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An instantaneous approach for determining the infrared emissivity of swine surface and the influencing factors

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ABSTRACT

Infrared thermal imaging technology has been widely employed in temperature measurements of human and animals and its accuracy relies on the determination process of the emissivity of the target to a large extent. However, common used methods were unable to determine the emissivity of the surface of living animals and thus lower the accuracy. In this paper, we suggested a new approach to acquire the infrared emissivity of living swine in real time. In the approach, the surface temperature of swine and reference body were measured to compute the emissivity and the measurement process was completed in a non-contact and non-invasive manner. We changed the surface reflection energy of animals and reference body by changing the ambient radiant energy and obtain the surface emissivity in real time without confirming the actual temperature of animal surface. In this way, the infrared emissivity of the animal surface can be determined instantaneously and without knowing the real temperature. Both swine specimen and a living swine were used in this study. Using this method, we measured the emissivity of different body sites of the swine. The results showed that the emissivity values at different body sites show the significant differences. The emissivity values at trotter and eye were respectively 0.895 and 0.930 and the emissivity on swine surface varied from 0.945 to 0.978. More important, the distribution of the infrared emissivity on a living swine was explored and the detailed differences of the emissivity on a swine surface can be cleanly seen. Furthermore, we studied the influencing factors on the emissivity of animal surface, through measuring the emissivity distribution on swine surface when pig specimens were sprayed with water on the surface or heated using this method. This study is of great significance for the accurate measurement of swine surface temperature.

1. Introduction

Infrared temperature measuring technology, as a non-contact and non-invasive mean, has been adopted in the temperature measurement of livestock and wildlife animals (GürdiL et al., 2007; Mccafferty and Dominic, 2007), disease detection (Montanholi et al., 2008; Schaefer et al., 2012) and animal welfare (Nääs et al., 2014; Stewart et al., 2005). Pigs, as an abundant domestic animal, provide meat and by-products to human beings. The temperature of pig body directly determines its health state. The infrared thermal image technique has been studied in the pig surface temperature measurement (Malmkvist et al., 2012; Loughmiller et al., 2001), core temperature measurement (Zinn et al., 1985; Chung et al., 2010), pig disease study (Siewert et al., 2014; Cook et al., 2015), and the quality monitoring of pork (Costa et al., 2010; Schaefer et al., 1989).

Skin emissivity is one of the crucial factors to acquire the temperature of people and animals and it directly affects the precision of temperature measurement (Mccafferty and Dominic, 2007; Taylor et al., 2014). The emissivity of human is 0.975 based on the study Vargas et al. (Vargas et al., 2009), however, the emissivity of pig body surface ranged from 0.920 to 0.980 (Metternick-Jones and Skevington, 1992; Gariepy et al., 1989; Kelly and Heitman, 1954; Soerensen et al., 2014). (Chung et al., 2010) studied the relationship between surface temperature and core temperature of gnotobiotic piglets with the emissivity of 0.98. (Malmkvist et al., 2012) surveyed the thermal effect of floor on newborn pig body temperature with the emissivity of 0.98. Siewert determined the temperature on swine head with 0.97 (Siewert et al., 2014).

The skin tissue emissivity was also previously studied. The skin emissivity was calculated by measuring the physical temperature and infrared radiation temperature (Kelly and Heitman, 1954; Soerensen et al., 2014). However, in the method, it was required to directly contact pigs, even penetrate the thermometer into skin

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surface or kill animals and it took time to complete the heat transfer, thus resulting in the huge error and the slow measurement. (Togawa, 1989) proposed a method to measure the skin emissivity by changing the infrared reflection of the surface via utilizing additional thermal radiator (TR) and the method was applied and improved in later skin emissivity study (Huang and Togawa, 1995; Otsuka et al., 2002). The method could quick complete the measurement, but it could not used to determinate the emissivity of living animals. In addition, transmissivity, absorptivity, and reflectivity were measured based on Kirchhoff's laws to acquire the emissivity of the skin indirectly (Sanchez-Marin, 2010; Villase Or-Mora et al., 2009).

