Chapter 5

CdTe Quantum Dot Fluorescence Thermometry of Rolling Bearing

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Additional information is available at the end of the chapter

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Abstract

Temperature is one of the most important parameters affecting the service life and performance of a rolling element bearing component. In this paper, a nonintrusive method is developed to monitor the temperature variation of the inner raceway during bearing operation utilizing CdTe quantum dots as the temperature sensors. The CdTe quantum dots were synthesized and were used in constructing a sensor film by means of layer-by-layer electrostatic self-assembly method on an ultrathin glass slice. The peak wavelength shift of the fluorescence spectrum of the sensor film shows a linear and reversible relationship with temperature, and it is used to sense the temperature of the inner raceway. The resolution of the CdTe optothermal sensor is determined to be 0.14 nm/°C. The temperature measurement of rolling element bearing was conducted on a bearing test rig incorporated with an optical fiber fluorescence spectrum detecting system. To verify the accuracy of the temperature obtained by quantum dots sensor film, a thermocouple was used to test the temperature of the inner raceway right before and after the operation. Results show that the temperature obtained by the CdTe quantum dots film sensor is consistent with that by the thermocouple, with an error typically below 10% or smaller.

Keywords: high speed rolling bearing, inner ring temperature monitoring, quantum dots

1. Introduction

Rolling bearings are basic mechanical components widely used in machinery for low friction, high rigidity, and reliability. They are required to operate at high speed for long period of time under uneven conditions with minimum maintenance. The operating status of bearings directly affects the performance of rotating machinery. Bearing failure can make machine breakdown, lead to cost increase and even human death [1]. Hence, the development of strategies for monitoring bearing health conditions while in operation has been of significant importance.

The contact friction between the inner component leads to large heat generation and elevated temperature, which could cause thinner lubricant film, higher asperity contact, and reduction of material properties. Thus, the temperature is considered to be one of the most important parameters affecting the service life and performance of a rolling element bearing component. However, because of the complex structure and extreme operating conditions, instrument for real-time, nonintrusive monitoring of bearing temperatures has been limited. This is particularly true for the rolling element of a bearing, whose temperature is often indirectly obtained from the measured temperature of outer raceway. Indirect measurements are known to be error-prone. Thus far, direct measurement of the temperature of the inner bearing components such as the inner raceway and cage has eluded researchers [2–6]. Joshi [2] has developed a battery-powered telemeter and a remotely powered telemeter to measure the cage temperature in a tapered roller bearing. Also, Jia et al. [6] used a remotely powered wireless temperature sensor to monitor the cage temperature in real-time. However, the battery-powered telemeter has an extremely short functional life, and both the wireless ones are easily affected by the electromagnetic environment and are not suitable for high speed situations.

Recently, luminescent semiconductor nanocrystals, quantum dots, have attracted extensive attentions due to its unique optical properties and have been applied in light-emitting diodes, solar cells, and bio-labeling [7–9]. These semiconductor nanoparticles offer several advantages including narrow fluorescence emission, tunable wavelength, relatively high quantum yield, outstanding photo stability as well as flexible photo excitation. It also has been reported that the behavior of the luminescent properties of quantum dots with temperature has suitable characteristics for application as temperature probes [10–15]. The luminescence properties, such as the excited state lifetime, emission intensity, and peak wavelength, have been proven to be good indicators of temperature. The wide range of temperature in which luminescent properties change makes them very suitable for temperature sensing applications.

This paper presents a study on the use of CdTe quantum dots as thermal sensor to measure the temperature of inner raceway of rolling bearing while in operation. The quantum dots sensor film is fabricated by means of layer-by-layer electrostatic self-assembly method on an ultrathin glass slice. The peak wavelength shows a linear and reversible relationship as temperature changes. The factors that would affect the acquired fluorescence signal have been studied. Results show that this method is feasible and effective for the temperature measurement of rolling bearing, especially in very high speed conditions.

