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STUDY OF THE RELATIONSHIP BETWEEN THE TEMPERATURE-HUMIDITY INDEX AND THE SURFACE TEMPERATURE OF THE EYE AND THIGH OF HOLSTEIN-FRESIAN COWS USING INFRARED THERMOGRAPHY

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Abstract

The report aimed to present our study of the relationship between the temperature-humidity index (THI) and the surface temperature of the eye, and the thigh of Holstein-Friesian cows raised on a farm in southeastern Bulgaria, using infrared thermography (IRT). Measurements were conducted twice a month, May, June and July, twice a day at 10:00 AM and 5:00 PM, respectively. The correlation coefficient between the maximum eye temperatures and the temperature-humidity index was 0.7. The correlation coefficient between the surface temperature of the skin of the cows in the thigh area and the temperature-humidity index was 0.92. With an increase in the temperature-humidity index values, the rate of increase in the maximum eye temperature values was the highest (Slope=0.136). The rate of increase of minimum thigh surface temperatures with rising THI values is around 0.30 (Slope=0.297). The increase in the values of the temperature-humidity index leads to an increase in the temperature of the eyes and the surface temperature of the thigh in dairy cows, which is a result of an increase in the heat load on their body. The temperature of the thigh increases faster than the temperature of the eyes when the THI increases because the thigh is an area with massive muscles, which, in addition to its other role, is probably used for increased heat loss under conditions of heat stress.

Key words: *infrared thermography, dairy cows, skin temperature, temperature-humidity index.*

INTRODUCTION

The temperature of living tissues arises from various physiological processes occurring within them. Maintaining thermal equilibrium in organisms is crucial for their survival. Deviations from normal thermal levels can be associated with diseases. Therefore, measuring the temperature of animals is particularly significant as an indicator for diagnosing health status. Body temperature remains approximately constant and is directly related to skin temperature. Monitoring body temperature provides valuable insights into the health status of each individual examined. Detecting changes in body temperature can aid in diagnosing diseases caused by pathogens that have invaded and multiplied within the animal's body (Jhora & Mairizwan, 2020). In recent decades, non-contact temperature measurements have increasingly replaced contact methods. This can be accomplished using radiometry in the infrared spectrum, allowing for accurate and rapid measurements from distances that, if necessary, ensure a safe distance for the operator. These methods are particularly useful when it is not possible to approach the subject of study (Zhao & Bergmann, 2023). Remote monitoring is being utilized more frequently in various applications within livestock farming. The combination of a drone and a camera has been successfully employed to assess grass in pastures (Petrova et al., 2024), and a drone equipped with a thermographic camera has also been used for observing grazing animals (Valkovski et al., 2023).

The advancement of radiometric systems over the past few decades has established infrared thermography as a fast, accurate, and reliable method for remote medical measurements (Ring et al., 2010). Infrared thermography has emerged as a dependable remote alternative to contact thermometers for clinical temperature assessments, successfully diagnosing and monitoring a variety of diseases (Lahiri et al., 2012). With its accuracy, speed, and discretion, infrared thermography is considered the preferred tool for temperature measurements in veterinary medicine. It is effectively utilized to diagnose inflammatory processes of the udder and to detect mastitis (Zaninelli et al., 2018; Sinha et al., 2018; Pampariene et al., 2016). Additionally, it helps in diagnosing hoof problems and in the rapid detection of lameness (Hristov & Penev, 2024), as well as traumas and injuries on the body's periphery. Infrared thermography is a valuable aid in studying heat stress, which causes significant losses for farmers each year (St-Pierre et al., 2003). Automating data collection related to this issue is essential (Koltes et al., 2018). This is important because heat stress is influenced by environmental conditions and can quickly impact all animals when it occurs. Therefore, it is crucial to explore methods for automating systems that collect, store, and process information, make decisions, and send notifications accordingly (Cuvliuc et al., 2018). All of this underscores the importance of the heat stress issue and directs research efforts, with infrared thermography being a vital tool in this investigation (Daltro D. S. et al., 2017). In this study, we aim to examine the relationship between the temperature-humidity index (THI) and the surface temperature of the eye and thigh of Holstein-Friesian cows raised on a farm in Southeastern Bulgaria using infrared thermography (IRT).

