

Review articles

Features of the formation and monitoring of the microclimate in non-insulated barns: unresolved issues

Received: 08 May 2020
Revised: 20 May 2020
Accepted: 06 June 2020

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Cite this article: Mylostyvyi, R., Vysokos, M., Timoshenko, V., Muzyka, A., Vtoryi, V., Vtoryi, S., Chernenko, O., Izhboldina, O., Khmeleva, O., & Hoffmann, G. (2020). Features of the formation and monitoring of the microclimate in non-insulated barns: unresolved issues. *Theoretical and Applied Veterinary Medicine*, 8(2), 73–85. doi: 10.32819/2020.82011

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Abstract. Modern non-insulated barns (NB) for free-stall housing of dairy cows differ from traditional (typical) capital buildings. The formation of the microclimate in such farms is significantly dependent on the state of the environment and their design features. The aim of the work was to give a review of the literature and the results of our own research on creating comfortable conditions for dairy cows in the NB. Our studies indicate the heterogeneity of the microclimate formation in different parts of the NB, which was largely due to the state of the external environment. The use of only natural ventilation through open side curtains and light ridges, as well as additional mechanical ventilation (due to horizontal axial fans) cannot always provide comfortable conditions for animals, especially in hot periods of the year. The literature analysis showed that this can be caused by factors affecting the formation and movement of air masses in the building itself (depending on the number of animals, the condition of the litter, the operation of internal equipment, including space-planning and design features, type and quality of materials of enclosing structures) as well as the weather conditions outside buildings (temperature, humidity, wind strength and also relief). Investigations related to remote methods of microclimate control (using appropriate portable devices) and identification of (critical) control points of deterioration of the air environment in NBs will be promising. Monitoring of them will allow timely to adopt the necessary management decisions for ensuring the comfort of dairy cows in extreme weather conditions. Climate prediction methods based on meteorological data in the area of the NB location and the development of intelligent ventilation systems using mathematical modeling that take into account the behavioral and physiological responses of animals to environmental changes will be especially in demand.

Keywords: naturally ventilated barns; design features; cow comfort; technical solutions; heat stress; modeling.

Особенности формирования и мониторинга микроклимата в неизолированных помещениях: нерешенные вопросы

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Аннотация. Современные неизолированные помещения (НП) для безпривязного содержания молочных коров отличаются от традиционных (типовых) капитальных зданий. Формирование микроклимата в таких помещениях значительно зависит от состояния окружающей среды и их конструктивных особенностей. Целью работы было обобщение литературных источников и результатов собственных исследований по созданию комфортных условий для молочных коров в НП. Наши исследования свидетельствуют о неоднородности формирования микроклимата в разных частях НП, который в значительной степени был обусловлен состоянием внешней среды. Применение только естественной вентиляции через открытые боковые шторы и световые коньки, а также дополнительная механическая вентиляция (за счет горизонтальных осевых вентиляторов) не всегда могут обеспечить комфортные условия

для животных, особенно, в жаркие периоды года. Литературный анализ показывает, что причиной этого могут быть как факторы, влияющие на формирование и перемещение воздушных масс в самом помещении (зависящие от количества животных, состояния подстилки, работы внутреннего оборудования, в т.ч. объемно-планировочных и конструктивных особенностей, вида и качества материалов ограждающих конструкций), так и погодных условий снаружи зданий (температуры, влажности, силы ветра, а также рельефа местности). Перспективными будут исследования, связанные с дистанционными методами контроля микроклимата (с применением соответствующих портативных устройств) и выявлением контрольных (критических) точек ухудшения состояния воздушной среды в НП, мониторинг которых позволит вовремя принять необходимые управленческие решения по обеспечению комфорта молочных коров в экстремальных погодных условиях. Особенно востребованы будут методы прогноза микроклимата на основе метеорологических данных в зоне расположения НП и разработка интеллектуальных систем вентиляции с использованием математического моделирования, учитывающие поведенческие и физиологические реакции животных на изменения окружающей среды.

Ключевые слова: натурально-вентилируемые помещения; конструктивные особенности; комфорт коров; технические решения; тепловой стресс; моделирование.

Introduction

Livestock should be acceptable to animals and the environment. Its effectiveness can be significantly improved through the introduction of low-cost sustainable agricultural technologies (Hempel et al., 2018; Sultan et al., 2019). However, in an artificially created closed space of modern industrial complexes, animals are not able to realize the whole spectrum of evolutionarily formed behavioral reactions; therefore we are obliged to provide them with comfortable conditions of keeping in accordance with their biological and physiological characteristics.

Global climate changes are accompanied not only by milder winters, but also significant (extreme) temperature rises in the warm season, which can be a significant challenge for livestock. Heat stress (HS) leads to physiological changes and a decrease in milk yield (Tao et al., 2018; Herbut et al., 2019), impaired reproductive function in cows (Dahl et al., 2016; Schüller et al., 2016) and losses associated with worsening animal welfare with long-term effects (Whay & Shearer, 2017). To determine HS effects in dairy cows the use of animal-related methods (Hoffmann et al., 2020) as well as mathematical modeling to predict the reaction of animals to heat stress (Heinicke et al., 2019; Pinto et al., 2019; Müschner-Siemens et al., 2020) are prevailed.

A feature of the indoor microclimate is that the numerous parameters that determine it (temperature of the air and building enclosures inside the building; gas composition, relative humidity, dustiness, microbial contamination of the air; natural and artificial lighting, air mobility, and sound pressure level inside the structure) themselves depend on or are derivatives of animal activity, the operation of machines, mechanisms and apparatuses serving the housing and animals. In addition, the indoor microclimate is influenced by the architecture and internal arrangement of the barn itself, its design and the materials from which the fencing is made. A great influence is exerted by the landscape surrounding the farm, as well as the state of the environment: temperature and humidity of the outdoor air, wind speed and direction, daily changes in temperature and humidity of the outdoor air (Popkov et al., 2018).

