Multiobjective optimization of 2DOF controller using Evolutionary and Swarm intelligence enhanced with TOPSIS

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Abstract

In this paper, Evolutionary (NSGA-II and NSGA-III) and Swarm Intelligence (MOPSO) based algorithms enhanced with Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) is employed to optimize five parameters of Two Degree Of Freedom (2DOF) controller. Three objective functions, one for set point tracking and two for disturbance rejections (flow variation of input fluid and temperature variation of input fluid both are in conflict) are deployed for the problem of shell and tube heat exchanger. Three test criteria IAE, ISE and ITAE function of error (set point tracking and disturbance rejection) and time are used for evaluation of objective functions. The Pareto set of solutions are obtained after optimizing all the five parameters of 2DOF controller. In order to obtain the comparative analysis of optimization algorithms (NSGA-II, NSGA-III, and MOPSO) all the Pareto optimal solutions are combined under three separate evaluation criteria IAE, ISE, and ITAE. TOPSIS a multiple criteria decision making method is used to rank the set of Pareto optimal solutions for reducing number of Pareto optimal solutions to a single solution. The best rank solution
obtain for 2DOF controller parameters after applying TOPSIS on set of Pareto optimal solutions using Evolutionary (NSGA-II and NSGA-III) algorithms are compared with Swarm Intelligence (MOPSO) algorithm. To evaluate the performance optimization of 2DOF controller tuning, we compared the values of peak overshoot of step response, set point tracking error, disturbance rejection (both flow and temperature), settling time, and the percentage of solutions obtained from optimization algorithms under all three evaluation criteria IAE, ISE, and ITAE. MATLAB software tool is used to implement the above algorithms.

Keyword: Electrical engineering

1. Introduction

The design of control systems is a multiobjective problem because; it involves the optimization of more than one objective functions like set point tracking, rejection of disturbances, and robustness to model uncertainty. Two degree of freedom controller is applied for set point tracking and disturbance rejections. Two objectives set point tracking and disturbance rejections are clashing and hence trade-off exists, this result in control problem of multiobjective optimization [1]. There are two major disturbances in the process of heat exchanger, flow variation of input fluid and temperature variation of input fluid. Increase in flow variation of process fluid result in increase in mass flow rate of the fluid causes reduction in mean exit temperature of process fluid. On the contrary, increase in temperature variation of process fluid causes increase in mean exit temperature of process fluid. The step increase is applied to both the disturbances which are in conflict [2]. The prime goal in the process of heat exchanger is to keep outlet temperature of the process fluid flowing through it at desire value in the presence of two major conflicting disturbances. Hence, the problem of shell and tube heat exchanger is taken as test bench due to conflicting objectives [3].

Controller tuning is a broad research area in which tuning rules are derived from the mathematical model of the system [4]. Classical computational methods fail in tuning controller for the multiobjective optimization problems due to following reasons: (1) These methods can generate single solution from single run hence; several runs are required in order to generate Pareto set of solutions. (2) Convergence to optimal solution depends on chosen initial condition. (3) It requires differentiability of both objective function and constraints. (4) These methods fail when Pareto front is concave or discontinuous [5]. Evolutionary and Swarm based controller tuning is appealing investigators due to its efficiency to optimize parameters based on cost function, without any know-how about the process [6]. Also, these algorithms work based on population of search instead of single search hence, it provides parallelism [7]. Here, tuning of 2DOF controller is a five dimensional search space or a
three dimensional objective space multiobjective optimization problem for the shell and tube heat exchanger system. Hence, outperformed evolutionary (NSGA-II and NSGA-III) and swarm intelligence (MOPSO) algorithms are used for tuning five parameters of 2DOF controller.

Multiobjective evolutionary optimization algorithms are classified into two categories: elitist MOEAs [8] and non-elitist MOEAs [9, 10, 11, 12, 13]. Nondominated Sorting Genetic Algorithm II (NSGA-II), is the known elitist multiobjective evolutionary algorithm. It is proved that elitism helps in achieving better convergence in MOEAs [14]. NSGA-III is an extension of NSGA-II though; it has significant changes in selection process [15]. NSGA-II and NSGA-III outperforms other MOEAs in terms of finding diverse set of solutions and converging towards true Pareto front [14, 15].

Particle Swarm Optimization (PSO) algorithm falls under the category of swarm intelligence [16]. The different multiobjective swarm intelligence based optimization algorithms proposed by researchers are [6, 13, 17, 18, 19, 20, 21, 22, 23]. In this paper, MOPSO algorithm proposed by Carlos, Gregorio and Maximino [23] is used for optimization of 2DOF controller parameters as it is relatively easy to implement and it improves the exploratory capabilities of PSO by introducing a mutation operator. This algorithm also uses an external repository of particles to guide their own flight.

The multiobjective optimization algorithms give number of nondominated set of solutions called Pareto optimal solutions. Practically, user needs only one solution from the set of Pareto optimal solutions for particular problem. Generally, user is not aware of exact trade-off among objective functions. Hence, it is desirable to first obtain maximum possible Pareto optimal solutions and select best one using multi-criteria decision making technique. The various multi-criteria decision making techniques are MAXMIN, MAXMAX, SAW (Simple Additive Weighting), AHP (Analytical Hierarchy Process), TOPSIS, SMART (Simple Multi Attribute Rating Technique), ELECTRE (Elimination and Choice Expressing Reality) and many more [24, 25]. The major advantage of TOPSIS method is it's rational, easy to implement, and good computational efficiency. Hence, TOPSIS is proposed as a decision support tool to rank the optimal solutions and select the best rank optimal solution [26].

The best rank solution obtain for 2DOF controller parameters after applying TOPSIS on set of Pareto optimal solutions using Evolutionary (NSGA-II and NSGA-III) algorithms are compared with Swarm Intelligence (MOPSO) algorithm. To evaluate the performance optimization of 2DOF controller tuning, we compared the values of peak overshoot of step response, set point tracking error, disturbance rejection (both flow and temperature), settling time, and the percentage of solutions obtained from optimization algorithms under all three evaluation criteria IAE, ISE, and ITAE.
The present paper is formulated as under: In Section 2, heat exchanger system’s explanation is provided. 2DOF controller optimization methods are proposed in Section 3. In Section 4, Implementation steps of TOPSIS algorithm is discussed. 2DOF controller parameter optimization and comparison of results are discussed in Section 5. Conclusion is in Section 6.

2. Theory

Shell and tube type of heat exchanger system is widely used in industries [27, 28, 29]. The diagram shown in Fig. 1 consists of shell and tube heat exchanger system with boiler, storage tank, and controller. The fluid in heat exchanger system heats up to a set temperature using steam supplied from the boiler. Here, a process of heat exchanger system is derived as FOPDT system [30].

