Development of Dental Autoclave Control System Using Fuzzy Logic and Optimized PID Algorithm

A. Elgarhy [1], M. T. Alwaked [2], S. Aboelkheir [2], A. F. Seddik [* 2]
1: Electronics and Communication Department, 2: Biomedical Engineering Department, Faculty of Engineering, Helwan University, Egypt,

*: Guide

Abstract

Sterilization process is widely used in the medical field.Dental autoclave is the most popular devicethat is used in sterilizing process. The heat control system of the sterilization process suffers from problems related to undesirable overshoots and longer settling time and oscillations. The purpose of this work is to obtain the best control system to solve these heat control problems through building a model for the dental autoclave heat control system and a simulation of different control systems, different control systems were applied to the model and evaluated to select the best system to improve the performance of a dental autoclave. Our experimental results have shown that the fuzzy-PID control system reached the desired temperature of sterilization faster and more accurate than other systems, also the average error of the desired temperature is 0.05 ° C which is very small compared to average errors of other control systems.

Keywords: Dental autoclave modeling, Sterilization heat control, Fuzzy logic application, Particle swarm optimization.

1. Introduction

Sterilization process [1] through saturated water vapor (steam) is widely used in pharmaceutical, food industries and medical fields. The sterilization process purpose is to eliminate micro-organisms of any nature. Dental autoclave [2] has one sterilizing cycle for a perfect and quick sterilization of different materials used in hospital and/or dental surgery. It is made of a boiler, a door, a gasket and a timer to count sterilizing time, a sensor to check temperature, and a safety valve for steam exhaust in case of over-heating as shown in figure 1.

Figure1. Dental autoclave.

Water steam heating process is not immediate in any case, and needs time to reach thermal equilibrium; this time varies according to the size of the autoclave, the quantity and quality of the material to be sterilized. So the time of sterilization is important and must be considered in the treatment cycle.

Scientific European and American community have fixed and defined three temperatures [3] 115°C, 120°C and 134°C relative exposures for different materials and their resistance to temperature. Cycles at 125°C for 15 minutes of sterilization is a middle cycle for sterilization of any metal instruments. This is the used sterilization cycle in this study.Steam [4] is an effective sterling for two reasons. First, saturated steam is an extremely effective "carrier" of thermal energy. It is many times more effective in conveying this type of energy to the item than is hot (dry) air. Steam, especially under pressure, carries their thermal energy very quickly, while hot air does so very slowly.

The second reason is that the steam is an effective sterling because any resistant, protective outer layer of the microorganisms can be softened by the steam, allowing coagulation of the sensitive inner portions of the microorganism.

Steam sterilization requires four conditions: adequate contact, sufficiently high temperature, correct time and sufficient moisture. Although all are necessary for sterilization to take place, sterilization failures in clinics and hospitals are most often caused by lack of steam contact or failure to attain adequate temperature. It also fails because it requires strict adherence to time, temperature and pressure settings. Many temperature control systems were used in order to improve sterilization efficiency PID temperature control system, fuzzy temperature control system, and fuzzy PID temperature control system. But evaluation of these systems is very difficult, as it needs a simulation model, this work introduces that model.

The system model simulation [5][6] aims to predict the autoclave inner temperature behavior [7], mainly the time period when the system reaches the desired temperature. This is the period when there is no more commonly losses occur by overheating. Modeling [8] should pursue simplicity and accuracy, but in general they are conflicting characteristics. Our first attempt led to complex models that treated the problem with distributed heat transfer [9][10] ruled by partial differential equations and thermodynamics basics [12][13][14]. But those models were unsuited to use with regular control theory. Searching for a simpler model, it was decided to use a model ruled by ordinary differential equations, depending upon quantity of energy transferred from the heater to the liquid per unit time. Microsoft excel software is used to import data from MATLAB/Simulink [15] to analyze the controller by studying the response generated from the modeling and simulation of the controller, The difference between the desired temperature and output feedback [16] temperature is passed as input into the controller subsystem.

