Optimal CRONE controller using meta-heuristic optimization algorithm for shell and tube Heat Exchanger

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Abstract. A meta-heuristic optimization algorithm based third generation CRONE controller is proposed for controlling the thermal interfaces in heat exchanger device. The primary aim of this work is to identify suitable optimization technique among the whale optimization Algorithm (WOA) and grey wolf optimization (GWO) algorithms that would improve the robustness of third order crone controller against the parameter variations. A mathematical model of HE is developed to compute non-integer parameters so as to realize the optimal performance of the controller. The objective function is to minimize cost of fluid flow rate and to maximize the heat transfer rate. The optimization of heat exchanger is complicated by number of process plants, area, and method of connection, pressure drop of fluid, and transfer rate. A competitive result is obtained with multi-objective non-linear WOA for wide range of the process variable variations. The simulation is performed in MATLAB software to verify proposed WOA optimized third order CRONE controller and the performance is compared with the GWO optimized CRONE controller.

Keywords: Shell and tube heat exchanger, CRONE controller, Whale Optimization Algorithm, Gray Wolf Optimization.

1. Introduction

Heat exchangers are commonly used for heat transfer applications in industries. Shell and tube heat exchanger (STHE) provides large space for heat transfer between two fluids compared to other heat exchanger types. The STHE are mostly used in the application of liquid to liquid heat transfer with higher density operating fluids. The working process of nano-fluid Shell and Tube heat exchanger is employed. The nano-fluid effect on heat exchanger improves the rate of heat transfer is experimentally evaluated [1]. Differential Evolution (DE) scheme of STHE optimization design is presented. An enhanced type of Genetic Algorithm (GA) namely Differential Evolution (DE) is employed for design optimization of STHE. Differential Evolution method shows improved performance than Genetic Algorithm [2]. For designing heat exchangers an artificial bee colony algorithm (ABC) is introduced. This algorithm is effectively manipulated for optimal design of STHE which gives more accurate and fast method as comparing to conventional trial-and-error method and a conventional GA technique [3]. Particle Swarm...
Optimization (PSO) is manipulated from economic perspective to design STHE. The PSO based optimization for STHE is simple in concept, convergence is quick and implementation is simple for different thermal systems [4]. A design approach based on imperialist competitive algorithm (ICA) is presented. This method reduces the cost of capital investment and operating cost that permit quick, good quality solutions which gives designer more freedom with respect to GA approach in the final choice [5].

In heat exchanger, the temperature of outlet liquid is controlled by conventional PID controller [6]. With traditional PID controller, a wide range of precise temperature control cannot be reached. So the combination of fuzzy and PID controller is proposed [7]. Genetic Algorithm based proportional integral derivative controller is presented to regulate heat exchanger’s output temperature. This controller produces maximum overshoot and higher settling time with high oscillation [8]. To overcome these drawbacks, a new hybrid model reference adaptive supervisory fuzzy controller is developed to regulate output temperature of co-current STHE. This method reduces overshoot problem and settling time is shorter with less oscillation when comparing to fuzzy and PID controller [9]. In order to control temperature in heat exchanger a FLC is presented. By using this controller, the mixed fluid maintains constant temperature [10].

The conventional PID controller to CRONE first generation controller is employed on anti-roll scheme to enhance traveler riding consolation in the sense of universal electric vehicle chassis control. For indeterminate perturbed plants, first generation CRONE controller delivers robust fractional order controller [11]. To enhance the behavior of conventional PID controller, the conventional PID controller is replaced by FOPID controller. By reducing the cost function with GA and PSO, the parameters of PID and FOPID are tuned by optimized value. With regard to optimized tuning parameters, PSO-FOPID has minimal integral error compared to GA-FOPID [12]. In STHE, the PID controller is implemented by Z-N tuning technique. Based on FCM algorithm, the fuzzy forward model of STHE is developed. The output model is then compared with real output of STHE [13]. Generally, for linear process PID controller with conventional tuning is employed, but for non-linear process the conventional PID controller provides robustness, steady state error, settling time is long and also not provides better control action. To overcome this problem PID controller is optimized with particle swarm optimization [14]. For integral and unstable systems, a set of tuning rules for Integer order Proportional-Integral and Derivative (IOPID) as well as FOPID are introduced. To reduce the integrated absolute error, the tuning rules are developed based on a simple model of operation. When compared with IOPID, FOPID provides enhanced performance [15].

