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Time-varying sliding mode controller for heat exchanger with dragonfly algorithm

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ABSTRACT

This article proposes the design of a sliding mode controller with a time-varying sliding surface for the plate heat exchanger. A time-varying sliding mode controller (TVSMC) combines the benefit of the control system's robustness and convergence rate. Using Lyapunov stability theory, the stability of the designed controller is proved. In addition, the controller parameters of the designed controller are specified optimally via the dragonfly algorithm (DA). The input constraint's effect is considered in the controller design process by applying the concept of the auxiliary system. The bounded disturbances are applied to investigate the robustness of the proposed techniques. Moreover, the quasi-sliding mode controller (QSMC) is developed as a benchmark to evaluate the convergence behavior of the proposed TVSMC technique. The simulation results demonstrate the proposed TVSMC with the optimal parameters provided by the DA algorithm (TVSMC+DA) can regulate the temperature to the desired level under bounded disturbances. When compared to the QSMC method, the TVSMC+DA performs significantly faster convergence speed and greater reduction in chattering occurrence. The results clearly indicate that the proposed controller can enhance convergence properties while being robust to disturbances.

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1. INTRODUCTION

Heat exchangers are devices that are widely employed in industrial applications for transferring heat among fluids with different temperatures. The heat exchangers are also classified into the following categories: double pipe, shell and tube, and plate types based on the surface of heat transfer. The primary function of the heat exchanger is to regulate the temperature of one of the fluids at its exit. This is performed in response to changes in the operating conditions. Flat plate heat exchangers work effectively when the temperature differences between hot and cold water are small [1].

Linear and nonlinear feedback controls have been applied for temperature control of heat exchangers [2]–[11], e.g., the robust controller [5], the linear quadratic regulator [6], and the proportional–integral–derivative (PID) controller based on the internal model [9]. However, since the heat exchanger is a nonlinear dynamical system, the feedback controller designed using an approximated linear model may perform effectively only around the equilibrium point. The nonlinear feedback controller can perform in a wider domain of state variables of the considered system [12].

Sliding mode control (SMC) is a variable structure control approach that has also been utilized for temperature regulation in the heat exchanger system [2]–[4], [7]. Under the SMC, the robustness of the control system can be achieved effectively [12]–[17]. For enhancing the convergence property of the control system, terminal sliding mode control (TSMC) containing fractional power terms has been used in this application. Almutairi and Zribi [4] applied the terminal sliding mode control method in the temperature regulation of the plate heat exchanger. This SMC approach may suffer from a singularity that can occur in the derivative of the sliding surface [18]–[20]. Consider the dynamical system with a control input as $\dot{x}_1 = x_2, \dot{x}_2 = f(x) + g(x)u(t)$, the sliding surface can be designed as $s = x^{r/m} + x^{h/p}$ where r, m, h, p are all positive odd integers with $0 < r/m < 1$ or $r = m = 1$ and $1 < h/p < 2$. However, the control input contains the term $(r/m){x_1}^{r/m}\dot{x}_1 = (r/m){x_1}^{r/m-1}x_2$ which can lead to the singularity of the control input when ${x_1}^{r/m-1} = 0$ and $x_2 \neq 0$ [20]. To avoid this problem while increasing the convergence rate, time-varying sliding mode control (TVSMC) is manageable.

According to [13], [21]–[27], the sliding mode control (SMC) design based on the time-varying sliding surface is an approach that can improve the convergence property. Using the sliding surface or variables in the SMC can also reduce the reaching phase of the control system. The sliding surface was defined to pass the initial state variable at the initial time [21], [23], [24]. Improvement of the convergence rate can be also improved simply through the reaching law [15], [16], [28]–[30]. The various developments and applications associated with the reaching laws of SMC have been presented in previous works [25], [28]–[36].