Therefore, in order to improve the surface temperature measurement precision of infrared thermal imaging technology, it is necessary to develop a fast and accurate approach to determine surface emissivity of living animals. In this paper, we changed the surface reflection energy of animals and reference body by changing the ambient radiant energy and obtain the surface emissivity in real time without confirming the actual temperature of animal surface. The paper aims to calculate the emissivity distribution differences of living porcine body surface and explore the influences of some environmental factors on porcine surface emissivity.

2. Materials and methods

2.1. Samples and instruments

One swine specimen and one growing swine were provided by the Beijing Academy of Agriculture and Forestry Sciences. The swine specimen was made by a real swine and was about 40 kg weight. The body surface was clean and could be heated by external heat source from the opening in abdomen. The living pig was robust with the weight of 80 kg. The swine specimen was used to study the influences of different environmental factors on the emissivity and the living swine was used to measure the distribution of surface emissivity,the living pig was narcotized by the veterinarian after feed 1 h in the moring, in order to keep it quiet in the experiment. Portable FLIR SC620 infrared camera (IRC) (FLIR Systems, Inc., Wilsonville, OR, USA) has the following parameters: the spectral band of 7.5–13 μm, the resolution of 640×480, thermal sensitivity < 40 mK, the camera lens of 24° and the instantaneous field of view (IFOV) is 0.65 mrad for one detector element. The reference body was a white hood paper. The emissivity of reference body (ε_r) was 0.93 (Flir Systems, 2011). The power of the TR source employed in this study was 400 W to alter the background radiation In the experimental period, a standard blackbody was used to calibrate the IRC; the ambient temperature was 25 ± 2 °C; RH was 45 ± 5%; the wind speed was 0.03 ± 0.01 m/s. Testo 435-2 multi-function meter (Testo AG, Germany) was adopted in the experiment. The remaining objects in the lab were covered by black velvet to reduce the emitted reflection. Alcohol was used to clean the sample surface.

2.2. Methods

Generally, IRC captures the infrared radiation emitted by the objects and then displays the radiation in the form of temperature on the screen through a series of transformation. In actual measurement, the infrared radiation entering an IRC includes the target radiation, environmental reflection, and the atmosphere radiation and can be expressed as:

$$I(T_R) = \tau_a[\varepsilon I(T_0) + (1 - \alpha)I(T_U)] + \varepsilon_a I(T_a) \tag{1}$$

where, $I(T_R), I(T_0), I(T_U)$, and $I(T_a)$ respectively represent the total radiation temperature, the target radiation temperature, and atmosphere radiation temperature. ε is the target emissivity; τ_a is atmospheric transmissivity; ε_a is atmospheric absorptivity; α is target absorptivity of the surroundings. In the short-distance measurement, $\tau_a = 1$; $\varepsilon_a = 0$. According to Kirchhoff's Law, α equals to ε in the temperature measurement for the opaque objects. Then, Eq. (1) is simplified as:

$$I(T_R) = \varepsilon[I(T_0) - I(T_U)] + I(T_U) \tag{2}$$

When the ambient temperature is T_{U1}, the total radiation temperatures of target $I(T_{R1})$ and reference body $I(T_{R3})$ received by the IRC are respectively expressed as:

$$I(T_{R1}) = \varepsilon[I(T_0) - I(T_{U1})] + I(T_{U1}) \tag{3}$$

$$I(T_{R3}) = \varepsilon_r[I(T_r) - I(T_{U1})] + I(T_{U1}) \tag{4}$$

When the ambient temperature is T_{U2}, the total radiation temperatures of target $I(T_{R2})$ and reference body $I(T_{R4})$ received separately by the IRC are respectively expressed as:

$$I(T_{R2}) = \varepsilon[I(T_0) - I(T_{U2})] + I(T_{U2}) \tag{5}$$

$$I(T_{R4}) = \varepsilon_r[I(T_0) - I(T_{U2})] + I(T_{U2}) \tag{6}$$

According to Eqs. (3)–(6), the emissivity is calculated as:

$$\varepsilon(T_0) = 1 - (1 - \varepsilon_r)\frac{I(T_{R2}) - I(T_{R1})}{I(T_{R4}) - I(T_{R3})}. \tag{7}$$

