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Research on Combustion Performance Optimization of Bio-fuel Combustion Machine Control System

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Abstract

In recent years, with the rapid development of society and economy, the energy shortage and the environmental pollution become more seriously, the heat industry, represented by the boiler, is of high energy consumption and emissions; it is facing tremendous pressure of energy conservation. Combustion machine is core of heating device; it controls the temperature distribution, thermal efficiency and service life of the boilers. In order to improve the thermal efficiency of combustion systems and save the energy, the burner is faced with the problem of optimizing the performance, solving these problems is of great social and economic significance. In this paper, in order to improve bio-fuel burner efficiency and decrease the pollution, after studying its control characteristics, we proposed the new performance control scheme, which use CO and O_2 *feedback correction as air volume to adjust bio-fuel combustion burner, based on it, we designed the software and hardware of control system, at the same time, we studied its combustion model and optimization algorithm, came up with the control algorithm of the burner based on LSSVM + GA. Finally, use the proposed control scheme and optimized control algorithm in this paper, to make the model of combustion efficiency and NOx emissions of bio-fuel machine, make the optimization experiments of* O_2*, CO amount based on GA gas, under the condition that NOx emissions is less than 0.52%, the combustion efficiency is less than 0.06%,the algorithm proposed can adjust the wind amount into burner timely and get the best combustion efficiency and nitrogen oxide emissions.*

Keywords*: Combustion Machine; Intelligent Control; Combustion Performance; Optimization Control*

1. Introduction

At present, the control technologies to optimize the combustion performance of bio-fuel combustion machine are mainly three categories: ①manual adjustment optimization based on on-line monitoring; ② optimization based on distributed control system (DCS); ③ optimization based on rectification of equipment performance [1-2]. With the gradual maturity of the advanced control technology and artificial intelligence, two kinds of technology of below have been key technologies in combustion optimization. They have been applied successfully in industry and have significant advantage to improve the combustion efficiency of the system and reduce NOx emissions with less investment[3].

American Ultramax Corporation developed the Ultramax combustion optimization system in the 90s of last century. The system uses Bayesian statistics+Weighted nonlinear regression analysis to build the model, it has precise identification, its biggest characteristic is it can send a feedback of performance parameters to the model, then model will update in each time of optimization, which makes the model update real-timely and realize the stable optimization. After the Ultramax, Pegasus Company developed the NeuSIGHT system[4], the core technology of the system is artificial

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intelligence neural network, it aimed at improving the thermal efficiency of the boiler and reducing NOx emissions.

GNOCIS PLUS system, which is made in British, used historical data to establish a model based on neural network to control the emissions of NOx and CO. At present, there are more than 49 coal power plant boilers using this system in the United Kingdom and the United States. Some scientific researchers and universities in China also have developed a variety of combustion optimization systems from the late 90's. Among them, the OCP3 system developed by Tsinghua University has solved the problem of nonlinear dynamic modeling of combustion engine operating characteristics, and the optimization of controlling combustion machine based on multi objectives. Combustion machine system with combustion guiding, which is developed by Xi'an Thermal Power Research Institute, achieved monitoring on combustion efficiency real-timely by monitoring wind speed, fuel flow rate and other important parameters, it acted as a guide to the burning machine operation. Southeast University developed a BCOS-2000/2.0 platform, it was based on integrated neural network model, the nonlinear optimization and correction model, it can guide combustion to make some adjustment, the application of the system showed that the combustion efficiency was improved by 0.5%~2.5%, NOx emission was reduced by10%~50%[5].

From domestic and foreign research we can know that: the burner control study mainly based on PID feedback and intelligent control algorithm, but the burner combustion control system based on online real-time modeling and optimization algorithm using PLC is still relatively lacking[6]. Therefore, it is necessary to conduct the research on optimizing combustion performance of the control system, it will provide a theoretical basis for improving optimal control.

