AN EXPERIMENTALLY VALIDATED CONTROL STRATEGY TO OPTIMIZE POWER GENERATION QUALITY FOR WASTE HEAT RECOVERY SYSTEM

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Roots-type engine is suitable for small power generation system fuelled by waste heat. The disorderly fluctuations of the waste heat source upstream of the power generation process and changes in external environmental factors cause the working parameters of the device to change, which makes the speed of roots engine unstable, and the output power quality of the system is not good. For this problem, this paper starts from the control structure and control strategy to improve the adjustment speed and anti-interference ability of the control system. In this contribution, the model transformation of the dynamic work unit of waste heat power generation device from engineering to theoretical model is performed, the temperature of working gas and the speed of output shaft of roots engine are determined as control objects,and the internal mode control strategy is introduced to optimize the controller of the system. Simulation results are in good agreement with the measurements, which verify that the optimized control system can effectively improve the following ability and anti-interference of the system, and shorten the response time.

Key words*: low-grade waste heat recovery, roots engineer, internal model control*

1. Introduction

In industrial production, a large amount of heat is discharged directly into the atmosphere in the form of low-grade waste heat, which pollutes the environment and wastes energy. In order to recover low-grade waste heat resources, the United States develops a twin-screw power machine that generates electricity through geothermal water, Belgium also conducts in-depth research on the screw power machine [1],and WU Z et al.[2] test the performance of the scroll expander under the condition of power load and pump capacity changes. Our team develop a roots engine, and its feasibility has been verified by experiments.

Quite a few practical problems in industrial control are solved by the classic PID (Proportional integral differential) controller [3]. However, the waste heat power generation process has a wide range of working fluid thermodynamic state spans, high flow rates, and large heat flux densities [4-5], and the device components have modular Characteristics, many physical and chemical processes are interconnected and coupled in the system, which results in complex operating environmental conditions and operating conditions of the waste heat power generation unit, causing fluctuations in the output shaft speed of the Roots-type engine and unstable power output by the system. For complex control objects such as the Roots-type waste heat power generation process, classic PID cannot obtain good control performance, and external noise, disturbances, and process model parameters and structural mismatches will also have a serious impact on control characteristics.

In order to keep the Roots-type engine's speed stable under interference conditions and to reach a new stable state quickly after the conditions change, the Internal Model Control (IMC) strategy is introduced to design the IMC-PID controller suitable for Roots-type waste heat power generation control system, which can improve the adjustment speed and anti-interference ability of the control system to achieve the purpose of stabilizing the output power.

2. The structure and working principle of the dynamic work unit of Roots-type waste heat power generation device

2.1. System composition

The Roots-type waste heat power generation device uses low-quality waste heat resources as an energy source, and obtains a saturated working medium gas through heat exchange. Through the expansion of the working gas, the pressure energy and internal energy of the working gas are converted into the mechanical energy needed by Roots-type engine to drive the rotation shaft of the generator, which is a process of dynamic work for the low-quality waste heat generation. The key equipment involved forms the dynamic work unit, as shown in Fig. 1.

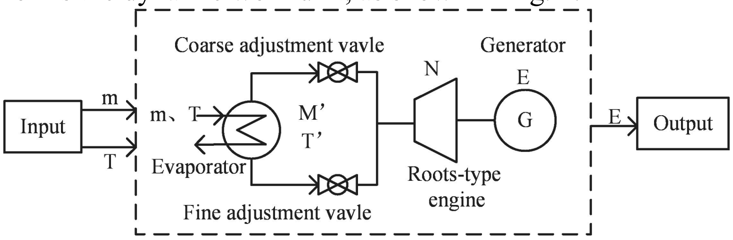


Fig. 1 Schematic diagram of dynamic work system

In the dynamic work system, the output shaft's speed of the Roots-type engine is directly related to the output of the system's electrical energy, which is affected by the gas volume, temperature, and pressure of the inlet and outlet ports per unit time. Therefore, the key to the quality of waste heat power generation is the effective operation of the dynamic work control system. Take the temperature T and the mass flow m of the waste heat source as the input, and take the electric energy production as the output. First, controller sets the speed of the Roots-type engine according to the parameters of the heat source, and uses the coarse adjustment valve to adjust the gas intake of the Roots-type engine to make the Roots-type engine' speed close to the set value.When the deviation of the actual speed does not exceed 5% of the set value, use the fine adjustment valve to precisely control the speed fluctuation to ensure the stable speed and make the output power of the generator stable and effective.

