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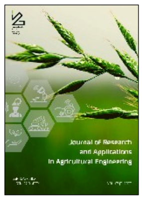

Milk temperature measurements in milking systems – own research

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The article presents the results of research conducted at the Department of Biosystems Engineering of the Poznań University of Life Sciences, related to the issue of temperature measurement in milking cluster. The construction of a four-quarter diagnostic milking system made it possible to re-examine the problem of using temperature sensors installed in teatcups for cow diagnostics. An original approach was the construction of a quarter milking system equipped with an electronic pulsator controlled by temperature sensors. Tests of temperature sensors using a modern laboratory station enable detailed identification of disturbances affecting temperature measurement conditions in the milking cluster. The main area of interest was to simulate phenomena occurring during cow milking, which for methodological reasons cannot be studied directly at units in cowsheds.
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1. Introduction

The use of modern methods of diagnosing cow udder health is one of the factors contributing to increased milk production efficiency on farms. In cowsheds, diagnostic assessment of animals is carried out both traditionally and using simple and more advanced electronic measuring devices [1]. A separate group consists of solutions that enable the diagnosis of cows at units during machine milking based on the analysis of selected physicochemical parameters of milk, including milk temperature [2]. A specific group of design solutions equipped with temperature sensors is available on the milking system market. Milk temperature measurements are performed in mass-produced milking machines with diagnostic functions, as well as in milking robots. Temperature sensors installed in milking systems enable the determination of the temperature of the milk from the udder or for individual cow quarters. Milking system manufacturers do not provide detailed information on the types of temperature sensors used, how they are installed in milking systems or how the measurement signals are processed. The milk temperature values recorded during milking are analysed using specialised software that is part of a herd computerised management

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system. Diagnostic messages (e.g. about elevated milk temperature) are generated on the displays of controllers, computers or smartphones [3].

Interest in the use of temperature sensors in milking systems in Polish academic centres can be divided into two periods. From the early 1980s to the early 21st century, agricultural universities in Krakow and Lublin were very active. The second period covers the years from 2009 to the present day and is related to activities carried out at the Department of Biosystems Engineering of the University of Life Sciences in Poznań [3]. Currently, it is the only centre in Poland dealing with the issue of temperature measurement in milking systems.

After 2000, there were few Polish and foreign publications on the subject of temperature measurement in milking systems. The dynamic development of electronic diagnostic systems for cows has once again sparked interest in temperature methods. The aim of the scientific research carried out since 2009 at the Department of Biosystems Engineering of the Poznań University of Life Sciences (initially in cooperation with the University of Agriculture in Krakow) is to identify factors influencing the conditions of temperature measurement in the teatcup (in older publications, this problem had only been partially addressed) and to study the dynamic properties of temperature sensors installed in various locations of the milking cluster (teatcup, claw, long milk tube). An important aspect of the research is the practical implementation of the results obtained in the construction of new milking systems. The construction and design work is being carried out in cooperation with a Polish manufacturer of milking systems.

2. Objective of the work

The aim of the study was to review selected scientific and design activities carried out at the Department of Biosystems Engineering of the Poznań University of Life Sciences, related to the issue of temperature measurement in milking systems. The functional properties of a computer system for temperature diagnostics of cows and a quarter milking cluster controlled by temperature sensors were described. The results obtained during field studies related to the issue of temperature diagnostics in cows were presented. Another area of activity described (still ongoing) was laboratory testing of temperature sensors installed in milking cluster under simulated cow milking conditions. The results obtained in laboratory tests using a special measuring station were presented.

3. The use of temperature sensors for temperature diagnostics in cows

Scientific studies conducted in Poland and other countries have confirmed the possibility of using milk temperature values recorded automatically during milking to diagnose oestrus in cows [4, 5, 7], including silent oestrus [6, 7], to detect early pregnancy [7, 8, 9], to detect subclinical and acute inflammation of the udder lobes in cows [10, 11, 12, 13] and other inflammatory conditions where fever may be one of the symptoms [7, 14].

In 2011, at the then Institute of Agricultural Engineering of the University of Life Sciences in Poznań, together with the University of Agriculture in Krakow, a four-quarter diagnostic milking machine was constructed. The design of the new milking system is an original solution with features not found in other mass-produced milking systems with diagnostic functions. An important novelty of the design is its ability to detect oestrus, early pregnancy and inflammation of the mammary glands during mechanical cow milking [15]. The new milking system (Fig. 1) is equipped with the following components:

- four TT4-5KC3-25-3500-UPP thermistors (manufactured by Tewa Temperature Sensors Sp. z o. o. from Lublin) installed in transparent inspection glasses of teatcups (Fig. 2);
- automatic measurement signal recorder (with 16-bit resolution) and battery-powered thermistor power supply module (mounted in a common housing with the display);
- milking equipment: electronic pulsator, vacuum tubes, short and long milk tubes and others;
- support platform made of acid-resistant steel, enabling the transfer of the milking cluster and measuring and electronic equipment between consecutively milked cows.