According to Planck's law, we get:

$$I(T_R) = \int_{\Delta\lambda} R_\lambda L_{b\lambda}(T)d\lambda = \int_{\Delta\lambda} R_\lambda \frac{C_1}{\pi}\lambda^{-5}\left[\exp\left(\frac{C_2}{\lambda T}\right) - 1\right]^{-1} d\lambda \approx CT^n \tag{8}$$

where R_λ is the spectral responsivity of the thermal imaging detector and it does not vary with the wavelength λ; C_1 and C_2 is the first and second radiation constant, respectively; C is a constant. Hence, Eq. (7) can be rewritten as:

$$\varepsilon(T_0) = 1 - (1 - \varepsilon_r)\frac{{T_{R2}}^n - {T_{R1}}^n}{{T_{R4}}^n - {T_{R3}}^n}. \tag{9}$$

The spectral band of SC620 IRC employed in the study is 7.5–13 μm and n=3.9889 (Okamoto, 1996). Eq. (9) is the final calculation equation adopted in the paper.

As shown in Fig. 1, the station of infrared data acquisition is composed of three parts. The infrared imaging part is consisted by IRC and laptop, which are connected by FireWare cable to record the infrared sequences at high speed. IRC was fixed by a tripod to ensure the stability and the dip angle between the IRC and the sample zone was 15°. For the opaque gray body, when the dip

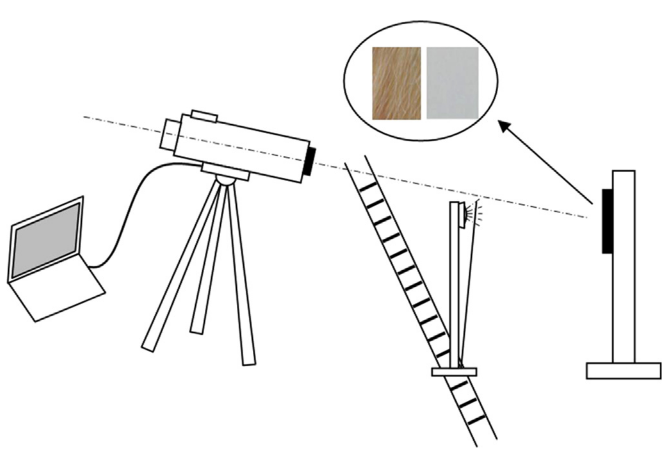

Fig.1. The experimental platform for emissivity measurement.

angle is above 30°, the emissivity is almost unchanged (Pantinakis and Kortsalioudakis, 2000). The TR part is composed of heat source, baffle, and guide rail. It is 0.5 m away from the IRC and TR is moving on the guide rail by the pulling force generated by the motor. Swine and reference body are paralleled in the view of IRC. The distance between IRC and the sample zone is 1 m and remains unchanged. In this way, the heater can radiates the sample zone vertically while the reflection from the IRC itself is reduced as possible.

The experimental platform was shown in Fig. 1. Before recording the videos, the parameters of IRC, such as distance, ambient temperature and humidity, should be set properly and the emissivity of the IRC was set as 1 in order to get the radiation temperature of the sample. Then the focal length was adjusted to make the picture of pig and reference body clear. With the temperature box of IRC, the exact measurement location was determined. The TR was started, put on one side of the guide rail and separated with baffle to prevent the heat interchange from the ambient environment. After setting the above parameters, it was ready for the measurement. The measurement steps were set as follows. Firstly, when IRC started to record infrared sequences, the TR moved to the field of vision. Once TR has entered the right place, the baffle was removed and the TR was turned off as soon as possible to avoid heating the sample surface by TR. Thus, the IRC could capture the change of infrared sequences caused by the external heater. At the end, TR disappeared in the field of vision and returned to the original position. Then the whole process of recording the infrared sequences was completed. According to the above process, 12 sets of measurement data were obtained and the interval of measurement sets was 2 min in order to acquire the independent measurement results.

The infrared sequences were stored in the laptop. The target temperature of pig and reference body before and after the TR entered the field of vision through FLIR Reporter software (Version 8.5 SP4, Flir system, USA) can be easily found and then the emissivity of the appointed zone was computed according to Eq. (9). In the study, standard deviations were used to analyze the error in Microsoft Excel (Microsoft office 2007, USA).