MATERIALS AND METHODS

Infrared thermography is a non-contact technique used to measure surface temperature and is commonly employed in veterinary diagnostics to monitor physiological changes in animals. The eye, due to its high vascularity and minimal for interference, is particularly well-suited for temperature assessment. For accurate thermographic measurement, it is essential to have a clear understanding of infrared radiation principles, an optimized experimental setup, appropriate emissivity adjustments, and statistical data analysis. Incorrect emissivity settings can result in significant measurement errors, while statistical analysis is crucial for deriving meaningful interpretations from multiple readings (Vollmer & Möllmann, 2010).

Infrared radiation is emitted by all objects with a temperature above absolute zero, and Planck's Law describes its spectral intensity at different wavelengths. This law states that the amount of energy radiated by a black body at a specific wavelength depends on temperature and is expressed by the equation (1)

$$M(\lambda, T) = \frac{2\pi hc^2}{\lambda^5} \frac{1}{exp\left(\frac{hc}{\lambda kT}\right) - 1} \quad (1)$$

where $M(\lambda,T)$ represents the spectral radiance at wavelength λ, T is the absolute temperature, h is Planck's constant (6.626×10^{-34} J·s), c is the speed of light (3.0×10^{8}m/s), and k is Boltzmann's constant (1.381×10^{-23} J/K). This equation demonstrates that warmer objects emit more infrared radiation and that the emission peak shifts toward shorter wavelengths as temperature increases. In biological tissues, where the typical surface temperature is approximately 38°C, the peak infrared emission occurs around 10 μm, making the 7.5-13 μm spectral range of the FLIR E6 thermal camera ideal for detecting thermal emissions with minimal atmospheric absorption.

While Planck's Law (1) describes the spectral energy distribution, Stefan-Boltzmann's Law simplifies this concept by integrating radiation across all wavelengths. According to this law, the total radiative power per unit area of an object is proportional to the fourth power of its absolute temperature and is expressed as:

$$M(T) = \varepsilon\sigma T^4 \quad (2)$$

where M denotes the total emitted radiation, ε represents the emissivity, σ is the Stefan-Boltzmann constant (5.670×10^{-8} W/m²K⁴), and T indicates the absolute temperature in Kelvin. Since thermal cameras do not measure temperature directly but instead detect radiative power, calculating temperature relies on setting the appropriate emissivity value.

Emissivity indicates how effectively a surface emits infrared radiation in comparison to a perfect black body. Most biological tissues, like skin and sclera, exhibit emissivity values near 0.98, which means they act almost like ideal emitters. However, the cornea has a lower emissivity, typically ranging from 0.94 to 0.96, due to its transparency and moisture content. According to Kirchhoff's Law, which asserts that the sum of emissivity and reflectivity equals one for opaque materials, a lower emissivity results in higher reflectivity. This means some of the detected radiation originates from reflected environmental sources instead of the eye itself. To minimize reflection artifacts, the camera should be positioned at an angle (15-30°) rather than directly perpendicular to the eye (Soroko-Dubrovina & Davies Morel, 2023).

Accurate temperature measurement also requires careful setup design. The FLIR E6 thermal camera has a 45° × 34° field of view (FOV), which means that the area captured in the thermal image depends on the measurement distance. The width of the *FOV* (Maldaque, X. P. V. 2023) at a distance *D* is given by the equation (3)

$$FOV\ Width = 2Dtan\left(\frac{\theta}{2}\right) \quad (3)$$

where θ=45° is the horizontal FOV angle. For a distance of 1 meter, the FOV width is approximately 0.83 meters, while at 2 meters, it expands to 1.66 meters. The instantaneous field of view (IFOV) determines the smallest detectable detail and is calculated as

$$Pixel\ Size = \frac{FOV\ Width}{Camer\ Resolution} \quad (4)$$

Given that the FLIR E6 has a resolution of 160 × 120 pixels, at 1 meter, each pixel covers approximately 5 mm, while at 2 meters, the pixel size increases to 10 mm. Since an animal's eye is typically 20 mm in diameter, a 1–1.5 meter distance is recommended to balance resolution and temperature accuracy.

Errors in temperature measurement due to incorrect emissivity settings can be substantial. If the camera is set to an emissivity of 0.90 instead of 0.98, the measured temperature can be determined using the equation.

$$T_m = \left(\frac{\varepsilon_a}{\varepsilon_m}\right)^{\frac{1}{4}} T_a \quad (5)$$

where T_m is the measured temperature, T_a is the actual temperature, ε_a is the actual emissivity, and ε_m is the incorrect emissivity setting. Assuming the actual eye temperature is 38°C (311.15 K) and substituting ε_a=0.98 and ε_m=0.90, the calculation yields T_m=39.75°C.

