Process control strategy and its impact on performance of the cold box of guarded hot box test facility for U-value measurement

Debasish Chowdhury, Rajesh Chatterjee, Subhasis Neogi*

School of Energy Studies,
Jadavpur University,
Kolkata-700032, India
Email: debasishthegr8@gmail.com
Email: rajeshthinks@gmail.com
Email: neogi_s@yahoo.com
*Corresponding author

Abstract: Overall heat transfer coefficient or thermal transmission coefficient or U-value is an important tool for thermal characterisation of any building material. The guarded hot box test facility is used for evaluation of U-value of any material. In this paper a detailed insight has been given into the overall control strategy to be implemented for maintaining a constant low temperature inside the cold box of a guarded hot box test facility. Thereafter impacts of varying control parameters of the controller on the overall system performance have also been given.

Keywords: guarded hot box; cold box; proportional integral derivative; PID.

Reference to this paper should be made as follows: Chowdhury, D., Chatterjee, R. and Neogi, S. (2016) 'Process control strategy and its impact on performance of the cold box of guarded hot box test facility for U-value measurement', *Int. J. Energy Technology and Policy*, Vol. 12, No. 2, pp.181–196.

Biographical notes: Debasish Chowdhury is a PhD Scholar at Department of School of Energy Studies at Jadavpur University, Kolkata, India. His specialisation is in solar thermal engineering, building energy management and biomass energy.

Rajesh Chatterjee is an MTech scholar at Department of School of Energy Studies at Jadavpur University, Kolkata, India. His specialisation is in solar thermal engineering, building energy management and wind energy.

Subhasis Neogi is a Professor at School of Energy Studies at Jadavpur University, Kolkata, India. He has 30 years of teaching and research experience and five years of industry experience. He has research interest in energy conservation and management, energy efficient buildings, wind energy, solar thermal engineering etc. He has several publications in various national and international journals.

This paper is a revised and expanded version of a paper entitled "Process Control Strategy and Its Impact on Performance of The Cold Box of Guarded Hot Box Test Facility for U-value Measurement" presented at International Conference on Advances in Energy Research (ICAER) at IIT Bombay 10th to 12th December 2013.

1 Introduction

Recent times have seen a tremendous increase in building construction in order to accommodate the ever increasing population. In order to maintain appropriate thermal comfort inside the dwelling, tremendous amount of energy (in form of electrical energy) is being consumed by installed HVAC system. The major part of this heating/cooling load is due to heat transmission through the walls of the building envelope. Therefore, reducing this load becomes one of the most effective ways to conserve energy in buildings. Now U-value can be used as a tool for thermal characterisation. Although thermal conductivity can be used to quantify the heat transfer but U-value takes into account all the three modes of heat transfer: conduction, convection and radiation. Thus prior actual construction of the building, knowledge of U-value can help predict the cooling load to be imposed on the installed HVAC system. A Guarded Hot Box Test Facility is used to measure the overall heat transfer coefficient. One such test facility has been set up at Building Energy Laboratory, School of Energy Studies, Jadavpur University. It consists of metering box and cold box, maintained at two different temperatures, separated by a surround panel containing the sample to be tested. The metering box is surrounded by a guard box. Now for maintaining a constant temperature inside the cold box, metering box and guard box, separate control strategies have been implemented.

At the first stage, the air temperatures of metering box, guard box and cold box have to reach their respective set points. Once the steady state conditions have been attained, the experiment needs to be continued for at least eight more hours as per BS 874: Part 3: Section 3.1: 1987. In this paper, the process control strategy for maintaining a constant air temperature inside the cold box has been presented along with its effect on performance of the system.

Chen and Wittkopf (2012) have made their study on SERIS Calibrated Hot Box. It uses chilled water based heat exchanger along with heat exchanger to maintain constant temperature in metering, guard box and cold box or climatic box. The chilled water in the climatic chamber was supplied by a second chiller. Very limited information is available about the control strategy being implemented in the same. In this study, the process control strategy being used for maintaining a constant temperature in the cold side of the guarded hot box is presented.

2 U-value and guarded hot box

2.1 Overall heat transfer coefficient or U-value

Overall heat transfer coefficient or U-value or thermal transmittance helps in evaluation of thermal properties of specimen. It gives a quantitative measure of the amount of heat flowing through unit area of a specimen for a unit degree differential temperature across the material. The thermal conductivity tool can be used to quantify the magnitude of conducted heat flow however the use of U-value will help in determining the heat flow taking into account the three modes of heat transfer i.e., conduction, convection and radiation. From the knowledge of the U-value, building cooling or heating load due to heat transfer from or to the external environment can be estimated. Thus lower is the U-value; higher is the degree of thermal insulation and lower is the degree of cooling or heating load imposed on the installed on the HVAC systems in the building for maintaining appropriate thermal comfort. Now Figure 1 shows the heat transfer scheme through a wall and Figure 2 shows the thermal resistance network of the same. Now we know that,