2. Sensor preparation and calibration

2.1. Sensor preparation

Colloidal solutions of CdTe quantum dots stabilized by TGA were prepared according to the method given by the previously reported paper [16]. Typically, 0.2 mmol $Cd(CH_3COO)_2{\cdot}2H_2O$

was dissolved into 50 ml deionized water in a three-neck flask and 18 μl TGA was added under stirring, then the pH was adjusted to 10.5–11 with 1 M NaOH solution. After that, 0.04 mmol K_2TeO_3, which was dissolved in 50 ml deionized water was added into the above solution. Then, 80 mg of $NaBH_4$ was added into the precursor solution. After the reactions proceeded for about 5 min, the flask was attached to a condenser and refluxed at 100°C under open-air condition. By controlling refluxing time, CdTe QDs with desired size and color can be obtained.

To implement the temperature measurement, QDs sensors were fabricated by the layer-by-layer electrostatic self-assembly (LBL ESA) technique [17, 18]. Quartz slides of 200 μm thickness were placed into Piranha Solution for 30 min for cleaning before the deposition of the QD coatings. Then the Quartz slides were immersed into 50 ml of a solution of 1%wt PDDA with the pH adjusted to 8.0 for the absorption of polycation for 15 min. Next, the substrates were cleaned in deionized water and dried by N_2. Then, the slides were removed into the CdTe QDs solution synthesized by ourselves for 10 min to absorb QDs followed by cleaned and dried. Repeating the above steps, a sensitive coating denoted by [PDDA/CdTe]n was formed, where n was chosen to be 15 for this paper. Afterward, the sensor films were cured at 150°C in a vacuum chamber. Thermal treatment yields a more repetitive and stable response when suffered to temperature change. When the fabrication was completed, the sensors were kept in darkness until the temperature response of emission spectrum was studied.

2.2. Sensor calibration

In order to utilize QDs as sensors for the temperature measurement of rolling bearings, the temperature-dependent emission properties of the sensor was first characterized using the experimental setup showing in **Figure 1**. The QDs sensor is placed on a heater cell with a thermocouple to monitor its temperature. Since the QDs have a wide absorption spectrum, a mercury lamp at 365 nm is used as the excitation light source. The light generated by the lamp is reflected by a dichroic mirror and directed to the QDs sensor through a focus lens, which is also used to prevent the excitation signal from masking the fluorescence of the QDs sensor. The fluorescence is collected by the same lens and leaded to an Andor Shamrock SR-303i spectrograph. Finally, an Andor iDus DU420A-BV CCD camera together with a computer is used to analyze the optical response of the QD with respect to changes in the temperature values. By adjusting the heater cell, its temperature varies and changes in wavelength and intensity of the luminescence emission of the quantum dots are registered.

To study the properties of the QDs sensor, the heater cell in **Figure 1** was adjusted to run several temperature cycles from room temperature to 70°C and back. **Figure 2(a)** shows the emission spectrum varies as the temperature increases and decreases. As it can be seen from the picture, the photoluminescence intensity decreases with the increase of temperature, while the peak wavelength red shifts and FWHM increases as the temperature increases. It means that there are three features that could be used to detect the variation of temperature. However, as the photoluminescence intensity is affected by the power of the excitation source as well as the distance between the focus lens and the QD sensor, it is not suitable for the temperature monitoring of rolling bearings, where slight or heavy vibration usually occurs. Besides, the average temperature sensitivity of the FWHM is generally small compared with peak

