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Sliding Mode Temperature Control for Hybrid Solar/Electricity Oven

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Abstract

This work presents sliding mode temperature control for hybrid solar/electricity oven. The system is primarily power by solar thermal air collector and solar photo-voltaic and supplemented by electricity utility on periods of little or no insolation. Solar thermal storage method is also shown. Sliding mode control (SMC) method is compared to PID control method on paint curing oven model using MATLAB/Simulink. The simulation results show that SMC has better performance due to its fast rise time of less than two minutes as against 195 minutes with PID controller. A flat-plate collector and paint curing oven has been built. From experimental results, the collector supplied 43.27% of the heat energy required to operate the oven at a temperature of 120℃. The SMC controller implementation is based on micro-controller programed in C++. The controller can automatically maintain different temperature levels for specified durations because it accepts multiple reference inputs. Return on investment calculation shows that the system has payback period of sixteen month.

Keywords: *Sliding Mode Control, Multi-Temperature-Level, Equivalent Control, Switching Control, Paint Cure.*

1. Introduction

Many industrial and domestic devices ranging from kiln, furnace, boiler, oven, to microwave oven in the kitchen required heat energy and proper control to function. Some of these devices are operated at multi temperature levels. In paint curing process for instance, temperature may require to be maintained at certain level for a particular duration before proceeding to another level due to melting and re-solidifying. Paint curing is the process of converting applied wet or powdered paint to dry and hard film. Paint may cure by solvent loss, chemical reaction, oxidation, melting and re-solidifying, or melting and crosslinking [1]. It may take few hours for liquid paints to dry but it takes days to months for proper cure (to harden). To reduce cure time, paint curing ovens are used where the process is sped up under elevated temperature [1, 2]. Some of the major challenges of multi temperature level devices are precise temperature control and automation of the temperature level change. There are various temperature control methods such as traditional PID control system, Adaptive and Fuzzy Algorithm, fuzzy-PID control system, PLC temperature control, Versatile temperature control, etc. [3, 4, 5, 6, 7, 8] that have been proposed in other works. These proposals may be satisfactory, however, the results obtained from their applications show slow response time, delayed settling time, high overshoots and oscillations outside the acceptable limits of modern car paints. Therefore, these control techniques have not adequately match up with the constraints in modern coatings where tolerance limits have become much tighter from ±14°C in liquid-based paints to ±5.6°C in organic and powder paints, [2, 9]. Hence a robust control method that can track the reference input(s) faster and more accurately is desired; as well as a technique that can automatically select reference input temperature level.

Moreover, the enormous heat energy required to operate these devices made them not only expensive but also less attractive to small and medium scale enterprises (SMEs).

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This work proposes to apply sliding mode control technique to paint curing oven temperature control in other to overcome the inefficiencies of existing control methods; automate the transition of the system from one reference input to another and use renewable energy source, which is cheap and available as the main source of heat energy supply.

2. Methodology

2.1. Overview of the system

Hybrid solar thermal/electricity paint curing oven system is illustrated in Figure 1. It consists of solar thermal heating system, electric heating system and the convective oven system. The solar thermal system is made up of solar thermal collector, heat exchanger, pumps and storage tanks. There are different types of solar thermal collector design available; here a flat plate solar collector is presented. The absorber is metal pan coated with black substance that can absorb solar radiation in the form of heat. The heat energy is trapped within the hydraulic space (between the glazing and the absorber) and the inlet air is heated up as it passes through the space.

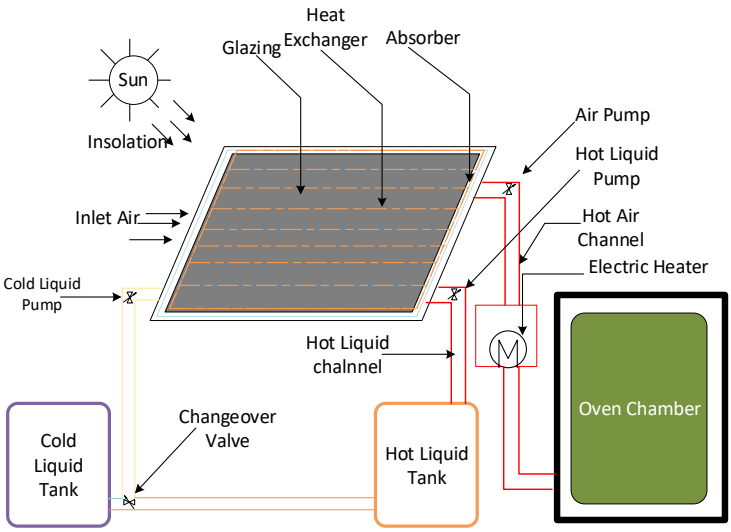

Figure 1: Schematic diagram multi temperature level oven system.