2. PROPOSED METHOD

The overall dental autoclave temperature control system model is represented in figure 2. The model consists mainly of the temperature controller system block and the heater system of dental autoclave block which controls the temperature inside the dental autoclave and the safety valve to prevent explosion in case of overheating. The inputs to the temperature controlled system block are the sterilization temperature and the temperature error (except ON/OFF it is forward system); and the inputs to the heater system block are energy supplied to the heater as a function of time and a constant representing the desired temperature (sterilization temperature).The output of the overall system is actual internal temperatures inside the autoclave with time.

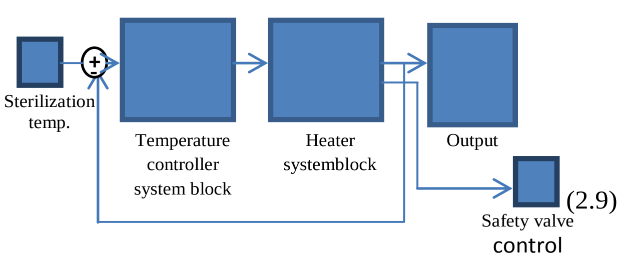

Figure 2.The overall dental autoclave model.

The heater system block simulation model depends upon the fact that the transfer of energy as heat can take place via conduction processes. Conductionis the transport of thermal energy through an object by a series of collisions between adjacent atoms, molecules, or electrons. Heat flow [11] is represented by equation (2.1).

Heat flow = $[K_{heater}(t)*Q_h(t)+K_{sys}(t)T_{sys}(t)]*A/L$ (2.1)

Where K_{heater} is the thermal conductivity of heater substance [m ^oC/ (J /s)], K_{sys} is the thermal conductivity of water inside autoclave [m ^oC/ (J/s)], Ais the cross sectional area of the autoclave (meters^2 or feet^2),Tis temperature (^oC or ^oF), Lis thickness (meters or inches), Q_h is the heat transferred to the water by the heater.

So heat transfer depends upon thermal conductivity of the heater material, the equation could be re-written as:

Energy transferred=heat flow*time (2.2)

Energy transferred/time=heat flow (2.3)

Energy transferred to water / time=

$$(K_hQ_h+K_WT_W) \quad (2.4)$$

Where K_h is a constant that depends on the material the heater is built and other factors, $K_w$is a constant depends on the specific heat of water and other factors, $T_w$iswater temperature, $K_w$is a constant that is directly proportional to specific heat difference between heater and water(K_{hw}).

$$K_W = K_{hW}(T_h - T_W) \quad (2.5)$$

$$dE/dt = K_h(t)*Q_h(t)+K_W(t)T_W(t) \quad (2.6)$$

C_h (t) and C_w(t) are time dependent because the closer the water temperature gets to the desired temperature(temperature of sterilization), the less influence the heater has over the water, So C_h approaches zero and it is exactly zero if water temperature is the same as heater temperature.

$$dE = K_h(t)Q_h(t)dt + K_W(t)T_W(t)dt \quad (2.7)$$

Using first law of thermodynamics:

ΔE =ΔE $_{system}$ +ΔE $_{surroundings}$= 0 (2.8)

By integration

$$E(t) = E_0 + \int_0^t K_h(t)Q_h(t)dt + \int_0^t K_W(t)T_W(t)dt \quad (2.9)$$

Where E_0 is the initial energy contained in the water. Considering outside surface effect K_{out} (surroundings), so the heater simulation model is implemented using equation 2.9. Where, E (t): quantity of energy transferred from the heater to the liquid with time,E_0:is the initial energy contained in the water**,** Q (t): is the heat transferred to the water by the heater, K_h: constant depending upon the material of the coil, T_w: iswater temperature, $K_{w:}$ constant depending on the difference between actual temperature and the desired temperature, T_{out}: outside temperature.

The Simulink model of heater system block using equation (2.9) is shown in section 4.

3. Proposedtemperaturecontroller systems

The heater system of dental autoclave needs a controller to achieve best autoclave efficiency by reaching the desiered sterilization temperature faster and continue at this temperature till the end of the sterilization cycle (15 minutes),Next subsections will discuss in details each of controller systems used.