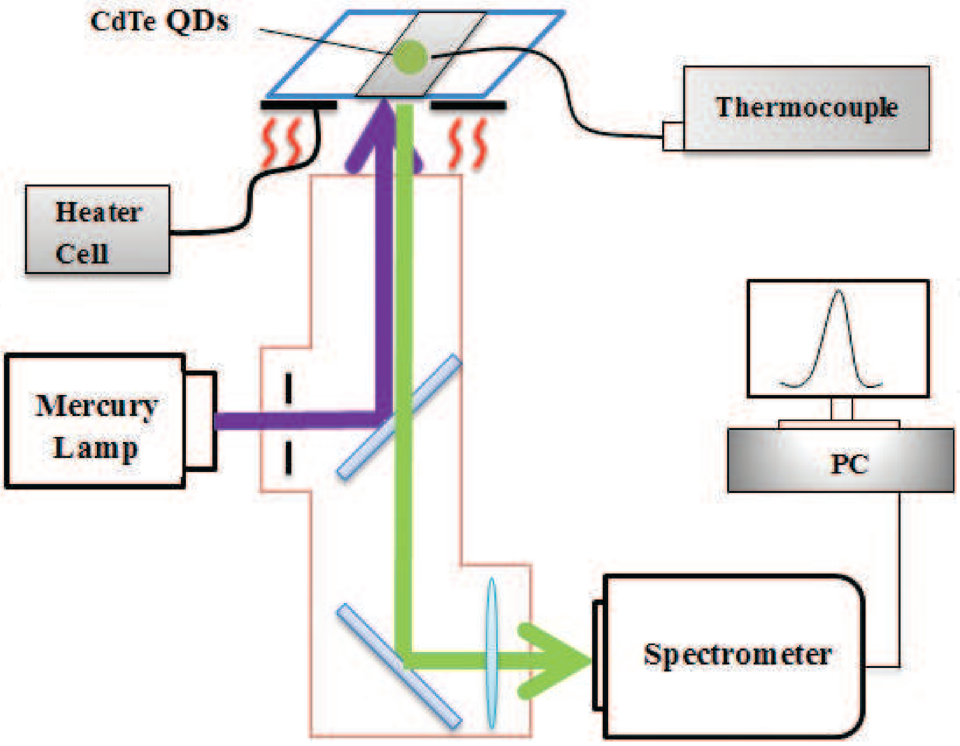

Figure 1. Schematic representation of the experimental setup.

