PID CONTROL OF INFRARED RADIATIVE POWER PROFILE FOR CERAMIC EMITTERS

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Abstract: This paper outlines the development and design of an infrared radiation heating profile controller. The study includes both the theoretical aspects of the design process as well as giving an overview of the practical facets involved. The controller was subjected to comparative testing with a proportional control model, in order to observe its performance and validate its effectiveness. The conclusions of these examinations do reveal the benefit of such a controller.

Keywords: infrared, controller, PID, temperature control, programmable

1. INTRODUCTION

In many industrial processes what is currently lacking is an effective and robust control of the infrared heating process. This study successfully developed a controller to achieve this. A programmable controller based on a closed loop control structure has been developed. Using the controller, the necessary referenced heating profile for various materials used in IR applications could be followed. A referenced heating (temperature) profile is a range of temperatures with a definite period that are necessary for the proper processing of a material (Altera, 1999). By automating the following of these profiles, industrial processes are more effective and efficient.

A need exists for these types of controllers and proved to be the motivation to embark on this investigation. Controllers of this nature that are commercially available either lacks the functionality of this unit or are too expensive to implement for research purposes (Gefran, 1999). This unit was designed with cost effectiveness in mind but still meet the standards required of an industrial style controller. The controller developed in this paper is able to within a fair degree of accuracy track a heating profile.

The results confirm that this programmable control model to be a benefit and a valuable tool in temperature regulation. This means that intensive studies into the effects of infrared radiation on materials are now feasible.

The controller developed in this study uses low cost digital components and power electronics techniques to improve the usefulness of an industrial IR emitter in infrared heating profile applications. The ability to control the input power to the IR emitter is through the mechanism of the pulse-width modulation (PWM) technique (Evalds, 2002). This technique varies the output temperature of an infrared emitter connected to the power controller. Although tests were conducted on this controller, they are not meant to serve as an exhaustive analysis.

In practical temperature control applications, the problem or difficulty is the incidence of thermal time lag, which leads to conditions such as overshoot and temperature cycling. These effects are of acute importance when the product being processed or heated is temperature sensitive and in danger of being damaged in this way. While lag is usually unavoidable in a practical process, there are ways of limiting it.

For accurate control of the load temperature an effective controller is required. A closed loop proportional integrated controller (PID) satisfies this need by providing a stable regulated temperature control. It is well known that temperature loop dynamics can be slow because of process heat transfer lags, which is the case in medium and long wave infrared heaters.

2. PID CONTROL

For optimal performance the type of heater chosen for a system should be one that has a low thermal mass (fast reaction time) or the temperature sensor employed should have a fast reaction time. Optical sensors when compared to other forms of sensing, such as thermocouples, provide the quickest temperature measurements and are consequently the type used in this paper (Ackland, 1998).

The PID controller required in order to satisfy the above criteria should be capable of reducing the heater power well ahead of the temperature reaching set point. This means that the power has to be minimised in proportion to the distance from the set point. This way the controller is capable of preventing temperature overshoot and cycling.

To automatically and continuously adjust the temperature by adjusting the power input, an integral action is needed. The controller needs to make the power increase in proportional to the deviation from the set point, so that the steady-state error is reduced to zero. The steady-state error is that deviation between system output and input after transient effects have died away.

With the addition of derivative control, the controller anticipates changes in temperature and modifies the input power proportional to the rate of change of temperature. The purpose of this type of action is to minimise and damp unwanted changes and speeds recovery from temperature disturbances, which is effective during transient periods. The ensuing controller known as proportional + integral + derivative (PID) control combines the advantages of the three individual control actions.

If a mathematical model of the plant is not known, then it is possible to apply diverse design techniques for determining parameters of the controller that will satisfy the transient and steady state specifications of the closed-loop system. The simplest approach in the design of PID controllers is an experimental one.

The process of selecting the controller parameters in order to obtain the required performance conditions is known as controller tuning. Ziegler-Nichols proposed rules for determining values of the proportional gain K_p, integral time T_i and derivative time T_d, based on the transient response characteristics of a given plant (Leigh, 1988). The transfer function $G_c(s)$ of the PID controller is given as:

$$G_c(s) = K_p\left(1+\frac{1}{T_i s}+T_d s\right) \qquad (1)$$

3. CONTROLLER DESIGN

3.1 Identification of the infrared heater

In order to obtain a mathematical description of the IR heater, a transfer function, the method outlined below was completed. This method is the Ziegler-Nichols design approach. Known as the process reaction method, it requires the open-loop step response of the process to be recorded and is a practical means of acquiring the transfer function of the IR heater.