To specify the controller parameters appropriately, the feedback control methods, including the SMC method, can be integrated with various choices of swarm optimization algorithms [37]–[51]. Dragonfly algorithm (DA) is one of the optimization techniques which has been employed for solving various optimization problems and has been extensively utilized in sliding mode controller parameters [39], [42]–[56]. The main concept of this optimization algorithm was presented by Mirjalili [52]. The development of the DA algorithm was inspired by the behavior of dragonfly swarms during hunting (static swarm) and migration (dynamic swarm). During hunting prey, the path of flying comprises local movements and abrupt changes, while many dragonflies have a long-distance path for migrating from one to another location. The dynamic swarm and static swarm can be appropriately characterized as an exploration and exploitation phase of optimization with a metaheuristic approach. The simplicity and ease in terms of implementation made this algorithm to be one of the attractive metaheuristics. In addition, due to the way of predator selection, the algorithm can search for optimal solutions effectively. The designer is required to tune only a few parameters. The DA algorithm provides an acceptable convergent rate for searching for optimal solutions. Furthermore, merging the DA algorithm with other optimization algorithms is simply conducted.

According to the benefit of using the TVSMC method and DA algorithm as mentioned previously, we propose the TVSMC method with DA controller parameter tunning applied for the plate heat exchanger. The aim is to regulate the outlet temperature based on the nonlinear feedback framework so that the domain of state variables in which the designed controller can be performed is not limited only to the nearby equilibrium point. In general, the control input of the system is constrained [4]. In this manuscript, by utilizing the concept of the auxiliary system presented in [57], [58], the significance of the input constraint is considered in the dynamic error of the controller design process. The bounded disturbances are applied to analyze the proposed controller's robustness. Moreover, the quasi-sliding mode controller (QSMC) is developed as a benchmark to evaluate the convergence behavior of the proposed TVSMC technique via simulation.

2. METHOD

2.1. Mathematical modeling of the plate heat exchanger

For control of the outlet temperature of cold water (T_{co}), the plate heat exchanger system as shown in Figure 1 is taken into consideration. Based on the energy conservation balance, the plate heat exchanger is originally developed by Hangos *et al*. [11] and the modified version is presented in [4]. This model is used for designing the control law for temperature regulation as shown in (1) [4], [16].

$$\dot{T}_{co}(t) = -k_1(T_{co}(t) - T_{ho}(t)) + \frac{U_c}{V_c}(T_{ci} - T_{co}(t))$$
$$\dot{T}_{ho}(t) = -k_2(T_{ho}(t) - T_{co}(t)) + \frac{1}{V_h}(T_{hi} - T_{ho}(t))u(t) \quad (1)$$

where $k_1 = \frac{UA}{C_{p,c}\rho_c V_c}$ and $k_2 = \frac{UA}{C_{p,h}\rho_h V_h}$. The system's parameters of (1) are summarized as: the inlet water temperature of the cold and hot sides is represented by T_{ci} and T_{hi} respectively. T_{co} and T_{ho} are the outlet water temperature of the cold and hot sides. U is the overall heat transfer coefficient. The area A is the total surface area of heat transfer. $C_{p,c}$ and $C_{p,h}$ are the specific heat coefficients of cold and hot water. The densities of cold and hot water are represented by ρ_c and ρ_h. The parameters V_c and V_h are the volume of the cold and hot sides. The cold water's flowrate is denoted by U_c. The hot water's flowrate, $u(t)$ is the control input of the system.

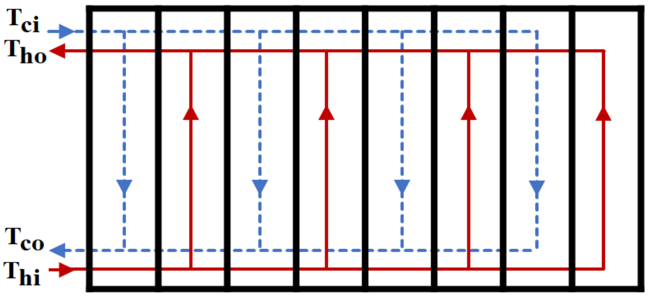


Figure 1. Plate heat exchanger schematic diagram with stream flows

According to [4], the mathematical model in (1) can be stated in input-output affine state-space form by algebraic transformation as follows. First, define the variables as (2).