At peak period of high insolation, the collector may produce more than required energy or at periods when the oven system is not in operation, high boiling point liquid is heated and stored. This is achieved by turning the changeover valve to the cold liquid channel and the liquid is pumped into the heat exchanger. The temperature of the liquid is monitored within the exchanger until it nears boiling point before it will be evacuated to the hot liquid tank for storage. The waiting time for the liquid to heat up conserves the energy required to run the pump continuously. When the oven is in operation the air pump delivers hot air from the hydraulic space to the oven. At period of little or no insolation (a cloudy day or at night) the changeover valve is turn to the hot liquid channel and hot liquid circulates in the heat exchange which in a reverse process heats up the absorber and consequently the air. The air pump serves dual purpose, to evacuate the heated air in the hydraulic space and to regulate the amount of heat energy supply to the oven chamber from the collector. The electric heating system is a supplementary heat source which operates only when the solar thermal collector cannot raise the air temperature to the required level. It is a system of heating elements that converts electric energy into heat energy. The convective oven system is an insulated chamber that dries and harden car paints by circulating hot air. The air preheated by the solar thermal collector and the electric resistance heater is circulated inside the chamber at regulated temperature over a period of time, depending on the fact sheet of the paint's manufacturer, to cure (dry and harden) paints applied on work-piece (objects). The regulation of the temperature in the oven is achieved by using sliding mode control method.

2.2. Modeling

Figure 2 is the block diagram model of energy flow in the convective oven system. With some assumptions the system is modeled thus:

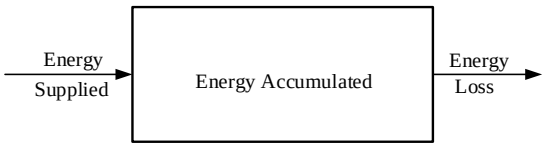

Figure 2: Energy flow model of a convective oven

Energy supplied E_s, to the convective oven is the sum of the accumulated energy E_u, and the energy loss E_L by the oven system.

$$E_s = E_u + E_L \tag{1}$$

$E_u = E_s - E_L = C_T \frac{dT}{dt}$

The total energy loss $E_L = \frac{T - T_a}{R_T}$

where,

$E_s, E_u, and\ E_L\ are\ in\ Joules$

$C_T = heat\ capacity = c_p \times m$

$c_p = specific\ heat\ capacity, J/kG\ K$

$m = mass, kG$

$T = \ temperature\ in\ the\ oven, K$

$T_a = temperature\ of\ the\ surrounding, K$

$R_T = total\ thermal\ resistance\ of\ the\ oven, m^2K/W$

$R_T = \sum_{i=1}^{n} \frac{L_i}{k_i A_i}$

$E_s - \frac{T - T_a}{R_T} = C_T \frac{dT}{dt}$

$$R_T C_T \frac{dT}{dt} + T \ = E_s R_T + T_a \tag{2}$$

Equation (2) is the temperature evolution of the oven.

$E_s R_T + T_a = \ T_{max}$ and $R_T C_T = \tau$

Thus,

$$\frac{dT}{dt} = -\frac{1}{\tau} T + \frac{1}{\tau} T_{max} \tag{3}$$

Since $\tau = time\ constant$ and

$T_{max} = constant$

Equation (3) is first order ordinary differential equation of the oven system. The transfer function of the system is gotten by taking Laplace transform of equation (3) and substituting for $T_{max}\ and\ \tau$

$$\frac{T_{(S)}}{E_{(S)}} = \frac{R_T}{\tau s + 1} \tag{4}$$

Re-arranging equation (2) gives equation (5),

$$\frac{dT}{dt} = \frac{1}{\tau}\{-T + E_s R_T + T_a\} \tag{5}$$

2.3. Sliding Mode Controller Design

Sliding mode controller is designed in two stages [10, 11, 12],

a. The first stage is defining the sliding mode surface: this is a surface that is invariant to system dynamics and where the controlled motion is exponentially stable and the system tracks the desired reference point.
b. The second stage is defining the control law: this is what drives the system state to the sliding surface and maintains it there for $t > t_0$.