3. The results and discussions

3.1. The emissivity measurement of swine specimen surface

According to the above method, firstly we measured the temperature on the flank of the pig specimen as this part was flatter than other parts. The thermograms of specimen and reference body before and after the TR are shown in Fig. 2.

The emissivity of the left black frame in (Fig. 2A, and B) (the same zone on porcine specimen) was about 0.973 ± 0.002. This result was close to the previous result (Monteith and Unsworth, 1990), indicating that the approach could be used to measure the surface emissivity of living pigs.

3.2. The emissivity distribution on the surface of the living pig

We carried out the measurement on 10 different body positions of living pig at the same time. The emissivity of each part is shown in Fig. 3. The standard deviation indicated the discrete degree of each emissivity. The smaller deviation indicated that the more values were concentrated around the average value.

As shown in Fig. 3, the lowest emissivity was 0.90, which was obtained at the trotter. The highest emissivity was 0.978, which was obtained at the ear base and shoulder. The emissivity values at shank, leg and the back were 0.945, 0.955, and 0.965, respectively. Obviously, the emissivity distribution on other body parts such as

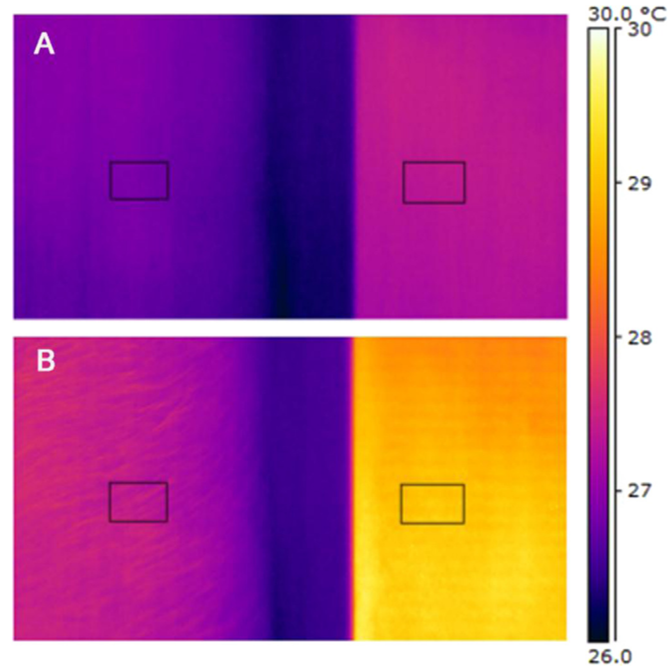

Fig.2. Infrared images of the porcine flank and reference body before TR (A) and after TR (B).

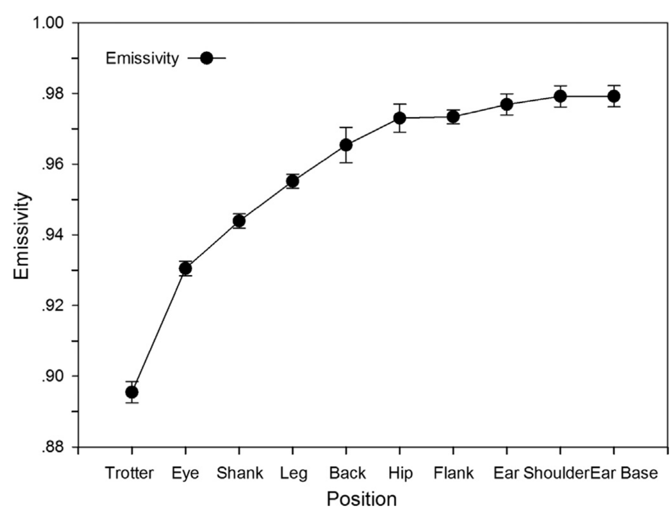

Fig.3. The emissivity of different position of swine.