A meta-heuristic optimization algorithm based third generation CRONE controller is proposed in this work for controlling the temperature of outlet fluid in HE system. To show the performance of third generation CRONE controller, the parameters are tuned by GWO and WOA. The tuned parameters of $K_p$, $K_i$, $K_d$, $\lambda$ and $\mu$, of WOA are compared with that of GWO, which provides better performance than GWO.

2. Proposed System

The standard chemical heating interaction method contains chemical reactor and STHE. The vapor comes from boiler moves into the pipes while, input liquid flows via the shells of STHE. The input of STHE is input liquid which is stored in storage tank. From boiler, it delivers vapor that heat up the heat exchanger input fluid to a wanted set value. With pump as well as non-returning valve (NRV), the storage tank delivers input fluid into a heat exchanger.

If the rate of inlet flow and outlet flow liquid are equal, the level of fluid is retained constant in STHE, also an insulation wall is neglected due to heat storage capacity. Two kinds of disturbances occur,
first disturbance is input liquid flow variation and second disturbance is input liquid temperature variation. The proposed system’s block representation is depicted in Fig 1.

![Figure 1. Shell and tube heat exchanger’s proposed control scheme](image)

The sensing unit and thermocouple are instigated in the feedback path of control architecture. The thermocouple calculates the temperature of output liquid and sends output of thermocouple into the transmitter device that ultimately transforms output of thermocouple to standardized \((4 - 20)\text{mA}\) signal. The transmitter device outcome is fed to third generation CRONE (TGC) controller. To improve performance of TGC controller, it is optimized by grey wolf optimization and whale optimization algorithm. The output of crone controller is compared with set value and then provides essential command through the actuator element to the last control unit. The actuator element is nothing but it is a current to pressure converter and an air open tap is the last control unit. The TGC controller’s outcome is in the range of \((4 - 20)\text{mA}\). This range is given to the input of current to pressure converter and it transforms into a standard pressure signal in the \((3 - 15)\text{psig}\) range. According to control decisions of the controller, the valve actuates.

3. Modeling of Proposed Scheme

3.1 Heat Exchangers (HE)

Heat Exchanger system transfers heat from one medium to other medium. By changing the speed of hot liquid pump, the rate of flow of hot liquid is controlled. By adjusting the percent opening of flow control valve, the rate of flow of cold liquid can be varied. At tube side, the hot liquid flows whereas at shell side, the cold liquid flows. The flow pattern is co-current, indicating that the hot liquid as well as cold liquid flows in similar direction. The main aim of HE is energy transfer.

Therefore, rate of heat flow \((Q)\) is formulated as,

\[
Q = \alpha \cdot A \cdot \Delta T \tag{1}
\]

Where, \(\alpha\) denotes coefficient of heat transfer, \(A\) denotes area of heat transfer, \(\Delta T\) denotes difference in temperature.

Instead of local heat flow, the overall heat flow rate for whole heat exchanger is formulated as,
\[
Q = U \cdot A \cdot F \cdot LMTD.
\]  

(2)

\[
\frac{1}{U} = \frac{D_D}{\beta_a} \frac{D_D}{\alpha} \frac{D_D}{\ln(D_D/D_A)} + \frac{1}{\alpha_s}.
\]  

(3)

\[
LMTD = \frac{\Delta T_a - \Delta T_b}{\ln(\Delta T_a/\Delta T_b)}.
\]  

(4)

Where, \(U\) denotes overall heat transfer coefficient, \(LMTD\) means Long-Mean Temperature Difference correction factor that depends on flow arrangement, \(\alpha_s\) and \(\alpha_c\) denotes heat transfer coefficients on the side of shell as well as tube, \(\Delta T_a\) and \(\Delta T_b\) denotes differences in temperature between two fluids on various sides of heat exchanger.

Usually, the fluids don’t flow via heat exchanger, they have to be pumped. The pressure drop \((\Delta p)\) defines how much energy is required by heat exchanger to pump the fluids.

