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A measurement system of high-temperature oxidation environment with ultrasonic $Ir_{0.6}Rth_{0.4}$ alloy thermometry

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ABSTRACT

Iridium-rhodium is generally applied as a thermocouple material, with max operating temperature about 2150 °C. In this study, a ultrasonic temperature measurement system was designed by using Iridium-rhodium (60%Ir–40%Rh) alloy as an acoustic waveguide sensor material, and the system was preliminarily tested in a high-temperature oxidation environment. The result of ultrasonic temperature measurement shows that this system can indeed work stably in high-temperature oxidation environments. The relationship between temperature and delay time of ultrasonic thermometry up to 2200 °C was illustrated. Iridium-rhodium materials were also investigated in order to fully elucidate the proposed waveguide sensor's performance in a high-temperature oxidation environment. This system lays a foundation for further application of high-temperature measurement.

1. Introduction

Temperature, an essential component within the International System of Units, is a crucial characteristic in almost all areas of our daily lives. In chemical, machinery, metallurgy, and industrial production fields, temperature is a very important parameter. Thus, it must be controlled carefully to protect personnel and property, improve production efficiency, save energy, reduce environmental pollution, and promote sustainable economic development. Rapid advances in nuclear and aerospace technologies requires stricter standards for high-temperature or ultra-high temperature measurement techniques in increasingly complex environments (e.g., advanced aircraft engine testing, nuclear reaction instruments).

Current ultra-high temperature measurement technologies include thermocouples and infrared radiation temperature measurement systems. Thermocouples are most commonly used for industrial temperature measurement. Material and structural constraints, unfortunately, makes most thermocouples inapplicable for those over 1600 °C at ultra-high oxidation environment [1–3]. Another problem of thermocouples are the breakdown of electrical insulation at high temperatures, due to electrical shunting above 1800 °C. Infrared radiation systems possess non-contact and fast response characteristics, and are often used in explosions, rocket tail flame, and other special environments. Their accuracy is, however, degraded by background environmental refractive indices, such as smoke, fog and other factors.

Ultrasonic temperature measurement technology is relatively unsophisticated, but its wide temperature range meets the strict requirements of complex environments. In the early 1960s, American scientist L.C. Lynnworth firstly attempted to apply ultrasonic pulse technology for the measurement of solid, liquid, and gas temperatures. The ultrasonic pulse echo method was the general focus of this research, with which the medium temperatures is over 1273 °C [4]. In 1992, at the Seventh International Temperature Symposium, American scientist S.C. Wilkins published the paper "Monocrystalline tungsten ultrasonic waveguide thermometer". He utilized monocrystalline tungsten, instead of thorium tungsten alloy, as a waveguide to obtain a stable ultrasonic echo signal with far less attenuation and has the accuracy up to 3000 °C [5]. In 2012, the US Department of Energy's Idaho National Laboratory developed an ultrasonic temperature measurement system for nuclear reactor interiors. They conducted not only the detailed analysis of ultrasonic temperature sensor materials and structures, but also the ultrasonic characteristic signal collection and processing [6–8]. This work

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was very influential in promoting the industrial application of ultrasonic temperature sensors. However, these studies failed to report the ultrasonic temperature measurement technology used in high-temperature environmental oxidation. In 2016, Wei et al. used Ultrasonic Al_2O_3 Ceramic Thermometry to detect high-temperature oxidation of a 1600 °C environment, broadening the ultrasonic thermometry application area

The melting point of Al_2O_3 Ceramic is 2049 °C, so this material can't be used to detect temperatures above 2000 °C. In this paper, we propose the use of anti-oxidation platinum group metals, including 60%Ir–40% Rh, as ultrasonic wave sensor materials for temperature measurement. We obtained an ideal calibration curve between 1600 and 2200 °C, and concluded that this potentially resolves the issue of ultrasonic temperature measurement in oxidation environments.

2. Principle

Ultrasonic temperature measurement is a relatively new technology based on the relationship between temperature and ultrasonic velocity in a given media [10–12]. In general, ultrasonic speed decreases as temperature increases in both a solid and liquid, while gas ultrasonic velocity is proportional to the square root of the thermodynamic temperature. The rate of ultrasonic velocity change is largest at low temperatures in gases. In liquids, the ultrasonic velocity rate does not change with temperature; it is highest in solids at high temperatures [13].