The microclimate reflects an environment close to animals, significantly affecting their productivity and well-being (Patbandha et al., 2018). The combination of its physical, chemical and biological factors can affect animals both positively and negatively. If external factors in the form of weather phenomena are uncontrolled, but predicted, then internal factors can be controlled by creating comfortable living conditions for animals (Timoshenko et al., 2017).

The greatest influence on the physiological state and productivity of cows is exerted by temperature, humidity, air velocity and barns illumination (Ilin & Vtoryiy, 2017; Yano et al., 2018; Hempel et al., 2018; Mylostyvyi & Chernenko, 2019). The content of carbon dioxide, ammonia, hydrogen sulfide, and more recently methane as a greenhouse gas, is also subject to control (Poteko et al., 2019; Sanchis et al., 2019).

By the degree of influence on productivity, the indoor microclimate is second only to the influence of breed and feeding. For example, when milk yield is 8 000–10 000 kg, milk loss due to violation of the conditions of keeping can be 1 000–1 500 kg per cow per year. However, to this day, indoor air exchange is calculated according to standards that practically do not take into account the biological activity of animals and their waste, specific biological and veterinary, thermophysical, technological and energy requirements for modern microclimate systems (Vtoryi et al., 2018). As a result, there are unforeseen deviations of real air parameters from the calculated ones and unreasonable excess of energy-consuming capacities. Also the active introduction of new foreign technologies and equipment without taking into account the climatic features of the regions creates problems in the operation of ventilation systems (Fedorenko et al., 2010).

The current standards of technological design of livestock facilities in Belarus require revision and updating. They do not reflect the experience of recent years in the widespread use of resource-saving technologies that take into account animal welfare and the capabilities of modern technology (Tymoshenko et al., 2015). It remains relevant to develop new microclimate standards for highly productive cows on the basis of a thorough study of the vital signs of the body and its interaction with the environment, the introduction of which will ensure comfortable living conditions, with a significant reduction in investment and energy costs.

It is not necessary to limit oneself only by monitoring the microclimate, although there are still many «gaps» (Hempel et al., 2018; Wang et al., 2018c). It is important to predict it using the capabilities of mathematical modeling (Maniatis et al., 2017).

The aim of the work was to summarize literary sources and our own research on creating comfortable conditions for dairy cows in modern non-insulated barns.

Experience in the use of lightweight constructions in dairy farming

Technological and technical solutions, especially in industrial complexes, often contradict the biological needs and capabilities of the body, which leads to a decrease in resistance, worsening of well-being and premature departure from the herd (Tymoshenko et al., 2017).

Milking of highly productive cows significantly depends on the necessary air exchange. It is believed that non-insulated barns are most acceptable both in terms of milk production and cow health. Compared to the capital (typical) cattle-breeding housing, the concentration of harmful gases is lower there and the conditions for animals are more comfortable (Loshkarev et al., 2018; Jovović et al., 2019). Due to the use of lightweight enclosing structures and modern natural ventilation systems, the cost of one place for growing cattle is lower 24–28%, however, the cost of the milking and other technological equipment increases construction costs by a third.

Observations of animal behavior during their implementation

of the basic processes of life showed (Trofimov et al., 2014) that in the conditions of the Republic of Belarus, cows felt comfortable in buildings made of metal structures due to the creation of the most optimal humidity regime. The use of light-aeration lamps (Gridin & Tyagunov, 2012) in NBs provided better and longer illumination of the feed table, having a positive effect on the time and rate of feed intake by animals, which increased the duration of rest period for the animals required for enhanced milk synthesis.

Such premises are well established in Estonia and Finland, with a content of 30 to 600 dairy cows on premises. Studies at ambient temperatures from -30 °C to +30 °C showed (Teye et al., 2007) that the microclimate in the cowsheds was within the recommended standards, however, it significantly depended on the design of the buildings, outdoor temperature and wind speed.

It was established (Vtoryi et al., 2016) that, in non-insulated livestock buildings, depending on the direction of the wind, the CO₂ concentration can be from 664 to 1 034 ppm, not exceeding the maximum permissible concentration (2 500 ppm for the standards of the Russian Federation). The highest CO₂ concentrations were observed at a distance of 1.5 m from the floor.

Problems in the functioning of non-insulated rooms usually occurred in winter at temperatures below -15 °C – when the manure passages began to freeze (Teye et al., 2007), as well as during the summer heat (up to +36 °C), when in animal resting areas it rose to +34 °C (Voloshchuk & Khotenko, 2017).

Ventilation systems through openings in the longitudinal walls and light lamps along the ridge of the roof turned out to be practically ineffective at -6–8 °C (Fedorenko et al., 2010), due to the large dimensions of the buildings (600–800 animals), which allow providing the necessary air parameters only in a narrow range of external temperatures. When the temperature was lowered to -33 °C for several days (Frederick Teye et al., 2006), in one of the NBs it dropped to -28 °C, and the problem was high humidity, which required more efficient ventilation.

In winter, in closed cowsheds during the day, CO₂ concentrations can vary from 1 500 to 2 380 ppm, in some cases increasing to 3200 ppm at night. The level of CO₂ concentration increased from the leeward to the windward side both in the length of 2.0–2.5 times and the width of the building 1.1–1.3 times (Vtoryi, 2016).

The additional work of the circulation fans did not provide a sufficient exchange rate and air velocity at the animal level (up to 1 m). The temperature from the longitudinal wall of the building to its middle practically did not change, which indicates the unsatisfactory operation of the ventilation system (Timoshenko et al., 2015); therefore, large-capacity buildings put forward additional requirements for microclimate support systems and require new approaches to its assessment and normalization (Vtoryi et al., 2018). At the same time Trofimov et al. (2014) report that for intensive ventilation and access of the required amount of fresh air inside the barns with a width of 18–24 m, it is enough that the side walls have a height of 3.0–3.2 m and a width of 30 m – 3.6 m. The extra height of the building is its inexpedient rise in price.