For nth order system, the sliding surface can be defined as [11]:

$$S = \left(\frac{d}{dx} + \lambda\right)^{n-1} \times e = 0 \tag{6}$$

n is the order of the system and λ is a small positive integer. Equation (6) ensures that the system error converges to zero in finite time, t [11, 12]. This implies that, there is a certain control input $u(t)$ that can drive the system state $x(t)$ to the sliding surface $S(t)$ and sustains it there at all values of $t > t_0$.

In equation (5), the system state variable T, is the actual output, if T_d is taken as the reference input, the error,

$$e = T_d - T \tag{7}$$

Equation (3) is a first order system, the sliding surface can be gotten by substituting equation (7) into equation (6) and putting n = 1.

$\therefore S = \left(\frac{d}{dx} + \lambda\right)^{1-1} \times (T_d - T) = 0$

Thus, the sliding surface is:

$$S = T_d - T = 0 \tag{8}$$

The control law is evaluated from the derivative of the sliding surface, $\dot{S}$. The control input $u(t)$, has two components, the equivalent control and the switching control [10]

$$U(t) = U_{equ} + U_{sw} \tag{9}$$

The switching control U_{sw}, is what drives the system to the sliding surface. It is achieved with sign function or saturation function for smoother output while the equivalent control U_{equ} keeps the system on the surface.

$$U_{sw} = \begin{cases} Msign(s) = 1 \; for \; S > 0 \\ -Msign(s) = -1 \; for \; S < 0 \end{cases} \tag{10}$$

$\dot{S} = \dot{T}_d - \dot{T} = 0$

$\dot{T}_d = 0 \; since \; T_d \; is \; a \; constant$

$\dot{S} = \frac{1}{\tau}\{T - E_s R_T - T_a\} = 0$

The input, E_s is made the subject to obtain the equivalent control.

$$E_{s-equ} = \frac{C_T}{\tau}\{T - T_a\} \tag{11}$$

Equation (11) is the equivalent control for the system and the control law is equation (12)

$$E_s(t) = \frac{C_T}{\tau}\{T - T_a\} + C_T\big(Msign(s)\big) \tag{12}$$

The block diagram for the control model of the system is shown in Figure 3, the Ref input 1 to 3 are different temperature reference points. The adder is a comparator that compares the actual temperature value T, to any reference value T_d to generate error signal e, for the controller. The controller is based on sliding mode control (SMC) modeled in equation (12). The output of the controller is a command signal that regulates the heat energy sources. The oven chamber walls and the work-piece temperatures are raised by convective heat transfer. The temperature evolution is monitored by sensors through a feedback loop. The process continues as the controller regulates the temperature until the actual temperature T, equals the reference temperature T_d. The temperature is maintained for a set time duration after which next reference input is selected.

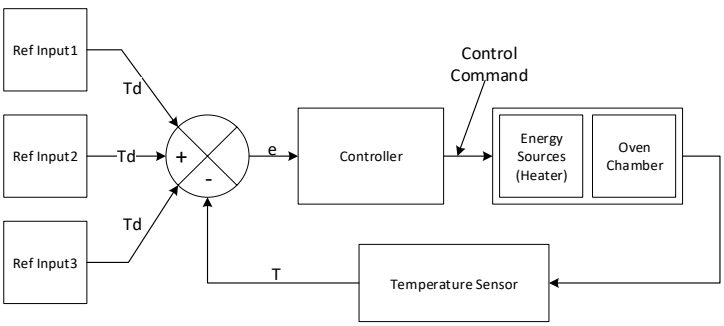

Figure 3: Block diagram of control model for the oven system

2.4. Simulation

The sliding mode-controlled oven system is simulated in MATLAB/Simulink 2014b, Figure 4 is the Simulink block model for the system. It shows the oven system with a reference input , set to , a comparator that compares the reference temperature to the actual temperature in the oven from the feedback loop. The error signal , is fed into the sliding mode controller (detailed in Figure 5) to generates command that controls the quantity of heat energy delivered to the oven chamber. The heat sources are solar thermal and electric resistance heater. Heat is transferred by forced convection from the heat sources to the oven chamber by heat pump (blower fan).

