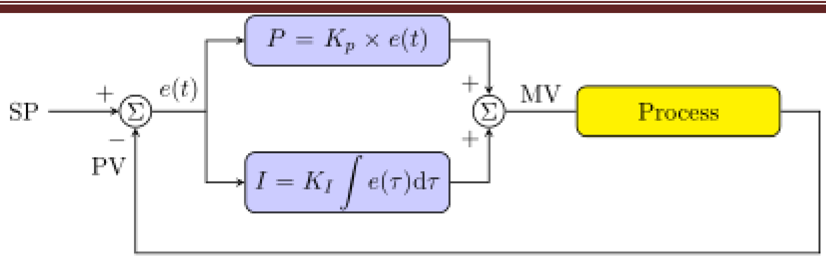

Figure 2: Ideal, Parallel form of the PID Controller (Wikipedia: PID Controller).

3.3 Cohen-Coon Parameters

This method was developed in 1953 and is based on a first order +-time delay model. Similar to the Ziegler-Nichols method, a set of tuning parameters were developed to yield a closed-loop response with a decay ratio of 1/4. Arguably the biggest problem with these parameters is that a small change in the process parameters could potentially cause a closed-loop system to become unstable (Wikipedia: PID Controller).

3.4 Relay (Åström–Hägglund) method

The relay method published in 1984 temporarily operates the process using bang-bang control and measures the resultant oscillations. The output is switched (as if by a relay, hence the name) between two values of the control variable. The values must be chosen so the process will cross the set-point, but need not be 0% and 100%; by choosing suitable values, dangerous oscillations can be avoided (VanDoren, 2009).
As long as the process variable is below the set-point, the control output is set to the higher value. As soon as it rises above the set-point, the control output is set to the lower value. Ideally, the output waveform is nearly square, spending equal time above and below the set-point. The period and amplitude of the resultant oscillations are measured, and used to compute the ultimate gain and period, which are then fed into the Ziegler–Nichols method.
Specifically, the ultimate period T_u is assumed to be equal to the observed period, and the ultimate gain is computed as $K_u = 4b/\pi a$, where *a* is the amplitude of the process variable oscillation and *b* is the amplitude of the control output change which caused it. There are numerous variants on the relay method (Hornsey, 2012).

4.0 METHODOLOGY

4.1 Heat Flow analysis in Extrusion Process

In all extrusion processes, the first law of thermodynamics, that is, the conservation of energy must be satisfied. During the extrusion process of polyvinylchloride (PVC), the energy needed for processing is provided by the mot or and the barrel heaters. Usually, a very small negligible portion of the motor energy is lost through the drive chain as frictional heat in the coupling and the gear box. Most of the mechanical energy of the motor consume din other to rotate the screw is converted in to heat by shearing the polymer melt. A large amount of heat is generated in the melt by viscous dissipation as the melt is sheared by the screw rotation. A very small portion of the mechanical energy is used to compact the polymer feed, to develop the melt pressure, and to move the melt out of the screw. The melt pressure developed at the end of the screw drops to ambient pressure as the melt comes out of the die, converting the mechanical energy associated with the melt pressure into heat. Virtually about 80% of the mechanical energy of the motor is converted into heat. The heat generated in the melt is the main source of heat used to melt the polymer feed. The thermal energy Q_i is conducted to the polymer through the barrel. When the melt overheats above the set point of the barrel heater, the cooling system on the barrel takes away heat, Q_C from the melt. Some reasonable amount of heat, Q_l is lost to the ambient through the barrel and the screw shaft. The balance of the total mechanical and thermal energies is equal to the increased heat content of the polymer from the feed temperature to the melt temperature as depicted in figure 3.