Fig. 1. Four-quarter diagnostic milking system in a cowshed (right)

Fig. 2. Method of installing a temperature sensor in an inspection glass of a teatcup

After milking is complete, the recorded temperature values are read using a PC, a USB interface and special computer software. The data (stored in the computer's semiconductor memory) can then be processed according to specific measurement and diagnostic algorithms. The computer software contains the following algorithms [16]:

- diagnostic algorithm for detecting oestrus – three data analysis variants are available;
- diagnostic algorithm for detecting early pregnancy (from the fifth day after insemination);
- diagnostic algorithm for detecting subclinical conditions in cows – three data analysis options are available;
- diagnostic algorithm for detecting acute conditions in cows;
- measurement algorithm for thermographic temperature analysis (determination of maximum milk temperature, initial sensor temperature and other parameters);
- algorithm for assessing the correct operation of temperature sensors installed in teatcups (detection of thermistors power supply interruptions).

In later publications, the term ‘Computer system for temperature diagnostics of cows’ was used in reference to the newly developed milking system with IT equipment [16].

The four-quarter diagnostic milking system was extensively tested in cowsheds during cow milking. The main research was carried out as part of a ministerial grant [17]. During milking, the temperatures of the milk flowing from the cows' udders were automatically recorded. A total of approximately 3,500 thermographs were obtained and in selected cases, milk samples were taken for microbiological testing (approximately 500).

The first group of studies conducted using a four-quarter milking system was related to the detection of oestrus and early pregnancy in cows. Milking was carried out in two cowsheds on a group of fifteen high-yielding cows [16, 18]. The results of analyses carried out using a special computer programme confirmed the possibility of detecting oestrus and early pregnancy in cows based on milk temperature measurements. Further studies were related to the detection of subclinical inflammation of cow udders [17, 19]. A total of eight research series were conducted in three cowsheds, during which nearly five hundred quarter milk samples (from a group of seventy cows) were additionally collected. The thermographs recorded during milking were interpreted using a computer programme containing three different versions of algorithms for detecting subclinical conditions in cows.

In diagnostic analyses, the health status of cow udder lobes was determined based on two ranges of somatic cell counts in quarter milk: 0-400,000 SCC in 1 ml of milk was considered a healthy lobe, while values above 400,000 SCC were considered a diseased lobe. In virtually every case of the algorithm variant used to analyse thermograms, higher average fluctuation values were obtained in cows with SCC in quarter milk > 400,000 per 1 ml. In many cases, no milk fluctuations were recorded during milking. The results of the analyses carried out using a special computer program confirmed the possibility of detecting subclinical mastitis in cows based on milk temperature measurements.

4. Use of temperature sensors to control the operation of the milking system

The correct milking process depends to a large extent on how the milking system is controlled [20]. Information on the use of temperature sensors to control milking machine operation is rarely found in the literature. In Poland, the possibility of using thermistors to control the automatic cluster remover (ACR) system was assesed [21, 22, 23]. The use of the ACR system prevents the occurrence of organisational overmilking. In the design solutions offered by milking system manufacturers, the decision to remove the machine from the cow's udder is made on the basis of the readings of an electronic milk meter [24]. In mass-produced quarter milking system, milk conductivity sensors are used to control the operation of the teatcups [25]. In turn, in the quarter pulsation milking machine developed at the Department of Biosystems Engineering of the University of Life Sciences in Poznań, “hot-wire” sensors are used to control the operation of the teatcups [26].

A prototype of a new quarter milking system is available at the Department of Biosystems Engineering of the Poznań University of Life Sciences [27]. The cluster allows for individual control of milking cups operation (the adjustable parameters are the pulsation rate and the pulsation ratio) in respective phases of cow milking. The cluster is equipped with temperature sensors (which act as milk flow indicators) and a quarter pulsator. The quarter pulsator can work with two types of dedicated NTC thermistors manufactured by Tewa Temperature Sensors Sp. z o.o. from Lublin (mounted in teatcups or in a claw in the form of a special measuring module). The pulsator has a wide range of operating parameters. The operating parameters of the teatcups (the pulsation rate and the pulsation ratio - individually for each quarter of the cow's udder) are programmed using a PC and specialised software. The pulsator includes an automatic measuring signal recorder (temperature, pulsation rate and pulsation ratio, individually for each teatcup). The quarter pulsator is equipped with an RS-485 interface, enabling communication with a computer over long distances. An original feature of the quarter pulsator programme is a special algorithm for controlling the operation of individual teatcups based on measured temperature values. The control algorithm consists of five operating modes: one time mode (a 60-second delay in changing the pulsator's operating parameters is programmed) and four temperature modes.