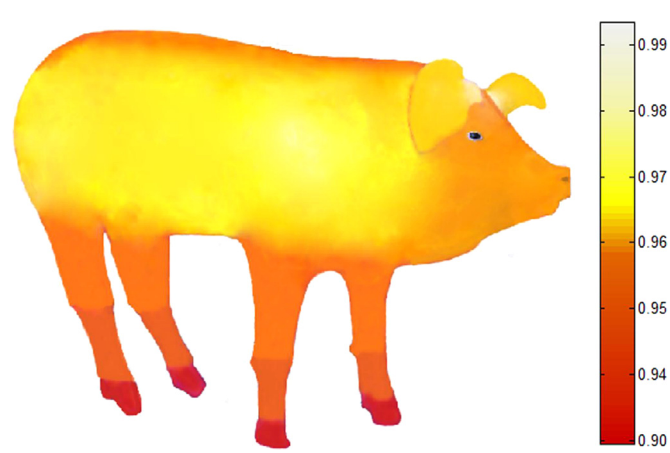

Fig.4. The surface emissivity distribution of the swine. Note: though the pig eye is described in the map, the emissivity is not marked on the color bar.

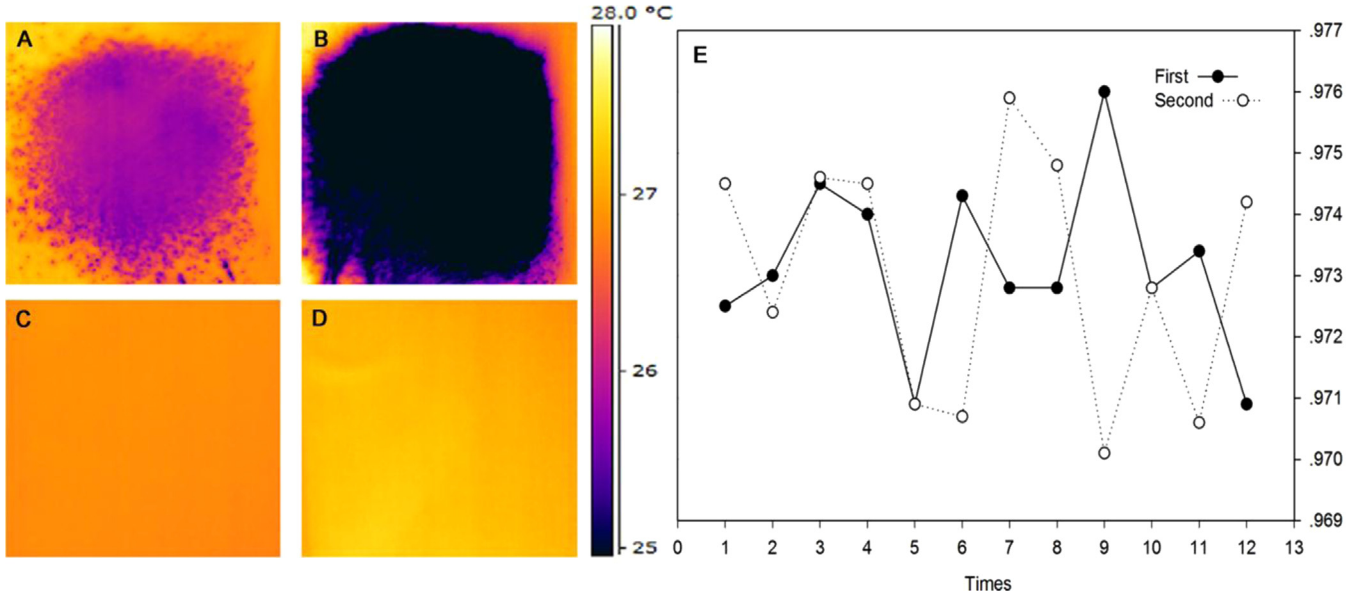

Fig.5. The first infrared image sprayed water after TR (A), the 10th after TR(B); the infrared image of reference body before TR(C), after TR (D); the change of emissivity when spraying water on the body surface of the two groups.

