Research on the robustness of the Roots waste heat power generation system

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Abstract The reuse of industrial waste heat is an important way to promote energy conservation and reduce emissions. However, low-quality waste heat has a wide distribution range. It is difficult to recover, and the recycling technology needs to be a breakthrough. Therefore, in this paper, we propose a Roots waste heat power generation device which is used to recover low-quality waste heat. However, the relative fluctuation of the air source is greater with the low-quality waste heat than that with the medium- and high-quality waste heat, which makes it difficult for the actual working condition of the device to maintain stability and even causes the generator to cut off automatically. Therefore, it is necessary to perform a study on the robustness of the measurement and control system of the Roots waste heat power generation process and to improve the stability of the device operation. To solve these problems, we propose a control method that combines a robust controller and an internal model controller to improve the robustness of the device. The experimental results showed that the robust internal model controller has a strong anti-interference ability and that the tracking performance is obviously improved.

INDEX TERMS Low-quality waste heat, Robustness, Roots power machine, Internal model control, Optimal control

I. INTRODUCTION

With the rapid economic and social development, energy consumption has increased rapidly and its production and utilization methods have been continuously improved. The impact of energy production and consumption modes on the environment has also become increasingly prominent, and energy and environmental issues have attracted increasing attention. In the current industrial production process, a large amount of industrial waste heat energy is emitted into the environment in the form of gas, resulting in a huge waste of resources.

Waste heat recovery power generation refers to the use of waste heat in the form of flue gas and waste steam in the industrial production process as an energy source to convert the originally wasted energy into electrical energy using a power equipment [1]. At present, with regard to waste heat recycling and power generation technology, high-quality waste heat has gradually formed a relatively complete industry, which has been applied and popularized in enterprises with high output ratios of high-temperature waste heat, such as the petrochemical industry [2-4]. In contrast, low-quality waste heat technology still remains in the initial stage because of its low unit thermal energy content, difficulty in recycling, and other factors, which tend to ignore the value of secondary recycling. In this regard, we propose the design of a new low-quality waste heat recycling power generation device using a Roots power machine as the working equipment. Owing to the lightweight working characteristics of this machine, the proposed device is especially suitable for waste heat recycling and reuse in small- or medium-sized factories, making up for the shortcomings of low-quality waste heat recycling technology in the market.

Low-quality waste heat has a small scale, frequent fluctuation, and low specific heat capacity, and its fluctuation range is larger than that of the waste heat at medium and high temperature levels, which makes it difficult to stabilize the operation state of the Roots waste heat power generation device. Owing to the requirement of constant output of the device, besides the differences in external environment factors such as time and place, other factors, such as irregular fluctuating gas source, strong inertia of the Roots power machine, and strong coupling effect of parameters such as temperature and pressure, make it easy for the electric energy output of the Roots waste heat power generation device to produce irregular deviation. Because the Roots waste heat power generation process is a controlled object with the characteristics of complex coupling and frequent nonlinear interference factors, it is not ideal to use the traditional control method in the design of the controller [5].
In this paper, the main purpose of the research on the control method of low quality waste heat is to obtain stable electric energy. Based on the research, this paper proposes an internal model control strategy based on robust optimization, which greatly improves the tracking performance and anti-interference performance of waste heat recovery system. This achievement is conducive to the realization of power supply for small equipment, but also provides the possibility of future grid connection.

II. Research status of low-quality waste heat power generation control systems

Owing to the lack of studies on low-quality waste heat power generation technology, studies on some control methods should consider the status of the studies on the control theory of waste heat recycling power generation systems with a medium or a high temperature level. Wei et al. proposed that the determination of the rated operating conditions of the generator set should be related to the operating environment parameters of the device to achieve the best utilization performance [6]. There have also been studies on the optimization of the setting value of the waste heat recycling power generation control system that show how to determine the rated operating conditions [7]. Because it is difficult to directly find the optimal setting value, Peralez et al. used a dynamic optimization algorithm to optimize the control of the waste heat recycling process to maximize the recycling and utilization of the waste heat produced by the diesel electric locomotive [8].

