Design of Air Conditioning System for Pcr Nucleic Acid Detection Laboratory

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Abstract: The ventilation design of PCR laboratory is the premise of ensuring the reliability, accuracy and safety of the experiment. In the architectural layout, the PCR laboratory should be divided into reasonable areas, the pressure gradient between each laboratory room should be strictly controlled, and the purification and adjustment system and sterilization device should be set up. The structure of BP neural network decoupler and neuron adaptive PID controller are designed, and the initial value of the controller weight is determined by the parameters of traditional PID control algorithm. The simulation results show that the proposed control scheme can complete the decoupling and control tasks of the system well, and can improve the control law by learning in the control process, which has good decoupling and robustness. When the indoor air supply state is not changed, the best air change frequency of this PCR nucleic acid detection laboratory is 22 times/h; When changing the indoor air supply state, the best air exchange rate of this PCR nucleic acid detection laboratory is 18 times/h, which is lower than the air exchange rate required by the code. It can run stably and save energy.

1. Introduction

Since the advent of PCR technology in 1985, with its advantages of high sensitivity, strong specificity, convenience and low requirements for samples, it can detect viruses that are difficult to be detected by ordinary tests, and has been widely used in clinical diagnosis of hospitals and disease diagnosis of various epidemic prevention and detection departments. However, this kind of experiment needs a laboratory that can guarantee absolute safety, reasonable configuration and very standard operation [1]. In recent years, more and more attention has been paid to the construction of clinical gene amplification laboratory, because it plays a vital role in the reliability, accuracy and safety of test results.

To build PCR laboratory, we must first have standardized management and internal quality control process, and then analyze the main disease objects treated by each hospital laboratory, and set up corresponding ventilation and air conditioning system according to the biological harm degree of pathogen and the number of experiments every day [2]. Among them, the control of cross-contamination in the experiment, the occupational protection of indoor personnel and the harmless treatment of the effluent to the outdoor environment should be emphasized [3].

PCR nucleic acid detection laboratory is a reliable screening and confirmation method for virus detection, which has been widely used in medical and other fields, especially during this Covid-19 virus, as an important means for patients' diagnosis and detection. The country is also strengthening the infrastructure construction in this area, but the nucleic acid detection process is easy to be polluted, and the whole operation needs to be in a strict experimental environment to ensure the accuracy of data results, without missing or wrongly detecting suspected cases. The air conditioning design of this kind of laboratory directly affects the testing environment of the laboratory, but the biggest problem at present is how to accurately control the pressure and air distribution of the laboratory, which is the key to be solved urgently, so I put forward a complete air conditioning design scheme to ensure a good laboratory environment. In this project, I will study the types of ventilation

and air conditioning systems, the layout of vents, the construction and debugging points by means of data inquiry, field investigation and CFD (Computational Fluid Software) simulation analysis, and put forward constructive ideas and suggestions, hoping to provide reference for similar projects.

2. Main Functions and Equipment Configuration of Pcr Laboratory

(1)Reagent storage and preparation area

The main operations in this experimental area are preparation of stored reagents, sub-packaging of reagents and preparation of main reaction mixture. Reagents and materials used for specimen preparation should be transported directly to this area, and must not pass through other areas. The reagent raw materials must be stored in this area, and prepared into the required storage reagent in this area.

(2)Specimen preparation area

The main operations in this area are the preservation of clinical specimens, the extraction and storage of nucleic acids (RNA, DNA), and the synthesis of cDNA when they are added to amplification reaction tubes and RNA is measured. The pressure gradient in this area is required to be positive pressure relative to the adjacent area to avoid aerosol pollution entering this area from the adjacent area. In addition, the pollution caused by aerosol may occur during the sampling operation, so unnecessary walking in this area should be avoided. For materials with potential infectious risk, the cover must be opened in the biosafety cabinet, and there must be clear procedures for sample processing and inactivation.

