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Analysis of the efficacy of a simplified infrared energy management system

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Abstract
This paper summarizes a comparison of an always-on and a programmable type industrial style infrared dryer. The load power supplied for each kind of dryer is analysed. The design and implementation of an infrared radiation controller is also presented. The study includes both the theoretical aspects of the design process as well as an overview of the practical facets involved. The infrared drying system controller was subjected to comparative testing with an on/off control model, in order to observe the controller's performance and validate its effectiveness. The proposed controller contributes to a more energy efficient drying system than the always-on techniques that are employed to fluctuate the heater temperature.

Keywords: infrared dryer, programmable controller, temperature control

1. Introduction

Many commercial industries are increasingly making use of infrared technology as a means of improving their processes. Numerous applications are found in industries involved in curing (Véchot et al., 2006), drying (Sharma et al., 2005) and heating (Deans et al., 2006).

Many industrial infrared drying or heating systems work on an always-on approach. The dryer is set to its maximum power output and left in this state for the duration of the process. The manner in which the process is controlled is done by varying the speed of the process. The product to be dried or heated is either moved slower or faster, on a conveyor, through the oven. A question arises as to whether this is an energy efficient practice. These types of ovens often require a large amount of floor space and are optimised and dedicated for the process. However, an oven that requires less space and has the ability to be programmed for many different types of processes, can present a versatile option.

This study successfully developed a controller to achieve an effective and robust control of the infrared heating process. 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 infrared (IR) applications could be followed (Altera, 1999). A referenced heating or temperature profile is a range of temperatures referenced to time. These profiles are necessary for the proper processing of many materials in manufacturing (Su *et al*., 1997 and Adonis and Khan, 2001). Through the automation and accurate tracking of these profiles, industrial processes can be made more effective and efficient.

The controller developed in this paper is able to accurately trail a heating profile. The results confirm this programmable control model to be of benefit to and a valuable tool in temperature regulation. The applications for this control system, although numerous have been limited for the purposes of this study, to fruit drying. Many instances of fruit drying using infrared radiation can be found in the literature (Meeso et al., 2004, Togrul, 2005 and Wang and Sheng, 2006). These studies also show infrared radiation, as a drying method, to be comparable to convective and solar drying processes. The convective drying method uses the movement of hot air to dry the fruit.

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 derived from the mechanism of the pulse-width modulation (PWM) technique (Evalds, 2002). This technique varies the output temperature of a long wave infrared emitter connected to the power regulator. 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 easily damaged (CIRAS, 2005).

For accurate control of the load temperature an effective controller is required. One type of control method used in this study is a closed loop proportional integral derivative (PID) controller that satisfies the requirement of 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 long wave infrared heaters. Another type of control method addressed is an on/off control mechanism. This simplified control mechanism is contrasted with the more complex implementation of the PID controller. The complete dryer system incorporating the feedback control mechanism is further evaluated for energy savings when compared to an always-on dryer model.

2. Experimental system

The dryer is configured as a batch type dryer with an open cavity for easy access of the loading tray. The long wave infrared ceramic heaters (Figure 1) are arranged in a grid at the top of the fruit directing the infrared radiation directly down onto the fruit. The convective element with fan is situated at the back of the dryer, blowing hot-air over the fruit and out of the cavity. Figures 1 and 2 show the ceramic heaters arranged in a grid and the experimental dryer setup respectively.

Figure 1: Infrared ceramic heaters

Figure 2: Experimental setup

3. Programmable 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 study (Ackland, 1998). The emissivity of the ceramic heaters is given by the manufacturer. The emissivity is the ratio of the energy radiated at a given temperature by an object to that of a blackbody at the same temperature. The emissivity of a material can be determined by using an array of different methods (Schmugge *et al.*, 2002 and Wen & Mudawar, 2006).

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 proportion 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.

3.1 Controller design

3.1.1 Design of a continuous controller and discretisation

To measure the performance of the controller proposed, the setup illustrated in Figure 1 was employed to generate comparisons between input (R) and output (C). From the general form for a PID controller, the expression for the continuous PID controller is given. Using the Ziegler-Nichols tuning rules (Ogata, 1990), a step response of the plant (heaters), the coefficients K_p, T_1 and T_d are solved for in equation 1.

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

The resultant discretisation expression for the controller based on these values is given in equation 2 as:

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

With the actuator output u_k and previous actuator value u_{k-1} which are evaluated in terms of the error value e_k and previous error values e_{k-1} and e_{k-2}.

