Development of a Control System for Shell and Tube Heat Exchanger in MATLAB Simulink

H. M. A. Zeeshan[1], O. Ahmed[2], A. Ghaffar[3], M. Atif[4], C. H. Riaz[5], M. Z. Rafique[6], H. M. Osaid[7]

[1,2,3,4,5,6,7]*Mechanical Engineering Department, The University of Lahore, Pakistan*
[1]hmazeeshan@yahoo.com

Abstract-The main objective of this research is to develop a control system for heat exchanger so that the desired outlet temperature can be achieved by controlling the flow rate. For this purpose, shell and tube heat exchanger was chosen and modeled it by using its mathematical equations in MATLAB (Matrix Laboratory) Simulink and calculated the outlet temperature by NTU (Number of Transfer Units) effectiveness method. For the purpose of Control system, MPC (Model Predictive Controller) was used. This research will open a new way of Modeling Equations instead of transfer functions in MATLAB (Matrix Laboratory) Simulink. Using the model, it was developed; with controller, so as to manipulate the output temperature by simply controlling the flow rate. It can be justified weather the design of a new heat exchanger would be feasible or not for the specific requirements. At last this research is very helpful in Industries for the purpose of designing, development and control of new Heat Exchangers.

Keywords-Heat Transfer, Fluid Flow, Shell and Tube Heat Exchanger, NTU Effectiveness Approach, MATLAB Simulink, MPC Controller

I. INTRODUCTION

This research will be very helpful to the students who are new to MATLAB Simulink and want to make models or continue their projects in it. So, a shell and tube heat exchanger model in MATLAB Simulink was modeled. This research is feasible for designing of a new heat exchanger and its control system. [i]

1.1 Introduction to Heat Exchanger

Heat exchanger is a device which is used for transfer of heat energy from one fluid to another fluid at different temperatures, fluids may be liquid or gas. Heat is transferred by direct or indirect contact. [ii]

There are many types of heat exchangers but Shell and Tube Heat Exchanger was selected for this research work, because Shell and Tube is universally applicable to non-compact duties. This can be used for high pressure and temperature applications. This can be used for large areas and cheaper compared to other types. [iii]

A shell and tube exchanger consists of tubes contained in a cylindrical shell. [iv]

More than 90% of the industrial heat exchangers are shell and tube type heat. [v]

Some basic components of shell and tube heat exchanger are: [vi]

Tubes
Tube Sheets
Shell and Shell-Side Nozzles
Tube-Side Channels and Nozzles
Gaskets
Pass Divider
Baffles

1.2 MATLAB/Simulink

MATLAB is a technical language which can be used to perform data visualization, data analysis, and numeric computation and to solve mathematical and engineering problems. Using the MATLAB product, technical problems can be solved very easily and faster than the traditional programming languages. [vii]

MATLAB can be used in a varied range of applications such as profiling, debugging, code indentation, signal processing, control design, iterative exploration, communications, problem solving, numerical integration and numerical analysis. [viii]

One of the modules of MATLAB known as Simulink was used. By using block diagrams in Simulink modeling, analyzing and simulating the system are done easily. It has inclusive block library which is used to simulate linear, nonlinear or discrete systems. It is fully integrated with MATLAB, easy and fast to learn and flexible. [ix]

1.3 Purpose of Using Simulink

The idea is that MATLAB Simulink is used the mathematical equation of the model in the system directly and will get different results by using different parameters. It is user friendly program in which equations of selected system can be easily modeled and after simulation behavior of the system can be studied to verify the correctness of work.

II. GOALS & OBJECTIVES

The goal of this research is to develop a control system for a Shell and tube Heat exchanger in

MATLAB Simulink to control the outlet temperatures by controlling flow rate. The model was controlled around a set outlet temperature that was achieved by controlling the flow rate of the fluid.

III. LITERATURE REVIEW/HISTORY

Till now people have worked regarding modeling of heat exchanger with its Transfer Function. The selected model proves to be an innovation in this field as Modeling a General Shell & Tube Heat Exchanger model by using NTU Effectiveness Equations.