The microclimate state depended on the design features of the NB. In particular, in the winter months the temperature was lower in a building made of metal structures without warming of the roof (MS), in a building made of prefabricated semi-frame reinforced concrete structures (SRS), as well as in a building made of metal structures with a warmed roof (MSW) by 7.3; 5.0 and 2.7 °C, respectively, than in a building made of sandwich panels (SP), i.e. +10.1 °C (Tymoshenko et al., 2017).

The relative humidity in the frontal part of the MS, SRS and MSW was 4.8; 1.0 and 0.5% higher in comparison with SP (80.4). In the central part of the building, the air temperature was correspondingly lower by 6.8; 4.3 and 2.5 °C than in SP (+9.1 °C). Relative humidity was 4.6%, 1.1% and 0.5% higher, compared with SP (80.9%).

The indicated microclimate parameters affected the milk productivity of cows: on average during the winter period, the average daily milk-yield of cows in SP (31.2 kg) exceeded the productivity of animals in MSW by 0.3%, SRS by 4.0 and MS by 5.4%.

They came to the conclusion (Tymoshenko et al., 2017) that not only more comfortable conditions for the livelihoods of animals are created in the SP buildings and MSW, but also the optimal mode for the operation of technological equipment (manure removal and watering systems for animals) in comparison with livestock buildings of SRS and MS.

Although these buildings were distinguished by a system of ventilation curtains in the longitudinal walls, the following dependence was typical for them: the temperature and relative humidity rose from the floor up and from the longitudinal wall of the building to its middle both in the end section and in the central one, which indicates satisfactory operation of the ventilation system during the winter period (at an average outdoor temperature of -3.4 °C and a relative humidity of 90.7%).

The study of Trofimov et al. (2014) confirms that in the winter period in the end portion of the MSW it was by 4.6 °C warmer than in the MS (-8.7 °C), with relative humidity of 77.3% (it was less by 17.3%). In the central part of MSW, it was warmer by 3.5 °C (it was -5.6 °C), humidity was 11.3 % lower than in MS (-9.1 °C and 95.2%). The difference in temperature and relative humidity in individual parts of the NB was 0.4–1.5 °C and 0.6–6.6% (with large differences in MSW). In summer, in the end sections of the MSW it was 1.6 °C cooler and the relative humidity was 2.8% lower than in SRS (+29.1 °C and 50.3%). In the central part of the MSW, the indicators were lower by 1.6 °C and 4.5 % than in SRS (+29.9 °C and 55.2%). Differences in these parameters in individual parts of the rooms amounted to 0.8 °C and 2.1% (with a larger difference in SRS). In addition, there was insufficient air velocity in the SRS: in the end section it was 0.11 m.p.s., in the central part 0.07 m.p.s.. In MSW, it was at the level of 0.42–0.46 m.p.s. The comfortable conditions of the MSW contributed to the fact that the cows spent more time in the stall lying in both the winter (by 0.9%) and the summer (by 5.3%) periods.

The temperature of the building was influenced by technological operations. In winter (Tymoshenko et al., 2015), when distributing feed using mobile means, there was a short-term decrease in air temperature by 1–2 °C with an increase in humidity by 1–2%. The difference in air velocity and the content of NH₃ and CO₂ was insignificant both in the end and central zones of the rooms. The illumination of the feed table at the head level of animals was on average 348–447 lx (in the central boxes 432–471 lx, in the end wall ones 360–465 lx). However, in head-to-head boxes, both in the end and central, the illumination was insufficient (with a norm of at least 200 lx) 163–185 and 188–215 lx, respectively.

The greatest influence on the milk production and physiological state of cows was exerted by relative humidity, air velocity and illumination in the NB (Martina & Yastrebova, 2013a). The “critical points” in the indoor microclimate deterioration (Martina & Yastrebova, 2013b) were the northern and southern parts of the buildings in winter, and the central and southern ones in summer. In transitional periods, according to the complex of microclimatic parameters, such «critical points» were not found. However, as well as in the previous publication of these authors, there are no data on the location of cowsheds relative to cardinal points.

Problematic issues

The hot summer season is a real test for NB. There is a certain temperature zone within which the processes of heat production and heat transfer in animals are of minimal importance. This zone is called the thermal indifference zone or comfort temperature. In

size, this zone is lower than body temperature and depends on the breed characteristics of animals, the degree of acclimatization, the level of feeding, age and productivity. It is known that for cattle the thermoneutral zone is quite wide (West, 2003). Within the comfort zone, animals show maximum productivity and spend the least amount of feed per unit of production. If dairy cattle tolerate cold more easily, then temperatures exceeding the comfort zone (according to the FAO data from +4 to +24 °C) lead to deterioration in well-being and decrease in productivity.

The reaction of cows to heat was manifested at a temperature exceeding 20 °C (Popkov et al., 2018). With its increase from 20 to 30 °C, the animals reduced the consumption of dry feeds by 1.5 kg, reducing milk-yield by 3–5 kg per day. At the same time, it should be noted that there is no exact data on how much milk production will decrease and how much feed consumption will increase if the parameters deviate from the optimal.

On the one hand, the main advantage of NBs is their energy-saving properties due to natural ventilation, which does not require energy consumption; on the other hand, this housing system is especially vulnerable, since the indoor microclimate directly depends on environmental conditions (Hempel et al., 2018).