In the Fig. 1, *m* and *T* are the mass flow and temperature of the waste heat source; m 'and T' are the mass flow and temperature of the working medium gas; N is the speed of the output shaft of the roots power machine, and E is the system output power.

2.2. System control structure

The working state of the dynamic work system is restricted by the fluctuating state of waste heat generated by the upstream process. And the physical and chemical processes involved in the dynamic process of the Roots-type engine are interrelated and coupled. In order to ensure that the dynamic work system can run efficiently, it's necessary to keep all parameters in the system at the required level.

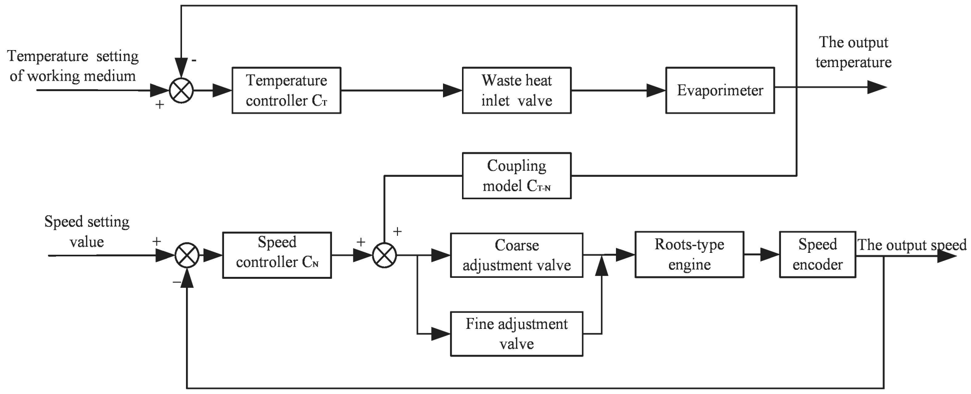


Fig. 2 Schematic diagram of the adjustment mechanism of the power work system

Around two key parts of the dynamic work system: the evaporator and the Roots-type engine, we can determine two key control quantities: the temperature of the working medium gas T' and the speed of the output shaft of the Roots-type engine N. The control system can control the temperature of the working medium gas that drives Roots-type engine to rotate by controlling the valve opening of the waste heat inlet valve. Under the coordination effect of the coarse regulating valve and the fine regulating valve regulating the flow of working gas into Roots-type engine, the precise control of Roots-type engine's speed can be realized to achieve the purpose of stable output electric energy. The control system adjustment block diagram is shown in Fig. 2, which is a double closed-loop coupling structure.

3. Design of controller

3.1. Modeling of the dynamic work system

3.1.1 Evaporator model

The heat source and working medium flow in the evaporator for heat exchange.

The principle is shown in Fig. 3.By analyzing the steady-state process of the evaporator, it can be obtained that: the heat transferred from the heat source side to the working medium side is written in Eq. (1); the heat absorbed from the working medium is written in Eq. (2);

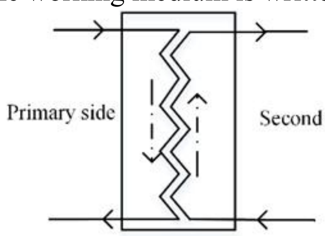


Fig. 3 Schematic diagram of the evaporator

$$Q_1 = c_1 q_1 (T_{1g} - T_{1h}) \tag{1}$$

$$Q_2 = c_2 q_2 (T_{2g} - T_{2h}) \tag{2}$$

Establish a thermal efficiency equation that takes the temperature difference of the fluid on both sides of the heat exchange as the driving force for heat transfer and write it as Eq. (3).

$$Q_3 = UA(T_{1h} - T_{2g}) \tag{3}$$

According to the thermodynamic equilibrium equation, the dynamic analysis of the heat source side and the working medium side of the evaporator is carried out. The heat balance equation on the heat source side is Eq. (3), and the heat balance equation on the working medium side is Eq. (5).

$$c_1 m_1 \frac{dT_{1h}}{dt} = c_1 q_1 \left(T_{1g} - T_{1h}\right) - UA(T_{1h} - T_{2g}) \tag{4}$$

$$c_2 m_2 \frac{dT_{2g}}{dt} = -\, c_2 q_2 \left(T_{2g} - T_{2h}\right) + UA(T_{1h} - T_{2g}) \tag{5}$$

Treat $T_{2g} - T_{2h} = \Delta t$ as a constant， and do Laplace transform to get Eq. (6).

