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DEVELOPMENT AND PERFORMANCE EVALUATION OF A VIRTUAL PID CONTROLLER FOR A GUARDED HOT BOX TEST FACILITY FOR U-VALUE MEASUREMENT

Amrita Ghosh[1], Trevor J. Hyde[2], Subhasis Neogi[3+]

[1,3]*School of Energy Studies, Jadavpur University,Kolkata-700032, India.*

[2]*School of the Built Environment, University of Ulster, Newtownabbey, Northern Ireland, UK.*

[+]Email: neogi_s@yahoo.com

ABSTRACT
One of the primary considerations in the evaluation of building components and construction materials used in energy efficient designs is in determining their thermal characteristics while operating under different temperature regimes. This is normally achieved by testing the product to determine its thermal conductivity or its overall heat transfer coefficient (U-value) using the Guarded Hot Box method. In this method regulated heat flow is to be maintained through the specimen under a steady state condition. To achieve these conditions the metering box and the guard box are to be maintained at a constant temperature level so as to ensure as far as possible one dimensional heat flow only through the specimen sample. This is achieved through the monitoring and measurement of both surface temperatures and air temperatures in the guard box and the metering box which are used to control the various heating and air circulating devices to achieve the desired level of accuracy. Heat is added into the system using tubular resistance heaters and DC plate heaters which allow for accurate measurement of the supply power used to maintain a temperature balance between the metering and guard chambers. A virtual PID controller has been developed using VEE software, the output of which is processed for operating the control relays which in turn actuate the heating units for providing the desired level of heating.

Keywords: PID controller, Guarded Hot Box, Metering Box, U-value, Thermocouple

1. INTRODUCTION

The U-value of a material is defined as its overall heat transfer coefficient and is measured in $W.m^{-2}.K^{-1}$. It is useful for determining the heat loss (or gain) through a building element such as wall, roof, floor or window. The higher the U-value the higher is the rate of heat transfer and therefore the poorer the thermal performance of the building envelope. Thus, the measurement of a building component U-value is very important from an energy conservation point of view.

A method for determining the U-value of a building component or material is the Guarded Hot Box method. In this method the accurate control of the temperatures in the guard box, metering box and the cold box is vital as constant temperatures are required to achieve the steady state conditions required for the accurate measurement of the U-value. In the present work, virtual PID controllers are designed to control the temperatures of the metering box and the guard box.

Proportional-integral-derivative (PID) controllers are extensively used in controlling temperatures at various temperature regimes such as very low temperatures in adiabatic demagnetisation refrigerators [1] and high temperatures in gas-fuel combustors [2]. These controllers perform well and show a very high level of reliability. These are the most extensively used feedback controllers today. The PID technology has gradually shifted from pneumatic, via electrical to digital control. Their performance has gradually improved. Tuning has become automatic [3]. Nowadays, these controllers can be implemented easily using software platforms [4]. Digital control signals are obtained from these controllers. These signals can be easily converted into analog signals to drive heating units which control the temperature of the process.

2. GUARDED HOT BOX FACILITY FOR U-VALUE MEASUREMENT

The overall heat transfer coefficient (U-value) is determined using the Guarded Hot Box method in accordance with BS EN ISO 8990:1996 [5]. The entire test setup consists of a metering box, a guard box and a cold box as shown in fig.1. The specimen to be tested is located in an aperture between the cold box and the guarded metering box. Heat supplied to the metering box passes through the test element to the cold box