There are two methods for Ziegler-Nichols tuning, both aimed at obtaining 25% maximum overshoot in step response. The process reaction method was chosen because the curve resulting from a unit-step input resembled the S-shaped curve characteristic of this method (Katsuhiko, 1990).

The type of IR heater used was a medium wave infrared ceramic type. The S-shaped curve is characterised by two constants, delay time L and time constant T. By drawing a tangent line at the inflexion point of the S-shaped curve and determining the intersections of the tangent line with the time axis and the line $c(t) = K$, the values for the delay time and time constant are determined. The transfer function $G_p(s) = C(s)/U(s)$ is approximated by a first-order system with a transport lag.

3.2 Experimental Results for Step Response of Plant

The open loop step response of the IR heater under test resulted in the curve shown in the figure 1 below. Using the Ziegler-Nichols process reaction method as described above, the plant (infrared heater) was found to have an approximate transfer function as expressed by equation 2.

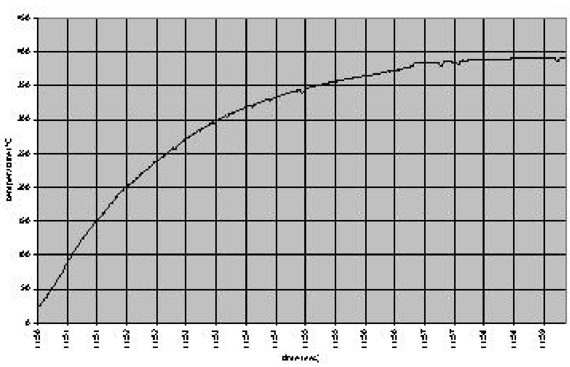

Fig. 1 Step response of plant (IR emitter)

In order to verify the validity of equation 2, a simulation using MATLAB was performed. This resulted in the curve in figure 2, which is a close approximation of figure 1. Although the trajectory was a fairly accurate one, a slight adjustment of the gain, K_p, from 3.96 to 4.2 provides a better estimation of the step response.

$$G_p(s) = \frac{3.96e^{-7s}}{140s+1} \qquad (2)$$

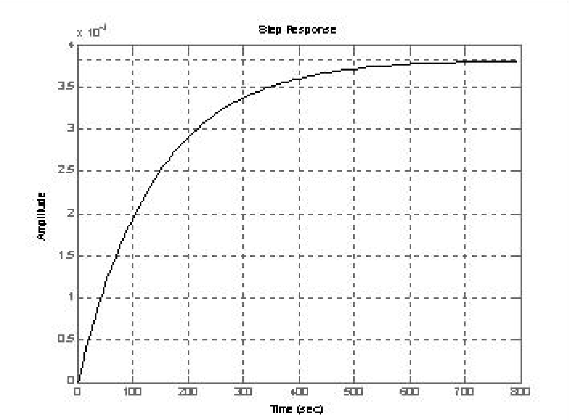

Fig. 2 Matlab verification of step response of plant in fig. 1.

3.3 Design of a Continuous Controller and Discretisation

From the general form for a PID controller in equation 1, the expression for the continuous PID controller is given.

$$G_c(s) = 6.06\left(1 + \frac{1}{14s} + 3.5s\right) \qquad (3)$$

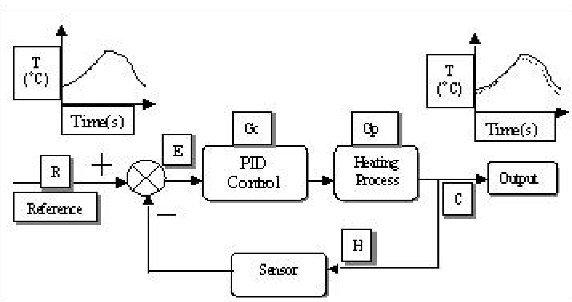

Fig. 3 Control system for the IR controller

In order to implement the controller on a digital platform, discretisation of the continuous expression is needed. There are various ways to do this, but two methods dominate. The first method is known as the *position* implementation since it controls the output of the controller, is given in equation 4. Using this method the actuator value, u_k, is derived for directly. Equation 4 is given as:

$$u_k = u_{k-1} + K_p(e_k) + \frac{K_p T}{T_i}(e_k) + \frac{K_p T_d}{T}(e_k - e_{k-1})$$

