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Research on Low-temperature Waste Heat Power Generation Device Control System based on Embedded Technology

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Abstract

Industrial waste heat is one of the most widely distributed and used potential of conventional recyclable energy in industrial production .However，for the low concentration and less energy of low quality waste heat resources, the mature traditional waste heat recovery technology is not suitable for this kind of the recycling of waste heat resources due to its recycling economy and feasibility of the restrictions. In this paper, the secondary utilization of low quality waste heat resources is studied, especially the control system research of low-temperature waste heat recovery power generation equipment by heat pipe waste heat recovery device matching with roots-type steam engine. Control system is managed by system hardware which with C8051F040 single-chip microcomputer as CPU, and fuses the signals of speed encoder and temperature sensor to realize real-time input, and realizes real time communication between touch screen and single chip microcomputer through RS232 bus. By testing, system works stably. Finally it is resulted that the recovery of low-temperature waste heat and the conversion of electric energy can be achieved by the test.

Keywords*: Low-temperature waste heat, Waste heat recovery, Waste heat power generation, Root-steam engine, Embedded technology*

1. Introduction

Industrial waste heat distribution is the most extensive and most potential application in industrial production. It is the recovery of energy. At present recycling of waste heat recovery at home and abroad is mainly targeted at high-temperature waste heat resources (350 ° above). For low concentration, low energy, low quality waste heat resources (less than 350 °), due to the economic and feasibility constraints of recycling, low quality waste heat resources are basically all released into the air, resulting in a large amount of energy loss[1]. Low quality waste heat resources are difficult to recover, waste heat accounted for more than 50% of the waste heat energy, Low quality waste heat resources are difficult to recover, waste heat accounted for more than 50% of the waste heat energy, and accounted for about 30% of the following 200°.

Among the waste heat recovery technology used both at home and abroad, using the overall use of resources by generating electricity, is the most reasonable ,and higher economic and environmental benefits. Waste heat in the process of the technology of production can be converted to electricity, which is an effective method to increase energy using efficiency and reduce environmental pollution[2]. In recent years, Japan and Germany design screw expansion of power systems, power generation systems and organic rankine's spiral cycle power generation system [3], which meet the needs of the part of low-temperature waste heat. After the Tianjin University in China national 863 project completed the experiment of screw expansion of power devices, many companies and research institutes carried on the thorough research, making the study of the

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technology of screw expansion of power generators in the climax[4]. However, these techniques in the low-temperature waste heat recovery exist obvious shortage, mainly manifested in its core equipment complex structure, high processing cost, maintenance is not convenient and high running cost, and so on. In view of the technical requirements of low-temperature waste heat recycling, our team has been studying a new roots type engine, and its feasibility has been verified by experiment [5] [6] [7]. But we did not do in-depth research on the device for steam recycling process and its control system. the working medium of Roots steam generating device is direct steam source, however, the most common industrial waste heat is flue gas waste heat, so studying a kind of waste heat recovery power generation system is particularly important.

Aiming at the above problems, a control system of low-temperature waste heat power generation device based on embedded technology is developed. The heat pipe waste heat recovery device is combined with a small steam generating unit, and the former converts other forms of waste heat into steam residual heat, which is directly used to provide power for the subsequent small steam generating units. Nowadays, embedded system plays a key role in many fields. Using embedded system as the control system of low-temperature waste heat power generation device can effectively reduce the equipment cost and convenient equipment improved, which is conducive to the promotion of use so a more in-depth study of the low- temperature waste heat recovery power generation technology has important significance [8].

2. Overall Scheme Design

2.1. Technological Process

Low quality waste heat recovery power generation device of the present topic studied mainly includes low-temperature steam recovery and low-temperature waste heat power generation two parts. Core equipment of the low-temperature steam recovery and low-temperature waste heat power generation were heat pipe steam generator and root-steam engine. Heat pipe steam generator converts flue gas waste heat into steam heat. Steam is used to promote the roots- steam power equipment thus converted to mechanical energy and then electricity generated by pushing generator.

Process flow chart of heat pipe low temperature waste heat recovery power generation device is shown in Figure 1. Setting entire cogeneration system: steam generator, drum, roots-steam engine, generator, fill the water tank, condenser, deaerator, economizer, also includes chemical water treatment equipment and pumps class, valves, sensors, and piping systems for flue gas bubbled wind power equipment.