2. The Design of Bio-fuel Burner Combustion Control System

2.1 Control Scheme

Bio-fuel burner control system consists of two parts: the air flow control and the fuel control. The co-ordination between two parts ensures that the fuel enters the combustion engine can burned completely and produces high combustion efficiency with low pollution emissions. General control system only use oxygen to adjust the amount of wind, but oxygen leakage and fuel performance has a greater impact, so in some cases, the mix working conditions of the machine and the severe presence of hypoxia can not be reflected directly, in addition, a small amount of carbon monoxide can react the deoxidization atmosphere in burner, with the increase of the temperature of the flame, carbon monoxide content also increases, but at this time, the impact of air leakage is less[7-8]. Therefore, in this paper, carbon monoxide feedback is introduced based on general principles of burner controlling, worked with oxygen feedback to adjust the air volume, the control scheme is showed in Figure 1, under the feedback of oxygen and carbon monoxide, fuel can burn more fully, we can get higher combustion efficiency and lower emissions.

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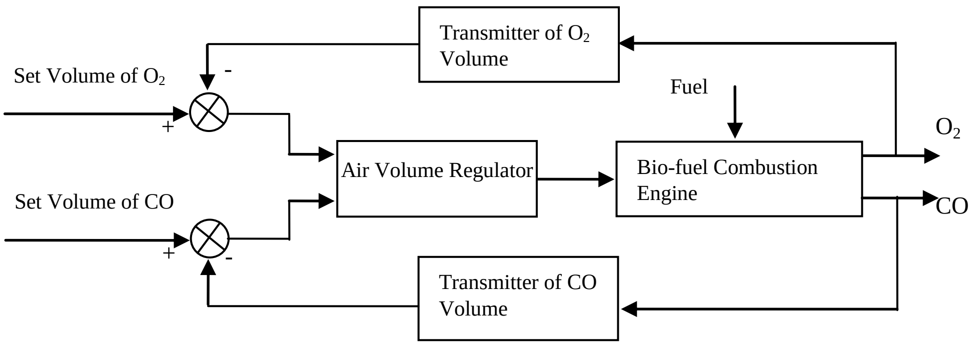

Figure 1. The Control Scheme of Bio-fuel Combustion Engine

2.2 The Design of Control System

2.2.1 Architecture of Hardware : Hardware platform is the center and core of the control system, at the same time, PLC had been applied widely in industrial control field, so the central controller module in this paper mainly based on PLC, hardware architecture is showed in Figure 2.

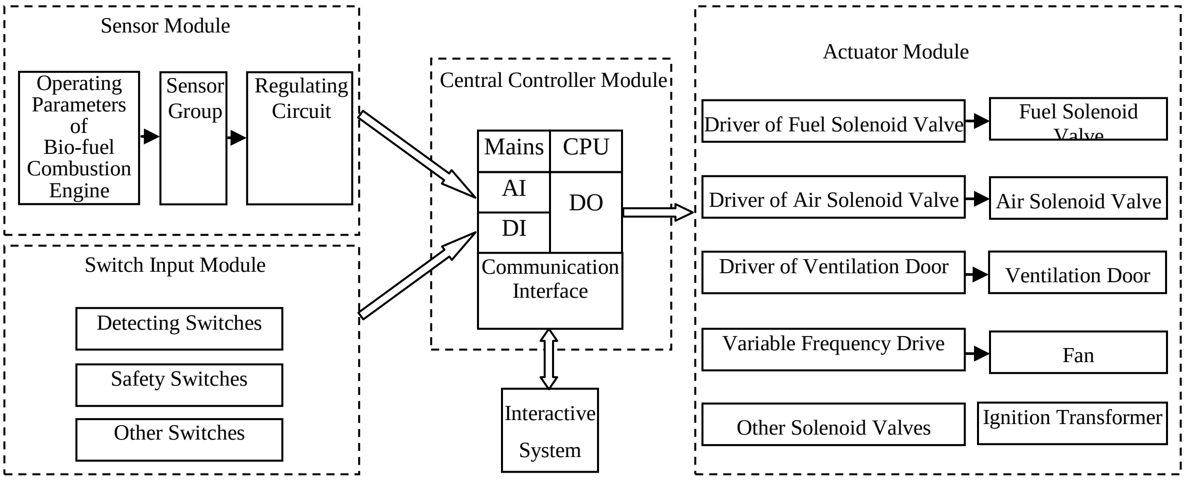

Figure 2. Hardware Architecture Diagram of Bio-fuel Combustion Engine Control System