The outlet fluid temperature of heat exchanger system is measured by temperature sensor. Controller generates electrical control output signal (4–20 mA) based on input error signal. The control output signal (4–20 mA) is transformed to pressure signal (3–15 psig) using electronic means. The pressure output signal is attached with valve actuator, whose function is to position valve proportional to control signal. Flow variation of input fluid and temperature variation of input fluid are the prominent disturbances in this process. Flow variation of input fluid is more prominent disturbance compared to temperature variation in input fluid [3]. Underlying two assumptions are considered in the heat exchanger system description [31].

![Fig. 1. Representation of heat exchanger control system.](https://doi.org/10.1016/j.heliyon.2019.e01410)
(1) Similar inflow and out flow rate of fluid (kg/sec) is retained for having constant fluid level in heat exchanger system. (2) Insulating wall of heat exchanger does not accumulate any heat.

The Fig. 2 shows heat exchanger system with feed forward type 2DOF control scheme. The transfer functions of individual block in Fig. 2 is as under: system plant transfer function is defined as, \( G(s) = \frac{50e^{-2s}}{(30s+1)} \), transfer function of flow disturbance of input fluid is \( F(s) = \frac{3}{(30s+1)} \), transfer function of temperature disturbance of input fluid is \( T(s) = \frac{1}{(3s+1)} \), control valve transfer function is \( A(s) = \frac{0.1}{(3s+1)} \), and sensor transfer function as, \( H(s) = \frac{1}{(10s+1)} \) [3, 31]. The resultant system consisting of heat exchanger with controller and disturbances are shown in following Fig. 2.

Here, feed forward type 2DOF controller comprising of serial compensator \( C_s(s) \) and feed forward compensator \( C_f(s) \) is used.

Where, \( C_s(s) \) and \( C_f(s) \) are represented as below.

\[
C_s(s) = \left[ K_p + \frac{K_p}{T_iS} + K_p \cdot T_D \cdot D(s) \right]
\]  \hspace{1cm} (1)

\[
C_f(s) = -K_p \left[ \alpha + \beta \cdot T_D \cdot D(s) \right]
\]  \hspace{1cm} (2)

The parameters of serial compensator \( C_s(s) \) are known as proportional gain \( K_p \), integral time \( T_i \), and derivative time \( T_D \), they are called as “basic parameters”. The parameters of feed forward compensator \( C_f(s) \) i.e., \( \alpha \) and \( \beta \) are called as “2DOF parameters”. Where, \( D(s) = \frac{s}{1 + s} \) is approximate derivative [27]. Assume, \( D_f(s) \) and \( D_f(s) \) are temperature and flow disturbance step inputs respectively. Derived transfer function based on superposition principle as under which is used for optimization of 2DOF control parameters in the programming.

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**Fig. 2.** Heat exchanger with controller and disturbances.
Case 1: Reference input \( r \) is present and both disturbances flow & temperature are zero.

\[
y(s) = \frac{C_f(s) + C(s)}{r(s)} \frac{C(s)A(s)G(s)}{1 + C(s)A(s)G(s)H(s)}
\]

(3)

Case 2: Flow disturbance input is present and both temperature disturbance & reference input is zero.

\[
y_{\text{flow}}(s) = \frac{F(s)}{D_f(s)} = \frac{F(s)}{1 + C(s)A(s)G(s)H(s)}
\]

(4)

Case 3: Temperature disturbance input is present and both flow disturbance & reference input is zero.

\[
y_{\text{temp}}(s) = \frac{T(s)}{D_T(s)} = \frac{T(s)}{1 + C(s)A(s)G(s)H(s)}
\]

(5)

The description of heat exchanger system is provided in the previously published paper by the same authors in [32] for the optimization of 2DOF controller using GA.

3. Methodology

Three objective functions set point tracking, flow disturbance rejection, and temperature disturbance rejection are formed. An objective is to minimize set point tracking error, and both flow and temperature disturbances (which are also considered to be error). Therefore, criteria applied to evaluate the quality of system response have taken into account the variation of error over the entire range of time. The performance indices considered for evaluation of objective functions are Integral of Absolute Error (IAE), Integral of Squared Error (ISE), and Integral of Time-weighted Absolute Error (ITAE) described as under [4, 33].

Criterion 1: Integral of absolute value of error IAE

\[
f(K_p, K_i, K_D, \alpha, \beta) = J \left( \sum_{k=0}^{n} |SP - y(k)|, \sum_{k=0}^{n} |y_{\text{flow}}(k)|, \sum_{k=0}^{n} |y_{\text{temp}}(k)| \right)
\]

(6)
Criterion 2: Integral of Squared Error ISE

\[ f(K_p, K_i, K_D, \alpha, \beta) = J \left( \sum_{k=0}^{n} [SP - y(k)]^2, \sum_{k=0}^{n} [y_{\text{flow}}(k)]^2, \sum_{k=0}^{n} [y_{\text{temp}}(k)]^2 \right) \]  

(7)

Criterion 3: Integral of Time-weighted Absolute Error ITAE

\[ f(K_p, K_i, K_D, \alpha, \beta) = J \left( \sum_{k=0}^{n} [t \times (SP - y(k))] \sum_{k=0}^{n} [t \times y_{\text{flow}}(k)] \sum_{k=0}^{n} [t \times y_{\text{temp}}(k)] \right) \]  

(8)

where,

SP = Set point or reference input.

\[ y(k) = \frac{C_t(k) + C(k)\alpha}{C(k)} \frac{C(k)y_{\text{flow}}(k)G(k)}{1 + C(k)y_{\text{flow}}(k)G(k)H(k)} \times r(k) \] from Eq. (3) is process value output at kth interval is a function of 2DOF controller parameters.

\[ y_{\text{flow}}(k) = \frac{F(k)}{1 + C(k)y_{\text{flow}}(k)G(k)H(k)} \times D_f(k) \] from Eq. (4) is flow disturbance output at kth interval is a function of 2DOF controller parameters.

\[ y_{\text{temp}}(k) = \frac{T(k)}{1 + C(k)y_{\text{temp}}(k)G(k)H(k)} \times D_T(k) \] from Eq. (5) is temperature disturbance output at kth interval is a function of 2DOF controller parameters.

