Output Feedback Adaptive Sliding Mode Control Design for a Plate Heat Exchanger

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Abstract
The heat exchanger is a device used to transfer heat energy between two fluids, hot and cold. In this work, an output feedback adaptive sliding mode controller is designed to control the temperature of the outlet cold water for plate heat exchanger. The measurement of the outlet cold temperature is the only information required. Hence, a sliding mode differentiator was designed to estimate the time derivative of outlet hot water temperature, which is needed for constructing a sliding variable. The discontinuous gain value of the sliding mode controller is adapted according to a certain adaptation law. Two constraints which imposed on the volumetric flow rate of outlet cold (control input) were considered within the rules of the proposed adaptation law in this work. These are the control input is a positive quantity, and it limited by a maximum value. The maximum allowable desired outlet cold water has been estimated as function of heat exchanger parameters and maximum control input. The simulation results demonstrate the performance of the proposed adaptive sliding mode control where the outlet cold water was forced to follow desired temperature equal to 45°. Additionally, the robustness of the proposed controller was tested for the case where the cold water inlet temperature is not constant, and also for the case of heat exchanger parameters uncertainty. The results were revealed the robustness of the proposed controller.

Keywords: Plate Heat Exchanger, Adaptive sliding mode control, Sliding mode differentiator.

1 Introduction
In the modern industrial engineering, plate heat exchanger takes an important role. It is the glossy device in controlling heat output from heating substation, especially for large scale zone heating system.

For plate heat exchanger processes, powerful control of plate heat exchanger is an indicator problem to improve its dynamic performance. To control the heat outputs to secondary networks in large scale district heating systems, plate heat exchangers are glossy components. By designing a powerful control for indicated heat exchanger, dynamic response will be developed and increases control system stability.

Several techniques have been developed in the literature to control of heat exchangers. For instance in [1], the robust model predictive control (MPC) with integral action was designed. To improve control functioning, two-degrees-of-freedom loop-shaping controller was worked out by [2] for plate heat exchanger depending on state space model. The control algorithm consists of an on-off type with hysteresis was proposed in [3]. It implemented with a PIC microcontroller and a relay as its actuator. In [4], a dynamic behavior identification of a through-flow heat exchanger was proposed and a self-tuning predictive was designed. The internal model based PID controller proposed in [5] to provide a satisfactory performance for the heat exchanger in both steady state and transient state. A simple bounded positive control system for heat exchangers was proposed by [6]. The controller does not need to feedback the whole state vector and additionally, the positivity and boundedness of the input flow rate was guaranteed. In [7] an approximate input-output linearizing feedback and an observer-based uncertainty estimator were used to design robust controller with uncertainty estimation for heat exchanger. The adaptive control with identification of a static behavior of a through-flow heat exchanger for its control was proposed by [8].

Sliding mode control (SMC) is a robust design methodology based on a systematic scheme ensures the attractiveness of a sliding manifold. During sliding motion, the system becomes invariant to system uncertainties and external disturbances. This is known as the invariance property, which represents the main advantage of sliding mode control. Conversely, the main disadvantage is the chattering problem. This can be overcome by suitable selection of the control gain. Of the pioneering method to reduce the dissentsious gain and attenuate chattering is the adaptive sliding control (ASMC) method. The ASMC consists of sliding mode controller and adaptive controller [9]. With the use of a sliding mode control system we can reduced the control...
effort by selecting a proper control gain related to the change of system parameters and uncertainty. An ASMC methodology that guarantees a real sliding mode controller only was proposed by [10]. The sliding mode controller was used by many authors to design robust controller to the heat exchanger system as in [11, 12, & 13].

The aim of the present work is to control the temperature of the outlet cold water. This consists of design an output state feedback ASMC, and a sliding mode differentiator to estimate the derivative of the outlet cold water.

2 Plate Heat Exchanger Mathematical Model

In Fig. (1), schematic diagram of the plate heat exchanger is depicted. It is incorporated of a mound of parallel thin plates which are assembled between heavy end plates. Where heat is exchanged through adjoining plates in the mound, cold and hot water proceed interchangeably between these plates. The control target is to accommodate the outlet cold water temperature, \( T_{co}(t) \), in order to retain this temperature as close as possible to the intended set point temperature.