Classically, heat stress (HS) is estimated by the temperature-humidity index (THI), which is based on simultaneous measurements of air temperature and relative humidity (Herbut et al., 2018; Mylostyvyi & Sejian, 2019), the combined effect of which can be extremely fatal for all livestock during periods of heat. Sometimes,

when calculating such indices (e.g., the equivalent temperature index ETIC, etc.), additional variables are taken into account that can increase or decrease the heat load, such as solar radiation or air velocity (Maderet et al., 2006; Wang et al., 2018b; Yao et al., 2019).

It is believed (Herbut et al., 2018) that the value of temperature-humidity index below 68 units corresponds to comfortable conditions for animals and is the limit above which they are prone to heat stress. The THI value at the level of 68–71 corresponds to a little stress, within 72–79 to moderate one, while at value of 80–89 the cows are in a state of severe stress, and 90–99 in a very strong (hard) stress. Typically, the effect of thermal stress can occur even at a temperature of +22 °C, if the relative humidity exceeds 50% (Table 1).

It is important to prevent the occurrence of heat stress by predicting it using weather forecasts (Herbut et al., 2018). To evaluate the THI in a NP, the temperature and humidity indicators from the nearest weather stations are mainly used or the average daily values (or maximums) of these parameters in the center of the building are taken into account.

Although data from nearby weather stations have long been considered acceptable in assessing the impact of weather on cow behavior, welfare, and productivity (Bohmanova et al., 2007), the weather conditions near livestock buildings can significantly depend on heat-insulating materials that significantly affect their energy efficiency and environmental performance (Schüller et al., 2013; Valančius et al., 2018).

Table 1. Calculation of THI* values taking into account regional climatic conditions of the steppe of Ukraine (Mylostyvyi et al., 2019a)

Temperature, °C	Relative humidity, %																
	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95
20	63	63	64	64	64	65	65	65	65	66	66	66	67	67	67	67	68
21	64	64	65	65	65	66	66	66	67	67	67	68	68	68	69	69	69
22	65	65	66	66	67	67	67	68	68	69	69	69	70	70	70	71	71
23	66	66	67	67	68	68	69	69	69	70	70	71	71	72	72	73	73
24	67	67	68	68	69	69	70	70	71	71	72	72	73	73	74	74	75
25	68	68	69	70	70	71	71	72	72	73	73	74	74	75	75	76	76
26	69	69	70	71	71	72	72	73	74	74	75	75	76	76	77	78	78
27	70	70	71	72	72	73	74	74	75	76	76	77	77	78	79	79	80
28	71	71	72	73	73	74	75	76	76	77	78	78	79	80	80	81	82
29	72	72	73	74	75	75	76	77	78	78	79	80	81	81	82	83	83
30	73	73	74	75	76	77	77	78	79	80	81	81	82	83	84	84	85
31	74	74	75	76	77	78	79	79	80	81	82	83	84	84	85	86	87
32	75	75	76	77	78	79	80	81	82	83	83	84	85	86	87	88	89
33	76	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	90
34	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92
35	77	78	79	81	82	83	84	85	86	87	88	89	90	91	92	93	94
36	78	79	81	82	83	84	85	86	87	88	89	90	91	92	94	95	96
37	79	80	82	83	84	85	86	87	88	90	91	92	93	94	95	96	97
38	80	81	83	84	85	86	87	89	90	91	92	93	94	96	97	98	99
39	81	82	84	85	86	87	89	90	91	92	94	95	96	97	98	100	101
40	82	83	85	86	87	89	90	91	92	94	95	96	98	99	100	101	103

Note. Green is a comfort zone; yellow is a slight stress; orange is a moderate stress; brown is a severe stress; purple is a very strong stress. *THI is the temperature-humidity index which was calculated to Kibler (1964)

It is known that a building can «smooth over» the amplitude of daily temperatures in the evening, at night and in the morning, therefore, a sensor near a building, as a rule, registers air temperature 5–10 °C higher than the real one (depending on cloud cover), that is, a temperature that is only 60% depends on the weather and 40% on the thermal radiation of the building.

The terrain, wind speed and location of farms above sea level can also significantly affect the indoor climate and milk production (Yi et al., 2018; Broucek et al., 2019). Through experiments in the large wind (aerodynamic) tunnel of the boundary layer (Yi et al., 2018), a significant effect of the size of the side openings of the curtains and the speed of the outside air on the distribution of air masses in the NB was proved, which must be taken into account when predicting the rate of air flow in the room.

As well as the individual microclimate parameters in the livestock building are in close connection with each other. It is reported (Jovović et al., 2019) that the content of harmful gases (NH₃ and CO₂) depended on the type of building, ventilation systems and livestock density. A reliable correlation was found between their concentration and indoor air temperature. A meta-analysis of a wide range of data on the influence of various factors on NH₃ and CH₄ emissions (Poteko et al., 2019) indicates the dependence of their level on the system of keeping, quantity, breed and productivity of animals, type of floor and air temperature, type of the farm structure and ventilation, and also feeding and herd management strategies.

For example, the emission of NH₃ from the floor of livestock buildings was strongly influenced by the temperature of the air and manure, as well as the air velocity and the intensity of turbulence above the surface emitting ammonia (Schrade et al., 2012; Bjerg et al., 2013; Rong et al., 2014; Saha et al., 2014). In addition, a close relationship was found between the relative humidity in the barn and NH₃ emissions (Saha et al., 2014). As well as (Bjerg et al., 2013) low values of relative air humidity around manure accelerated the evaporation of NH₃, while higher values slowed down. The pH level of manure depended on humidity, which significantly affected the rate of ammonia evolution. Regarding greenhouse gases, their emission can occur both from manure and from the gastrointestinal tract of animals. In the case of dairy farming, their emissions (especially methane), although mainly associated with metabolism of the first stomach in cows (Monteny et al., 2006), also depended on average air temperature and relative humidity in the cow building (Saha et al., 2014). The lowest methane emissions were recorded when cows were in the thermoneutral zone (Hempel et al., 2016), associated with the THI value in the housing.