In the multiobjective optimization problem vector of objective functions is required to be supplied for optimization. Here, vector of three objective functions are supplied for optimization of 2DOF controller parameters as under.

\[ f(K_p, K_i, K_D, \alpha, \beta) = ([J_{\text{setpoint}} \; J_{\text{flow}} \; J_{\text{temp}}]) \]  

(9)

where,

\[ J_{\text{setpoint}} = \text{Function of set point tracking considering any of the above three criteria for evaluation one at a time.} \]

\[ J_{\text{flow}} = \text{Function of flow disturbance rejection considering any of the above three criteria for evaluation one at a time.} \]

\[ J_{\text{temp}} = \text{Function of temperature disturbance rejection considering any of the above three criteria for evaluation one at a time.} \]

Implementation of algorithms and comparison of results are discussed in the following section.
4. Calculation

The Multi-criteria decision making tool is used to select best solution among a finite set of solutions available for multiobjective optimization problems. TOPSIS was implemented by Hwang and Yoon [24]. TOPSIS works based on calculating the Euclidian distance from each alternative to a best performing attribute called Positive Ideal Solution (PIS) and a poorest performing attribute called Negative Ideal Solution (NIS) that are defined in n-dimensional space [26]. It consists of two criteria positive and negative. Positive criteria need to be increased and negative criteria need to be decreased. This process is implemented by taking the below steps:

**Step 1:** Specify alternative and criteria for non-dominated set of solutions of the 2DOF controller parameters. Assume that there are \( m \) possible alternatives called \( A = [A_1, A_2, \ldots, A_m] \) which are evaluated against criteria \( C = [C_1, C_2, \ldots, C_c] \).

**Step 2:** Assign ratings to criteria and alternatives using matrix \( X \) shown below where, \( x_{ij} \) indicates the value of alternative \( A_i \) for criterion \( C_g \).

\[
X_{m \times c} = \begin{bmatrix}
A_1 & \cdots & A_i & \cdots & A_m \\
X_{11} & \cdots & x_{1g} & \cdots & x_{1c} \\
\vdots & \ddots & \vdots & \ddots & \vdots \\
\vdots & & \vdots & & \vdots \\
x_{m1} & \cdots & x_{mg} & \cdots & x_{mc}
\end{bmatrix}
\]

**Step 3:** Calculate weight of criteria by entropy technique to normalize decision matrix \( X_{m \times c} \) using following formula.

\[
q_{ig} = \frac{x_{ig}}{x_{1g} + x_{2g} + \ldots + x_{mg}}; \forall g \in \{1, 2, \ldots c\}
\]

The information entropy of criterion \( g \) is represented as under.

\[
\Delta_g = -k \sum_{i=1}^{m} q_{ig} \ln q_{ig}; \forall g \in \{1, 2, \ldots c\}
\]

where, \( 0 \leq \Delta_g \leq 1 \) is assured with \( k = 1/\ln(m) \).

The entropy method for measuring weights of criteria is an objective weight technique determined by data statistical properties. Here, the index with higher information entropy \( \Delta_g \) has greater variation hence, weight is calculated based on deviation degree

\[
d_g = 1 - \Delta_g; (g = 1, \ldots, c).
\]

The weight for criteria by the entropy method is calculated as under (14):
\[ w_g = \frac{d_g}{(d_1 + d_2 + \ldots + d_c)} \]  
(14)

Let \( \lambda_g \) be weight vector used to obtain the aggregated weight \( w'_g \) shown in (15).

\[ w'_g = \frac{\lambda_g w_g}{(\lambda_1 w_1 + \lambda_2 w_2 + \ldots + \lambda_c w_c)} \]  
(15)

\[ w' = \{w'_1, w'_2, \ldots, w'_c\} \]  
(16)

**Step 4:** Construct a normalized decision matrix using the vector normalization method, calculate normalized value \( r_{ig} \) by (17) and construct matrix \( N_{m \times c} \) given by (18).

\[ r_{ig} = \frac{x_{ig}}{\sqrt{x_{i1}^2 + x_{i2}^2 + \ldots + x_{im}^2}} \]  
(17)

\[ N_{m \times c} = [r_{ig}]_{m \times c} (i = 1, \ldots, m; g = 1, \ldots, c). \]  
(18)

**Step 5:** Construct the weighted normalized decision matrix by building the diagonal matrix \( w'_{c \times c} \) with element \( w'_g \) in (15) to reach the \( V \) matrix:

\[ V = N_{m \times c} w'_{c \times c} = (w_{ig})_{m \times c} (i = 1, \ldots, m; g = 1, \ldots, c). \]  
(19)

**Step 6:** Compute the positive ideal solution (PIS) \( A^+ \) and the negative ideal solution (NIS) \( A^- \) of the alternatives:

\[ A^+ = \{(\text{max } v_{ig} | g \in G); (\text{min } v_{ig} | g \in G') \} = (v^+_1, v^+_2, \ldots, v^+_c) \]  
(20)

\[ A^- = \{(\text{min } v_{ig} | g \in G); (\text{max } v_{ig} | g \in G') \} = (v^-_1, v^-_2, \ldots, v^-_c) \]  
(21)

where, \( G \) and \( G' \) are the subsets of positive and negative criteria.

**Step 7:** Compute the distance of each alternative from PIS \( d^+_i \) and NIS \( d^-_i \):

\[ d^+_i = \sqrt{\sum_{g=1}^{c} (v_{ig} - v^+_g)^2} \]  
(22)

\[ d^-_i = \sqrt{\sum_{g=1}^{c} (v_{ig} - v^-_g)^2} \]  
(23)
Step 8: Compute the closeness coefficient of each alternative:

\[ CC^+_i = \frac{d_i^-}{(d_i^- + d_i^+)} ; i = 1, 2, ..m \]  \hspace{1cm} (24)

Step 9: Rank the alternatives.

\[ v = \left\{ v_i \left| \max_{1 \leq i \leq m} \left( CC^+_i \right) \right. \right\} \]  \hspace{1cm} (25)

MATLAB software tool is used to implement above steps.

5. Results & discussion

The proposed steps for 2DOF controller parameters optimization using MOPSO, NSGA-II, and NSGA-III algorithms enhanced with TOPSIS are as under.
Fig. 5. Pareto plot of NSGA-II under ITAE criterion.

Fig. 6. Pareto plot of NSGA-III under IAE criterion.

Fig. 7. Pareto plot of NSGA-III under ISE criterion.
Step 1: Derive transfer function of plant, actuator, sensor, temperature disturbance, flow disturbance, serial controller, and feed forward controller considering the values as shown in Fig. 2.

Step 2: Set the upper & lower bound values of 2DOF controller parameters.

Step 3: Define the magnitude of input, flow disturbance and temperature disturbance as step input of magnitude 1, 0.1 and 0.01 respectively [1].

Step 4: Form the objective function, and define fitness same as objective function.

Step 5: Select the evaluation of objective function criteria IAE, ISE and ITAE one at a time.

Fig. 8. Pareto plot of NSGA-III under ITAE criterion.