2.2.2 The Design of Key Hardware Modules

① Sensor module

According to the hardware control architecture, the module will collect and send data regularly to the PLC, then PLC analog input module completes A/D conversion, the converted data will be sent to central processor to generate commands for controlling. Therefore, the sensor module in the intelligent control system in this paper consisted of temperature sensors, pressure sensors, oxygen sensors, carbon monoxide sensors, flame detectors and other components.

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② Switch input module

Digital switch input module includes detecting switches, safety switches and other switches, it is used to get some manual star, stop or other control commands information timely, at the same time, it is expected to complete the safety checking before the burner start and run to ensure the operational safety of the system.

③ Actuator Module

The module can control the burner combustion efficiency and low emission combustion directly, it includes atomization solenoid valve, purge solenoid valves, fans, inverters, damper servo motor, fuel valve, flow regulating valve servomotor, safety valve, the main valve, the ignition valve, ignition transformer and other components.

④ PLC central controller module

According to the design of peripheral module, the type of PLC used in bio-fuel burner control system can be determined, in this paper, we use S7-400 series PLC produced by Siemens corporation as the central controller, which uses modular structure, I/O points is between1024 and 2,048 points, I/O processing methods includes generic PLC scan mode and direct process approach.

2.3 Control Software Design

According to the main function of the burner and the intelligent control system design principles, software has main four tasks: collect and process the data from the field sensor and switch, implement the actuator control command generating and transmitting, record the mission scene data and check the safety, monitor the system. The overall architecture of the control system software is showed in Figure 3.

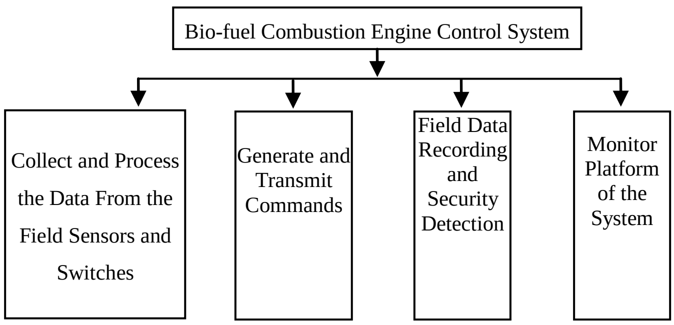

Figure 3. Software Architecture Diagram of Bio-fuel Combustion Engine Control System

2.3.1 The Flowchart of Control System : Bio-fuel working process consists of the following five parts: start-up stage, purging stage, ignition stage, stable combustion stage and normal shutdown stage.

①start-up stage: before the normal start, we should ensure that the air pressure switch and ventilation door are normally closed, and check the oil pressure and oil temperature. When checking results are correct and then it is allowed to go in combustion stage. However, if safety fault is found in subsequent control processes, it can lock the burner control and send alarm signal.

②purging stage: When the combustion burner work in normal way, the residual impurities in pipelines should first be purged. The fan is controlled by inverter, after starting the inverter and fan, the fan driver drives the damper to the maximum thermal to purge the impurities. Purge time can be set, if not set, it defaults to 15s.

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③ignition stage: After the second stage, the damper the ignition transformed from maximum thermal state to the ignition state. Ignition valve is also right in ignition position. the general process of ignition: start the ignition transformer →connect the ignition valve→shutoff the ignition transformer → detect the flame →open the main fuel valve.

