



A Non-Dominated Sorting Genetic Algorithm li-Based 3 Degree of Freedom Controller for Shell and Tube Heat Exchanger

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ABSTRACT

This research presents a three Degree of Freedom (3DoF) based outlet fluid temperature controller for Shell and Tube Heat Exchanger (STHX). Shell and Tube Heat Exchangers are classes of heat exchangers which are utilized for heat transfer between fluids in industries. The ultimate goal of any controller design is to track the set point by the STHX, especially, in the presence of noise and disturbance. Great results have been achieved by the use of a 2 degree of freedom controller; however, tracking of the set point is hampered by a tradeoff that exists between noise suppression and disturbance rejection. In order to address this challenge, an existing STHX experimental data was employed to develop a three degree of freedom Proportional Integral Derivative (PID) controller. A Multi-Objective Optimization Problem (MOP) of set point tracking, disturbance rejection, and noise suppression was formulated using Integral Absolute Error (IAE), Integral of Squared Error (ISE), and Integral of Time-weighted Absolute Error (ITAE) as cost functions. The Non-Dominated Sorting Genetic Algorithm II (NSGA) was deployed for the optimization of the parameters of the PID while subjecting the system to noise. The simulations results were obtained and compared to those obtained with 2DoF controller. The settling times, rise times and overshoots obtained from the simulations reveal the superior performance of the developed 3DoF controller. Hence, great rejection of noise is achieved with a 3DoF controller for STHX.

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INTRODUCTION

Heat exchanger, an indispensable system in industries, is mostly used to transfer heat energy from a fluid of higher temperature to a cooler fluid (Padhee *et al.*, 2011). There are various kinds of heat exchangers available in the process industry such as, plate heat, plate fin, pillow plate heat exchangers, but the most frequently used is Shell and Tube Heat Exchanger (STHX). The STHX is popular due to its efficiency and less complexity (Duran *et al.*, 2009). Typically, it consists of some special designed pipes in a cylindrical shaped shell in which a set of fluid is allowed to flow through the tubes, and while the other fluid is directed to flow between the tubes

and the shell (Sodja & Zupan^ˇ, 2009). The main purpose of a heat exchanger (HEX) unit is to ensure that the temperature of an outlet fluid is maintained at a specific value. This is normally achieved by implementing a control law that will regulate the exit temperature of the fluid in the presence of varying operating conditions such as noise and disturbances (Berto & Jr, 2000). Heat Exchangers are extensively used in areas such as petroleum refining, petrochemical processing and food industries as well as nuclear reaction systems, aircraft and space vehicles (Dhakad *et al.*, 2013).

In order to maintain a specific temperature of the outlet fluid irrespective of the

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disturbance, controllers are used (Araki & Taguchi, 2003). Different controllers, ranging from classical PID, PID with feedforward as well as internal model based controllers, have been implemented and studied with their merits and demerits in terms of transient behavior and computational complexity (Padhee *et al.*, 2011). In terms of the number of control variables in the system, an extensive shift has been achieved from the use of one degree of freedom (1DoF) controller and two degree of freedom (2DoF) controllers. The 1DoF controllers, irrespective of their simplicity, lack the ability to ensure setpoint tracking and disturbance rejection. This led to the development of the 2DoF controllers which ensure desired setpoint tracking; although, there exist a tradeoff between disturbance rejection and noise suppression (Araki & Taguchi, 2003; Suthar & Gadit, 2017b). Hence, there is a need to design a 3DoF control scheme for determining setpoint tracking, disturbance rejection and noise suppression independently (Suzumura & Fujimoto 2015; Umar *et al* 2019). In this research, a controller, with three degrees of freedom, capable of achieving a desired setpoint. tracking and disturbance. rejection with noise suppression has been developed.

Classical tuning methods, such as Ziegler Nichols (ZN), Choen-Coon, Chien-Hrones-Reswick (CHR), have been used for tuning the parameters of PID controllers. However, many of these classical methods never guarantee improved result in high frequency applications (Gupta *et al.*, 2017). Hence, evolutionary algorithms have been adopted as superior substitutes to these classical approaches based

on the formulation of cost function. One of such is the application of genetic algorithm (GA) in optimizing parameters of a 2DoF controller for STHX system (Suthar & Gadit, 2017b). In this work, in order to achieve an enhanced setpoint tracking, disturbance rejection and noise suppression at a goal, a multi-objective optimization problem is formulated. A Non-Dominated Sorting Genetic Algorithm (NSGA-II) which is a multi-objective optimization algorithm is used for the optimization of the parameters. A 3DoF controller. Using NSGA-II. Is designed for Shell and Tube Heat Exchanger.

LITERATURE REVIEW

This section shall be discussed under two sub-sections: Fundamental Concept and Review of Previous works.

Heat Exchangers

Heat exchangers(Hex) are systems or units that are widely used in various process industries such as petrochemical industries, food processing industries among others mainly for the transfer of heat energy from one solid surface or fluid to another fluid (Suthar & Gadit, 2017b). The main function of a HEx unit is mainly to maintain a desired setpoint temperature of an outlet fluid. in the presence of obvious disturbances such as deviation in input fluid flow rate and deviation in input fluid temperature (Dhakad *et al.*, 2013). There are varieties of HEx available for use in industries, but the commonly used, is the Shell and Tube. Heat. Exchanger (Suthar & Gadit, 2017a).

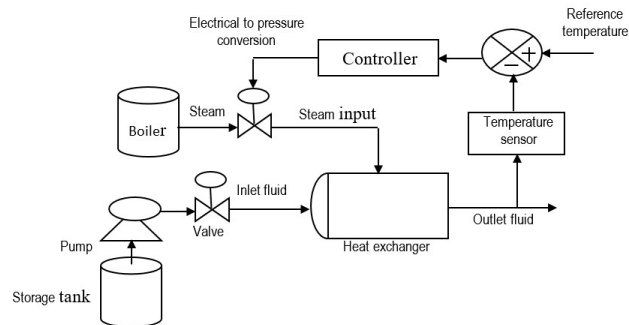


Figure 1: Block Diagram of the Physical Model of STHX

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Shell and Tube Heat Exchanger

The Shell and Tube. Heat Exchanger. (STHX) is made of bundles of pipes or tubes enclosed within a cylindrical shaped shell, this allows fluid (which is to gain temperature) to flow through the tubes while the other fluid (which is losing temperature) is allowed to flows in between the tubes and the shell (Padhee *et al.*, 2011) as shown in Figure 1. STHXs are the commonly used heat exchangers due to the fact that it is used for a wide range of varying temperature and pressure, they also have a better and larger ratio of heat

energy transfer in terms of surface area than other types of HEx.

The heat exchanger model is adopted from the work of Suthar & Gadit (2017a). Two assumptions will be applied in the heat exchanger system representation as applied in Dhakad *et al.*, (2013).

1. Same inlet and outlet fluid flow rate (kg/sec). This is to have a constant fluid level in the system, i.e. heat exchanger.
2. The insulation wall of the system does not store any heat.

Table 1: The parameters of the steam flow response of the heat exchanger

PHYSICAL QUANTITY	VALUE
Steam flow gain	50 °C / (kg/Sec)
Time constant	30 Sec
Process fluid gain	3°C / (kg/sec)
Process temperature gain	1°C / (kg/sec)
Capacity of control valve	1.6 kg/sec of steam
Control valve (time constant)	3 sec
Sensor range	50 °C to 150 °C
Sensor time constant	10Sec
Gain of the valve	0.133
Gain of 1 to P converter	0.75
Critical gain	KC

The transfer function model of a heat exchanger including temperature and flow

disturbances is shown in Figure 2 as adopted from Suthar & Gadit, (2017a).