3.1 ON/OFF controller system

This is the simplest type of control [18] used, if the input is below the set-point then the system is fully ON and if the input rises above the set-point then the system is fully OFF. In practice the use of ON/OFF control can cause problems [19] such as that the system rapidly switches ON and OFF leading to inefficient system operation and increased mechanical wear.No feedback process (only feedforward process) takes place in this controller system.

3.2 PID controller system

A PID controller incorporates a mix of proportional, integral and derivative control action [21]. In this case the control output is a function of the size of the error (*e* (*t*)), the rate of change of the error with time $T_d \dfrac{de(t)}{dt}$ and the integral of the error over time $\dfrac{1}{T_i}\int_0^t e(t)dt$,as shown in equation(3.1).

$$\dot{Q}_o = K\left[e(t) + Td\frac{de(t)}{dt} + \frac{1}{T_i}\int_o^t e(t)dt\right] \qquad (3.1)$$

Where, Td is the derivative action time (s), T_i the integral action time (s) and K the gain. PID control offers close control system, the control action responds to the rate of change of the error, while the integral control acts to eliminate the set-point error experienced with proportional control. The PID controller subsystem contains the proportional gain scaling factor, The derivative gain scaling factor and the integral gain scaling factor.

3.3 Fuzzy controller system

Block diagram of fuzzy controller system is shown in figure 3.

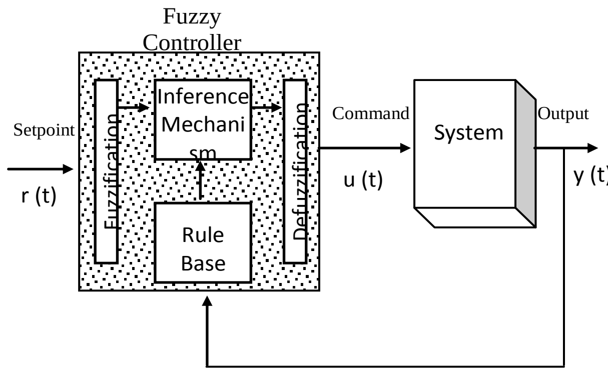

Figure3. Fuzzy controller system block diagram.

Fuzzy techniques to control systems[22] consists of two very different stages, first stage must be completed before the control algorithm is executed and it consists of establishing the controller's input and output variables (linguistic variables), then defining each variable's fuzzy set, thendefining the sets' membership functions, after that establishing the rule base, defining the fuzzification, inference and defuzzification mechanisms. Second stage, to be completed with each step of the control algorithm, and consists of obtaining the precise input values, then fuzzification takes place by assigning the precise values to the fuzzy input sets and calculating the degree of membership for each of those sets, then Inference by applying the rule base and calculating the output fuzzy sets inferred from the input sets, finally defuzzification takes place by calculating the precise output values from the inferred fuzzy sets.These precise values will be the controller's outputs (commands) and is applied to the system to be controlled (heating system of dental autoclave).

Fuzzy controller for a dental autoclave considers temperature error e(t) and temperature error variationsde(t)/dt as inputs and energy supplied to the system as output.

Rule base of controlling temperatur is represented in table1.Consider, LN: Large Negative ,MN:Medium Negative, SN:Small Negative, ZE:Zero,SP :Small Positive,MP :Medium Positiv,LP: Large Positive

ISSN: 2278-0181
Vol. 2 Issue 8, August - 2013

Table1 . representing rule base of controlling temperature.

error/error-variation	LN	MN	SN	ZE	SP	MP	LP
LP	LN	LN	LN	LP	LP	LP	LP
MP	LN	LN	LN	MP	LP	LP	LP
SP	LN	LN	LN	SP	SP	LP	LP
ZE	LN	LN	LN	ZE	MP	MP	LP
SN	LN	LN	LN	SN	ZE	SP	MP
MN	LN	LN	LN	MN	SN	ZE	SP
LN	LN	LN	LN	LN	MN	SN	ZE

3.4 PID/ fuzzycontrol system

It is a combination between PID control and fuzzy [23]control in order to increase efficiency of dental autoclave by increasing temperature stability inside the autoclave and by reducing time taken to reach the desired temperature this may also led to decrease time of sterilization as shown in figure 4

.