Insulation of the ceiling under the asbestos roof and the use of sand as bedding in the boxes improved the indoor microclimate. This reduced the heat load on the cows, helped to maintain their normal physiological parameters and increased daily milk-yield (Sahu et al., 2018). It was concluded (Andreasen & Forkman, 2012) that sand had a positive effect on milkyield compared to other stall surfaces. It is reported that Danish Holstein cows, which were kept on mattresses, had a significantly lower milk-yield compared to cows that rested on the sand. This information is confirmed by other scientists (Calamari et al., 2009) by studying the effect of various bedding materials in the animal rest area (straw, rubber carpet, mattress and sand) in an experimental barn for loose keeping.

The problem is that the air parameters are not evenly distributed among the sources, since the sources of heat and moisture, as well as the air speed, are not uniform throughout all the barn. The reason for this may be the peculiarities of the formation and movement of air masses in the NB, since (Fedorenko et al., 2010) in large-sized buildings of three possible modes of natural convection, the regime of stochastic (turbulent) convection, which is characterized by random gas flows with intense mixing, is implemented.

It is reported (Pajumägi et al., 2008) that the traditional method of estimating the ventilation rate for NBs turned out to be unreliable,

since of all the parameters affecting the distribution of indoor air (temperature, relative humidity and air velocity), it is temperature that is the most sensitive indicator for evaluation of ventilation. Therefore, an alternative method for assessing its effectiveness may be to study the spatial distribution of temperature in the housing, which is more informative than the ventilation rate.

In the central part of the structure (Sofronov et al., 2016), the temperature was 2–3 °C higher than at the ends of the barn. Relative humidity in this part of the building exceeded the standard value by 7–12%, while at the ends it was within normal limits. The most favorable area for animals was at the entrance to the room, however, information on the location of the building relative to the cardinal points and wind rose was not indicated, therefore it is difficult to draw conclusions, which factors positively affected the state of the air.

It was established (Vtoryi et al., 2016) that in various zones of the NB, ammonia concentrations on average ranged from 1.35–2.51 mg/m³ to 4.00–4.28 mg/m³. However, the highest concentrations of NH₃ were observed in the center of the barn (up to 5.42 mg/m³), not exceeding the maximum permissible values (20 mg/m³).

The standard microclimate parameters should be maintained in the space up to 1.5 m above the floor (at the level of the size of the animal). To measure all these parameters, analog and digital sensors with computer processing of the received signals can be used. It is advisable to use digital sensors, since they have lower energy consumption and overall dimensions (Ilyin & Vtoryiy, 2018).

Evaluated (Mylostyvyi et al., 2019 b) the state of the microclimate in one of the frame-type buildings with a roof made of sandwich panels (48°34'03.1"N, 34°54'47.0"E) located along the longitudinal axis from the northeast to southwest relative to the cardinal points in the summer season (at a temperature of +16.6 to +37.2 °C). Remote sensors were mounted at a height of 50 cm from the floor in the central and extreme boxes of the section. Data was recorded every 5–20 minutes at the same time indoors and outdoors (in the shade). It was found that the difference between the average air temperatures during the day was 0.2–4.0 °C, relative humidity 0.7–6.8% (according to THI it was up to 1.5 units). The uneven distribution of these air parameters in the NB was revealed. The difference between its individual parts was 1.1–3.6 °C and 6.8–11.8%, with maximum differences in THI of 1.6–5.1 units. In general, during the day, cows of the Schwyz breed, which were in the central and southeastern parts of the room, could feel discomfort for 18 hours, in the northwestern part during 22 hours. Moreover, the time corresponding to the stress state of the animals (THI > 68) outside the cow building (in the shade) was 16 hours. Earlier it was reported (Vasilenko et al., 2018a,b) that, compared with the most favorable weather conditions in May, milk-yield among Schwyz cows in June in this farm decreased by 3.0%, the yield of milk fat and protein decreased by 5.2 and 3.4%, respectively. In July and August, milk-yield fell by 4.6 and 5.5%, fat-yield fell by 3.1 and 7.3%, protein by 3.4 and 5.7% (P < 0.001). A THI value exceeding the comfortable value was recorded for 100 days, with a loss of 146 kg of milk per cow (loss of about 40 euros).

Studies (Mylostyvyi, 2019) in the range of external temperatures from +19.2 °C to +36.9 °C (from 64.9 to 79.7 THI units) in a hangar-type building (48°28'44" N, 35°36'46" E), located from north to south relative to the cardinal points, confirmed the previous results. The daily average THI value in the room ranged from 64.1 to 81.0 units, differing in 2.5–4.4 units in individual sections of the NB. A comfort THI value was exceeded for 18 hours per day, even in the morning and evening hours, increasing the likelihood of heat stress in cows.

The data obtained indicate the need for additional use of active ventilation, not only in the hot period (as we previously expected), but also other hours of the day, depending on the area of the building. The importance of this event is confirmed by



Fig. 1. Manifestation of signs of heat stress in Schwyz cows (hypersalivation, tachycardia and polypnoea) in the shade of the walking area (a) and in the rest area of animals in the building (b).

Patbandha et al. (2018), who report that the effect of heat stress can be mitigated if the room temperature drops below 21 °C, at least for 3–6 hours at night, as the animals are able to completely dissipate their heat load.

Open side curtains and the operation of horizontal axial fans (HAF) did not provide animals with a comfortable environment during the hot season (Mylostyyvi, 2020), since the air mobility in their resting zone increased to a maximum of 0.9 m.p.s., while in the zone of manure passages (from the side of the feed table) it averaged 1.4–1.9 m.p.s., confirming that the box or stall (Collier et al., 2006; Schüller et al., 2016; Wang et al., 2018a) is the place where dairy cows experience the greatest heat load. It was found out (Mylostyyvi, 2020) that the efficiency of air cooling by HAF in the hot period of the day (from 12:00 to 14:00 h) at an altitude of 4 m from the floor was 1.8–2.1 °C, whereas in boxes at an altitude of 0.5 m it was only 0.4 °C. However, the inclusion of HAF after detecting the first signs of HS (Fig. 1), even with slight air movement in the boxes, prevented further manifestation of HS signs in Schwyz cows (with an increase in THI to 77.2 units). See QR Code 1 & 2.