There is another technique to find the heat transfer in Shell and Tube Heat Exchanger which is LMTD (Log Mean Temperature Difference) approach. This is not effective approach to find the outlet temperature of tube side or shell side fluid in Shell and Tube Heat Exchanger. [x]

Previously Fuzzy Controller was used for controlling the Heat Exchanger with its Transfer Function. But this technique to control the heat exchanger is not easy because formation of the transfer function for any system is complex so use the MPC Controller for control system. [xi-xiii]

Another PI controller is used in which water flows through the tubes of electric power heater. In this heater outlet temperature of the tube is controlled by changing the flow rate of tube fluid. [xiv]

An article in which design of a control system for heat exchanger was prepared by using two partial differential equations. In this article, it elaborates the control of the outlet temperature of the fluid in parallel-flow by manipulating the inlet temperature of the fluid. [xv]

IV. METHODOLOGY

An Adaptive Neuro-Fuzzy Inference System (ANFIS) is a technique for modeling of double-pipe heat exchanger and control of important parameters on heat transfer and fluid flow and compared the experimental data for training of controller. [xvi]

Another interesting research makes a Dynamic model and control of Heat Exchanger. A dynamic model of Heat Exchanger has been developed by developing a concept for a new Heat Exchanger, developing its equations and modeling them in MATLAB Simulink. The main characteristic of this Heat Exchanger was to develop a District Heating Network and secondly to Design a non-linear model predictive controller. [xvii]

The model of relevant heat exchanger can be developed in MATLAB Simulink, verified and then controlled through controller in Simulink.

When satisfied then the program may be developed and burnt in the relevant controller to be attached with the Heat Exchanger and achieve the Automated Heat Exchanger.

Initially investigate different design parameters of heat exchanger (especially about Shell and Tube). For that Shell and Tube Heat Exchanger has been applied thoroughly. [xviii]

According to flow arrangement there are three basic types of configuration namely; the Simple parallel, counter flow and cross flow configuration. The counter flow configuration was used because in this configuration more heat is transferred than the parallel flow. [xix]

Some parameters were assumed in counter flow configuration there are: flow is single stream, single tube and single shell and without baffles. [xx]

The NTU effectiveness approach for heat transfer can be used, so it is useful for finding the heat transfer of unknown system without the outlet temperature. [xxi]

NTU effectiveness approach were used in (1-4) [xxii]

ϵ = Actual Heat Transferred / Maximum Possible Heat Transfer

ϵ = Effectiveness

$$\epsilon = \frac{\mathrm{Cc\,(TCout - TCin)}}{\mathrm{Cmin\,(THin - TCin)}} \quad (1)$$

$$\epsilon = \frac{1 - \exp[-(1 - \mathrm{Cmin/Cmax})\mathrm{NTU}}{1 - (\mathrm{Cmin/Cmax})\exp[-(1 - \mathrm{Cmin} - \mathrm{Cmax})\mathrm{NTU}]} \quad (2)$$

$$\mathrm{NTU} = \frac{\mathrm{UA}}{\mathrm{Cmin}} \quad (3)$$

$$Q = \epsilon \mathrm{Cmin}(\mathrm{THin} - \mathrm{TCin}) \quad (4)$$

By using (1-4) Modeled the Shell and Tube Heat Exchanger in MATLAB Simulink Which is shown in Fig. 1.