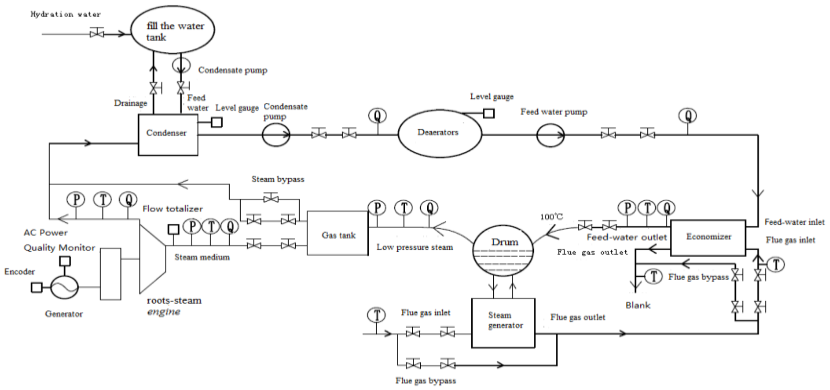


Figure 1. Process Flow Chart of Heat Pipe Low-Temperature Waste Heat Recovery Power Generation Device

The whole process of waste heat recovery involves multiple detection points and multi-line control. Control process is complex, the more controlled points, by Figure 1 shows, the device is controlled with liquid level meter, electric butterfly valve, electric proportional control valve, pressure gauge, thermometer, flow meter, water pump, electric energy quality monitor, speed measuring encoder, and so on. The system is seen as more than one variable, more complex control systems.

2.2. Control Technology Research

The whole process of low-temperature waste heat power generation system is divided into three processes according to the technology, which is the flue gas process, the boiler water process and the steam process.

(1) Flue gas process

Industrial waste heat of flue gas through a gas channel function of wind power equipment into the heat pipe steam generator, and contact with the evaporation end of the heat pip, Evaporation end heat, through the heat pipe working medium heat to the condensation end of heat pipe, heat again after the release of condensate return to the evaporation end, so that the flue gas waste heat into steam heat [9]. In addition, in order to ensure the balance of the steam drum water level in the flue gas heat transfer process, a flue gas bypass can be arranged in the flue gas inlet, and the amount of the excess flue gas can be reused or discharged into the atmosphere by flue gas bypass.

(2) Boiler water process

The heat circulating system of waste heat power generation is mainly the reciprocating transformation process between steam and hot water [10]. Steam to drive roots steam engine rotate, after the work of the steam entering the condenser cooling, then entering the deaerator in the action of condensate pump. Steam is purified and heated by deaerator, and then is pumped into a heat pipe economizer, At this point, the steam is treated as saturated water, after the saturated water is fed into the heat pipe steam generator to carry out steam conversion.

(3) Steam process

100 degrees of saturation water from the coal saving device, after entering the steam drum of the heat pipe steam generator, through the steam drum and the heat pipe steam generator connected to the rise and fall of water vapor pipeline flow heat transfer. The combination of heat pipe steam generator and steam drum realizes the conversion of flue gas heat to steam heat, heat pipe working medium absorbs the heat of the flue gas, the heat transfer to the saturated water pipeline under the precipitation, the endothermic gasification by steam rising pipe into the drum. Separate from the saturated water in the steam drum. After the steam superheater overheating, has been sent to the qualified quality of superheated steam steam gas tank, From the low pressure steam tank out through the main steam circuit into roots steam power machine used to drive to work, so as to drive the generator to generate electric energy.

2.3. Control System Design

The hardware structure is mainly composed of the core controller, power module, analog signal acquisition and processing module, communication module, digital I/O module. The overall structure of the hardware system is shown in Figure 2.

1) Core controller: C8051F040 as the core control system of the control system, to achieve the comprehensive control of low-temperature waste heat recovery power generation device.

2) Intelligent instrument signal acquisition module: intelligent instrument signal acquisition input part of the main acquisition system data a total of 16 variables as pressure, temperature, flow, liquid level, power quality, *etc*. Due to the controlled object more, in order to simplify the system structure and improve the overall processing speed,

485 bus mode is used here to collect more than 485 meters of the output signal of the field, and the design of a dedicated 485 communication interface circuit.