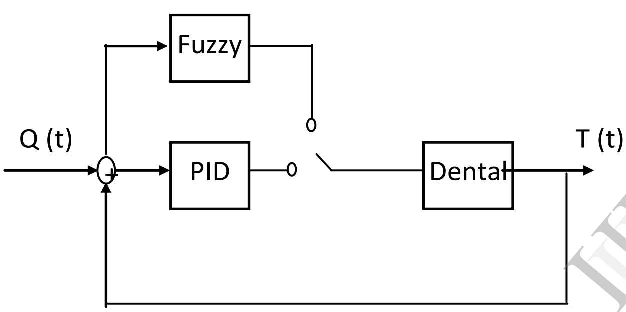

Figure4. PID /Fuzzy control system scheme.

The simulink model of the PID/ fuzzy control system of dental autoclave consists mainly of the fuzzy logic controller block and the heating system in the dental autoclave block. The fuzzy logic controller block contains a reference to a fuzzy logic inference system. The inference system has four linguistic variables which are two inputs (error signal and error derivative) and two output (energy supply control and safety valve control). The fuzzy logic inference system for the fuzzy proportional-integral-derivative controller contains a set of fuzzy logic rules thatdefine thebehavior of the system in relation between the error signal, error derivative signal and the control signals (energy supplied to autoclave and safety valve). A multiplexer is used to combine the two inputs to the fuzzy logic controller

.

3.5 Optimized PID control system (using PSO technique)

The system is initialized with a population of random solutions and searches for optima by updating generations. In PSO [25] [26], the potential solutions, called particles, fly through the problem space by following the current optimum particles. Each particle keeps track of its coordinates in the problem space which are associated with the best solution (fitness) it has achieved so far (The fitness value is also stored) .This value is called *pbest*. Another "best" value that is tracked by the particle swarm optimizer is the best value, obtained so far by any particle in the neighbours of the particle. This location is called *lbest*. When a particle takes all the population as its topological neighbours, the best value is a global best and is called *gbest*. The particle swarm optimization concept consists of, at each time step, changing the velocity of (accelerating) each particle toward its p*best* and *lbest* locations (local version of PSO). Acceleration is weighted by a random term, with separate random numbers being generated for acceleration toward *pbest* and *lbest* locations. MATLAB M-file where utilized to run the PSO technique and apply it to the PID controller system in order to improve the system performance , The PID block calls the PID controller file, which in turn calls the PSO technique .

4. Results

In this study results aresubdivided into: the heater system model results, the temperature controller model results and the output response of different controller systems.

4.1. Results of heater control system using Simulink

Using Simulink/ Matlab the simulation model of the overall dental autoclave temperature control system is shown in figure 5.

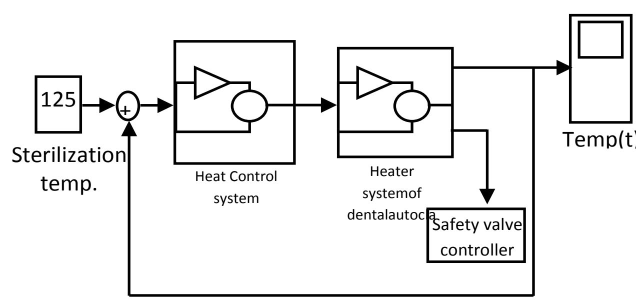

Figure5. The overall of dental autoclave temperature control system simulation.

Dental autoclave heater model simulation using equation (2.9) is shown in figure 6.