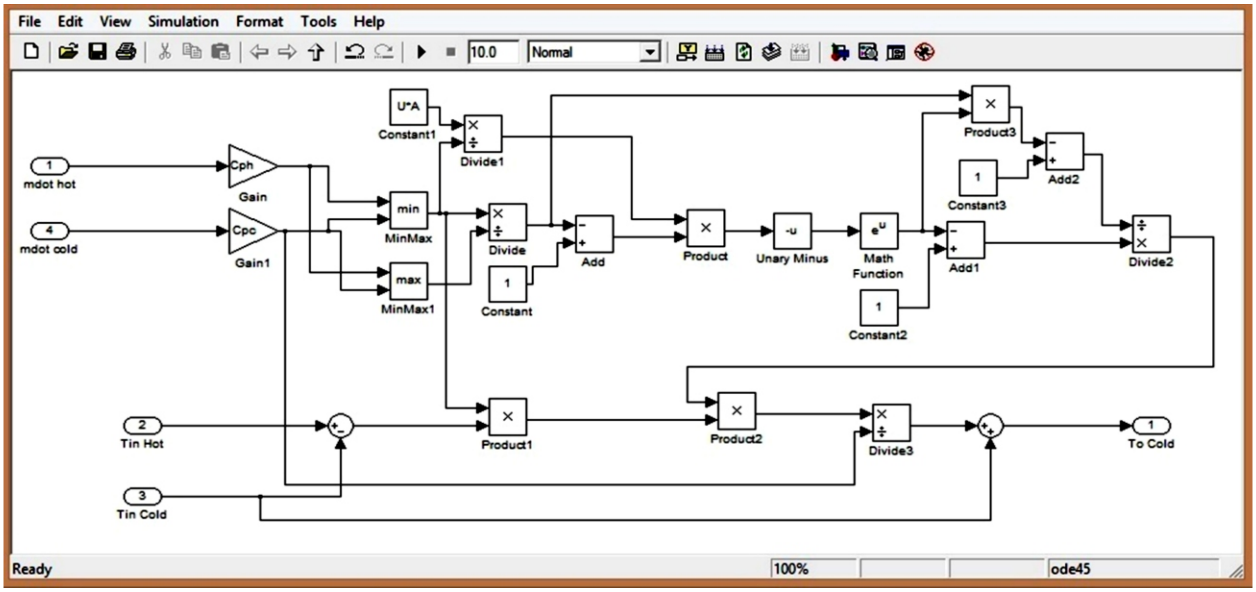

Fig. 1. Shell & Tube Heat Exchanger Model in MATLAB Simulink

V. What is MPC?

MPC controller (Model Predictive Controller) was used for controlling model. This is an advanced method and it has been used since 1980's in several industries (process, chemical, oil refineries). MPC is based on iterative, finite horizon optimization of a plant model. It uses Numerical Minimization Control Algorithm & Euler-Lagrange Equations to iterate a value and control strategy. [xxiii]

The MPC Controller block receives the current measured output signal (mo), reference signal (ref). The block computes the optimal manipulated variables (mv) by solving a quadratic program (QP).

When use the block for simulation and code generation, must specify an MPC object, which defines a model predictive controller. This controller must have already been designed for the plant that it will control. Because the MPC Controller block uses MATLAB Function blocks to implement the QP solver, it requires compilation each time the MPC object and block is changed. Also, because MATLAB does not allow compiled code to reside in any MATLAB product folder and must use a non- MATLAB folder to work on the chosen Simulink model when MPC blocks are used. [xxiv, xxv]

VI. Data Analysis

A single shell, single tube and single phase shell and tube heat exchanger was used for verification of the chosen model. In tube side cold distilled water was flowing and in shell side hot water.

Known parameters of the exhaust gases and working fluid in Heat Exchanger are given in Table I:

TABLE I
PARAMETER OF DIFFERENT FLUIDS

Description of Parameters	Values
Surface Area of tubes A	0.0149 m^2
Overall Heat Transfer Co-efficient U	1200 W/m^2K
Specific heat of Cold Fluid Cp_c	4.18 KJ/kg.K
Specific heat of Hot Gas Cp_h	4.18 KJ/kg.K
Mass Flow Rate of hot water m_h	0.05 kg/s
Mass Flow Rate of cold water m_c	0.1 kg/s
Inlet Temperature of Cold fluid T_{Cin}	32 °C
Inlet Temperature of Hot fluid T_{Hin}	58 °C

The Outlet temperature of cold fluid T_{Cout} can be calculated as follows:

