Research on Industrial Control Technology of Hydraulic Stability of Condensing Unit on Ethanol Distillation Tower

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Abstract. Aiming at the problem that the hydraulic pressure of the condensing control device at the top of the ethanol rectification tower is unstable, which affects the efficiency of chemical production, a strategy for controlling the hydraulic stability by controlling the nozzle opening time is proposed. Firstly, the functional relationship between elastic modulus and pressure is obtained by polynomial interpolation fitting. Then, based on the Navier-Strokes fluid theory, the differential equation of density of the condensate and the continuous equation of flow are obtained. From the static and dynamic perspectives, the goal planning based on the concept of least squares is traversed to obtain the optimal check valve opening time. A simulation experiment with a standard value of 100 MPa was used to obtain the optimal solution of 0.308 ms, and a comparison experiment was performed to verify the accuracy and rationality of the solution.

1. Introduction
In the industrial design of the ethanol distillation tower, the effective control of the pressure and temperature is an important means to effectively remove product impurities [1]. At present, the commonly-used condensation control device is an air cooler, which is composed of multiple condensing pipes, and uses the principle of heat exchange to cool the hot matter in the pipes [2].

Aiming at this condensation process, Geng S.Y. [3] proposed the application of steam condensate and analyzed the applicability of other condensates. In order to improve the cooling effect of the air cooler at high temperature, Li Yan et al. [4] introduced the \textit{Atomization Nozzle} to transform the dry air cooler into a dry-wet hybrid air cooler. However, the condensate must be atomized under a certain hydraulic pressure, and pumping the condensate into the high-pressure condensate tube and then spraying it from the nozzle is an intermittent working process, which will change the pressure in the tube, so the amount of liquid ejected from the nozzle will be uneven, which in turn affects the efficiency of condensation control [5]. For industrial production, the stability of process control often determines the ability of cost control, and thus determines whether the technology can be applied on a large scale [6]. Therefore, it is necessary to study the stability control of the spray pressure of the condenser of the air cooler.
On the other hand, in the existing studies, most scholars focus on improving the efficiency and reducing the cost through the design of air cooler equipment [7] and the selection of condensate. Few people have studied the pressure control strategy of the condenser tube nozzle in the air cooler to do the work. Based on the basic principles of the Navier-Stokes equation, a continuous differential equation for the flow in the tube is derived, and four critical constraints are employed. Having taken all the aspects into consideration, a target planning model based on the least squares idea is established. The optimal solution of the nozzle opening time is found by traversal. The fluctuation of the pressure of the condensing pipe is minimized within the required range, and verification experiments are performed to provide a reference for the application research of stability control in the field of chemical production.

2. Hydraulic Stability Control Theory
The change in liquid pressure has a great correlation with the elastic modulus of the liquid. In this section, firstly, based on the collected data on the relationship between the elastic modulus and the pressure, a polynomial interpolation fitting method is used to obtain the expression of the elastic modulus about the pressure. The density differential equation and the continuous flow equation of the condensate in the tube are reasonably derived. Since the strong stability control of the condensing pipe spray pressure is also directly related to the opening time of the condensing pipe nozzle, this section builds a target planning model based on the least squares idea based on the above theoretical equations, the optimal solution of nozzle switching time under different conditions was obtained by traversing.

2.1. Polynomial interpolation fitting
The cftool toolbox in MATLAB software was employed to fit the pressure (Independent Variable) and elastic modulus (Dependent Variable) to obtain the primary and secondary fitting curves, as shown in figure 1.

![Figure 1](image_url)

Figure 1. Polynomial interpolation fitting curve: (a) One-time fitting curve; (b) Quadratic fitting curve.

Obviously, the \( R^2 = 0.9991 \) of the quadratic fit is closer to 1 than the \( R^2 = 0.9714 \) of the first fit, and the values of the sum of the squared error and the root mean square error of the quadratic fit are much smaller than the first-order form, so the quadratic function fit form is closer. Therefore, we get the expression of elastic modulus with respect to pressure as:

\[
E = 0.02893P^2 + 3.077P + 1572
\]  

(1)
2.2. Condensate density differential equation
The pressure change of the condensate is proportional to the change of its density [8]. According to this theory, the differential equation of the condensate with respect to the pressure can be listed, and the expression of the condensate density with respect to the pressure is obtained. Based on the Navier-Stokes equation, the condensate is analyzed from the static and dynamic angles, and the continuous equation of the condensate flow is derived.