Fig. 9. Pareto plot of MOPSO under IAE criterion.
Table 1. Pareto set of solutions using NSGA-II, NSGA-III, and MOPSO.

| Type of algorithm | Number of non-dominated set of solutions under three test criteria |
|-------------------|------------------------------------------------------------------|
|                   | IAE | ISE | ITAE |
| NSGA-II           | 27  | 27  | 27   |
| NSGA-III          | 80  | 80  | 80   |
| MOPSO             | 95  | 26  | 9    |
| Combined non-dominated solutions under each criteria. | 202 | 133 | 116 |
**Step 6:** Initialize MOPSO parameters: Maximum Number of Iterations ‘100’, Number of populations ‘100’, Repository Size ‘100’, Inertia Weight ‘0.5’, Inertia Weight Damping Rate ‘0.99’, Personal Learning Coefficient c1 ‘1’ and Global Learning Coefficient c2 ‘2’, Number of Grids per Dimension ‘7’, Mutation Rate (varied from 0.1 to 0.9) [23].

**OR**

**Step 6:** Initialize NSGA-II parameters: Cross over percentage ‘0.8’, Mutation rate ‘0.09’, the maximum number of iterations ‘100’, Population size ‘100’ [14, 34].

| Rank of nondominated set of solution under IAE | Rank of nondominated set of solution under ISE | Rank of nondominated set of solution under ITAE |
|-----------------------------------------------|-----------------------------------------------|-----------------------------------------------|
| Solution number | Closeness coefficient CC | Rank | Solution number | Closeness coefficient CC | Rank | Solution number | Closeness coefficient CC | Rank |
| 1 | 0.139499983 | 25 | 1 | 0.916156397 | 2 | 1 | 0.736904849 | 4 |
| 2 | 0.999790511 | 1 | 2 | 0.969106095 | 1 | 2 | 0.568957309 | 14 |
| 3 | 0.450991856 | 21 | 3 | 0.111113239 | 27 | 3 | 0.599328282 | 11 |
| 4 | 0.612548684 | 15 | 4 | 0.124500851 | 26 | 4 | 0.398997174 | 24 |
| 5 | 0.000873994 | 26 | 5 | 0.874856154 | 5 | 5 | 0.568651174 | 16 |
| 6 | 0.500815242 | 18 | 6 | 0.28202096 | 23 | 6 | 0.743282348 | 3 |
| 7 | 0.245774548 | 23 | 7 | 0.245031117 | 24 | 7 | 0.63607864 | 7 |
| 8 | 0.716252347 | 8 | 8 | 0.206231281 | 25 | 8 | 0.444637078 | 21 |
| 9 | 0.834714135 | 4 | 9 | 0.89583837 | 3 | 9 | 0.637014324 | 5 |
| 10 | 0.713062952 | 9 | 10 | 0.780720049 | 11 | 10 | 0.521594285 | 19 |
| 11 | 0.176315852 | 24 | 11 | 0.564060093 | 17 | 11 | 0.615701589 | 9 |
| 12 | 0.523272748 | 17 | 12 | 0.414971725 | 18 | 12 | 0.636593288 | 6 |
| 13 | 0.838580319 | 3 | 13 | 0.386584924 | 20 | 13 | 0.576239573 | 13 |
| 14 | 0.619401354 | 14 | 14 | 0.570190088 | 16 | 14 | 0.487027384 | 20 |
| 15 | 0.999670866 | 2 | 15 | 0.323650959 | 22 | 15 | 0.96421824 | 1 |
| 16 | 0.602867228 | 16 | 16 | 0.407643506 | 19 | 16 | 0.385520134 | 26 |
| 17 | 0.70763622 | 10 | 17 | 0.77134111 | 12 | 17 | 0.416764044 | 22 |
| 18 | 0.620119539 | 13 | 18 | 0.799426983 | 10 | 18 | 0.52914569 | 17 |
| 19 | 0.470478286 | 20 | 19 | 0.848795482 | 8 | 19 | 0.170838835 | 27 |
| 20 | 0.717695573 | 7 | 20 | 0.865987777 | 6 | 20 | 0.407484677 | 23 |
| 21 | 0.730277754 | 6 | 21 | 0.839758921 | 9 | 21 | 0.578041421 | 12 |
| 22 | 0.65026265 | 12 | 22 | 0.601596904 | 15 | 22 | 0.947696444 | 2 |
| 23 | 0.76601709 | 5 | 23 | 0.86343887 | 7 | 23 | 0.605737 | 10 |
| 24 | 0.000873994 | 26 | 24 | 0.732148897 | 14 | 24 | 0.619770205 | 8 |
| 25 | 0.660481014 | 11 | 25 | 0.335439278 | 21 | 25 | 0.396036663 | 25 |
| 26 | 0.476964994 | 19 | 26 | 0.884289536 | 4 | 26 | 0.525753039 | 18 |
| 27 | 0.346500567 | 22 | 27 | 0.751702822 | 13 | 27 | 0.568957309 | 14 |
Table 3. Rank of 2DOF controller parameters using TOPSIS for NSGA-III under IAE, ISE, and ITAE.