Equation (2) is a discrete form of a linear difference equation that is sampled at a particular period and provides discrete values for actuator output.

The implementation of the PID controller designed for this paper based on the Ziegler-Nichols method, 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.

3.2 Comparative testing of PID and on/off control

In order to gauge the effectiveness of the PID controller developed, a simpler on/off 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.

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.

3.2.1 Results of comparative tests of PID vs. on/off controller

The comparative tests performed utilised two sampling periods, a period of 1 second and another of 100 ms. Figure 4 illustrates a curve traced from a temperature set point of 100°C to 220°C with a sampling period of 1 second. The results given in Table I summarily show that the on/off controller out-performs its PID counterpart.

Figure 5 shows a curve between a temperature set point of 100°C to 160°C with a sampling period of 100 ms. The curve in Figure 6 presents trajectory from a set point temperature of 160°C to 220°C, with a sampling period of 100 ms. Table 2 summarizes the results of this comparative test. The results demonstrate the improved performance of the PID controller over its on/off counterpart. The results indicate a minimal decrease in the rise time and temperature offset of the PID controller with respect to the on/off controller.

From these figures it is also evident that there is some incidence of ringing with the on/off control and a minimal improvement in the rise time and stability of the PID controller as opposed to the on/off controller.

This leads to the conclusion that the PID controller implemented for this paper does not exhibit a significantly improved performance when com-

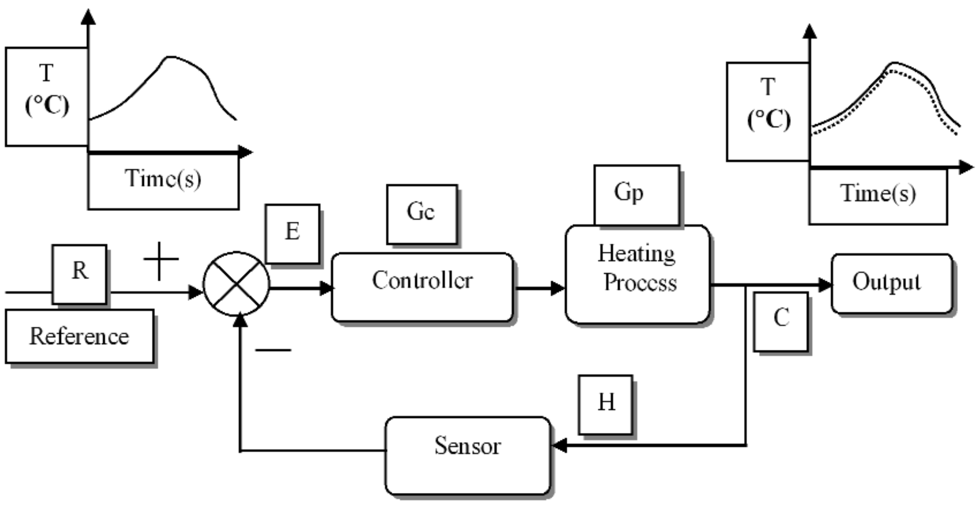

Figure 3: Control system for the IR controller

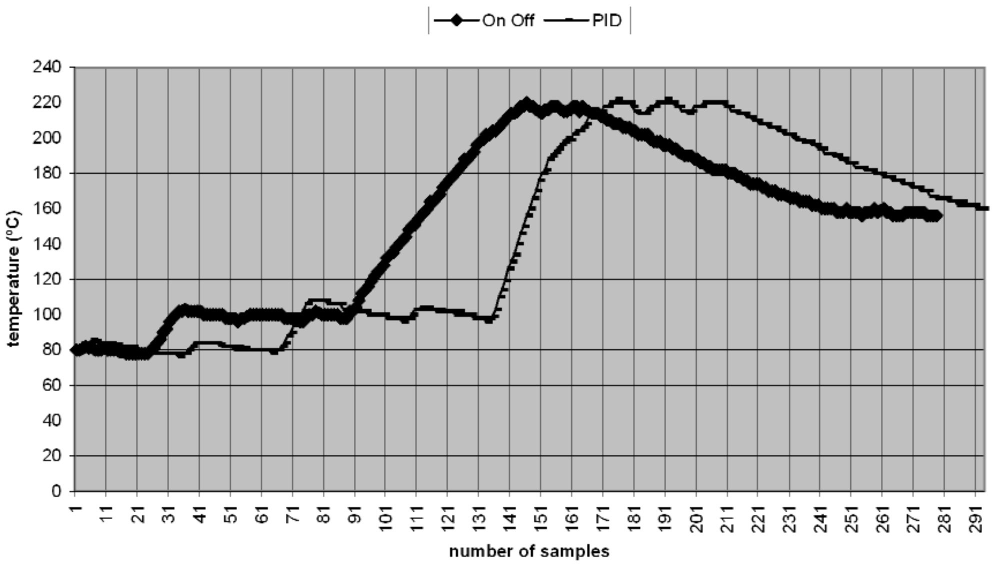

Figure 4: Comparative test of PID vs on/off control at a sampling period of 1 sec