Position implementation although simple to implement suffers from some drawbacks. When the controller is switched on for the first time, the values of u_{k-1} and e_{k-1} are not known. The chance that by simply implementing equation 4 and obtaining a proper controller output is very remote. As a result the control action of the position implementation suffers from a 'bump'.

In addition another problem with equation 4 known as integral windup occurs when the actuator encounters a constraint, which then produces a persistent offset between the plant output and the set point. This then results in the integral term increasing without bound over time. Reconfiguring equation 4 the problems highlighted are overcome. Equation 5, known as the *velocity* implementation, computes the increment or change of the actuation rather than the actuation itself. Equation 5 is given as:

$$u_k - u_{k-1} = K_p(e_k - e_{k-1}) + \frac{K_p T}{T_i}(e_k) + \\ + \frac{K_p T_d}{T}(e_k - 2e_{k-1} + e_{k-2})$$

The equation 5 produces a 'bumpless' transfer when it computes the increment of the output of the controller. Using equation 3 and the Ziegler-Nichols tuning rules, the coefficients K_p, T_i, T_d are solved for. The sampling period, T, is set initially to 1 second. The resultant expression for the controller based on these values is given in equation 6. Equation 6 is given as:

$$u_k = u_{k-1} + 27.7(e_k) - 48.5(e_{k-1}) + 21.2(e_{k-2})$$

Equation 6 is a discrete form of a linear difference equation that is sampled at a particular period and provides discrete values for actuator output. In order to directly implement equation 6 on a microcontroller, a preliminary understanding of this difference equation is warranted. This expression incorporates values for previous error calculations as well as a previous value for the actuator output. These values need to be stored in on-board memory and be available when the final output is evaluated.
The chosen method for the programming of the algorithm was the high level language, C, because of its powerful ability to compute mathematical intensive calculations and operations involving floating point operations are straightforward. These features are notably absent in the use of an assembly language.

Achieving a 'bumpless' transfer requires that when evaluating equation 6, two sampling intervals are passed before entering the control loop. This allows the values for the previous errors, e_{k-1} and e_{k-2} as well as the previous actuator output, u_{k-1}, to be computed. The algorithm for the velocity implementation of the PID controller is given below.

The algorithm functions as follows:

- After variables and functions to be used are initialised, the program waits for the user to enter a value for the set point temperature, via an interrupt service routine (ISR).
- When this is done the program within two sampling periods, measures the heater temperature via the ADC and calculates the two previous error values, e_{k-1} and e_{k-2}, as well as the previous actuator output, u_{k-1}.
- The program then enters the main PID loop and calculates the value of the actuator deviation.
- If the actuator deviation is a positive value (> 0), an appropriate the pulse-width modulation of the firing pulse is determined dependent on the actuator deviation.
- If the actuator deviation is negative or equal to zero (<= 0), no firing pulse is initiated.
- The program waits for the sampling period to complete before taking another measurement of the heater temperature and repeats the loop.

A complete listing of the C code for the PID controller designed is provided in another publication. An excerpt of the source code given below shows how the value for e_{k-2} is evaluated.

```
y_out = ADC();            /*sample output*/
error_0 = r_in - y_out;   /*compute error*/
error_2 = error_0;        /*set error equal to second
                                  previous error*/
```

The following excerpt shows how e_{k-1} is computed.

```
y_out = ADC();            /*sample output*/
error_0 = r_in - y_out;   /*compute error*/
error_1 = error_0;        /*set error equal to first
                            previous error*/
```

The value for u_{k-1} on start-up is derived using the source code described below.

```
u_old_1 = 28*error_0;
u_old_2 = 49*error_1;
u_old = u_old_1 + u_old_2;        /*compute
                            previous actuator output*/
```