Fig.3. Laboratory station for testing a quarter milking system controlled by temperature sensors

Currently, advanced tests and laboratory research are underway at the laboratory of the Department of Biosystems Engineering at the Poznan University of Life Sciences, using a prototype quarter milking system controlled by temperature sensors [28]. A new laboratory test station has been developed for the purposes of the research (Fig. 3).

5. Laboratory testing of temperature sensors

The Department of Biosystems Engineering at the University of Life Sciences in Poznan conducts laboratory tests on temperature sensors installed in teatcups. The scope of activities includes testing the dynamic properties of thermistors, measuring temperatures under simulated cow milking conditions, and identifying disturbances affecting temperature measurements in the milking machine [29]. A new specialised measuring station has been built for the research [Fig. 4]. It is equipped with unique measuring and milking apparatus, which allows for the partial imitation of mechanical milking conditions in a laboratory setting. An additional feature of the measuring station is the ability to simulate disturbances affecting temperature measurement conditions in the milking cup: generating interruptions in the substitute liquid flow, programming the time of suction of external atmospheric air into the teatcup and the ability to conduct tests with and without pulsation liner's pulsation, with the liner completely open or completely closed [30].

Fig. 4. Laboratory station for testing temperature sensors installed in a teatcup

The following equipment was used in the construction of the laboratory station:

– a transparent teatcup placed on a special stabilising platform (to ensure complete washing of the thermistor during substitute liquid flow). The teatcup is equipped with a transparent liner and a transparent inspection glass, where the tested temperature sensor is mounted. Special plastic plugs are used to imitate a cow's teat;

- temperature sensors installed in teatcups. In laboratory tests, thermistors marked TT3-5KC3-68 (without additional protective material) and TT4-5KC3-25-3500-UPP (equipped with an additional acid-resistant steel cover with a wall thickness of 0.2 mm) were used. The sensors were designed and manufactured by the Polish company Tewa Temperature Sensors Sp. z o.o. The accuracy of the thermistors is ±0.1°C in the temperature range from 30°C to 45°C. The high nominal resistance of the thermistors (5000 Ω) allows long transmission cables to be connected without the need for special measurement procedures;
- our-channel automatic measurement signal recorder. This device can work with temperature sensors (thermistors). Thermistor power supply modules are installed inside the recorder. The recording frequency is 1 measurement per second, and the maximum operating time of the device is 90 minutes. The recorder's design incorporates a modern analogue-to-digital converter with very high resolution. The device can be battery-powered. Measurement data is read using a computer, a USB interface and special computer software;
- dual-channel solenoid valve controller. A characteristic feature of the device is the ability to automatically control the operation of solenoid valves using a computer, USB interface and special computer software. The controller allows for precise programming of the opening and closing times of the solenoid valves. The station uses two-state solenoid valves (fully open and fully closed) powered by 230 V AC. The first solenoid valve controls the flow of substitute liquid (tank - teatcup). The second solenoid valve allows atmospheric air to be sucked into the teatcup. Depending on the combination of solenoid valve operations, it is possible to supply the teatcup with substitute liquid, atmospheric air or a mixture of substitute liquid and atmospheric air;
- rotameters - mechanical rotameters are used to measure the flow rate of substitute liquid and atmospheric air intake. The medium flows through the rotameter from bottom to top. The flow rate of substitute liquid and air is regulated manually using shut-off valves;
- vacuum unit - it consists of a vacuum pump with a vacuum control valve, a transparent bucket with a vacuum gauge and vacuum and milk tubes;
- other equipment: electronic pulsator, substitute liquid tank, temperature gauge, indicator lights, computer, USB interface and more.

The thermographs recorded in laboratory tests were analysed mainly in terms of determining the maximum and minimum temperatures and the possibility of fluctuations (temperature differences $\Delta T \geq 0.5$oC) in the teatcup [28]. In earlier field studies of temperature sensors installed in teatcups, the fluctuations observed there were interpreted as interruptions in milk flow due to a pathological condition of the cow's udder lobes [10]. Changes in temperature during the entire milking process were not analysed, nor were other causes of temperature fluctuations investigated [21, 31].