Before our discussion on ultrasonic wave's propagation along rods in high-temperature environments, we will first briefly introduce its propagation in thin rods (The diameter of the waveguide rod must be below 1/10 of the longitudinal wavelength to prevent wave dispersion) at ambient temperature. According the principle of the elastic mechanics, ultrasound propagation in a thin rod can be expressed as follows:

$$E\frac{\partial^2 u}{\partial x^2} = \rho\frac{\partial^2 u}{\partial t^2} \tag{1}$$

$$\frac{\partial^2 u}{\partial x^2} = \frac{1}{c_0^2}\frac{\partial^2 u}{\partial t^2} \tag{2}$$

where $c_0 = \sqrt{E/\rho}$, c_0 is the velocity of ultrasound. E is the Young's modulus of the waveguide material, ρ is the media density. The Young's modulus and density change with the temperature change in the high temperature environment, which leads to the change in ultrasonic velocity. The longitudinal wave velocity of ultrasonic propagation in the waveguide can be calculated as follows:

$$V(T) = \sqrt{\frac{E(T)}{\rho(T)}} \tag{3}$$

where E(T) is the Young's modulus of the waveguide material, ρ(T) is the media density, and V(T) is the propagation of ultrasonic waves in the pole of the longitudinal wave velocity. We can solve for the temperature by measuring the ultrasonic velocity in a high temperature environment.

3. Ultrasonic thermometry measurement system

As it is not easy to obtain precise results through Formula (3) theoretically, the relationship between the ultrasonic velocity and temperature is generally obtained through experiments. In such an experiment, the ultrasonic pulse velocity at a high temperature is detected by means of velocity measurement in a fixed distance. The delay time of the ultrasonic signal in the notch and at the end is detected, while the distance, the notch, and the end signal are all fixed at constant values. The delay time and distance divide is the ultrasonic speed, which represents speed in a given environment.

As shown in Fig. 1, the high-voltage pulsed impulse instrument excites narrowband pulses, which are then converted by piezoelectric transducers into ultrasonic signals propagating through the sensing element. The ultrasonic signal is then transmitted along the ultrasonic concentrator and waveguide rod, which reflected at notch and end. The amplitude of wavelet is amplified by ultrasonic concentrator. The ultrasonic reflection signal is thus converted into an electrical signal by a piezoelectric transducer. Following the linear amplification module, the electrical signal is amplified and transmitted to the oscilloscope and counter. This allows the user to calculate the time difference between the notch signal and the end signal, which is the delay time corresponding to the average temperature of the temperature sensitive area. The speed in a high-temperature environment can then be calculated as follows:

$$V(T) = \frac{2^{*}\Delta l}{\Delta t} \tag{4}$$

where V(T) indicates the speed corresponding to the high-temperature environment, Δt represents the delay time between the notch signal and the end signal, and Δl represents the distance between the notch and the end of the wave guide.

4. Ultrasonic thermometry wave guide properties and ultrasonic thermometry equipment

4.1. Waveguide material

Waveguide materials used in ultrasonic thermometry sensors typically require high melting points (2000–3000 °C) and have high oxidation resistance properties. These conventional high-melting materials are the refractory metals that include tungsten, rhenium, tungsten-rhenium alloy, and tungsten-thorium alloy, all of which have a melting point of 3000 °C or higher [14–20]. In addition to high melting points, they have small acoustic impedance, significant sound velocity changes with temperature, and applicability in nuclear fuel core temperature measurement projections for detecting high temperatures. However, engine combustion chambers and other complex temperature environments often utilize the introduction of oxygen. These refractory metals in high temperature oxidation environments are easily oxidized, causing the formation of tungsten oxide [21–23]. For example at 900 °C, tungsten becomes completely oxidized, resulting in ultrasonic sensor failure and inability to accurately measure temperature, as shown in Fig. 2.

Platinum and rhodium are commonly utilized in high-temperature applications involving simultaneous chemical attacks and mechanical loading. They have excellent chemical stability, oxidation resistance, and resistance to many molten oxides. The melting point of platinum is 1683 °C, with platinum and rhodium thermocouple working temperatures below 1800 °C in oxidation environment [24,25]. The melting point of iridium is 2446 °C. Its oxidation rate is significantly high, and antioxidant capacity is insufficient. Thus, it does not readily provide sufficient oxidant protection in strong oxidizing environments at temperatures as high as 1000 °C. The melting point of rhodium is 1964 °C, and the material has both corrosion and oxidation resistance. The melting point of IrRh alloy is at least 2000 °C, however, so by adding rhodium to iridium, IrRh alloy oxidation can be enhanced significantly.

According to the National Bureau of Standards, reference tables of temperature versus EMF for thermocouples of iridium-rhodium alloys versus iridium have been established to cover all three of the currently used thermocouples. These tables are now available for thermocouples of $Ir_{0.6}Rh_{0.4}$ and IrRh versus Ir, and provide EMFs for temperature ranging in 0–2150 °C [26]. In this paper, we used 60%Ir–40%Rh as the ultrasonic sensor material to detect higher temperatures in oxidizing environments.