$$\bar{z}_1(t) = T_{co}(t)$$
$$\bar{z}_2(t) = T_{ho}(t) - T_{co}(t) \quad (2)$$

Then, the state equations of the $z_1(t)$ and $z_2(t)$ with the corresponding input-output equation can be determined as (3).

$$\dot{\bar{z}}_1(t) = k_1\bar{z}_2(t) + \frac{U_c}{V_c}(T_{ci} - \bar{z}_1(t))$$
$$\dot{\bar{z}}_2(t) = -k_2\bar{z}_2(t) + \frac{1}{V_h}(T_{hi} - \bar{z}_1(t) - \bar{z}_2(t))u(t)$$
$$y(t) = \bar{z}_1(t) \quad (3)$$

The model in (3) can be further transformed for the convenience of the TVSMC design by defining the state variables as $x_1(t) = \bar{z}_1(t) - T_{cr}$ and $x_2(t) = k_1\bar{z}_2(t) + \frac{U_c}{V_c}(T_{ci} - \bar{z}_1(t))$. The desired temperature is denoted by T_{cr}. Then, the mathematical model can be transformed into the state-space representation as (4).

$$\dot{x}_1 = x_2$$
$$\dot{x}_2 = f(x) + g(x)u(t) \quad (4)$$

where $f(x) = f_0 - f_1x_1(t) - f_2x_2(t)$ and $g(x) = g_0 - g_1x_1(t) - g_2x_2(t)$. The constants terms of (4) are defined as $f_0 = \frac{k_2U_c}{V_c}(T_{ci} - T_{cr})$, $f_1 = \frac{k_2U_c}{V_c}$, $f_2 = k_2 + \frac{U_c}{V_c}$, $g_0 = \frac{k_1}{V_h}\left(T_{hi} - \left(1 + \frac{U_c}{k_1V_c}\right)T_{cr} + \frac{U_c}{k_1V_c}T_{ci}\right)$, $g_1 = \frac{k_1}{V_h}\left(1 + \frac{U_c}{k_1V_c}\right)$, and $g_2 = \frac{1}{V_h}$. As the goal is to regulate the cold temperature at its exit (T_{co}) to the desired temperature, the corresponding input-output equation of (4) is obtained as (5).

$$y(t) = x_1(t) + T_{cr} \quad (5)$$

2.2. Design of time-varying sliding mode controller
2.2.1. Controller design

The heat exchanger's control system aims to constant the outlet temperature of cold water at 40 °C such that $T_{co}(t) = T_{cr}$. Consequently, in the transformed state space in (4), the controller needs to be designed such that is regulated to zero. Thus, the dynamic error is defined as (6).

$$e_1 = x_1 - x_{1r} \tag{6}$$

Practically, the control input of the system is constrained with a nonnegative bound. The positive sign of the control input represents the inlet flow. If the value of the control input is negative, the sign convention of the system cannot be satisfied. According to [57], [59], the dynamic error and the sliding variable can be defined as (7).

$$e_1 = x_1 - x_{1r} - z_1 \tag{7}$$

The variable z_1 is the auxiliary system's state variable and its dynamic is defined as (8) [57], [59].

$$\begin{aligned} \dot{z}_1 &= -c_{z1}z_1 + z_2 \\ \dot{z}_2 &= -c_{z2}z_2 + g(x)\Delta u \end{aligned} \tag{8}$$

where Δu is the difference between the control input u and the nominal control input v, and denoted as $\Delta u = v - u$. The auxiliary system parameters c_1 and c_2 where $c_{z1} > 0$, and $c_{z2} > 0$. According to [23], the time varying sliding surface is expressed as (9).

$$s = \dot{e}_1 + c_1 e_1 + \lambda(t), \tag{9}$$

where the function $\lambda(t)$ is $\lambda(t) = ae^{-bt}$. The coefficient a is chosen according to the condition that the initial condition is crossed by the sliding surface, and the exponent term b is defined as $b > 0$ [21]–[27]. The coefficient c_1 is denoted as $c_1 > 0$. In this work, Gamorski's reaching law [31] is applied, which basically reduces the magnitude of the SMC's switching gain. The proposed controller is designed using the following reaching law approach.