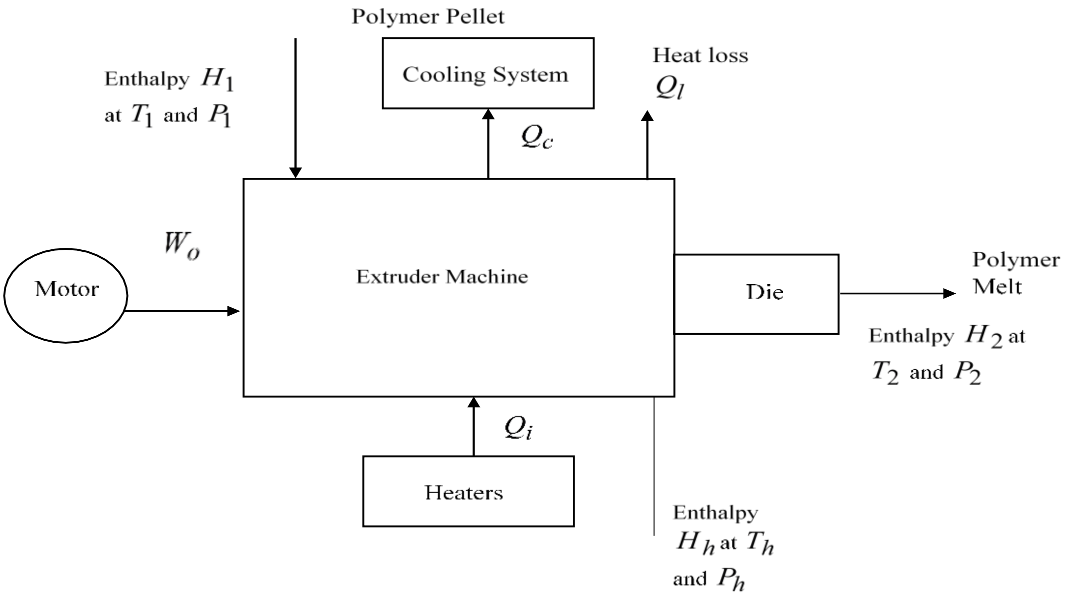

Figure 3: Typical Energy Balance Representations in Polymer Extrusion.

From figure 3, typical polymer extruder takes in resins in the solid form at temperature, T_1 and pressure, $P_1$with enthalpy $H_1$and extrudes the melted polymer at temperature, T_2 and pressure, $P_2$with enthalpy H_2. It is noted that enthalpy is a function of both temperature and pressure. At a constant temperature, enthalpy increases with increase pressure. The analysis presented by Barr and Chung, 1966 using thermodynamic law used in this context.

$$\Delta H + \Delta PE + \Delta KE = \Delta Q + \Delta W \qquad (2)$$

Where $\Delta H = H_2 - H_1$ = enthalpy increase per unit polymer mass (J/kg),
ΔPE = potential energy increase per unit polymer mass (J/kg).
ΔKE = kinetic energy increase per unit polymer mass (J/kg).
ΔQ = net thermal input in to unit polymer mass (J/kg).
ΔW = net mechanical input into unit polymer mass(J/kg).
Because ΔPE and ΔKE are negligible in comparison to ΔH in extrusion, eqn. (2) is reduced to

$$\Delta H = \Delta Q + \Delta W \qquad (3)$$

From figure 3 above, ΔQ and ΔW can be express as:

$$\Delta Q = (Q_o - Q_c - Q_1)/G \qquad (4)$$

Noting that $\Delta W = W_o/G$ (neglecting mechanical losses)

where G = mass output per unit time = mass output rate (kg/s).
Q_o = total thermal energy input by the heaters per unit time (J/s).

Q_c = total thermal energy removed by cooling per unit time (J/s).
Q_l = total thermal energy lost in the surrounding per unit time J/s).
W = mechanical energy input by the motor per unit time = motor power.

Combining eqns. (2), (3) and (4), the required motor power can be obtained, as:

$$W_o = G.\Delta H - (Q_o - Q_c - Q_1) \quad (5)$$

In situations where there is no heat exchange between the extruder and the surroundings (adiabatic systems) i.e.:

$$\Delta Q = (Q_O - Q_C - Q_l) = 0, \quad (6)$$

the theoretical motor power in the adiabatic operation becomes:

$$W^1O = G\Delta H(W) \quad (7)$$

Where W^1O = theoretical motor power in the adiabatic operation.