$$G_1(s) = \frac{c_2 UA \Delta t}{c_1 c_2 m_1 m_2 s^2 + (c_1 c_2 q_1 m_2 + c_2 UA m_2 + c_1 UA m_1)s + c_1 q_1 UA} \tag{6}$$

Considering the delay of the monitoring signal of actual heat source temperature and working medium flow, the transfer function of evaporator is obtained：

$$G_1(s) = \frac{K_1}{(T_{11}s + 1)(T_{12}s + 1)} e^{-s\tau_1} \tag{7}$$

Where,

$$K_1 = c_2 UA \Delta t \tag{8a}$$

$$T_{11} + T_{12} = (c_1 c_2 q_1 m_2 + c_2 UA m_2 + c_1 UA m_1)/c_1 q_1 UA \tag{8b}$$

$$T_{11} T_{12} = c_2 m_1 m_2 / q_1 UA. \tag{8c}$$

3.1.2 Control valve model

Roots-type waste heat power generation device flue gas regulating valve and Coarse regulating valve, fine regulating valve before the Roots-type engine, are electric regulating valve. The transfer function of electric regulating valve can be represented using Eq. (9).

$$G_2(s) = \frac{K_{21}K_{22}\frac{K_{23}}{s}R(s)}{1 + K_{24}\frac{K_{23}}{s}R(s)} \tag{9}$$

$$R(s) = \frac{C}{T_2 s + 1} \tag{10}$$

Where， $R(s)$ is the open-loop transfer function of the motor, T_2、 C are structural parameters of servo motors.

Obtained by Eqs. (9) (10):

$$G_2(s) = \frac{K_2}{(T_{21}s + 1)((T_{22}s + 1)} \tag{11}$$

Where,

$$K_2 = K_{21}K_{22}K_{23}C \tag{12a}$$

$$T_{21} + T_{22} = \frac{1}{K_{23}K_{24}C} \tag{12b}$$

$$T_{21} + T_{22} = \frac{T_2}{K_{23}K_{24}C} \tag{12c}$$

The structure of the flue gas inlet valve is the same as that of the coarse and fine adjustment valves, but due to different parameters, the transfer functions of the flue gas inlet valve, coarse adjustment valve, and fine adjustment valve are described as $G_{21}(s)$, $G_{22}(s)$, $G_{23}(s)$.

3.1.3 Roots-type engine model

The Roots-type engine is a rotating fluid power machine, and its physical model belongs to a volumetric turbine. Its simplified physical model is shown in Fig. 4.

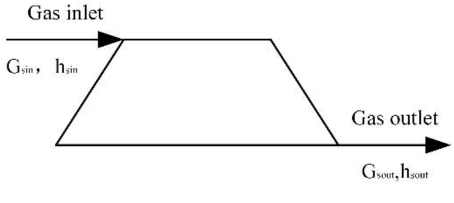


Fig. 4 Simplified model of Roots-type engine

Define $G_3(s)$ for the transfer function of the roots-type engine [6]:

$$G_3(s) = \frac{K_3 e^{-\tau_3 s}}{T_3 s + 1} \tag{13}$$

3.1.4 Rotary encoder model

The encoder is used to detect the rotation speed of the Roots-type engine output shaft. Without considering the processing delay and the error of the electric signal, it can be considered that the encoder can lossless reproduce the angular velocity of the output shaft of the Roots-type engine. So, the transfer function of the encoder can be expressed as:

$$G_4(s) = \frac{P(s)}{\theta(s)} = K_4 \tag{14}$$

In Eq. (14):$P(s)$ is the coefficient of the encoder line number, and $\theta(s)$ is the function of the rotation angle of the output shaft. The calculated transfer function is a time-independent coefficient.

3.1.5 System control model

Through the above-mentioned mechanism modeling, a simple model is established for each unit of the system, and the models are connected to derive the process model of the temperature regulation system of the working medium gas and the speed regulation system of the Roots-type engine:

$$\mathrm{G}_T(s) = G_1(s)G_{21}(s) \tag{15}$$

$$\mathrm{G}_N(s) = (G_{22}(s) + G_{23}(s))G_3(s)G_4(s) \tag{16}$$

If the controller is designed according to a high-order process model, it is an extremely complicated and tedious process, and the high-order process model may contain unnecessary factors, which makes the designed controller unsuitable. Therefore, we can first use the least square method to reduce the order of the model and identify the model parameters, then there are:

$$\mathrm{G}_T(s) = \frac{0.98e^{-10s}}{s(60s+1)} \tag{17}$$

$$\mathrm{G}_N(s) = \frac{1.21e^{-40s}}{(12s+1)(58s+1)} \tag{18}$$

$$\mathrm{G}_{T-N}(s) = \frac{1.3e^{-12s}}{3.87s+1} \tag{19}$$

We can get Eqs. (20) and (21).