$$\dot{s} = -k_{sw}(1 - e^{-|s|/p})sign(s) \triangleq \Pi \tag{10}$$

where the exponent p is defined as $p > 0$. Substituting (9) into (10) yields.

$$\begin{aligned} &\ddot{e}_1 + c_1\dot{e}_1 + \dot{\lambda}(t) = \Pi \\ &f(x) + g(x)u(t) - \ddot{x}_{1r} - \ddot{z}_1 + c_1\dot{e}_1 + \dot{\lambda}(t) = \Pi. \end{aligned} \tag{11}$$

From (11) and (8), it can be obtained as (12).

$$f(x) + g(x)u - g(x)\Delta u - \ddot{x}_{1r} + c_{z1}(-c_{z1}z_1 + z_2) + c_{z2}z_2 + c_1\dot{e} + \dot{\lambda}(t) = \Pi \tag{12}$$

Based on the selected reaching law, the actual control input can be identified as (13).

$$f(x) + g(x)v - \ddot{x}_{1r} + c_{z1}(-c_{z1}z_1 + z_2) + c_{z2}z_2 + c_1\dot{e} + \dot{\lambda}(t) = \Pi \tag{13}$$

Thus, v can be determined as (15).

$$v = g(x)^{-1}\big(\Pi - [f(x) - \ddot{x}_{1r} + c_{z1}(-c_{z1}z_1 + z_2) + c_{z2}z_2 + c_1\dot{e} + \dot{\lambda}(t)]\big) \tag{14}$$

Substituting (10) into (14) yields.

$$\begin{aligned} v = g(x)^{-1}\big(&-k_{sw}(1 - e^{|s|/p})\mathrm{sign}(s) - [f(\mathrm{x}) - \ddot{x}_{1r} + c_{z1}(-c_{z1}z_1 + z_2) + c_{z2}z_2 + c_1\dot{e} - \\ &abe^{-bt}]\big), \end{aligned} \tag{15}$$

The (15) shows that the nominal control v contains several controller parameters including k_{sw}, p, c_{z1}, c_{z2}, c_1, and b. These parameters are specified by the designer.

2.2.2. Proof of stability

In this section, the stability property of the designed controller is analyzed. The stability of the control system can be conducted according to the defined Lyapunov function. The Lyapunov function is defined as (16).

$$V = \frac{1}{2}s^2 \tag{16}$$

The derivative of (16) can be obtained as (17).

$$\dot{V} = s\dot{s} \tag{17}$$

$$\begin{aligned}\dot{V} &= s\big(f(x) + g(x)u + d(t) - \ddot{x}_{1r} - [-c_{z1}(-c_{z1}z_1 + z_2) - c_{z2}z_2 + g(x)\Delta u] + c_1\dot{e} + \dot{\lambda}(t)\big)\\ &= s\big(f(x) + g(x)u - g(x)\Delta u + d(t) - \ddot{x}_{1r} + c_{z1}(-c_{z1}z_1 + z_2) + c_{z2}z_2 + c_1\dot{e} + \dot{\lambda}(t)\big)\\ \dot{V} &= s\big(f(x) + g(x)v + d(t) - \ddot{x}_{1r} + c_{z1}(-c_{z1}z_1 + z_2) + c_{z2}z_2 + c_1\dot{e} + \dot{\lambda}(t)\big)\end{aligned} \tag{18}$$