This results in an overestimation error of +1.75°C. Similarly, if an emissivity of 1.00 is used instead of 0.98, the temperature is underestimated to 37.05°C, introducing a -0.95°C error. Such deviations can lead to misinterpretations of health conditions. An overestimated temperature may falsely indicate a fever or inflammation, while an underestimated reading could result in missing the diagnosis of an early-stage infection or thermal stress.

To extract meaningful insights from thermographic data, statistical analysis is crucial. In veterinary thermography, several measurements are taken to evaluate thermal regulation, stress responses, and disease conditions. Minimum and maximum temperature values reveal physiological heat dissipation patterns, while the mean temperature provides a more accurate estimate of the true physiological state by reducing the influence of outliers. The standard deviation measures the variability in measurements, with larger deviations indicating greater thermal instability.

Correlation analysis is regularly performed between eye temperature and environmental or physiological parameters, such as the Temperature-Humidity Index (THI), which combines ambient temperature and relative humidity to assess heat stress in animals. The correlation coefficient is calculated using

$$r = \frac{\sum(T_i-\bar{T})(THI_i-\overline{THI})}{\sqrt{\sum(T_i-\bar{T})^2}\sqrt{\sum(THI_i-\overline{THI})^2}} \quad (6)$$

where r represents the correlation strength, Ti are individual eye temperature values, and THIi are the corresponding environmental measurements. A correlation coefficient (6) close to 1 indicates a strong relationship, which supports the use of ocular thermography as a non-invasive tool for monitoring heat stress (Jorge et al., 2022).

Incorporating infrared radiation theory, designing effective experimental setups, and using statistical analysis, thermography serves as a powerful diagnostic tool for identifying fever, inflammation, and stress-related conditions in animals. Correctly adjusting emissivity, optimal camera placement, and

thorough statistical evaluation are essential for ensuring reliable veterinary assessments.
Infrared thermography is a relatively new research method in the field of animal husbandry and veterinary medicine, which combines accuracy, speed and research directly in production conditions. In the present study, the eye and thigh areas were selected as the object of study with infrared thermography for the following reasons. In order to obtain more accurate thermal data, it is necessary to select a part of the body that is well supplied with blood and, accordingly, emits sufficiently good thermal radiation into space. In Figure 1, we have shown a thermographic image of a cow from our study, which shows both areas of interest, the eyes and the thigh.

Figure 1. Thermal image from our research (original)

THI is an index that gives a quantitative value of the joint influence of humidity and temperature on living organisms. Its levels allow for the classification of heat stress (Armstrong, 1994), and diagrams have been made to account for its influence (Lakritz, 2012). Its values are used to assess the risk of heat stress in cows. Several formulas have been derived by which it is calculated (Dikmen & Hansen, 2009).
All known formulas for calculating THI have been developed with a view to most accurately covering the influence of all environmental factors (temperature, relative humidity, air velocity, dew point, solar radiation, etc.) on the thermal comfort of cows. However, these are environmental factors that affect animals. The effect of this influence on animals requires additional studies of some physiological indicators to be conducted. Such indicators are rectal temperature, respiratory rate, heart rate, daily milk yield, milk composition, etc. All these research methods are relatively difficult to perform, time-consuming, require fixation of cows and equipment for research. That is, in order to confirm the influence of heat stress on the comfort of dairy cows using classical methods, a complex of studies is required. In Figure 2 we have presented an image of a free-stall dairy farm located in Southeastern Bulgaria.

Figure 2. Dairy Farm in the SE part of Bulgaria (original)

Our study was conducted on a free-stall dairy farm that has approximately 150 Holstein-Friesian cows, located in the southeastern part of the Republic of Bulgaria. The period covered is from May to July 2018. Measurements were taken two days each month, twice a day. The first measurement of the day was recorded at 10 am, and the second at 5 pm. Thermal images were captured using a FLIR E6 thermal camera. Surface temperatures were obtained with the specialized FLIR Tools software. In our study, THI values were measured manually using a Kestrel device and were documented simultaneously with the thermal images.