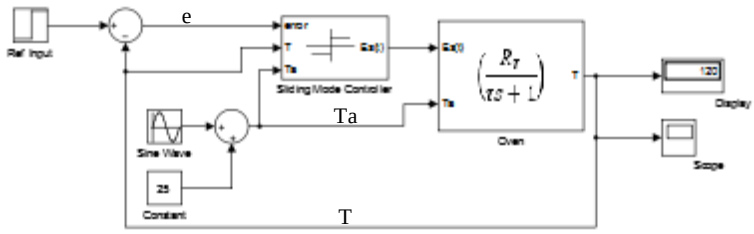

Figure 4 Simulink model of sliding mode-controlled oven

As the oven temperature evolves heat and mass transfer take place; this includes change of state of volatile materials in the paint which vaporize and are carried away by hot exhaust air. These result to temperature drops and temperature sensors in the oven chamber send feedback signal (actual temperature value in the oven) to the controller which send commensurate command signal to the heat sources to return the temperature to the set-point. The process repeats and the controller keeps adjusting the heat energy delivered to the oven to maintain it at the reference temperature level until the cure time is completed. The display block in the Simulink model shows the oven chamber temperature value at every time instant, while the scope records the temperature evolution over the whole duration. The sliding mode controller subsystem block is replaced with optimized PID controller block and the simulation was repeated for comparison.

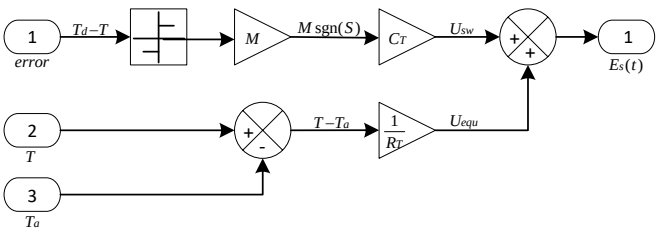

Figure 5 Sliding mode controller

2.5. Simulation results and discussion

The temperature evolution of the oven system when simulated using sliding mode controller is shown in Figure 6. It took just one minute and thirty-eight seconds rise time and two minutes four seconds to settle. A zoom in to the steady-state plot shows the chattering characteristic of SMC, which is acceptable since the maximum deviation from the reference point is $\pm 0.3°C$ and is nowhere close to $\pm 5.6°C$ tolerable in modern paints. The repeat of the simulation with optimized PID controller block replacing the SMC controller subsystem block gives the result shown in Figure 7. The rise time of the PID controlled oven is three hours fifteen minutes. It also has oscillating steady-state which is outside the allowable limits. PID controller was further tested with a non-varying ambient temperature T_a, which eliminates the oscillation but the rise time, settling time and overshoot are still high, Figure 8. Table 1 compares the responses of SMC and PID controllers. Figure 9 shows how the SMC controller seamlessly migrates the oven temperature from one reference to another after each specified time duration.

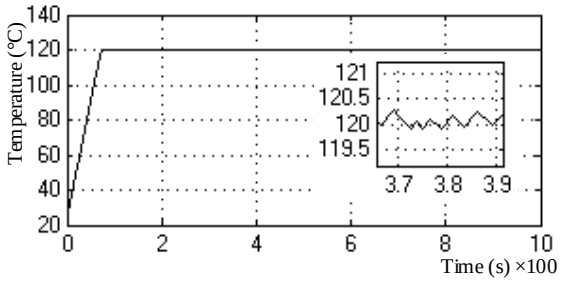

Figure 6 SMC plot of oven chamber temperature evolution

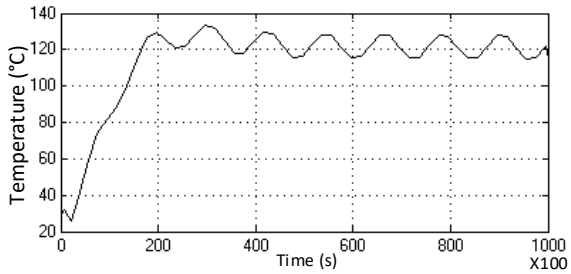

Figure 7 PID plot of oven chamber temperature evolution

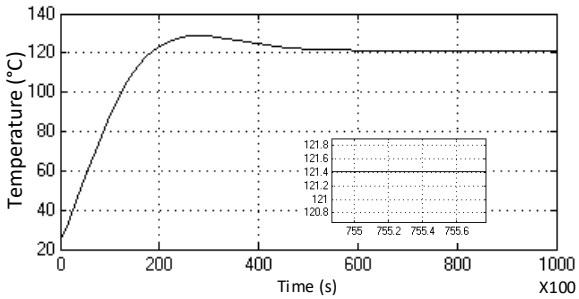

Figure 8 PID plot of oven chamber temperature evolution with constant ambient temperature