(3)Preparation of amplification reaction mixture and amplification zone

The main operation in this area is DNA or cDNA amplification. In addition, the addition of prepared DNA template and synthesized cDNA (from sample preparation area) and the preparation of main reaction mixture (from reagent storage and preparation area) into reaction mixture can also be carried out in this area [4-5]. In nested PCR, the reaction tube must be opened after the first round of amplification, so nested amplification has high pollution risk, and the second sampling must be carried out in this area.

3. Principle Analysis of Cfd Numerical Simulation

The basic process of CFD numerical simulation is to simplify and establish geometric model, mesh the geometric model, and then use fluent to simulate and calculate. No matter any fluid, its movement must follow the following three basic laws: the law of conservation of mass; Law of conservation of momentum; Law of conservation of energy. This subject simulates the airflow distribution of indoor air, which satisfies the three laws and should follow the governing equation of incompressible viscous fluid.

The law of the immortality of matter is represented as the mass conservation equation in fluid dynamics, which is also called continuity equation. Its conservative differential form is expressed as follows:

$$\frac{\partial \rho}{\partial t}+\frac{\partial}{\partial x_i}\left(\rho u_i\right)=S_m \quad (1)$$

In which:

ρ -Density, kg/..;

t -Time, s;

x_i -Different directions;

u_i -Velocity vectors in different directions, m/s;

S_m -Source item.

The equation is a general form of mass conservation, which is applicable to compressible and incompressible fluids. Where S_m is the added source item, and the source item can also be other

user-defined source items. If there is no source item, S_m is equal to zero. If the fluid is incompressible, the density is constant, i.e $\frac{\partial \rho}{\partial t} = 0$. If there is no incompressible fluid with source term, the above formula can be written as:

$$\frac{\partial u_x}{\partial x} + \frac{\partial u_y}{\partial y} + \frac{\partial u_z}{\partial z} = 0 \quad (2)$$

The form of column coordinates is:

$$\frac{u_r}{r} + \frac{\partial u_r}{\partial r} + \frac{\partial u_\theta}{r \partial \theta} + \frac{\partial u_z}{\theta z} = 0 \quad (3)$$

4. System Design

4.1 Design Parameter

There is no strict purification requirement in PCR laboratory, but in order to avoid the possibility of cross-contamination among experimental areas, it is advisable to adopt the air flow organization form of full delivery and full discharge. According to the process requirements of this project, the purification level of PCR laboratory is set as Grade 7 (Grade C) [6]. There are no special requirements for temperature and humidity in the laboratory, which can be considered according to the temperature and humidity requirements of general PCR nucleic acid detection laboratories. The air supply mode in the purification area adopts the non-unidirectional air flow organization form of top delivery and side down return.

4.2 Purified Air Conditioning System

The purified air conditioning system is equipped with coarse, medium and high air filtration. The first stage is a coarse filter, which has a counting efficiency of not less than 50% for atmospheric dust with a particle size greater than 5μm and is set at the population of the air conditioning unit; The second stage is a medium-efficiency filter, which has a counting efficiency of not less than 70% for atmospheric dust with a particle size larger than l μm and is installed at the outlet of the air conditioning unit; The second and third stage is a high-efficiency filter, which has a counting efficiency of no less than 99.99% for atmospheric dust with a particle size larger than 0.3 μ m and is installed in the high-efficiency air supply outlet at the end of the system.

Because the PCR nucleic acid detection laboratory selected by the research is an inner area surrounded by corridors and another PCR nucleic acid detection laboratory, its cooling load is only caused by the temperature difference heat transfer of the inner envelope, which can make stable heat transfer and does not change with time, and can be calculated according to the following formula [7]:

$$Q_{c(\tau)} = K_i A_i \left(t_{o.m} + \Delta t_a - t_R \right) \quad (3)$$

In which,

$Q_{c(\tau)}$ -Cooling load through internal maintenance structure, w;

K_i -Heat transfer coefficient of inner envelope, w/(m 2 • ℃);

A_i -Area, m^2;

$t_{o.m}$ -Calculate the average daily temperature outside the air conditioner in summer, ℃;

Δt_a -Additional temperature rise.