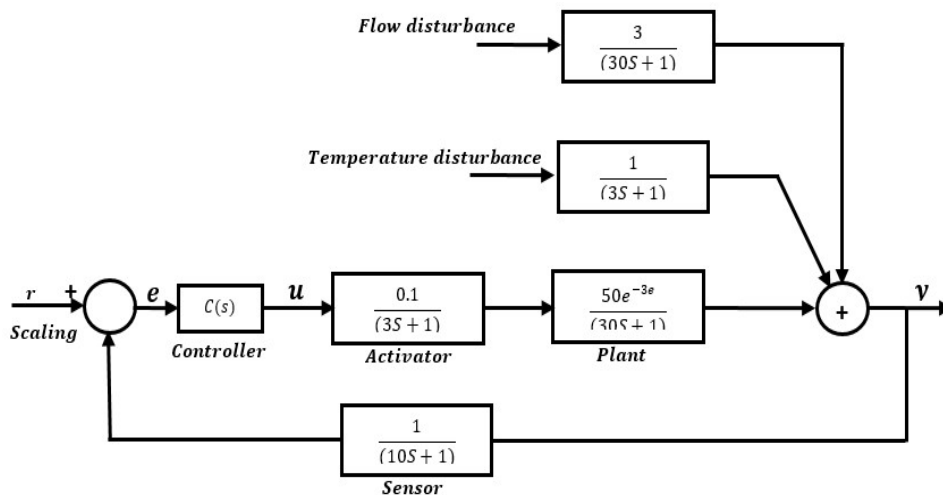


Figure 2: Heat Exchanger Transfer Function Model (Suthar & Gadit, 2017a).

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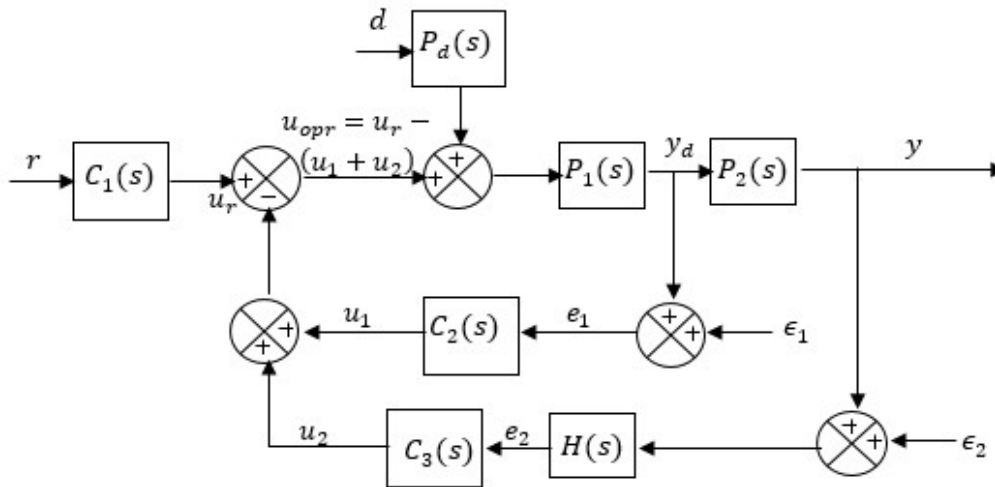


Figure 3: Configuration for 3DoF control system

$$T_{y_r}(s) = \frac{y}{r} = \frac{P_1(s)P_2(s)C_1(s)}{1 + P_1(s)C_2(s) + P_1(s)P_2(s)C_3(s)H(s)} \quad (1)$$

$$T_{y_d}(s) = \frac{y}{d} = \frac{P_d(s)P_1(s)P_2(s)}{1 + P_1(s)C_2(s) + P_1(s)P_2(s)C_3(s)H(s)} \quad (2)$$

$$T_{y_\epsilon}(s) = \frac{y}{\epsilon} = \frac{-P_n(s)P_1(s)P_2(s)C_3(s)H(s)}{1 + P_1(s)C_2(s) + P_1(s)P_2(s)C_3(s)H(s)} \quad (3)$$

The transfer functions for the three controllers are:

$$C_1(s) = K_p \left[\frac{\eta}{T_i * s} + T_D * D(s) \right] \quad (4)$$

$$C_2(s) = K_p + \frac{K_p}{T_i s} + K_p * T_D * D(s) \quad (5)$$

$$C_3(s) = \frac{\zeta}{K_p * H(s)} \quad (6)$$

The set point tracking response is dependent on the three controllers $C_1(s)$, $C_2(s)$ and $C_3(s)$ with $C_1(s)$ serving as filter to the input signal. The $C_2(s)$ is essentially a PID controller that cut across all responses but more visible in the disturbance rejection characteristics while $C_3(s)$ is another filter whose primary function is prominent in noise suppression at the output of the

system. In this model, the parameters η and ζ can be adjusted independently even after the $C_2(s)$ parameters are set to fine-tune the set point tracking and noise suppression property.

It can easily be verified by final value theorem that the disturbance and noise responses tend to zero at steady state shown as in equations (7) and (8) respectively.

$$y_{dss} = \lim_{s \rightarrow 0} s \cdot \frac{P_d(s)P_1(s)P_2(s)}{1 + P_1(s)C_2(s) + P_1(s)P_2(s)C_3(s)H(s)} \cdot \frac{1}{s} = 0 \quad (7)$$

$$y_{nss} = \lim_{s \rightarrow 0} s \cdot \frac{-P_n(s)P_1(s)P_2(s)C_3(s)H(s)}{1 + P_1(s)C_2(s) + P_1(s)P_2(s)C_3(s)H(s)} \cdot \frac{1}{s} = 0 \quad (8)$$

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Non-dominated Sorting Genetic Algorithm (NSGA)

The NSGA is a multiple-objective optimization algorithm of the genetic algorithm (GA). The NSGA has two versions, the classical version and the extended version developed by Deb *et al.*, (2002) to address three critical issues of lack of elitism, complexity and need for parameter sharing for fitness sharing. This version is called Non-Dominated Sorting Genetic Algorithm II (NSGA II) (Brownlee, 2011). The NSGA II has three main features which includes:

- i) Non-dominated sorting: Here, sorting is done according to the level of non-domination.
- ii) Elitism: Keeps all non-dominated solutions that improve fast convergence properties.
- iii) Crowding Distance: Ensuring diversity and spread of solution.

These features are depicted in the flowchart in Figure 4 which is adopted from the work of Kannan *et al.*, (2009). The non-dominated sorting approach is based on the scheme that no solution of one objective function is better than the other. This will give birth to a set of non-dominated solution called pareto-optimal set. The resultant values of the objective functions of the pareto-optimal set are the Pareto front of the NSGA-II solution.

For this purpose of this work, composite function (functional) consisting of separate objective functions for the set point tracking, flow disturbance rejection, temperature disturbance rejection and noise is formulated. The chosen criterions for evaluating these objective functions are Integral of Absolute Error (IAE), Integral of Squared Error (ISE) and Integral of Time-weighted Absolute Error (ITAE).

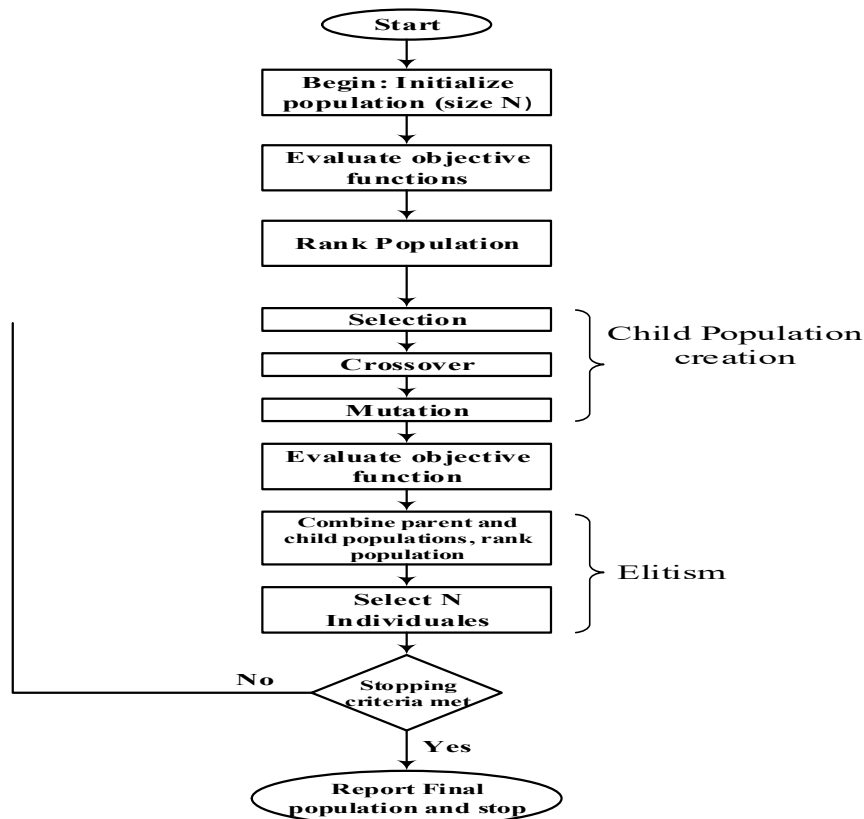


Figure 4: NSGA II Flowchart (Kannan *et al.*, 2009)