$$U = \frac{1}{R_{eq} A}$$

Figure 1 Heat transfer scheme through a wall

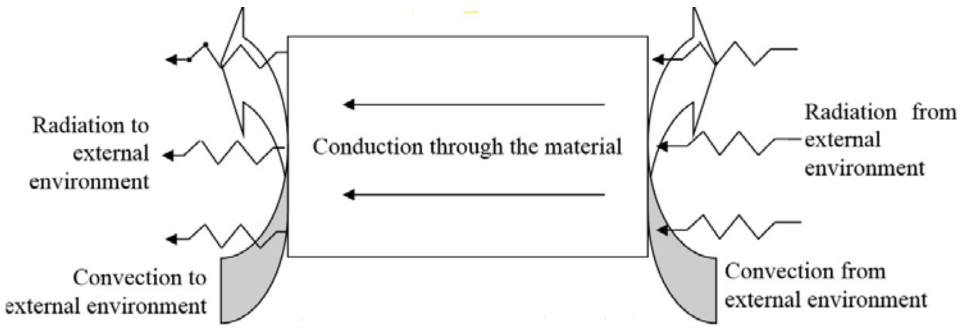
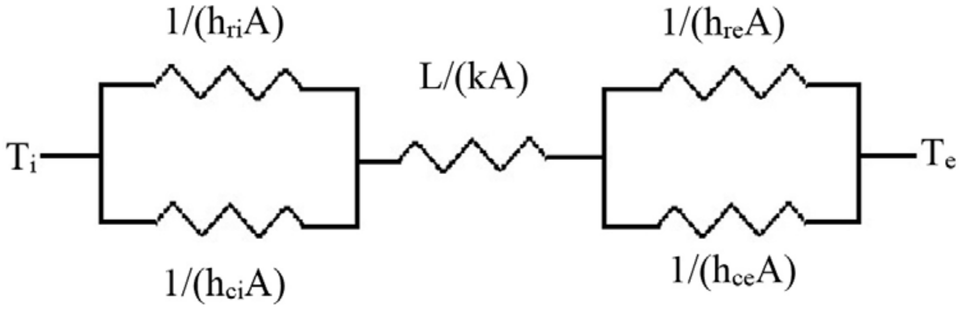


Figure 2 Thermal resistance network of the wall in Figure 1



So from Figure 2 and using the above stated equation, one can derive the U-value of the wall as:

$$U = \left[\left(\frac{1}{h_{ce} + h_{re}} \right) + \sum_{i=1}^{n} \frac{l_i}{k_i} + \left(\frac{1}{h_{ci} + h_{ri}} \right) \right]^{-1}$$

where

h_{ce} and h_{ci} convective heat transfer coefficients for external and internal surface respectively

h_{re} and h_{ri} radiative heat transfer coefficients for external and internal surfaces.

l_i thickness of individual layers of specimen to be tested.

k_i thermal conductivity of the *i*th layer of specimen.

n number of different layers of specimen.

A area of the specimen perpendicular to the face of the heat flow.

R_{eq} equivalent thermal resistance.

In some cases (Suleiman, 2011), where surface resistance due to convection and radiation has been neglected in comparison to thermal resistance to conduction, the above equation reduces to:

$$U = \left[\sum_{i=1}^{n} \frac{l_i}{k_i}\right]^{-1}$$

2.2 Guarded hot box test facility (GHB)

Guarded Hot Box test facility helps in evaluation of steady state thermal transmittance of any construction element under laboratory conditions. It essentially consists of Metering Box (MB), Guard Box (GB) and Cold Box (CB). The sample to be tested is placed in the aperture of the surround panel. The surround panel is sandwiched between the metering box and cold box. Schematic view of the same is given in Figure 3 (as described by Chowdhury, 2013). The walls of GHB are made of 250mm thick extruded polystyrene walls having thermal conductivity k = 0.027 W/mK (as per Lafarge Texas Styrofoam Thermal insulation Catalogue). The GHB method of U-value measurement is primarily intended for measurement of large inhomogeneous and homogenous specimens. Several standards are available for experimental determination of U-value using GHB and they have been also compared by Asdrubali and Baldinelli (2011) in their study. Literature survey have shown numerous instances where the above standards and Guarded Hot Box Test facility has been used for thermal characterisation such as in Geola et al. (2009), Fang et al. (2007), Gorgolewski (2007), Blanusa et al. (2005), Chen and Wittkopf (2012).

At Building Energy Laboratory of School of Energy Studies (SES), Jadavpur University the GHB test facility has been developed as per BS 874: Part 3: Section 3.1: 1987 and BS EN ISO 8996:1986. It measures the U-value of any construction element with thermal transmittance and conductance in the range of 0.1W/ (m^2.K) to 15W/(m^2.K), for testing within temperature range –20ºC to 50ºC. The overall dimension of the GHB is 2760mm by 4470 mm by 2500mm.

The metering box is of rectangular cross-section having dimensions of 1840 mm by 600 mm by 1600 mm. The walls of are made of 50 mm thick extruded polystyrene sheets with an internal plywood skin on four sides. The guard box is having an exterior dimension of 2100 mm by 2760 mm by 2500 mm and is made of same material as that of metering box and cold box. The walls of guard box are 250 mm thick. The cold box is also made of 250 mm thick extruded polystyrene walls having overall dimension of 2100 mm by 2760 mm by 2500 mm. The purpose of the guard box is to establish air temperature and surface coefficients around the metering box so as to minimise the heat flow through metering box walls. The walls of the metering box should be well insulated to ensure that any heat flux through it is very small compared to the heat flux through the specimen. Under such a condition, all the heat added by heaters and the circulating fan installed inside the metering box flows through the sample into the cold box, which is maintained at a constant low temperature(T_i). Measuring this heat flow(Q) and from the knowledge of the area of the specimen(A), air temperatures inside the cold box and metering box(T_e), U-value of the specimen can be evaluated using the equation below:

$$U = \frac{Q}{A\left(T_e - T_i\right)}$$

For thermal transmittance measurements, a baffle is fixed in metering box and cold box parallel to surface of the specimen. The baffle thermal resistance should be adequate to shield the specimen surface from radiative heat exchange with any energy sources located behind it. Gaps are provided at top and below to allow air circulation. Provision is kept for adjusting baffle-to-specimen spacing in order to adjust the air curtain velocity over the sample.