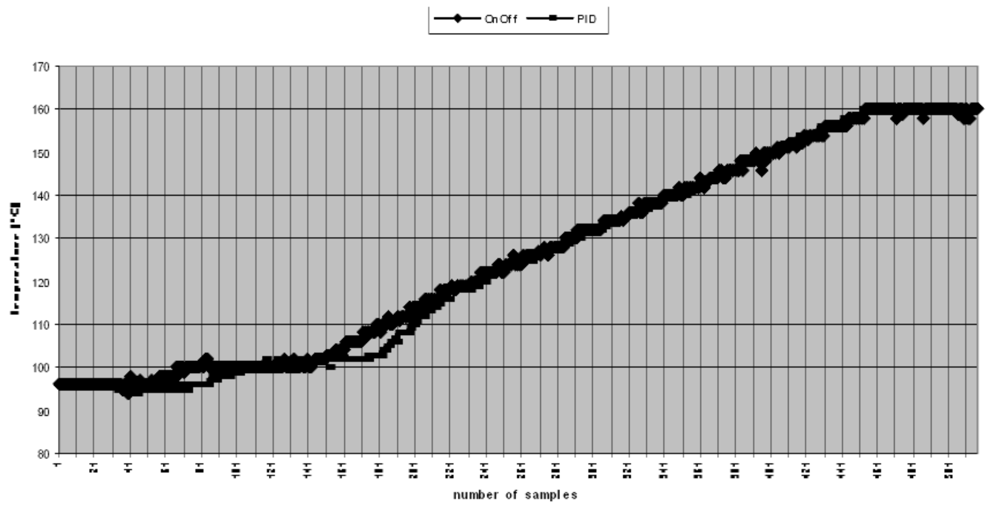

Figure 5: Comparative test of PID vs. on/off control at a sampling period 100 ms

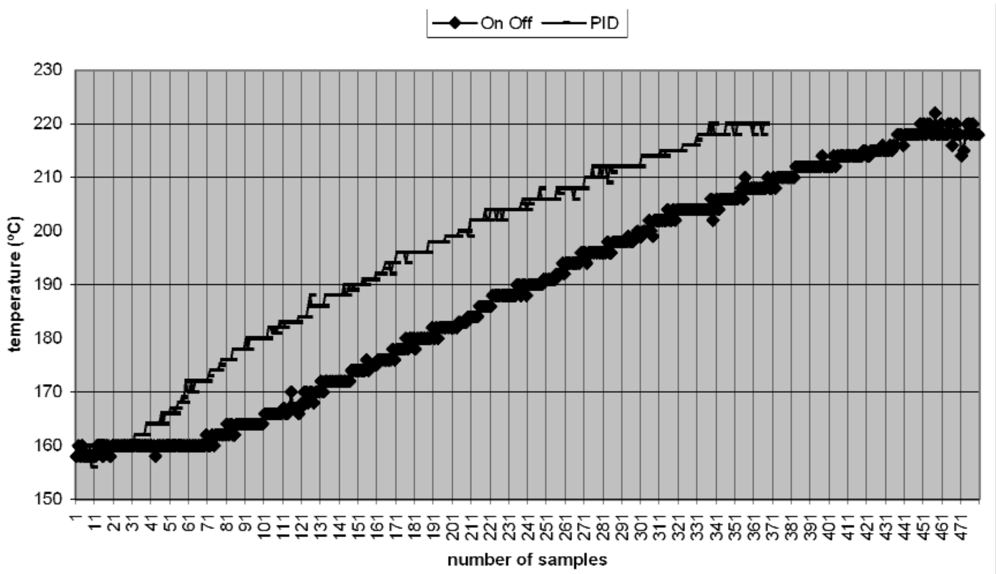

Figure 6: Comparative test of PID vs. on/off control at a sampling period

pared to the simple on/off controller. Furthermore, a simple on/off controller would be adequate for implementation in an industrial drying process.

