Key Engineering Materials Vols. 381-382 (2008) pp 65-68
online at http://www.scientific.net

Online available since 2008/Jun/12

The Development of a Separated Mini-environment

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Keywords: Micro/Nano-metrology, TEC, Mini-environment, Temperature Measurement and Control, Adaptive PID

Abstract. This paper develops a new separated mini-environment to provide a constant temperature chamber for the placement of Micro/Nano-metrology instrument. In this paper, the rule of temperature change with time under natural convection and coercive convection is presented. The measurement and control system is composed of TEC, programmable power source and precise temperature measurement system. The mathematic model of the constant temperature chamber is identified making use of system identification theory and system identification toolkit of MATLAB. The temperature stability is improved by applying auto-adaptive PID method. Experiments show that the temperature fluctuation of a single-point is less than 0.02°C and the whole field is within 0.05°C. The goal of high-precision temperature control is achieved.

Introduction

An important problem of micro/nano-measurement technology is the environment control, including temperature, humidity, cleanliness and vibration [1]. The influence of temperature on the measurement uncertainty is critical for nano scaled dimension. Usually, a clean room has to be built up to place in high precision measuring equipment. Its construction cost is high. The indoor activities will also affect the temperature stability. However, all measurement equipments need the high precision environment. Designing a mini-environment has fundamental significance. Traditional temperature-controlled chamber is an integrative body using natural convection or fans to generate air circulation, which is composed of a constant temperature chamber and a refrigeration chamber. The compressor and the fans will induce unavoidable vibration to the equipment base.

This study develops a new mini-environment that separates the constant temperature chamber from the refrigeration chamber. Two parts achieve air circulation between each other. This kind of structure reduces costs and improves accuracy.

Design of a Separated Mini-environment

This mini-environment is composed of three detached chambers, including constant temperature chamber, static pressure chamber and refrigeration chamber. Air, be cooled by TEC [2] and mixed in refrigeration chamber, blows to the static pressure chamber with a blower. Then, air is mixed once again in the static pressure chamber and flows to the constant temperature chamber through a mulit-hole plate. Only the static air circulation operates within the constant temperature chamber. It ensures temperature stability that any noise caused by the moving parts of the refrigeration chamber can be completely isolated from the constant temperature chamber.

The intake air in the static pressure chamber will firstly be reflected by a cone-reflector yielding to an evenly distributed air flow field. It then passes through the uniformly distributed array-hole plate to the constant temperature chamber. When the pressure of static pressure chamber is higher than that of constant temperature chamber, air passes through the array-hole plate and forms uniform piston airflows. Since the air is mixed adequately, so that the temperature field is proportional to the velocity field.

It is noted that there are also heat sources generated from the motors of the measuring instrument in the constant temperature chamber. The airflow in the constant temperature chamber is, thus, of mixed convection that is composed of the forced convection and the natural convection that yields to turbulent heat transfer. It conforms to the Boussingesq hypothesis that the flow of the airstreams is unstable at the beginning and becomes stable at steady-state temperature condition[3]. Models of airflow and thermodynamics can be expressed by the Momentum equation (Navier-Stokes equation) and Kinetic Energy equation as follows:

$$\frac{\partial}{\partial x_i}(\rho u_i u_j) = -\frac{\partial}{\partial x_i}(p + \frac{2}{3}\rho k) + \frac{\partial}{\partial x_i}[(\mu + \mu_t)\frac{\partial u_j}{\partial x_i}] + \frac{\partial}{\partial x_i}[(\mu + \mu_t)\frac{\partial u_i}{\partial x_j}], \tag{1}$$

$$\frac{\partial}{\partial x_i}(\rho u_i k) = \frac{\partial}{\partial x_i}(\frac{\mu_t}{\sigma_k} \cdot \frac{\partial k}{\partial x_i}) + G - \rho\varepsilon, \tag{2}$$

where ρ - fluid density, p - pressure, K - coefficient of heat conduction,
t-time, u- speed vector, ε - turbulent energy dissipation rating,
k- turbulent pulsant kinetic energy, μ_1 - turbulent glutinosity

The intensity of heat exchange lies on the intensity of the heat source and is dependent not only on the difference in temperature, velocity of flow, thermodynamic and transportation characteristics but also on the angle between the airflow rate vector and heat flow vector. Reducing this angle can increase the heat exchange. Within constant temperature chamber, air flows to heat source device through holed plank. It is in favor of increasing intensity of heat exchange.

The simulation model of CFD software is established by taking the experienced parameters[3] c_μ=0.09, c_1=1.44, c_2=1.92, σ_k=1.0, σ_ε=1.3.

(1) Without heat source in constant temperature chamber

At the entrance the air velocity is v=0.5m/s and temperature is 293K. Simulated experiments show that if the temperature at the entrance is uniform, heat exchange rate is increased by increasing the air speed. The flow of air must have little effect on instruments because of precision demand of micro/nano-measurement. So the speed of airflow is controlled of under 1m/s when air is at steady-state and can be chosen to be bigger at the beginning.

(2) With heat source in constant temperature chamber

Assuming that the temperature of entrance is 293 K, speed is 1m/s and there is heat source of 323K in constant temperature chamber, simulated experiments show that if speed at entrance is increased, the heat exchange effect is significant. If the speed increases to a certain amount, this heat exchange will be no more effective. As long as there are heat sources it will cause great effect on temperature field of which the quantity of heat cannot be removed. In other words, these heat sources must be locally isolated.