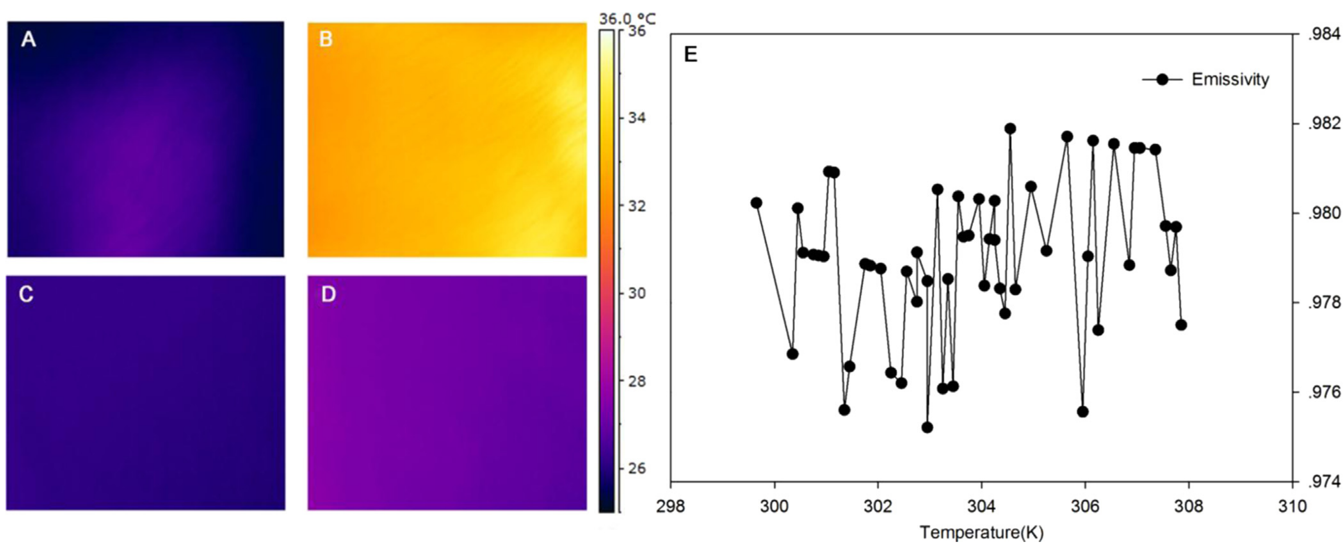

Fig.6. The infrared image when the specimen was at 26 °C after TR (A), at 35 °C after TR (B); the infrared image of reference body before TR(C), after TR (D); the change of emissivity when the body surface temperature is elevated.

hip, flank and ear showed no significant differences and the emissivity ranged from 0.973 to 0.976.

The emissivity values of pig body surface at different sites in the experiment were higher than partial previous results (Metternick-Jones and Skevington, 1992; Gariepy et al., 1989; Kelly and Heitman, 1954; Soerensen et al., 2014). The emissivity ranged from 0.92 to 0.978. The emissivity at the ear was in accordance with previous results and the minimum emissivity at the shoulder in this study was in accordance with the maximum emissivity (Soerensen et al., 2014). The reason for the higher emissivity values in the paper can be interpreted as follows. Firstly, the adopted measurement principles were different. In the paper, the reference body with the known emissivity was adopted in the measurement. In previous studies, the physical temperature was measured by piercing the thermocouple into or pasting the thermometer on the skin tissues, thus leading to the measurement inaccuracy. Secondly, ambient temperature was considered in the paper, thus eliminating the background influence to a large extent, if the ambient temperature keeps constant, the results would be more accurate. Thirdly, a living pig was adopted in the measurement and the killed pigs or pig carcass was used to measure the emissivity in previous studies (Metternick-Jones and Skevington, 1992; Soerensen et al., 2014). Since the pig was growing, strong metabolism would elevate the surface emissivity. Besides, it was worth noting that the pig body was cleaned in the measurement. Therefore, the measured emissivity was close to the actual emissivity on the body surface to a certain extent.