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REVIEW OF PREVIOUS WORKS

A comparative study by Dhakad *et al.*, (2013) validated that fuzzy logic controller (FLC) outperforms the Internal model controller (IMC) when used in regulating the temperature of outlet fluid of heat exchanger; however, it involves significant expert knowledge. A PID feed-forward efficient controller for STHX was tuned using Ziegler-Nichols (ZN) which gives the desired set point and disturbance rejection; its performance is limited to low frequency applications (Khalili Dizaji, 2015). Genetic algorithm (GA) is used in optimizing the parameters of a PID-based outlet fluid temperature control of the STHX in Singh & Goel, (2015); it gave better result in terms of maximum overshoot, settling time and overshoot when compared to the use of ZN for the same purpose. A 2DoF PID controller was proposed by Deshmukh & Kadu, (2017) for temperature control of a laboratory setup; different analytic tuning techniques were used to tune the parameters of the PIDs for improved response in terms of disturbance rejection, settling time and percentage overshoot. However, the presence of measurement noise will affect the determination of parameters of step response. Furthermore, a minimal oscillation was achieved by using a cascaded (PID and PI) controllers to regulate the temperature of the outlet fluid in a STHX; however, there was poor system performance (Tridianto *et al.*, 2017). In Automatic Generation Control (AGC) of a hybrid power source, a 3DoF PID controller was developed and used while the optimal parameters of the PIDs were obtained using Teaching Learning Based Optimization (TLBO) technique; there was significant superior performance of the developed controller over PID and the 2DoF PID controller, however, the use of TLBO may not guarantee a global solution (Debnath *et al.*, 2017). Suthar & Gadit, (2017b) proposed the optimized 2DoF controller using GA for regulating the STHX; setpoint tracking was achieved but there was a tradeoff between disturbance rejection and noise attenuation. Further improvements were made by Suthar & Gadit, (2017a) by establishing a well-posed multi-objective optimization problem for the 2DoF controllers in order to achieve setpoint tracking and disturbance rejection; NSGA. II was used to obtain the optimal solutions to the optimization

problem which gave setpoint tracking and disturbance rejection, however, the design is sensitive to noise. In this research, a 3DoF controller for STHX using NSGA II is designed to ensure better setpoint tracking, disturbance rejection and noise suppression.

METHODOLOGY

The following procedures were done to achieve results:

1. Design a 2DoF multi-objective optimization controller for STHX using NSGA-II base on the work of Suthar & Gadit, (2017a)
 - a. Adopting the standard transfer function of a heat exchanger and model of the 2DoF controller for optimization problem.
 - b. Formulation of the multi-objective optimization problem for the STHX
 - c. Conversion of the multi-objective to single objective optimization problem of a 2DoF controller for dominate-solution
 - d. Formulation of multi-objective optimization problem considering vector of three objective functions for non-dominated solution using NSGA II
 - e. Implementation and simulation for
 - i. Determining dominate solution
 - ii. Determining non-dominated set
 - iii. Obtaining the pareto optimal set
2. Design of a 3DoF multi-objective optimization controller for STHX using NSGA-II subjected to noise.
 - a. Adopting the standard transfer function of a heat exchanger.
 - b. Modeling of the 3DoF controller for optimization problem.
 - c. Formulation of the multi-objective optimization problem for the STHX.
 - d. Conversion of the multi-objective to single objective optimization problem of

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- a 3DoF controller for dominate-solution.
- e. Formulation of multi-objective optimization problem considering vector of four objective functions for non-dominated solution using NSGA II.
- f. Implementation and simulation for:
 - i. Determining dominate solution
 - ii. Determining non-dominate solution
 - iii. Obtaining the pareto optimal set
3. Performance evaluation of 2DoF controller and 3DoF controller in terms of overshoots, rise times and settling times.

2DoF controller in Figure 2 and the 3DoF controller presented in Figure 3. The objective is to minimize the set point tracking error, flow and temperature disturbances, and finally noise. In the case of 3DoF control system, GA is used for optimal tuning of controllers for dominated solution while NSGA-II is used for the solution of the multi-objective functions.

Two Degree of Freedom Controller Functional

The functional consist of three objective functions: the set point tracking error, flow disturbance rejections and temperature disturbance rejections.

Let:

Controller Optimization Method Adopted

Genetic Algorithm (GA) is used to optimize the controller parameters in the case of S_p denotes set point,

$y(n)$ denots Process value output at n^{th} interval,

$y_{flow}(n)$ denotes Flow disturbance output at n^{th} interval and

$y_{temp}(n)$ denotes Temperature disturbance output at n^{th} interval

Then for each of the criterions we adopt the functional L for multi-objective function as Equations (9) to (11).

Criterion 1: IAE

$$L(K_p, K_i, K_d, \alpha, \beta) = L([\sum_{n=0}^N [S_p - y(n)], \sum_{n=0}^N y_{flow}(n), \sum_{n=0}^N y_{temp}(n)]) \quad (9)$$

Criterion 2: ISE

$$L(K_p, K_i, K_d, \alpha, \beta) = L([\sum_{n=0}^N [S_p - y(n)]^2, \sum_{n=0}^N [y_{flow}(n)]^2, \sum_{n=0}^N [y_{temp}(n)]^2]) \quad (10)$$

Criterion 3: ITAE

$$L(K_p, K_i, K_d, \alpha, \beta) = L([\sum_{n=0}^N [t * (S_p - y(n))], \sum_{n=0}^N [t * (n)], \sum_{n=0}^N [t * y_{temp}(n)])] \quad (11)$$

For dominated solution, the multi-objective function is converted to a single objective function for each of the criterion by adding the three objective functions $g_{setpoint}$,

$$L(K_p, K_i, K_d, \alpha, \beta) = L([g_{setpoint}] + [g_{flow}] + [g_{temp}]) \quad (12)$$

g_{flow} , and g_{temp} for set point tracking, flow and temperature disturbance rejection respectively as given in Equation (12).

Three Degree of Freedom Controller Functional

In this configuration, noise is separated from the disturbance and added back to the system. For simplicity, the process noise ϵ_1 of figure 3.4, is assumed to be negligible compared to the measurement noise ϵ_2 thus, we refer to this

as simply noise ϵ in the system. As a result, another (fourth) objective function is formulated in addition to those of set point tracking, flow disturbance and temperature disturbance rejection with respect to Equations (3.10) to (3.12).

Then for each of the criterions given, we develop new functional L for multi-objective function as presented in Equations (13) to (15).

Criterion 1: IAE

$$L(K_p, K_i, K_d, \eta, \zeta) = L([\sum_{n=0}^N [S_p - y(n)], \sum_{n=0}^N y_{flow}(n), \sum_{n=0}^N y_{temp}(n), \sum_{n=0}^N y_{noise}(n)]) \quad (13)$$

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Criterion 2: ISE

$$L(K_p, K_i, K_d, \eta, \zeta) = L\left(\left[\sum_{n=0}^N [S_P - y(n)]^2, \sum_{n=0}^N [y_{flow}(n)]^2, \sum_{n=0}^N [y_{temp}(n)]^2, \sum_{n=0}^N [y_{noise}(n)]^2\right]\right) \quad (14)$$

Criterion 3: ITAE

$$L(K_p, K_i, K_d, \eta, \zeta) = L\left(\left[\sum_{n=0}^N [t * (S_P - y(n))], \sum_{n=0}^N [t * y_{flow}(n)], \sum_{n=0}^N [t * y_{temp}(n)], \sum_{n=0}^N [t * y_{noise}(n)]\right]\right) \quad (15)$$

And for the dominated solution, the single objective function formed is given in Equation (16)

$$L(K_p, K_i, K_d, \eta, \zeta) = L\left(\left[[g_{setpoint}] + [g_{flow}] + [g_{temp}] + [g_{noise}]\right]\right) \quad (16)$$

Simulation Setup

The step responses for set point tracking, flow disturbance and temperature disturbance and noise rejection were given step input of magnitude 1, 0.1 and 0.01 respectively, while the noise profile was generated for simulation purpose. For the turning of the NSGA-II on 3DoF controller parameters, the vector of lower bound values for $[K_p, K_i, K_d, \eta, \zeta]$ is $[10, 10, 10, 0, 0]$ while the upper bound vector is $[100, 200, 100, 1, 1]$. Further study, and trails show better result for fixed values of $[\eta, \zeta]$ set to $[0.02, 10^{-4}]$ run over a hundred generations. The NSGA-II properties; crossover and mutation operators were set to 8 and 9 respectively.