Substituting (15) into (18) yields that

$$\begin{aligned}\dot{V} &= s\Bigg(f(x) + g(x)\bigg\{g(x)^{-1}\bigg(-k_s(1 - e^{-\frac{|s|}{p}})sign(s) - [f(x) - \ddot{x}_{1r} + c_{z1}(-c_{z1}z_1 + z_2) + c_{z2}z_2\\ &\qquad + c_1\dot{e} + \dot{\lambda}(t)]\bigg)\bigg\} + d(t) - \ddot{x}_{1r} + c_{z1}(-c_{z1}z_1 + z_2) + c_{z2}z_2 + c_1\dot{e} + \dot{\lambda}(t)\Bigg)\\ &= s\big(f(\boldsymbol{x}) - k_{sw}(1 - e^{-|s|/p})sign(s) - [f(\boldsymbol{x}) - \ddot{x}_{1r} + c_{z1}(-c_{z1}z_1 + z_2) + c_{z2}z_2 + c_1\dot{e} + \dot{\lambda}(t)\\ &\qquad + d(t) - \ddot{x}_{1r} + c_{z1}(-c_{z1}z_1 + z_2) + c_{z2}z_2 + c_1\dot{e} + \dot{\lambda}(t)\big)\\ &= s(-k_{sw}(1 - e^{-|s|/p})sign(s) + d(t))\\ &= s(-k_{sw}(1 - e^{-|s|/p})sign(s) + sd(t))\\ &= -k_{sw}(1 - e^{-|s|/p})|s| + sd(t)\\ \dot{V} &\le -k_{sw}(1 - e^{-|s|/p})|s| + sD\end{aligned} \tag{19}$$

select $k_{sw} > D$

$$\dot{V} < 0 \tag{20}$$

According to the designed TVSMC controller, the derivative of the control Lyapunov function is negative as shown in inequality (20) [12]. Also, inequality (20) implies that the designed nominal control input v can stabilize the control system under the effect of control constraint. Once the condition is satisfied, the dynamic error converges to zero according to $\dot{e}_1 + c_1e_1 + ae^{-bt} = 0$ [23].

2.3. Controller parameter tunning via dragonfly algorithm

The MATLAB Simulink model is implemented to provide the optimal set of controller parameters for the heat exchanger system. The simulation returns the dynamic responses of both control effort and control output error to the calling function. The DA was employed since it is a reliable optimization algorithm that has been tested with several benchmark functions [60]. The DA algorithm's original MATLAB code has been slightly modified [60]. The schematic diagram of the modified DA algorithm is illustrated in Figure 2. The upper and lower bound of the controller parameters are specified in the DA algorithm's main script to provide the search space. The objective function for the DA algorithm is redefined to call the heat exchanger Simulink model with the set of controller parameters selectively provided by the DA algorithm function. In each step, the DA algorithm function selects the updated set of controller parameters in the provided search space by the normal DA updating algorithm. The DA function is intact, ie., the function has not been modified. The Simulink simulation returns the output error and control effort to the DA objective function at every time step. The sum of the square output errors and the sum of the square control effort at every time step are the multiple (two) objectives of the controller tuning. The two objectives are added together with a specific weight fraction, and then returned to the DA algorithm function. To share the tuning parameters, the controller parameter variables are defined as the MATLAB global variables inside both the DA objective function and the Simulink model callback functions (plant and controller).

By the DA algorithm, the controller parameters are optimally tuned to minimize the cost function defined as (21).

$$J = \int_0^t [w_1 e(\tau)^2 + w_2 u(\tau)^2] d\tau \quad (21)$$

where w_1 and w_2 are weighting coefficients. The controller parameters including k_{sw}, p, c_1 and b are considered as a set of optimization variables under the following constraints $0 \le k_{sw} \le k_{sw,max}$, $0 \le p \le p_{max}$, $0 \le c_1 \le c_{1,max}$, and $0 \le b \le b_{max}$.