| Solution number | Closeness coefficient CC | Rank | Solution number | Closeness coefficient CC | Rank | Solution number | Closeness coefficient CC | Rank |
|-----------------|--------------------------|------|-----------------|--------------------------|------|-----------------|--------------------------|------|
| 1               | 0.439553488              | 41   | 1               | 0.317155401              | 33   | 1               | 0.659965912              | 9    |
| 2               | 0.210662124              | 64   | 2               | 0.28830177               | 58   | 2               | 0.359385135              | 62   |
| 3               | 0.348456745              | 49   | 3               | 0.405056451              | 12   | 3               | 0.447136428              | 46   |
| 4               | 0.971350992              | 1    | 4               | 0.251428197              | 67   | 4               | 0.661714626              | 8    |
| 5               | 0.28768881               | 57   | 5               | 0.267608639              | 61   | 5               | 0.415263455              | 55   |
| 6               | 0.545861924              | 28   | 6               | 0.360409747              | 20   | 6               | 0.407534457              | 56   |
| 7               | 0.322304835              | 52   | 7               | 0.302603379              | 48   | 7               | 0.669751306              | 6    |
| 8               | 0.677678826              | 14   | 8               | 0.301588821              | 49   | 8               | 0.545724189              | 25   |
| 9               | 0.128213252              | 70   | 9               | 0.252740132              | 64   | 9               | 0.346273572              | 64   |
| 10              | 0.279717395              | 59   | 10              | 0.330748807              | 26   | 10              | 0.257145617              | 76   |
| 11              | 0.617646691              | 19   | 11              | 0.231743511              | 72   | 11              | 0.54913437               | 24   |
| 12              | 0.682728137              | 10   | 12              | 0.762647655              | 2    | 12              | 0.416525188              | 54   |
| 13              | 0.679302693              | 13   | 13              | 0.302847732              | 47   | 13              | 0.556628155              | 21   |
| 14              | 0.774979908              | 6    | 14              | 0.307250078              | 41   | 14              | 0.432646626              | 50   |
| 15              | 0.62145335               | 17   | 15              | 0.266339439              | 63   | 15              | 0.302926938              | 69   |
| 16              | 0.676856737              | 15   | 16              | 0.303263049              | 46   | 16              | 0.421798675              | 53   |
| 17              | 0.537558448              | 29   | 17              | 0.304146372              | 44   | 17              | 0.352838672              | 63   |
| 18              | 0.125314425              | 71   | 18              | 0.227281613              | 74   | 18              | 0.539847249              | 28   |
| 19              | 0.438500882              | 42   | 19              | 0.319061088              | 31   | 19              | 0.52008084               | 31   |
| 20              | 0.216546243              | 63   | 20              | 0.375424795              | 17   | 20              | 0.600674629              | 17   |
| 21              | 0.043885699              | 79   | 21              | 0.249535522              | 69   | 21              | 0.292728238              | 72   |
| 22              | 0.526132336              | 34   | 22              | 0.251778613              | 66   | 22              | 0.44545096               | 47   |
| 23              | 0.311369363              | 54   | 23              | 0.305825024              | 42   | 23              | 0.308414571              | 68   |
| 24              | 0.682728137              | 10   | 24              | 0.314250724              | 38   | 24              | 0.373881496              | 61   |
| 25              | 0.440849961              | 40   | 25              | 0.377903814              | 15   | 25              | 0.431643379              | 51   |
| 26              | 0.116707029              | 73   | 26              | 0.317903252              | 32   | 26              | 0.44350692               | 49   |
| 27              | 0.497799896              | 36   | 27              | 0.371390856              | 19   | 27              | 0.500983321              | 34   |
| 28              | 0.80613819               | 5    | 28              | 0.451705244              | 11   | 28              | 0.339246264              | 65   |
| 29              | 0.820746197              | 4    | 29              | 0.387367782              | 14   | 29              | 0.467652281              | 43   |
| 30              | 0.830172755              | 3    | 30              | 0.356523335              | 21   | 30              | 0.541719928              | 27   |
| 31              | 0.141246346              | 69   | 31              | 0.333724201              | 25   | 31              | 0.407310364              | 57   |
| 32              | 0.429036049              | 44   | 32              | 0.845854233              | 1    | 32              | 0.299969542              | 70   |
| 33              | 0.451551397              | 38   | 33              | 0.546454591              | 8    | 33              | 0.468112783              | 42   |
| 34              | 0.668844559              | 16   | 34              | 0.326851505              | 29   | 34              | 0.596182603              | 18   |
| 35              | 0.116542605              | 74   | 35              | 0.459874427              | 9    | 35              | 0.619882015              | 15   |

(continued on next page)
| Solution number | Closeness coefficient CC | Rank | Solution number | Closeness coefficient CC | Rank | Solution number | Closeness coefficient CC | Rank |
|-----------------|--------------------------|------|-----------------|--------------------------|------|-----------------|--------------------------|------|
| 36              | 0.451943192              | 37   | 36              | 0.311084497              | 40   | 36              | 0.297375514              | 71   |
| 37              | 0.345296355              | 50   | 37              | 0.28994159               | 57   | 37              | 0.318827228              | 67   |
| 38              | 0.022754558              | 80   | 38              | 0.327410882              | 28   | 38              | 0.337132887              | 66   |
| 39              | 0.185450287              | 65   | 39              | 0.233241297              | 70   | 39              | 0.664750022              | 7    |
| 40              | 0.060141258              | 78   | 40              | 0.328769444              | 27   | 40              | 0.000953462              | 80   |
| 41              | 0.371430373              | 47   | 41              | 0.32490235              | 30   | 41              | 0.78279646               | 2    |
| 42              | 0.297161091              | 55   | 42              | 0.268815717              | 60   | 42              | 0.278149462              | 73   |
| 43              | 0.682728137              | 10   | 43              | 0.352404163              | 23   | 43              | 0.698814442              | 4    |
| 44              | 0.100956242              | 75   | 44              | 0.3047964               | 43   | 44              | 0.544724408              | 26   |
| 45              | 0.356684181              | 48   | 45              | 0.458483638              | 10   | 45              | 0.472524781              | 41   |
| 46              | 0.570876027              | 24   | 46              | 0.232892679              | 71   | 46              | 0.426289835              | 52   |
| 47              | 0.583773938              | 23   | 47              | 0.209475178              | 77   | 47              | 0.389772951              | 59   |
| 48              | 0.184572682              | 66   | 48              | 0.295368743              | 53   | 48              | 0.671815216              | 5    |
| 49              | 0.529087805              | 33   | 49              | 0.398952889              | 13   | 49              | 0.592719166              | 19   |
| 50              | 0.331470436              | 51   | 50              | 0.291712576              | 56   | 50              | 0.399685147              | 58   |
| 51              | 0.597368105              | 20   | 51              | 0.316013762              | 35   | 51              | 0.154826454              | 78   |
| 52              | 0.555316163              | 27   | 52              | 0.226845923              | 75   | 52              | 0.638824441              | 12   |
| 53              | 0.535023021              | 31   | 53              | 0.303662915              | 45   | 53              | 0.63286338              | 13   |
| 54              | 0.559704347              | 25   | 54              | 0.372804087              | 18   | 54              | 0.278083112              | 74   |
| 55              | 0.312915395              | 53   | 55              | 0.349561114              | 24   | 55              | 0.501480823              | 33   |
| 56              | 0.082540688              | 76   | 56              | 0.377702607              | 16   | 56              | 0.465948466              | 44   |
| 57              | 0.279300330              | 60   | 57              | 0.316151501              | 34   | 57              | 0.500214902              | 35   |
| 58              | 0.29060933               | 56   | 58              | 0.295719881              | 52   | 58              | 0.690017616              | 16   |
| 59              | 0.532056477              | 32   | 59              | 0.295243241              | 54   | 59              | 0.380915994              | 60   |
| 60              | 0.726377935              | 8    | 60              | 0.698258206              | 3    | 60              | 0.534416068              | 30   |
| 61              | 0.232050518              | 62   | 61              | 0.266474158              | 62   | 61              | 0.49156618              | 39   |
| 62              | 0.772625012              | 7    | 62              | 0.137002069              | 80   | 62              | 0.27260422              | 75   |
| 63              | 0.384688528              | 46   | 63              | 0.315243759              | 37   | 63              | 0.537982991              | 29   |
| 64              | 0.695940402              | 9    | 64              | 0.284592551              | 59   | 64              | 0.49740558              | 36   |
| 65              | 0.286374769              | 58   | 65              | 0.227692657              | 73   | 65              | 0.553231672              | 23   |
| 66              | 0.517743307              | 35   | 66              | 0.225047538              | 76   | 66              | 0.589466716              | 20   |
| 67              | 0.596985476              | 21   | 67              | 0.674972666              | 5    | 67              | 0.496807092              | 37   |
| 68              | 0.448623576              | 39   | 68              | 0.658994266              | 6    | 68              | 0.778863734              | 3    |
| 69              | 0.423921555              | 45   | 69              | 0.599593893              | 7    | 69              | 0.062615749              | 79   |
| 70              | 0.067369531              | 77   | 70              | 0.300966448              | 50   | 70              | 0.473048576              | 40   |

(continued on next page)
Step 6: Initialize NSGA-III parameters: Cross over percentage ‘0.8’, Mutation rate ‘0.09’, the maximum number of iterations ‘100’, Population size ‘100’, Number of reference point supplied ‘66’ [15].