RESULTS

A number of plots describing the condition of the STHX scenarios during simulations are generated, presented and discussed. Furthermore, the effectiveness of the developed 3DoF controller is validated by a comparison with the existing 2DoF controller applied to the system of STHX.

Solution of SOP Optimization

With the four objective functions of the developed 3DoF control of STHX converted to a single objective function by adding them together, the solution obtained by GA is hereby presented. Figure 4.1 show the plot of fitness value verses number of generations for the two criterions IAE and ISE considered in this work.

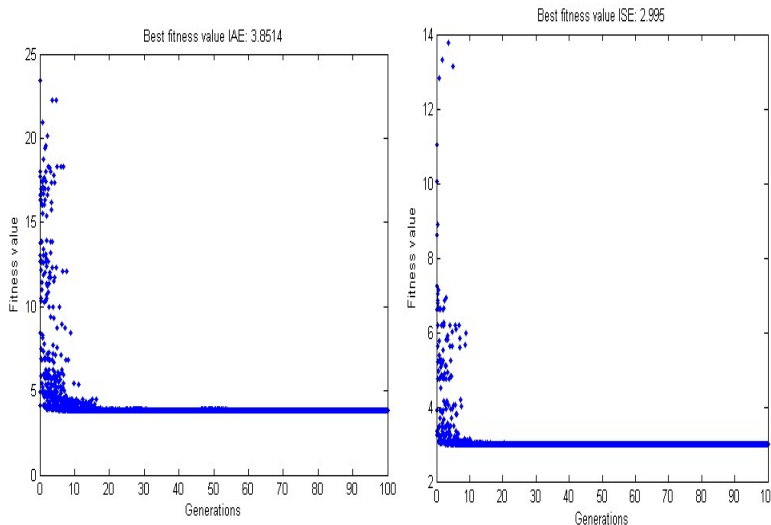


Figure 5: Fitness Values for SOP Optimization of IAE and ISE Criteria

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From Figure 5, it can be seen that the fitness values converge to nearly a single constant value for each of the criterions before the termination of the optimization process. Values of the best fitness values for the criterions considered are hereby presented as 3.8514, 2.995 and 2.99 for the IAE and ISE respectively. The lowest, being that of ISE is expected to exhibit

better tracking response than those of the IAE and ITAE.

The results of the set point tracking, flow disturbance reduction and temperature disturbance reduction are presented in Figure 5, Figure 6 and Figure 7 as compared with those of 2DoF controller for each of the criterions.

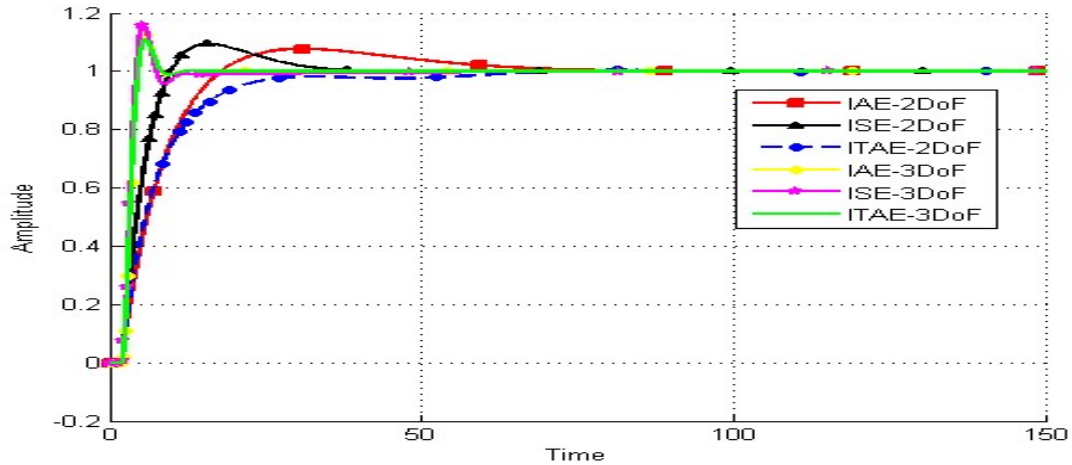


Figure 6: Set Point Tracking Response to Step Input

From Figure 6, the set point tracking responses for IAE-3DoF, ISE-3DoF and ITAE-3DoF are faster than those of 2DoF. The 3DoF responses settle in less than 25 seconds (secs) compared to those of 2DoF that settled at about

50 secs. The overshoots recorded in both scenarios for the SOP are almost the same, and fall within acceptable level (being less than 20% in all cases).

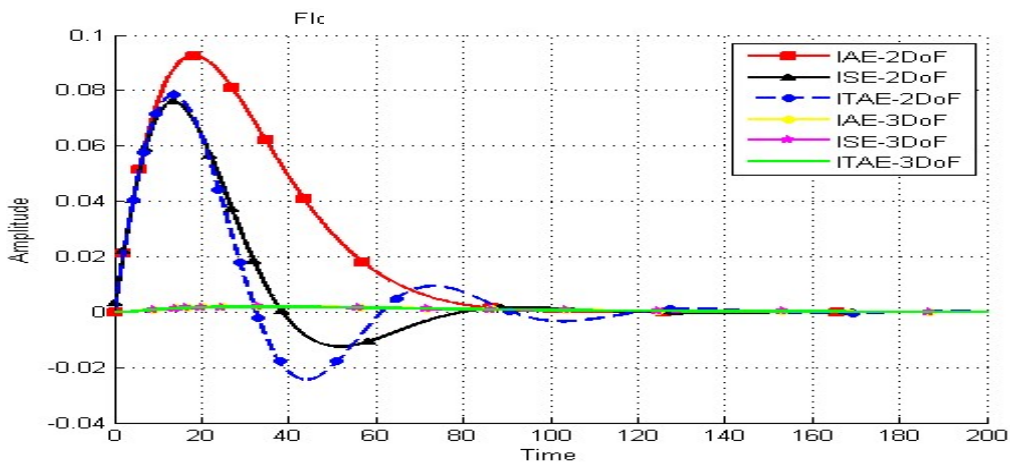


Figure 7: Flow Disturbance Response

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From Figure 7, the 3DoF controller gives 98% improvement in flow disturbance rejection characteristics. It gives approximately zero disturbance responses for all criteria which is a good measure of how insensitive the system is to flow disturbances compared to those of 2DoF that

peaked up to 0.08 for ISE and ITAE respectively, and 0.09 for IAE. It means that the system will respond appreciably to flow disturbance under 2DoF controller before settling to zero at about 100

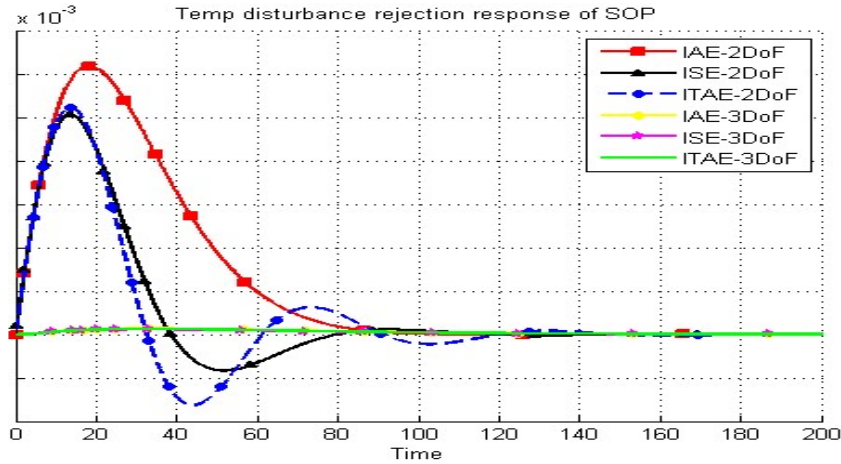


Figure 8: Temperature Disturbance Response

Figure 8 is similar to Figure 7, in the sense that the 3DoF controller gives better temperature disturbance rejection characteristics. It also gives approximately zero disturbance responses for all criteria as good measure of how insensitive the system is to temperature disturbances compared to those of 2DoF that

peaked above 2.5×10^{-3} for IAE, ISE and ITAE criteria. The system will respond to some levels of temperature disturbance under 2DoF controller before settling to zero at about 100 secs. A summary of some other metrics are tabulated in Table 2.