3) Analog output module: electric proportional valve control part 0-5V analog output voltage signal and electric butterfly valve. The object number exceeds the number of MCU DAC channel, using TI 12 bit resolution DAC expansion chip.

4) Communication Interface Module: According to different functional requirements of the system, three communication interface modules are designed: RS232 communication interface module to realize the communication between MCU and industrial touch screen; RS485 communication interface module to achieve multi site instrument signal real-time acquisition and long-distance transmission; CAN bus communication interface design is to achieve system during the later part of the study between the low-temperature waste heat power generation system and the factory network distributed connection.

5) Digital I/O module: digital I / O interface design mainly includes high speed engine speed measuring encoder inputs, switch input and relay and multi state indication lamp output.

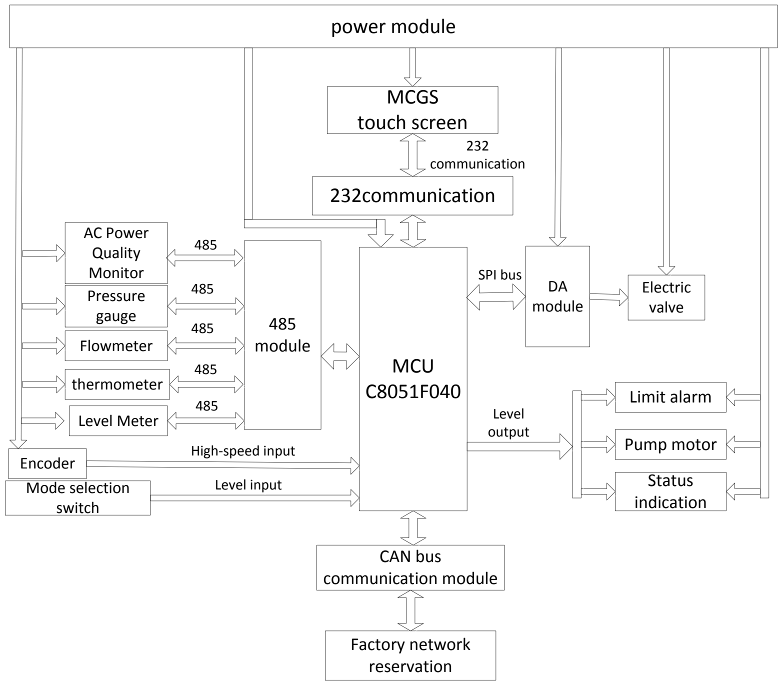


Figure 2. Overall Structure of the Hardware System Block Diagram

3. System Hardware Circuit Design

3.1. Control Chip Selection

This control system is applied in the waste heat recovery and power generation control system which have multiple data acquisition and multiple controlled objects. Too many controlled objects and the steam parameters greater lag can put forward higher requirements for hardware and software development. Therefore, we need to choose a core control chip which is fast and multi-functional. In addition to this, In order to facilitate the experimental research, the chip should be as simple as possible, easy to extension and low of the cost. Cygnal company's 51 Series MCU C8051F040 is rich in resources, it is conducive to improving the overall system integration, and increase the system's anti-interference ability. It represents the development direction of the 8 bit single chip microcomputer control system[11]. PIC series single chip microcomputer hardware system design is simple, the instruction is refined, has low power consumption, strong drive ability, fast running speed and other characteristics, which is a relatively easy to learn and use of MCU[12]. Integrated the above factors, the system selects the single chip microcomputer which named C8051F040.

3.2. Field Instrument Signal Acquisition Circuit Design

There are 16 field acquisition instruments in the system. In order to simplify the hardware circuit of the field instrument data acquisition module, improve the efficiency of data acquisition and enhance the versatility, the system selects 485 signal output in the form of industrial grade pressure gauge, thermometer, flow meter and liquid level meter. The system through the 485 bus data acquisition module to achieve digital signal, and sent useful data to the single-chip microcomputer efficiently.

Figure 3 shows RS-485 interface circuit. The value of R24 is 120Ω. In general, when the 485 bus signal transmission distance is more than 200m, the resistance is needed to avoid communication failure. When the 485 bus is a main mode, that is, there are a number of data acquisition module, in order to achieve the normal communication, we must take the resistance of 120Ω at the end of the bus. According to the characteristics of the data acquisition of multiple intelligent instruments in the embedded system, the circuit will be set aside 120Ω resistance access port. Circuit using MAX485 chip to achieve the standard TTL level to 485 level signal conversion. The chip is compatible with 3.3V logic level. Using half duplex communication mode.