To this day, there are no recommendations on the number and location of measuring devices in the NB, nor on the frequency of parameter measurements (Hempel et al., 2018). For example (Vtoryi et al., 2018), at measuring temperature and humidity in real time, electronic sensors were placed at a height of 2.5 m above the stalls, motivating this by inaccessibility to animals and personnel (recorders should not interfere with the execution of technological processes and operations). This position of the sensors was convenient for data collection, however, as we believe, it could not fully reflect the state of the environment in the animal zone. As well as Hempel et al. (2018), who recommend to measure the

microclimate in the NB at an altitude of 3–3.5 m from the floor, based on the features of the movement of air flows.

It is clear that in our case, the points indicated above (2.5–3.5 m from the floor) will not be informative, which may be related not only to the construction of the building itself (Sahu et al., 2018), but also to those already mentioned above factors (Fregonesi et al., 2007; Morabito et al., 2017; Poteko et al., 2018), as well as animal body position, which can significantly affect airflow distribution (Bustos-Vanegas et al., 2019).

This confirms that the placement of the most indicative sensor positions should be done separately for each room to reduce the error in assessing animal welfare from a THI perspective (Hempel et al., 2019). Such control points (Banhazi, 2013) should provide an accurate and representative assessment of the entire building or specific problem areas (cows resting, emission of harmful gases, etc.).

It must be taken into account that the accuracy of microclimate measurements in NBs can vary greatly due to the inhomogeneous distribution of heat and humidity sources associated with the operation of the equipment and the turbulence of the air flow. Errors (Hempel et al., 2018) in the temperature (up to ± 2 °C) and air humidity (up to ± 20 %) data were related to the accuracy of the instruments and the spatial arrangement of the sensors. Therefore, it is quite reasonable that a single temperature sensor inside the building is not enough to assess the risk of HS based on microclimatic parameters.

Animal comfort

Summarizing strategies for adapting dairy cows at high temperatures, both physiological and behavioral mechanisms of



QR Code 1



QR Code 2

adaptation were identified by Polsky and von Keyserlingk (2017). However, some of these coping strategies can lead to well-being problems, causing depression, aggression, and pain associated with hunger and thirst (Whay & Shearer, 2017).

It is known that cows spend most of their time (about 13 hours per day) in stalls (Cook et al., 2007). If the animal is exposed to heat stress, it will stand longer to increase the surface of the body and thereby enhance heat transfer (Hillman et al., 2005; Allen et al., 2015; Heinicke et al., 2018). It is with increasing residence time of the cows in a standing position that most researchers attribute a seasonal increase in lameness at the end of summer (Whay & Shearer, 2017). Therefore, any design of the cooling system that causes the cows to lie longer should give particular emphasis to improving the heat transfer of the cows while lying down (Wang et al., 2018c).

Round-the-clock monitoring of cow behavior (Mylostyyvi, 2020) showed that natural ventilation through open side curtains is not able to create comfortable conditions for animals. In one part of the room there was an excessive accumulation of them (usually near drinkers), the other remained empty (Fig. 2), and not only during the day (a, b), but also at night (c, d). Therefore, not all animals could comfortably accommodate in the boxes, and time spent in a standing position increased significantly.

The feed behavior of the cows also changed (Fig. 3). In the places where animals were gathered, there was not enough food (a), while near the «empty» parts of the section they remained intact (b).

It should be noted that the use of additional forced ventilation (AFV) led to a relatively uniform distribution of animals in sections during the day and almost the same feed intake over the entire length of the feed table.

During movement (Timoshenko et al., 2015), air changes the heated air shell around the animal's body and exerts a cooling effect, causing a decrease in temperature first on the surface of the hairline, then in its thickness and on the surface of the skin (convective heat transfer), enhancing heat transfer due to evaporation. The speed with which heat is dissipated in a cow in a standing position is higher than in a lying position, since it has a larger surface contact area with air.

Effective ventilation could reduce HS by increasing the rate at which heat is convectively transferred from the animal to the surrounding air (Broucek et al., 2019). However, none of the systems can provide a sufficient amount of fresh air and the necessary cooling of each individual animal (Wang et al., 2018c), including due to the uneven distribution of air and significant differences in the THI value in the room (Schüller et al., 2016; Mylostyyvi et al., 2019a).

Dairy producers could improve herd health through events aimed at increasing the time the animals are in stalls in a lying position when THI exceeds a threshold for HS (Zimelman et al., 2009). Therefore, to cool the cows in hot conditions, it is necessary, if possible, to direct a horizontal air flow into the zone of animals presence (Wang et al., 2018c).



Fig. 2. Crowded (a, c) and «empty» (b, d) parts of the section



Fig. 3. Uneven feed intake in different areas of the feed table (*a* – completely eaten; *b* – almost untouched)

Most enterprises rely on natural ventilation systems with additional cooling systems (for example, cooling fans, ceiling ventilation, pipe cooling, etc.) to soften the HS of cows when natural ventilation is insufficient (usually in hot, humid, calm weather). However, the effects of such additional cooling are in many cases insufficient (Cook et al., 2007; Wang et al., 2018c). Therefore, any design of the cooling system that causes the cows to lie longer should pay particular attention to improving the heat transfer of animals in a lying position.