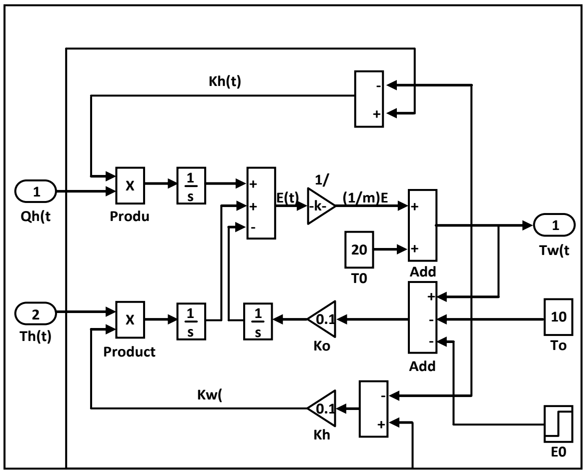

Figure 6. Heating system of dental autoclave simulation

4.2. Results of temperature controlled systems using Simulink/ Matlab.

ON/OFF temperature control system simulation is shown in figure 7.

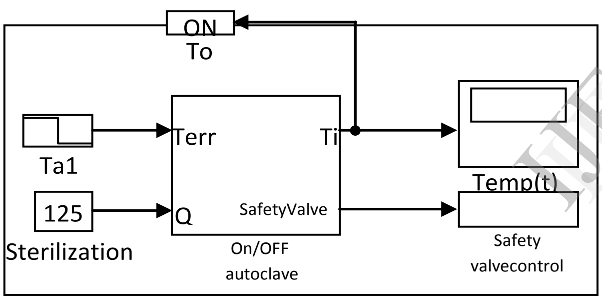

Figure 7.Simulink model of dental autoclave control by ON/OFF controller.

PID temperature control system simulation is shown in figure 8.

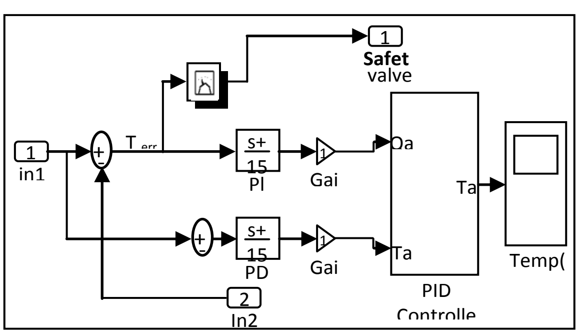

Figure 8.Simulink model of dental autoclave controlled by PID controller.

The Simulink model of the PID/fuzzy control system of dental autoclave heater is shown in figure 9.

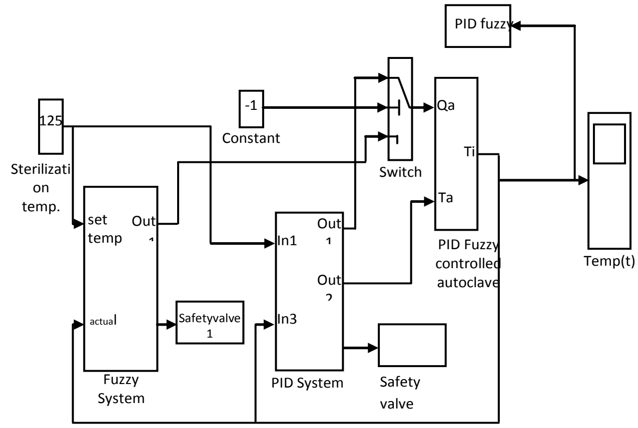

Figure 9.Simulink model of dental autoclave controlled by PID/fuzzy controller.

The output of the each controller system is discussed in details in the next section.

4.3. Output block results

4.3.1. ON/OFF temperature controller output

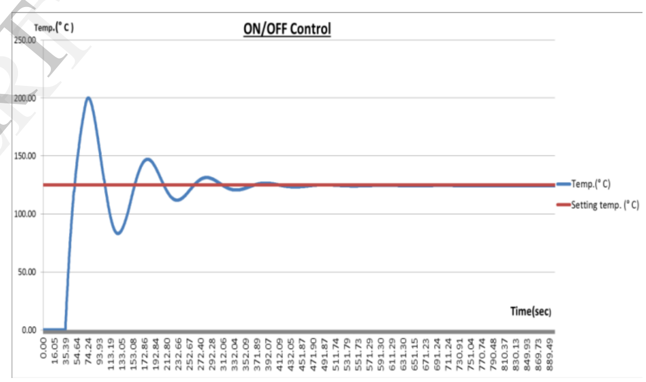

Figure 10.Output response of the conventional ON/OFF controller.