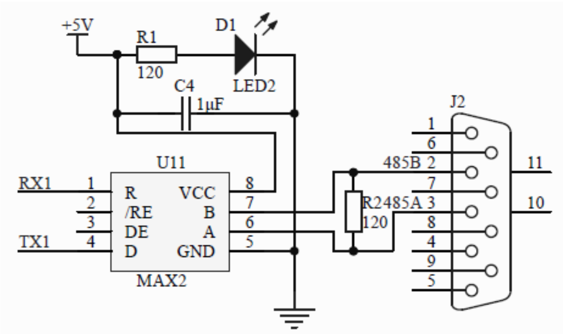


Figure 3. RS-485 Interface Circuit

3.3. Electric Proportional Valve Control Circuit Design

In the low-temperature waste heat power generation equipment, electric valve has twelve. However, C8051F040 built only two 12 bit DAC channel, the control function is insufficient and the choice of electric valve input signal form are 0~5V voltage signal ,it does not support the 485 bus signal, so here to consider the C8051F040 chip external extension DAC chip. Sampling precision and speed determine the control precision of the electric valve and the signal conversion speed. In order to improve the accuracy of the sampling data, the analog output circuit of the system chooses the DAC7568 chip of the United States TI Corporation as an extension to realize the precise control of the electric valve. In order to ensure the system to control the function of the 12 proportional valve, and leave the redundancy of 15-20%,the system use two DAC7568 chips, a total of 16 output channels. DAC7568 basic interface circuit diagram is shown in Figure 4.

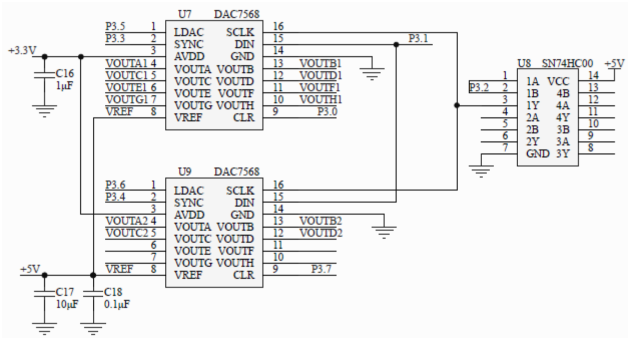


Figure 4. DAC7568 Basic Interface Circuit Diagram

3.4. Communication Interface Circuit Design

3.4.1. RS-232 Communication Interface Circuit Design

The RS-232 interface circuit is used to realize the communication connection between the single chip microcomputer system and the industrial touch screen. The power supply voltage of the touch screen is DC24V. The external interface includes serial interface and USB interface and the serial communication interface can realize RS-232 communication and RS-485 communication. Because the equipment is relatively concentrated, the communication distance is short, and the MCU and touch screen are point-to-point communication, so using RS232 serial communication. RS-232 interface circuit is shown in Figure 5.

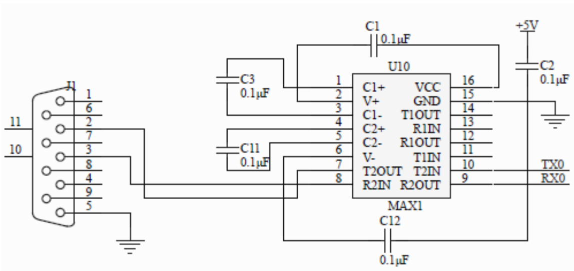


Figure 5. RS-232 Interface Circuit

3.4.2. CAN Bus Interface Circuit Design

System to ensure the low-temperature waste heat recovery power generation device can work independently, and is convenient for late functions to further improve the system upgrade, namely with the factory network connection distributed equipment, so as to systems with reserved the CAN bus interface. CAN bus interface circuit as shown in Figure 6 below.