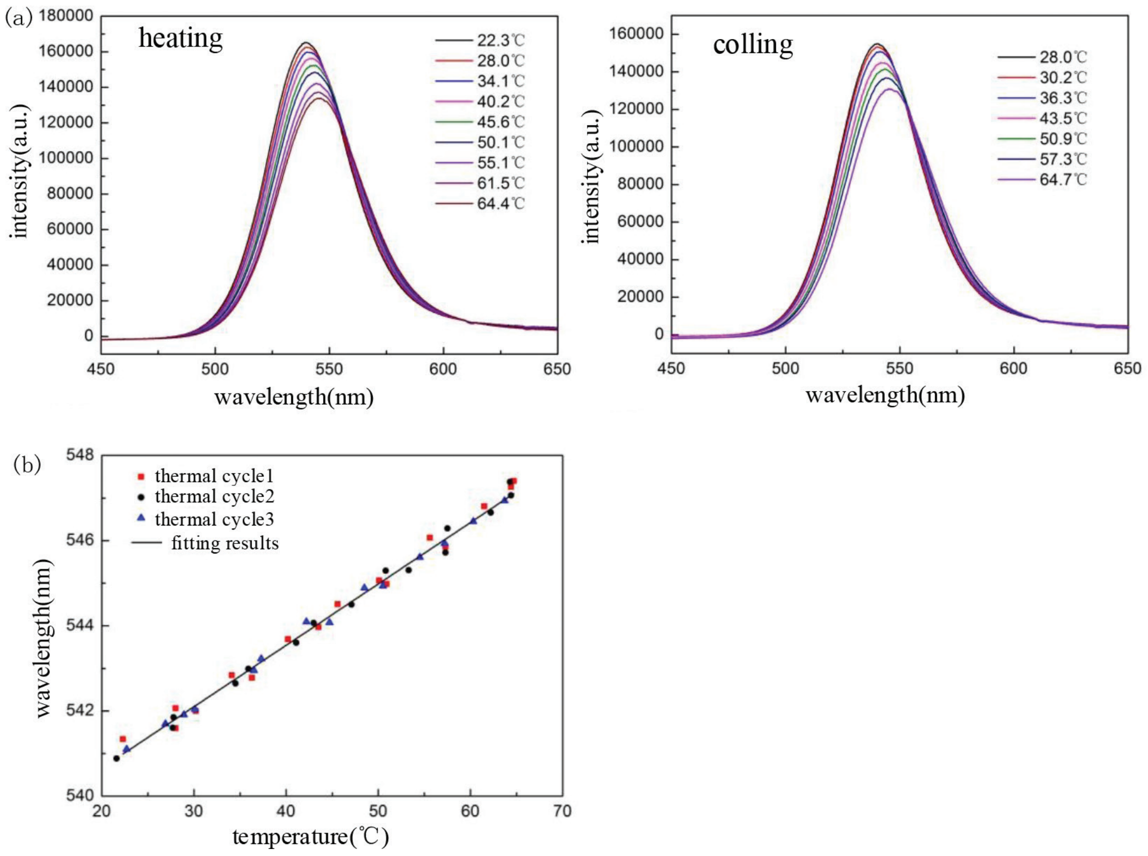

Figure 2. (a) Behavior of emission spectrum of QDs with different temperatures in heating and cooling. (b) Dependence of the emission peak wavelength with respect to the temperature in three thermal cycles.

wavelength. Therefore, here we choose the peak wavelength as the parameter for temperature measurement of rolling bearings. The temperature dependence of peak wavelength in three thermal cycles is depicted in **Figure 2(b)**. It is shown that the response of emission spectrum peak wavelength is linear and reversible as the temperature changes. The R square value with respect to the linear approximation is about 0.994 for both cases. And the sensitivity shown by the sensor is around 0.14 nm/°C. The wavelength shift can be explained by the fact that heat expands the crystalline of the quantum dots material and causes a change in the band gap [13], which is only decided by the properties of the quantum dots.

3. Rolling bearing temperature measurement

For the temperature measurement of rolling bearings, the influence of rotating to the fluorescence signal acquisition was studied first. The same setup shown in **Figure 1** was used with some modification. The QD sensor was mounted to a disk, which was drove by a motor, with its rotating speed detected by a photoelectric tachometer. The excitation light generated by the mercury lamp continuously is illuminated on the disk. What is different from the calibration state is that the QD sensor is excited at intervals when the disk is rotated with a certain speed. And the total amount of fluorescence detected by the CCD changes in time as the QD sensor moves into, though, and out of the focus lens's field of view, as is shown in **Figure 3**.

Generally, a specific exposure time is needed to collect fluorescence when the spectrograph is set to acquire the emission spectrum. Assuming that the exposure time is T, the angular velocity of the disk is ω, and the central angle of the QD sensor to the disk is α, the total time the QD sensor excited within the exposure time is: $t = T\alpha/2\pi$. This means that there is no difference whether the QD sensor is stable or in rotation, but the exposure time multiplies a factor of $\alpha/2\pi$. And it is proved by the results shown in **Figure 4**. We studied the