Modeling and Control of the Separated Mini-environment

The measurement and control system is composed of eight TECs, programmable power source and precise temperature measurement system. The photo of the separated mini-environment is shown in Fig. 1.

When the mathematic model of the separated mini-environment is built, not only the structure of chamber but also all kinds of environment factors are considered. Forcing step-response signal to TEC and logging input and output data are applied to the System Identification Toolbox of MATLAB. According to identification steps of Process Models[4], we can easily build the mathematic model of he separated mini-environment.

Using MATLAB, the transfer function of the system's step-response is identified by:

$$G_p(s) = \frac{7.1}{705s+1} e^{-189s}, \tag{3}$$

It is a first-order inertia object with delay[5].

The design method of pole configuration self-adaptive PID controller is employed. Firstly, we convert the transfer function of controlled object into the impulse transfer function with zero-order holder. Secondly, we convert the above-mentioned transfer function into the best dynamic response model of second-order system in view of pole configuration. Finally, we convert the pole configuration self-adaptive to incremental PID controller [6] and receive three parameters of pole configuration self-adaptive PID controller.

$$K_p = 0.8579 \;, T_I = 28\text{s} \;, T_D = 0.41, \tag{4}$$

Applying these three parameters to Simulink of MATLAB to simulate the control model, we can obtain the step-response curve, as shown in Fig.2.

The developed program uses MATLAB script in the LabVIEW to improve the ability of data operation so that the advanced control arithmetic can be applied in the LabVIEW G program.

Fig. 1 Photo of the Separated Mini-environment

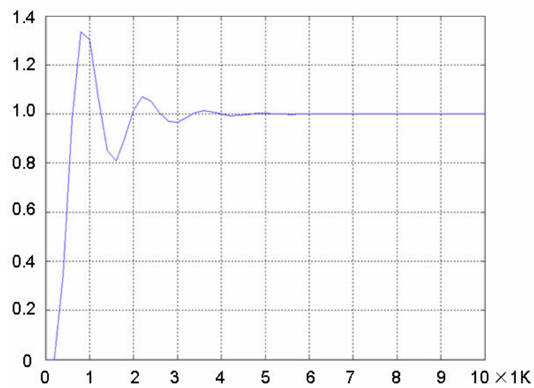

Fig. 2 MATLAB step-response curve

Experiments

Place a temperature sensor at the center of constant temperature chamber as the feedback sensor and four temperature sensors around to observe change of the temperature field in the chamber. During a two-hour run the temperature variation are recorded, as shown in Fig.3 and Fig.4. It can be seen that the temperature fluctuation of a single-point is less than 0.02°C and the whole field is within 0.05°C. We can find that the designed system is reasonable and identified model is correct. The goal of high-precision temperature control is achieved.

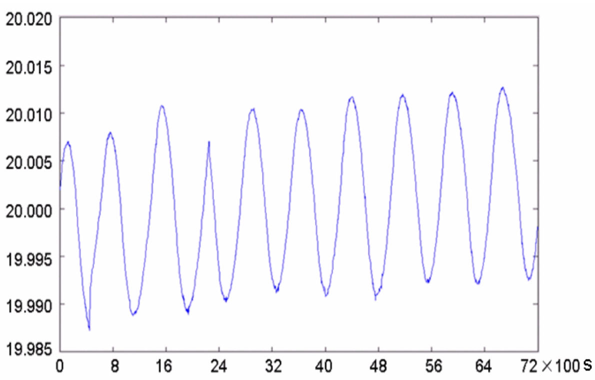

Fig.3 temperature change of a single-point curve

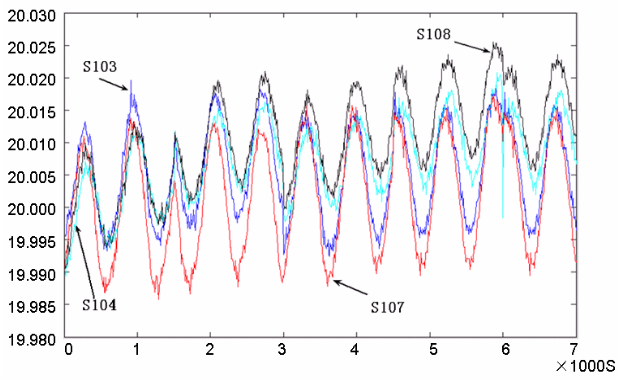

Fig.4 change temperature field curve

Conclusions

This paper has analyzed the temperature rule of a separated temperature-controlled chamber with the consideration of forced convection state and identiified the mathematic model with advanced system identification toolbox. The temperature precision is improved by applying the auto-adaptive PID method. The process of program is simple and effective due to applying the method of MATLAB embedded in LabVIEW. Experiments show that the model is correct and the control method is effective. The goal of high-precision temperature control is achieved. The method of identification and control can be widely applied to similar process control.

Acknowledgement

This research is part of an International Cooperation Project with University of Australia and funded by National Natural Science Foundation of China under contract number: 50420120134.

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Measurement Technology and Intelligent Instruments VIII
doi:10.4028/3-908453-33-X
The Development of a Separated Mini-Environment
doi:10.4028/3-908453-33-X.65