Design and development of temperature collection system on solid granular beds

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ABSTRACT: *On the basis of analyzing the heat transfer performance of solid granular beds, an unsteady-state heat conduction model describing the temperature change of the grains is built and the finite-difference implicit schemes are theoretically deduced using the volume equilibrium method for numerical simulation. The validation of the numerical model is checked through compared with the experimental results. A temperature collection system is designed and developed. As a part of the system, an initial temperature simulator for measuring the initial temperature of grains is also developed according to the similarity principle. This system can accurately measure the temperature field and real-time average temperature of the grains and simultaneously transfer the temperature information to the computer terminals through the controller area network bus.*

Keywords: Temperature collection system, Measurement technology, Similarity theory, Solid granular beds

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1. Introduction

In the production and management process of mechanical industry, chemical industry, food industry, national defence industry and other fields, the internal temperature field of products and goods in store often require to be real-time monitored for eliminating security risks, promoting safety production and management, reducing unnecessary personal and economic loss. For example, monitoring the real-time temperature of dangerous chemicals into storage tank to remove the danger sources, monitoring the temperature of grains in store to prevent sprouting and spoiling, monitoring the temperature changes inside solid propellants to be without spontaneous combustion, detecting the internal temperature of ammunition to obtain accurate loading parameters, etc. A common feature of this kind of measurement problem is the internal temperature of the measured object, similar to the solid granular beds, cannot be directly obtained. At present, there are many temperature measurement technology, such as thermocouple, infrared measurement and spectral measurement technology, are all able to determine the temperature of the measured object. However, they are not available for this kind of measurement issues. Using thermocouple methods to measure the temperature inside solid propellants, the holes must be drilled on the surface to place thermocouples. This is obviously not allowed in practical use. The infrared measurement and spectral measurement technology can only detect the outer surface temperature, not obtain the internal temperature of solid granular beds accurately.

The In recent years, through a lot of theoretical and experimental studies on the applications of temperature measurement technology as the background, experts and scholars all over the world make a lot of research results, and develop a number of new and practical temperature measurement technology and method, such as infrared thermal imaging technology [1-4], spectral measurement technology [5, 6], laser measurement technology, etc. Spanjers, et al. discuss the effect of propellant temperature on efficiency of a pulsed plasma thruster by using infrared thermal imaging technology [2]. Kolasa and Flyash apply telemetry technology to ammunition temperature [7]. They put the temperature sensor made of beryllium copper alloy into the cartridge to measure the charge temperature and transmit the experimental data to the recorder through the antenna. Chyu and Bizzak investigate two-dimensional temperature field distribution of circular surface using the laser-induced fluorescence thermal imaging technology [8, 9]. Sun, et al. introduce the application of liquid crystal thermography in the temperature measurement and analyse the advantages and disadvantages of this method and its applicable range [10]. Gong, et al. develop the charge temperature measurement system of a solid rocket motor to test the propellant temperature, and obtain the empirical formula of equivalent temperature by the theoretical computation of the simulation software ANSYS [11]. The common characteristic of these studies is focused on the temperature change process of the measured objects without paying attention to the determination of real-time temperature. In this paper, for this kind of solid granular beds whose internal temperature can not be directly measured, a temperature collection system to determine the real-time temperature field distribution is designed and developed. The primary idea of design and development is software solution and hardware realization through the combine of heat transfer theory and computer information processing technology on the basis of the theoretical analysis and experimental study on the temperature field of solid granular beds.