The variations of surface emissivity on different body sites are directly originated from the tissue structure, which leads to the obvious emissivity difference among different body sites. Since the structures of extremity and torso of the swine are close to those of human beings, porcine skin is often used as the substitute to human skin to carry out related studies (Villase Or-Mora et al., 2009; Sanchez-Marin, 2010). The emissivity of human skin was 0.98. The emissivity of living pig in this study was close to that of human. Especially in the bare skin zone, the emissivity of ear base was 0.978, which was close to that of human. The obtained emissivity of porcine eye in this paper was 0.93, whereas it was previously advised that the emissivity of human eye ranged from 0.97 to 1 (R, 1968), the reason why the emissivity of pig eye is much lower than human may be because of there is hair in the eye periocular area and the eye surface is moist. The obtained emissivity of trotter in this paper was 0.90 because the trotter was mainly composed of cartilage, which was significantly different from other skin tissues in the physical properties. The smooth degree of body surface leads to the variation of emissivity (Del Campo et al., 2006; Bernard et al., 2012; Ono, 1980). The greater radian of the surfaces of some parts, such as extremity, hip, and back leads to the lower emissivity. The greatest radian occurred at the extremity and represented the lowest emissivity value. The density and thickness of hair also influence the surface roughness, and leads to the emissivity difference in different body parts. The emissivity of naked area without hair, such as the ear base, is relatively large and roughly equal to that at the udder (Soerensen et al., 2014) because of the thinning hair at the udder. The back zone has the coarser hair than other parts, thus leading to the lower emissivity. Several factors influence the emissivity on porcine surface. The emissivity difference on body surface is shown in Fig. 3.

Further, another 5 different black frames were selected to measure the emissivity at the 10 different body positions in order to get the surface emissivity distribution of the whole porcine body. The measured data were processed with by the method mentioned above. The emissivity distribution on the swine surface is shown in Fig. 4.

3.3. The influences of surface physical property on the emissivity

3.3.1. The influence of water on surface

In the intensive livestock farm, the water content on the surface of different body parts is different because of the treatment of disinfection or animal activities. The influence of water on the body surface on the emissivity was not reported. Therefore, we sprayed water on the body surface of the pig specimen. Firstly, about 2 mL water was sprayed on the body surface in every time. One spraying was performed after each measurement. In total, water was sprayed on the body surface for 10 times. It was experimentally verified that spraying water for more than 10 times would allow water to drop down along the pig body, thus affecting the experimental results. The thermographs acquired are shown in Fig. 5A, B, C, and D. The darker part in the picture represents the spraying area.

The surface emissivity after spraying water is shown in Fig. 5E. The emissivity varied randomly with the spraying time in the two groups. The emissivity variation was within 0.006. In addition, water has no effect on the infrared properties of skin (Hardy, 1934). Therefore, we boldly believed that the surface emissivity of swine was a fixed value for different moistures.

3.3.2. The influence of surface temperature

Naturally, the surface temperature of animals varies with ambient temperature and the process of animal disease. The surface temperature of pig ranged from 17 to 35 °C (Costa et al., 2010; Schaefer et al., 1989). We studied the influence of surface temperature on the emissivity. Similarly, the experiment was carried out through heating the body cavity of pig specimen from the bottom of abdomen. The temperature was heated from 26 °C to 35 °C. The thermographs are shown in Fig. 6A, B, C, and D.

The emissivity was obtained after heating for three times, as shown in Fig. 6E. The interchange of heat on swinish body surface happens all the time. However, the infrared emissivity is almost a constant within the range of the temperature on porcine surface body, the emissivity variation was within 0.007 as can be seen in the picture. Thus, the emissivity can be treated as a constant in accurate temperature measurement.

4. Conclusions

Based on the infrared thermal imaging technology, in this paper, based the reference body with the known emissivity, we developed a new approach to measure the infrared emissivity of swine in a non-contact and fast way to avoid damaging pigs. With the porcine specimen, we firstly verified the feasibility of this method. The emissivity of pig surface at different areas was measured in this paper and the emissivity discrepancy was analyzed. Moreover, a diagram of emissivity distribution was described in the paper. It is found that the emissivity varies among different region of swine surface. The emissivity values at trotter and eye were respectively 0.895 and 0.930 and the emissivity on swine surface varied from 0.945 to 0.978. In addition, the emissivity remains unchanged when water was sprayed on pig surface or the surface temperature was changed. In short, the consequence is of great significance to the temperature measurement. More important, the emissivity of living swine can be determined with real-time using this method, so it is possible to compensate the emissivity to the infrared signals when measuring the temperature of animals, which will enhance the accuracy of thermal imaging techniques for biological temperature measurement. However, there were also some limitations of the experiment: (1) it is very hard to control the ambient temperature constant which will influence the measuring results, (2) the camera position is also an error factor which may bring tiny differences to the infrared signals.

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