A fixed air volume control valve is installed in front of the high-efficiency filter air supply outlet, mainly because the initial resistance of the high-efficiency filter is small, and then the resistance increases greatly due to the accumulation of dust particles, which leads to the reduction of air supply volume, and the unstable air volume will make the indoor pressure difficult to control. Installation of

air volume control valve can avoid the adverse effects in this respect and keep the indoor pressure constant to the maximum extent.

4.3 Design of Neuron Adaptive Pid Controller for Vav System

Single neuron is the basic part of neural network, which has the ability of self-adaptation and learning, and its structure is simple and easy to calculate. At the same time, the traditional PID control has a simple structure and is convenient to adjust, and the parameter setting is closely related to the engineering index. It is essentially a linear weighted summation network with continuous values. Its characteristic is that there are multiple processing units in the input layer, but only one processing unit in the output layer, which realizes the weighted summation function for multiple inputs. In actual control, the weight can be corrected according to the deviation, so the final control accuracy is relatively high [8-9]. The control block diagram of VAV air conditioning system unit is shown in Figure 1.

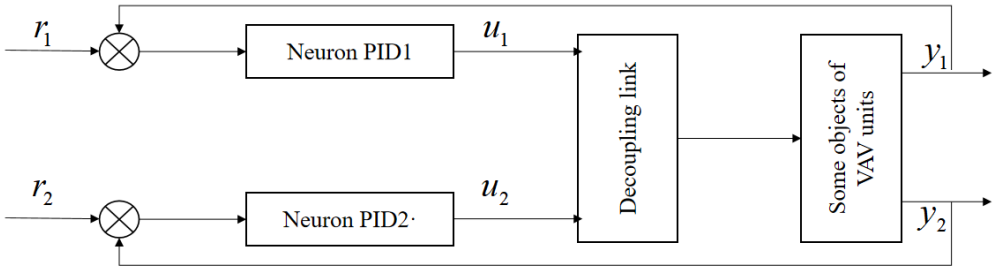

Fig.1 Block Diagram of Unit Control of Vav Air Conditioning System

The neuron adaptive controller realizes self-organization and self-adaptation by adjusting the weight coefficient, which is realized according to the supervised Hebb learning rule. Taking the first neuron PID controller as an example, the control algorithm and learning algorithm are as follows:

$$u_1(k) = u_1(k-1) + k_1 \sum_{i=1}^{3} w_1'(k)\, x_i(k) \quad (4)$$

$$w_1'(k) = \frac{w_i(k)}{\sum_{i=1}^{3} |w_i(k)|} \quad (5)$$

$$w_i(k+1) = w_i(k) + \eta_i \times r_i(k) \quad (6)$$

In the formula, η_i is the learning rate, which can be described as different learning rules according to different forms of $r_i(k)$. here, $r_i(k) = e(k)u(k)x_i(k)$ is taken.

Single neuron adaptive control algorithm, which essentially establishes performance index through system error, is a nonlinear optimal control. This algorithm only needs to test the expected and actual output of the system on line in order to form the adaptive control law, so this kind of controller is realizable.

4.4 Energy Saving Optimization of Pcr Nucleic Acid Detection Laboratory

Generally speaking, due to the requirement of cleanliness level, a large amount of air supply must be used to reduce the concentration of pollutants and increase the cleanliness, but this greatly increases the operating cost. Especially in the main control area, the concentration of pollutants must be controlled so that the production process or products are not polluted; However, the primary goal of biosafety laboratory is to ensure its biosafety, while other standards are secondary requirements, and ensuring the flow direction of biosafety airflow organization is the most basic guarantee; For most PCR nucleic acid detection laboratories, in order to ensure cleanliness, many designers simply rely on increasing air changes to ensure cleanliness, which virtually increases the energy consumption of PCR nucleic acid detection laboratories. The energy consumption of biosafety laboratories is higher

than that of general PCR nucleic acid detection laboratories. Due to the safety requirements, biosafety laboratories need to keep running frequently, which virtually increases the running cost.