After the initialisation routine has completed the program proceeds to the main control loop. With every sampling interval the PID model in equation 6 is evaluated and an increment of the actuator output computed. An excerpt of the source code used to achieve this is given below.

```
y_out = ADC();                    /*sample
output*/
error_0 = (r_in - y_out);   /*compute error*/
u1 = 28*error_0;
u2 = 49*error_1;
u3 = 21*error_2;
u = u1 + u2 + u3 + u_old;  /*compute actuation*/

/* The computation of the incremental actuator
output */

u_delta = (u - u_old);
```

The implementation of the PID controller designed for this paper is based on the Ziegler-Nichols method and represents a significant simplification when compared to some of the other methods available. Especially considering that the system derived for the plant was a first order model plus lag. Other tuning methods available are:

- Trial and error method, whereby the tuning parameters are tweaked and continually adjusted. This method is usually reserved for experienced control engineers.
- Graphical design methods, which include the root-locus, Nyquist and Bode plots. These methods are usually reserved for higher order systems.

The Ziegler-Nichols tuning method was selected because it is the oldest and most established method available. It is also much more simpler to implement than the other methods listed above. Many modifications of the controller developed are possible and probably warranted in some instances. However, for the purposes required of this controller in this study, the design proved adequate.

4. COMPARATIVE TESTING OF PID AND ON/OFF CONTROLLERS

In order to gauge the effectiveness of the PID controller developed, a simpler proportional type of controller was designed to serve as a basis for comparison. The *on/off regulator* does not require the same intense computations as that of the PID instituted. The on/off algorithm simply ensures that the set point temperature is maintained within reasonable limits. The algorithm does not adjust the pulse-width of the firing pulse when increasing the temperature, as in the case of the PID algorithm.

A brief explanation of the on/off algorithm is as follows:

After the initialisation of the variables and functions used, the program executes with the set point as zero, until the user enters a temperature set point above zero.

- The heater temperature is sampled and an error is generated. If the error is positive (> 0), a firing pulse is initiated, however if the error is less than or equal zero (<= 0), no firing pulse is initiated.
- The program waits for the sampling period to complete before taking another measurement of the heater temperature and repeats the loop.

Laboratory tests have been performed using both the PID and on/off controllers. Each controller was set to follow a predetermined temperature profile and the results plotted on MsExcel charts. Figure 4 illustrates the laboratory set up for the IR heater and the Raytek temperature sensor and how they were arranged in order to complete the tests outlined below.

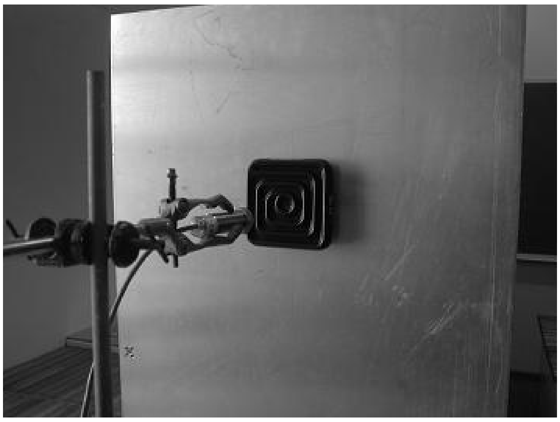

Fig 4. Laboratory arrangement of IR emitter and temperature sensor

The infrared heater was aligned and fixed to an aluminium plate. The reason for the aluminium used, was that it possesses a low emissivity and a high degree of reflectivity. Since the temperature sensor is a function of the emissivity, only the emissivity from the IR heater then has a bearing on the temperature reading.

4.1 Results of comparative tests of PID vs. Proportional controller

The comparative tests performed utilised two sampling periods, a period of 100ms and another of 1s. Figure 5 illustrates a curve traced from a temperature set point of 40ºC to another at 200ºC, with a sampling period of 1s.

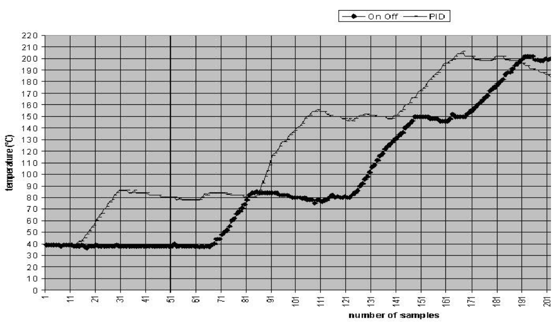

Fig. 5 Comparative test of PID (--) vs. P (**--**) controller at a sampling period of 1s.