In case of measuring U-value of specimen having smaller area than that of the metering box opening (such as glazing), the sample is to be mounted in the surround panel. Using calibration panels, net heat flow through the sample mounted inside the surround panel can be evaluated.

2.2.1 Temperature measurements and data acquisition systems

For the purpose of temperature measurement K-type thermocouples (made of Chromel and Alumel wire) of 0.2mm diameter were used. These thermocouples were made at the laboratory itself using a spot welding kit and were calibrated using a constant temperature oil bath. These thermocouples have an operating range of –200°C to 1370°C with a tolerance of ±0.4% (complying with BS 4937–30:1993).

In total around 86 thermocouples were used for measurement of temperature at various locations. However for control and analysis of air temperature inside the cold box, three thermocouples have been placed in the air curtain between the sample and the baffle. For the purpose of data-logging, AGILENT 34970A Data Acquisition /Switch (basically a data-logger) has been used. The placement of thermocouples intended for measurement of air temperatures inside MB, GB and CB are also shown in the Figure 3. The sensors are placed outside the thermal boundary layer. In order to maintain a constant temperature inside the metering box and guard box a virtual PID controller has been developed using Agilent VEE software. The air temperature values from thermocouples located inside the guard box and metering box are averaged respectively to form input signal to the virtual PID controller. Thereafter a control circuitry has been developed for interfacing with the data-logger to send control signals for turning on or off the heaters in the metering box and guard box. Similarly for maintaining constant low temperature inside the cold box, a chilled storage based cooling system incorporating a Fan-Coil unit is used. The flow of the heat transfer fluid (40% diluted Ethyl glycol) inside the heat exchanger coming from the chilling plant is controlled by a PID controller. Out of the three temperature sensors located in the air curtain in front of the sample inside the cold box, the sensor located midway is used as input sensor to controller. A detailed analysis regarding the chilled storage used in the cold box of the guarded hot box has been made by Chowdhury et al. (2013).

Figure 4 shows time temperature profile of air temperature inside the guard box, metering box and cold box. The set point of the guard box, metering box is at 40ºC and that of cold box is at 0°C.

Figure 3 Schematic view of guarded hot box

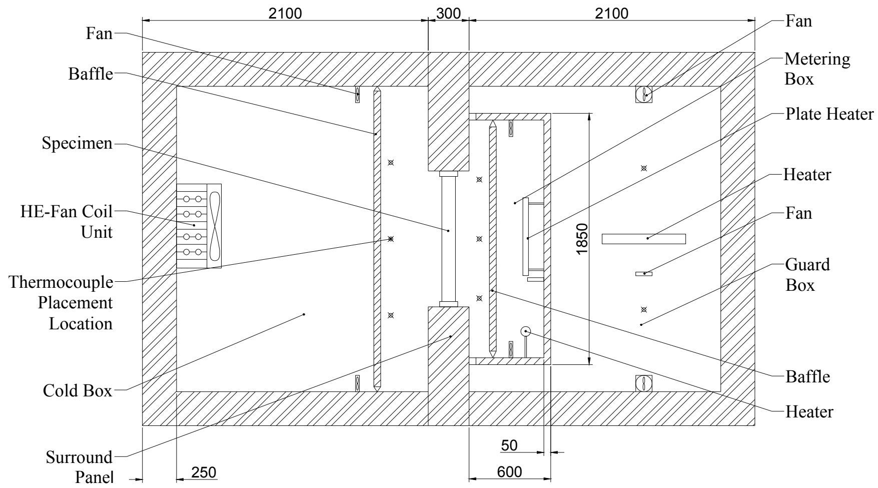
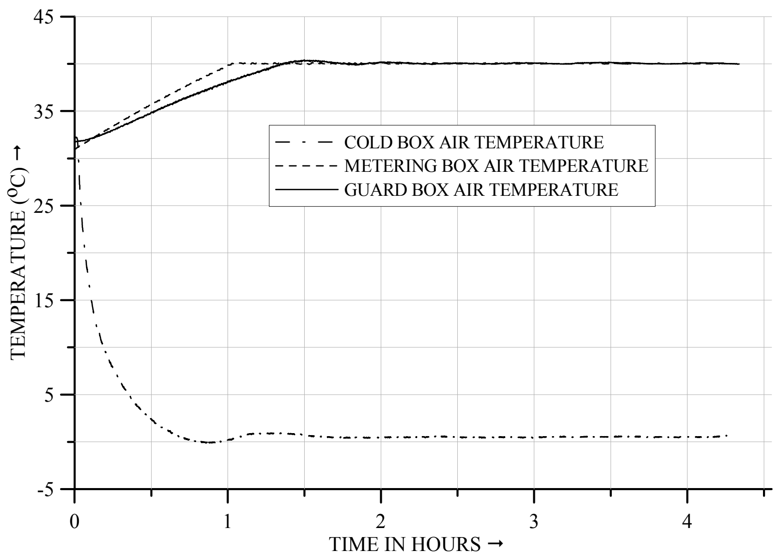