④stable combustion stage:After the burner is ignited successfully, open the main fuel valve, during the combustion process, the sensors collect the data send them back to the controller timely, according to the control and feedback amount, the system dispatches each electronic control execution unit real-timely and remain the air-fuel ratios within reasonable limits, which can achieve the balance between combustion efficiency and NOx emissions .

⑤normal shutdown stage: Generally first close the fuel valve, then start purging process, and finally close the executive agencies.

2.3.2 The Software Design : The program running on S7-400PLC central processor, is made by Siemens, include systems and applications, the application is the focus of the design, it is generated in STEP7 and then loaded into the central processor to run. To procure the merger of the bio-fuel burner control system, according to the flow of control system and the idea of structured programming, the software program is divided into nine sub-programs:

①EK1 main program, call other subroutines. Scanning the cycle and the interrupt program execution, start and error of PLC, are all handled by the user control.

②EK100 initial startup program, it will be called automatically when the system starts.

③EK34 cyclic interrupt organization program, which calls the PID sequence control function block DK41 to achieve the adjustment to the amount of fuel and air flow. Execute the PID control adjustment once every 100ms.

④press DK1 button to control procedures, achieving jog button input, every time the jog button is pressed, switch state (ON_OFF) will flip once.

⑤DK2 set parameters program, complete the parameter calibration and storage of the pre-purge time and post-purge time.

⑥DK3 value conversion program, it can compute the pressure of fuel line, the density of oxygen and carbon monoxide, and the temperature of the fuel pipe, by calling STEP7 built-in numerical conversion function DL105.

⑦DK4 servo motor control program, it is responsible for the following valve servo motor control program, driving the throttle servo motor, atomizing air valve servo motors, fuel valve servo motor.

⑧DL1 inverter control program. Fan is controlled with inverter; we can adjust the amount of wind turbines by controlling the frequency of the inverter. The analog of inverter will be set in the interrupt program EK35, which will send an analog every 50ms, it will also provide data to MW20 by the man-machine interface. DL1 is responsible for drive’s stop, reverse, acceleration / deceleration and run permission.

⑨DL2 safety test program, during the normal operation of the combustion engine, it will complete safety inspection during normal interval work, which includes fuel valve leaking of fuel pipeline, pressure level, oil pressure level, oil temperature, once the fault is detected, it will lock the combustion controller, and call the police promptly.

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3. The Combustion Performance Optimization Control of Bio-fuel Burner

3.1 Optimization Control Algorithm

From analyzing the control scheme showed in 2.1, when the combustion system is operating in steady state, the amount of gas oxygen, carbon monoxide will be stabilized, both of which can show indirectly whether the fire combustor could achieve the goal of high efficiency and low pollution, therefore, the paper started from optimizing the amount of oxygen and carbon monoxide, we proposed a new optimal control theory based on least squares support vector machine (LSSVM) (Figure 4,)[9], it consists of the combustion model and optimization algorithm. In combustion model, there are n ($n \geq 3$) main factors X_i ($i = 1, 2, 3 \cdots, n$) used as input vector, the combustion efficiency and NOx emissions are used as output vectors to describe the combustion process, The model can predict the combustion efficiency and pollution emissions in optimization process. In optimization algorithm, the output of combustion model (combustion efficiency, NOx emissions) and other input vectors X_i ($i = 1, 2, 3 \cdots, n-2$) (except the amount of O_2 \and CO, X_{n-1}, X_n in feedback flue gas) of combustion mode, O_{2b} and CO_b, are output vectors, which are optimized amount of O_2 \and CO. Use O_2, CO to realize feedback modeling and optimization and output O_{2b}, CO_b, which are optimum value of O_2, CO. They will be used as set-value of the burner and participate in the control process showed in Figure 1.