The proportional-integral-derivative (PID) control method is widely used in the process control of actual industrial production. At present, it also has an unquestionable leading position in addressing control problems in the field of thermal engineering and power plants [9]. However, for complex thermal process control, its control effect in the face of random external interference is relatively inferior. The main idea of a PID controller and a self-anti-interference controller is to use a certain operating point to analyze, obtain the dynamic characteristics required by the controller design, and implement the design of the control system according to these objectives [10]. The control system designed in this manner has a strong anti-interference ability when the device is running under the rated conditions. At the same time, as the system operating conditions in actual environments change, the control effect will get worse, and, thus, the tracking ability needs to be improved. Predictive control is a model-based optimal control algorithm that combines rolling optimization and feedback correction [11]. Imran et al. used the heat exchanger in a waste heat recycling power generation system as the main part of the controller, designed a model predictive controller, and verified that its dynamic response is better than that of the traditional PID controller [12]. Predictive control can make the controller overcome the uncertainties of the system; however, in practical applications, real-time calculation is required and the workload is large, requiring higher hardware specifications for the controller, which is not convenient for application and promotion. In recent years, the robust control theory has received attention in the field of thermodynamics. The purpose of modern robust control theory is to enable a system to deal with uncertainties such as unmodeled dynamics and external interferences, so that it can maintain stability and good regulation performance even under such uncertainties. The research objects of this theory are generally unknown, but the uncertain objects are limited [13].

Therefore, according to the dynamic characteristics and control functions of the roots waste heat power generation process, the robust control and internal mode control theories are applied to the robustness optimization of the device measurement and control system, so that the roots waste heat power generation system can operate stably even if there are changes in external interferences and in its internal structure or parameters.

III. Analysis of the characteristics of the Roots waste heat power generation system

A. Structure and indicators of the waste heat power generation device

The Roots waste heat power generation device is a power generation device that directly uses the waste heat gas source as the working medium, uses a Roots power machine as the power mechanism, and relies on the expansion of the working medium to cause the machine to rotate to realize the conversion of air source energy to mechanical energy. The research object of this study is the Roots waste heat power generation device independently developed by our research group. A schematic diagram of the structure of the device is shown in Fig 1.

Fig 1. Schematic diagram of the structure of the Roots waste heat power generation device.

The device is mainly composed of roots power machine, generator, regulating valve, sensor, transmission pipeline and connecting parts. Its working principle is as follows. The gas source flows through the admission line and then enters the Roots power machine cavity after the air flow is adjusted through the regulating valve. The Roots power machine blade rotates under the influence of the gas expansion and pressure difference of the working medium, and the connecting parts such as the coupling drive the rotating shaft of the generator to generate electric energy. After the work is done, the working medium gas is discharged after a harmless treatment. The rated power of the generator is 4.5 kW, and the fluctuation range of speed is ±5%.

B. Characteristics of the waste heat resources
Considering the small scale of the low-quality waste heat and the low energy content, for the pressure of the industrial waste heat, waste heat can be used more effectively if it can directly enter the Roots power generation device to directly drive the power machine to work to produce mechanical energy, i.e., the process of heat exchange between the working medium and the waste heat is omitted. This method reduces the number of energy conversion and transmission processes, reduces the irreversible loss of energy, and improves the utilization rate of energy recovery [14].

In this case, the frequent fluctuation of the waste heat directly affects the fluctuation of the rotational speed of the Roots power machine. Moreover, owing to the overall low temperature and pressure of the low-quality waste heat in the industry, the relative fluctuations they cause to the temperature or pressure of the low-quality waste heat in the generation system is also more severe. Therefore, fluctuations in the working condition of the Roots power generation system are more severe.