In this sense (Wang et al., 2018a), the design of the «precise air supply system» (PASS) is based precisely on the concept of providing the exact amount of fresh (or additionally chilled) air for each cow in the stall, taking into account the position of its body (including diameter, air velocity and angle). In the same way a satisfactory cooling effect was achieved due to the multi-pipe ventilation system based on the supply of fresh air through large diameter polycarbonate plastic pipes, first around the perimeter of the room, and then through the holes of smaller diameter directing its flow directly to animal habitat (Mondaca & Choi, 2016).

The issues of cost-effectiveness of new cooling technologies, for example, heat transfer beds (Ortiz et al., 2015), in combination with herd management methods (avoiding congestion, reducing the time spent in places with high temperature), diet and breeding (Gunn et al., 2019); as well as monitoring the temperature of milk in high-tech enterprises can be a useful tool in determining and predicting the reaction of dairy cows to HS in robotic systems with a large set of online data (Ji et al., 2019).

Thus, the concepts of adaptation to HS from the point of view of «intellectual ventilation» should take into account the features associated with individual physiological and behavioral responses of cows to actual microclimatic conditions (Hempel et al., 2018). Taking into account the body position in dairy cows during TS periods will help to develop effective strategies to mitigate the heat load on dairy cattle (Cook et al., 2007; Wang et al., 2018c; Nordlund et al., 2019).

Solutions and challenges

The microclimate can be improved by introducing technical solutions during problem periods of the year. In order for warm air emanating from animals to be easily removed, the roof surface must have a rise in the direction of the ventilation opening. For narrow two-row cowsheds, a slope of 15° is sufficient. The buildings with a normal width should have a roof slope of 20–25°. A roof with an insulating layer also has a positive effect on exhaust ventilation.

In the presence of a single-layer, tin-coated roof, the rising warm air is cooled in winter by touching the roof, and without reaching the outlets, it is lowered again. A roof with an insulating layer also protects from strong heat in the sun during summer.

For the proper functioning of natural ventilation, it is advisable to position the cowshed across the main direction of the wind. Thus, wind pressure contributes to a better outflow of air from the barn through the ventilation hood. The removal of air from the room is organized through the ridge gap (ventilation hood), while the building is under discharge.

The effectiveness of natural ventilation is influenced by the topography of the site and the location of the building with respect to the prevailing winds, surrounding trees and structures. Ventilation is unsatisfactory in cases where the barn is blocked from the wind by nearby buildings or trees, or is located in a valley, or is placed along the longitudinal axis in the direction of the prevailing winds. When constructing a building for «cold» keeping animals, it is advisable to place it on the windward side with respect to existing buildings that can block the barn from the wind. If it is placed on the leeward side, then it should be removed to a distance that excludes turbulence caused by the obstacle and changes in the direction of the air flow. Usually it is believed that 15–30 m is enough.

It is reported (Tymoshenko et al., 2015; 2016) that large horizontal ceiling fans can provide farm buildings with fresh air. These fans with diameters from 4 to 7 m provide air circulation and replace approximately 10 circulation fans. The airflow is directed vertically downward, is collected on the floor and deflected into all directions. The horizontal wind generated during this brings the animals cool with an air speed of up to 2.5 m.p.s. Thanks to the additional work of large horizontal ceiling and circulation fans, more comfortable conditions for animals to relax are created in the NB, which helps to avoid conflict situations and the struggle between animals for a certain place even in the wall and double boxes.

Due to the optimal operating mode of ventilation and microclimate systems in buildings where light-aeration lamps are installed and large horizontal ceiling and circulation fans are used, more comfortable conditions are created for animals to rest both in the wall boxes and in the double ones. In these barns for the entire observation period, there were no conflicts or fights between animals for a certain place in boxing (Trofimov et al., 2016).

The installation of a SolarWay light aerator could improve the barn's microclimate (Loshkarev et al., 2018). It consists of a light and ventilation shaft according to the type of coaxial pipe (pipe in

pipe), thus ensuring a uniform supply of fresh air and room lighting at a level of at least 170 lx. In this case, energy is saved due to natural lighting and the absence of electric fans, in contrast to the traditional solution (light ridge). The light aerator is able to create good ventilation even during the transition period of the year, when the temperature on the street and in the barn is the same, which means there is no draft or air exchange. Economic calculations show that the introduction of such a system will reduce ventilation costs by up to 5%.

Research results (Yao et al., 2019) showed that a diffuser with an inclination angle of 10° works better than with an elevation angle of 0°, achieving an increase in jet stream length of 0.5 m and an increase in energy efficiency of 1.39%. This was achieved due to the greater axial wind speed and better coefficients of uneven flow distribution at the level of dairy cattle.

The combination of active ventilation and small-drop irrigation (as opposed to forced ventilation) at high temperatures in Slovakia (Broucek et al., 2019) increased the milk-yield of cows by 1 122 kg, the yield of fat and protein by 34 and 32 kg ($P < 0.001$). Thus, evaporative cooling associated with an increase in air velocity can be a good protection of animals from high temperatures.

The additional use of small-drop irrigation (Milostyvyj et al., 2016) during the heat contributed to a decrease in rectal temperature in Holstein cows by 0.4 °C and a decrease in respiratory rate by 7.4%, compared with the use of AFV alone. The device (Puhach et al., 2016) for humidification and cooling of air in livestock buildings allows the use of small-drop irrigation in the form of fog at necessary times of the day at the required height above the floor.

Usually, the necessary parameters of the air environment can be achieved by artificial induction of air (fans, heat exchangers, air conditioning, duct system, multifunctional automatic devices, etc.), however, a logical question arises about the economic efficiency of such ventilation systems – it is ventilation (which accounts for up to 70% of the total energy), are the most electro-intensive process in production.

While the current trends in the development of microclimatic installations (Zaitseva, 2016) are aimed, specifically, at reducing energy costs, material consumption and the efficient use of heating and ventilation systems. In particular (Ilyin & Vtoryi, 2018a), the main requirements for microclimate monitoring systems are scalability, ease of operation, maintenance and repair, as well as the ability to use wireless communications for continuous recording of parameters.