\[ \dot{T}_{co}(t) = -k_1(T_{co}(t) - T_{ho}(t)) + \frac{U}{V_c} \left(T_{ci}(t) - T_{co}(t)\right) \]
\[ \dot{T}_{ho}(t) = -k_2(T_{ho}(t) - T_{co}(t)) + \frac{1}{V_h}(T_{hi}(t) - T_{ho}(t))u(t) \]  
(1)

where:
\( k_1 = UA/(C_{p,ho}V_h) \) and \( k_2 = UA/(C_{p,ho}V_h) \)

To this end, define the system states in terms of \( x_1 \) and \( x_2 \):
\[ x_1 = T_{co}(t) \]
\[ x_2 = T_{ho}(t) \]  
(2)

Hence, the plate heat exchanger dynamics, in terms of state variables \((x_1, x_2)\), is given by:
\[ \begin{aligned}
\dot{x}_1(t) &= -k_1(x_1(t) - x_2(t)) + \frac{U}{V_c}T_{ci}(t) - x_1(t) \\
\dot{x}_2(t) &= -k_2(x_2(t) - x_1(t)) + \frac{1}{V_h}(T_{hi}(t) - x_2(t))u(t)
\end{aligned} \]  
(3)

Additionally, and in order for the heat exchanger model to be more appropriate for control design, let:
\[ \begin{aligned}
z_1 &= x_1 \\
z_2 &= \dot{x}_1 = \dot{x}_1
\end{aligned} \]  
(4)

Eventually, with respect to the new states \((z_1, z_2)\) the heat exchanger model becomes:
\[ \begin{aligned}
\dot{z}_1 &= z_2 \\
\dot{z}_2 &= a x_1 + b x_2 + c(t) + g(x(t), u(t)) = f(t, x) + g(x(t), u(t))
\end{aligned} \]  
(5)

where:
\[ a = (k_1)^2 + 2k_1 \frac{U}{V_c} + k_1k_2 - \left( \frac{U}{V_c} \right)^2 \]
\[ b = (k_1)^2 - k_1k_2 - k_1 \left( \frac{1}{V_h} + \frac{U}{V_c} \right) \]
\[ f(x) = ax_1 + bx_2 - \left( \frac{k_1}{V_c} + \left( \frac{U}{V_c} \right)^2 \right)T_{ci}(t) + k_1 \frac{1}{V_h}T_{hi}(t) + \frac{U}{V_c}T_{ci}(t) \]
and \( g(x, t) = k_1 \frac{1}{V_h}(T_{hi}(t) - x_2) \).

Note that \( g(x, t) > 0 \forall x_2 \), since physically \( T_{hi}(t) > T_{ho}(t) \) \forall t. Also, this model will be considered uncertain. That is, the model parameters and inputs, \( a, b, c(t) \) and \( g(x, t) \), are uncertain but bounded by finite values.

In this work, the heat exchanger model is transformed, via Eq. (4) in Eq. (5), to a second order system. In sliding mode control, it is quite simple to derive the system state towards sliding...
manifold. However, for the heat exchanger application, there are two obstacles which prevent from designing the controller as in the usual case. The first obstacle is that the control input is positive only. That means the control action is from one side only, hence; it derive the state to the sliding manifold from one side only. In the other side of the sliding manifold, the attractiveness of the sliding manifold depends on inherent heat exchanger system dynamics. As a result, it is needed, from the control system designer, to prove the sliding manifold attractiveness for the open loop. Secondly, the volumetric flow rate of the hot water has a maximum value, which it named, in control theory, as control input saturation. The control design is accordingly semi-global, and again we need to show that when the state initiated outside the control area, it reenter this area, and then the control input direct the state to the sliding manifold.

The heat exchanger model, as given in Eq. (5), will be used in the next section to design a robust control system utilizing the theory of sliding mode control.

3 Sliding Mode Control

Physical systems are often subjected to model inaccuracies; these inaccuracies may come from un-modeled or neglected system dynamics, uncertainty in model parameters (i.e. deviation of the system parameters from actual values) and external disturbances. Many challenges will be arising when the physical system is uncertain, i.e., the model is uncertain and subjected to external disturbances. This may lead a non-satisfactory performance or even system instability. For this reason, when a control methodology considers the system uncertainty, it named as robust control. One these robust control methodologies, is the sliding mode control (SMC), which characterized by high simplicity and robustness [14].

4 Adaptive Sliding Mode Control Law

For application of sliding mode control, there exist two main obstacles. These are the chattering and large gain of control action. The magnitude of a discontinuous control is responsible of high amplitude of chattering. These two problem, which prevent using the SMC for many applications, can be solved if the discontinues gain is reduced to a minimum admissible value with preserving global or semi-global attractiveness of the sliding manifold.