3.2 Shell and Tube Heat Exchangers (STHE)

STHE contains two kinds of fluids such as “tubeside” fluid and “shellside” fluid. The “tube side” liquid flows inside a set of parallel tubes called “tube bundle”. These tube bundles are surrounded inside a shell metal. The “shell side” liquid flows within the shell but around the tubes. The shell metal and pipes are pressurized. During the planned life of equipment, they have to withstand specified pressure design. The STHE schematic diagram is depicted in Fig 2.

![Figure 2. Schematic diagram of shell and tube heat exchanger](image)

To model STHE various methods are used. Generally, TEMA i.e. Tubular Exchanger Manufactures Association method is used. Normally, for classification of shell design TEMA standards are mainly used.

3.3 Shell Side

Due to complex geometry as well as flow patterns on side of shell, dissimilar correlations are established for various arrangements. There are two separate shells considered, i.e. TEMA E i.e. one-phase as well as TEMA G i.e. condensation. The first method developed is Kern’s technique that predicts the drop in pressure. It is expressed as,

\[
\Delta p_s = 2 \frac{f_g D_s^2 D_s(n_b+1)}{D_p \rho_s (\frac{\eta_s}{\eta_{sw}})^{1/4}.}
\]  

(5)
Where, number of baffles is denoted as $n_b$, number of cross flow segments in HE is denoted as $(n_b + 1)$. The drop in pressure is directly proportional to number of cross-flow segments, which is considered by kern’s technique.

The configuration consideration is TEMA G condenser in addition to TEMA E. The geometry is much simpler than that of TEMA E, but the shell side two-phase flow makes modeling more complex. The combined heat transfer coefficient for gravitational as well as heat transfer coefficient for shear is known as heat transfer coefficient.

$$\alpha = (\alpha_{shear}^2 + \alpha_{grav}^2)^{1/2}. \quad (8)$$

### 3.4 Tube Side

Normally, the tube has a simple geometry that leads to easier and improved correlations for heat transfer coefficients as well as drop in pressure. A few examples of heat transfer correlations are Dittus-Boelter & Gnielinski that are given in the expressions (9) & (10).

$$Nu_D = 0.023Re_D^{0.8}Pr^n \quad \quad (9)$$

From equation (9) if tube wall temperature is greater than liquid temperature, the value is mentioned as $n = 0.4$ and if tube wall temperature is lesser than liquid temperature, the value is mentioned as $n = 0.3$. By using friction factor the above equation is written as,

$$Nu_D = \frac{(f/B)(Re_D-1000)Pr}{1+12.7(f/B(Pr^{2/3}-1))^2}. \quad (10)$$

$$f = (0.79ln(Re_D) - 1.64)^{-2}. \quad (11)$$

Where, hydraulic diameter is denoted as $D$.

By using friction factor the pressure drop $\Delta p$ is represented as,

$$\Delta p = f \frac{L \rho u^2}{D} \quad (12)$$

A mathematical model of HE device is developed on the side of shell and tube in STHE.
4. Design of Third Generation CRONE (TGC) Controller

The structure of third generation CRONE controller is depicted in Fig 3. The design of TGC controller expands CRONE’s previous generations by allowing more handling general uncertainties.

![Figure 3. Closed loop structure of third generation CRONE controller](image)

From the diagram, $Y_{ref}(s)$ denotes input reference signal, $C_T(s)$ denotes CRONE controller, $G(s)$ denotes process transfer function, $Y(s)$ denotes plant output, $U(s)$ denotes controller output, $D_i(s)$ denotes input disturbance, $D_y(s)$ denotes output disturbance, $N_m(s)$ denotes sensor disturbance, transfer function of open loop fractional order third generation CRONE controller is denoted as $\beta_T(s)$

The third generation CRONE controller scheme design consists of 3 levels, they are generalized template, optimal template as well as optimization of open loop behaviour. The control scheme design is based on generalized template description to be depicted in Nichols plane by each straight line section in each direction across the crossover frequency $\omega_{cg}$ of open loop gain. Generalized template, i.e. Nichols plane is depicted in Fig 4.