Generally speaking, indoor pollutants are mainly considered from the following aspects [10]:

(1)Distribution of building materials in PCR nucleic acid detection laboratory;

(2)Particulate matter brought in by fresh air;

(3)Particulate matter produced by the production process of PCR nucleic acid detection laboratory;

(4)Infiltration of adjacent PCR nucleic acid detection laboratories;

(5)PCR nucleic acid detects the amount of emission caused by the activities of the staff in the laboratory.

The dust emission of indoor workers is related to their activity intensity, which is generally estimated by the following formula:

$$\begin{cases} \text{Labor intensity (low)} & \mathrm{M}=83.3+2000\mathrm{g} \\ \text{Labor intensity (middle)} & \mathrm{M}=83.3+3333\mathrm{g} \\ \text{Labor intensity (high)} & \mathrm{M}=83.3+4467\mathrm{g} \end{cases} \quad (7)$$

In which:

M --Dust emission per unit volume, PC/($\mathrm{m}^3\cdot\mathrm{s}$);

g -Personnel density, people/m^3, equation (7) applies to the case of $g \le 0.5p/\mathrm{m}^2$.

Under the normal operating environment of PCR nucleic acid detection laboratory, the emission of people in static state is 1×105 grains/,and the emission of ground surface is 130 PC/($\mathrm{m}^2\cdot\mathrm{min}$), so the indoor dust emission per unit volume G is:

$$G=(4g+0.42)\times 104 \quad (8)$$

In which: G is indoor dust emission per unit volume, PCV/($\mathrm{m}^2\cdot\mathrm{min}$).

The number of people entering PCR nucleic acid detection laboratories is limited: the staff density of PCR nucleic acid detection laboratories not lower than level 5 should not be higher than 0.1, and that of PCR nucleic acid detection laboratories not higher than level 6 should not be higher than 0.25; For example, in a Grade 5 area with an area of 50 m2, the number of people entering the clean room at the same time should be higher than 5; Therefore, the personnel density of PCR nucleic acid detection laboratory is controlled at 0.05 persons/m^2.

Then the emission intensity C of dust caused by the activities of operators and dust emission from the ground in the room of this experimental model is:

$$C=G\times V \quad (9)$$

In which: G is the emission intensity of dust, g/s;

The air density $\rho=1.293\mathrm{kg/m}^3$ at normal temperature, i.e. $\rho=1.293\mathrm{g/cm}^3$; As we all know, the density of dust in the air is higher than that in the air; And general cohesive soil $\rho=1.8-2.0\mathrm{g/cm}^3$; Sand $\rho=1.6-2.0\mathrm{g/cm}^3$; Humid soil $\rho=1.5-1.7\mathrm{g/cm}^3$, so the limit of dust density ρ is 2.0.

Therefore, the dust emission intensity of PCR nucleic acid detection laboratory is $C_0=C\times\left(0.5\times10^{-6}\right)^3\times2.0\times10^3/\left(10^{-2}\right)^3=0.0271625\mathrm{g/s}$.

5. System Analysis

According to the neural network decoupling learning algorithm introduced above, the M file is compiled to train the neural network. After the neural network decoupling training is completed, according to the above neural PID control algorithm and initial weights, the control program can be compiled to carry out the simulation experiment of the neural PID controller. To compare the control

effects, we use the traditional PID control instead of the single neuron PID controller, and the following simulation results can be obtained (Figure 2).