6.1 Theoretical Verification

Equations 1, 2, 3 and 4 are used for theoretical verification

$C_{cold} = mc\,Cpc$ $\quad$ $C_{hot} = mh\,Cph$

$= 0.1 \times 4.18$ $\quad$ $= 0.05 \times 4.18$

$C_{cold} = 0.418$ KW/K $\quad$ $C_{hot} = 0.209$ KW/K

$Cmin = C_{hot} = 0.209$KW/K

$Cmax = C_{cold} = 0.418$KW/K

$$NTU = \frac{UA}{Cmin}$$

NTU= 1200×0.0149/209= 0.0856

$$\epsilon = \frac{1 - \exp[-(1 - Cmin/Cmax)NTU]}{1 - (Cmin/Cmax)\exp[-(1 - Cmin - Cmax)NTU]}$$

$\boldsymbol{\epsilon = 0.0804}$

Tcout = (€× Cmin/ Ccold) × (Thin TCin) + TCin

Tcout = 33.04 °C

$Q = \epsilon C_{min}(T_{Hin} - T_{Cin})$

$\mathbf{Q = 0.0804 \times 209 \times 26 = 436.8\ W}$

6.2 Model Verification

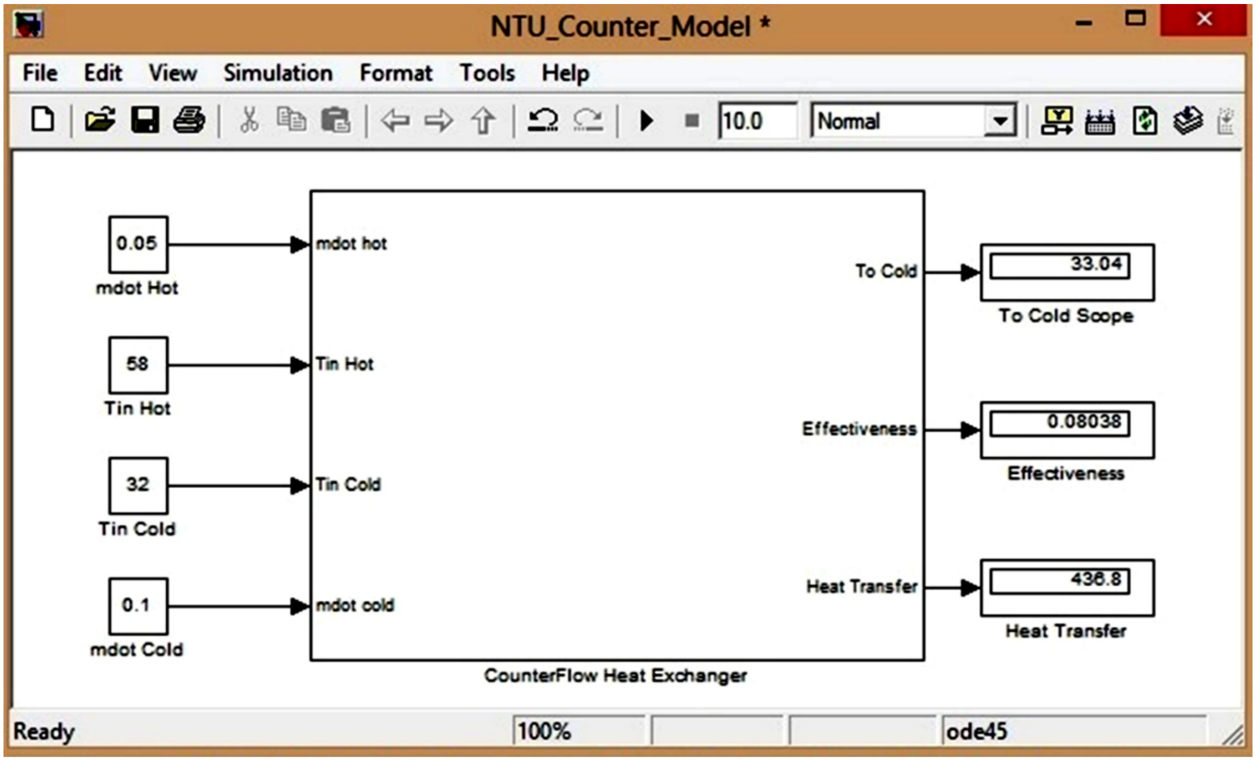

Fig. 2. Shell & Tube Heat Exchanger Model Verification in MATLAB Simulink

6.3 Experimental Verification

An equipment of SOLTEQ® Equipment for Engineering Education was used for experimental verification.