![Figure 4. Generalized template (Nichols plane)](image)

From Nichols plane, frequency template phase position specifies the value of real order, i.e. $a$, and angle to vertical specifies the value of imaginary order, i.e.$b$. The transfer function of complex fractional order integral is expressed as,

$$\beta_T(s) = C_T(s)G(s) = \left( \cos \left( \frac{\pi}{2} \right) \right) \frac{\text{sign}(b)}{s^{a}} \left( \frac{\omega_{cg}}{s} \right)^{a} \cos \left( b \ln \left( \frac{s}{\omega_{cg}} \right) \right)^{-s \text{sign}(b)}.$$  \hspace{1cm} (13)

The angle of generalized template to vertical is formulated from the derivatives of the $\beta(j\omega)$ i.e. magnitude and phase at frequency i.e. $\omega_{cg}$, as a function of $a$ and $b$. 
Generalized template transfer function is band-limited and is changed by a common equation.

\[
\beta_T(s) = C \cdot \text{sign}(b) \left( \frac{\omega_l}{s} + 1 \right)^{n_l} \left( a_0 \left( \frac{1 + \frac{s}{\omega_h}}{1 + \frac{s}{\omega_l}} \right) \right)^{a} \times \left( \text{Re} \left( \frac{a_0 \left( \frac{1 + \frac{s}{\omega_h}}{1 + \frac{s}{\omega_l}} \right)^{b}}{\left( \frac{1}{\left( 1 + \frac{s}{\omega_h} \right) n_h} \right)} \right)^{-q \cdot \text{sign}(b)} \right). \tag{15}
\]

So, third generation fractional order CRONE controller is expressed as,

\[
C_T(s) = \frac{\beta_T(s)}{G(s)}. \tag{16}
\]

The complex fractional order integral transfer function for open-loop \( \beta_T(s) \), has eight high level variables they are \( n_l, n_h, a, b, \omega_l, \omega_h, \omega_r \) and \( C \). The parameter \( n_l \) and \( n_h \) are set by control system designer. The parameter \( \omega_r \) and \( C \) are condition of tangency, are mentioned. For the four independent variables, a nonlinear optimization algorithm based on optimal template reduces price function \( J \) based on variations of resonant peak and achieves group of shaping constraints.

\[
J = M_{r_{\text{max}}} - M_r. \tag{17}
\]

Synthesizing such a template that leads the parameterization of 3 dependent variables \( a, b \) and \( c \) by optimizing three independent parameters \( \omega_l, \omega_h \) and \( \omega_r \) depicted in Fig 5.

**Figure 5.** Asymptotic Nichols locus - effect of parameters

The common form of TGC controller is expressed in equation (16). This equation is not in an instigated form, because this equation has terms of fractional order integro-differentiation. Therefore, using recursive
distribution method it is transformed into a rational form. Using the technique of recursive distribution, the attainable rational order CRONE controller \( C_R(s) \) is expressed as,

\[
C_R(s) = \frac{R(s)}{G(s)}
\]  

(18)

To improve the performance of third gene ration CRONE controller, the parameters \( K_p, K_i \) and \( K_d \) are tuned by means of grey wolf optimization and whale optimization algorithm.

5. Design of Grey Wolf Optimization

To tune the parameters like \( K_p, K_i \) and \( K_d \) in CRONE controller, Grey Wolf Optimization technique is used. Mirjalili developed the leadership hierarchy as well as hunting technique that imitate grey wolves in nature. Grey Wolf Optimization consists of four kinds of grey wolves to hunt leadership hierarchy, namely \( \alpha, \beta, \delta, \omega \). To achieve improved optimization, the hunting mechanisms are mathematically modelled. Hunting is led through \( \alpha \) to search best solution for population and rest of 3 pursues \( \alpha, \beta \) aid \( \alpha \) to determine decision making and also act as a bridge from \( \alpha \) to less high in position. The \( \delta \) and \( \omega \) follows the above two. Grey Wolf Optimization’s flow chart is depicted in Fig 6.

![Flow chart of Grey Wolf Optimization](image)

**Figure 6.** Flow chart of Grey Wolf Optimization
Steps involved in GWO are as follows,

- First initialize $a, \beta, \text{and } \delta$.
- Search the number of search agents.
- Number of iterations found is maximum.
- Number of positions are chosen for searching the neighborhood and stopping criteria.