Here an adaptation law will be utilized to adapt the gain of the SMC at minimum sufficient value. Using this gain, the chattering amplitude will be eliminated or reduced with minimum control effort.

Consider the following sliding mode controller in Eq. (6) with adaptive gain [15]

\[ u(s, t) = -k(t)\text{sign}(s(x, t)) \]  

where \( k(t) \) is the discontinuous gain which computed according to the following; let \( \epsilon \) be a small positive constant, then \( k(t) \) is determined as follows:

Set the initial value of \( \mu \) as \( \mu_{\text{initial}} = k \), then:

\[ \dot{\mu} = \rho \times |s(x, t)| \times \text{sign}(|s(x, t)| - \epsilon) \]  

After that \( k(t) \) is selected according to the following rules:

\[ k = \begin{cases} \\mu & \text{if } K_{\text{min}} < \mu < K_{\text{max}} \\ K_{\text{min}} & \text{if } \mu \leq K_{\text{min}} \\ K_{\text{max}} & \text{if } \mu \geq K_{\text{max}} \end{cases} \]  

where \( \rho > 0, \epsilon > 0, K_{\text{min}} < k(0) < K_{\text{max}}, K_{\text{min}} \) is the minimum possible value of \( k(t) \) and \( K_{\text{max}} \) it's maximum possible value.

Equations (7) and (8) represent the adaptation law for the SMC gain, which has been used in many applications as in [16, 17]. The adaptation law above will be used in section (5), after certain modification considering that the control action is a positive quantity.

5 Adoptive Sliding Mode Control Design

In this section, the adaptive sliding mode control for the plate heat exchanger is designed according to the previous section. In the first design step, the sliding variable is selected as:

\[ s = e_2 + \lambda e_1, \lambda > 0 \]  

where \( e_1 \) and \( e_2 \) are the error functions which are defined by:

\[ e_1 = z_1 - z_{1r} = T_{c0}(t) - T_{car}(t) \]  

\[ e_2 = z_2 - z_{2r} = \dot{T}_{c0}(t) - \dot{T}_{car}(t) \]  

Here \( T_{car}(t) \) is the desired outlet cold temperature, while \( \dot{T}_{car}(t) \) is its time derivative.

According to the SMC theory, the control task is to direct the state trajectory (the error state \((e_1, e_2)\)) to the sliding manifold. This will be done in finite time. After the state reaches the sliding manifold, the error dynamics becomes;

\[ e_2 + \lambda e_1 = 0 \]  

The error \( e_1 \) goes to zero asymptotically, i.e., \( e_1 \to 0 \), as \( t \to \infty \).

Now let the sliding mode control law is given by;
\[ u = k(t) \cdot \Gamma(s) \]  
(12)

where \( \Gamma(s) \) is a discontinuous function, given by:
\[
\Gamma(s) = \begin{cases} 
0 & \text{if } s > 0 \\
1 & \text{if } s \leq 0
\end{cases}
\]  
(13)

and \( k(t) \) is the discontinuous gain, with its value adapted according to the following law;
\[ \dot{\mu} = \rho \cdot |s(x,t)| \cdot \Gamma(s) \cdot \text{sign}(|s(x,t)| - e) \]  
(14)

After that, \( k(t) \) is selected according to the following rules;
\[
k = \begin{cases} 
\mu & \text{if } 0 < \mu < u_{\text{max}} \\
u_{\text{max}} & \text{if } \mu \geq u_{\text{max}} \\
0 & \text{if } \mu < 0
\end{cases}
\]  
(15)

where \( u_{\text{max}} \) is the maximum volumetric flow rate of the hot water value.

5.1 Maximum Allowable Desired Outlet Cold Water Estimation

In this section the maximum allowable desired outlet cold water \( T_{\text{cor-max}}(t) \) will be estimated. The \( T_{\text{cor-max}}(t) \) can be estimated by solving Eq. (1) for the case where steady state conditions hold. That means by equating
\[ T_{\text{cor}}(t) = T_{\text{ho}}(t) = 0 \]

Then solve for \( T_{\text{cor}}(t) \) in terms of heat exchanger parameters, hot and cold inlet water temperatures, and \( u_{\text{max}} \). According to above, we have:
\[
-k_1(T_{\text{cor}}(t) - T_{\text{ho}}(t)) + \frac{U_c}{V_c}(T_{\text{ci}}(t) - T_{\text{cor}}(t)) = 0