2. Design and development of temperature collection system

As well-known, the grains inside solid granular beds are always in the thermal non-equilibrium status due to the change of the environment temperature. The temperature field of the grains is the unbalanced temperature field and varies with the environment temperature and time. From the view of practical use, the grain temperature is not allowed to be measured by holing or other contact measurement methods. Therefore, a temperature collection system is designed and developed for solid granular beds. Using the collection system, the temperature of grains can be successively obtained. The collection system is composed of a PC104 microprocessor, special computation software and two sets of the special temperature sensors. The main function of the special computation software is to determine the current values of the grain temperature through the numerical solution of the unsteady heat transfer equations. Two sets of the special temperature sensors are used to obtain respectively the initial condition and boundary condition, i.e. the initial grain temperature and environment temperature, for the unsteady heat transfer equations. When the system powers on and begins to work, one set of sensors are used to measure the current values of the grain temperature as the initial values of the grain temperature field and another set are used to measure successively the environment temperature as the boundary condition of the unsteady heat transfer equations on the grain temperature field. The temperature field and current average value of grains are real-time calculated through the special computation software installed on the system.

2.1 Heat Transfer Model Used in The Special Computation Software

The heat transfer process of solid granular beds can be described by the unsteady heat conduction model of a two-dimensional axisymmetric cylinder. Generally, the solid granular beds consist of the container shell, grains and air. Thus, the differential equation should be written as follows

$$\rho c \frac{\partial \theta}{\partial t} = \frac{\lambda}{r}\frac{\partial \theta}{\partial r} + \frac{\partial}{\partial r}\left(\lambda \frac{\partial \theta}{\partial r}\right) + \frac{\partial}{\partial x}\left(\lambda \frac{\partial \theta}{\partial x}\right) \quad (1)$$

where θ is the temperature of solid grains. ρ, c and λ are the density, specific heat and thermal conductivity of materials respectively.

In order to solve equation (1), the initial condition and boundary condition need to be given. The initial temperature of grains can be expressed as

$$\theta(x,r,t)\big|_{t=0} = \theta(x,r,0) = \theta_0 \tag{2}$$

The initial temperature of grains may be measured by the special temperature sensors called initial temperature simulators. Consider the heat transfer between the surface of solid granular beds and the environment as natural convection. The boundary conditions at the outer surface and the center of the container are respectively

$$\begin{cases} -\lambda \dfrac{\partial \theta}{\partial n} = \alpha(\theta_w - \theta_f) & \text{at the surface} \\ \dfrac{\partial \theta}{\partial r} = 0 & \text{at the center} \end{cases} \tag{3}$$

In equation (3), n is the outer normal direction of the surface. α is the convection heat-transfer coefficient. θ_w and θ_f are the outer surface temperature of the container shell and the environment temperature. The environment temperature θ_f may be obtained by the special temperature sensors.

Since the unsteady two-dimension axisymmetric heat exchange problem mentioned above is difficult to find an analytical solution, numerical methods are adopted and the discretization method is used here. The control volume method is applied to discretize the above heat exchange equations. In order to establish the finite difference expression of the temperatures, integrate Eq. 1 at the interval [t, $t + \Delta t$] for any nodal point within the domain, then it can be discretized as

$$\begin{aligned}(\rho c)_{i,j} \frac{\theta_{i,j} - \theta_{i,j}^0}{\Delta t} \Delta x \Delta r = {} & \frac{1}{r_{i,j}} \left(\lambda_{i,j+1} r_{i,j+1} \frac{\theta_{i,j+1} - \theta_{i,j}}{\Delta r} - \lambda_{i,j-1} r_{i,j-1} \frac{\theta_{i,j} - \theta_{i,j-1}}{\Delta r}\right) \Delta x \\ & + \left(\lambda_{i+1,j} \frac{\theta_{i+1,j} - \theta_{i,j}}{\Delta x} - \lambda_{i-1,j} \frac{\theta_{i,j} - \theta_{i-1,j}}{\Delta x}\right) \Delta r \end{aligned} \tag{4}$$