In any unit volume, the pressure change is proportional to the density change, and the proportionality coefficient is \( E/\rho \), whose expression and differential form are listed as equation (2).

\[
\frac{\Delta P}{\Delta \rho} = \frac{E}{\rho} \rightarrow \frac{\Delta P}{E} = \frac{\Delta \rho}{\rho} \rightarrow \frac{dP}{E} = \frac{d\rho}{\rho}
\]

(2)

Among them, \( \Delta P \) indicates the change in pressure of the condensate per unit volume, \( \Delta \rho \) is the change in density of the condensate, \( \rho \) is the density of the condensate, and \( E \) is the elastic modulus. Substituting the functional expression of the elastic modulus with respect to the pressure into the above formula, the following differential equations regarding the hydraulic pressure and density of condensation are obtained:

\[
\frac{dP}{a_1P^2 + a_2P + a_3} = \frac{d\rho}{\rho}
\]

(3)

, and \( a_1, a_2, a_3 \) are the fitting equation coefficients. According to the solution results of the previous part, they are 0.02893, 3.077 and 1572 respectively. Then, integrate equation (3) as follow:

\[
\int \frac{dP}{a_1(P + \frac{a_2}{a_3})^2 + a_3} = \int \frac{d\rho}{\rho}
\]

(4)

Furthermore, Fourier integral transform formula is employed to solve this binary differential equation [9], and equation (5) can be obtained.

\[
\frac{1}{\sqrt{a_1(a_3 - \frac{a_2^2}{4a_3})}} \text{arc tan} \left( \frac{a_3 - \frac{a_2^2}{2a_3}}{a_3 - \frac{a_2^2}{4a_3}} \right) = \ln \rho + c
\]

(5)

Therefore, the density formula of the condensate can be finally derived as:

\[
\rho = e^x
\]

\[
x = \frac{1}{\sqrt{a_1(a_3 - \frac{a_2^2}{4a_3})}} \text{arc tan} \left( \frac{a_3 - \frac{a_2^2}{2a_3}}{a_3 - \frac{a_2^2}{4a_3}} \right) - c
\]

(6)

The example simulation experiments show that when the pressure is 100 MPa, the density of the condensate is 0.850 mg/mm^3, which means \( P_0 = 100 \text{MPa} \) and \( \rho_0 = 0.0859 \text{mg/mm}^3 \), and the unknown parameter \( c \) in equation (6) is 0.2529.

2.3. Condensate flow continuity equation
The internal structure of the condensate tube is analysed firstly. As shown in figure 2, the condensate can only enter and exit the condensate tube through the pump inlet and the nozzle. To maintain the
flow balance in the condensate tube, the difference between the condensate tube and its external liquid exchange must be within a certain range. Inside. In addition, since most condensate is a compressible viscous fluid, there is a Common Rail Effect [10], that is, the pressure inside the condenser tube is basically constant. However, because the high-pressure condensate is input to the pump inlet and the condensate is output at a relatively low pressure from the nozzle, the condensate is analyzed from a microscopic perspective. When it is small enough in figure 2, the pressure at the condensate boundary in this area can be considered. It is different, that is, small changes will occur. It can be inferred that the change of pressure in general will also affect the amount of condensate input.

Figure 2. Schematic diagram of the relationship between the amount of liquid condensate in the condensate tube and the flow equilibrium: (a) Schematic diagram of the change in the amount of liquid; (b) Schematic diagram of the relationship between flow equilibrium.

Thus, condensate flow rate in the tube is the key to solve the condensing pressure change in the condensing tube. Based on the basic principle of the Navier-Stokes equation for viscous compressible fluids, a continuous equation for the flow of condensate in a condensing tube can be derived.

2.3.1. Navier-Stokes equation. The Navier-Stokes equation is an equation used to describe fluid motion and can be regarded as Newton’s second law of fluid motion. It consists of three parts: conservation of continuity, conservation of energy and conservation of momentum. Continuity conservation plays a leading role in the fluid movement in the condenser tube studied in this paper [11]. With m as the boundary mass of the condensate flowing into the volume unit, the continuity conservation equation can be expressed as

$$\frac{dm}{dt} = \sum \text{m}$$

2.3.2. Static analysis of condensate flow. Due to the Common Rail Effect inside the condenser tube, the change in the volume and mass of the fluid due to the pressure can be ignored for the condensate flow rate change in the condenser tube. Therefore, the flow rate of condensate sprayed by the nozzle during a spraying cycle is the same as the mass (volume) of the condensate provided by the nozzle opening during a liquid supply cycle, that is $Q_{\text{in}} = Q_{\text{out}}$, $Q_{\text{out}}$ is the condensate flow rate from the nozzle and $Q_{\text{in}}$ is the condensate flow rate provided by the nozzle opening, between which the relationship is expressed as follows.