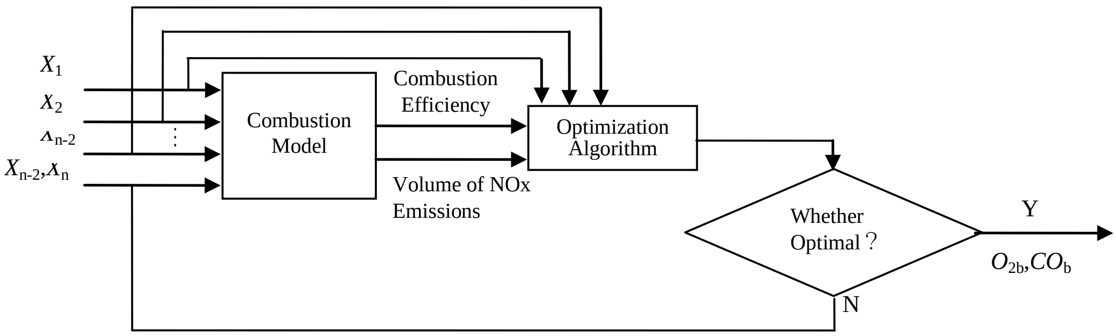

Figure 4. Principle of Optimal Control for Combustion Performance of Combustion Engine

3.2 Combustion Process Model Based on LSSVM

3.2.1 The Mechanism and Method of Combustion Process Modeling Based on Least Square Support Vector Machine: In order to realize the optimization of combustion performance, we proposed that applying the modeling method based on least square support vector machine in to combustion system. In this paper, we chooses four main factors, which can determine the combustion efficiency and nitrogen oxide emissions, as input, (fuel quantity B, air flow F, inlet air temperature and the temperature difference T of exhaust gas, calorific value of bio-fuel Q), the combustion efficiency, emissions amount of nitrogen oxide N as output to establish the combustion model based on Least squares support vector. The modeling process mainly includes obtaining the experimental data, constructing the training sample set, modeling for regression and predicting the combustion efficiency and nitrogen oxide amount[10].

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3.2.2 LSSVM Model Parameters of Combustion Process Based on PSO : The kernel function of LSSVM model is radial basis function $K(x_i, x_j) = \exp\left(-\|x_i - x_j\|^2 / (2\sigma^2)\right)$, which has better performance, the model performance is determined by two unknown parameters, they are the kernel function parameters σ and regularization parameter γ, σ and γ can affect the prediction performance of model directly[11]. PSO algorithm is an optimization algorithm based on smart groups, which depart from random solutions, find the optimal solution by iterating, the iterative formula is:

$$\begin{cases} v_{i(k+1)} = \omega_k v_{ik} + c_1 r_1 \left(P_{p(ik)} - x_{ik}\right) + c_2 r_2 \left(P_{gk} - x_{ik}\right) \\ x_{i(k+1)} = x_{ik} + v_{i(k+1)} \end{cases} \quad (1)$$

$v_{i(k+1)}$ is the first velocity vector of the i particle, x_{ik} is the number i particle after iterating k times, r_1、$r_2 \in (0,1)$ are random numbers, c is the learning factor (the value are c_1, c_2 generally), ω is the weight value to describe the influence that previous generation speed has on current generation speed. (it becomes inertia weight and will diminish gradually with the increase of iteration) $P_{p(ik)}$ is local optimum particle after iterations, P_{gk} is global optimization particles.

Since PSO algorithm has excellent performance of optimization, it is applied to optimize the LSSVM model parameters: σ and γ real-timely. The LSSVM model with optimized parameters can be used to predict the new target volume of combustion machine, the result works as the input of genetic algorithm, which can realize the optimization of oxygen amount and carbon monoxide. Fitness function of PSO is:

$$fit_{PSO} = t_1 \times |\eta_e - \eta| + t_2 \times |N_e - N| \quad (2)$$

η, N is the actual combustion efficiency and nitrogen oxide emissions, take the combustion efficiency of LSSVM model and predicted emissions of NOx as output; t_1, t_2 are their weight coefficients respectively. The value depends on concern degree of combustion efficiency and NOx emissions.