It is clear from curve in figure 10 that the ON/OFF control system there are many oscillations for about 368 second while the sterilization cycle takes about 900 sec. (15 minutes), so it reduces both efficiency of sterilization in dental autoclave and also affects the power unit efficiency with time.

T_{Error}= Settimg temperature - T_{avg}

= 125 – 119.79 = 5.21°C

4.3.2. PID temperature controller output

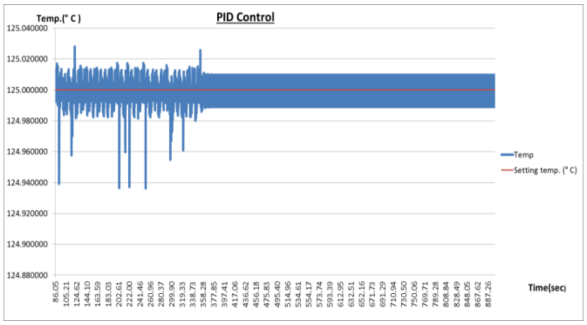

Figure 11. Output response of the PID controller.

It is clear from curve above in figure 11 that PID control system reached the set point (125°c) very fast (after about 86 seconds), but there are a lot of oscillations which affects efficiency of sterilization in dental autoclave and affects the power unit efficiency with time as it goes up & down.

T_{Error}=Settimg temperature - T_{avg}
= 125 – 124.4=0.6°C

4.3.3. Fuzzy temperature controller output

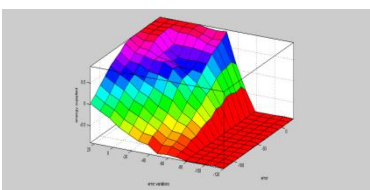

Figure 12. Surface view of fuzzy controlled autoclave.

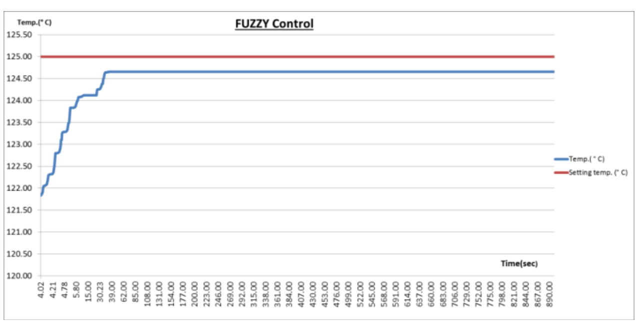

Figure 13.Output response of the fuzzy controller.

It is clear from curve in figure 18 that the fuzzy control system reached (124.6° c) while the desired temperature is (125° c) but it is more stable than (PID control system) and (ON/OFF control system) as no oscillations occur, also it reaches this temperature with no oscillations in about 40 seconds only.

T_{Error}= Setting temperature - T_{avg}
= 125 – 124.5= 0.5°C

4.3.4. Optimized PID control system results: (using PSO technique)

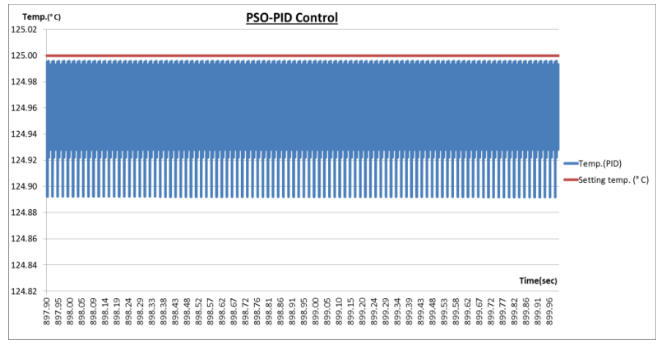

Figure 14.Output response of Optimized PID control system.