4.2 Approximating the Temperature Change through the Die

In figure 3, the theoretical exit temperature of polyvinylchloride (PVC) can be found using eqn. (8) below, the melt pressure at the end of the screw, that is the head pressure P_h .The melt pressure drops to $P_2 = 0$, as the melt is extruded into the surrounding through the die. If there is no heat exchange between melt and the die, the enthalpy of melt at the head, $H_h$at T_h and P_h, should be equal to the enthalpy of the melt exiting the die H_2 at T_2 and P_2. The pressure drop through the die from P_h to P_2 is converted into heat, raising the melt temperature from T_h to T_2. Assuming no heat exchange through the die and negligible compressibility of the melt ($\Delta V = 0$), the temperature rise through the die can be approximated as follows:

For $\Delta V = 0$, Cp = Cv

$$\Delta H = \Delta E + \Delta (P.V) = \Delta E + V.\Delta P + P.\Delta V = \Delta E + V.\Delta P = 0$$

$$\Delta E = -V.\Delta P = -V(P_2 - P_h) = V.(P_h - P_2) = Cv.\Delta T = C_p(T_2 - T_h) \quad (8)$$

Therefore:

$$\Delta T = (T_2 - T_h) = V(P_h - P_2)/C_p \quad (9)$$

where;
ΔE = internal energy increase per unit polymer mass (J/kg).
V = specific volume, i.e. volume of unit polymer mass (m^3/kg).
C_p = specific heat

4.3 Overview of Proposed System

The proposed system to be designed in this context is a proportional integral and derivative controller. A controller including all three components –proportional, integral and derivative is often referred to as three term or PID controllers. Its outputs a combination of its three components as shown in figure 4.

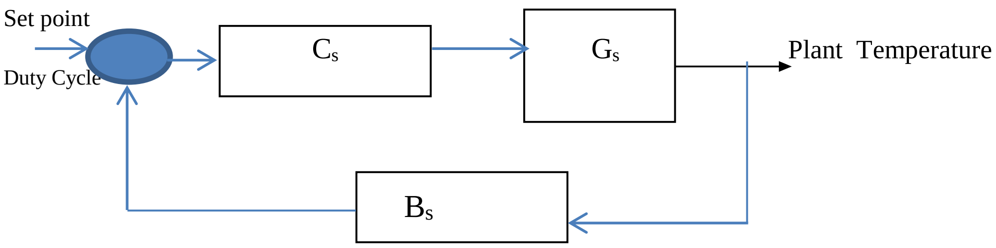

Figure 4: Block Diagram of the Implemented Temperature Controller.

The Ziegler-Nichols method (ZNM) can be used in both open and closed loop configurations to ascertain the parameters of a plant thereby enabling a reasonable controller to be defined. In this work the response to a step input on the open-loop plant was found to be sufficient. According to ZNM the open-loop unit step response, $G(s)$, can be approximated by the Laplace transform.