In this relation, the superscript 0 designates the current time increment. If the increments of space coordinates are chosen such that $\Delta x = \Delta r$, it may be represented as

$$\begin{aligned}\left[\lambda_{i-1,j} + \lambda_{i+1,j} + \lambda_{i,j-1} \frac{r_{i,j-1}}{r_{i,j}} + \lambda_{i,j+1} \frac{r_{i,j+1}}{r_{i,j}} + (\rho c)_{i,j} \frac{\Delta x^2}{\Delta t}\right] \theta_{i,j} = {} & \lambda_{i-1,j} \theta_{i-1,j} + \lambda_{i+1,j} \theta_{i+1,j} + \lambda_{i,j-1} \frac{r_{i,j-1}}{r_{i,j}} \theta_{i,j-1} \\ & + \lambda_{i,j+1} \frac{r_{i,j+1}}{r_{i,j}} \theta_{i,j+1} + (\rho c)_{i,j} \frac{\Delta x^2}{\Delta t} \theta_{i,j}^0 \end{aligned} \tag{5}$$

The difference equation (5) is formulated by computing the space derivations in terms of the temperatures at the future time increment. Such an arrangement is a backward-difference formulation because the time derivative moves backward from the times for heat conduction into the node. It can be seen that this backward-difference formulation does not permit the explicit calculation of the temperatures $\theta_{i,j}$ at the next time increment in terms of the temperatures $\theta_{i,j}^{\ 0}$ at the current time increment. Rather, a whole set of equations must be written for the entire nodal system and solved simultaneously to determine the future temperatures $\theta_{i,j}$. Thus backward-difference methods produce an implicit formulation for the future temperatures in the transient analysis. Comparing with the explicit formulation, the implicit formulation can not directly solve the future nodal temperatures; however, no restriction of the stability requirement is imposed on the solution of the equations that are obtained from the implicit formulation. This means that larger time increments can be selected to speed the calculation. The obvious disadvantage of the implicit method is the larger number of calculations for each time step. For problems involving a larger number of nodes, however, the implicit method may result in less total computer time expended for the final solution because very small time increments may be imposed in the explicit method from stability requirements. Much larger increments in Δt can be employed with the implicit method to speed the solution.

2.2 Design And Development of Temperature Collection System

On the basis of the studies of solid grain heat-transfer characteristics and unsteady heat transfer model describing grain temperature change, a temperature collection system is designed and developed for solid grain beds. It can accurately measure the temperature field and real-time average temperature of the grains inside the beds. From the working principle as shown in Figure 1, it can be seen that the temperature information obtained from the collection system may be transferred to the computer terminals through the controller area network bus interface.

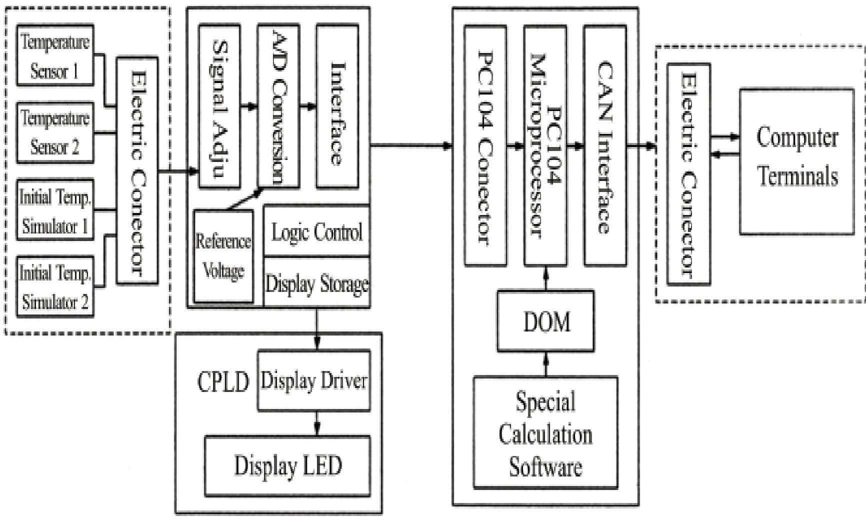


Figure 1. Working principle diagram of the temperature collection system

Figure 2 is the photograph of the control unit and computation unit of temperature collection system. When this system powers on and begins to work, one set of sensors is used to measure the current values of the grain temperature as the initial values of the temperature field in solid granluar beds and another set is used to measure successively the environment temperature as the boundary condition of the unsteady heat transfer equations on the temperature field. The temperature field and current average value of the grains inside beds are real-time calculated through the special computation software installed on the system.

