Fuzzy PID Control Applied in Evaporator of Organic Rankine Cycle System

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ABSTRACT

In this paper, the organic Rankine cycle (ORC) in waste heat utilizing process is investigated. In order to study the performance of the ORC system, the method of mechanism analysis is applied in modeling. In order to achieve both transient performance and steady-state energy saving, a control strategy is proposed for the system by incorporating a Fuzzy control with a PID controller. MATLAB software of Simulink toolbox is applied in this system to study the dynamic characteristics of the object to adapt to parameter changes and anti-interference of control object. Simulations demonstrate that the proposed strategy can obtain satisfactory performance.

1. Introduction

In recent years, more attention has been paid to saving energy and alleviating environment problems [1-4]. And the world energy consumption has risen to a level never reached before, releasing in the same process large quantities of CO$_2$ into the atmosphere [5]. In the actual industrial field, the number of low temperature waste heat resources is quite large, but there is a lack of effective technical methods to use waste heat. With the need to reduce CO$_2$, low temperature waste heat utilization has appealed more and more attention. In addition to waste heat, low temperature Geothermal resources can be used. In particular, ORC system has generated much interest in medium-low temperature heat sources and renewable energy [5]. ORC is used and studied widely because of its simple structure and high efficiency. In ORC system, water is replaced with different low boiling point compounds (or mixture) as working fluids, so low temperature heat can be used to produce power. Therefore, ORC is regarded as a feasible green energy technology.

Traditional PID control, based on a precise mathematical model, is suitable for simple control problems, and it has less control performance for complex system. Fuzzy control is a product of the combination of fuzzy mathematics and control theory, which simulates the ambiguity of human thinking, by using fuzzy membership function in mathematics, fuzzy relation, fuzzy reasoning etc. In this paper, Fuzzy PID control will be applied in ORC system, compared with traditional PID control. According to simulation about these two strategies, it is shown that Fuzzy PID control has better performance for this system. The most important part of this system is toll tools control table based on expert or operator experience.

2. System Description

The schematic diagram of the investigated ORC system is showed in Fig. 1. The fundamental components of the system are the heat source, throttle valves, a working fluid evaporator, a screw expander coupled with a generator, a condenser, a feed pump and other auxiliary equipment. The waste heat comes from the exhaust gas heat exchange with the working fluid R245fa in the evaporator, in which R245fa is vaporized at constant sub-critical pressure until it changes
into an ideal superheated vapor. The working fluid R245fa is suitable at the temperature of heat source range from 380–430K. The superheated vapor of R245fa enters into the turbine and expands, turning mechanical power into electrical power. Then the superheated vapor is condensed into liquid in an air-cooled condenser. After that, the liquid is pressured by the feed pump and sent back to the evaporator for the next cycle.

In this paper, supposing evaporator as main controlled object, then the detailed controlled output variable and manipulated input variable are listed in Table 1.

3. Dynamic Model of Evaporator in ORC System

In this paper, the evaporator is the focus of the study. The temperature of the working fluid at outlet of evaporator must be maintained at a desired level to ensure the highest efficiency of ORC system.

The model of evaporator will be established by the method of mechanism analysis. According to the step change test of the working fluid flow in the evaporator model, the temperature response curves at the outlet of the evaporator can be obtained in the condition of decreasing working fluid at the speed of 1kg/s. The temperature response curve of the evaporator outlet is calculated by two points. The transfer function \( W(s) \) can be written as the form of first-order inertia with delay when the working fluid flow has changed. \( W(s) \) is written as following:

\[
W(s) = \frac{T(s)}{V(s)} = \frac{K e^{-ts}}{T_s + 1}
\]

In this formula, \( K, T, \tau \) stand for steady-state gain, inertia time constant and delay time respectively. According to the temperature response curve of the evaporator outlet, we can obtain \( T = 33.4 \), \( \tau = 7 \), \( K = 80.8 \). Finally, we can get the function of the temperature of vapor at the evaporator outlet.

\[
W(s) = \frac{T(s)}{V(s)} = \frac{80.8 e^{-7s}}{33.4s + 1}
\]

4. PID Control Design for ORC System

The conventional PID control strategy for the waste heat recovery power plant is shown as Fig. 2.

The transfer function of the ideal PID controller is shown as follow:

\[
D(s) = \frac{U(s)}{E(s)} = K_p \left( 1 + \frac{1}{T_i s} + T_d s \right)
\]

In the PID control system, the error can be described as \( e(t) = u(t) - y(t) \), and \( K_p, T_i, T_d \) represent proportional coefficient, integral time constant and differential time constant respectively. These three parameters can be set by the Ziegler-Nichols theory. The formulas are shown in Table 2.

By adjusting \( K_p, T_i, T_d \) parameters, the control of the object can be realized. When \( K_p = 0.01, T_i = 20, T_d = 2.3 \).
5. Fuzzy PID Control Design for ORC System

Fuzzy control is an intelligent control theory based on fuzzy set theory, fuzzy language variable and fuzzy inference. The structure of fuzzy controller is shown in Fig. 3.

Fuzzy PID control combines the advantages of the fuzzy control algorithm and PID control algorithm with complete fundamental theories. Fuzzy self-tuning parameter PID controller is composed of fuzzy controller, which is used to give the PID controller online self-tuning PID parameters. Fuzzy PID controller is consisted with fuzzy controller and PID controller, whose structure is shown in Fig. 4.