3.3 Optimization of Oxygen and Carbon Monoxide Volume

At present, there are many optimization algorithms, and in this paper we choose genetic algorithm, which has good performance in optimization process, to optimize the volume of oxygen and carbon monoxide. The algorithm retains a set of candidate solutions and chooses the better individual according to certain indicators, then combine them by genetic operators to produce a new generation of candidate solutions group, and repeat the process until the result reach certain convergence indicators[12].

In this paper, the optimization objectives of genetic algorithm can be described as follows: in some conditions, once given a certain amount of input to combustion machine, the algorithm will find the optimal amount of oxygen and carbon monoxide. In theory, the fitness function should be constructed based on the overall error that produced in LSSVM prediction model, taking into account the computational complexity of optimizing parameter, we construct the fitness function only according to the prediction error produced by predetermined number of input setting value, at the same time, considering

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the differences of in values of combustion efficiency and nitrogen oxide, the fitness function of genetic algorithm used in this paper as the formula (3) :

$$fit_{GA} = t_3 \times |\eta_b - \eta_e| + t_4 \times |N_b - N_e| \tag{3}$$

η_b, N_b are ideal values of combustion efficiency and NOx emissions; t_3, t_4 are weight coefficients of combustion efficiency and NOx emissions in genetic optimization algorithm, they are related to the concern degree.

3.4 Experimental Results and Analysis

The front part of this paper investigated the LSSVM model of combustion process and objective optimization method of genetic algorithm, then the performance of algorithm will be verified in following part by using MATLAB.

3.4.1 Establish the Model of Combustion Process Based on Least Squares Support Vector Machine : In this part, we use Matlab to model and simulate the process of combustion process based on LSSVM. Steps are as follows:

Get sample set: use the data showed in Table 2 to simulate, then get the experimental data sample set, build 2 LSSVM Models, which has two 4-input, 1 output:: η -LSSVM, N -LSSVM;

The optimization of LSSVM parameters: using first 11 operating conditions in Table 2 as a training sample data, the 12th operating conditions are test samples, using PSO (particle swarm optimization) to optimize σ ,γ , in order to reduce the impact made by the error of NOx emissions and combustion efficiency on PSO direction, the magnitude of them should be corrected, taking into account the proportion of their optimization, we take the coefficient t_1, t_2 as 9 and 0.2. The parameters of PSO algorithm are set in Table 1.

Table 1. PSO Algorithm Parameter Settings Table

Parameter Name	Parameter Value
Number of Particles	15
Iteration Times	40
Upper Bound of Particle	[15,100]
Lower Bound of Particle	[0,0]
Weight Interval	[0.3,0.8]

LSSVM training model: Under LSSVM model with optimized parameters, the predicted values for each operating conditions are showed in Table 2. From table 2 we can know, for the first 11 group of training samples, the predicted value and the measured value are very close, the relative error of nitrogen oxide emissions and combustion efficiency are both less than 0.06%. For the first 12 non-training input parameters, the relative error of combustion efficiency and nitrogen oxide emissions were 0.8121% and -0.0652%, which is very small, so LSSVM model has good generalization ability and can used to model for combustion efficiency and nitrogen oxide emissions.

Table 2. Training Results Based on LSSVM Model and Forecast Results

Operating Conditions	Fuel Volume (kg/h)	Air Volume (m^3/s)	Item	Measured Value	Predictive Value	Relative Error (%)
1	179.6	0.62	NO_x/mg·㎥$^{-3}$	709.52	810.61	0.0820
			Combustion Efficiency/(%)	94.1002	94.0215	-0.0021
2	175.1	0.61	NO_x/mg·㎥$^{-3}$	851.31	852.13	0.2453
			Combustion Efficiency//(%)	94.1541	94.2652	0.0512
3	173.4	0.58	NO_x/mg·㎥$^{-3}$	821.17	825.01	0.3006
			Combustion Efficiency//(%)	94.4118	94.4043	-0.096
4	172.3	0.57	NO_x/mg·㎥$^{-3}$	941.21	989.74	0.4085
			Combustion Efficiency//(%)	94.3928	94.3938	0.0011
5	171.5	0.55	NO_x/mg·㎥$^{-3}$	843.92	843.39	0.0278