The following research topics were addressed in laboratory studies conducted at the Department of Biosystems Engineering of the Poznań University of Life Sciences:

- the effect of substitute liquid flow rate on shaping of temperature in the teatcup. The results obtained showed that in the case of a thermistor without additional protective material, temperature differences $\Delta T \geq 0.5$°C were recorded at a substitute liquid flow rate of 1.00 $l \cdot min^{-1}$ and lower, while for a thermistor with a metal cover, they only appeared during substitute liquid flow at a minimum flow rate of 0.17 $l \cdot min^{-1}$ [32]. The temperature differences recorded in thermistor tests were caused by incomplete washing of the sensors with the flow of substitute liquid. In cowshed, it is not possible to observe the degree of washing of the sensors with milk flowing out of the udder. Even if the thermistors are correctly installed in the teatcups, the intensity of milk flow, which varies during milking, may affect on shaping of temperature at the measuring point [21];
- the effect of sucking atmospheric air into the teatcup on shaping of temperature in the teatcup. The results of the study showed that the presence of a mixture of air and liquid in the teatcup causes temperature differences of $\Delta T \geq 0.5$°C, even with a short suction time of atmospheric air [33, 34]. The suction of atmospheric air into the teatcup is a phenomenon that occurs particularly in the final phase of cow milking, when milk with lower flow rates flows from the udder [35]. It is not possible to measure the flow rate of sucked air in cowshed. This phenomenon can be reduced, among other things, by selecting the appropriate liners [36];
- the impact of interruptions in the flow of substitute liquid on shaping of temperature in the teatcup. The results of the study showed that even a few seconds of interruption in the flow of substitute liquid caused temperature differences of $\Delta T \geq 0.5$°C in the teatcup [33]. In cowshed, interruptions in milk flow during milking may be caused by: udder disease, individual animal characteristics, disturbances in the milking process or other reasons [31];

- the effect of liner's pulsation on shaping of temperature in the teatcup. The results obtained showed that the pulsating action of the liner, with varying pulsation rate and pulsation ratio, did not cause temperature differences of $\Delta T \geq 0.5^{\circ}C$ in the temperature sensors tested [28].

Currently, new research on temperature sensors installed in milking systems is being conducted at the Department of Biosystems Engineering of the Poznań University of Life Sciences. The laboratory station is being gradually modernised [37], which creates new research opportunities.

6. Conclusions

- Despite extensive literature on the possibilities of temperature diagnostics in cows, these have not been put to practical use by milking system manufacturers. Only a small number of milking clusters and milking robots are equipped with temperature sensors. For the purposes of cow diagnostics, milk temperature measurement is used as an additional parameter. Specialised measuring tools are used in cowsheds to detect the physiological condition of cows, while the health of cows' udders is assessed on the basis of milk conductivity measurements.
- Currently, there are no mass-produced milking systems available on the market that use temperature sensors to control the operation of the milking cluster or individual teatcups. The use of temperature sensors to control the operation of teatcups would also enable diagnostic assessment of cows during milking (using the same milking system).
- Research conducted at the Department of Biosystems Engineering of the Poznań University of Life Sciences has enabled a new understanding of the problem of using temperature sensors in milking systems. The result of this work was the construction of a computer system for temperature diagnostics of cows and a quarter milking system. Modern electronic and IT technologies have been extensively used in the construction of new milking systems. The possibility of programming the configuration of milking systems allows their operating parameters to be selected according to the specific characteristics of the cowshed.
- Temperature sensor tests, conducted using a modern laboratory station, enabled detailed identification of disturbances affecting temperature measurement conditions in the teatcup. Particular attention was paid to simulating phenomena occurring during cow milking, which for methodological reasons cannot be studied directly at milking stations in dairy barns.
- Currently, the Department of Biosystems Engineering at the Poznań University of Life Sciences is planning new research on temperature sensors installed in milking systems. First, the impact of disturbances on the control of teatcups in a quarter milking system will be analysed. Another planned activity will be temperature measurements in the teatcup at varying flow rates of substitute liquid. Another area of activity will be the modernisation of laboratory stations and their equipment with new components (e.g. proportional solenoid valve).
- The research and design work carried out at the Department of Biosystems Engineering of the Poznań University of Life Sciences was conducted in cooperation with a Polish manufacturer of milking systems. Cooperation with the manufacturer enabled the development of an effective method of installing temperature sensors in teatcups. Part of the measurement and control equipment was based on the company's component base. The Polish manufacturer also provided technical and organisational support during scientific research in cowsheds.
- Further research related to temperature measurement in milking systems should take into account the methodological and technological limitations that arise. Firstly, these limitations result from the limited possibilities of simulating the milking process in laboratory conditions, including the physical and chemical properties of milk flowing from cows' teats, which differ from those of substitute liquid and the diverse microclimatic conditions in cowsheds (compared to laboratories), the inability to take into account the microbiological properties of milk and the behavioural characteristics of milked animals in laboratory tests. In turn, planning new field studies would require cooperation with a milking system manufacturer. The new milking devices designed at the Department of Biosystems Engineering of the Poznań University of Life Sciences are prototypes. Their use in long-term studies at milking units requires access to modern production technologies. A critical problem would be to develop a reliable method of installing temperature sensors in teatcups or to construct a special measuring module installed in the claw.

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