Heat Exchanger Training Apparatus

Model: HE 158

Error Tolerance of this apparatus is 5% which is shown in Table II

TABLE II

EXPERIMENTAL RESULTS OF SHELL AND TUBE HEAT EXCHANGER

m_{cold} (kg/s)	$T_1 = T_{Hin}$ (°C)	$T_2 = T_{Hout}$ (°C)	$T_3 = T_{Cin}$ (°C)	$T_4 = T_{Cout}$ (°C)	Simulated Result T_{Cout}	% Error
0.1	58	57	32	36	33.04	8 %
0.133	58	55	32	35	32.79	7 %
0.2	58	53	32	34	32.53	4.5 %

VII. RESULTS

Simulated result which is shown in Fig. 2 and theoretical result which is shown in Table II are matched perfectly which indicates that model is working absolutely fine to the extent of the requirement. But there is a little error in experimental results which is Tolerance of apparatus. So, this model is used for practical purpose.

MPC controller was applied, after the verification of model, for controlling of the model which is shown in Fig. 3. Different values at different discrete points were achieved. So, the reference value which is required at outlet of cold fluid was set.

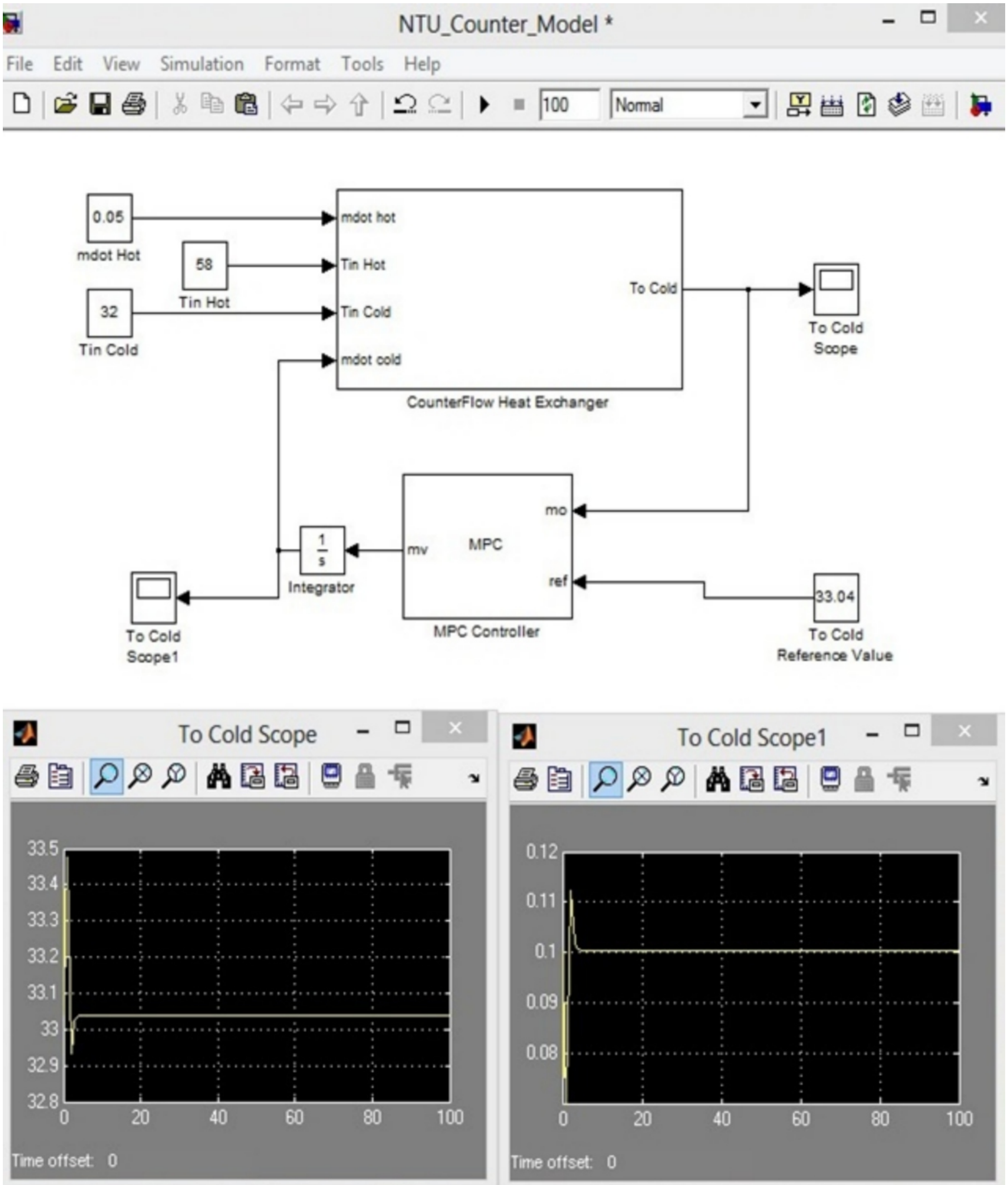

Fig. 3. Shell & Tube Heat Exchanger Model with MPC Controller in MATLAB Simulink

One practical example for confirmation of our model was used that was improvement in hospital equipment.

Power Plant Exhaust Gases heat used in the Heat Exchanger for the purpose of heating the water around 80 to 100 °C which is used for Sterilizing the hospital surgical equipment.

For this purpose the data given in Table III was used to modify the model which is shown in Fig. 4 and this shows result.

The Outlet temperature of cold fluid TCout can thus be calculated by using Table III.

TABLE III
PARAMETER OF DIFFERENT FLUIDS

Description of Parameters	Values
Area A	22 m^2
Overall Heat Transfer Co-efficient U	270 $W/m^2.K$
Specific heat of Cold Fluid Cpc	4.18 KJ/kg.K
Specific heat of Hot Gas Cph	1.00 KJ/kg.K
Mass Flow Rate of exhaust gases mh	7 kg/s
Mass Flow Rate of cold fluid mc	5 kg/s
Inlet Temperature of Cold fluid TCin	20 °C
Inlet Temperature of Hot Gas Thin	350°C