-k_2(T_{\text{ho}}(t) - T_{\text{cor}}(t)) + \frac{1}{V_h}(T_{h_i}(t) - T_{ho}(t))u_{\text{max}} = 0
\]

The solution in matrix form is:
\[
\begin{bmatrix} T_{\text{cor-max}} \\ T_{\text{ho-max}} \end{bmatrix} =
\begin{bmatrix} k_1 + \frac{U_c}{V_c} \\ -k_2 \end{bmatrix}^{-1}
\begin{bmatrix} 
\frac{U_c}{V_c} & 0 \\
-k_2 & \frac{u_{\text{max}}}{V_h}
\end{bmatrix}
\begin{bmatrix} T_{\text{ci}}(t) \\ T_{h_i}(t) \end{bmatrix}
\]  
(16)

As can be seen from Eq. (16), \( T_{\text{ho-max}} \), which is the maximum outlet hot temperature, is estimated too. The numeric values for \( T_{\text{cor-max}} \) and \( T_{\text{ho-max}} \) will be presented in section (7) below.

6 State Differentiator Design

In Eq. (12), the proposed control law assumes that the state variables \( z_1 \) and \( z_2 \) are available. The first state \( z_1 \) is available since it represents the \( T_{co}(t) \), which is the measured outlet cold water temperature. The second state \( z_2 \) is the time derivative of \( z_1 \). Hence, we need to obtain it using an observer. A robust sliding mode differentiator (SMD) is proposed here to get \( z_2 \) by knowing only \( z_1 \). The sliding mode differentiator is given by [18]:
\[
s = z_1 - \eta
\]
\[
\dot{\eta} = \alpha \cdot \tan^{-1}(\gamma z_1)
\]
\[
\tau \dot{\psi} + \nu = \alpha \cdot \tan^{-1}(\rho z_1)
\]
(17)

where \( s \) is the SMD variable, \( \alpha \) and \( \rho \) are differentiator parameters. The third equation in (17), \( \tau \dot{\psi} + \nu = \alpha \cdot \tan^{-1}(\rho z_1) \), is a low pass filter (LPF) with time constant \( \tau \), where the output of the LPF, \( \nu \), is the estimated derivative of \( z_1 \).

According to [18], the bound on the steady state estimation error is given by:
\[
|\nu(t) - z_2| \leq \frac{2 \tan(\frac{\pi}{2}h)}{\tau p}
\]
(18)

where \( h = \sup|e_1| \). Utilizing the output of the SMD, accordingly; the sliding variable \( s \) becomes;
\[
s = e_2 + \lambda e_1 = (z_1 - z_{1r}) + \lambda(v - z_{2r})
\]
(19)

In the following section, the proposed SMC in Eq. (12) with the sliding variable \( s \) will be applied to the heat exchanger control system. The block diagram, that depicts the feedback control system for the heat exchanger, is shown below in Fig. (2).

![Figure 2: Block Diagram for the ASMC.](image)

7 Result and Discussion

In this section the results of the numerical simulations for the heat exchanger control system are presented. The parameters that were used in the simulations are shown in Table 1, while the SMC and SMD parameters, are given in Table 2.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0.0672 m²</td>
</tr>
<tr>
<td>C_{p,h}</td>
<td>4180 J/kg°C</td>
</tr>
<tr>
<td>C_{p,c}</td>
<td>4180 J/kg°C</td>
</tr>
</tbody>
</table>
\[ \rho_h = 1000 \, kg/m^3 \]
\[ \rho_c = 1000 \, kg/m^3 \]
\[ U = 300 \, W/m^3\cdot C^o \]
\[ U_c = 150 \, cm^3/min \]
\[ V_c = 5.37 \times 10^{-4} \]
\[ V_h = 5.37 \times 10^{-4} \]
\[ T_{ci}(t) = 20 \, C^o \]
\[ T_{hi}(t) = 80 \, C^o \]
\[ u_{max} = 280 \, cm^3/min \]

**Table 2: SMC and SMD parameter values.**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \lambda )</td>
<td>1</td>
</tr>
<tr>
<td>( \rho )</td>
<td>1</td>
</tr>
<tr>
<td>( \varepsilon )</td>
<td>0.005</td>
</tr>
<tr>
<td>( \alpha )</td>
<td>1</td>
</tr>
<tr>
<td>( \gamma )</td>
<td>100</td>
</tr>
<tr>
<td>( \tau )</td>
<td>0.05</td>
</tr>
</tbody>
</table>