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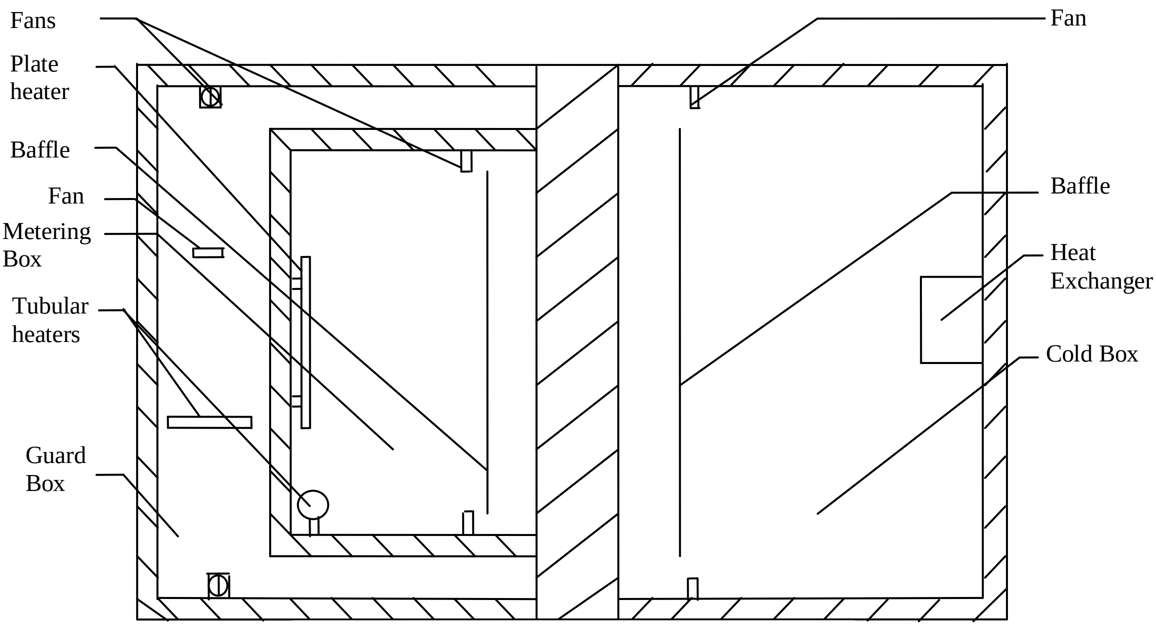

Fig.1. Guarded Hot Box U-value Test Setup

which is maintained at a constant low temperature. This heat flux through the test element and the corresponding temperature difference across it are measured to determine the U-value of the sample.

2.1 Metering box – Heat is supplied to the metering box from the heating units. As a result the apparatus reaches the desired set point temperature gradually. The one open side of the metering box is pressed against the test element, such that the air flow between the metering box and the guard box is prevented. The walls of the metering box are well insulated to ensure that the heat loss through the sides and back are small compared to the heat flow through the test element. A baffle plate is placed parallel to the surface of the test element to provide a radiating surface of uniform temperature. A 100 W plate heater and two 60 W tubular heaters are used to heat the metering box to reach the set point. Circulating fans are installed inside the metering box to bring uniformity in the temperature.

2.2 Guard box – In the guarded hot box the metering box is placed inside the guard box. The purpose of the guard box is to establish such temperature around the metering box that the heat flow through the metering box walls is minimized. Adequate width of the guard space is provided to minimize the effects of changes in the laboratory environment temperature on the test element in the metering area. The guard box is highly insulated to reduce heat loss to the surrounding environment. Two 120 W tubular resistance heaters are used to maintain the guard box temperature. Circulating fans are incorporated to ensure mixing of the air in the guard box thus avoiding stagnant hot or cold spots.

2.3 Cold box – The cold box provides a controlled environment at a constant low temperature using a heat exchanger and a cooled circulating medium (Ethylene glycol). It is also highly insulated to reduce the load on the cooling system. Temperature control is achieved via a PID controller. Circulating fans are installed to achieve uniformity in the temperature.

3. EXPERIMENTAL DETAILS

During experimental testing, the temperatures in the metering box and the guard box are controlled. For calibration of the system an insulation blank is used in place of the specimen. K type thermocouples are used to measure the air temperature and surface temperature at different locations of the metering box and the guard box respectively. This K type thermocouple (made of chromel and alumel) possesses a wide operating temperature range from -200 ^{o}C to 1370 ^{o}C. The voltage signals originating from the thermocouple junctions are logged sequentially by the Agilent Data Acquisition System 34970A through its multiplexer slots. In the metering box the temperature at three different locations in the air are measured using thermocouples. The average of these three gives the mean air temperature in the metering box. In the guard box thermocouples are located on the outer surface of the metering box at twelve different locations. The air and surface temperature data so acquired are processed through the data acquisition system and subsequently fed into the computer system. In the program, the three air temperatures of the metering box and the twelve surface temperatures of the guard box are averaged out separately to form the input signal parameters for the virtual PID controllers. Two individual virtual PID controllers are designed and implemented to control the temperatures of the metering box and the guard box separately. The required proportional, integral and derivative controls are provided for maintaining the temperatures at the set points.