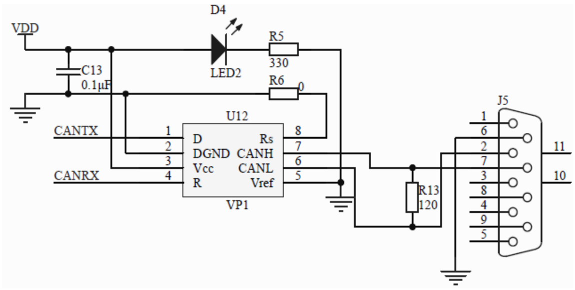


Figure 6. CAN Bus Interface Circuit

4. System Software Design and Implementation

After the system of hardware design is completed, the system of software is developed on the basis of the system. Software development is the core of the hardware system, it plays an important role in the control system design process. According to the function of the system, the software module is divided and studied. Programming embedded system software with C programming language, And through the communication between the microcontroller and industrial touch screen, the system can realize the human-computer interaction, which is convenient for real-time monitoring and control of the system.

4.1. Software Design Procedure

The software flow diagram as shown in Figure 7. The main program first to complete the initialization, boot self-checking, and so on .Subprogram module are: waste heat recovery module; steam power generation module; Grid-connected generation module. The work process is that: After the system is started, the state of each sensor and control valve is self-checking. Self-inspection by later, began to waste heat recovery, after a period of time, calculate the temperature gradient of the waste heat inlet temperature and outlet temperature .Abnormal situation occurs, the program will perform the fault diagnosis module, then into the steam power generation.

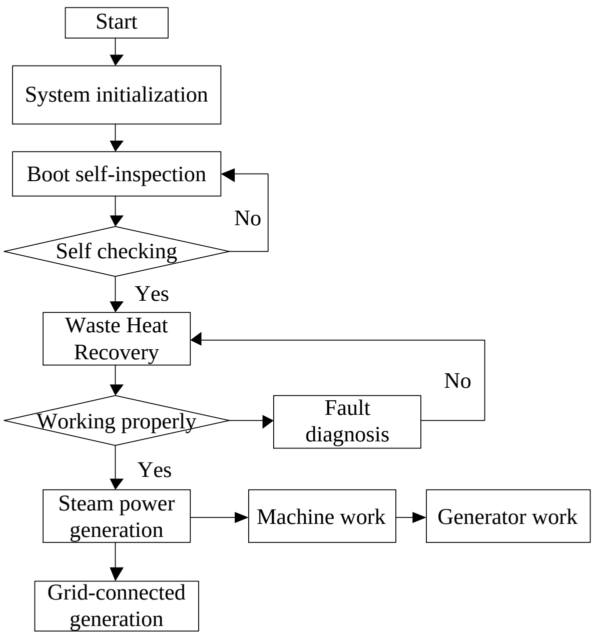


Figure 7. Software Procedure

4.2. Human-Machine Interface

Heat pipe low-temperature waste heat power generation device control system has 13 user window: Boot welcome interface, Manual control interface, Automatic operation control interface, Alarm display interface, Real-time data display interface, Historical data query interface, Parameter setting interface, Alarm limit interface, Real-time data curve display interface, Run time display interface, Research unit profile, Use unit profile, Online help. The operator can enter from the welcome interface to the automatic operation main control interface through the user authorization authentication.

The main control interface window contains the low-temperature waste heat recovery power generation system running process picture, alarm information prompt window and user window switching button. In order to facilitate the distinction, different flow media uses a different color, in the main control interface, blue flow block represents water medium, red flow block represents low-temperature steam medium, and green flow block represents the low-temperature flue gas waste heat. Multiple data acquisition instruments and all kinds of automatic regulating valve are installed in the transmission pipeline, The parameters of the equipment real-time display on the touch screen by "real-time data display" window, so that the unit running status be clear at a glance**Error! Reference source not found.**. Human-machine Interface is shown in Figure 8.