$$Y_1 = \mathrm{G}_T u_1 \tag{20}$$

$$Y_2 = \mathrm{G}_N(u_2 + u_3) \tag{21}$$

Where,G_T is the process model of the temperature regulation system, G_N is the process model of the speed regulation system, G_{T-N} is the process model for temperature and speed coupling; Y_1 is the working gas temperature, u_1 is the output signal of the temperature controller; Y_2 is the speed of the Roots-type engine output shaft, u_2 is the output signal of the speed controller, u_3 is the output signal for speed after temperature coupling.

3.2. Design of IMC-PID controller

Internal Model Control (IMC) is mainly applied to industrial sites with multiple variables, nonlinearity, strong coupling and large time delay, and has strong anti-interference, especially for systems with large time delay [7].

The design process of IMC-PID controller is performed in two steps:

Step 1: Decompose process model M (s)

$$M(s) = M_+(s)M_-(s) \tag{22}$$

Among them, $M_+(s)$ is the part of the model that contains pure hysteresis and unstable zeros, $M_-(s)$ is the smallest phase part in the model.The decomposition result of the process model of the temperature regulation system is Eq. (23). The decomposition result of the process model of the speed regulation system is Eq. (24).

$$M_{T+}(s) = e^{-10s} \tag{23a}$$

$$M_{T-}(s) = \frac{0.98}{s(60s+1)} \tag{23b}$$

$$M_{N+}(s) = e^{-40s} \tag{24a}$$

$$M_{N-}(s) = \frac{1.21}{(12s+1)(58s+1)} \tag{24b}$$

Step 2: Introduce a filter $f(s)$

A low-pass filter $f(t)$ is added to the inverse of $M_-(s)$ to ensure the stability and robustness of the system. Where, the order of $f(t)$ is 2. Define the IMC controller as Eq. (25)

$$Q(s) = f(s) \Big/ M_-(s) = \frac{1}{(1+\lambda s)^2 M_-(s)} \tag{25}$$

Then the IMC-PID controllers are written:

$$C_T(s) = \frac{s(60s+1)}{0.98(\lambda_1 s+1)^2 - e^{-10s}} \tag{26}$$

$$C_N(s) = \frac{(12s+1)(58s+1)}{1.21(\lambda_2 s+1)^2 - e^{-40s}} \tag{27}$$

The delay link of eqs. (26) and (27) is approximated by all poles. Take $\lambda_1 = 2$， $\lambda_2 = 1$, and transform the IMC-PID controllers into the standard form of Eq. (28):

$$C(s) = K_p\left(1 + \frac{1}{T_i s} + T_d s\right) \tag{28}$$

The two groups of parameters of the IMC-PID controller of the temperature regulation system and the speed regulation system are calculated as

$$K_{p1} = 0.3076; T_{i1} = 8.6128; T_{d1} = 17.2604 \tag{29}$$

$$K_{p2} = 1.8303; T_{i2} = 153.7452; T_{d2} = 25.8241 \tag{30}$$

4. Experiment

4.1. Simulation test

In order to initially verify the effect of IMC-PID controller, simulation experiments were performed on IMC-PID controller and traditional PID controller to compare the control effect.

(1) Temperature setpoint tracking test

At t=10s, set the working medium gas temperature setting value from 130℃ up to 140℃; at $t = 30s$, set the value from 140℃ fall to 130℃. Roots-type engine speed is initially set to 1500r/min. Response curves in the Fig. 5 and Fig. 6 show that, after the temperature setting value of the working medium is changed, under the action of the IMC-PID controller, the temperature reaches the set value after tracking change of 5.1s, the speed returns to a stable state after a fluctuation of 5.8s, and the speed fluctuation is not higher than 3r/min, within the allowable range. Under the same conditions, the PID controller needs 6.7s and 7.2s respectively.