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The output signals of the PID controllers are then fed to a DAC slot for the conversion of the digital signal into an analog signal. A 12V DC voltage is obtained from the DAC depending on the output value of each controller. This DC voltage is processed electronically and then used to operate control relays. These relays in turn operate the heating units installed inside the metering box and the guard box.

Thus, a closed loop system, as shown in fig.2, is obtained for accurate temperature control.

4. PID CONTROLLER

PID control is useful in systems that sample an output, compare the sample to a desired result, and take corrective action to force the controlled element closer to the desired result (set point). In a well-tuned PID control loop, the output reaches the desired value rapidly with minimal over and undershoot.

The words Proportional, Integral, and Derivative describe the correction algorithms based on the error, the integrated error over time, and the rate of change of the error term. The PID controllers designed in this work calculate the corrective output using the formula:

Output = K_p × Error + K_i × sum(Error)/64 + K_d × d(Error)/dt.

The K_p, K_i, and K_d terms are the proportional, integral and derivative coefficients that tune the PID control loop. The Error term is the difference in the set point and the actual value.

The first parameter to be adjusted in the designed virtual PID controller is the *Proportional constant* K_p. Its corrective action is proportional to the error term derived by subtracting the current load value from the set point value. This coefficient operates only on the latest measured value.

The second parameter to be adjusted is the *Derivative constant* K_d, so named because the amount of correction applied depends on the rate at which the error term is changing. In this controller the derivative term is computed by subtracting the previous error term from the current error term.

The final parameter to be adjusted is the *Integral constant* K_i, so named because it represents the integrated error over a reasonable time period. It is used to minimize the accumulated error. In this controller, the integral term is calculated by summing the last 64 error terms and then dividing it by 64 [6].

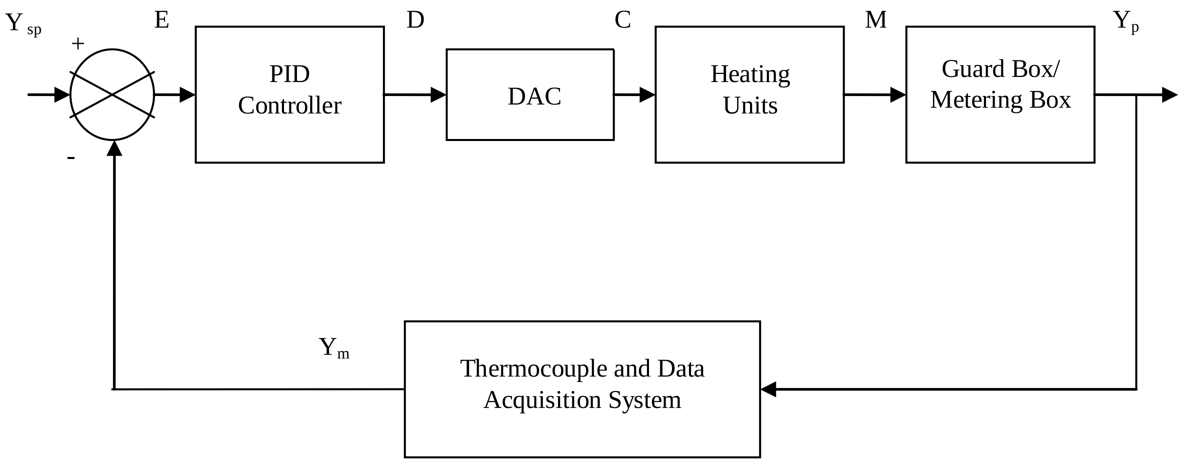

Fig.2. Block diagram of the system

5. RESULTS & DISCUSSIONS

In the present work, three cases with three different set point temperatures have been investigated.