RESULTS AND DISCUSSIONS

The correlation coefficient between minimum eye temperatures and the values of the temperature-humidity index is 0.32. The correlation coefficient between average eye temperatures and the values of the temperature-humidity index is 0.67. The correlation coefficient between maximum eye temperatures and the values of the temperature-humidity index is nearly 0.71. The correlation coefficient among the minimum, average, and maximum surface temperatures of the cows' skin in the thigh area and the values of the temperature-humidity index ranges from 0.90 to 0.92. The rate of increase of minimum eye temperatures with rising THI values is approximately 0.06 (Slope=0.059). The rate of increase of average eye temperatures with rising THI values is Slope=0.13. The rate of increase of maximum eye temperatures with rising THI values is nearly 0.14 (Slope=0.136). The rate of increase of minimum thigh surface temperatures with rising THI values is around 0.30 (Slope=0.297). The rate of increase of average surface temperatures in the thigh area with rising THI values is Slope=0.274. The rate of increase of maximum surface temperatures in the thigh area with rising THI values is approximately Slope=0.256.

In Table 1, we present average values of minimum, average, and maximum surface temperatures in the eye area, corresponding to the measured THI values.

Table 1. Average values of surface temperatures in the eye area corresponding to measured THI values

THI	Average Minimum Eye Temperature	Average Eye Temperature	Average Maximum Eye Temperature
69.3	35.6125	35.925	36.225
72.1	34.7	35.1	35.6
72.8	35.6	36	36
73.2	34.9	35.7	36
73.4	35.3	35.5	35.8
73.5	35.9	36.2	36.4
74.2	35.94	36.38	36.7
74.5	35.75	36.15	36.55
74.6	35.5	36.2	36.5
75.6	35.5	35.9	36.2
76.1	36.3	36.5	36.6
79.1	35.6	36.9	37.3

From the data in Table 1, it is evident that the eye temperature varies within one degree at different THI levels. The only exception is the maximum measured eye temperature, which at a THI above 79 reaches 37.3°C. At the remaining levels of THI, the average and minimum temperature values are up to 36.9°C. These results can be explained by the fact that the eye has a rich blood supply and lacks insulating layers such as skin or hair. Therefore, the temperature of the eye remains relatively constant and does not significantly depend on the ambient temperature.

In Figures 3, 4 and 5 we have visualized the dependence of the average values of the minimum, average and maximum ocular temperatures on the THI values.

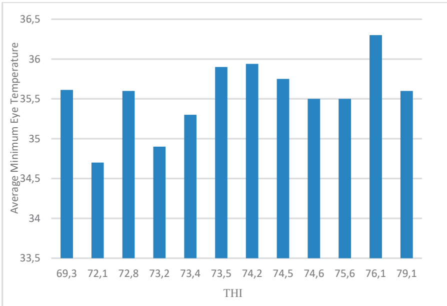

Figure 3. The relationship between average minimum ocular temperatures and THI values

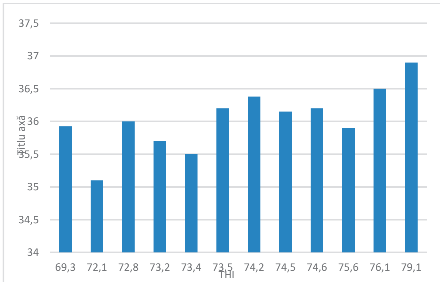

Figure 4. Relationship between average mean ocular temperatures and THI values

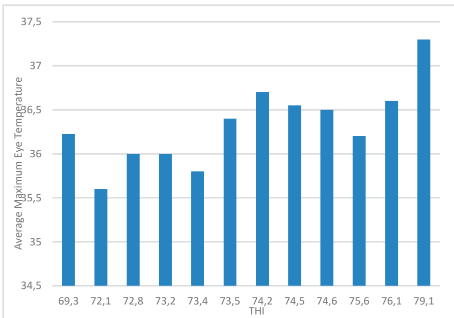

Figure 5. Relationship between average maximum ocular temperatures and THI values

To visualize the measurement results in a tabular format, we have presented some average values of the minimum, average, and maximum surface temperatures in the area of the cows' thighs, corresponding to the measured THI values. A more detailed analysis of the data in Table 2 reveals a variation of 2°C in the minimum and maximum temperatures of the thighs, depending on the THI values.