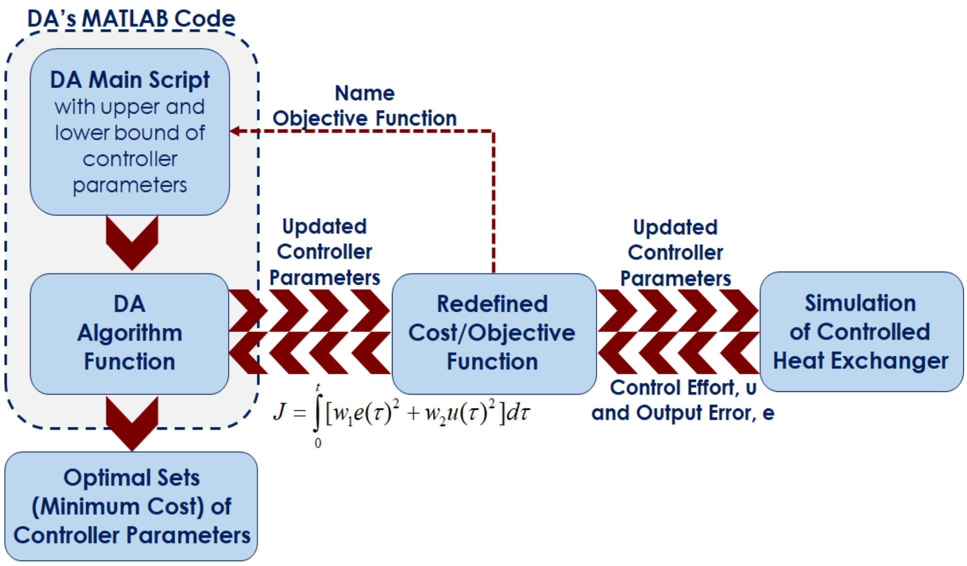


Figure 2. Tunning of controller parameters using DA

3. RESULTS AND DISCUSSION

This section comprises two parts. First, the designed controller was applied to the simulation example. Second, the controlled heat exchanger system under the designed controller was simulated. The simulation aims to assess the robustness and convergence capabilities of the proposed controller.

3.1. Simulation example

The heat exchanger with the system parameters shown in [4] is used to demonstrate the designed controller's functionality in this application. In Table 1, the system's numerical parameters are summarized. The control input (hot water's flowrate) is constrained as $0 \le u \le u_{max}$, where $U_{max} = 3000\ cm^3/min$. To investigate the robustness of the proposed controller, the bounded disturbances are introduced as $d(t) = 0.1\, sin\, 5\pi$ at $350 \le t \le 500$ seconds. The MATLAB application is used to simulate the control system from 0 seconds to 1,200 seconds with incremental times of 0.01 seconds.

Table 1. Summary table of the plate heat exchanger's numerical parameters [4]

Parameter	Value	Parameter	Value
T_{ci}	20 °C	ρ_c	1,000 kg/m^3
T_{hi}	80 °C	ρ_h	1,000 kg/m^3
U	300 W/m^3. °C	V_c	0.000537 m^3
A	0.0672 m^2	V_h	0.000537 m^3
$c_{p,c}$	4,180 J/kg. °C	U_c	150 cm^3/min
$c_{p,h}$	4,180 J/kg. °C		

3.2. Simulation results

To exhibit the controller's functionality, the controlled heat exchanger system is simulated. The DA algorithm described in section 2.3 is implemented to identify the optimal set of controller parameters for the designed control law. In the cost function (21), the weighting coefficients are expressed as $w_1 = 0.3$ and $w_2 = 0.7$. The upper bound constraints are set as $k_{sw,max} = 80$, $\sigma_{0,max} = 60$, $c_{1,max}$=15, and $B_{1,max}$=15. The number of agents and iterations for the DA tunning scheme is defined as 50 agents and 20 iterations, respectively. Consequently, the tunning scheme based on DA algorithm yields the optimal set of the controller parameters as k_{sw}=71.5615, p=57.3265, c_1=3.1369, and b=15. The plot of the cost function versus the iteration number is presented in Figure 3. All positive optimal controller parameters can stabilize the control system. Also, the cost function corresponding to the control effect and error is minimized. Note that, the cost function from the first iteration could be already small because the DA algorithm search for the optimal parameters (providing the smallest cost function) from the 50 (agents) random sets of parameters in the whole search space since the first iteration. In the next iterations, the algorithm searches another 50 random sets of the parameters in the narrow spaces around the previously found optimal parameters. To compare the convergence behavior of the proposed TVSMC approach, the quasi-sliding mode controller (QSMC) is introduced. The control input under the QSMC method without an auxiliary system is presented as (22):

$$u = g(x)^{-1}(-k_{sw}sat(s) - [f(x) - \ddot{x}_{1r} + c_1\dot{e} - abe^{-bt}]) \quad (22)$$

where the sliding surface is defined as $s = \dot{e}_1 + c_1 e_1$. To mitigate the chattering phenomenon's effects, the switching control is approximated by a saturation function with the value of $\Delta = 10{,}000$ as (23).