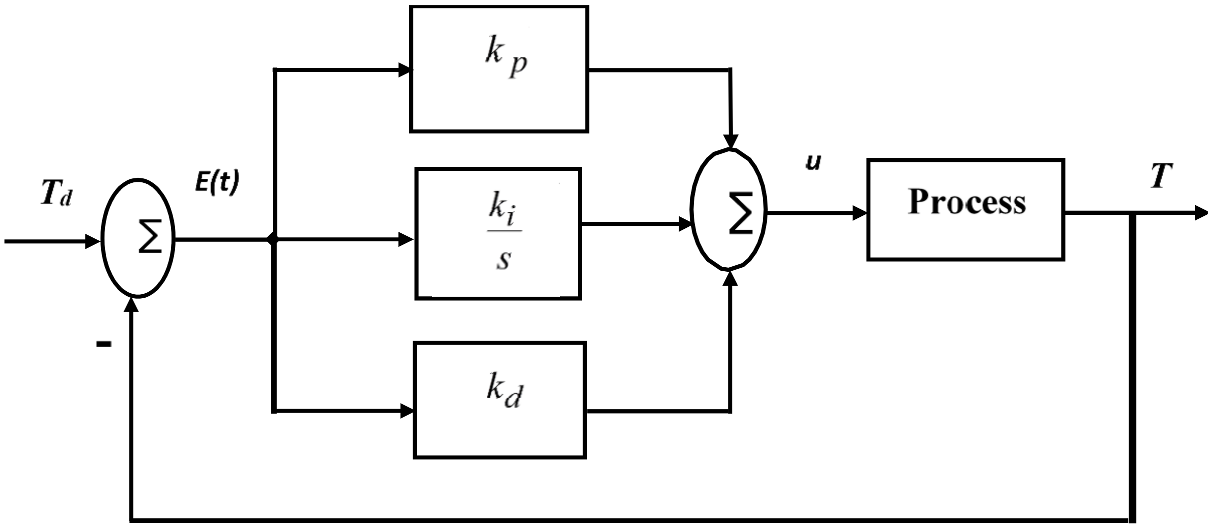

Figure 5: Block Diagram of the Open-Loop Response

4.4 Simulation

In this work, simulations were performed considering two conditions based on when the designed proportional integral and derivative (PID) controller was not in the loop and when it was in the loop. The simulations were carried out in MATLAB/Simulink environment. The simulation programme for the two conditions considered is presented in figures 6 and 7.

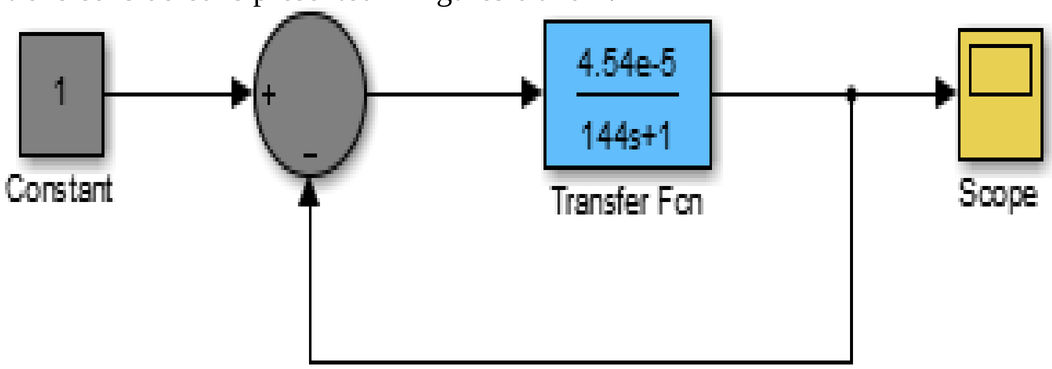

Figure 6: Simulink Programme (without PID controller)