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			Combustion Efficiency//(%)	94.6475	94.6417	-0.0051
6	170.7	0.54	$NO_x/mg\cdot m^{-3}$	658.39	662.01	0.3726
			Combustion Efficiency//(%)	94.6675	94.7254	0.0497
7	170.0	0.53	$NO_x/mg\cdot m^{-3}$	639.83	641.17	0.0342
			Combustion Efficiency//(%)	94.6139	94.6472	0.0254
8	163.4	0.51	$NO_x/mg\cdot m^{-3}$	741.25	742.61	0.1485
			Combustion Efficiency//(%)	94.7253	94.7059	-0.0313
9	160.1	0.50	$NO_x/mg\cdot m^{-3}$	684.58	685.83	0.0826
			Combustion Efficiency//(%)	94.7160	94.6868	-0.0201
10	156.25	0.48	$NO_x/mg\cdot m^{-3}$	618.15	618.18	0.0092
			Combustion Efficiency//(%)	95.0689	95.0387	-0.0304
11	148.3	0.41	$NO_x/mg\cdot m^{-3}$	577.31	578.01	0.0078
			Combustion Efficiency//(%)	95.0317	95.0507	0.0181
12	130.0	0.35	$NO_x/mg\cdot m^{-3}$	678.16	682.23	0.6698
			Combustion Efficiency//(%)	94.7827	94.7317	-0.0432

3.4.2 The Optimized Result Based on Genetic Algorithm of Oxygen and Carbon Monoxide Volume: Genetic algorithms is based on binary coding strategy, the scale of population is 50, the code length is 20, the selected probability is 0.75, the crossover probability is 0.6, the precision is 0.02, the amount of oxygen ranges from 2% to 6%, the amount of carbon monoxide in the range of 50ppm ~ 100ppm, the fitness function is formula (3), taking the experimental characteristic data of the maximum combustion efficiency 95.1% as ideal combustion efficiency and the minimum NOx emission 577mg • m-3 as ideal NOx emission value. And the coefficients in formula (3) were set 9 and 0.2.

Based on 11 trained sample data of work conditions, use the 12th working conditions result to simulate and optimize, the result is showed in chart 5 to 8, compare the actual values with the simulation results, as showed in Table 3.