Table 1: Comparison of PID and on/off controllers at a sampling period of 1 sec

	Set-point	*PID Controller*	*On/off Controller*
% Overshoot	100°C	8%	3%
Temperature offset	220°C	8°C	4°C
Rise time (sec)	100–220°C	38 sec	57 sec

Table 2: Comparison of PID and on/off controllers at a sampling period of 100 ms

	Interval	*PID Controller*	*On/off Controller*
% Overshoot	100°C	1%	0%
	160°C	0%	0%
Temperature offset	100°C	2°C	3°C
	160°C	0°C	2°C
Rise time (sec)	100°C to 160°C	284 sec	312 sec

4. Heater efficiency comparisons

Industrial installations employing an industrial dryer or heater application are under increasing pressure to reveal their energy efficiency capability.

An example of an infrared drying application implementing a 6.4 kW capacity is presented. The system was implemented with a 230 V supply for a grid of 16 x 400 W ceramic infrared heaters.

4.1 Load power comparisons

The curves presented in Figures 7-10 indicate the principle of using power efficiently. Always on approach, the heater power output would be 6.4 kW all the time and demanding a constant 28 amps from the supply. In order to process a particular material at a range of temperatures or a specific temperature, the material would have to be moved through the dryer faster or slower. This is to ensure that the heaters provide the material with the only the exact required amount of heat necessary for its processing.

Contrast this action with the programmable controlled dryer which is capable of varying the heater temperature and provides the material being processed with the exact required amount of heat necessary at that required instant for its processing, but at a lower power output demand from the supply.

By programming the dryer system the user is able to control the heating process through manipulating the infrared heater power output as indicated below:

- At a load power demand of 75% of the total power, only 4 800 W heater power is delivered. This saves the process 1 600 W for that particular timeframe.
- When 50% of load power is required, the load will only deliver 3 200 W to the process, saving 3200 W.
- At 25% of load power only 1 600 W is delivered to the load, saving the process 4 800 W.

Figure 11 graphically illustrates the heater power output demand comparisons. In the light of South Africa's current energy crisis, this type power demand complements the electricity utility's current load requirement. This strategy reduces peak load demand throughout the day and allows the electricity utility not to operate at maximum capacity but to