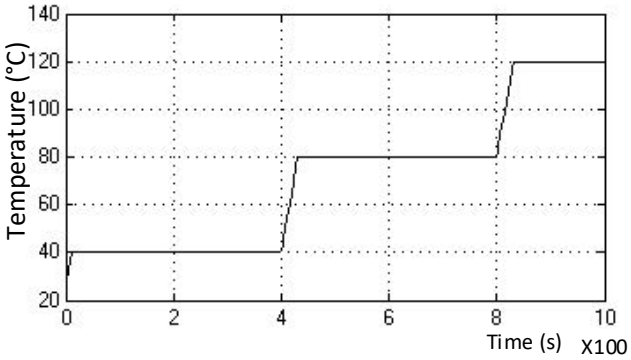

Figure 9: SMC plot of oven chamber temperature evolution for three reference inputs and three time durations

Table 1: Comparison of SMC and PID controllers

Response	SMC Value	PID Value	PID Value $T_a = 25$
Rise Time:	98.39 (s)	11700 (s)	13200 (s)
Settling Time	124.14 (s)	64800 (s)	51400 (s)
Settling Min	119.709°C	115.026	121.286°C
Settling Max	121.144°C	133.36°C	130.769°C
Overshoot:	0.9535%	11.13%	9.25%
Undershoot:	0.2425%	4.145%	0%
Peak:	121.144°C	133.36°C	130.769°C

3. Implementation

A convective paint curing oven of dimension $1200mm \times 900mm \times 600mm$ is designed in AutoCAD 2007 software and realized as shown in Figure 10 and Figure 11. Figure 10 shows the oven and solar collector under construction, with air inlet channel and outlet air exhaust hole where extraction fans are installed. It also shows the insulation foam for the solar collector. Figure 11 shows picture of the completed oven and solar collector. The picture also, shows the oven exhaust channel and the exhaust fans housing. The Sliding Mode Controller is implemented using micro-controller coded in $C++$. The design can take multiple reference inputs and automatically drive the oven to those set-points. The flowchart shown in Figure 12 is the control algorithm of the system. It starts by initializing the variables, T1, T2, t1, t2 which are first and second reference inputs and first and second cure durations respectively. The controller reads the keypad and displays the numeric entry on liquid crystal display LCD screen. Negative Temperature Coefficient Thermistor are used as sensors. The sensors' data are logged on external storage for analysis. The controller enters sliding mode controller sub-routine which regulates the heat sources and the fans until the oven temperature Toven equals the reference point. A timer equal to the value of t1 is set immediately Toven equals T1; "First Stage Completed" flashes on the screen to signify end of the stage once the time elapses. Then the controller updates to T2 and the process is repeated using T2 and terminates as t2 timer ends. The sliding mode subroutine (Figure 13) executes once anytime it is called. It uses the data from temperature sensors and the values of total heat capacity C_T, total thermal resistance R_T and Lipschitz constant, M to compute the switching and equivalent controls. The switching control function determines the rate and magnitude of increment or decrement of heat energy supply. The operation returns to the main program once the control signal is generated.