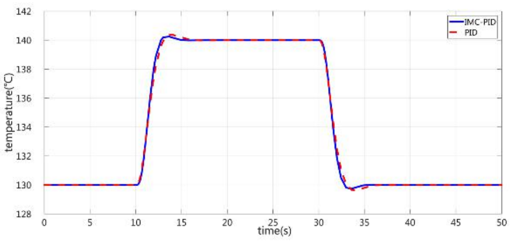


Fig. 5 Response curve of working medium temperature

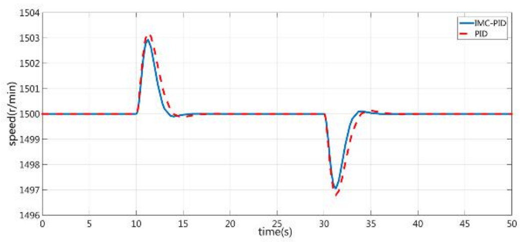
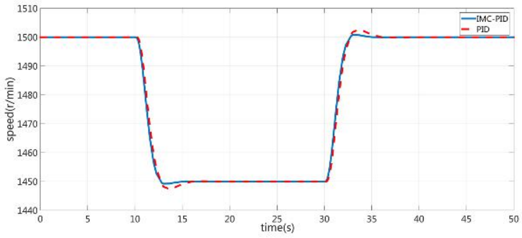


Fig. 6 Response curve of speed of the Roots-type engine output shaft

(2) Speed setpoint tracking test

At $t = 10s$, decrease the speed setting value of Roots-type engine from 1500r/min to 1400r/min; at $t = 30s$, the rotational speed increases from 1400r/min to 1500r/min. The temperature of the working medium is 130℃ and remains unchanged. The response curves in the Fig. 7 show that after the set value of the speed is changed, the IMC-PID controller needs 4.7s, and the PID controller needs 6s to reach the set speed, and the output overshoot of the IMC-PID controller is smaller.



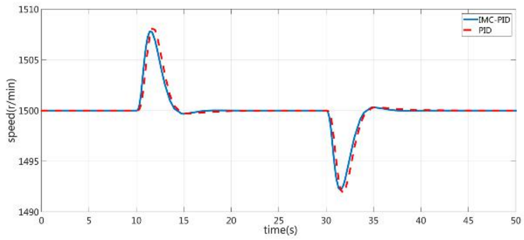


Fig. 7 Response curve of output shaft speed of Roots-type engine

Fig. 8 Response curve of output shaft speed of Roots-type engine

(3) Interference test of speed regulation system

Working medium temperature is set at $130℃$, and the speed of Roots-type engine is set at $1500r/min$. At $t = 10s$ and $t = 30s$, the positive and negative step disturbances with a magnitude of 2% of the speed are added respectively to the speed regulation system to simulate the speed jitter. The response curves in the Fig.8 shows that under the action of the IMC-PID controller, the speed adjustment system needs 7s to return to a stable state, while the PID controller requires 11s, and the IMC-PID controller has a fast adjustment speed.

The simulation results show that when changing the temperature or speed setpoint, that is, when changing the system working state parameters, the output of the IMC-PID controller can follow the setpoint change faster, the adjustment time is shorter, and have stronger anti- interference and better control quality.

4.2. Experimental test

4.2.1 Test platform

In order to thoroughly verify the effect of the speed regulation system, the designed IMC-PID controller is applied to the Roots-type waste heat power generation device shown in Fig. 9.

Fig. 9 Test platform for power module of Roots-type waste heat power generation device

The operating status of the device is displayed on the mcgs touch screen, including the collected data of each instrument (temperature, pressure, flow, liquid level and other parameters), the opening of the regulating valve, and the speed of the Roots-type engine. There are also al arm prompt records, real-time data curves of various parameters, and archival records of historical data, which is convenient for experimental research on the fluctuation of speed. Fig. 10 shows the main control interface of touch screen automatic operation. The performance indexs of the control system are shown in Tab. 1.