The heat energy contained in the waste heat resource can be expressed as

\[ Q = mC_p(T - T_0) + mC_p(T_{solid} - T_0) \]  

where \( m \), \( C_p \), \( r \), \( T \), and \( T_{solid} \) are the mass flow, constant pressure specific heat, latent heat, discharge temperature, and phase transition temperature of the sensible heat object, respectively, and \( T_0 \) is the ambient temperature.

Because industrial waste heat is mainly a mixture of smog and gas, most of the smog and gas contain different amounts of dust, and the heat transfer coefficient is affected by the proportion of dust, and, therefore, the state parameters such as the temperature of the working medium gas produced by the heat transfer are not uniform and have irregular changes. The heat transfer process can produce water vapor, which is a mixture of saturated water and vapor, or it can be the saturated gas of an organic working substance. Its composition and energy are both different. Moreover, in the industrial production of the gas source of the previous process, there is a certain irregular change in the working medium gas source, which is an uncontrollable factor owing to certain changes in the environmental factors and state parameters.

From the result of the above analysis, it can be concluded that the low-quality residual heat source and the working gas source have the characteristics of disordered fluctuation and multiparameter coupling, which increases the uncertainty of the system operating conditions.

C. Characteristics of the flow control valve

The flow control valve consists of two parts: an electric actuator and a valve body. The flow control valve is responsible for regulating the intake air flow of the Roots waste heat power generation device, and, therefore, its flow characteristics are also determined by the effect of these two parts.

Valve body flow characteristics refer to the relationship between the relative flow (Q) of the medium through the valve body and the relative opening (L) of the valve body [15]. The relationship can be expressed as

\[ \frac{Q}{Q_{max}} = f(L) \]  

The electric control valve used in the Roots waste heat generation unit has a linear flow characteristic. After the above derivation, it can be concluded that

\[ \frac{dQ}{L} = k \]  

Moreover, the equation can be obtained after the integration:

\[ \frac{Q}{Q_{max}} = kL + c \]  

When \( L = 0 \), \( Q = Q_{min} \) represents the minimum adjustable flow of the control valve, and when \( L = L_{max} \), \( Q = Q_{max} \) represents the maximum adjustable flow of the control valve. The size of the actual flow cannot simply be determined by the valve opening and structure as it is also restricted by the valve body before and after the pressure difference. In industrial field applications, the pressure drop in the intake pipe of the Roots waste heat power generation device will be distributed in accordance with a certain rule in the regulating valve and in the pipeline in the front and back of the regulating valve.

The mathematical model of the electric actuator is

\[ y = \alpha x + \beta \]  

where \( x \) is the input current of the actuator, i.e., the command; \( y \) is the feedback current of the actuator; \( \alpha \) is the gain coefficient of the electric actuator; and \( \beta \) is the zero point error. The electric actuator error is mainly composed of the gain coefficient and the zero point error [16].

The electric actuator uses a voltage signal of 1-5 V as the control signal, and the output is its linear displacement. The electric actuator is connected to the spool, and its transfer function is

\[ \frac{S_y(S)}{S_i(S)} = \frac{K_c}{T_sS+1} \]  

where \( T_s \), \( K_c \), and \( T_d \) are the control signal, gain, and time constant of the electric actuator, respectively.

In summary, it can be determined that the adjustment valve is not a single-input and single-output system; therefore, when the electric adjustment valve performs a flow adjustment, the problems of strong variable coupling and nonlinear fluctuations will occur.

IV. Robust optimization of the internal model controller in the waste heat power generation process

A. Cause analysis of the poor control effect

Generally speaking, the control system is divided into open-loop and closed-loop control types according to whether a feedback link exists or not. The closed-loop
control system can automatically correct the deviation through negative feedback; that is, when the output value is inconsistent with the setting value, the system can realize an autonomous correction. At present, the advantages of the commonly used PID control algorithm are mainly reflected in its easy realization: through the control of the PID algorithm, the output is constantly adjusted and gradually tends to be close to and consistent with the input value.