Table 2: Optimized Parameter and Performance Metrics of the SOP for 2DoF and 3DoF Controllers Optimization in GA

Controllers parameters' values for each Criteria		Best values of fitness function (<i>g</i>)		% Overshoot of step response		% Reduction of flow disturbance		% Reduction of temperature disturbance	
2DoF	3DoF	2DoF	3DoF	2DoF	3DoF	2DoF	3DoF	2DoF	3DoF
IAE	IAE								
$K_p = 0.530$	$K_p = 87.71$								
$K_i = 0.017$	$K_i = 91.31$	8.98	3.85	15.17	12.39	7.4	98	69	99
$K_d = 3.339$	$K_d = 54.83$								
$\alpha = 0.094$	$\eta = 0.02$								
$\beta = 0.0068$	$\zeta = 10^{-4}$								

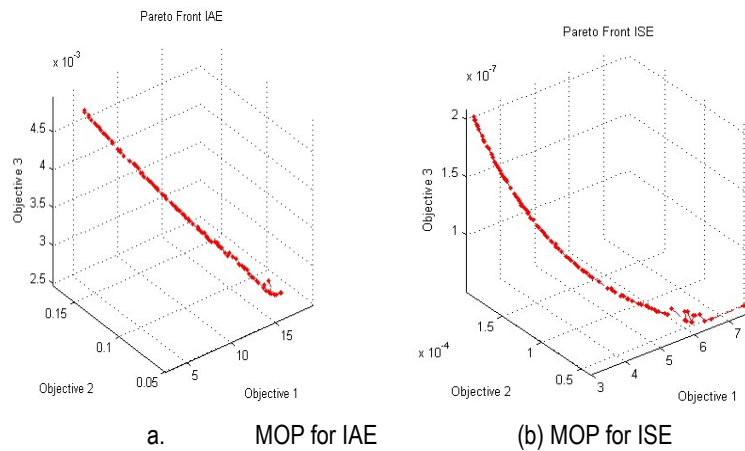
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ISE	ISE								
$K_p =$	$K_p =$								
0.854	82.18								
$K_i =$	$K_i =$								
0.042	101.4	40.85	2.99	17.39	16.17	24.1	98	75	99
$K_d =$	$K_d =$								
5.242	60.0								
$\alpha = 0.424$	$\eta = 0.02$								
$\beta = 0.027$	$\zeta = 10^{-4}$								

The peak overshoot for set point tracking under 3DoF controller is lower in IAE and ISE compared to those of 2DoF controller while the percentage reduction in the overshoot for flow and temperature disturbances are at all-time higher in the 3DoF controller than in the 2DoF controller for all the three criteria.

Non-dominated Solution of MOP Optimization

The 3DoF control system of STHX formulated as MOP and the controller parameters are optimized using NSGA-II. The Pareto optimal front of three objective functions – set point tracking, flow disturbance and temperature disturbance, obtained are presented in Figure 9 for each of the criteria.



a. MOP for IAE (b) MOP for ISE
 Figure 9: Pareto Optimal Front of MOP for IAE and ISE (L-R)

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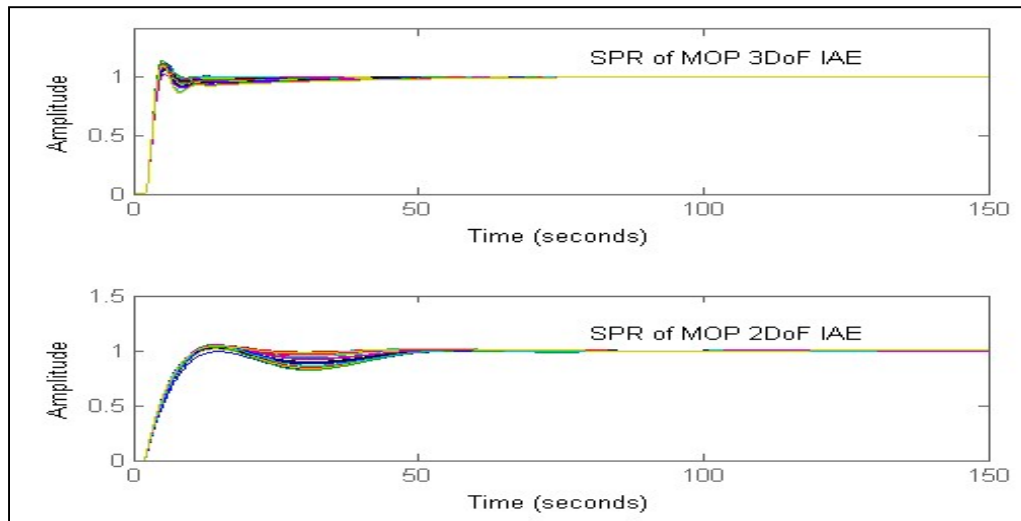


Figure 10: Set Point Response of MOP under IAE for 2DoF and 3DoF Controllers

The set point responses (SPR) of the MOP of 3DoF controller as shown in Figure 10, responded faster compared to the response of MOP of 2DoF and settle in less than 20 secs for a set of 20 optimal non-dominated solutions. The percentage overshoot for of the best controller parameters under 2DoF is however, better than that of the 3DoF counterpart with a difference of

1%, which is the only trade-off for the fastest response for the criterion IAE considered under 3DoF. The overshoot in both cases are less than 10%. The flow disturbance rejection characteristics under this criterion for MOP, is presented in Figure 11 while that of the temperature rejection characteristic is given in Figure 12.

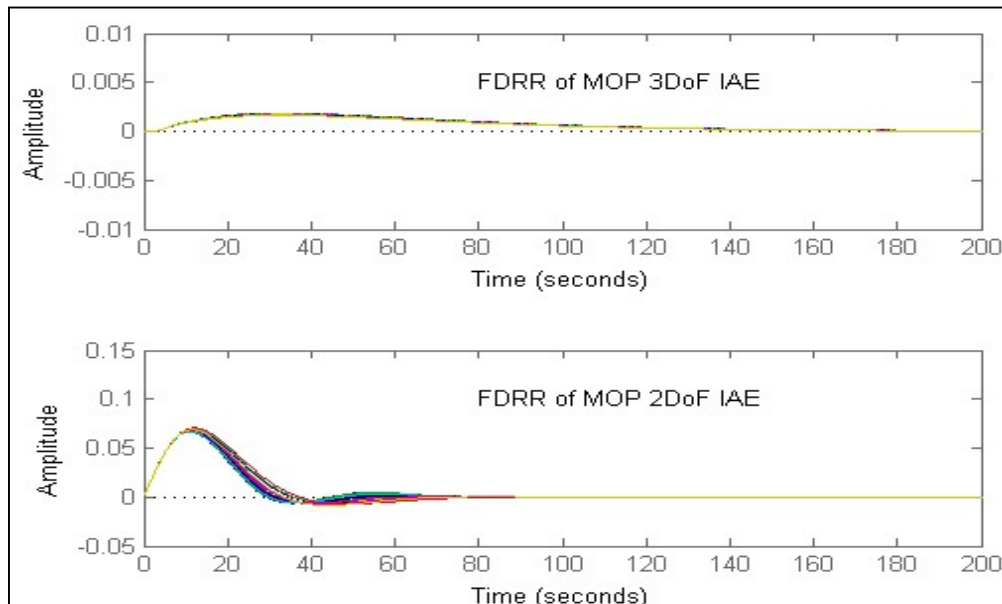


Figure 11: Flow Disturbance Response of MOP under IAE for 2DoF and 3DoF Controllers