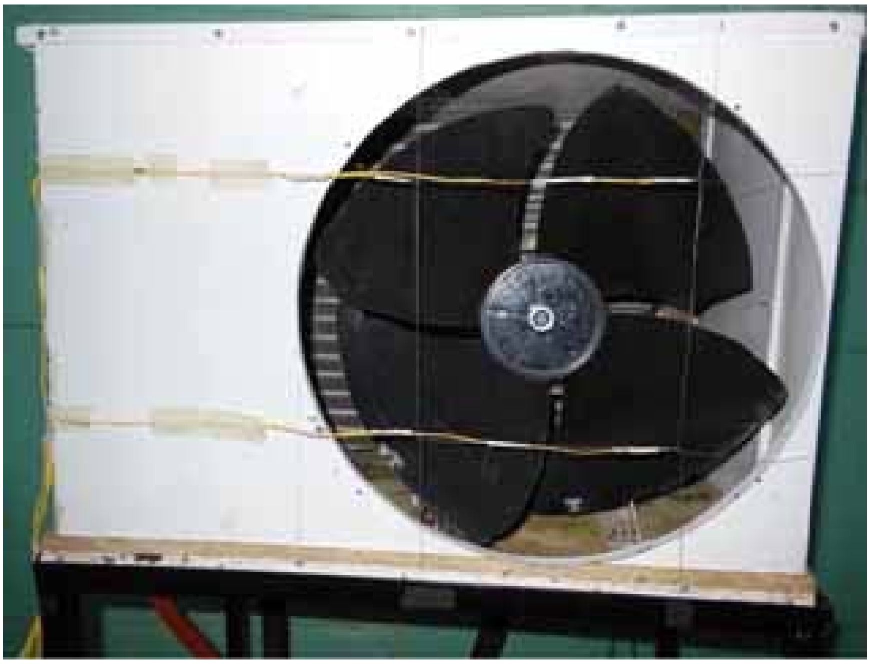
Figure 4 Time temperature profile of air inside guard box, metering box and cold box



As per BS EN ISO 8990:1996 at steady state, any random temperature fluctuations and long term drifts should be kept within 1% of the air to air temperature (i.e., in our case it is 0.4ºC). In the cold side, the sensor located at the top-most position measured an average value of 0.57°C with a deviation of ±0.12°C, temperature from sensor located at middle had an average value of 0.51°C with a deviation of +0.13°C to –0.12°C and that located at the bottom had an average value of 0.67°C with a deviation of +0.04°C to –0.11°C. In the metering box, the sensor located at the top-most position measured an average value of 40.35°C with a deviation of ±0.08°C, temperature from sensor located at middle position had an average value of 40.47°C with a deviation of +0.09°C to –0.08°C and temperature from sensor located at bottom had an average value of 39.69°C with a deviation of +0.11°C to –0.09°C. Similarly, for guard box, the sensor at top most position measured an average value of 40.061°C with a deviation of +0.15°C to 0.11°C while the sensor located at the bottom measured an average value was 39.92°C with a deviation ranging between +0.24°C to –0.14°C. Thus it is evident that steady state has been reached for the selected time period for which the above calculations were carried out. Moreover for cold side we can see that variation in temperature between the sensors located in the air curtain before the baffle is very small. Thus the temperature sensed by the thermocouple placed midway in the air curtain can be more or less true representation of the entire air curtain temperature.

Figure 5 Cold bath–35 based chilling plant (see online version for colours)

Figure 6 Fan-coil assembly inside the cold box (see online version for colours)



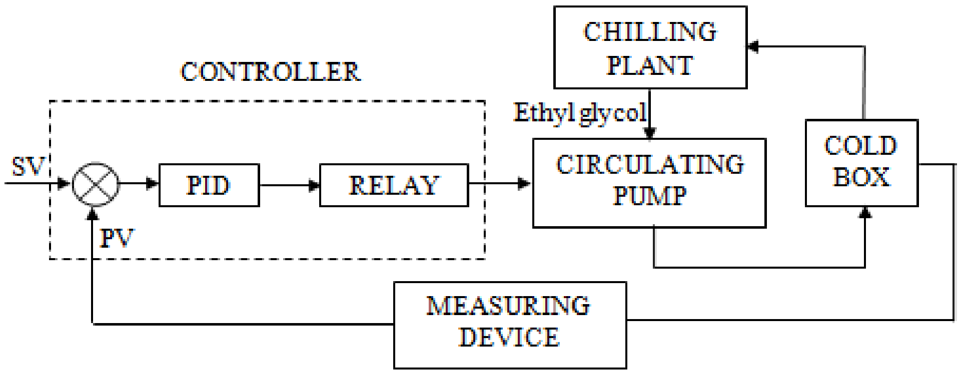
3 Experimental set-up

The experimental set-up consists of the heat exchanger – fan or Fan-Coil assembly, COLD BATH-35 make chilling plant, circulating pump along with interfacing circuit for controlling circulation of chilled ethyl glycol inside the heat exchanger. The purpose of the heat exchanger provided is to continuously remove the heat entering into the cold box for maintaining appropriate temperature conditions. The purpose of the fan is to facilitate and enhance the heat removal rate of the heat exchanger. Figures 4 and 5 show the chilling plant itself along with the Fan-Coil unit.