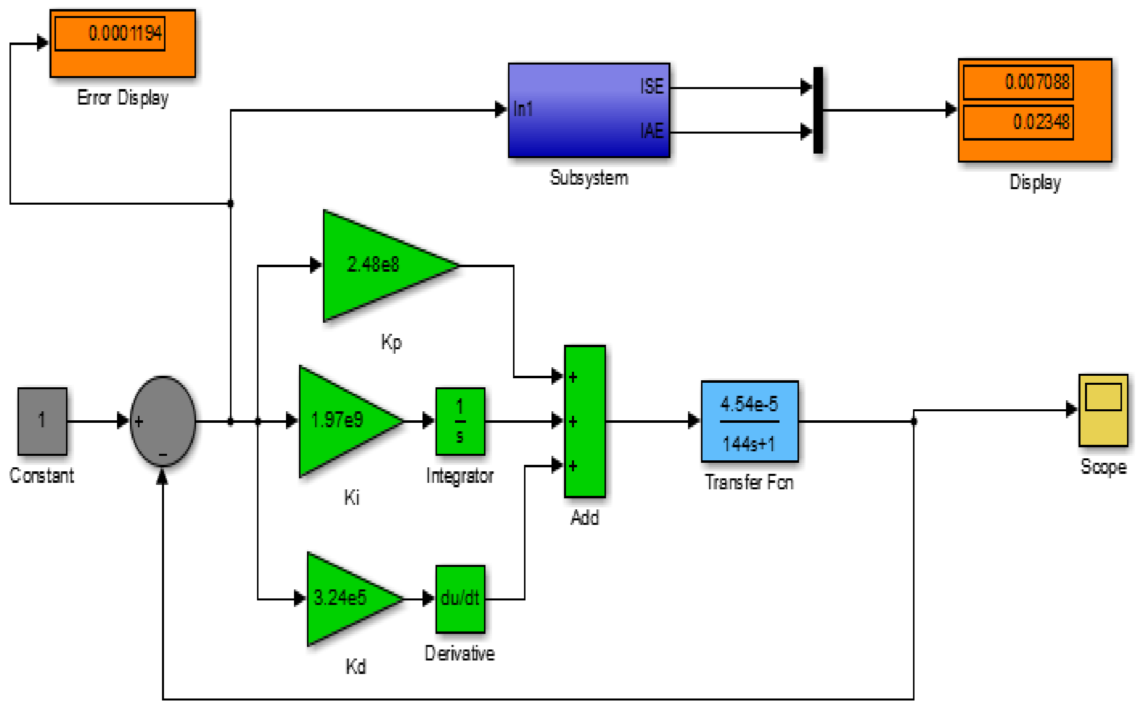

Figure 7: Simulation programme (with PID controller)

In this work, two variables that will be maintained within the loop are initialized to zero, and then the loop begins. The current *error* is calculated by subtracting the *measured-value* (the process variable, or PV) from the current *set-point* (SP). Then, *integral* and *derivative* values are calculated, and these and the *error* are combined with three preset gain terms – the proportional gain, the integral gain and the derivative gain – to derive an *output* value. In the real world, this is D-to-A converted and passed into the process under control as the manipulated variable (MV). The current error is stored elsewhere for re-use in the next differentiation, the program then waits until dt seconds have passed since start, and the loop begins again, reading in new values for the PV and the set-point and calculating a new value for the error. It should be noted that for real code, the use of "wait (d_t)" would be inappropriate because it does not account for time taken by the algorithm itself during the loop, or more importantly, any preemption delaying the algorithm.

5.0 RESULTS

The results obtained from the simulation performed for the melt zone temperature of extrusion process for Polyvinyl Chloride production for efficient cable manufacturing considered in this work is presented in figures 8 and 9.