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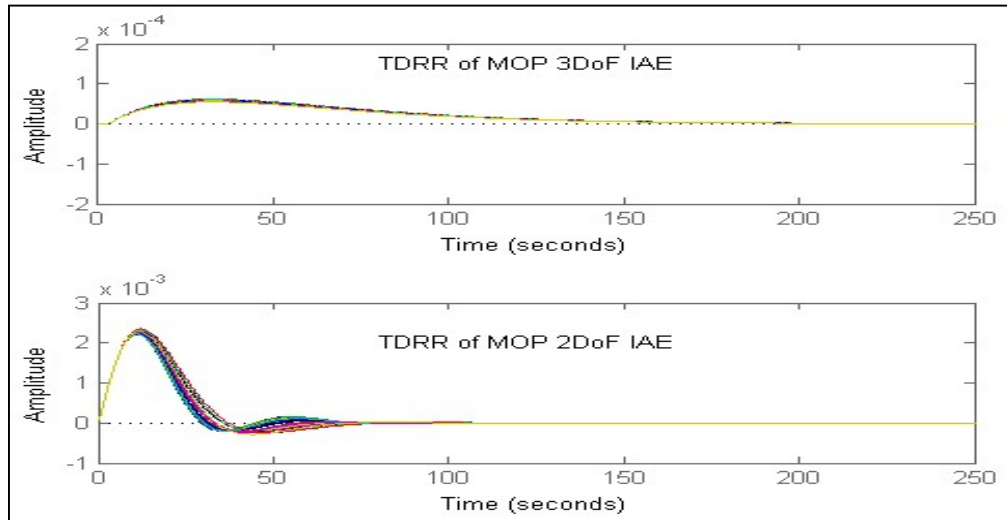


Figure 12: Temperature Disturbance Response of MOP under IAE for the Controllers

Figure 11 shows the flow disturbance rejection responses (FDRR) of the MOP under IAE criterion. The percentage rejection in the case of 3DoF controller is 98% as against 33% in the case of 2DoF controller. This shows that the 3DoF controller is better at flow disturbance rejection with utmost certainty. The Figure also shows that the peak jittery for the 3DoF is at 0.02 while that of 2DoF is above 0.05 for step input 0.1.

Similarly, Figure 12 shows that the peak shoot of the temperature disturbance rejection response (TDRR) is less in the 3DoF controller than in the 2DoF controller by more than 10 peak value for a step input of 0.1. This amount to a 99% success in 3DoF controller compared to 78% in 2DoF controller for the criterion under consideration. For the ISE criterion, the set point tracking response is shown in Figure 13.

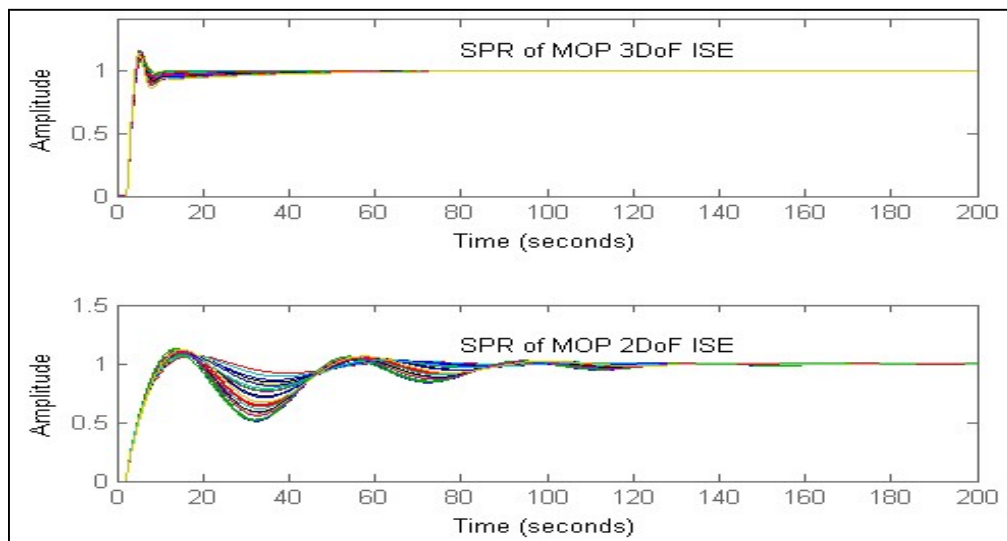


Figure 13: Set Point Response of MOP under ISE for 2DoF and 3DoF Controllers

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Figure 13 shows the set point tracking responses for a set of 20 non-dominated optimal solutions set. The responses with 3DoF controller are faster (settling time less than 15 secs) for each solution set under criterion ISE. Whereas, with 2DoF controller, the responses' settling time is

beyond 80 secs for each solution set. While the results with the 3DoF exhibit little overshoot, those of the 2DoF rose slowly. The flow disturbance rejection of the MOP under ISE criterion is shown in Figure 14.

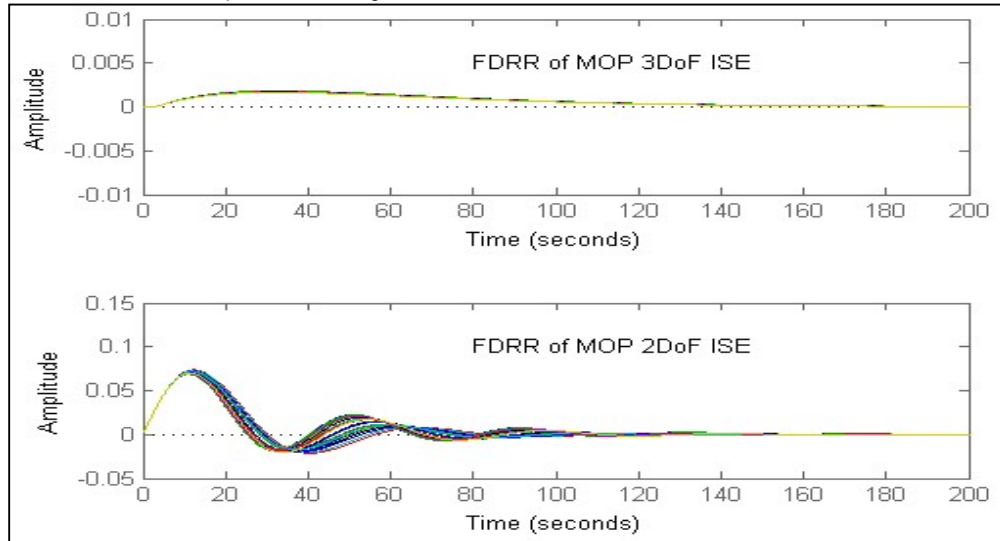


Figure 14: Flow Disturbance Response of MOP under ISE for the Controllers

The Figure 14 shows that the peak value for the 3DoF is at 0.02 while that of 2DoF is above 0.05 for step input 0.1. The percentage

rejection in the case of 3DoF controller is 98% while 31% is the success rate in the case of 2DoF controller.