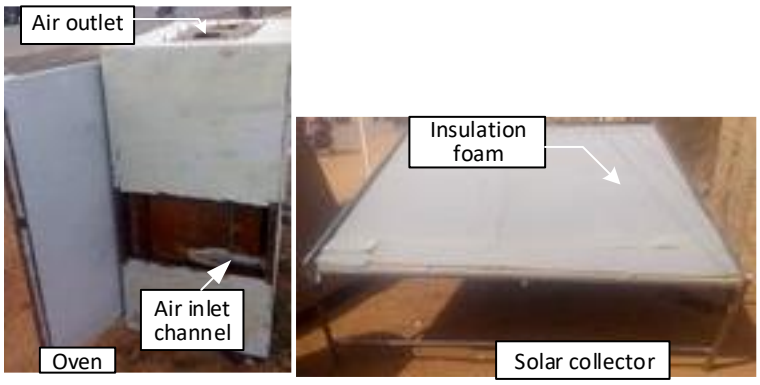

Figure 10: Picture of oven and solar collector under construction

Figure 11: Picture of paint cure oven and flat-plate solar collector

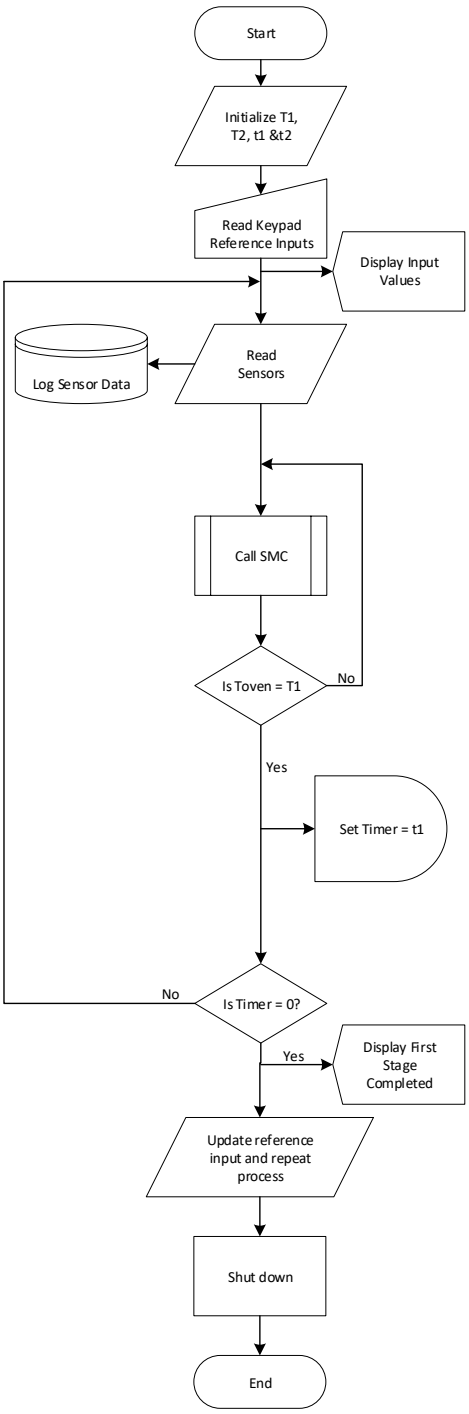

Figure 12: Flowchart control algorithm of the oven system

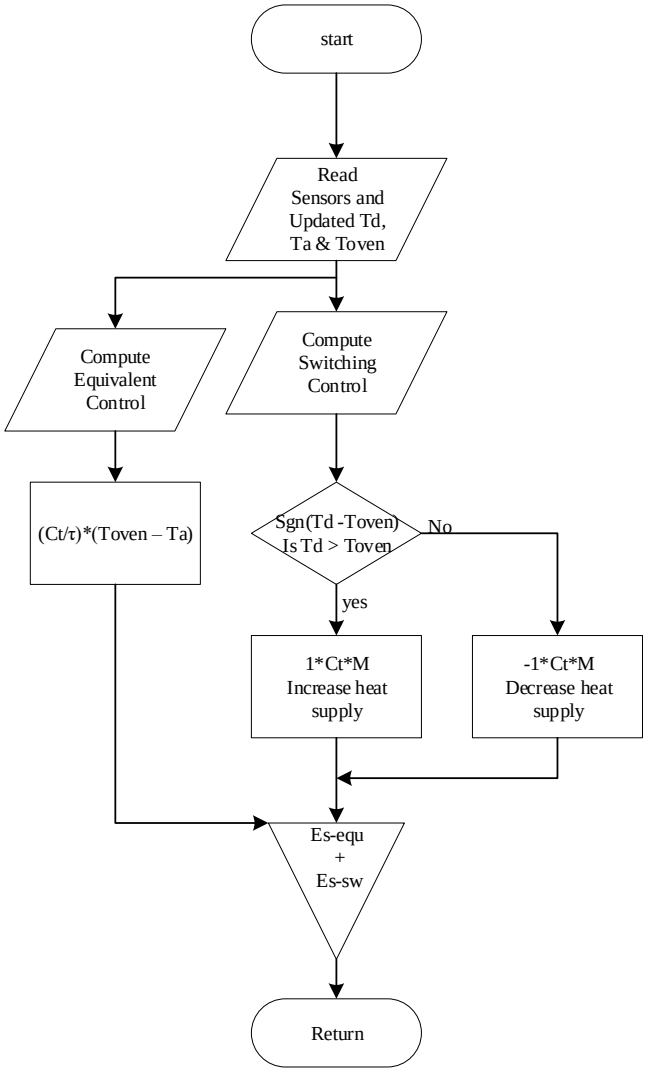

Figure 13: Flowchart algorithm of the sliding mode controller

4. Verification

The system (oven and collector) is setup and tested with single reference input of $60℃$ and with double reference inputs of $50℃$ and $120℃$ to verify the sliding mode controller behavior. The experimental results are shown in Figure 14 and Figure 15 for the single and double reference inputs respectively. The yellow and green lines are the reference inputs while the blue plots are the actual temperature evolution in the oven chamber. The controller tracks the reference inputs very well with tolerable overshoots. The plot however, became too noisy as the temperature elevates due to the sensors' limitations. The sensors are bead type negative temperature coefficient thermistors with maximum temperature range of $150℃$. Heat energy supplied by the collector is measured from oven inlet air temperature and flow rate. Analysis of this data (collected in University of Nigeria, Nsukka at average insolation of $200W/m^2$) shows that the collector provides 100% heat energy required to operate the oven below $65℃$ and 43.27% at maximum capacity of $120℃$. Payback period analysis calculation (at average of 7hrs of insolation per day) shows that in sixteen months the collector will have saved equivalent cost of its installation.