This system reached the desired temperature only in 59 seconds then after that time this temperature remained till the end of the sterilization cycle as shown in figure14.

T_{Error}= Setting temperature - $T_{average}$
= 125 – 124.9 = 0.1°C

5. CONCLUSION

The most desirable heat control system performance requires that the controllers to have the smallest possible value for rise time, overshoot, and settling time. It also requires the final value to be as close as possible to the desired value which is 125° C as soon as possible; also the system temperature must be without oscillations as long as possible. From the output results it is clear that the PID controller systemhas good performance but it has a lot of oscillations till the end of sterilization cycle so it is not the best controller system. PID/FUZZY controller system has the bestperformance also it reaches accurately the desired temperature (125°C).

6. References

[1] Sridhar RaoPn., Sterilization and disinfection, 2008.
[2] Leah Vern Barnett, The manual of dental assisting 4e, 2008.
[3] Ellen Roberta Dietz, Safety Standards and Infection Control for Dental Assistants, 2008.
[4] Liesl K. Massey., The effect of sterilization methods on plastic and elastomers, 2nd edition, 2005.
[5] Anu Maria, Introduction to modeling and simulation, State University of New York at Binghamton , Department of Systems Science and Industrial Engineering, 1997.
[6] N. Deo., System Simulation, Prentice Hall of India.
[7] Francisco Carlos de AmorimTerceir, Roberto Vieira da Fonseca Lope, HélioKoiti Kuga., Modeling the internal temperature of an autoclave using parameter estimation.
[8] DshalabahSrivastava, Process modeling& simulation, 2010.
[9] Mark W. Zemansky and Richard H.Dittman, Heat and Thermodynamics, 1997.
[10] William S. Janna, Engineering Heat Transfer, 2009.

[11] LatifM.Jiji, Heat Transfer Essentials, 2006.
[12] Evelyn Guha., Basic Thermodynamics, 2000.
[13] Charles Leonard Brawn, Thermodynamics basics, 2009.
[14] A. S. Morton and Peter John Beckett, Basic thermodynamics, Michigan University, February 2010.
[15] ArunRajagopalan and Gregory Washington, Simulink tutorial, 2002.
[16] John Doyle, Bruce Francis and Allen Tannenbaum, Feedback Control Theory, 1990.
[17] James E. Braun, Donghun Kim, Miroslav Baric, Pengfei Li, Satish Narayanan and Shui Yuan, Whole Building Control System Design and Evaluation: Simulation-Based, 2012.
[18] Stephen W. Fardo and Dale R. Patrick.Industrial Process Control Systems, in: Process control system overview, 2009.
[19] Ernest O. Doebelin, Control system principles and designs, in: Open loop, input-compensated (feedforward) control.
[20] Tore Hägglund andKarl Karl Johan Åström, Advanced Pid Control, 2006.
[21] R.M. Aguilar, V. Muñoz and Y. Callero, Fuzzy Inference System - Theory and Applications, in: Control Application Using Fuzzy Logic Design of a Fuzzy Temperature Controller, 2012.
[22] Yunseop Kim, Fuzzy Logic Temperature Controller, 2001.
[23] ConstantinVolosencu, Introduction to PID Controllers - Theory, Tuning and Application to Frontier Areas, in: Tuning Fuzzy PID Controllers, 2012.
[24] F. ZHANGa, J. WANGa S. L. FUb and Z. T. HEa X. P. LIa, Adaptive Fuzzy PID Temperature Control System based on Single-chip Computer for the Autoclave, 2012.
[25] M.AMRITA and SAROJINI Jajimoggala, Design optimization by using particle swarm optimization in matlab and APDL in ANSYS, 2012.
[26] Edwin K. P. and Stanislaw H., An Introduction to Optimization, in: Particle swarm optimization, 2013.