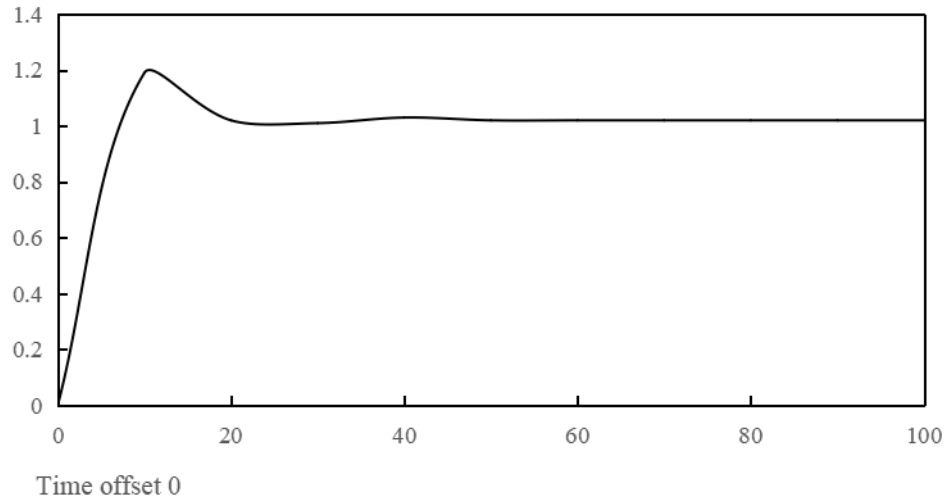

Fig.2 Static Pressure Control Effect under Traditional Pid Controller

From the above comparison chart, it can be clearly seen that under the traditional PID control, the static pressure and temperature overshoot are increased, and the time to reach stability is also lengthened, which is far less effective than the single neuron PID controller. In order to show the effect of neural network decoupler, we can get the following effect by changing the parameters of the controlled object (Figure 3).

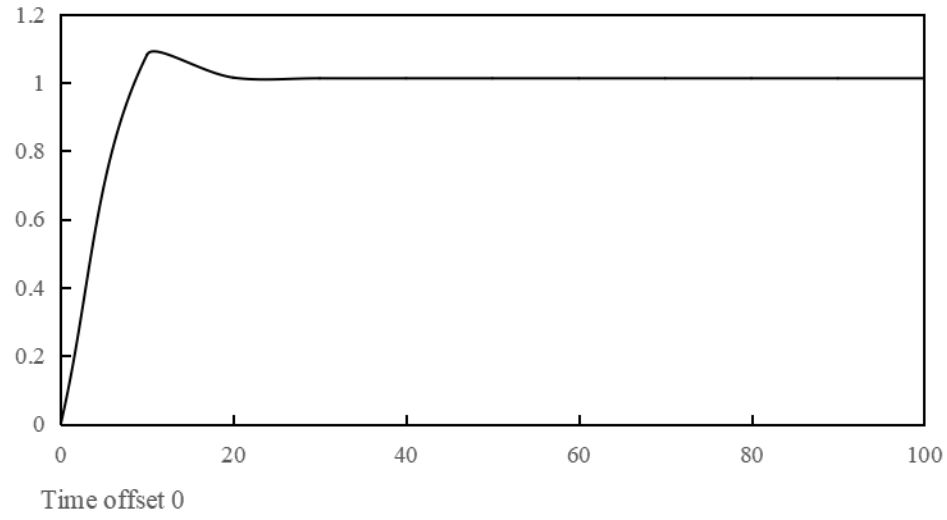

Fig.3 Effect Diagram of Static Pressure Control after Changing the Controlled Object

Comparing fig. 2 with fig. 3, it can be found that after changing the controlled object, the simulation results do not produce large difference, but the decoupling can still be completed well, which shows the adaptability of neural network decoupler, which is also its advantage. In a word, neural network decoupler and single neuron PID controller can accomplish the decoupling and control tasks of multivariable systems well. The learning algorithm of single neuron PID controller is simple, the computation is small, and it is easy to realize. Moreover, it needs less object model information, so it can learn reasonable control rules in the control process, thus achieving the purpose of system decoupling and control.