The regulating goal of the control system of the Roots waste heat power generation process is to maintain a stable speed. On this basis, the control system can be divided into four parts according to their functions: speed detection link, flow regulation link, working medium work link, and mechanical transmission link. The control system will compare the expected speed with the real-time speed, combined with the air source state parameters, to ensure that the control signal is sent to make the flow control valve move to change its opening degree and adjust the speed of the power machine by modifying the change in air intake of the Roots power machine [17].

In the design of the PID controller, the coefficient values of the three links of the PID calculation determine the performance of the controller, and the numerical value should be selected according to the characteristics of the control object. Besides the fact that the adjustment of the three parameters have an impact on the control effect of the system, it is also necessary to point out that, because the design basis of the PID controller is the process model obtained by the designer, the accuracy of the model will restrict the effect of the controller. Therefore, for the PID controller of the Roots waste heat power generation process, in the single-input and single-output loops, the internal coupling parameters that affect the output of the system are fitted to the parameters under the standard operating conditions, which ignores the actual Roots waste heat power generation. Thus, the time variation and nonlinearity of the other coupling parameters of the process have errors under actual working conditions.

For example, as shown in Fig. 2, to control the output stability of the unit, we adjust the flow link according to the deviation of the output of the unit, to realize the stable adjustment of the system output. However, at the same time, because the change in the valve opening during flow regulation has a reverse effect on the pressure value of the intake pipeline of the Roots power machine, the increase in the valve opening of the machine tends to reduce the pressure. This causes a deviation between the actual pressure value in the pipeline and the original assumed value, which can have an impact on the effect of flow regulation and have a reverse interference effect on the system output.

**Fig. 2. Schematic diagram of the control mechanism of the Roots waste heat power generation system.**

From the results of the above analysis, the reasons for the poor performance of the PID controller can be summarized as follows. Owing to its simple algorithm, the PID controller is suitable for a system with no other coupling relationship except for the input and output. When dealing with the Roots waste heat power generation device with frequent and complex interference, we find that the parameter tuning result is often not ideally controlled. The design of the PID controller depends on the model accuracy of the controlled object. However, it is difficult to obtain an accurate model owing to the complex coupling of the parameters of the Roots waste heat power generation process. Because of the limitations of the design principle, it is difficult to meet the requirements of rapid tracking of the setting value and stability in restraining the disturbance.

**B. Optimal control concept**

In the robust control theory, the concept of optimal control is to treat the pursued control goal as an optimal problem. By solving this optimal problem, we can develop the design method and obtain the corresponding parameters of the controller. $H_2$ and $H_\infty$ optimal controls are two of the robust optimization methods.

1) $H_2$ optimal control

For $H_2$ optimal control, the theoretical purpose is to minimize the square error integral of the system for a specific input. That is,

$$\|e\|^2_2 = \int e^2(t)dt$$  \hspace{1cm} (4.1)

In the frequency domain, it can be expressed as

$$\min\|e\|^2_2 = \min \frac{1}{2\pi} \int |e(j\omega)|^2 d\omega$$  \hspace{1cm} (4.2)

The relationship between the input and the output of the structure of the standard feedback control systems

$$e(s) = \frac{y}{d} = \frac{1}{1+P(s)C(s)}$$  \hspace{1cm} (4.3)

Substituting Equation 4.2 into Equation 4.3, we can obtain Therefore, the goal of $H_2$ optimal control is to minimize

$$\min\|e\|^2_2 = \min \frac{1}{2\pi} \int |e(j\omega)a(j\omega)\|^2 d\omega$$  \hspace{1cm} (4.4)

the 2-norm of the modulus of $e(s)$ weighted by $a$, which corresponds to the area where the system response curve deviates from the input [18].

