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Research Paper

A method for two-dimensional temperature field distribution reconstruction

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HIGHLIGHTS

- Ultrasonic thermometry is applied in reconstruction methods.
- The proposed method has higher accuracy than the least square method.
- The reconstructed images accurately represent the actual experiment.
- The proposed method will be applied in industrial application.

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ABSTRACT

The information of temperature field distribution is significant for industrial applications because it can reflect the internal running state of industrial equipment and assist to develop control strategy and ensure safety in operation of industrial equipment. Ultrasonic thermometry is a kind of acoustic pyrometry and it has been evolving as a new temperature measurement technology for various environment. The principle of ultrasonic thermometry is based on the dependence of ultrasonic sound velocity on temperature. In this paper, a reliable method for two-dimensional temperature field distribution reconstruction via ultrasonic thermometry is investigated. The results of actual experiment demonstrate that the proposed reconstruction method possesses a relatively better information reflection of temperature field distribution and higher reconstruction accuracy than common reconstruction algorithm, the least square method.

1. Introduction

For industrial applications, such as burning, heating and drying, temperature field distribution is significant because it may show the internal running state of industrial equipment. Furthermore, it would reflect the thermodynamic process, assist to develop control strategy and ensure safety in operation of industrial equipment. In the meantime, temperature field distribution may be used to detect and control the temperature of hot pots which may lead to unexpected safety accidents, like explosion and spontaneous ignition [1–4].

Traditional temperature measurement techniques, for instance, thermocouples [5], thermal resistances [6], infrared radiation and optical are not appropriate for reconstructing temperature filed distribution. Thermocouples and thermal resistances are intrusive temperature measurement methods and only fit for single-point temperature measurement [7–9], not temperature filed distribution. The temperature measurement technique of infrared radiation is only appropriate for temperature measurement of material surface in a non-contact way. Moreover, influence due to different emissivity and reflectivity of infrared radiations from other sources often leads to deterioration of measurement accuracy [10,11]. The measurement precision of optical temperature measurement method may be degraded, because the camera lenses could be smeared by the ash in environment [12].

In order to solve the problems mentioned above, this paper aims to develop a reliable method for two-dimensional temperature field distribution reconstruction via ultrasonic thermometry.

Ultrasonic thermometry is based on the dependence of ultrasonic sound velocity on temperature [13–16] and it could be used to reconstruct temperature field distribution. In a specific measurement region, with several ultrasonic transmitters and

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ultrasonic receivers installed, ultrasonic flying time (UFT) could be estimated between ultrasonic transmitters and ultrasonic receivers. Then, using appropriate reconstruction algorithm, temperature field distribution in this region might be obtained.

In this paper, a reliable method for two-dimensional temperature field distribution reconstruction via ultrasonic thermometry is investigated. The results of actual experiment demonstrate that the proposed method possesses a relatively better information reflection of temperature field distribution and higher reconstruction accuracy than common reconstruction algorithm, the least square method [15,16].

2. The measurement theory

The theory of ultrasonic thermometry is based on that the ultrasonic sound velocity is a function of gas temperature [20]. The simplest ultrasonic thermometry is the single path temperature measurement. It consists of an ultrasonic transmitter installed on one side and an ultrasonic receiver installed on the other side along the same path. The ultrasonic transmitter and receiver are used to transmit ultrasonic signal and detect it, respectively. The relationship between ultrasonic velocity and temperature is described as [8,17,19]

$$c = \sqrt{\frac{\lambda R}{M}T} = Z\sqrt{T} \tag{1}$$

where c is the ultrasonic velocity, λ is the ratio of specific heats, R is the specific gas constant of the intervening medium, M is the average molecular weight of the gas and T is the absolute temperature (K). For different gas, λ, M and R are fixed constants. Hence, they could be replaced by Z .

On the contrary, if ultrasonic velocity c and gas properties are known, then the mean temperature T of the path ultrasonic travels is determined as

$$T = \left(\frac{c}{Z}\right)^2 \tag{2}$$

Moreover, T also can be expressed by the following equation:

$$T = \frac{1}{Z^2}\left(\frac{L}{t'_k}\right)^2 \tag{3}$$

where L is the distance between the ultrasonic transmitter and receiver, t'_k is the UFT and $c = L/t'_k$.