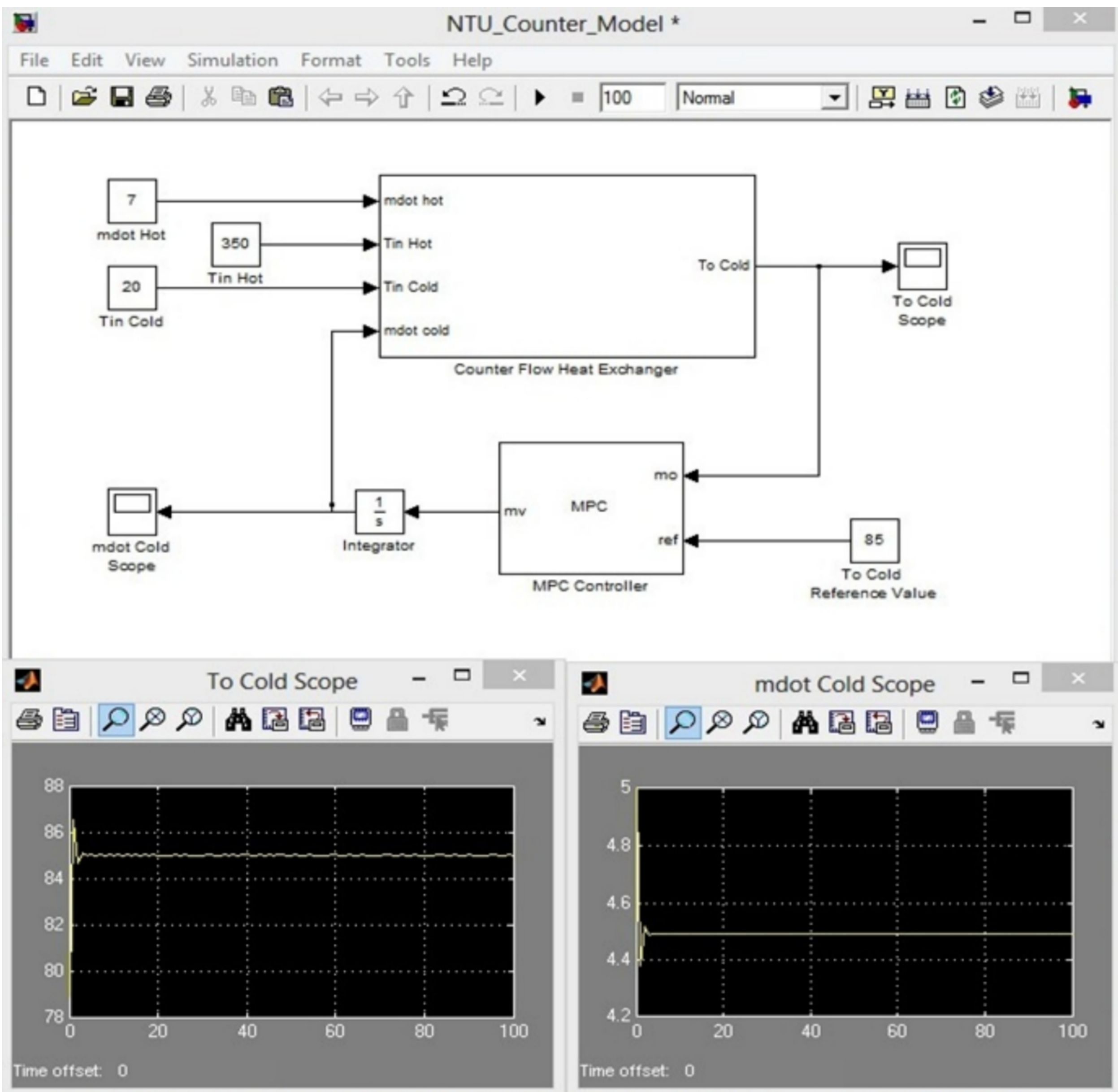

Fig. 4. Shell & Tube Heat Echanger Model with Modified values in MATLAB Simulink

VIII. CONCLUSION AND RECOMMENDATIONS

In this research work, the feasibility of a new heat exchanger without fabrication was checked. It proves to be a good tool for development and designing of shell and tube heat exchanger and its control system. Controller designed in the selected model is very effective and working quite satisfactorily.

This model can be used for designing, development and experimentation of control systems in Industries and Universities. This model entered in new era of mechatronic world in designing, modeling, verification and control of heat exchangers in MATLAB Simulink at different operating conditions.

Research work can further be explored in future, in which some future trends and recommendations can be discussed and implemented in different ways regarding their technicality, utilization and control systems.

This research work has been done on laminar flow of Shell and tube Heat Exchanger in this paper and further this work could be considered regarding turbulent flow in Shell and Tube Heat Exchanger.

Single tube, single phase Shell and Tube Heat Exchanger consideration in this current research work has been taken but it could be further explored regarding multi tube, multi-phase Shell and Tube Heat Exchanger.

Anyhow on the basis of plant equipment requirements and control systems can be implemented on other equipment accessories like boiler, compressors and in HVAC equipment.

REFERENCES

[i] G. Asbjornsson, E. Hulthen and M.Evertsson, Modelling and simulation of dynamic crushing plant behavior with MATLAB/Simulink, Minerals Engineering, Volumes 4344, April 2013

[ii] K. Anoop, J. Cox and R. Sadr, Thermal evaluation of Nanofluids in heat exchangers, International Communications in Heat and Mass Transfer, Volume 49, December 2013

[iii] M. Stewart and O. T. Lewis, Heat Exchanger Configurations, Heat Exchanger Equipment Field Manual, 2013, Pages 93-251

[iv] R. W. Serth and T. G Lestina, Design of Shell-and-Tube Heat Exchangers, Process Heat Transfer (Second Edition), 2014, Pages 151-197

[v] R. Mukherjee, Electively Design Shell-and-Tube Heat Exchangers, Engineers India Ltd., February 1998