2) $H_\infty$ optimal control
$H_\infty$ and $H_2$ optimal controls are both optimal control methods in the robust control theory. The difference lies in their calculation methods and in the meaning of the parameter indexes. Corresponding to $H_2$ optimal control, $H_\infty$ optimal control aims to minimize the $\infty$-norm of $\varepsilon(s)$ weighted by $\omega$ [19].

$H_\infty$ optimal control is usually expressed as

If the controller satisfies Equation 4.5, then the system composed of the controllers satisfies the $H_\infty$ performance index.

C. Design of the internal model controller

To improve the unsatisfactory control effect of the internal model controller in the face of the model error mentioned above, we divided the controller design into two steps. The first step only considers the tracking ability of the setting value, and the second step adds the robustness requirements of the system.

Step 1: Ignore the uncertainty and consider only the control performance of the nominal model without considering the system robustness.

On the basis of the sensitivity function and the $H_2$ optimal control method, the controller $Q_u$ of the nominal model was designed to make its ability to track the setting value the strongest. A typical structure of an internal model control system is shown in Fig 3.

For the classical internal model control system, the sensitivity function $\varepsilon(s)$ is

$$\frac{e}{d-r} = \frac{y}{z} = \frac{1-\varepsilon Q(s)\varepsilon}{1+\varepsilon Q(s)\varepsilon + M(s)\varepsilon} = \varepsilon(s)$$ (4.6)

According to $\varepsilon(s) + \eta(s) = 1$,

$$\frac{1}{1+Q(s)\varepsilon + M(s)\varepsilon} = \eta(s)$$ (4.7)

At this point, the uncertainty is not considered and the model is considered to be accurate, i.e., $P(s) = M(s)$. Therefore, the above two expressions are simplified as

$$\varepsilon(s) = 1 - Q(s)M(s)$$ (4.8)

$$\eta(s) = Q(s)M(s)$$ (4.9)

From these, the conditions that the controller $Q_u$ needs to meet are obtained as

$$\min \| -Q_u(s)M(s)\|_1 \leq 1$$ (4.10)

Then, $Q_u$ is made as close as possible to the inverse of $M(s)$, and the error can be close to zero. However, when $M(s)$ is not the minimum phase system, the reciprocal cannot be obtained directly. Therefore, the nominal model $M(s)$ is divided into two parts.

$$M(s) = M_+(s)M_-(s)$$ (4.11)

where $M_+(s)$ represents the part containing the pure hysteresis and unstable zero points in the nominal model, and $M(s)$ represents the part with the minimum phase. Therefore,

$$\| -Q_u(s)\|_1 < 1$$ (4.4)

the ideal controller can be obtained as follows:

$$Q_u(s) = [M_+(s)]^{-1}$$ (4.12)

Step 2: Increase the robust performance and robust stability.

Aiming at system robustness, to overcome the impact of unmodeled uncertainty, we introduce a low-pass filter into the control loop and constantly adjust the structure and parameters of the filter to achieve the best control performance and obtain the expected robustness quality.

For robust controllers,

$$Q(s) = Q_u(s)f(s) = f(s)/M_+(s)$$ (4.13)

In the equation, one of the purposes for choosing $f(s)$ is to make it reasonable. We take the order of the filter $f(s)$ as 2 and choose the following form:

$$f(s) = \frac{1}{(1+\lambda s)^2}$$ (4.14)

where $\lambda$ is the filter time constant. This is the only parameter that designers need to design, as it will determine the robustness of the system. At present, it is generally determined through continuous debugging based on experience.

D. Robust optimization design

A system can be said to be robustly stable if it remains stable while fluctuating within the range of all defined models with errors. The stable operation of the system is the premise of all other functional requirements, so it is very important to conduct robust stability test for the system containing uncertainty. In the magnetic levitation field, when the magnetic levitation train travels on the track, the air gap between the electromagnet and the track must be maintained. Magnetic levitation system has strong nonlinear, flexible track, and feedback signal has the characteristics of network time delay, which makes the open loop of magnetic levitation system unstable and prone to safety accidents. Therefore, the target air gap must be maintained by active control. The researchers designed control systems based on neural networks and deep learning[20-21].