The results given in table 1 in fact show that the proportional controller (on/off) out-performs its PID counterpart. A sampling period of 1 second does not represent a practical situation and for an industrial type controller the sampling periods need to be considerably increased.

Table 1 Comparison of PID and P controllers at a sampling period of 1s

	PID controller	P controller
% Overshoot (100ºC)	8%	3%
Temperature offset (220ºC)	8ºC	4ºC
Rise time (sec) (100ºC to 220ºC)	38sec	57sec

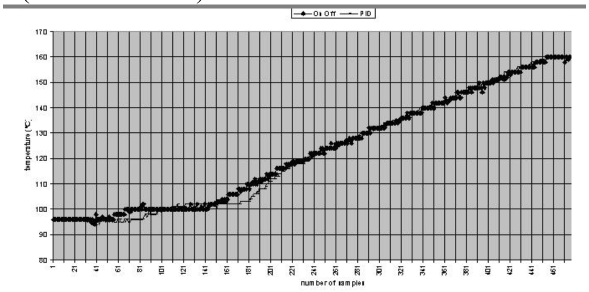

Fig. 6. Comparative test of PID (--) vs. P (**--**) controller at a sampling period 100ms

The sampling period was then increased to 100ms and the curve in figure 6 then resulted.

Table 2 summarises the results of this comparative test. The results clearly demonstrate the improved performance of the PID controller over its P (on/off) counterpart. The results indicate a decrease in the rise time and less temperature offset of the PID controller with respect to the on/off or P controller.

Table 2 Comparison of PID and P controllers at a sampling period of 100ms

	Interval	PID	On-off
% Overshoot	100ºC	1%	0%
	160ºC	0%	0%
Temperature offset	100ºC	2ºC	3ºC
	160ºC	0ºC	2ºC
Rise time (sec)	100ºC to 160ºC	284s	312s

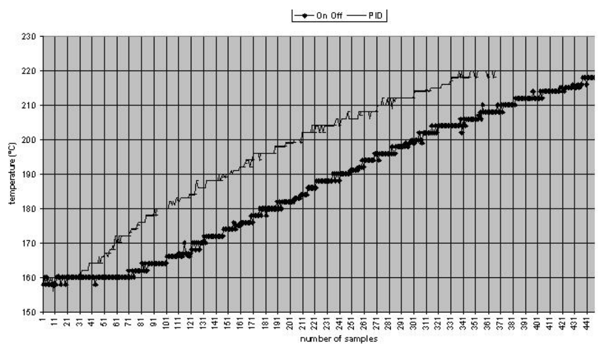

Fig.7 Comparative test of PID (---) vs. P (**--**) controller at a sampling period of 100ms.

The curve in figure 7 presents trajectory from a set point temperature of 160ºC to 220ºC, with a sampling period of 100ms. From this figure its is also evident that there is a marked improvement in the rise time in the PID controller as opposed to the on/off proportional controller. This leads to the conclusion that with an increased sampling period the PID controller implemented for this paper exhibits an improved performance when compared to a simple on/off controller.

5. CONCLUSION

This report is based on theoretical and practical work regarding the design of an infrared radiation heating profile controller. Both modeling and experimental techniques have been employed. The focus has been on developing a programmable and cost-effective controller. This study considered only electric infrared heaters.

A model for a temperature profile controller for an infrared radiation heater has been proposed. The model is based on a proportional-integral-derivative (PID) control structure. The PID control design is the oldest and most widely used form of control in industry. Temperature control is particularly suited to this type of design. Ziegler-Nichols methods have been employed because of their simplicity and effectiveness. The Ziegler-Nichols method is another tried and trusted technique used for many years by control engineers. The controller developed though only a simplified first order model with lag, proved very effective for the purposes of temperature profiling.

The results obtained from comparative tests performed revealed the high efficiency of the PID model relative to an on/off controller. The tests using a sampling period of 100ms, although they only covered a restricted temperature range, exposed the improved performance of the PID design over its on/off counterpart. Although extensive tests have not been conducted on the controller for the purposes of this study, the PID model showed promising results. Elaborate testing and verification of the results are left as a suggestion for any further work and study.

6. ACKNOWLEDGEMENT

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