[vi] A. S. Sahin, B. Kılıc and U. Kılıc, Design and economic optimization of shell and tube heat exchangers using Artificial Bee Colony (ABC) algorithm, Energy Conversion and Management, Volume 52, Issue 11, October 2011

[vii] S. Attaway, Introduction to MATLAB, Matlab (Third Edition), 2013, Pages 3-32

[viii] M. Gdeisat and F. Lilley, Matlab Debugging, Profiling, and Code Indentation Matlab By Example, 2013, Pages 271-309

[ix] G. Asbjornsson, E. Hulthen and M. Evertsson, Modelling and simulation of dynamic crushing plant behavior with MATLAB/Simulink, Minerals Engineering, Volumes 4344, April 2013, Pages 112-120

[x] R. Selbas, O. Kizilkan and M.Reppich, A new design approach for shell-and-tube heat exchangers using genetic algorithms from economic point of view, Chemical Engineering and Processing, Volume 45, Issue 4, April 2006

[xi] D. Hanafi, M. N. M. Than, and A. A. A. Emhemed, Heat Exchangers Shell & Tube Modeling for Intelligent Control Design, International Conference on Computer and Communication Devices (ICCD 2011)

[xii] A. Maidi, M. Diaf and J. P. Corriou, Optimal linear PI fuzzy controller design of a heat exchanger, Chemical Engineering and Processing 47, 2008

[xiii] S. K. Al-Dawery, A. M. Alrahawi and K. M. Al-Zobai, Dynamic modeling and control of plate heat exchanger, International Journal of Heat and Mass Transfer, Volume 55, November 2012

[xiv] L. R. Toth, L. Nagy and F. Szeifert, Nonlinear inversion-based control of a distributed parameter heating system, Applied Thermal Engineering, Volume 43, October 2012

[xv] A. Maidi, M. Diaf and J. P. Corriou, Boundary control of a parallel-flow heat exchanger by input output linearization, Journal of Process Control, Volume 20, Issue 10, December 2010

[xvi] M. Mehrabi, S.M. Pesteei and T. Pashaee, Modeling of heat transfer and fluid flow characteristics of helicoidal double-pipe heat exchangers using Adaptive Neuro-Fuzzy Inference System (ANFIS), International Communications in Heat and Mass Transfer, Volume 38, Issue 4, April 2011

[xvii] I. Dobos, J. Jaschke, J. Abonyi and S. Skogestad, Dynamic Model & Control of Heat Exchanger Networks For District Heating, Hungarian Journal of Industrial Chemistry Veszprem, Volume 37, 2009 Pages 37-49

[Xviii] S. Fettaka, J. Thibault and Y. Gupta Design of shell-and-tube heat exchangers using multiobjective optimization, International Journal of Heat and Mass Transfer, Volume 60, May 2013, Pages 6873-6880

[xix] K. Mohammadi and M. R. Malayeri, Parametric study of gross flow maldistribution in a single-pass shell and tube heat exchanger in turbulent regime ,International Journal of Heat and Fluid Flow, Volume 44, December 2013, Pages 14-27

[xx] A. Bahadori, Simple method for estimation of effectiveness in one tube pass and one shell pass counter-flow heat exchangers, Applied Energy, Volume 88, Issue 11, November 2011, Pages 4191-4196

[xxi] A. Hesam A. Kashani, A. Maddahi and H. Hajabdollahi, Thermal-economic optimization of an air-cooled heat exchanger unit, Applied Thermal Engineering, Volume 54, Issue 1, 14 May 2013, Pages 43-55

[xxii] J. H. Lienhard, Heat Exchanger Design, Heat Transfer Textbook, 4th Edition Phlogiston Press, CAMBRIDGE Massachusetts, June 18, 2012 Pages 99-102

[xxiii] A. Afram and F. J. Sharifi, Theory and applications of HVAC control systems A review of model predictive control (MPC), Building and Environment, Volume 72, February 2014

[xxiv] A. H. González, D. Odloak and J. L. Marchetti, Predictive control applied to heat-exchanger networks, Chemical Engineering and Processing: Process Intensification, Volume 45, Issue 8, August 2006

[xxv] Help of Simulink Library Browser in MATLAB 7.10.0