The commonly used theory bases are Nyquist stability criterion, small gain theorem and so on. The small gain theorem is an extension of Nyquist stability criterion, and the theory is based on the small gain theorem: if the norm of the system's transfer function is less than 1, the closed-loop system has robust stability.

Aiming at the structure of the internal model control system with a feedback form, we derive the index expressions for the robust stability and tracking performance.
of the system. According to the minimum gain theorem, the necessary and sufficient conditions for obtaining robust stability are

$$\left| \frac{M(j\omega)c(j\omega)d(j\omega)}{1 + M(j\omega)c(j\omega)d(j\omega)} \right| < 1, \forall \omega \in R \quad (4.15)$$

From this, it can be concluded that robust stability limits the unique parameter $\lambda$ of the internal model controller.

Let the transfer function $h(s)$ between the error and the setting value be

$$h(s) = \frac{1}{r + M(s)c(s)(1 + dW(s))}$$

Therefore,

$$\left\| e(t) \right\| + \left\| \theta \right\| = \frac{1}{2\pi} \int_{\omega_1}^{\omega_2} |h(j\omega)| d\omega$$

That is,

$$\left\| e(t) \right\| + \left\| \theta \right\| = \frac{1}{2\pi} \int_{\omega_1}^{\omega_2} |h(j\omega)\theta(j\omega)| d\omega$$

To simplify the writing, we omitted the Laplace operator in the analytical relation below. If the internal model control system meets the robust stability condition, then

$$\| + MC \| - \| MCC \| > 0 \quad (4.19)$$

According to this condition, the formula can be obtained as

$$\left\| e(t) \right\| + \left\| MC \| + dW \right\| \leq \left\| e(t) \right\| + \left\| MC \right\| + \left\| dW \right\|$$

The right end of the above equation is defined as $|e(t)|$; then,

$$\left\| e(t) \right\| \leq \frac{1}{2\pi} \int_{\omega_1}^{\omega_2} |h(j\omega)\theta(j\omega)| d\omega \quad (4.21)$$

Taking the unit step signal as the given value $r$, we determine the robust performance index as follows:

$$J = \frac{1}{2\pi} \int_{\omega_1}^{\omega_2} |h(j\omega)| d\omega \quad (4.22)$$

According to the form and order of the Roots power generation process model, the following can be obtained:

$$M_1(s) = e^{-\alpha}, M_2(s) = \frac{K}{T_s^2 + T_s + 1} \quad (4.23)$$

The feedback control system and a robust controller are combined to obtain the feedback controller of the Roots waste heat power generation process:

$$C(s) = \frac{(T_s^2 + T_s + 1)}{K[(1 + \lambda\alpha) - e^{-\alpha}]}$$

Its robust stability condition is

$$\lambda \leq 1.32 \quad (4.25)$$

V. Simulation and experimental research

A. Analysis of the simulation performance

To verify the performance of the robust internal model controller designed for the Roots waste heat power generation device, we used a PID controller commonly used in the industry and a robust internal model controller to compare and observe the device robustness. The control effect of the internal model controller was analyzed when the setting value was changed and an external continuous interference occurred.

Moreover, the PID controller designed for the Roots waste heat power generation process for the simulation comparison test was designed on the basis of the conventional PID control structure. The nominal model obtained by parameter identification was used as the control object. Its parameters were $K_p = 1.4964$, $T_i = 60.14$, and $T_d = 60.98$.

(1) Step response test

(2) The step response test can simulate the problem of changing the setting value in the closed-loop control system in actual production, and the adjustment process reflects the dynamic tracking performance of the system. Therefore, to test the ability of the controller to track the setting value, we used the step signal as the input signal of the system and set the initial signal amplitude to 500 units. When $t = 200$ s, a step signal of -300 was added. When $t = 400$ s, the step signal was +200, so that the input of the model corresponded to the speed setting values of 500, 200, and 400 r/min. The response curve of the system is shown in Fig 4.