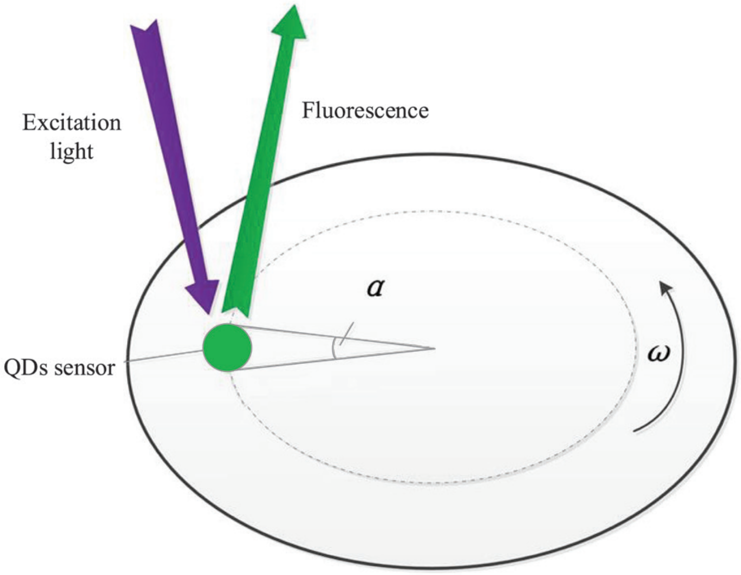

Figure 3. The rotation causes the QDs sensor to move with respect to the fluorescence collection input aperture.

effect under different speeds: 650, 1525, 2515, and 3012 r/min, with the exposure time of the spectrograph set at 500 ms. There are 20 spectrum lines captured every 1 min for different speeds. As is shown in the picture, the emission intensity acquired at different speed keeps nearly unchanged from 650 to 3012 r/min, which means that the rotating speed has no effect on the fluorescence signal. Therefore, we could take temperature measurement of rolling bearings by a common fluorescence spectrum measurement system, and the utilization of QD as temperature senor for rolling bearing thermometry could be applied in very high speed conditions.

3.1. Experimental setup

A new optical fiber fluorescence spectrum detecting system was established to measure the temperature of the inner raceway of the ball bearing of a bearing test rig, which is depicted in **Figure 5**. The bearing test rig was built on a rigid platform and one of its bearing was chosen as testing target. The cover of the bearing block was taken away for convenient measuring. The QDs sensor was mounted to the inner raceway by an epoxy binding agent. An optic fiber with a fluorescent probe was used to conduct the excitation light and collect the fluorescence. By setting the bearing test rig operating at different constant speeds, the fluorescence spectrum of the CdTe film sensor was acquired by the spectrograph (QEpro6500) every 1 min from the moment the setup started until running 20 min, which is thus used to obtain information