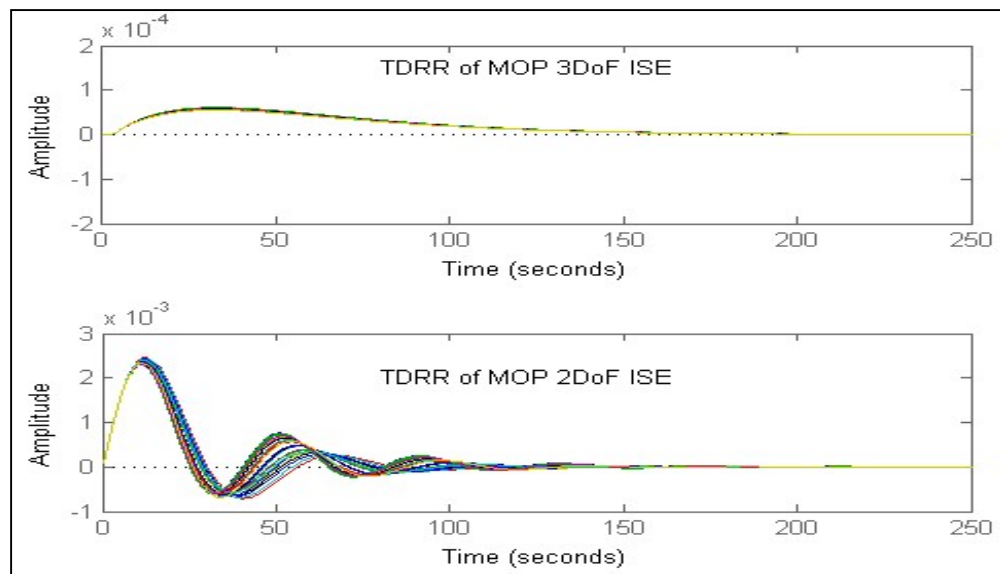


Figure 15: Temperature Disturbance Response of MOP under ISE for the Controllers

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Figure 15 shows that the temperature disturbance rejection response is of superior performance in the 3DoF controller to that of the 2DoF controller. The peak disturbance rejection value is less by more than a factor of 10 units in 3DoF compared to the 2DoF rejection profile, for

a step input of magnitude 0.1. This amount to a 99% temperature disturbance rejection success in 3DoF controller compared to 77% in 2DoF controller for the criterion ISE. The set point tracking response for the last criterion ITAE is presented in Figure 16.

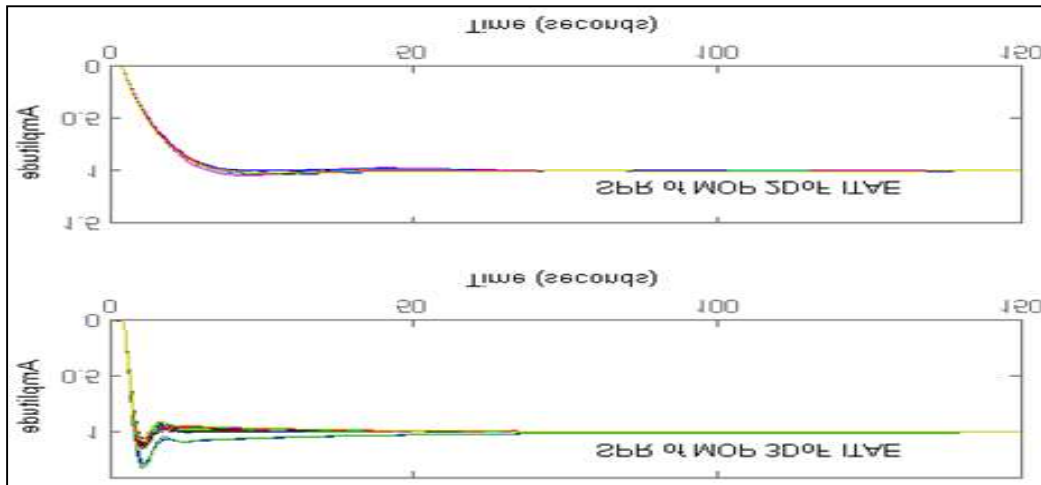


Figure 16: Set Point Response of MOP under ITAE for 2DoF and 3DoF Controllers

Figure 16 shows the set point tracking responses for a set of 20 optimal non-dominated solutions for the MOP under the criterion ITAE considering 3DoF and 2DoF controllers. While the responses are faster (settling time less than 15 secs) in 3DoF controllers, they suffer significant

amount of over shoot (more than 17%) compared to that of 2DoF controller. Figures 17 and Figure 18 present the flow disturbance rejection and temperature disturbance rejection characteristics respectively for the criterion ITAE.

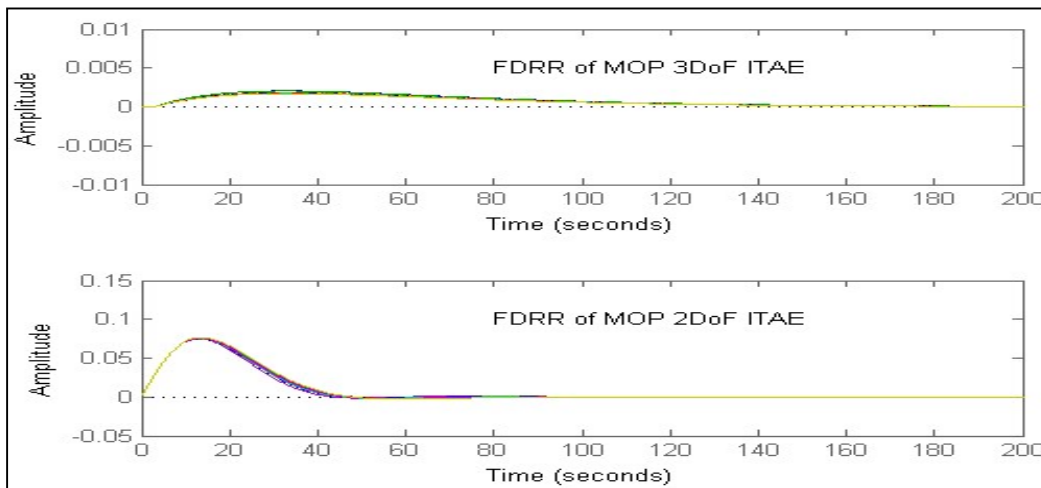


Figure 17: Flow Disturbance Response of MOP under ITAE for the Controllers

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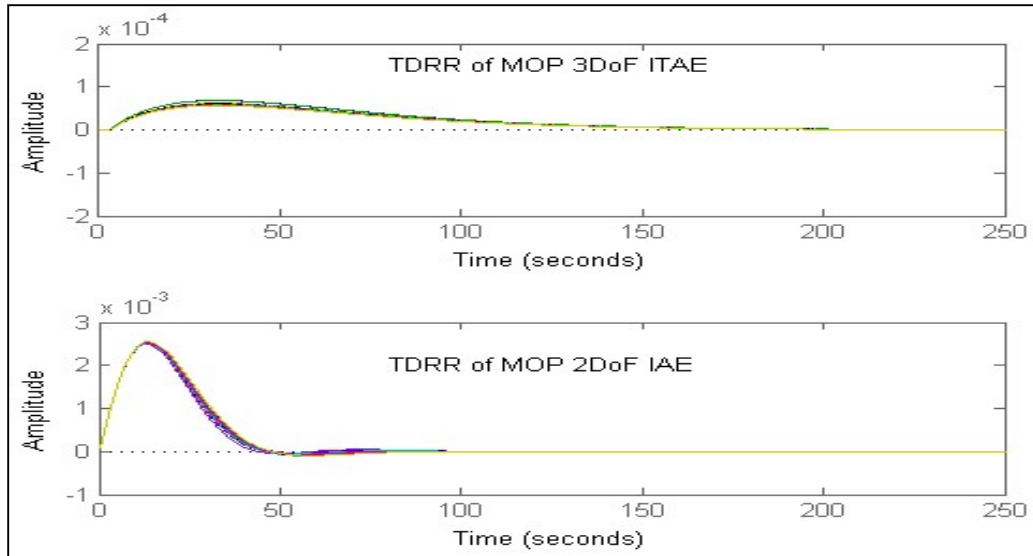


Figure 18: Temperature Disturbance Response of MOP under ITAE for the Controllers

Figure 17 shows the flow disturbance rejection responses for the criterion ITAE with 98% rejection success in 3DoF controller application. Similarly, Figure 18 shows up to 99% success rate in temperature disturbance rejection

characteristic in the case of 3DoF controller. The values of performance metrics are illustrated in Table 3. Other results relating to the noise suppression responses of the 3DoF controllers are presented in Figures 19 to 21.