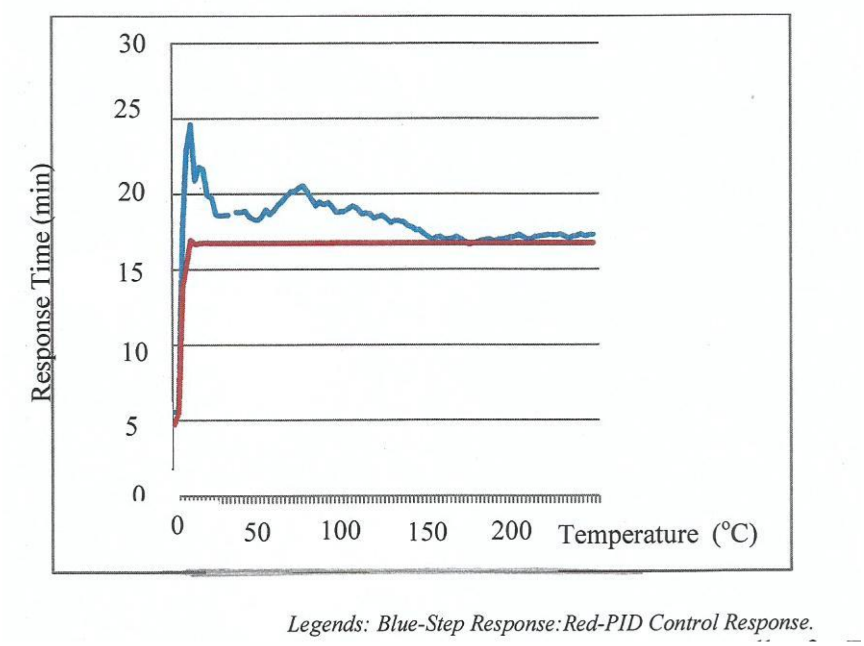

Figure 8: Step Response without and with PID Controller for Flexible Cable

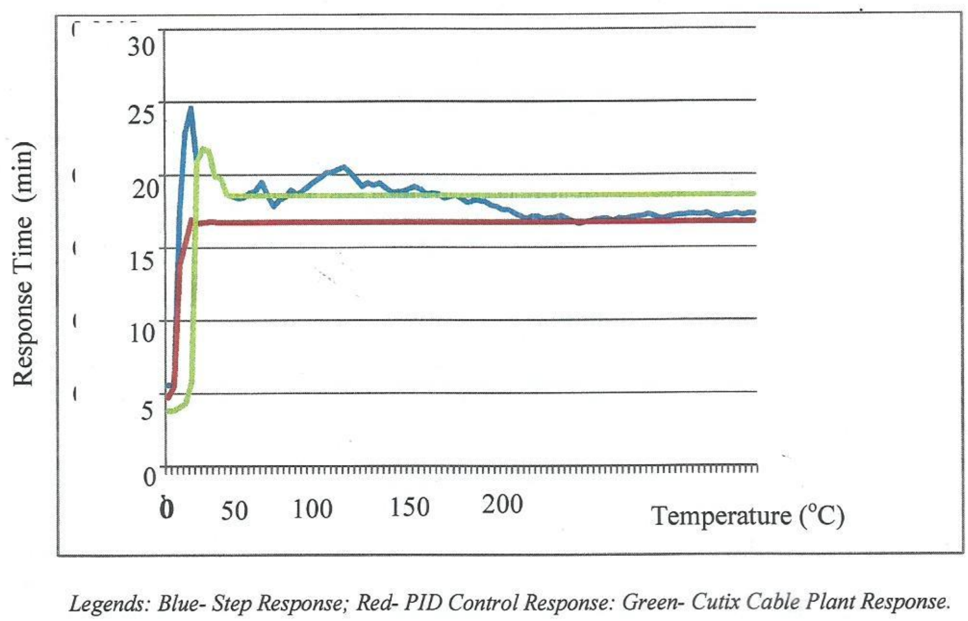

Figure 9: Step Response with PID Controller and Verification for Flexible Cable

Figures 8 and 9 show the response of the process plant response and the PID control for flexible cable.

Table 3: Performance Analysis

System	Rise time	Settling time	Overshoot	Remark
Without Controller	316 seconds	563 seconds	0 %	Slow and over damped
With Controller	0.0245 seconds	0.237 seconds	6.92 %	Fast and efficient

Table: 4: System Analysis in terms of ISE and IAE

Parameter	Value	Remark
ISE	0.007088	Minimized
IAE	0.02348	Minimized

Figure 8 is the step response of the extrusion process stem temperature of the extruder melt zone when the designed proportional integral and derivative (PID) controller has not been integrated with the extrusion process. It can be seen from the performance analysis table (Table 3) that the system rise time is 316 seconds; settling time is 563 seconds, and overshoot of 0 %. This transient response characteristics to a unit step input temperature shows that the system is slow, sluggish and over damped and as such requires it response time to be improved so as to have efficient and fast system that will quickly respond to a unit step input. This will ensure efficient and fast production in cable manufacturing.

In figure 9, the step response of the extrusion process temperature of the extruder melt zone with the designed (PID) controller integrated with the process plant. It can be seen from that the rise time has been improved to 0.0245 seconds, the settling time to 0.237 and overshoot to 6.92 %. This performance index shows that the compensated process is now efficient and fast. Hence the manufacturing process is now enhanced with the controller achieving the design specifications.

In terms of integral square error (ISE) and integral absolute error (IAE) as shown in table 4, it can be seen that a good compromise between reduction of rise time to limit the effect of large initial error, reduction of peak overshoot and reduction of settling time to limit the effect of small error lasting for a long time has been achieved by using the PID controller. Hence a minimized ISE and IAE were achieved. This indicates that the designed controller is efficient and can improve cable manufacturing efficiency.

Controller tuning allows for optimization of a process and minimizes the error between the variable of the process and its set point. Types of controller tuning methods include the trial and error method, and process reaction curve methods. The most common classical controller tuning methods is the Ziegler-Nichols. This method is often used when the mathematical model of the system is not available. The Ziegler-Nichols method can be used for both closed and open loop systems. A closed-loop control system is a system which uses feedback control. In an open-loop system, the output is not compared to the input.