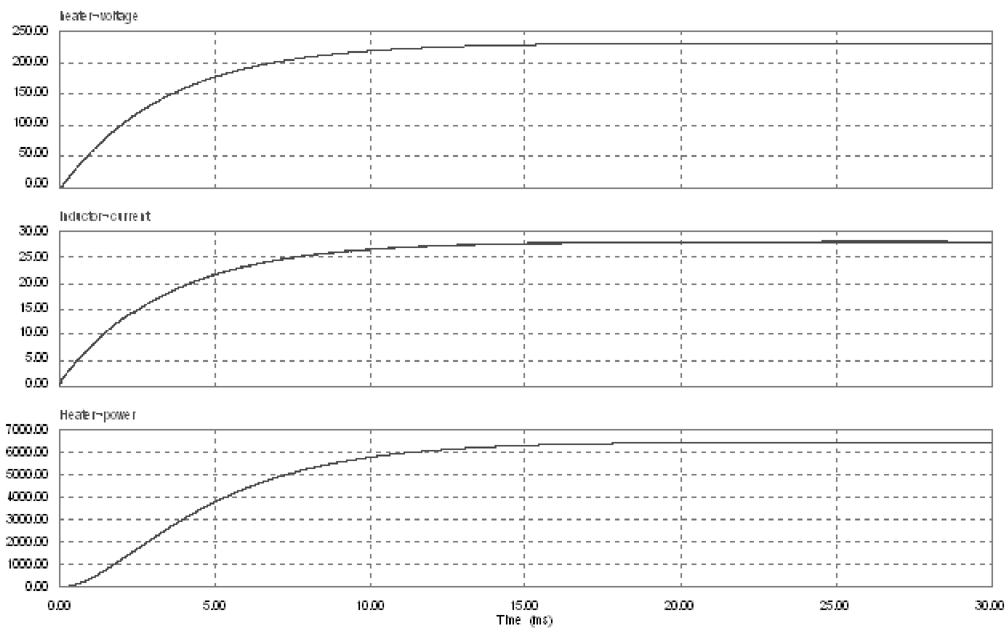

Figure 7: Heaters at 100% power

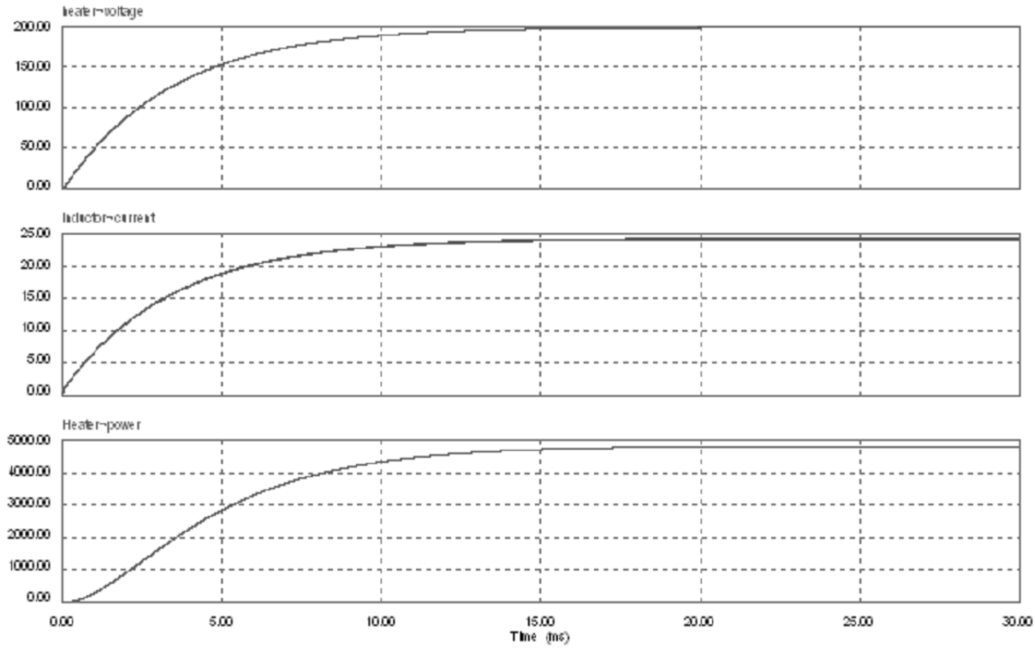

Figure 8: Heaters at 75% power output

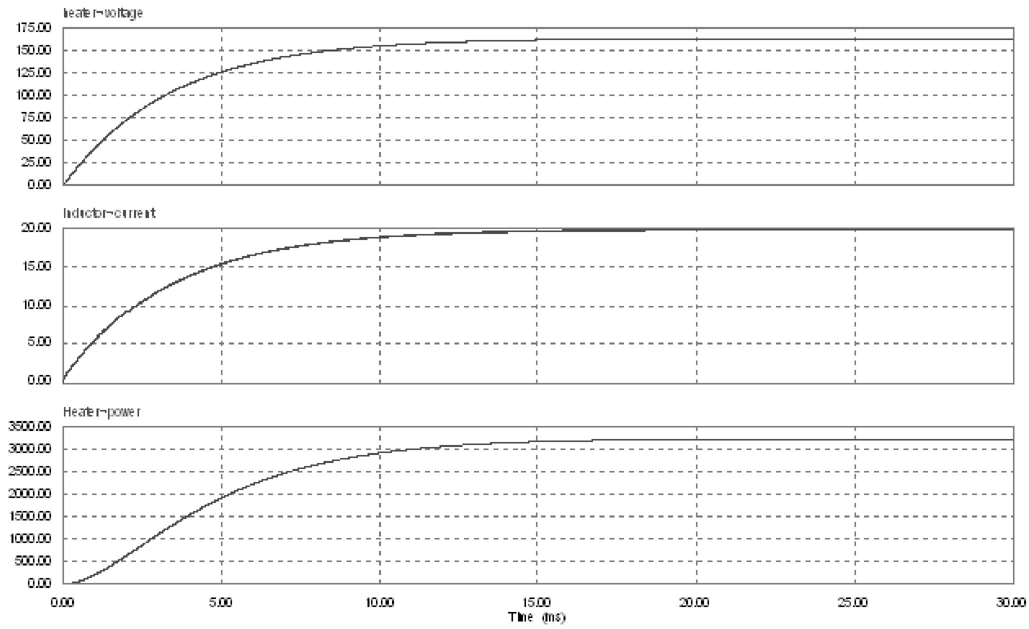

Figure 9: Heaters at 50% power output

function with reserve capacity, which should reduce the incidence of power outages and the need for load-shedding.