As it is well known, the discontinuous control induces chattering in control system response. To eliminate chattering, the following approximation is used for \( \Gamma(s) \):

\[
\Gamma(s) = \begin{cases} \frac{1}{2} & \text{if } s > 0 \\ \frac{1}{s} \cdot \tan^{-1}(\beta|s|) & \text{if } s \leq 0 \end{cases} \tag{20}
\]

where \( \beta = 50 \). The SMC, that will be used in the present simulations, uses is given by the following control law:

\[
u = k \cdot \Gamma(s) \tag{21}\]

The SMC and SMD, which will be used in the present work, are given in Eq. (21) and Eq. (17) respectively. In addition, from Eq. (16), the maximum allowable desired outlet cold water and the maximum outlet hot temperature are obtained as \( T_{cor-max} = 49.2^o \) and \( T_{ho-max} = 64.35^o \) respectively.

Figure (3) shows the outlet hot and cold water, where the desired outlet cold temperature \( T_{cor}(t) = 45^o < T_{cor-max} \). In addition the outlet hot water temperature is plotted, where it can be seen that its value is decreased as a result of transferring heat to the cold water. The volumetric flow rate of the hot water \( u(t) \) and the adapted discontinuous gain \( k(t) \) are depicted in Fig. (4) and Fig. (5) respectively. The control input \( u(t) \) forces the outlet cold temperature \( T_{co}(t) \) to follow the desired temperature in about 300 sec. This was done as follow; first the sliding variable \( s \) is first regulated to the sliding manifold \( s = 0 \) in about 200 sec. (Fig. (6)), after that \( T_{co}(t) \) is asymptotically converges to \( T_{cor} \) as shown in Fig. (3). Finally, the phase plot is shown in Fig. (7), where the state slides along the sliding manifold until it reaches the invariant set around the desired point. The state will stay there for all future time. As in [19], the invariant set size is function to \( \beta \), in \( \Gamma(s) \), and \( u_{max} \). Increasing \( \beta \) and \( u_{max} \) will decrease the steady state error. The steady state error, as can be seen from Fig. (7), is \( |T_{co}(t) - T_{cor}(t)| < 0.5^o \).
z₂ is shown in Fig. (8) in addition to the actual value of z₂. The plotted result in this figure, shows clearly the ability of the SMD in estimating the derivative of z₂ in presence of the uncertainty in heat exchanger model.

![Figure 8: Actual and Estimated Derivative of T_co.](image)

Eventually, the simulation was repeated but with the inlet cold water is not constant; instead it is given by \( T_{ci}(t) = 20 + 3 \times \sin \left( \frac{30t}{2\pi} \right) \), where \( 3 \times \sin \left( \frac{30t}{2\pi} \right) \) is regarded as a disturbance. The result, which is plotted in Fig. (9), demonstrated clearly the robustness of the proposed SMC, where the \( T_{co}(t) \) converges, as in the previous result, to 45°C with small assoliation of amplitude less than 0.2°C. Additionally, the robustness was examined again when the some of the heat exchanger parameters are changed. In Fig. (10), the outlet cold and hot water are plotted where the heat transfer coefficient \( U \) and the fixed volumetric flow rate of cold water \( U_c \), which are used in the simulation, are taken equal to 265 W/m²°C and 170 cm³/min respectively. As can be seen, the outlet cold water reaches 45°C as in Fig. (3), where \( U = 300 \) W/m²°C and \( U_c = 150 \) cm³/min.

![Figure 9: Outlet Cold and Hot Water Temperatures.](image)

![Figure 10: Outlet Cold and Hot Water Temperatures with Uncertainty in Model Parameters.](image)

8 Conclusions

The adaptive sliding mode control was effectively applied to the heat exchanger system. The heat exchanger model has been transformed first to a second order system, considering the outlet cold water \( T_{co}(t) \) as the first state, while its derivative considered as the second state. Utilizing \( T_{co}(t) \) as the only measured or given state, the sliding mode differentiator was used to robustly estimate the second state. Using the measured and the estimated states, the sliding variable, accordingly; was constructed.

The proposed controller was discontinuous, since the control input is a positive value only. To eliminate chattering the proposed SMC was approximated according to Eq. (20).