Case 1: In the first case the experiment was initiated from a cold state i.e. with an average ambient temperature of 26.5 ^oC. The set point temperature was set at 35 ^oC for both the metering box and the guard box. It was found that after a time-duration of about 1 hr and 2 min the temperature of the metering box reached the set point. The temperature of the guard box reached the set point after a time-duration of about 1 hr and 5 min from the start of the experiment. From the Time-Temperature characteristics as shown in fig.3 it is evident that the temperatures of both the guard box and the metering box overshot from the set point and continued to rise steadily even when the heating devices were turned off. This may be due to the addition of heat from the circulating fans which resulted in the continuous increase of temperature in both the metering box and the guard box.

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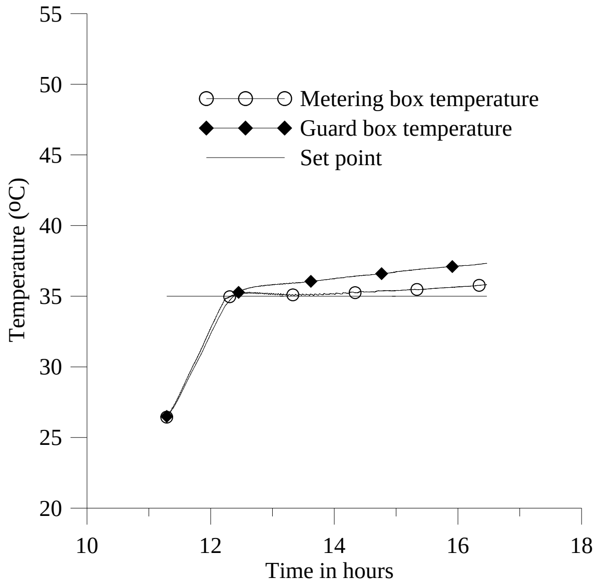

Fig.3. Time – Temperature Characteristics (Case 1)

Case 2: In the second case the set point temperature was set at 40 ^{o}C. The average ambient temperature was 26.7 ^{o}C.

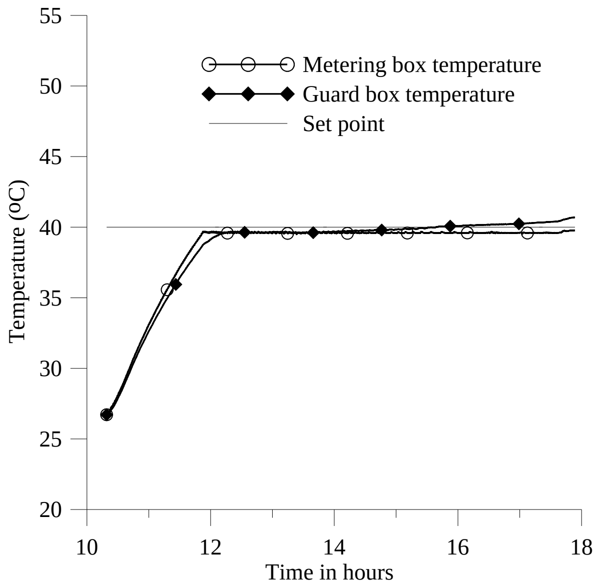

Fig.4. Time – Temperature Characteristics (Case 2)

In this case, the program was designed such that the heating units were turned off prior to reaching the set value point of the PID controller output. This was done in order to reduce the overshoot caused by the addition of heat by the circulating fans. The heating units of the metering box were turned off by the controller after about 1 hr and 33 min when the temperature was about 39.6 ^{o}C. The heating units of the guard box were turned off after about 1 hr and 44 min when the temperature was about 39.6 ^{o}C.

It was found that though the heating units were turned off, the temperatures of both the metering box and the guard box continued to rise as shown in fig.4. The increase of the temperatures was due to the addition of heat by the circulating fans. However, the rate of increase of temperature of the metering box as well as the guard box was found to be slower than case 1. This may be explained from the fact that as the temperatures inside the metering box and the guard box increased the differential temperatures between the metering box and the operating fans and also between the guard box and the operating fans were reduced. This resulted in less heat dissipation from the fans.

Case 3: In the third case the set point was set at 50 ^{o}C. The average ambient temperature was 26.6 ^{o}C.