With the feedback controlled scheme the system conforms to the simplest of energy saving principles: use energy only at the precise time, the precise place and in the particular amount that is required for the process to be completed (Pehanich, 2005).

Another advantage of this type of control is that it demonstrates the versatility of this kind of dryer. The dryer due to its programmability is able to be used in an assortment of processes. Reprogramming the algorithm for a different type of material or process is the only restriction of the system. This also demonstrates the cost-effectiveness of this type of dryer because a completely new oven is not required if the specifications of a process is changed or a new process is added.

5. Conclusion

This paper highlights the comparison of a system utilizing a programmable control mechanism as

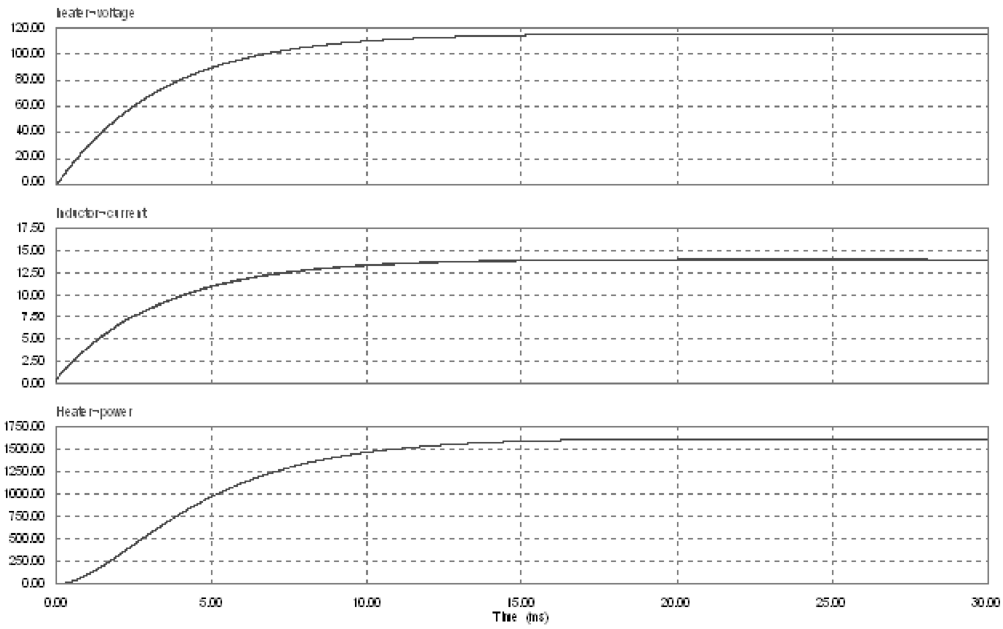

Figure 10: Heaters at 25% power output

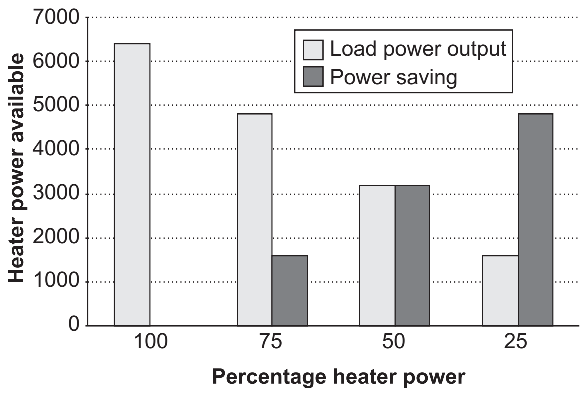

Figure 11: Heater power output demand comparisons

opposed to that of an always-on method. Significant power savings are possible with the programmable structure. Another benefit of this method of control is that the resultant system is versatile in its applications, providing the unit with more flexibility and making the unit more cost-effective.

The paper also presented theoretical and practical work regarding the design of an infrared radiation controller. Both modelling and experimental techniques are employed. The focus has been on developing a programmable and cost-effective controller. This study considered only electric infrared heaters.

Two models for a programmable temperature controller for an infrared radiation heater have been proposed. The first model is based on a proportional + integral + derivative (PID) and the other on an on/off control structure. The on/off controller in this instance of temperature control was found to be suitable and showed that the PID controller had no significant improvement over that of the simpler on/off controller.

A suggestion for further improved performance of the dryer is to incorporate air re-circulation by returning part of the expelled warm air into the cavity. This method should provide an increased energy saving compared to the existing dryer model, because the air temperature in the cavity would be increased thus requiring less heater power to keep the cavity at the same temperature.

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