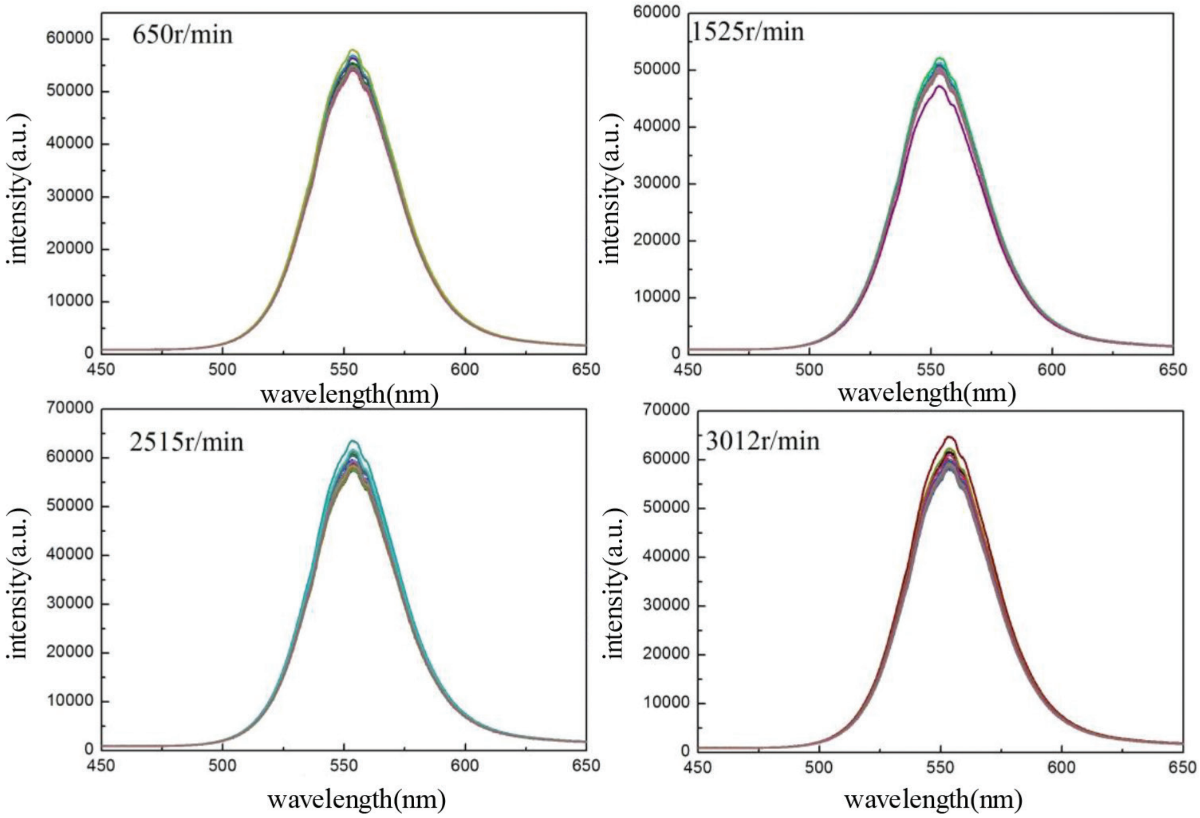

Figure 4. The influence of rotating speed of fluorescence signal.

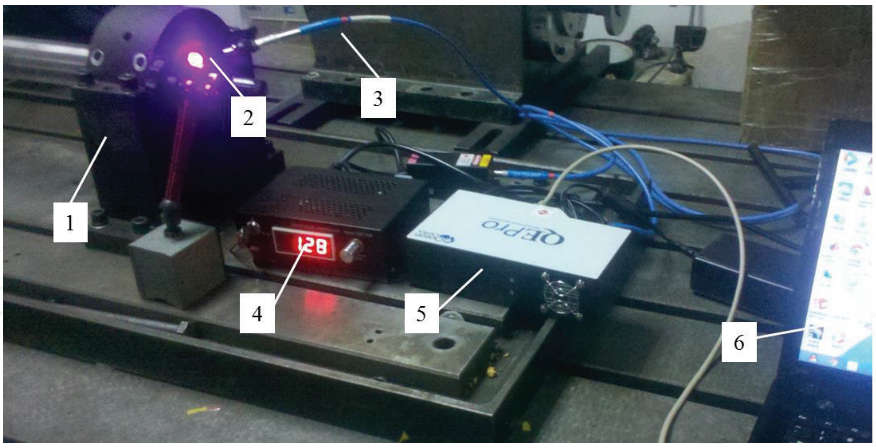

Figure 5. Rolling bearing temperature measurement system. (1) Testing bearing; (2) QDs sensor; (3) optic fiber; (4) 405 nm laser; (5) QEPro spectrograph; (6) computer. Inset: No excitation light irradiates on QDs sensor.

on the temperature variation of inner raceway. To verify the accuracy of the temperature obtained by quantum dots sensor film, a thermocouple was used to test the temperature of the inner raceway right before and after the operation.

3.2. Results and discussion

Temperature measurements were conducted at shaft speed of 1000, 1600, 2200, and 2800 r/min, respectively without any load. **Figure 6** depicts 20 fluorescence spectrum lines acquired every 1 min from the moment the setup started until running 20 min. As we can see from the picture, for different constant shaft speeds, the variation tendency of the fluorescence spectrum is similar to each other: the photoluminescence intensity decreases and the peak wavelength red shifts as time goes on, indicating that the temperature of the bearing inner raceway rises up in the testing 20 min. Comparing the fluorescence spectrum obtained at different shaft speeds, the red shift of the peak wavelength increases as the shaft speed increases, which means that the heat generation and the temperature rise vary with speed. The variation of bearing inner raceway temperature measured by QDs sensor with time at four different conditions of shaft speed is shown in **Figure 7**. It clearly shows that there are more heat generation and large temperature rise at higher speed.