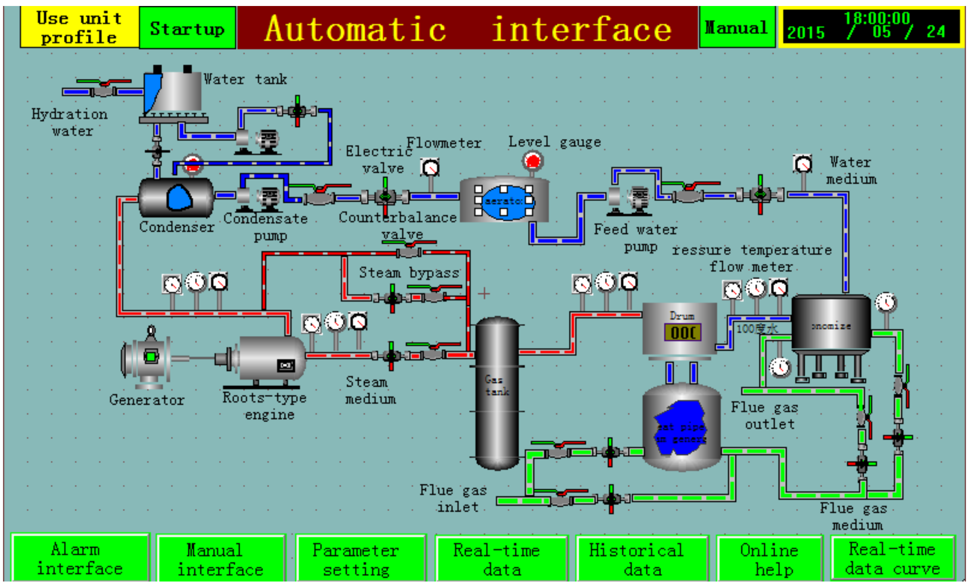


Figure 8. Human-Machine Interface

5. Test and Analysis

5.1. Field Instrument Signal Acquisition Test Based On the 485 Bus

The data of the field pressure gauge, thermometer, flow meter and liquid level meter are transmitted to the control system through the 485 bus, in which the 485 bus adopts the "hand in hand" type bus topology. The system has 16 slave stations. One master- three slave mode be used in this experiment. By the microcontroller to read the three temperature transmitter register value, through the industrial touch screen display.

During the test, the test temperature of the three temperature sensors is changed by the manual intervention, and through real-time data, real-time curve, historical data and historical curve forms on the industrial touch screen for real-time display.485 bus debugging data display interface as shown in Figure 9.

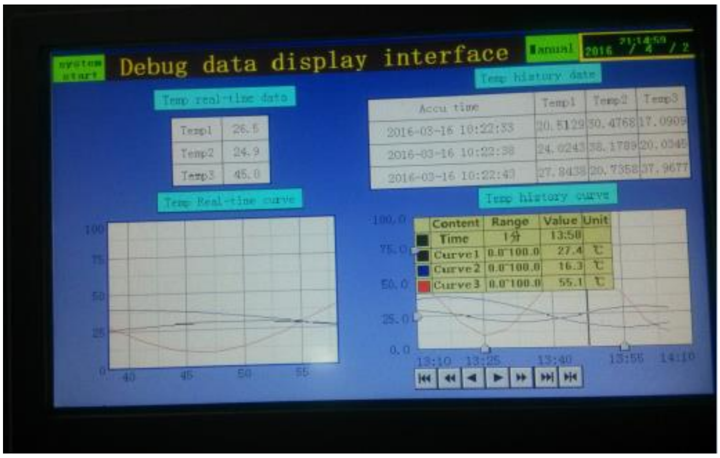


Figure 9. 485 Bus Debugging Data Display Interface

In addition, through the touch screen to three sensors set limit alarm, the upper limit values were set to 20 DEG and 30 DEG and 50 DEG C, the alarm time and causes were recorded, 485 bus debugging of the alarm recording interface as shown in Figure 10.

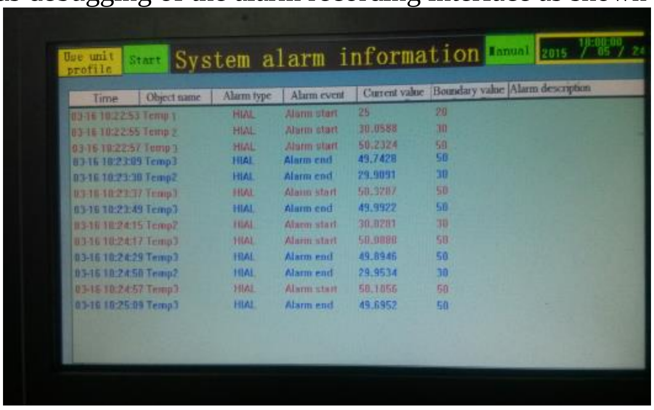
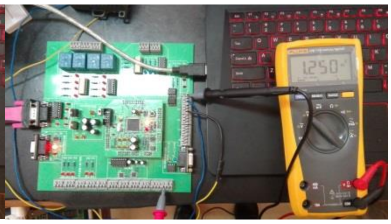