Noteworthy (Ilyin & Vtoryi, 2017) are the automatically controlled processes of maintaining the microclimate depending on the time of day and day of the week, intermittent heating (cooling) and ventilation of the rooms, the algorithm of which is based on numerous simultaneous studies of the parameters of the air environment in the rooms and outside.

Such equipment mainly consists of a monitoring system (designed to collect, register, monitor and analyze the state of the main microclimate parameters in real time), an actuator control system (driving or not driving fans, heaters, dampers, sprinklers, etc.) and software (which manages the system by implementing mathematical models developed on the basis of analytical laws and the results of experimental studies specific to a particular automation object).

Moreover, to predict the state of the microclimate in livestock buildings, it is possible to use various models. These (Karpenko & Petrova, 2016; Matsoukis & Chronopoulos, 2017) are usually multi-parameter problems with fuzzy variables. Therefore, in recent years, more and more they are using the so-called «black box» models, which are based on intelligent calculation methods (fuzzy logic, genetic algorithms, neural networks, etc.).

Their software is based on the functioning algorithm of an automated microclimate support system (Kuvshinov &

Mansurov, 2011). This algorithm can be in two main versions. Within the first one, under appropriate weather conditions, a pre-calculated option for controlling the microclimate system is selected from the database. Within the second one, the system itself calculates the combination of decision-making and selects the necessary decision, depending on existing and forecasted weather conditions. Accordingly, a multivariate or adaptive system of algorithms is required.

Statistical regression is a common method for developing a mathematical model, where the accuracy of the prediction is highly dependent on the number of tests (Bezerra et al., 2008). Performing a large number of tests using laboratory or field experiments is expensive and time consuming (Wang et al., 2018c).

Being of great theoretical importance for the further construction of mathematical models and applied in relation to the efficient use of ventilation equipment, such studies require considerable time and effort; therefore it is especially valuable in a particular facility, given the possibility of subsequent implementation of their results into production (Mylostyvyi et al., 2019b).

Using statistical methods of data processing (Vtoryi et al., 2018), regression models were built to calculate the temperature and relative humidity of the air inside the barn depending on the parameters of the external environment. High coefficients of determination of models ($R^2 = 89.8\text{--}94.9$) indicated a close relationship between the parameters and the high probability of their prediction.

Limited information on long-term multiple measurements of the microclimate in NBs in the literature, and especially data on direct measurements in the animal rest area (using appropriate devices), makes it difficult to develop universal methods for monitoring and predicting the microclimate (Hempel et al., 2019).

Difficulties are also associated with approaches to statistical modeling processes that require a large number of tests (Wang et al., 2018c). In particular, it was reported (Wisnieski et al., 2019a) that the results of models, as a rule, overestimated the real results in cases with a small number of samples and underestimated the results with a large number of observations.

The limitations of modeling were also that most researchers used explanatory rather than predictive modeling (Wisnieski et al., 2019a). The drawback of such studies is that these models are not validated under production conditions (Wisnieski et al., 2019b). Although the coefficient of determination is considered a good criterion for evaluating the effectiveness of statistical models (Maniatis et al., 2017; Müschner-Siemens et al., 2020), reports on the accuracy of such models in experimental conditions are difficult to find.

Previous studies show that when using linear regression, the accuracy of models for predicting THI in NBs (based on the external state of the air environment outdoors) ranged from 93 to 96%. However, the difference in THI values between the predicted and experimental data was quite large (from 0 to 4.4 units).

Summarizing the literature data and research results (Mylostyvyi et al., 2020), we note some points related to the problem of creating comfortable conditions for dairy cows in NB:

- modern wide-sized buildings of large-capacity for milk cows (for 600 animals and more) put forward additional requirements for microclimate support systems and require new approaches to its assessment and normalization;
- the reason for the miscalculations is the active introduction of new foreign technologies and equipment without taking into account the climatic features of the region, which leads to unforeseen deviations of real air parameters from the calculated ones, and unreasonable use of the capacities of ventilation systems;
- despite the high dependence of the indoor microclimate on the state of the environment, their design features prevent overheating of air during the daytime heat on the one hand (creating

shadow protection for animals), and on the other hand, lead to the preservation of heated indoor air when it cools in the environment, thereby prolonging the effect of high temperatures on the animal organism;

– not only differences between the state of the air environment inside and outside the rooms, but also a significant difference in individual areas associated with the location of the NB relative to the cardinal points were revealed (the intensity of its heating by sunlight during the daylight hours);

– features of the formation of the air environment in the NB indicate the need for a differentiated approach to the regime and duration of the use of cooling systems during the day for different technological zones of the room with natural ventilation;

– identification of «critical points» reflecting the deterioration of the indoor microclimate and constant monitoring of their condition will help prevent a decrease in the comfort of the living conditions, leading to a decrease in animal productivity;

– round-the-clock use of powerful axial fans may not be sufficient to create comfortable conditions in the animal rest area, which indicates the need for additional technical solutions to normalize the microclimate in the hot period (for example, small-drop irrigation);

– the concepts of adaptation to HS from the point of view of «intelligent ventilation» should take into account the features associated with individual physiological and behavioral responses of cows to real microclimatic conditions.

Thus, NBs have a number of features that must be taken into account when controlling and predicting the microclimate, taking into account their structural, technical and technological solutions and weather and climate conditions.

Conclusions

Energy-saving lightweight construction has become widespread in dairy farming. Despite the persistent conviction of the producers about its acceptability for livestock and obvious economic advantages, many issues of creating and maintaining comfortable conditions for animals, especially in extreme weather conditions, remain open. This requires completely new approaches to the development of monitoring systems, forecasting and normalization of the air environment in NB taking into account the biological characteristics of animals.

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