2.3 Initial Temperature Simulator

A kind of initial temperature simulator is developed according to the similarity principle. To ensure that the heat-transfer process of initial temperature simulator is the same as that of the solid grain, it is required that the model should have characters of geometric similarity and physical similarity with the prototype. From the similarity principle and dimensional analysis, it is known that the Fourier and Biot numbers of the model should be equal to those of the prototype, that is, $Fo_m = Fo_p$ and $Bi_m = Bi_p$. The subscript m and p are designated as the model and prototype respectively. If γ_i ($i = \lambda, t, p, c, R, h$) is introduced to represent the ratios of homonymous physical quantity between the model and prototype, the ratio coefficient groups should satisfy the following relations

$$\frac{\gamma_\lambda \gamma_t}{\gamma_p \gamma_c \gamma_R^2} = 1 \quad \text{and} \quad \frac{\gamma_h \gamma_R}{\gamma_\lambda} = 1 \tag{6}$$

Since the model and prototype are in the same environment and the temperature change of the model is required in synchronism with that of the prototype, $\gamma_h = 1$ and $\gamma_t = 1$. From equation (6), we obtain

$$\gamma_\rho \gamma_c \gamma_R = 1 \text{ and } \gamma_\lambda = \gamma_R \qquad (7)$$

Figure 2. Photograph of control and computation unit of the temperature collection system

Provided the selected or artificial materials of the model satisfy the equation (7), it can be ensured that the heat-transfer process of the model is the same as that of the prototype. Figure 3 is the actual photograph of the initial temperature simulator developed according to the similarity principle.

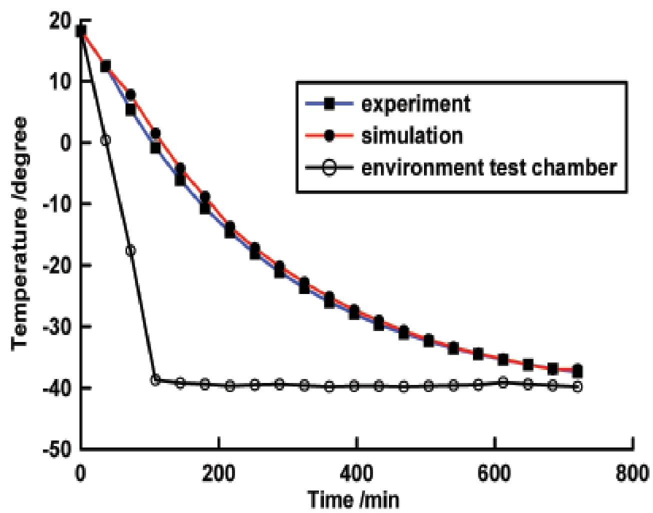
Figure 3. Actual photograph of initial temperature simulator