Figure 10. 485 Bus Debugging Alarm Record Interface

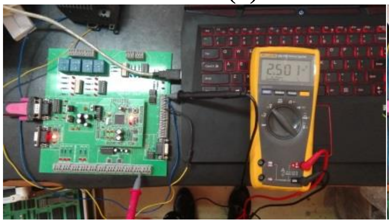
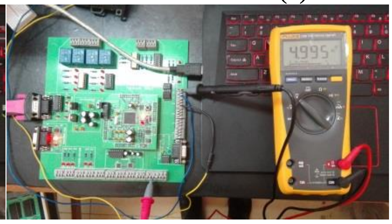
5.2. Electric Proportional Valve Control Test Based on SPI Bus

The system uses SPI bus to control the 12 electric valves, and the electric actuator is input to the 0~5V voltage signal to change the opening degree of the electric proportional valve. This experiment uses the CPU sends binary value and ideal conversion voltage value displayed on the computer through RS-232 serial port. The actual output voltage of each channel is measured with digital display and high precision .Then compared with the theoretical value to verify the accuracy and reliability of the system. The test measured five sets of data, the actual data show that the Figure 11.





(a) A1 Channel-0.3125V (b) B1 Channel -0.625V (c) C1 Channel -1.25V

(d) D1 Channel -2.5V (e) E1 Channel -5V

Figure 11. DAC Chip Output Voltage Value of Each Channel

The decimal value and the ideal output voltage of the CPU real binary number are shown in Figure 12.

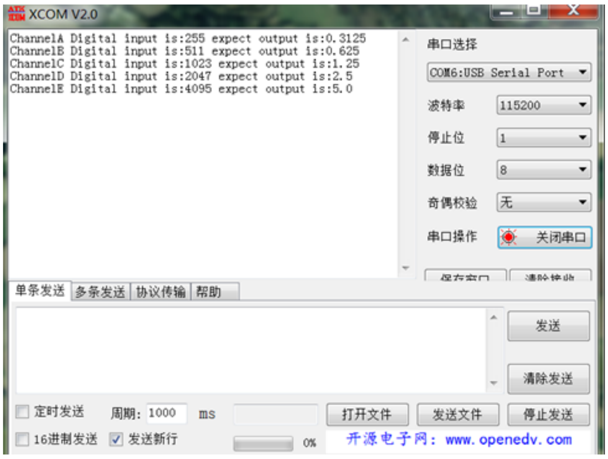


Figure 12. Digital Analog Conversion Results Print Output

The list of ideal voltage and measured voltage is compared with the following Table 1.

Table 1. Comparison of Ideal Voltage and Measured Voltage

CPU send digital quantity	Ideal voltage value (V)	Measured voltage value (V)
255	0.3125	0.312
511	0.6250	0.625
1023	1.2500	1.250
2047	2.5000	2.501
4095	5.0000	4.995

Analysis of the data found that the ideal value and the maximum deviation of the measured value is:

$$\Delta_{V_{\max}} = 5.000 - 4.995 = 0.005V \qquad (5.1)$$

The average deviation value can be calculated by the deviation value of each group：

$$\overline{\Delta V} = \frac{1}{n}\sum_{i=1}^{n}\Delta_{V_i} = 0.0013V \qquad (5.2)$$

The maximum reference error is:

$$\gamma_{\max} = \frac{\Delta V_{\max}}{5} \times 100\% = 0.1\% \qquad (5.3)$$

Through the data table and deviation calculation results can be seen, the measured value and the ideal value is slightly deviation, but the measurement results show that the SPI bus based electric proportional valve control accuracy to meet the requirements.

5.3. Field Test

The main function of the control system is that heat pipe steam generator used for changing the flue gas waste heat into steam heat to generate steam to drive *root-steam engine*, thus converted into mechanical energy, and then through the drive a generator to produce electricity. This part of the test is mainly produced by waste heat recovery of low-temperature waste heat steam to roots type power machine, by judging the generate electricity of the system can be judged the feasibility. The control system is applied to the field and debugging, the field test as shown in Figure 13.