The accuracy of the temperature obtained by the QDs sensor was studied by comparing with the temperature tested by a thermocouple. The thermocouple was used to test the temperature of the inner raceway at the point near QDs sensor right before and after the operation. Results show that the temperature acquired by these two methods has good consistency. The temperature of the inner raceway at 2800 r/min was about 26.1 and 50.2°C before and after the operation of the test rig by thermocouple, while the first and last obtained spectrum line indicate that the temperature was 28.7 and 51.4°C, respectively. The error of the temperature rise between these two methods is 5.8%. Because of the different measuring time and other affects, the temperature measured by two methods shows little difference, but the temperature rise error all blow 10% for different shaft speed.

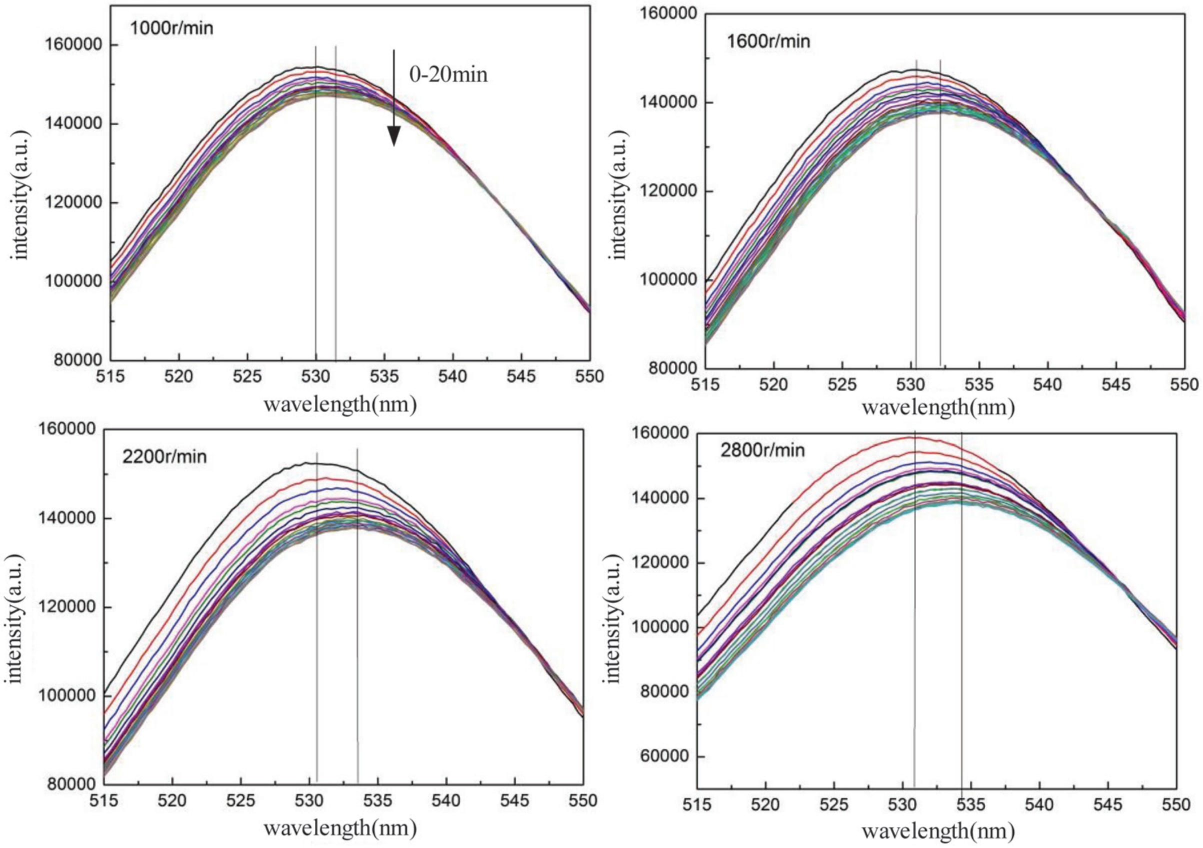

Figure 6. Fluorescence spectrum of different shaft speed in 20 min.

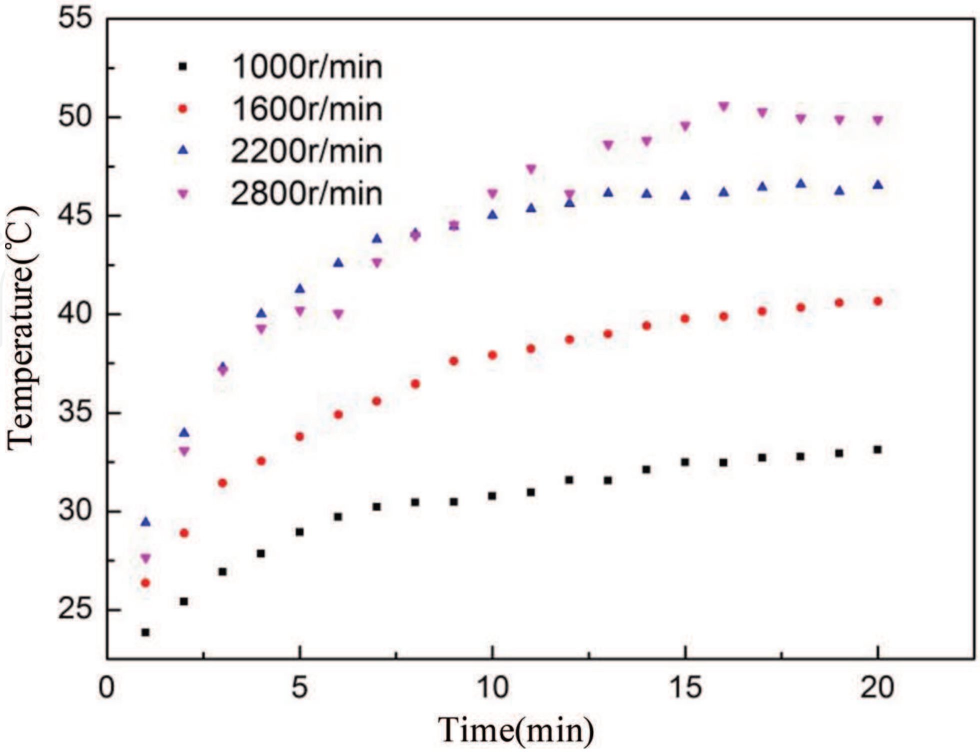

Figure 7. The temperature of inner raceway as a function of time at different speed.

4. Conclusions

In this paper, we have proposed a quantum dot fluorescence-based thermometry method for rolling element bearings. Temperature sensor has been fabricated by the deposition of quantum dot films on quartz slide by means of layer-by-layer technique. It has been shown that the emission peak wavelength of the QD sensor has a very linear relationship with the temperature, making it applicable of noncontact temperature measurement of rotating surface. We have managed to take temperature measurement of rolling bearings by a common fluorescence spectrum measurement system. The rotating speed shows no effect on the acquired fluorescence signal, which makes the QD fluorescence-based thermometry method, suitable for very high rotating speed temperature measurement. The practical experiment proves that the CdTe quantum dot fluorescence thermometry could be a feasible and accurate temperature measurement method of bearing inner raceway in operation.

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