On the basis of the previous section, this section will simulate a series of parameters such as cleanliness, temperature and humidity of the laboratory by reducing the number of indoor air changes. See table 1 for the simulated air exchange rate and air exchange volume.

Table 1 Air Exchange Rate and Air Exchange Rate in Simulation Experiment

Number of air changes/h	24	22	20	18	16
Ventilation capacity m^3	1583.4	1507.1	1475.3	1402.8	1278.5
Number of air changes/h	14	12	10	8	6
Ventilation capacity m^3	1063.9	912.47	814.7	669.8	554.7

According to the air exchange rate and air exchange rate in table 1, the simulation experiment of air flow organization in PCR nucleic acid detection laboratory was carried out, and its cleanliness, temperature and humidity were detected, and then the indoor air exchange rate was adjusted, which reached the goal of optimal air exchange rate, thus providing data basis for reducing indoor energy consumption. Figure 4 shows the trend diagram of concentration change at each point following the change of ventilation frequency obtained from simulation experiment.

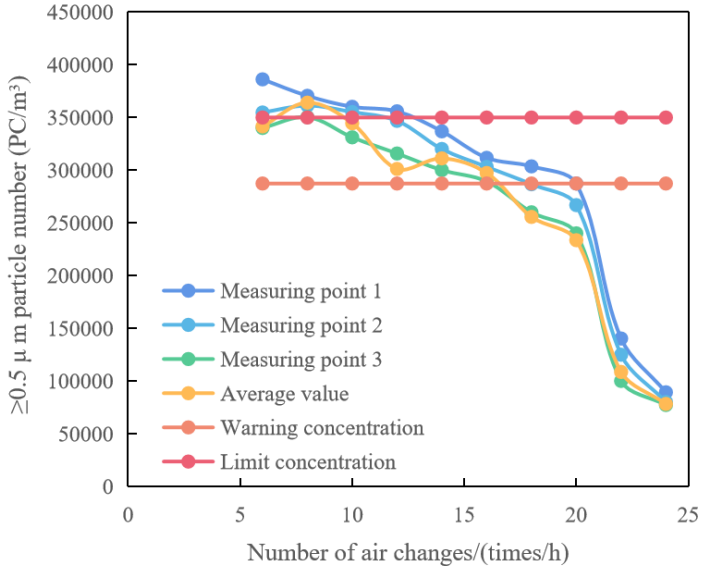

Fig.4 Trend Diagram of Concentration Change of Each Measuring Point with Change of Air Exchange Rate

It can be seen from Figure 4 that when the air exchange rate is less than 20 times/h, the amount of pollutants will increase sharply with the decrease of air exchange rate; When the air exchange rate continues to increase from 20 times/h, the amount of pollutants gradually decreases with the increase of air exchange rate. When the air exchange rate exceeds 24 times/h, the decreasing speed will be relatively slow. When the air exchange rate exceeds a certain range, the indoor pollutant concentration basically does not change with the increase of air exchange rate. With the decrease of air exchange times, the concentration of pollutants basically decreases regularly; Therefore, according to the above knowledge, considering the error factor, the best ventilation frequency in our laboratory is 18 times/h.

6. Summary

According to the different heat and humidity load characteristics in different areas of PCR nucleic acid detection laboratory, different air-conditioning forms are set in this project, and the high-temperature ground source heat pump system and solution humidity control system are adopted to avoid a large amount of reheating load, provide the operation efficiency of cold source and significantly reduce the system energy consumption. The common multivariable decoupling methods are studied and compared, and the intelligent decoupling technology of multivariable process control

system is obtained. According to the actual situation of this paper, it is decided to adopt the intelligent decoupling control technology based on neural network. Under the same air supply temperature, the indoor temperature increases gradually when the air exchange rate decreases, and when the air exchange rate decreases to 22 times/h, the indoor temperature basically reaches the highest temperature in design; With the further decrease of air changes, the indoor temperature rises more obviously.

Acknowledgments

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