$$\frac{t_{\text{in}} \times Q_{\text{in}}}{t_{\text{in}} + 10} = \frac{10 \times Q_{\text{out}}}{100}$$

Among them, $t_{\text{in}}$ represents the working time of the nozzle; $Q_{\text{out}}$ can be obtained from the liquid ejection rate curve, and its value is the area between the liquid ejection rate curve and the X-axis; the working time of the liquid ejecting nozzle is 100 ms. Because this method is only suitable for the case
where the pressure change is 0, the dynamic analysis method is used in the next section to analyze the
general situation when the pressure change is not 0.

2.3.3. Study on the change of condensate flow rate based on microelement method. According to the
idea of the microelement method, we divide the condensate into countless small squares, and study the
relationship between the quality of each micro-element, as shown in figure 3.

![Figure 3. Mass flux of microelements and their surfaces.](image)

In figure 3, the yellow arrows indicate the mass of the condensate flowing into the microcell per
unit time, and the blue arrows indicate the mass of the condensate flowing out of the microcell per unit
time. Taking the X-axis as an example, the condensate inflow and outflow speeds are expressed as follows:

\[
\rho v_x \frac{dy dz dt}{dx} \left[ \rho v_x + \frac{\partial (\rho v_x)}{\partial x} dx \right] dy dz dt = -\frac{\partial (\rho v_x)}{\partial x} dx dy dz dt
\]  

(9)

It can be concluded that the quality of the input and output of the entire hexahedron within \( dt \) is
different:

\[
- \left[ \frac{\partial (\rho v_x)}{\partial x} + \frac{\partial (\rho v_y)}{\partial y} + \frac{\partial (\rho v_z)}{\partial z} \right] dx dy dz dt = \frac{\partial \rho}{\partial t} dx dy dz dt
\]  

(10)

Its vector form is:

\[
\nabla (\rho \vec{v}) + \frac{\partial \rho}{\partial t} = 0
\]  

(11)

which means the algebraic sum of the mass difference between the input and output of the
condensate flowing through a unit volume in a unit time and its internal mass change is 0.

2.3.4. Solution of condensate flow continuity equation. According to the above analysis, in order to
maintain pressure balance in the condenser, it is necessary to keep the amount of condensate input the
same as the sum of the amount of condensate compression change and the amount of condensate
ejection, among which the relationship is shown in figure 4.

![Figure 4. Equilibrium structure when condensate flows in the tube.](image)
At time $t + \Delta t$, the relationship of liquid balance in the high-pressure pipe is

$$Q_{in} = Q_{cg} + Q_{out}$$

$Q_{in}$ is the instantaneous pressure of the liquid supply port, $Q_{out}$ is the instantaneous flow rate through the nozzle, and $Q_{cg}$ is the rate of change of the compressed liquid volume due to the change in the pressure inside the condenser tube, which can be calculated as

$$Q_{cg} = \frac{V}{E} \cdot \frac{dP}{dt}$$

Among them, $u$ represents the flow rate of condensate, $A$ represents the cross-sectional area of the flow, and the subscripts $in$ & $out$ represent the inflow and outflow respectively; $V$ is the volume of the condenser, $E$ is the elastic modulus, and $P$ is the pressure inside the condenser. Above all, formula of pressure change in high-pressure condensing tube is showed as equation (13).

$$\frac{dP}{dt} = \frac{E}{V} (Q_{in} - Q_{out})$$

### 2.4. Objective planning model for determining the opening time of the condenser nozzle

Controlling the pressure stability of the condensing tube spray liquid is directly affected by the opening time of the condensing tube nozzle. Below we solve the nozzle opening time. According to the formula deduced previously, first traverse all possible opening durations, and then use the idea of least squares to find the pressure change in the tube under different conditions for a certain time, and finally find the pressure change range from all the results of the traversal the minimum time is the optimal solution for the nozzle opening time.