![FIGURE 4. Comparison of the step responses.](image)

The data in Fig 4 were analyzed and calculated, and the results are shown in Table 1. It can be seen that, when the controlled object model is accurate, the two controllers have similar adjustment speeds. After all, the PID controller was designed on the basis of the nominal model, and, therefore, it performs well in the control of the nominal model, although its overshoot is almost twice that of the robust internal model controller. According to the data obtained from the simulation curve, the ratio of the integral absolute time error of the system output using the action of the robust internal model controller and the PID controller was calculated to be 0.67. In general, the robust internal model controller is superior to the conventional PID controller in terms of overshoot and adjustment time.

| PERFORMANCE | DECOUPLING CONTROL | PID CONTROL |
|-------------|---------------------|-------------|
| OVERSHOOT   | 3.9%                | 8%          |
| ADJUSTMENT TIME | 66 s               | 70 s        |

(2) Disturbance test

There are often some disturbances in the actual industrial sites. To verify the anti-interference performance of the designed control system, under the condition that the output of the simulation model was maintained at a stable working condition of 500 r/min, we added a 10-s step disturbance and a 20-s slope disturbance signal to the output port of the
process model at \( t=20 \) s and \( t=120 \) s, respectively. We simulated the disturbance of the Roots waste heat power generation system under actual working conditions. The output curve of the system is shown in Fig 5.

![Response curve under interference conditions.](image)

**FIGURE 5.** Response curve under interference conditions.

The curve shows that, when a disturbance is applied to the system, the control output of the two controllers of the system deviates from the setting value. After a period of time, all control outputs can return to the setting value; however, as can be seen in the curve in Fig 5, when the system is subjected to a step disturbance with an amplitude of 20 for 10 s, the robust internal model controller tends to be stable after 20 s, which is 20% shorter than the adjustment time of the conventional PID controller. When the system receives a slope signal of 20 s, the robust internal model controller tends to be stable after 31 s and the adjustment time is shortened by 18% compared with that of the conventional PID controller. It is obvious that the system has lower volatility and faster regulation speed under the action of the robust internal model controller.

**B. Experimental test**

In this section, we present the results of the experimental tests we performed using the hardware test platform we built to verify the control effect of the controller of the Roots waste heat power generation process. The experiments had two specific purposes: to verify the control effect of the controller when the Roots waste heat power generation process is disturbed and to verify the tracking ability of the controller when the setting condition of the Roots waste heat power generation unit changes.

The operating conditions can be calculated according to the structural parameters of the Roots power machine, and the air source pressure required for the experiment should be above 0.14 MPa. In this experiment, an air compressor was used as the simulated gas source and a gas storage tank was used to transition between the air source and the waste heat recovery device. The air source and the gas storage tank are illustrated in Fig 6. The roots waste heat power generation system is shown in Fig 7. The red part in the figure is the base, which is used to support the whole experimental platform and place the power control cabinet. The light green part is the generator. Dark green shows the inlet and outlet air ducts, which are fitted with relevant sensors. The blue part is the Roots motor, which is used to output mechanical energy. The specific working process is the same as described in Chapter 3, Section 1.

![Air source and gas storage tank.](image)

**FIGURE 6.** Air source and gas storage tank.

![Roots waste heat power generation system.](image)

**FIGURE 7.** Roots waste heat power generation system.

(1) Anti-interference test

To verify the suppression interference ability of the controller, we continuously adjusted the outlet valve opening of the Roots power machine under the stable working condition of the test device, kept the parameters of the other components unchanged, fluctuated the outlet pipeline continuously, and collected the output speed information at this time to simulate the changes in the operating condition of the device during an external disturbance. Fig 8 shows the output speed curves of the two controllers under the continuous fluctuation of the gas source.