The temperature of the metering box reached the set point after about 2 hrs and 25 min. Whereas, the temperature of the guard box reached the set point after about 3 hrs and 37 min. It was found that after reaching the set point the temperatures of both the guard box and the metering box were maintained at that level by the PID control system almost precisely as shown in fig.5.

In this case, the differential temperatures between the metering box and the operating fans and also between the guard box and the operating fans were further reduced. So, there was almost zero heat dissipation from the fans. Thus, the PID controllers were capable of controlling and maintaining the temperatures at the set point.

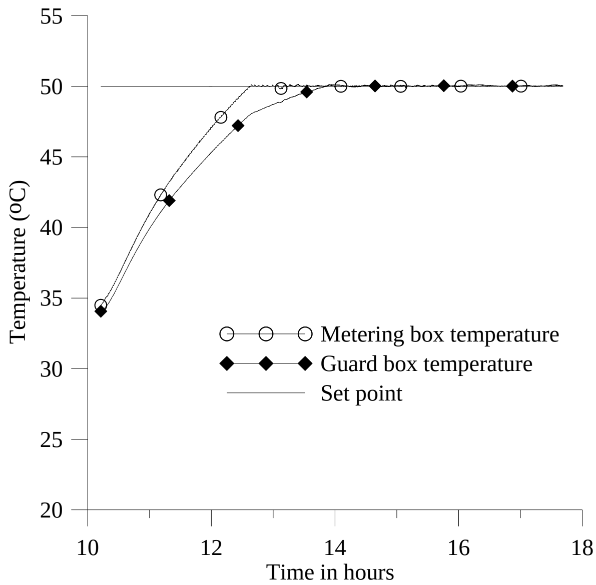

Fig.5. Time – Temperature Characteristics (Case 3)

6. CONCLUSIONS

Temperature data from different locations of the metering box and the guard box are averaged separately in the program. These average temperatures are then compared with the set points and the required control actions are taken by the PID controllers to operate the heating devices.

From the experimental data it is observed that for higher set point temperatures improved controls are achieved by the PID controllers.

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While for lower values of set points, the temperatures of both the metering box and the guard box continue to rise beyond the set points even with the heating units turned off. This heat gain is due to the heat dissipation from the circulating fans. For higher values of set points, the differential temperatures between the metering box and the fans and also between the guard box and the fans are reduced. This results in less heat dissipation from the fans by radiation and convection. Thus, an improved temperature control is achieved. In the present work, for the highest values of set points i.e. 50 ^oC, the maximum deviation of the average temperature of the metering box from the set point is found to be 0.38% after the steady state is reached. The maximum deviation of the average temperature of the guard box from the set point is found to be 0.25% after the steady state is reached.

However, the measurement of temperature at more number of locations inside the metering box and the guard box may be undertaken for more accurate knowledge of the system characteristics. The same test cases may be repeated to find out the repeatability of the results.

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NOMENCLATURE

Symbol

Y	Signal
E	Error signal
D	Digital control signal
C	Analog control signal
M	Manipulated variable
K_p	Proportional constant
K_i	Integral constant
K_d	Derivative constant

Subscripts

m	Measured
sp	Set point
p	Process output

AUTHOR BIOGRAPHY

Ms. AMRITA GHOSH is an M.Tech scholar at School of Energy Studies at Jadavpur University, Kolkata, India. She has specialization in Solar Thermal Energy Systems and Bio Energy Systems. She is currently working in Building Energy Management.

Dr. TREVOR J HYDE is a Reader at School of the Built Environment at University of Ulster, Northern Ireland, UK. He has 6 years of teaching experience in Construction Technology and Building Services. He has 10 years of research and industrial experience. He has research interests in Design methodologies and fabrication of vacuum glazing, Characterisation and environmental performance of advanced glazing and window systems for Sustainable energy technologies. He has several publications in international journals.

Prof. SUBHASIS NEOGI is a Professor at School of Energy Studies at Jadavpur University, Kolkata, India. He has 25 years of teaching experience and 5 years of industry experience. He has research interest in Energy Conservation & Management, Energy Efficient Buildings, Wind Energy, Solar Thermal Engineering etc. He has several publications in various national and international journals.