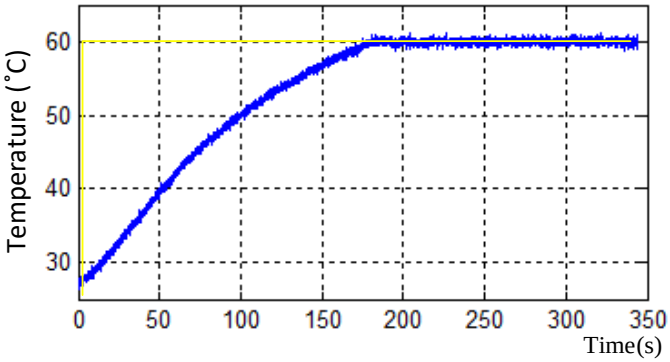

Figure 14: Single reference input oven temperature evolution for the experiment

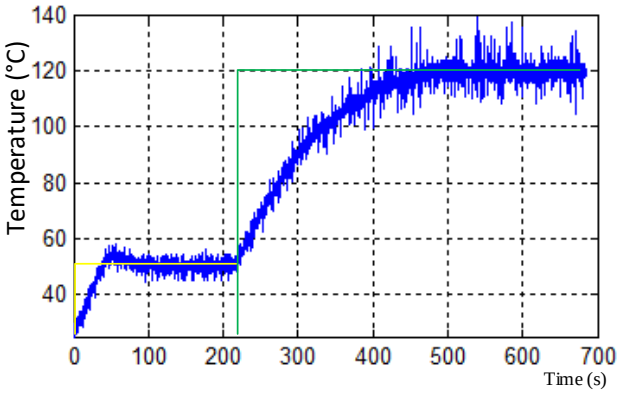

Figure 15: Double reference inputs oven temperature evolution for the experiment

6. ACKNOWLEDGEMENTS

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CONCLUSION

In this work sliding mode control (SMC) has been compared to PID control in Matlab/Simulink simulation for paint curing oven model. Results show that SMC has quicker rising and settling time. The practical implementation of the work has been done and verification test conducted. Experimental results conform with the SMC simulation performance; this shows that SMC is an improved control technique for oven system control. Further more, advanced paint curing process that is normally achieved by moving coated objects from one chamber maintained at a temperature level to another chamber of deifferent temperature level has been automated such that the oven chamber migrates from various preset temperature references after specified time. Renewable energy sources incorporated into the system offers reduction in heat energy cost from 43.27% to 100% depending on the operating temperature.

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