The mathematical model of wolf performance is expressed as,

$$\bar{D} = |\vec{C}.\vec{X}_p(t) - \vec{X}(t)|. \quad (19)$$

$$\vec{X}(t + 1) = \vec{X}_p(t) + \vec{A}.\bar{D}. \quad (20)$$

Where, current iteration is denoted as $t$, coefficient vectors denoted as $\vec{A}$ and $\vec{C}$, prey position vector denoted as $\vec{X}_p$, grey wolf position vector denoted as $\vec{X}$. The expression for $\vec{A}$ and $\vec{C}$ are given below,

$$\vec{A} = 2\vec{a}.\vec{r}_1 - \vec{a}. \quad (21)$$

$$\vec{C} = 2.\vec{r}_2. \quad (22)$$

Where, component of $\vec{a}$ linearly decreases from 2 to 0 over course of iterations and $\vec{r}_1$ and $\vec{r}_2$ are random vectors in [0, 1].

Update current gray wolf position is mathematically expressed as,

$$\vec{X}(t + 1) = \frac{\vec{X}_1 + \vec{X}_2 + \vec{X}_3}{3}. \quad (23)$$

The third generation CRONE controller parameters are tuned by means of grey wolf optimization algorithm. The results evaluated in this algorithm are compared with whale optimization algorithm.

6. Design of Whale Optimization Algorithm

Meta-heuristic algorithm is nothing but whale optimization algorithm (WOA) that optimizes the third generation CRONE controller parameters like $K_p, K_i, \text{and } K_d$ and provides better performance than grey wolf optimization. WOA is inspired from bubble net hunting activities of humpback whales. Generally, the humpback whales are chosen to kill small fishes that are near to water surface. The whales are intelligent and makes 9-shaped path at the period of encircling the prey. The humpback whales identify the location of prey that is near to the sea surface. Whale optimization algorithm’s flow chart is depicted in Fig 7.
Following steps include in WOA are,

Step 1: Initialization

- First initialize CRONE controller parameters such as $K_p$, $K_i$ and $K_d$.

  There are some random values allocated that are used to initiate the optimization process.

Step 2: Calculate the fitness function

The aim of whale optimization algorithm is to reduce the Mean square error that is calculated from equation (24).

$$MSE = \sum_{i=1}^{n} \frac{(x_i - y_i)^2}{n}.$$  \hspace{1cm} (24)

Where, $x_i$ denotes input data, $y_i$ denotes output data, $n$ denotes number of iterations.

Step 3: Update the location

The following equations represents modernized process that are shown below,

$$\vec{U} = | \vec{y} \cdot \vec{p}_{best}(t) - \vec{p}_{best}(t) |.$$  \hspace{1cm} (25)

$$\vec{p}(t + 1) = \vec{p}_{best}(t) - \omega \cdot \vec{U}.$$  \hspace{1cm} (26)
Where, \( t \) denotes current iteration, \( \vec{y} \) denotes coefficient vector, \( \vec{p}_{\text{best}} \) denotes position vector for best description and \( \vec{p} \) denotes existing position vector.

The vectors \( \vec{w} \) and \( \vec{z} \) are expressed as,

\[
\vec{w} = 2 \vec{\mu} \cdot \vec{r}_i - \vec{\mu}.
\]

\[
\vec{z} = 2 \cdot \vec{r}.
\]  

(27)  

(28)

Here, \( \vec{\mu} \) is decreased from 2 to 0 and \( \vec{r}_i \) denotes unsystematic vector in \((0,1)\).

\[
\vec{p}(t + 1) = D \cdot e^{\vec{\eta}} \cdot \cos(2\pi \vec{\eta}) + \vec{p}_{\text{best}}(t) \quad .
\]

\[
\vec{p}(t + 1) = \begin{cases} 
\vec{p}_{\text{best}}(i) - \vec{w} \cdot \vec{U} & \text{if } R < 0.5 \\
D \cdot e^{\vec{\eta}} \cdot \cos(2\pi \vec{k}) + \vec{p}_{\text{best}}(t) & \text{if } R \geq 0.5
\end{cases} .
\]

\[
\vec{U} = |\vec{y} \cdot \vec{p}_{\text{rand}} - \vec{p}|.
\]

\[
\vec{p}(t + 1) = \vec{p}_{\text{rand}} - \vec{A} \cdot \vec{U}.
\]

(29)  

(30)  

(31)  

(32)

Where, \( \vec{p}_{\text{rand}} \) denotes random position vector. The search mediators are typically implemented to modernize their position via an ideal search mediator or best description is Recursive method.