The experimentally obtained controller gain which gives the stable and consistent oscillations for closed loop systems, or the ultimate gain, is defined as K_u. K_c is the controller gain which has been corrected by the Ziegler Nichols methods, and can be input into the overall equation. K_u is found experimentally by starting from a small value of K_c and adjusting upwards until consistent oscillations are obtained, and as shown in figure 10, if the gain is too low, the output signal will be damped and attain equilibrium eventually after the disturbance occurs.

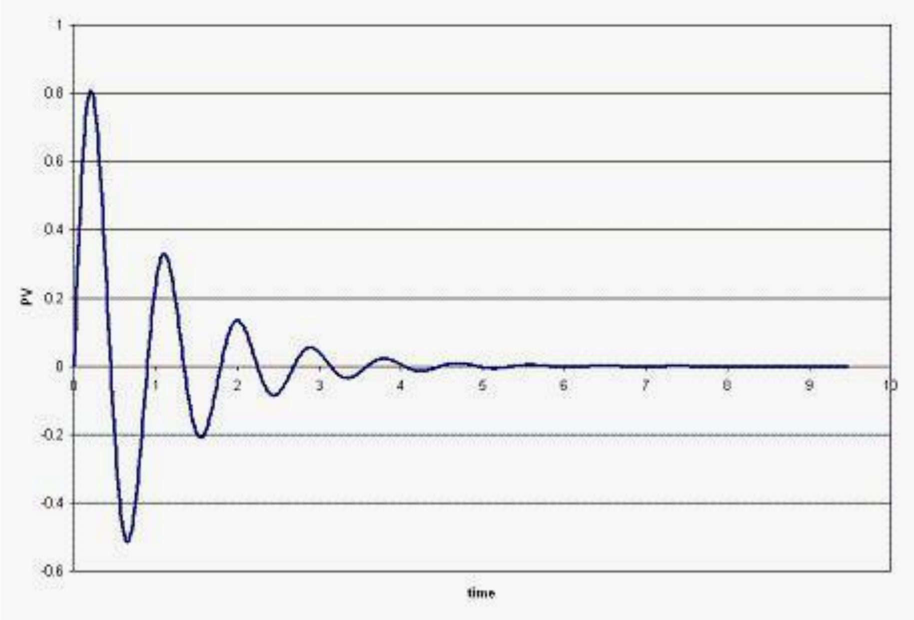

Figure 10: Process Variable vs Time - Oscillation Closed Loop for the System.

On the other hand, if the gain is too high, the oscillations become unstable and grow larger and larger with time as shown in figure 11.

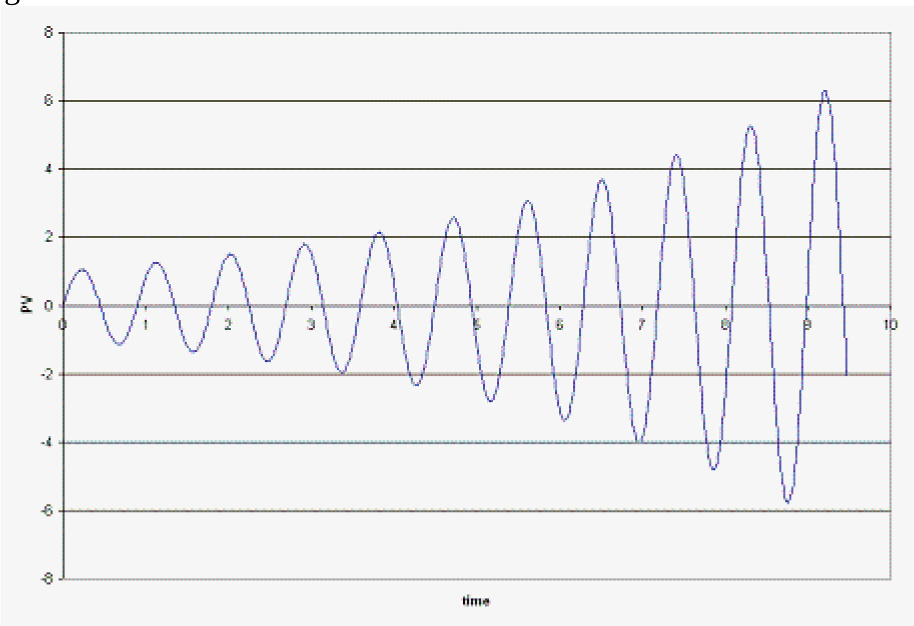

Figure 11: Process Variable vs Time - Unstable Response of the System.