Step 7: Supply the objective function as vector of three objectives.

Step 8: Call optimization functions MOPSO OR NSGA-II OR NSGA-III as required one at a time.

Step 9: Run the algorithm till maximum number of iteration.

Step 10: Obtain Pareto optimal set of solutions from above three algorithms NSGA-II, NSGA-III, and MOPSO under three evaluation criteria IAE, ISE, and ITAE.

Step 11: Apply TOPSIS to rank the set of Pareto optimal solutions obtained in Step 10.

Step 12: Plot the results with best rank solutions.

Following Figs. 3, 4, 5, 6, 7, 8, 9, 10, and 11 are plots of Pareto optimal front of optimization of three objective functions i.e. set point tracking and disturbance rejections (Both flow and temperature) obtained for evaluation criteria IAE, ISE & ITAE using NSGA-II, NSGA-III, and MOPSO algorithms.

The number of non-dominated set of solutions obtained for 2DOF controller parameters optimization using NSGA-II, NSGA-III, and MOPSO algorithms under three test criteria IAE, ISE, and ITAE are shown in following Table 1.

Table 3. (Continued)

| Solution number | Closeness coefficient CC | Rank |
|-----------------|--------------------------|------|
| 71              | 0.618913651              | 18   |
| 72              | 0.555501545              | 26   |
| 73              | 0.866894865              | 2    |
| 74              | 0.536261437              | 30   |
| 75              | 0.116868948              | 72   |
| 76              | 0.432585716              | 43   |
| 77              | 0.177506132              | 67   |
| 78              | 0.270286649              | 61   |
| 79              | 0.590010232              | 22   |
| 80              | 0.158613181              | 68   |

| Solution number | Closeness coefficient CC | Rank |
|-----------------|--------------------------|------|
| 71              | 0.205619461              | 78   |
| 72              | 0.698258206              | 3    |
| 73              | 0.354380485              | 22   |
| 74              | 0.250648242              | 68   |
| 75              | 0.197234242              | 79   |
| 76              | 0.298779771              | 51   |
| 77              | 0.313631301              | 39   |
| 78              | 0.252374139              | 65   |
| 79              | 0.315782746              | 36   |
| 80              | 0.293856154              | 55   |

| Solution number | Closeness coefficient CC | Rank |
|-----------------|--------------------------|------|
| 71              | 0.465774347              | 45   |
| 72              | 0.510743801              | 32   |
| 73              | 0.624099411              | 14   |
| 74              | 0.24223292               | 77   |
| 75              | 0.443820198              | 48   |
| 76              | 0.651996723              | 11   |
| 77              | 0.656274124              | 10   |
| 78              | 0.493524766              | 38   |
| 79              | 0.976027897              | 1    |
| 80              | 0.556425336              | 22   |
Table 4. Rank of 2DOF controller parameters using TOPSIS for MOPSO under IAE, ISE, and ITAE.

| Solution number | Closeness coefficient CC | Rank | Solution number | Closeness coefficient CC | Rank | Solution number | Closeness coefficient CC | Rank |
|-----------------|--------------------------|------|-----------------|--------------------------|------|-----------------|--------------------------|------|
| 1               | 0.23019673               | 43   | 1               | 0.158978146              | 8    |
| 2               | 0.23019673               | 43   | 2               | 0.482927944              | 4    |
| 3               | 0.312720045              | 34   | 3               | 0.292044621              | 7    |
| 4               | 0.243222672              | 42   | 4               | 0.650128628              | 3    |
| 5               | 0.050949174              | 87   | 5               | 0.369120678              | 6    |
| 6               | 0.122341775              | 71   | 6               | 0.400733273              | 5    |
| 7               | 0.118887117              | 74   | 7               | 0.002442736              | 9    |
| 8               | 0.195762628              | 55   | 8               | 0.986438065              | 1    |
| 9               | 0.180892406              | 60   | 9               | 0.668850975              | 2    |
| 10              | 0.068071498              | 83   | 10              | 0.36837245               | 6    |
| 11              | 0.36837245               | 23   | 11              | 0.438498015              | 2    |
| 12              | 0.438498015              | 15   | 12              | 0.255182165              | 17   |
| 13              | 0.220514515              | 47   | 14              | 0.21453224               | 5    |
| 14              | 0.247074255              | 40   | 16              | 0.261211809              | 14   |
| 15              | 0.217878313              | 48   | 18              | 0.007278731              | 15   |
| 16              | 0.046581497              | 88   | 19              | 0.244337626              | 4    |
| 17              | 0.337775271              | 32   | 22              | 0.003006195              | 10   |
| 18              | 0.376072103              | 22   | 24              | 0.355282527              | 16   |
| 19              | 0.538133766              | 11   | 26              | 0.056130698              | 1    |
| 20              | 0.163327677              | 65   | 27              | 0.143472658              | 68   |
| 21              | 0.126395308              | 70   | 28              | 0.120716072              | 73   |
| 22              | 0.107963358              | 75   | 29              | 0.344657339              | 30   |
| 23              | 0.045972154              | 89   | 30              | 0.171095354              | 63   |
| 24              | 0.538133766              | 11   | 31              | 0.171095354              | 63   |

(continued on next page)
Table 4. (Continued)

| Solution number | Closeness coefficient CC | Rank | Solution number | Closeness coefficient CC | Rank | Solution number | Closeness coefficient CC | Rank |
|-----------------|--------------------------|------|-----------------|--------------------------|------|-----------------|--------------------------|------|
| 36              | 0.021098635              | 93   | 37              | 0.04404276              | 90   | 38              | 0.189419127              | 58   |
| 39              | 0.13554931               | 69   | 40              | 0.169115449              | 64   | 41              | 0.055317839              | 86   |
| 42              | 0.29813782               | 35   | 43              | 0.354978976              | 28   | 44              | 0.09546303               | 76   |
| 45              | 0.17216143               | 62   | 46              | 0.292668621              | 36   | 47              | 0.364034251              | 25   |
| 48              | 0.36039207               | 26   | 49              | 0.227814308              | 45   | 50              | 0.227003254              | 46   |
| 51              | 0.353056452              | 29   | 52              | 0.654700592              | 7    | 53              | 0.367726791              | 24   |
| 54              | 0.753944692              | 5    | 55              | 0.99148973               | 1    | 56              | 0.566617107              | 9    |
| 57              | 0.260907806              | 38   | 58              | 0.214582939              | 51   | 59              | 0.183988557              | 59   |
| 60              | 0.070307479              | 81   | 61              | 0.058823445              | 84   | 62              | 0.080369764              | 80   |
| 63              | 0.091854976              | 77   | 64              | 0.069951752              | 82   | 65              | 0.429008931              | 16   |
| 66              | 0.401808726              | 19   | 67              | 0.481777661              | 13   | 68              | 0.033793742              | 91   |
| 69              | 0.120970091              | 72   | 70              | 0.425816038              | 17   |