$$sat(s) = \begin{cases} 1, s > \Delta \\ k_{sw}s, |s| \leq \Delta, k_{sat} = 1/\Delta \\ -1, s > \Delta \end{cases} \quad (23)$$

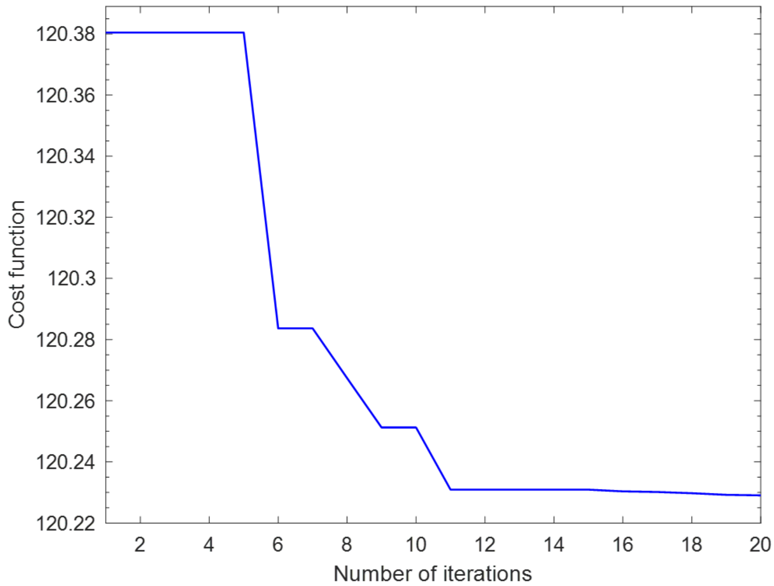
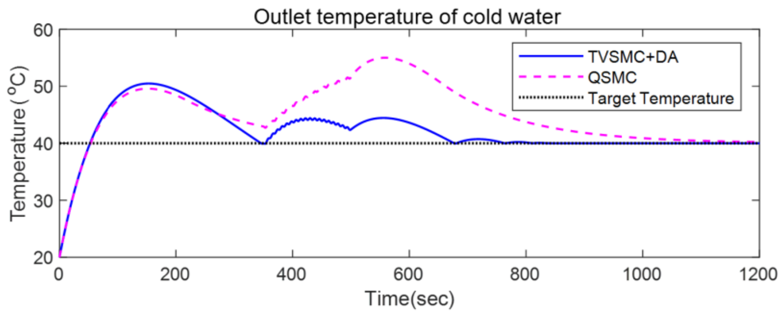
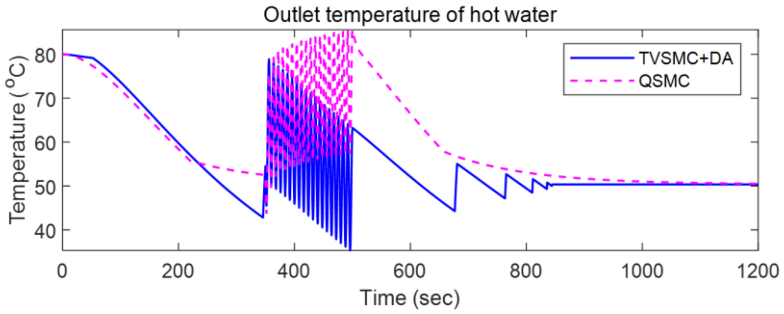