Figure 13. The Field Test Picture

In the experimental process, The device has a larger vibration and is accompanied by a roar, when in a smaller valve opening. With the valve opening increases, the amplitude decreases gradually, and the roar is reduced. When the valve opening is about 1/2, the rated voltage is reached, so that the valve is fully opened, and the voltage is kept constant. Root-steam engine no-load - low pressure data data are shown in Table 2:

Table 2. Root-Steam Engine No-Load - Low Pressure Data

Generator speed(r/min)	Line voltage			Steam flow (t/h)	Steam pressure(MPa)
	AB (V)	BC (V)	CA (V)		
210	10	3	7	0.51	0.07
265	32	40	38	0.65	0.09
732	46	42	49	2.46	0.25
986	138	143	150	2.87	0.32
1200	202	200	200	4.32	0.45
1270	290	289	284	5.03	0.59
1400	343	349	336	5.74	0.67
1430	363	369	355	5.83	0.68
1490	378	380	379	6.45	0.69
1700	383	385	383	7.56	0.77
1930	389	389	389	8.72	0.81

when the pressure increases from 0.07MPa to 0.32MPa, the flow rate increases from 0.51 t/h to 2.46 t/h, the generator speed increased gradually and the variation is larger, but a little voltage change of power by Table 2 shown. When the speed is increased from 986r/min to 732r/min, the output voltage of power in jump, the pressure reaches 0.32MPa, the flow rate is 2.87t/h .When the speed increased from 1200r/min to 1270r/min, and the average voltage increased by 87V, the flow and pressure increased by 0.14MPa and 0.71t/h respectively. the average voltage value reaches 333V, the generator speed of 1400 r/min, the steam flow rate can be measured is 5.74 t/h, and the pressure value is 0.67MPa.During the process of the voltage value to achieve the rating value, the generator speed, steam flow and pressure compared to the last stage changes smaller. Generator power output voltage value is essentially remain unchanged after the generator speed is over 1490r/min.

For more intuitive reaction generator from the relationship between electric voltage and steam flow, pressure and rotating speed, using MATLAB, the Table 2 data were collected in order to obtain the voltage generator speed as shown in Figure 14.

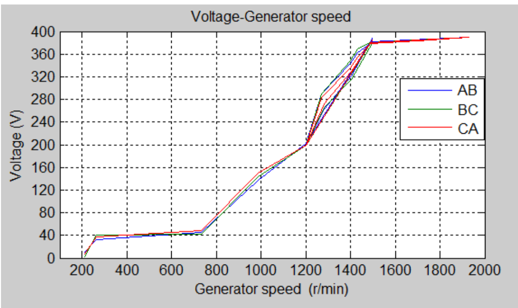


Figure 14. Voltage - Generator Speed Diagram

It can be seen in the diagram of output voltage and speed approximately "s" type and can be seen with the speed of increasing voltage also increases accordingly, but when the speed is in-creased to the rated speed voltage to remain stable.

From the below curve of Figure 15 can be seen steam is a kind of strong coupling gas, steam flow and pressure will affect the speed and may indirectly affect voltage, so the traditional control difficult to achieve stable control.

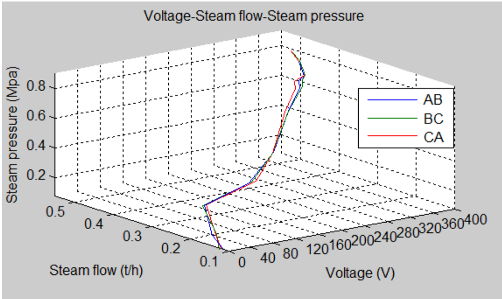


Figure 15.Voltage - Steam Flow - The Steam Pressure Diagram

Through the above Table 2 record the experimental data can be found, the roots - steam generator under no-load condition can be output in line with the requirements of electric energy.

6. Conclusion

The paper studies the secondary utilization of low quality waste heat resources, and put forward the scheme that heat pipe waste heat recovery device matches with roots-type steam engine to realize low-temperature waste heat recovery power generation. Process flow of low- temperature waste heat recovery power generation device and control system of low-temperature waste heat power generation device based on Embedded Technology are studied. The modular design method is used to develop embedded control system, and modular programming and software system development are completed based on process. Finally, the control system is tested, and it is showed that the embedded system can complete the voltage quality control and realize high efficiency recovery of low-temperature waste heat power generation device and conversion of electrical energy. In the paper, the system designed adopting modular method not only meets the needs of new generation control system control system, has the high openness, flexibility and versatility and has good reference for other embedded control system design.

Acknowledgements

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