(continued on next page)
TOPSIS algorithm is applied to prioritize the pareto set of solutions shown in Table 1. Here, minimization of peakover shoot, flow disturbance rejection, and temperature disturbance rejection are considered as three criteria $C_1$, $C_2$, and $C_3$ for TOPSIS. All three criteria are negative as it requires to be minimized. The weights of criteria assumed to be identical ($w = 1$). After applying TOPSIS, rank of each non-dominated solution along with closeness coefficient is obtained shown in following Tables 2, 3, and 4.

In order to obtain the comparative analysis of optimization algorithms (NSGA-II, NSGA-III, and MOPSO) all the Pareto optimal solutions are combined under

| Solution number | Closeness coefficient CC | Rank | Solution number | Closeness coefficient CC | Rank | Solution number | Closeness coefficient CC | Rank |
|-----------------|--------------------------|------|-----------------|--------------------------|------|-----------------|--------------------------|------|
| 71              | 0.161906037              | 66   |                 |                          |      |                 |                          |      |
| 72              | 0.401404308              | 20   |                 |                          |      |                 |                          |      |
| 73              | 0.846366476              | 4    |                 |                          |      |                 |                          |      |
| 74              | 0.752990374              | 6    |                 |                          |      |                 |                          |      |
| 75              | 0.420206792              | 18   |                 |                          |      |                 |                          |      |
| 76              | 0.633409989              | 8    |                 |                          |      |                 |                          |      |
| 77              | 0.513723146              | 12   |                 |                          |      |                 |                          |      |
| 78              | 0.191753614              | 56   |                 |                          |      |                 |                          |      |
| 79              | 0.99148973               | 1    |                 |                          |      |                 |                          |      |
| 80              | 0.379157043              | 21   |                 |                          |      |                 |                          |      |
| 81              | 0.030601199              | 92   |                 |                          |      |                 |                          |      |
| 82              | 0.540654964              | 10   |                 |                          |      |                 |                          |      |
| 83              | 0.467590372              | 14   |                 |                          |      |                 |                          |      |
| 84              | 0.314745086              | 33   |                 |                          |      |                 |                          |      |
| 85              | 0.190332633              | 57   |                 |                          |      |                 |                          |      |
| 86              | 0.343038099              | 31   |                 |                          |      |                 |                          |      |
| 87              | 0.161042883              | 67   |                 |                          |      |                 |                          |      |
| 88              | 0.99148973               | 1    |                 |                          |      |                 |                          |      |
| 89              | 0.208701266              | 53   |                 |                          |      |                 |                          |      |
| 90              | 0.089212406              | 78   |                 |                          |      |                 |                          |      |
| 91              | 0.080776326              | 79   |                 |                          |      |                 |                          |      |
| 92              | 0.180689375              | 61   |                 |                          |      |                 |                          |      |
| 93              | 0.20032953               | 54   |                 |                          |      |                 |                          |      |
| 94              | 0.216205294              | 49   |                 |                          |      |                 |                          |      |
| 95              | 0.216103897              | 50   |                 |                          |      |                 |                          |      |
evaluation criteria IAE, ISE, and ITAE. The combined non-dominated set of solutions are 202(IAE), 133(ISE), and 116(ITAE) shown in Table 1. TOPSIS is used to obtain top 10 high rank individual solution from combined set of solution shown in Table 5.

As shown in Table 5 after merging the solutions of the algorithms, the percentage of solutions from NSGA-II is greater than NSGA-III and MOPSO under each evaluation criteria. Also, the best rank solution is obtained from NSGA-II (under IAE and ISE) and MOPSO (under ITAE). Here, NSGA-II algorithm outperforms NSGA-III and MOPSO algorithms. Following Figs. 12, 13, and 14 are plots of set point tracking, flow disturbance rejection, and temperature disturbance rejection using the best rank result obtained after applying TOPSIS.

From the above figures (Figs. 12, 13, and 14), it is derived that IAE criterion of NSGA-II (Solution No-177) algorithm has minimum peak overshoot of step response (4.8%), maximum rejection of flow (33.4%), and temperature (78%) disturbances for non-dominated set of solution [1.363,0.052, 6.855,0.601,0.439]. The minimum peak overshoot of step response, maximum rejection of flow, and temperature disturbances are achieved under ISE and ITAE using NSGA-II (Solution No-82) and MOPSO(Solution No-115) algorithms respectively, values are shown in following Table 6.

The settling time for set point tracking response, flow disturbance rejection response, and temperature disturbance rejection response is derived from the above figures (Figs. 12, 13, and 14), shown in following Table 7.

| Top 10 solution from the combined set of solution under IAE | Top 10 solution from the combined set of solution under ISE | Top 10 solution from the combined set of solution under ITAE |
|-----------------------------------------------------------|-----------------------------------------------------------|-----------------------------------------------------------|
| Algorithm | Solution number | Closeness coefficient CC | Rank | Algorithm | Solution number | Closeness coefficient CC | Rank | Algorithm | Solution number | Closeness coefficient CC | Rank |
| NSGA-II | 177 | 0.999790511 | 1 | NSGA-II | 82 | 0.969106 | 1 | MOPSO | 115 | 0.986438 | 1 |
| NSGA-II | 190 | 0.999670866 | 2 | NSGA-II | 81 | 0.916156 | 2 | NSGA-II | 79 | 0.976028 | 2 |
| MOPSO | 55 | 0.99148973 | 3 | NSGA-II | 89 | 0.895838 | 3 | NSGA-II | 95 | 0.964218 | 3 |
| MOPSO | 79 | 0.99148973 | 4 | NSGA-II | 106 | 0.88429 | 4 | NSGA-II | 102 | 0.947696 | 4 |
| MOPSO | 88 | 0.99148973 | 5 | MOPSO | 133 | 0.881947 | 5 | NSGA-III | 41 | 0.782796 | 5 |
| NSGA-III | 99 | 0.971350992 | 6 | NSGA-II | 85 | 0.874856 | 6 | NSGA-III | 68 | 0.778864 | 6 |
| NSGA-III | 168 | 0.866894865 | 7 | NSGA-II | 119 | 0.866528 | 7 | NSGA-II | 86 | 0.743282 | 7 |
| MOPSO | 73 | 0.846366476 | 8 | NSGA-II | 100 | 0.865988 | 8 | NSGA-II | 81 | 0.736905 | 8 |
| NSGA-II | 188 | 0.838580319 | 9 | NSGA-II | 103 | 0.863439 | 9 | NSGA-III | 43 | 0.698814 | 9 |
| NSGA-II | 184 | 0.834714135 | 10 | MOPSO | 117 | 0.854689 | 10 | NSGA-III | 48 | 0.671815 | 10 |

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Fig. 12. Set point response with the best rank result from TOPSIS for 2DOF controller optimization.