Figure 6 shows the schematic view of the overall control system implemented. As seen from Figure 6, the PID compares the temperature of the cold box with the set point and automatically turns on or off the relay. The function of the circulating pump is to circulate chilled ethyl glycol present in the cold bath through heat exchanger located inside the cold box. The PID controller is actually governing the duty cycle of the relay so as to control the circulation of chilled ethyl glycol inside the heat exchanger. This brings about the desired cooling effect inside the cold box. The thermocouple sensor which is used for control purpose is placed midway from all the edges of the cold box in front of the baffle.

The PID controller discussed here is actually a digital controller. It has a sampling frequency of 250ms. Control strategy implemented by the controller is actually Pulse Width Modulation or PWM control. By controlling the amount of time for which the relay is operated i.e., by varying the duty cycle (% of Cycle time for which relay is ON), the rate of heat removed by heat transfer fluid i.e., chilled ethyl glycol is controlled. Let us consider an example in which cycle time of controller was set to15 seconds and a volumetric flow rate of 15 litres per minute was set for ethyl glycol. So for a duty cycle of 3 seconds the relay is actually on for 3 seconds in total cycle time of 15 seconds. This is equivalent to maintaining the volumetric flow rate at 15(3/15) i.e., 3 lpm. Thus by varying the duty cycle of the relay, the volumetric flow rate of the ethyl glycol flowing through the heat exchanger is controlled. In other words heat removal rate of ethyl glycol is controlled. A number of experiments were conducted to understand how duty cycle of the relay is varied by the controller and its effect on the cooling performance.

Figure 7 Schematic overview of control circuit



Thereafter operating characteristics of the controller are monitored by studying the effect of varying different parameters of the controller on the air temperature profile inside the cold box.

The PID controller compares the set value (SV) with process value (PV) i.e., the measured temperature of cold box air and turns on or off the circulation of chilled ethyl glycol through the heat exchanger in cold box via a relay to maintain a constant temperature inside the cold box.

Initially the guard box, metering box and cold box were at ambient temperature. Then set point for metering box and guard box was set at 40°C and that of cold box was set at 0°C. The metering box and cold box was separated by a surround panel with thickness 300mm. The surround panel is provided with a sample fixing window of 500 x 500 mm where an insulation sheet of 50 mm thickness is used as sample case. Air temperature profile of cold box air was monitored for set point 0°C at default values of parameters i.e., with proportional band(P) = 10°C, Integral time(T_i) = 2 minutes and Derivative time(T_d) = 30 seconds.

4 Results

Figure 7 shows the temperature profile of the sensor which is used both monitoring and control purpose. For the sake of understanding the temperature profile of air is divided into number of zones based on the duty cycle of the relay as shown below:

Zone 1 Duty cycle is 100% i.e., relay is operated continuously.

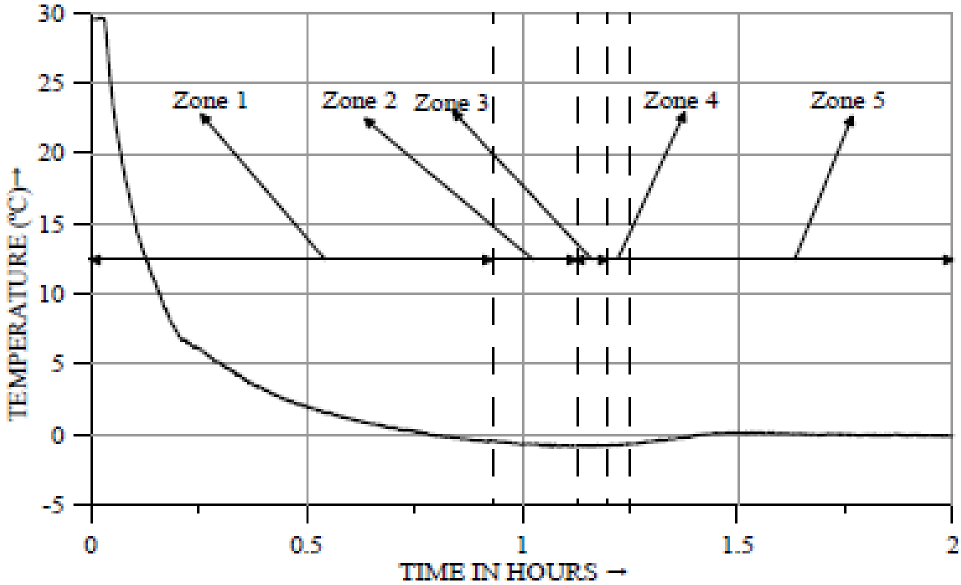
Zone 2 Duty cycle is 80% (i.e., ON time is 12 seconds and OFF time is 3 seconds in total CYCLE time of 15 seconds).

Zone 3 Duty cycle is 60% (i.e., ON Time is 9 seconds and OFF time is 6 seconds).

Zone 4 Duty cycle is 40% with an ON time of 6 seconds and OFF time of 9 seconds.

Zone 5 Duty cycle is reduced to 20% i.e., the relay in ON for 3 seconds in CYCLE time of 15 seconds.