The third generation CRONE controller parameters are tuned by whale optimization algorithm and it provides improved performance. The result evaluated in this algorithm is compared with grey wolf optimization. From the comparison it is observed that whale optimization algorithm provides better performance.

### 7. Result and Discussion

A meta-heuristic optimization algorithm based third generation CRONE controller is proposed for controlling the temperature of outlet fluid, i.e. for hot water in STHE. The third generation CRONE controller for HE system with GWO and WOA optimization technique is performed in this segment. The controller tuning parameters for third generation CRONE controller is attained and the parameters are optimized through GWO and WOA technique and the performance is evaluated. The simulation is performed in MATLAB software to verify proposed WOA optimized third order CRONE controller and the performance is compared with the GWO optimized CRONE controller.

The open loop response is obtained for Step inputs which are depicted in Fig 8. The response of hot water outlet temperature is set at \(55^\circ C\), after certain period a sudden step change occurs in both negative and positive directions.
Figure 8 Open loop response for Step input

Step input is depicted in Fig 9. The cold water inflow rate is set at 0.0014 LPS, after certain period a sudden step change occurs in both negative and positive directions.

Figure 9. Step input

The comparison waveform of WOA, GWO, and CRONE is depicted in Fig 10. The parameters of third generation CRONE controller are tuned and it is optimized by GWO and WOA techniques. From this waveform it is observed that WOA provides improved performance than GWO with faster settling time and minimize peak overshoot problems.

Figure 10. Comparison waveform of WOA-CRONE, GWO-CRONE and CRONE
Table 1. Results for error indices of CRONE controller, WOA- CRONE controller and GWO- CRONE controller for servo response.

| REGION/RANGE [°C] | I (52-54) | II (54-56) | III (56-58) |
|-------------------|-----------|------------|-------------|
| SETPOINT [°C]     | 53        | 55         | 57          |
| SAMPLING INSTANTS | 0-29      | 30-49      | 50-65       |
| CRONE             | ISE 0.002 | 0.024      | 0.038       |
|                   | IAE 0.21  | 0.03       | 0.05        |
|                   | ITAE 5.32 | 3.25       | 3.86        |
|                   | Tr 2.568  | 0.01       | 0.002       |
|                   | %Mp 0.035 | 0.601      | 0.73        |
| GWO-CRONE         | ISE 0.02  | 0.022      | 0.034       |
|                   | IAE 0.18  | 0.03       | 0.05        |
|                   | ITAE 5.30 | 3.22       | 3.84        |
|                   | Tr 2.565  | 0.01       | 0.002       |
|                   | %Mp 0.032 | 0.598      | 0.68        |
| WOA-CRONE         | ISE 0.001 | 0.016      | 0.025       |
|                   | IAE 0.14  | 0.02       | 0.03        |
|                   | ITAE 4.53 | 2.87       | 2.34        |
|                   | Tr 2.452  | 0.01       | 0.001       |
|                   | %Mp 0.031 | 0.582      | 0.62        |

Table 1 lists the result for error indices of CRONE, GWO-CRONE and WOA-CRONE controller for servo response. From this table, the performance criteria and time responses are evaluated. Through this evaluation, it is clear that crone-controller provides better response than other controllers.
8. Conclusion

A meta-heuristic optimization algorithm based third generation CRONE controller is proposed for controlling the temperature of outlet fluid in HE device. The primary aim of this work is to identify suitable optimization technique among whale optimization Algorithm (WOA) and grey wolf optimization (GWO) algorithms that would improve the robustness of third order crone controller against the parameter variations. The objective function is to minimize cost of fluid flow rate and to increase the heat transfer rate. The controller tuning parameter of $K_p, K_i, K_d, \lambda$ and $\mu$ for third generation CRONE controller is attained through GWO and WOA technique and the performance is evaluated. Drawbacks of GWO are comparatively poor robustness, settling time period is long, peak overshoot problem. To overcome these limitations WOA is employed that provides enhanced performance than GWO. The output is executed through MATLAB software.

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