Figure 3. The plot the cost function versus number of iterations

Figure 4 shows the simulation results of the outlet temperature of the cold side as shown in Figure 4(a) and the hot side as shown in Figure 4(b) under the proposed time-varying sliding mode control (TVSMC) method with the optimal parameters given by the DA algorithm (TVSMC+DA) and the QSMC method. In Figure 4(a), as the objective is to regulate the outlet water temperature of the cold side to the desired temperature of 40 °C, both control techniques can regulate the temperature under the bound disturbance. However, the outlet temperature under the TVSMC+DA method can converge to the desired level faster than that of the QSMC method. Similarly, compared to the QSMC method, the outlet temperature of hot water controlled by the TVSMC+DA method performs a better convergence rate as presented in Figure 4(b). During the bound disturbance period (350 to 500 seconds), the TVSMC+DA method shows the ability to keep the marginal difference between the controlled temperature and the desired level. Figure 5 shows the input signal in the system which is the hot water's volumetric flow rate by using the TVSMC+DA as shown in Figure 5(a) and the QSMC method as shown in Figure 5(b). Using the QSMC method, the chattering phenomena exist in the control input. By applying the TVSMC+DA technique, chattering in the control input can be decreased. The decrease in chattering caused by the TVSMC is consistent with the findings conducted by Wang *et al.* [24].

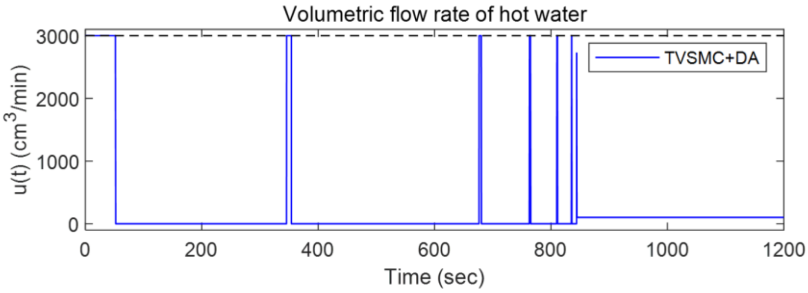


(a)

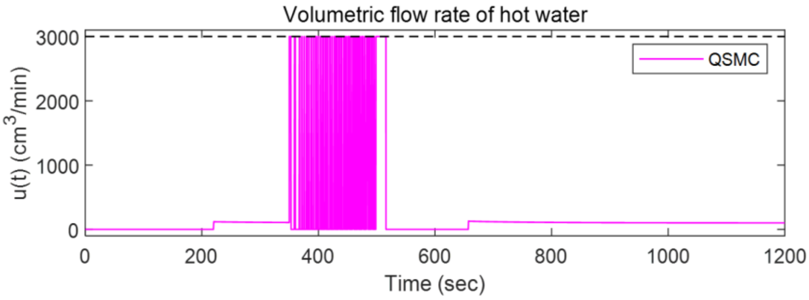


(b)

Figure 4. Time responses of the proposed TVSMC+DA and QSMC method for outlet temperature of (a) cold water and (b) hot water



(a)



(b)

Figure 5. Control signals of (a) TVSMC+DA method and (b) QSMC method

4. CONCLUSION

In this study, the TVSMC method is formulated for outlet temperature regulation of the plate heat exchanger system. To include the effect of input constraint, the auxiliary system is utilized in the controller design procedure. Moreover, the controller tuning parameters are optimized using the DA algorithm, with both the output error and the control effort as the multiple objectives. The bounded disturbances are applied to verify the proposed controller's robustness. In addition, the proposed control system is benchmarked against the QSMC method to assess its convergence behavior. The simulation results show that the designed TVSMC with the optimal parameters given by DA algorithm (TVSMC+DA) approach can drive the outlet temperature to the target under the bounded disturbances. Compared to the QSMC method, the outlet temperature under the TVSMC+DA method can converge to the desired level with faster rate. The proposed technique is robust to bounded disturbances and has the capability to enhance convergence properties. Additionally, the reduction of chattering in control input can be achieved.

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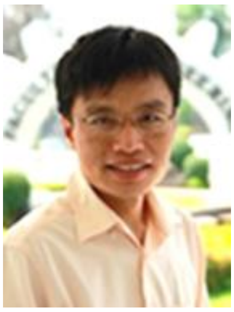

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