Figure 8 Diagram showing varying duty cycle of relay



In zone 1, we see that after around 0.25 hours from start the rate of fall of temperature decreases but duty cycle of the relay remains same. This is because of the fact that significant ice formation in the fins of heat exchanger installed inside the cold box has resulted in decreased heat removal rate of air. As a result the rate of fall of temperature decreases. Moreover as the temperature decreases the overall cooling load increases due to increased structural cooling load. After that as the temperature approaches the desired set point, the controller adjusts the duty cycle of the relay so to maintain the desired set point. As a result we can see that the duty cycle reducing in zones 3, 4 and 5.

Results of varying PID control parameters i.e., Proportional Band (P), Integral Time (T_i) and Derivative Time (T_d) on air temperature profile of the cold box are shown in Figures 8(a)–(d).

We know that in case of Proportional control, the proportional control action takes place only when the process value (which in our case is the cold box air temperature) enters the proportional band. In the proportional band the control signal is generated proportional to the error (Process value – Set value). Below and above the proportional band, no control action takes place. In general in control systems, using proportional action generally leaves a steady state offset. Moreover the response is also sluggish depending upon the proportional band or proportional gain (k_p).

In case 3 and case 4, only proportional band has been set and rest all parameters have been set to zero. In case 3, Proportional band = 10°C, so k_p = proportional gain = 100/P = 10. In case 4, Proportional band = 1°C, so k_p = proportional gain = 100/P = 100. Steady state temperature for P = 10°C is 1.601°C while for steady state temperature for P = 1°C is 0.936°C.

Figure 9 Time temperature profile of cold box air temperature for varying PID parameters

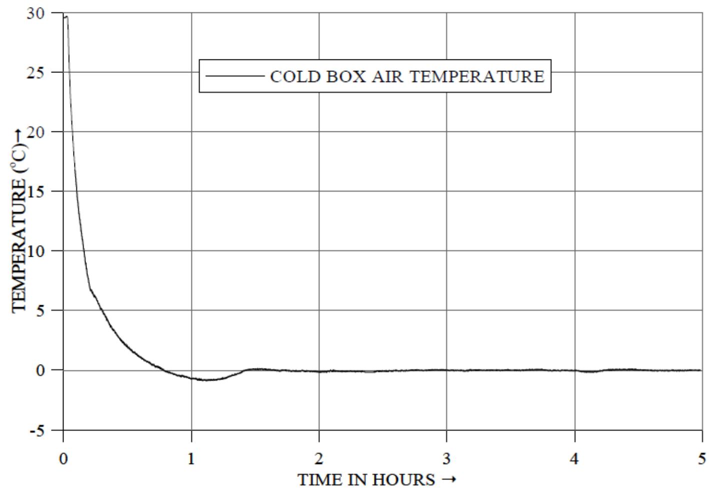
Case 1:

Parameters:-

P = 10°C

T_i =2 minutes

T_d = 30 seconds.



(a)

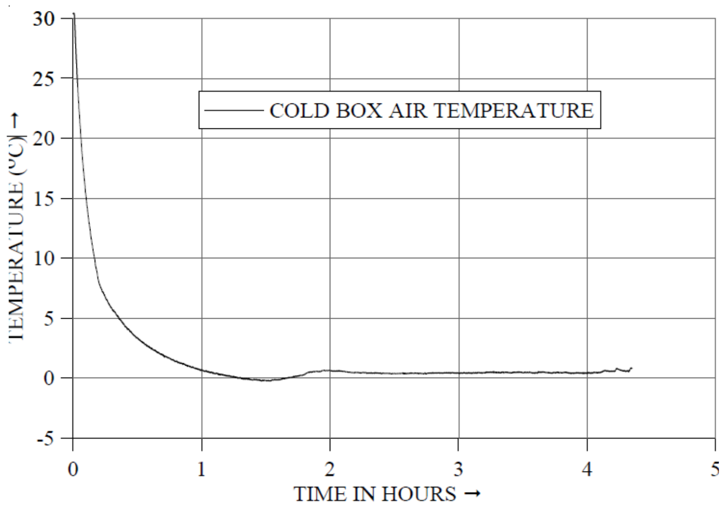
Case 2:

Parameters:-

P = 10°C

T_i = 2 minutes

T_d = 0 seconds.



(b)

Figure 9 Time temperature profile of cold box air temperature for varying PID parameters (continued)

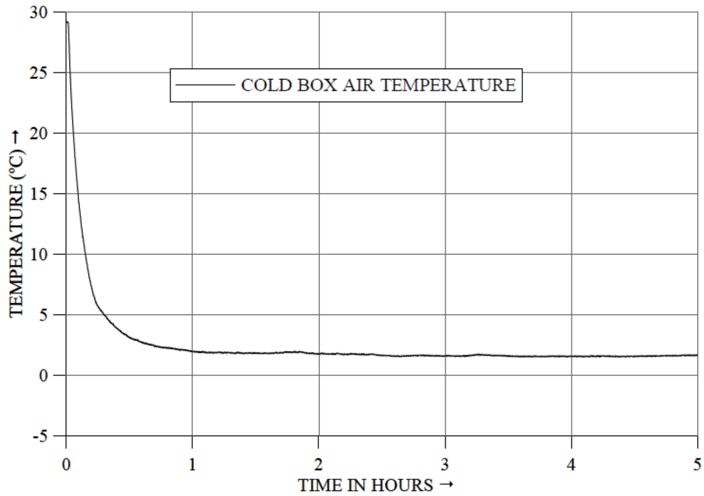
Case 3:

Parameters:-

P = 10°C

T_i = 0 minutes

T_d = 0 seconds.