Fig. 13. Flow disturbance rejection response with the best rank result from TOPSIS for 2DOF controller optimization.

Fig. 14. Temperature disturbance rejection response with the best rank result from TOPSIS for 2DOF controller optimization.
Table 6. Parameters of 2DOF controller after applying TOPSIS from NSGA-II, NSGA-III, and MOPSO.

| Optimization of 2DOF controller parameter \([K_p, K_i, K_d, \alpha, \beta]\) | Peak overshoot of step response in (%) | Reduction of Flow disturbance in (%) | Reduction of temperature disturbance in (%) |
|---|---|---|---|
| NSGA-II (Solution No-177) under IAE \([1.363, 0.052, 6.855, 0.601, 0.439]\) | 4.8 | 33.4 | 78 |
| NSGA-II (Solution No-82) under ISE \([1.677, 0.0454, 4.886, 0.619, 0.215]\) | 12.59 | 31 | 77 |
| MOPSO(Solution No-115) under ITAE \([1.090, 0.035, 5.876, 0.433, 0.40]\) | 11.35 | 28.5 | 76 |

Table 7. Settling time of the system from the best rank solution under IAE, ISE, and ITAE.

| Optimization of 2DOF controller parameter \([K_p, K_i, K_d, \alpha, \beta]\) | Set point response in (sec) | Flow disturbance response in (sec) | Temperature disturbance response in (sec) |
|---|---|---|---|
| NSGA-II (Solution No-177) under IAE \([1.363, 0.052, 6.855, 0.601, 0.439]\) | 52 | 120 | 89 |
| NSGA-II (Solution No-82) under ISE \([1.677, 0.0454, 4.886, 0.619, 0.215]\) | 150 | 186 | 187 |
| MOPSO(Solution No-115) under ITAE \([1.090, 0.035, 5.876, 0.433, 0.40]\) | 62 | 149 | 100 |

It is derived from Table 7, that settling time of the system is minimum under IAE criterion of NSGA-II (Solution No-177) algorithm.

6. Conclusion

In this paper, Evolutionary (NSGA-II and NSGA-III) and Swarm Intelligence (MOPSO) based algorithms enhanced with Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) is employed to optimize five parameters of Two Degree Of Freedom (2DOF) controller for the problem of shell and tube heat exchanger system. The test problem involves maintaining outlet temperature of process fluid flowing through heat exchanger at set point in the presence of two major conflicting disturbances, (1) Flow variation of input fluid and (2) Temperature variation of input fluid. The step input is applied as disturbance for both flow and temperature disturbances. Three test criteria IAE, ISE and ITAE function of error (set point tracking and disturbance rejection) and time are used for evaluation of objective functions. The Pareto set of solutions are obtained after optimizing all the five parameters of 2DOF controller using Evolutionary (NSGA-II and NSGA-III) and Swarm Intelligence (MOPSO) algorithms, results shown in Table 1. TOPSIS
a multiple criteria decision making method is used to rank the set of Pareto optimal solutions for reducing number of Pareto optimal solutions to a single solution. In order to obtain the comparative analysis of optimization algorithms (NSGA-II, NSGA-III, and MOPSO) all the Pareto optimal solutions are combined under evaluation criteria IAE, ISE, and ITAE. The combined non-dominated set of solutions are 202(IAE), 133(ISE), and 116(ITAE). TOPSIS is used to obtain top 10 high rank individual solution from combined set of solution. The performance optimization of 2DOF controller tuning was evaluated by comparing the values of peak overshoot of step response, set point tracking error, disturbance rejection (both flow and temperature), settling time, and the percentage of solutions obtained from optimization algorithms under criteria IAE, ISE, and ITAE. Here, three negative criteria $C_1$ (peak overshoot), $C_2$ (flow disturbance rejection), and $C_3$ (temperature disturbance rejection) having identical weights ($w = 1$) are considered for prioritizing the solutions using TOPSIS.

From the results shown in Table 5, it is concluded that after merging the solutions of the algorithms, the percentage of solutions from NSGA-II is greater than NSGA-III and MOPSO under three evaluation criteria IAE, ISE, and ITAE. Also, the best rank of solution is obtained from NSGA-II (under IAE and ISE) and MOPSO (under ITAE). From the above figures (Figs. 12, 13, and 14), it is concluded that IAE criterion of NSGA-II (Solution No-177) algorithm has minimum peak overshoot of step response (4.8%), maximum rejection of flow (33.4%), and temperature (78%) disturbances for non-dominated set of solution $[1.363,0.052, 6.855,0.601,0.439]$. The minimum peak overshoot of step response, maximum rejection of flow, and temperature disturbances are achieved under ISE and ITAE criteria using NSGA-II (Solution No-82) and MOPSO(Solution No-115) algorithms respectively. It is derived from Table 7, that settling time of the system is minimum under IAE criteria of NSGA-II (Solution No-177). From this, it is concluded that, NSGA-II algorithm outperforms NSGA-III and MOPSO algorithms for this particular test problem.

The following recommendations are proposed for future work in tuning of 2DOF controller parameters:

1. The performance of NSGA-II, NSGA-III and MOPSO algorithms may be compared with other class of algorithms like: Ant colony algorithm, Artificial Bee colony algorithm and others.

2. The criteria for evaluation of objective functions can be tried other than used one IAE, ISE and ITAE to see the results.

3. Here, results are tested by applying step inputs of magnitude 1, 0.1 and 0.01 for set point tracking, flow disturbance, and temperature disturbance. The other inputs can be applied to verify the performance of algorithms.
4. No modifications in the standard proposed algorithms NSGA-II, NSGA-III, and MOPSO is done except varying algorithmic parameters for better result like; number of population, crossover, mutation, supplying reference points, repository Size, inertia weight, values of random numbers, number of grids per dimension, and mutation rate. Hence, modification in existing algorithm can be thought to improve the performance of algorithms.

5. Instead of considering just three objective optimization problem, many other objectives can be added and problem can be extended to many-objective optimization instead of multi-objective optimization.

Declarations

Author contribution statement

Haresh A. Suthar: Conceived and designed the experiments; Performed the experiments; Wrote the paper.

Jagrut J. Gadit: Conceived and designed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data.

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The authors declare no conflict of interest.

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