(1) Fuzzy Sets

If given field \( X \), \( A = \{x\} \) is the fuzzy sets of field \( X \). It refers to making use of \( \mu_A : X \rightarrow [0,1] \) as membership functions to represent the characteristics of the sets. The fundamental fuzzy sets can be expressed with the method of ordered couples:

\[
A = \{(x, \mu_A(x)) | x \in X\}
\] (4)

(2) Membership Function

The degree of a fuzzy set judge \( x_i \) with \([0,1]\). In the practical application of fuzzy logic, there are several kinds of membership functions, such as: Gaussian type, Triangle type, Trapezoid type.

(3) Fuzzification

The fuzzification operation is to map the input space into the fuzzy set on the input domain. Fuzzification plays an important part on dealing with uncertain information. For example, usually calculating \( e = r - y \) and \( e' = de / dt \) (\( r \) is the set value, \( y \) is the output of system, \( e \) is the error) is the main task.

(4) Rules Database

The rules database contains a relatively clear requirement and the characteristics of the controlled object, and a similar performance of the system can be controlled in the reference of the rules database.

(5) Fuzzy Reasoning

According to the method of logical reasoning, the input amount of the fuzzy vectors is combined with fuzzy relation to obtain the controlled fuzzy vector.

(6) Defuzzification

Through defuzzification, fuzzy controlled quantities transfer into the scope of the domain of clarity. After that, the clear quantities change into actual controlled quantities by scale transformation. There are several methods of defuzzification, such as the weighted average method. Every element \( X_i (i=1,2,...,n) \) in the domain is the fuzzy set \( U_i \) of membership degree \( \mu_{U_i}(u) \) of weighted coefficient, that is \( X_i \mu_{U_i}(u) (i=1,2,...,n) \).

\[
X_0 = \frac{\sum_{i=1}^{n} X_i \mu_{U_i}(u)}{\sum_{i=1}^{n} \mu_{U_i}(u)}\] (5)

When the ORC system is controlled with Fuzzy PID control, the rules database is shown in Table 3. In the Fuzzy control rules, there are several linguistic variables: NB is negative big, NM is negative medium, NS is negative small, ZO is zero, PS is positive small, PM is positive medium, PB is positive big.
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**Table 3.** Rules database for Fuzzy PID control.

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<th>Kp, Ki, Kd</th>
<th>NB</th>
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<th>NS</th>
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In Fuzzy PID controller, $K_p$, $K_i$, $K_d$ are adjusted according to Fig.5(a), (b), (c).

### 6. Simulation Study

In this section, the MATLAB software of Simulink toolbox will be utilized to simulate the control capability of Fuzzy PID and the conventional PID control. It shows the simulation result of temperature control by conventional PID control and Fuzzy PID control, in Fig. 6.

When Fuzzy PID and conventional PID control systems are both set to the same values:

- **Fuzzy PID control:** $K_p = 0.01$, $T_i = 20$, $T_d = 2.3$;
- **Conventional PID control:** $K_p = 0.01$, $T_i = 20$, $T_d = 2.3$.

From the Fig. 6, it is shown that the temperature response speed with Fuzzy PID control is faster than response from the conventional PID. Setting the value of temperature is 120°C, with the PID control, the response time is 176s when the system achieves stability. With Fuzzy PID control, the response time is 105s, when the response curve was stable. And with there is both no error in the period of stability. Therefore, the conclusion is that Fuzzy PID control has better performance than conventional PID control in the ORC system.

When changing the temperature at 180s, the vapor temperature $T$ decrease 10°C at the rate of 2°C /s, and then the vapor temperature increase 10°C at the rate of 2°C /s when $t=200$s. When the temperature set value varies, the working fluid input follows the
changing quicker with Fuzzy PID control to achieve the desired control. The results of working fluid with different control show in Fig. 7, that the system has good anti-interference ability.

When changing the temperature at 180s, the vapor temperature $T_T$ increase $10^\circ C$ at the rate of $2^\circ C/s$, and then the vapor temperature decrease $10^\circ C$ at the rate of $2^\circ C/s$ when $t=300s$. The temperature of the evaporator tracking capability is shown in Fig. 8.

From the Fig.8, it is shown that the vapor temperature with Fuzzy PID control has a better tracking ability than conventional PID control.

7. Conclusion

In this paper, the control-oriented model of waste heat utilizing power plant is build, the temperature vapor of evaporator outlet control strategy is presented for the waste heat recovery system by incorporating a fuzzy with PID controller. Simulations illustrate that the proposed strategy can obtain satisfactory performance. And its applicability can be demonstrated in a 100kW waste heat utilizing power plant. It can be concluded that the output of electrical power has faster response with low overshoot and steady-state performance. Even there are load variations or disturbances in the waste heat utilizing process, the temperature of the working fluid and vapor outlet can be kept within the acceptable error near their set-points.

Although, the design of Fuzzy PID control strategy is a bit complicated than conventional PID control, it is effective for the investigated waste heat recovery power plant with ORC system. The control strategy can be applied in the other waste heat recovery power plants.

References