The simulation results, which have been done using Matlab software, demonstrated the robustness and performance of the proposed SMC, where the \( T_{co}(t) \) forced to follow the desired temperature as shown in Fig. (4) in spite of the uncertainty in heat exchanger model. Additionally, the output of the SMD was compared with actual derivative of \( T_{co}(t) \), and the result showed it was very close to the actual value as was clarified in Fig. (6), and less than the given bound in Eq. (18). Eventually, by disturbing the heat exchanger model with a siniosidal perturbation to the inlet cold water, and by changing the heat transfer coefficient \( U \) and the fixed volumetric flow rate of cold water \( U_c \), the results, which are plotted in Fig. (9) and Fig. (10), validate the robustness of the proposed controller.

References


صمم مسيطر متكيف ذو شكل منزلق لتبادل حراري صفائح

الخلاصة

التبادل الحراري هو جهاز يستخدم لنقل الطاقة الحرارية بين سائلين ، حار وبارد. في هذا العمل ، تم تصميم مسيطر متكيف ذو الوضع المنزلق من أجل التحكم في درجة حرارة ملفت مبادل حراري. تم تكييف قيمة معامل الشكل المنزلي وفاصلي قانون التكيف مع دورة التحكم الخاصة. تم استخدام المعادلات الحجمية للعوامل المختلفة لتقييم الحمل الحراري. تم اتخاذ مجموعة من القياسات اللازمة للمراقبة والتحكم في مبادل حراري. تم استخدام نظام التحكم المستمر لتحديد القيم المطلوبة في جهاز التحكم. تم قياس درجة الحرارة داخل مبادل الحراري وتم قياس درجة الحرارة المطلوبة. تم تحديد درجة الحرارة المطلوبة وتم قياس درجة الحرارة داخل مبادل الحراري. تم تحديد درجة الحرارة المطلوبة وتم قياس درجة الحرارة داخل مبادل الحراري. تم تحديد درجة الحرارة المطلوبة وتم قياس درجة الحرارة داخل مبادل الحراري. تم تحديد درجة الحرارة المطلوبة وتم قياس درجة الحرارة داخل مبادل الحراري. تم تحديد درجة الحرارة المطلوبة وتم قياس درجة الحرارة داخل مبادل الحراري. تم تحديد درجة الحرارة المطلوبة وتم قياس درجة الحرارة داخل مبادل الحراري. تم تحديد درجة الحرارة المطلوبة وتم قياس درجة الحرارة داخل مبادل الحراري. تم تحديد درجة الحرارة المطلوبة وتم قياس درجة الحرارة داخل مبادل الحراري. تم تحديد درجة الحرارة المطلوبة وتم قياس درجة الحرارة داخل مبادل الحراري. تم تحديد درجة الحرارة المطلوبة وتم قياس درجة الحرارة داخل مبادل الحراري. تم تحديد درجة الحرارة المطلوبة وتم قياس درجة الحرارة داخل مبادل الحراري. تم تحديد درجة الحرارة المطلوبة وتم قياس درجة الحرارة داخل مبادل الحراري. تم تحديد درجة الحرارة المطلوبة وتم قياس درجة الحرارة داخل مبادل الحراري. تم تحديد درجة الحرارة المطلوبة وتم قياس درجة الحرارة داخل مبادل الحراري. تم تحديد درجة الحرارة المطلوبة وتم قياس درجة الحرارة داخل مبادل الحراري. تم تحديد درجة الحرارة المطلوبة وتم قياس درجة الحرارة داخل مبادل الحراري. تم تحديد درجة الحرارة المطلوبة وتم قياس درجة الحرارة داخل مبادل الحراري. تم تحديد درجة الحرارة المطلوبة وتم قياس درجة الحرارة داخل مبادل الحراري. تم تحديد درجة الحرارة المطلوبة وتم قياس درجة الحرارة داخل مبادل الحراري. تم تحديد درجة الحرارة المطلوبة وتم قياس درجة الحرارة داخل مبادل الحراري. تم تحديد درجة الحرارة المطلوبة وتم قياس درجة الحرارة داخل مبادل الحراري. تم تحديد درجة الحرارة المطلوبة وتم قياس درجة الحرارة داخل مبادل الحراري. تم تحديد درجة الحرارة المطلوبة وتم قياس درجة الحرارة داخل مبادل الحراري. تم تحديد درجة الحرارة المطلوبة وتم قياس درجة الحرارة داخل مبادل الحراري. تم تحديد درجة الحرارة المطلوبة وتم قياس درجة الحرارة داخل مبادل الحراري. تم تحديد درجة الحرارة المطلوبة وتم قياس درجة الحرارة داخل مبادل الحراري. تم تحديد درجة الحرارة المطلوبة وتم قيас