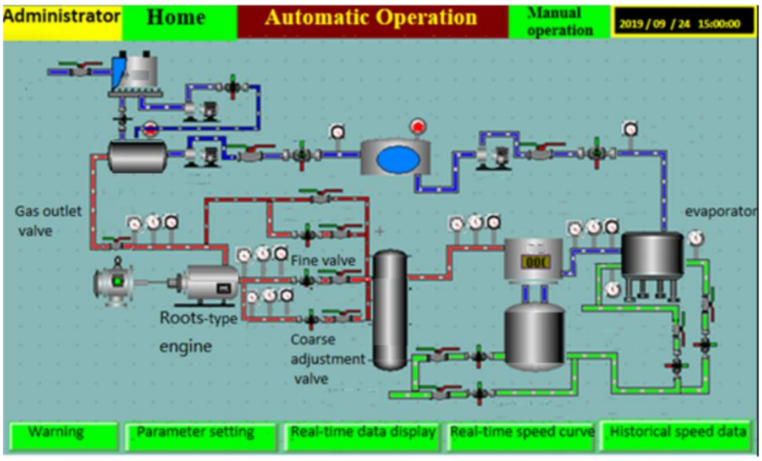


Fig. 10 Touch screen auto-run main control interface

Tab. 1 Performance index requirements for low-grade waste heat generating units

Name	index	Name	Index
Speed fluctuation rate	±0.5%	Time to stabilize speed	10s
Transient modulation rate	5%	steady-state modulation rate	3.5%

4.2.2 Test data analysis

Before the experiment, the experimental device was on the automatic operation, and the speed of the Roots-type engine maintained a set value of 1500r / min, and the waste heat power generation process ran smoothly. In the experiment, the data display and report generation were completed by the human-computer interaction system MCGS, which saved the historical data as a .CSV file.

(1) Speed adjustment test

In this experiment, by adjusting the waste heat intake valve, the waste heat flow is changed, the set value of speed of the output shaft of the Roots-type engine is changed, then the speed information of the output shaft of the Roots-type engine is recorded. According to the .csv file obtained from repeated the experiment for 5 times, the statistical experimental results are shown in Tab. 2.

Tab. 2 Speed adjustment information table after the set value is changed

The initial speed（r/min）	1500			
The set value of the speed（r/min）	1450		1550	
Regulatory process information	minimum rotative speed(r/min)	1441.4	maximum rotative speed(r/min)	1557.8
	Mean adjustment time(s)	5.3	Mean adjustment time(s)	5.0

The speed deviation in the experiment is not higher than 8.6r / min, which is within the allowable fluctuation range. The adjustment time for tracking the set value does not exceed 5.3 seconds. It shows that when the gas source changes, the IMC-PID controller can adjust the coarse adjusting valve and fine adjusting valve to make the speed of roots power machine change to realize the tracking of the set value.

(2) Speed shake test

In the experiment, the opening degree of the outlet valve of the Roots-type engine was adjusted to change the work parameters in the cavity of the Roots-type engine, which was used to simulate the external disturbances.Then observe the change in the speed of the output shaft of the Roots-type engine. The data of repeated experiments was summarized, and the results are shown in the Tab. 3.

Tab. 3 Speed adjustment information table after external disturbance

Outlet valve opening	settling time (s)	Speed deviation （r/min）
Increase 10%	8.3-9.4	-19.3 ~ +42.4
Reduce 10%	8.1-9.7	-49.1 ~ +19.8

According to the data in the table, when the Roots-type engine is subject to external disturbances, the speed will have certain transient fluctuations. However, after the transient fluctuation, the response speed of the speed adjustment is fast, and the speed deviation is no more than 3.27% of the stable speed, meeting the requirements of the dynamic performance index.

In summary, it can be seen that the actual speed adjustment effect is in good agreement with the simulation results. Although there are some deviations in the speed fluctuations due to environmental factors such as temperature and pressure, the IMC-PID controller can be very good in both cases, so that the system can quickly enter a stable working state, in line with the dynamic performance indicators.

5. Conclusions

In this paper, the dynamic work system of the Roots-type waste heat power generation device is studied in depth. Through the analysis of the process, a coupling control structure of the working medium gas temperature and the output speed of the Roots-type engine is proposed, with the working medium temperature and roots engine output shaft speed as control object, and verify the designed IMC-PID controller experimentally. The simulation results show that the IMC-PID controller is better than the PID controller in adjusting the temperature, speed and the disturbance of temperature to the speed. And the test results of the controller on the test platform show that under the action of IMC-PID controller, the tracking ability and anti-interference regulation performance of the speed setting value of the dynamic work system are superior, and the stability performance of the speed of Roots-type engine output shaft is good, meeting the requirements of the index, so the output power quality is guaranteed.

Acknowledgment

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Nomenclature

A – heat exchange area,[m^2]
K_{21} – electric gas valve flow gain,[–]
K_{22} – servo amplifier gain, [–]
K_{23} – reducer gain,[–]
K_{24} – displacement feedback gain,[–]
m1 – flow masses of flue gas,[kgs^{-1}]
m2 – flow masses of working medium,[kgs^{-1}]
U – heat transfer coefficient, [W/(m^2 • ℃)]

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