From the output speed curves of the two controllers, it can be seen that the output speed of the Roots power machine deviates from the setting value when the system is disturbed. Moreover, the fluctuations generated under the conventional PID algorithm are more severe and the adjustment effect is poor. It can also be seen that, under the robust internal model control algorithm, the output speed of the Roots power machine deviates from the setting value to a small extent and always remains within the required range.

![Output speed curves of the two controllers.](image)
FIGURE 8. (a) Robust internal model controller; (b) conventional internal model controller.

The system under the action of the robust internal model controller was tested repeatedly, and the data obtained from the disturbance test were summarized. The results are shown in Table 2.

| OUTLET VALVE OPENING | STABILIZATION TIME (s) | SPEED DEVIATION (r/min) |
|----------------------|------------------------|-------------------------|
| Increase 10%         | 8.3 to 9.4             | -12.3 to +20.4          |
| Decrease 10%         | 8.1 to 9.7             | -23.1 to +10.8          |

In the face of external disturbances, the output speed of the Roots power machine will produce transient fluctuations, although there may be some deviation in the number of speed fluctuations due to environmental factors such as temperature and pressure. However, under the action of the robust internal model controller, the response speed is fast when adjusting to the stable speed after the transient fluctuation and the speed deviation is not more than 4.62% of the stable speed, which meets the index requirements of the system dynamic performance.

(2) Tracking performance test

The test process for tracking the setting value reflects the dynamic adjustment performance and the robust tracking performance of the controller. When the system runs stably near the working point of 500 r/min, the setting value of the speed of the Roots power machine is increased from 600 r/min.

When the system was under the action of the robust internal model controller, its speed output increment began to fall to around 85% of the setting increment after 70 s when the setting value changed. Before 110 s, the system output of the two control methods tended to be within the stable fluctuation range of the setting value. The data are shown in Fig 9.

FIGURE 9. Test results of the tracking performance.

The dynamic performance of the robust internal model controller was faster than that of the conventional PID controller, and the overshoot was smaller. To further determine the effect of the robust internal model controller, we tested the device under the action of the robust internal model controller five times. The statistical experimental results are shown in Table 3.

| INITIAL ROTATIONAL SPEED (r/min) | TARGET SPEED (r/min) | WAVE PEAK (r/min) | AVERAGE ADJUSTMENT TIME (s) |
|----------------------------------|----------------------|------------------|-----------------------------|
| 500                              | 600                  | 621.4            | 75.3                        |

The speed deviation in the experiment was not higher than 21.4 r/min and, thus, was within the allowable fluctuation range. The adjustment time for tracking the setting value should not exceed 75.3 s. The experiment result showed that, when the gas source changes, the controller can respond quickly to change the speed of the roots power machine and track the setting value.

VI. Conclusion

The situation of the energy supply is grim and the pressure of environmental protection is increasing. Recycling low-quality waste heat from industrial output for power generation is an important way to explore the cascade utilization of energy, energy conservation, and emission reduction. Using the roots waste heat power generation device applied in a factory as the research object, we extensively studied the control method of the device in view of the problem that its actual working condition is easily subject to external interference and produces fluctuation, and we found that the working performance of the control system is improved by the robust control theory. The specific research content of this paper includes the following aspects:

1. The actual working conditions of Roots waste heat power generation device are unstable. According to the actual operating conditions of the Roots waste heat power generation device, the characteristics of the important components were analyzed and the reasons for the poor performance of the control system were studied.

2. The idea of combining robust control theory with internal model control method is proposed. The robust performance index is used to set the unique parameter of internal model controller, and the robust internal model controller is designed.

3. The robust internal model controller is simulated by using process model. The results showed that the latter controller performed well in both the anti-interference experiment and the experiment with the setting value changed.

4. The robust internal model controller we designed for the Roots waste heat power generation system was applied to the experimental device, and its abilities to suppress interference and track the setting value were tested to verify the correctness and availability of the system optimization.

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