Table 3: Optimized Parameter and Performance Metrics of the MOP for 2DoF and 3DoF Controllers Optimization in GA

Controllers parameters' values for each criterions		% Overshoot of step response		% Reduction of flow disturbance		% Reduction of temperature disturbance	
		2DoF	3DoF	2DoF	3DoF	2DoF	3DoF
2DoF $[K_p, K_i, K_d, \alpha, \beta]$ IAE [1.362, 0.052, 6.85, 0.601, 0.439] (Best Set point tracking & disturbance rejections)	3DoF $[K_p, K_i, K_d, \eta, \zeta]$ IAE (S/N-19, Table B1) [100.00, 111.22, 60.00, 0.02, 10^{-4}] (Best Set point tracking & disturbance rejections)	4.79	7.71	33.43	98	78	99
ISE [1.676, 0.045, 4.88, 0.619, 0.215] (Best Set point tracking)	ISE (S/N-12, Table B2) [98.91, 105.53, 60.00, 0.02, 10^{-4}] (Best Set point tracking)	12.5	6.60	31.02	98	77	99

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ISE [1.696, 0.045, 4.89, 0.604, 0.228] (Best disturbances rejections)	ISE (S/N-12, Table B2) [98.91, 105.53, 60.00, 0.02, 10^{-4}] (Best disturbances rejections)	15. 63	6.60	31.17	98	77	99
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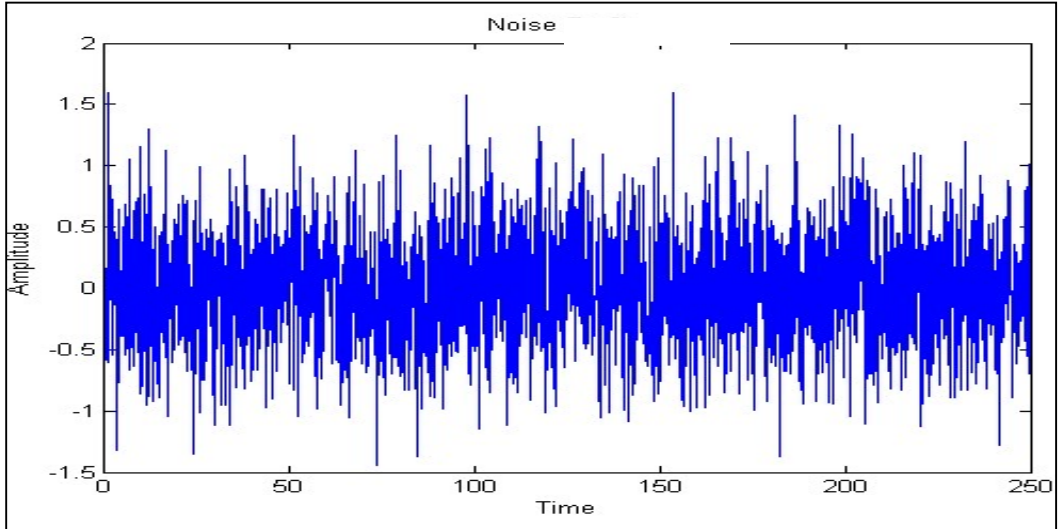


Figure 19: Noise Profile

In 2DoF controller, noise is coupled with disturbances affecting the system, while in 3DoF controller, measurement and process noise is separated from the disturbances in the system. Figure 19 shows the generated Additive White Gaussian Noise (AWGN) profile injected into the

system. The 3DoF controller has the capacity to suppress noise of this magnitude due to its in-built filter in the feedback path. Figure 20 shows the noise reduction responses of the SOP for all criterions.

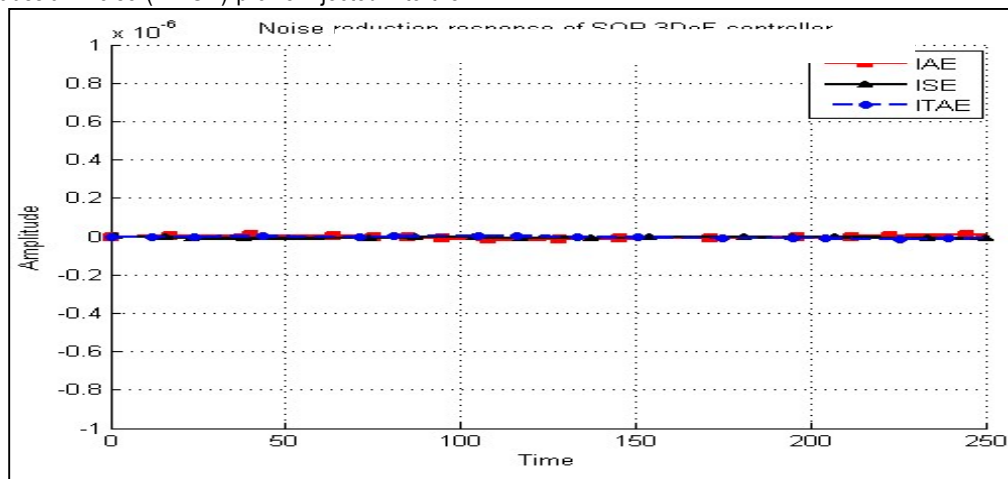


Figure 20: Noise Reduction Responses of MOP formulated as SOP 3DoF Controller

This result showed significant suppression of noise under all the criterions

considered for the SOP optimization. Even up to 10^{-6} , the noise level remained approximately at

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zero level. This means that the system is insensitive to measurement and process noise under SOP formulations and optimization of the

3DoF controller. Figure 21 shows the noise profile and its reduction responses for MOP 3DoF controller optimization.

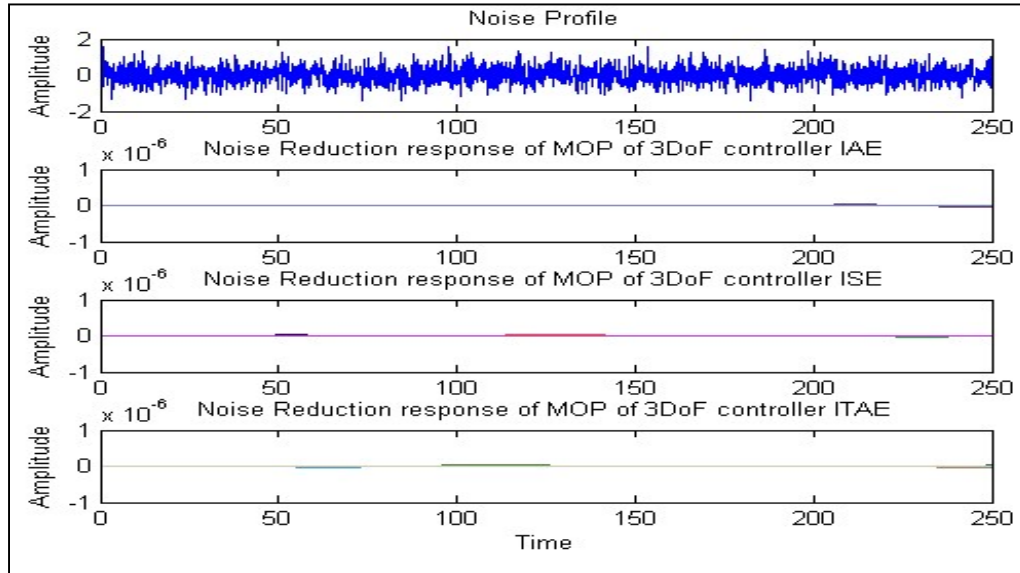


Figure 21: Noise Reduction Responses of MOP 3DoF Controller IAE, ISE and ITAE

For the noise profile of magnitude up to 2 units, Figure 21 shows that the noise reduction responses for the criteria IAE, ISE and ITAE flattened out even with the view up to the micro-level (10^{-6}), for a set of 20 non-dominated optimal solutions considered for all the respective criteria. This shows the ability of the system to be insensitive to presence of process noise and measurement noise.

CONCLUSION

This research developed a 3DoF controller which is able to optimally maintain a desired temperature value of the outlet fluid of an STHX. The controller achieves setpoint tracking, total disturbance rejection and noise suppression. In order to achieve this, a well-posed multi-objective optimization problem was established by using certain cost functions (IAE, ISE and ITAE). A non-dominated sorting genetic algorithm was used to optimize the controller parameters which minimized the cost functions. The results obtained under all the three criteria were compared with a 2DoF controller which showed significant improvement in set point tracking, flow

disturbance response and temperature disturbance response using overshoot, rise time and settling time as performance metrics. It is highly recommended that the performance of this work can be investigated with the use of other metaheuristic algorithms for multi-objective optimization problems.

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