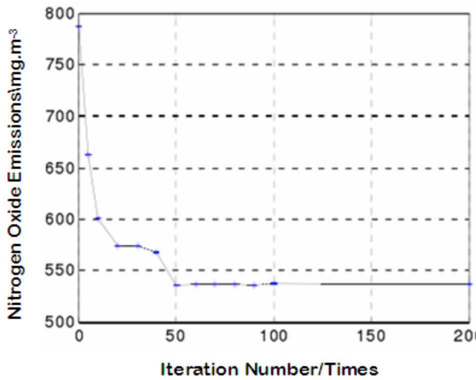

Figure 5. Nitrogen Oxides Optimization Process Diagram

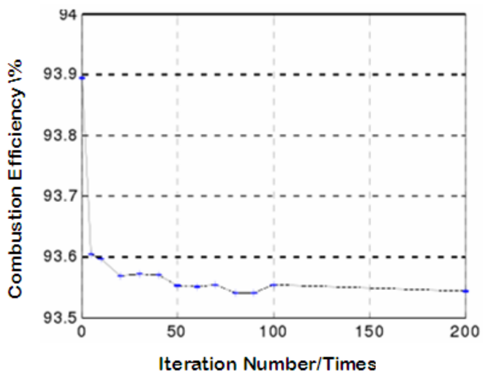

Figure 6. Combustion Efficiency Optimization Process Diagram

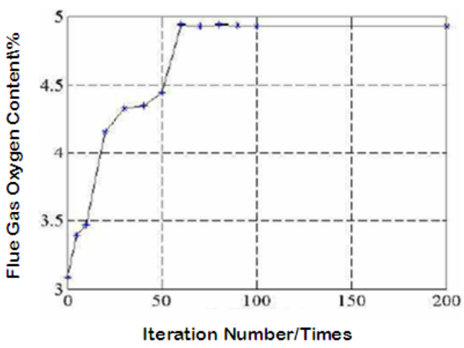

Figure 7. O_2 Volume Optimization Process Diagram

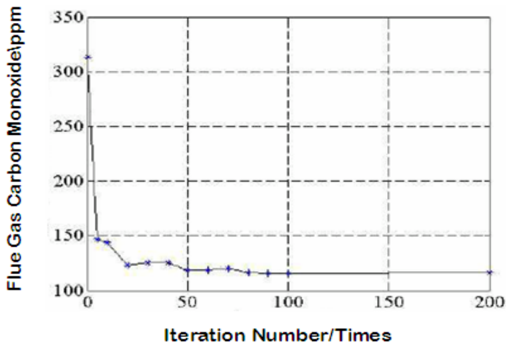

Figure 8. CO Volume Optimization Process Diagram

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From Figure 7 to Figure 8, we can see the optimization algorithm has converged after 98 generations, and compare the optimized result got in experiment with the actual measured data value, we can get Table 3, which shows that the amount of oxygen increased, the amount of carbon monoxide reduced, if η has a smaller reduction, NO_X emissions will lower obviously, such as working conditions of 10 and 11, the combustion efficiency of 11 working conditions declined by 0.084 percent than working conditions 10, but nitrogen oxides emissions increased by 5.6%, in conclusion that combustion optimization scheme can not only ensure the combustion efficiency, but also achieve the purpose of energy saving.

Table 3. Result Comparison Between Before Optimized and After Optimized

Item	Before Optimized	After Optimized
Oxygen Content/(%)	2.9789	3.0232
Carbon Monoxide Content/(ppm)	201.0015	109.7908
Combustion Efficiency/(%)	94.7827	94.4324
$NO_x/mg \cdot m^{-3}$	678.16	498.69

From optimization experiments of the prototype combustion and combustion performance control we can know that on the condition that the fuel amount is 148.3kg/h and the air volume is $0.41m^3/s$, the combustion efficiency is optimum, and at the same time the NOx emissions is also relatively low, the working conditions of combustion machine is optimal.

4. Conclusion

In this paper, we studied the method to optimize the combustion performance of the bio-fuel combustion machine and proposed the control scheme to optimize the combustion performance, in which the feedback amount of CO and O_2 are used to adjust and correct the air volume, also proposed the optimization control algorithm of combustion machine based on LSSVM + GA algorithm.

After analyzing the hardware architecture of bio-fuel combustion machine control system, we chose PLC as the central controller of control system and designed the core module of the control system, in addition, after studying the flowchart of the system, we refined the software tasks of PLC system and completed the function design of each module, finally achieved the optimization of control system.

Using the control optimization algorithm proposed in this paper, firstly, establish the model of combustion efficiency and NOx emission of bio-fuel combustion machine, which is based on LSSVM and can achieve the goal that the modeling errors of NOx emissions is less than 0.52% and of the combustion efficiency is less than 0.06%, on the basis of below, we conducted the O_2, CO amount optimization experiments based on GA, the method proposed can adjust the amount of into wind real-timely to get the best combustion efficiency and nitrogen oxide emissions.

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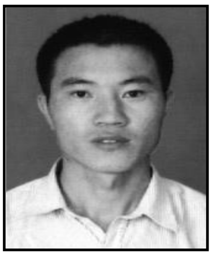

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