Open loop systems typically use the quarter decay ratio (QDR) for oscillation dampening. This means that the ratio of the amplitudes of the first overshoot to the second overshoot is 4:1. This work was further validated with an actual cable manufacturing plant as shown in the result of figure 9. The response of the plant process of the manufacturing company compared with the step response and the PID implemented control response. It was shown that the PID control gives better performance, hence a homogeneous pallet coating of the cables for safety and reliability.

CONCLUSION

In industrial electric cable manufacturing, extruders are used extensively. There are several approaches to achieving efficient control strategy for industrial extruder in electric cable manufacturing. There are also many techniques available for quality cable manufacturing. In this work, temperature control in the melt zone of an extruder has been considered. The objective of the work has been significantly achieved. A dynamic model of a hot melt zone of an extruder was obtained. A proportional integral and derivative (PID) controller was developed using MATLAB software. The developed controller was added to the dynamic model of the extrusion process temperature at the hot melt zone. The resultant closed loop control system was implemented and the results obtained show that the controller efficiently and effectively improved the temperature performance of the system.

REFERENCES

Anthony, K. (2014), *Fundamental of PID Control*, PDH Center Publication, USA.

Atherton, D. P. (2014), *Almost Six Decades in Control Engineering*, IEEE Control Systems Magazine, Vol. 34, No. 6, pp. 103–110.

Bechhoefer, J. (2005), *Feedback for Physicists: A Tutorial Essay On Control,* Reviews of Modern Physics. Vol. 77, No. 3, pp. 783–835.

Covas, J. and Cunha, A.(2011), *Optimization in Polymer Processing*, Nova Science Publisher, Inc., pp.1 – 35.

Fountaine W. R. (1975), *Analysis and Modeling of the Dynamic Behavior of a Plasticating Extruder*, Ph.D, Thesis, University of the Ohio State.

Gardiner, R. A. (1975),*Extruder and Temperature Control Apparatus Therefor*, U.S. Patent.

Hornsey, S. (2012), *A Review of Relay Auto-tuning Methods for the Tuning of PID-type, Controllers*, Reinvention, Vol. 5, No. 2.

Introduction: PID Controller Design, www.ctms.engin.umich.edu/CTMS/index.php?example=Introduction&section= Control PID, Retrieved February 1st, 2019.

Khanam, P. and Almaadeed, M. (2015),*Advanced Manufacturing*, Polymer and Composites Science,Vol.1,pp. 63 – 79.

Kiam, H. A., Chong, G. and Yun, L. (2005), *PID Control System Analysis, Design and Technology*, IEEE Transactions on Control Systems Technology, Vol. 13, No. 4, pp. 559–576.

Ogbuagu, J. and Ogburubi, I. (2000), *Polymer Chemistry: Practice and Industrial Applications*, Optimum Press, pp. 1 – 127.

Ogunnaike, B. A. and Garge, M. D.(2010), *Inference-Based Scheme for Controlling Product End-Use Properties in Reactive Extrusion Processes*, Industrial Engineering Chemistry, Vol. 49, pp. 8021 – 8034.

Previdv, F., Savaresi, S. M. and Panarotto, A. (2006),*Design of a Feedback Control System For Real-Time Control Of Flow in a Single-Screw Extruder*, Control Engineering Practice, Vol. 14, pp. 1111 – 1121.

Steel, C., Leoro, M., Schmiele, M., Ferreira, R. and Chang, Y. (2011), *Thermoplastic Extrusion in Food Processing*, Thermoplastic Elastomers, Affiliation of State University of Campinas Brazil, pp. 5772 – 5874.

VanDoren, V. (2009), *Relay Method Automates PID Loop Tuning*, Control Engineering.

Wikipedia: *PID Controller*,www.en.wikipedia.org/wiki/PID_controller.