(c)

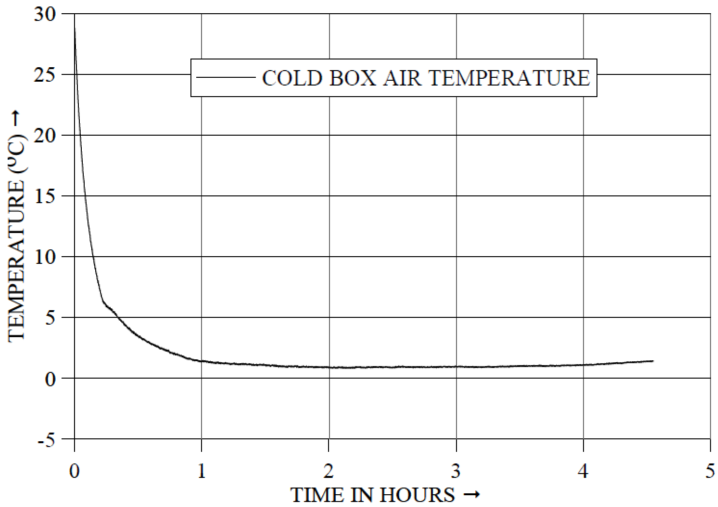
Case 4:

Parameters:-

P = 1°C

T_i = 0 minutes

T_d = 0 seconds.

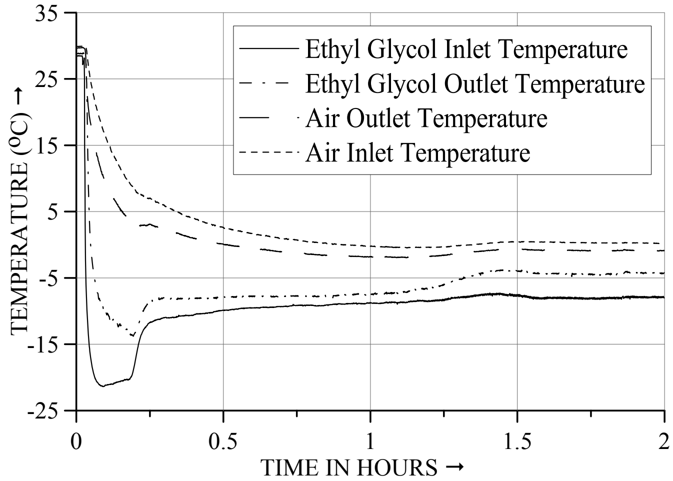


(d)

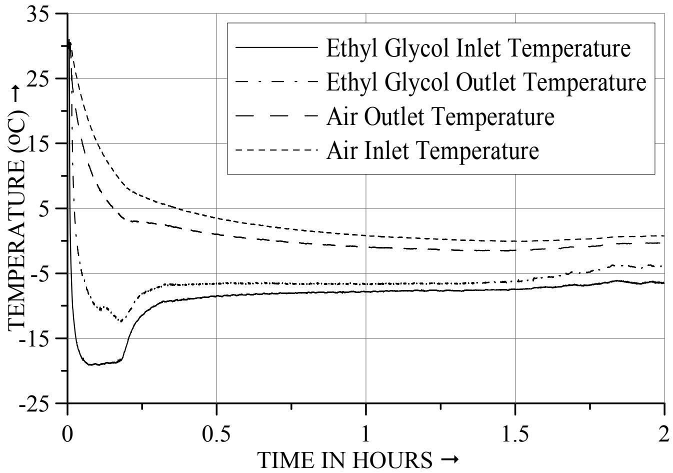
In general, integral action is introduced into the system to reduce the steady state error as much as possible. Derivative action is introduced to damp out rapid changes in the process value. So we can say derivative action has a stabilisation effect on the system and it damps out or reduces the steady state oscillations in the systems. Now such steady state oscillations occur in systems having a fast response time (for e.g., servo motor). The guarded hot box system as whole has a very large response time. In the cold box we can say that structural heat load (i.e., cooling load from ambient), cooling load due to fan in fan-coil unit and circulating fans inside the cold box, cooling load due to heat transfer from metering box and cooling load due to leakage heat infiltration, all these have an inherent stabilising effect on the system. As a result we do not see any oscillations after the air temperatures have reached their respective steady state values. Moreover ideally we can say that using the controller in Proportional + Integral mode (PI mode) and Proportional + Integral + Derivative (PID) mode should give same results.

Now for fixed parameters of P, T_i and T_d, the controller calculates the error based on difference between the set value and process value. Thereafter the controller adjusts the duty cycle of the relay so as to balance the heat transfer between cold box and metering box bringing about stability of air temperature in the cold box. Now if the specimen thickness is altered keeping the material thickness same or vice-versa, the controller will automatically bring about the required change in duty cycle, based on the error generated, so as to maintain the stability in air temperature.

Figure 10 (a) Time temperature profile of heat exchanger fluids for case 1 (b) Time temperature profile of heat exchanger fluids for case 2



(a)



(b)

There is a slight mismatch between the two results where the steady state average values seems to be different. This is obviously not because of the derivative action involvement in the first case and its absence from the second case. For better understanding time temperature profile of heat exchanger fluids i.e., inlet and outlet temperatures of air and ethyl glycol, are presented for case 1 and case 2 (Figure 9). Chilled ethyl glycol is circulated through tubes of fin and tube heat exchanger used while air is circulated through the fins.