#### 2.4.1. Goal planning model based on least squares

In order to limit the fluctuation of the spray pressure above and below the standard pressure value, this section adopts the idea of least squares, uses the minimum sum of the square of the difference between the pressure value and the standard value as the objective function, and uses the step length of the traversal time as the constraint condition to establish the model. Find the optimal time for nozzle opening.

- **Objective function**

  Using the idea of least squares, within a certain time range, the pressure value of the condenser tube at different time lengths is obtained, and the square sum of the difference between the pressure value and the standard value is minimized. The objective function is as follows:

  $$\min \sum_{i=0}^{10} (P_i - P)^2$$

  in which the $P_i$ represents the pressure in the high-pressure pipe when the nozzle opening time is $i$, and $P = 100 MPa$.

- **Constraints**

  | Constraint I | Liquid supply switch working time limit. |
  | Constraint II | Observation time limit. |
  | Constraint III | Pump inlet working time limit. |
  | Constraint IV | Nozzle working time limit. |

  Above all, the target planning model for determining the opening time of the condenser nozzle is showed as equation (15).
\[
\min \sum_{i=0}^{10} (P_i - P)^2
\]
\[
\begin{align*}
0 \leq t & \leq 10 \\
0 \leq t_i & \leq 15000 \\
Q_{out} & \neq 0, \quad 0 \leq t_i \% (t + 10) \leq t \\
Q_{out} & = 0, \quad \text{else} \\
Q_{out} & \neq 0, \quad 0 \leq t_i \% 100 \leq 2.4 \\
Q_{out} & = 0, \quad \text{else}
\end{align*}
\]

(15)

The nozzle works 10 times per second, that is, the working cycle of the nozzle is 100 ms. It can be known from the spraying rate curve of the nozzle that the working time of the nozzle is 2.4 ms.

3. Hydraulic Stability Control Simulation Results

With MATLAB software, the nozzle opening time that makes the condensing hydraulic pressure in the high-pressure pipe with the smallest fluctuation around 100 MPa is 0.308 ms, and an image of the pressure change in the condensing pipe when the time is 0.308 ms is obtained.

![Figure 5](image)

Figure 5. Curve of the pressure in the condensing tube with time and the correctness verification experiments when the nozzle opening time is different: (a) Curve of the pressure in the condensing tube when the observation time is 15000 ms; (b) Curve of the pressure in the condensing tube when the observation time is 1500 ms; (c) The curve of the pressure in the condensing tube when the nozzle opening time is 0.298 ms; (d) Change curve of the pressure in the condensing tube when the nozzle opening time is 0.318 ms.

When the nozzle opening time is 0.308 ms, the absolute error value is 6.607 MPa, that is, the average fluctuation value of the pressure distance in the condensing tube after the plateau is 100 MPa is 6.607 MPa.
Based on the above experiments, the correctness of the results has also been tested with changing the nozzle opening time. Take the nozzle opening time as 0.298 ms and 0.318 ms respectively, which is the relative optimal solution 0.318ms floats 0.01ms up and down. Observe the pressure in the condensing tube to verify whether the nozzle opening time 0.318 ms is the optimal solution or not.

When the nozzle opening time is 0.298 ms, the absolute error is 6.875 MPa, and the pressure variation range is 85-115 MPa. When the nozzle opening time is 0.318ms, the absolute error is 8.457MPa, and the pressure fluctuation range is between 90-120 MPa. Obviously, the fluctuation range is larger than the optimal solution range.

In summary, the nozzle opening time of 0.308 ms is the optimal solution to stabilize the pressure in the condensing tube at about 100 MPa.

4. Conclusion
This paper explores the hydraulic stability control strategy of the ethanol distillation tower condensing device. Based on the Navier-Strokes fluid theory, the equilibrium equation of the high-pressure condensate flow change is obtained, and the condensate density differential equation and continuous flow equation are derived. And the method of combining static analysis and dynamic analysis is used to make the research more universal from special to general. The goal planning based on the least squares idea can more accurately solve the nozzle opening time with the smallest fluctuation of the spray pressure within the standard pressure range. Finally, through comparative experiments, the proposed model has higher accuracy and applicability. However, because the current hydraulic stability control method still stays in theoretical calculations, further simulation experiments are needed to discover problems in actual production and propose more convenient solutions. In addition, the choice of condensate directly affects the actual results. Ignoring the differences between different condensates, assuming a condensate for calculations autonomously. Therefore, the hydraulic stability control method is improved for different media, making it suitable for practical production, which is also the focus of subsequent research.

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