Table 2. Part of the averaged values of surface temperatures in the thigh area, corresponding to the measured THI values

THI	Average Min Thigh Skin Temperature	Average Thigh Skin Temperature	Average Max Thigh Skin Temperature
69.2	33.8	34.1	34.2
71.6	33.3	33.8	34.3
72.1	34.2	34.6	34.9
72.4	33.9	34.4	34.7
72.5	34	34.5	35.1
73.1	34.6	35	35.4
73.5	34.8	35.2	35.6
73.6	35.1	35.3	35.5
74.2	35.2	35.8	36.3
74.5	35.4	35.8	36
74.6	35.3	35.5	35.7
75.3	35.4	35.9	36.4
76.2	35.3	35.8	36
76.3	35.5	35.7	35.8
76.7	35.4	35.7	35.9
77.2	35.6	35.8	36

The variation in average thigh temperatures is 1.7°C based on the THI values. These data indicate that as THI values increase, the surface temperature of the thighs rises. This can be attributed to the presence of large muscle groups in the thigh area, which likely experience increased blood circulation as ambient temperature rises. This change occurs due to the body's thermoregulation adaptive mechanisms. When elevated body temperature occurs, the heat dissipation mechanisms are enhanced (Rana, 2025), leading to the observed trends in this study.
To illustrate the measurement results, Figures 6, 7, and 8 show the minimum, average, and maximum surface temperatures of the cows' thighs at different THI values.

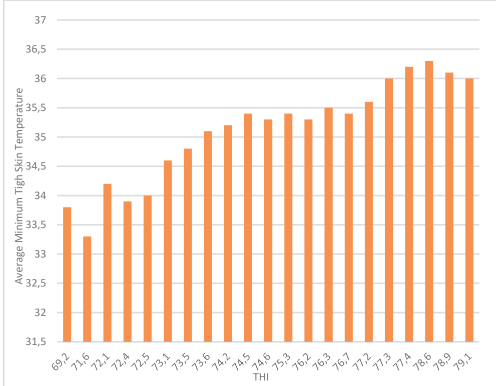

Figure 6. Dependence of the average values of the minimum surface temperatures of the skin in the thigh area on the THI values

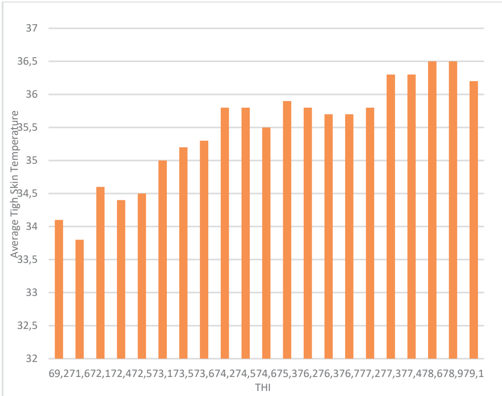

Figure 7. Dependence of the averaged values of the average surface skin temperatures in the thigh area on the THI values

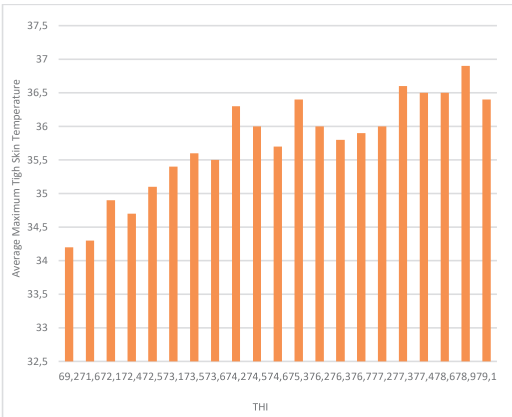

Figure 8. Dependence of the average values of the maximum surface temperatures of the skin in the thigh area on the THI values

The visual representation highlights a 2°C variation in minimum and maximum temperatures influenced by changes in THI.

The figures indicate that higher THI values are associated with increased maximum temperatures, likely due to greater blood flow and thermoregulation, while minimum temperatures remain more stable, possibly because of insulating effects. This graphical approach improves the understanding of heat stress impacts on cattle.

CONCLUSIONS

As the temperature-humidity index rises, the rate of increase in maximum eye temperature also rises. Higher values of the temperature-humidity index contribute to an elevation in both the temperature of the eyes and the surface temperature of the thigh in dairy cows, resulting from an increased heat load on their bodies. The stronger correlation coefficient between the thigh surface temperature and the temperature-humidity index indicates that the thigh surface temperature is more significantly influenced by changes in the temperature-humidity index than by variations in eye temperature. This is likely because the eyes have a rich blood supply and lack insulating anatomical structures. In the thigh, as a large area composed of muscles, the elevated body temperature induced by increased environmental temperature and humidity likely results in greater heat dissipation, which contributes to a more pronounced rise in the thigh surface temperature and facilitates body cooling by releasing excess heat into the environment.

In conclusion, we emphasize that the complexity of these studies, dictated by numerous factors affecting thermographic measurements and the unique challenges of working with large animals, necessitates additional research to refine practices.

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