For case 1 (Controller operated in PID mode)

Steady state average value is 0.15°C.

Minimum temperature reached was –0.890°C after about 1.088 hours from start.

For case 2 (Controller operated in PI mode)

Steady state average value is 0.262°C

Minimum temperature reached was –0.262°C after about 1.685 hours from start.

It is evident from Figure 9 that ethyl glycol fluid inlet temperature in case 1 is greater than that of case 2. Therefore the rate of heat removed from air in case 1 is greater than that of case 2. As a result steady state air temperature achieved in case 1 is slightly lower than the air temperature of case 2.

6 Conclusions

In this paper a PID based controller was designed for maintaining a constant air temperature inside the cold box. Experimental results showed that when the controller was operated in PI and PID mode, the steady state air temperature achieved inside the cold box was closest to the set point value given to the controller. But when the controller was operated in P-mode only, there was a significant offset between the air temperature inside the cold box and the set point. Although the overall sluggish response of the Proportional controller can be improved slightly by decreasing the proportional band, still there remains a steady state offset between the cold box air temperature and the required set point.

Thus from the above experimental results it is evident that in the present cooling strategy implemented, varying the parameters of the controller has a significant effect on the cooling performance.

References

Asdrubali, F. and Baldinelli, G. (2011) 'Thermal transmittance measurements with the hot box method: calibration, experimental procedures, and uncertainty analysis of three different approaches', *Energy and Buildings*, Vol. 43, No. 7, pp.1618–1628.

Blanusa, P., Bundi, R., Tanner, Ch. and Muehlebach, H. (2005) 'Thermal analysis of a wooden door system with integrated vacuum insulation panels', *Energy and Buildings*, Vol. 37, No. 11, pp.1107–1113.

British Standards BS EN ISO 8990 (1996) 'Thermal Insulation', *Determination of Steady-State Thermal Transmission Properties - Calibrated and Guarded Hot Box*.

BS 874: Part 3: Section 3.1 (1987) *British Standard Method for Determining Thermal Insulating Properties: Part 3, Test for Thermal Transmittance and Conductance - Section 3.1 Guarded Hot-Box Method*.

Chen, F. and Wittkopf, K.S. (2012) 'Summer condition thermal transmittance measurement of fenestration systems using calorimetric hot box', *Energy and Buildings*, Vol. 53, pp.47–56.

Chowdhury, D. (2013) *Study on the Performance of Secondary Cooling Circuit Under Varying Loads of a Guarded Hot Box System For U-value Measurement*', Unpublished, M. Tech. Thesis, School of Energy Studies, Jadavpur University, Kolkata, India.

Chowdhury, D., Ghosh, A. and Neogi, S. (2013) 'Performance evaluation of a chilled storage based cooling system for guarded hot box facility', *International Journal of Emerging Technology and Advanced Engineering,* Vol. 3, Special Issue 3, ICERTSD, pp.394.

Fang, Y., Eames, C.P. and Norton, B. (2007) 'Low emittance coatings and the thermal performance of vacuum glazing', *Solar Energy*, Vol. 81, No. 1, pp.8–12.

Geola, F., Kashti, Y., Levi, A. and Brickman, R. (2009) 'Study of the overall heat transfer coefficient of greenhouse cladding materials with thermal screens using the hot box method', *Polymer Testing*, Vol. 28, No. 5, pp.470–474.

Gorgolewski, M. (2007) 'Developing a simplified method of calculating U-values in light steel framing', *Building and Environment*, Vol. 41, No. 1, pp.230–236.

Lafarge Texas Styrofoam Thermal insulation Catalogue.

Sala, J.M., Urresti, A., Martin, K., Flores, I. and Apaolaza, A. (2008) 'Static and dynamic thermal characterisation of a hollow brick wall: tests and numerical analyses, *Energy and Buildings*, Vol. 40, No. 8, pp.1513–1520.

Suleiman, M.B. (2011) 'Estimation of U-value of traditional North African houses', *Applied Thermal Engineering*, Vol. 31, Nos. 11–12, pp.1923–1928.

Nomenclature

A	Area of specimen perpendicular to heat flow
BS	British standards
CB	Cold box
EN	European nation
GB	Guard box
GHB	Guarded hot box
h_{ce}	Convective heat transfer coefficient due to external environments (in W/(m^{2}K))
h_{ci}	Convective heat transfer coefficient due to external environments (in W/(m^{2}K))
h_{re}	Convective heat transfer coefficient due to external and internal environments (in W/(m^{2}K))
h_{ri}	Convective heat transfer coefficient due to internal environments (in W/(m^{2}K))
HVAC	Heating, ventilation and air conditioning
ISO	International standards organisation

Nomenclature (continued)

k_i	Thermal conductivity of the i^{th} layer of specimen
L	Thickness of specimen
l_i	Thickness of individual layers of specimen
lpm	Litres per minute
MB	Metering box
N	Total number of layers in specimen
PI	Proportional integral
PID	Proportional, integral and derivative
PV	Process value
PWM	Pulse width modulation
SV	Set value
T_e	Temperature of metering box (High temperature environment)
T_i	Temperature of cold box (Low temperature environment)