3. Test verification and result comparison

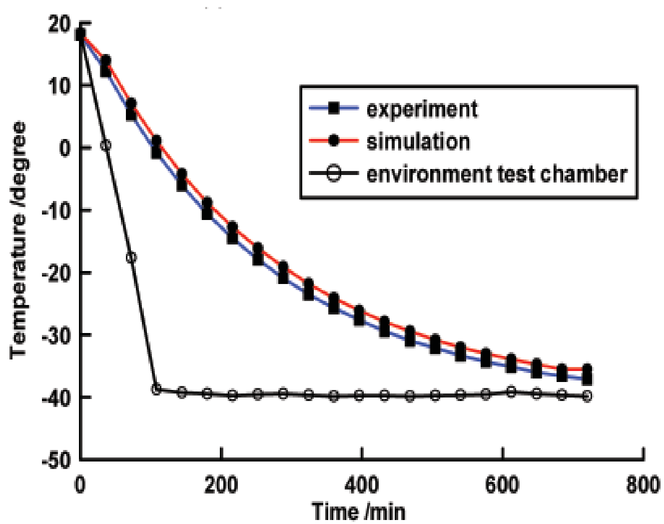
An experimental measurement system based on real-time data collection platforms equipped with resistance temperature detectors (RTDs) is constructed to investigate the heat conduction performance of solid granular beds. The measurement system is primarily composed of a computer, a universal multifunction data collector and resistance temperature detectors. The resistance temperature detector is used to measure the temperature of grains within solid granular beds along with the changing ambient temperature around them. The resistance temperature detectors selected in this paper are Pt100 sensors, a kind of platinum resistance thermometer with greater stability, accuracy and repeatability as compared to thermocouples. The selected data collector is the Fluke 2620A series multi-channel intelligence data acquisition instrument. The greatest advantage of this unit is that it is available for a variety of commonly compatible Pt100 resistive temperature devices with varying range and other performance characteristics on the market while still maintaining a relatively high measurement accuracy of ±0.3°C between -40°C and 70°C. The Fluke 2620A collects temperature data from grains via Pt100 RTD elements.

Before the experiment begins, a solid granular bed is placed into an environmental test chamber. First, open the power supply of the environmental test chamber and set the temperature at 18°C. To ensure the temperature field of the grains within solid grain beds to achieve a state of heat equilibrium, it should be placed at least 12 hours in the environmental test chamber after the temperature reaches 18°C. Then, set the experiment temperature of the environmental test chamber to -40°C and the temperature descent speed to 1°C /min, meanwhile, start the computer and Fluke 2620A data collector. The measurement system reads automatically the temperature of grains at the configured sampling frequency via Pt100 RTD elements. The sampling frequency of Fluke 2620A is set to five minute in advance, that is, temperature reads are made at five minute intervals. The temperature measurement test is carried out continuously for 12 hours. The change history of measured temperature versus time at each test post is recorded by the measurement system to analyze the heat conduction characteristics of grains and verify calculation results.

A comparison between simulation curves and experimental results is shown as Figure 4. In the experimental configuration, test points are arranged along the axial and radial direction of solid granular beds. Platinum resistance thermometers are mounted into the actual grains located at the test spots. The history of grain temperature change is measured and recorded by platinum resistance thermometers. From Fig. 4, it can be seen that calculation results are well matched with measured ones. This indicates that the used physical models and the developed application software are correct and might be applied to predict the real-time temperature of solid granular beds. Therefore, only if the grain thermal performance and change history of environment condition, including the thermal characteristic parameters of materials, environment temperature and heat transfer conditions, are known, the distribution of the grain temperature field can be determined using the application software developed in this paper.



(a) at the half of the radius



(b) at the outer third of the radius

Figure 4. Comparison between numerical simulation and experimental measurement

4. Conclusions

Under the premise of discussing the unsteady heat conduction model describing the variation in the grain temperature within solid granular beds, a temperature collection system is designed and developed. The primary idea of design and development is software solution and hardware realization through the combine of heat transfer theory and computer information processing technology on the basis of the theoretical analysis and experimental study on the temperature field of solid granular beds. Comparing calculated curves with experiment results indicates that the used physical model reflects the real-time change process of the grain temperature with the environment temperature. Thus, the developed system can accurately measure the temperature field and real-time average temperature of the grains and simultaneously transfer the temperature information to the computer terminals through the controller area network bus. This work is valuable for a kind of measurement problem in which the internal temperature of the measured objects cannot be directly tested.

Acknowledgments

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