3. Reconstruction method

In order to achieve the reconstruction of temperature field distribution, the single path temperature measurement with ultrasonic thermometry is insufficient. However, with several ultrasonic transmitters and receivers installed appropriately in a measurement region, multiple paths ultrasonic travels will emerge. Then, proper reconstruction algorithm could be adopted to reconstruct the temperature field distribution of the measurement region.

3.1. Arrangement of ultrasonic transmitters and receivers in a measurement region

Fig. 1 shows a typical ultrasonic transmitter and receiver layout installed in a measurement region, which is a square. Ultrasonic transmitters T_0 - T_3 and receivers R_0 - R_7 are represented by black dots. Effective ultrasound flying paths among the ultrasonic transmitters and receivers are expressed by solid lines within the measurement region, which is divided into several blocks by dashed lines. The order of transmitting and receiving ultrasonic signal follows the sequence: when transmitter T_0 emits ultrasonic signal, receivers R_2, R_3, R_4, R_5, R_6 and R_7 detect the signal. Then, when transmitter T_1 emits ultrasonic signal, receivers R_4, R_5, R_6, R_7, R_0 and R_1 detect the signal. This cycle ends when transmitter T_3 emits ultrasonic signal and receiver R_5 detects the signal. The transmitters and the receivers installed in the same side of the measurement region do not constitute the ultrasound flying paths, because these paths have no practical significance. When all the UFT values of the effective ultrasound flying paths are obtained, the two-dimensional temperature field distribution in the measurement region can be reconstructed by using suitable algorithms [18].

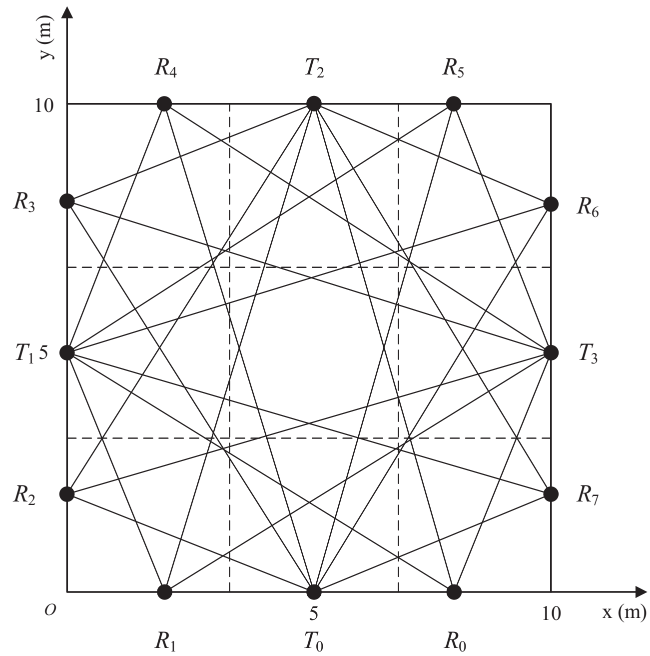

Fig. 1. A typical ultrasonic transmitter and receiver layout installed in a measurement region.

3.2. The least square method

Theoretically, the UFT, t'_k in the kth effective ultrasonic flying path is described as [4,20,21,23]

$$t'_k = \int_{l_k} a\,dl_k \tag{4}$$

where a is the reciprocal of ultrasonic velocity and l_k is the length of the kth effective ultrasound flying path.

If the measurement region in Fig. 1 is divided isometrically into P blocks, assuming that temperature in each block is unknown and uniform, therefore, a_i is a constant in the ith block. Then, Eq. (4) is turned into

$$t'_k = \sum_{i}^{P} \Delta S_{ki} a_i \tag{5}$$

where k and i denote the kth path and the ith block, respectively. ΔS_{ki} indicates the length of the kth path passing through the ith block.

The difference ε_k between the practical UFT t_k and the theoretical one in the kth ultrasound flying path is expressed as

$$\varepsilon_k = t_k - t'_k = t_k - \sum_{i}^{P} \Delta S_{ki} a_i \tag{6}$$