Ventilation Systems for Adult Dairy Cattle

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KEYWORDS

• Ventilation • Dairy • Economic • Microclimate

KEY POINTS

- The most common types of ventilation systems are natural, tunnel, cross, and hybrid ventilation.
- Ventilation needs to provide appropriate airspeeds at the stall, adequate ventilation rate, and a methodology to operate effectively year-round.
- The cost of different types of mechanical ventilation systems is similar making the choice between systems dependent on the location of the barn, herd size, and preferences of the owner.

INTRODUCTION

Ventilation is the provision of fresh air to a space. It is a necessary part of confinement housing to avoid the buildup of temperature, humidity, and harmful gases in animal housing beyond safe levels[1] and to eliminate areas of still air.[2] Although the cost of ventilation is significant, the cost of inadequate ventilation is much higher due to poor performance, heat stress, and respiratory disease in dairy cattle.

There are theoretic and practical limits for pathogen removal[3] and cooling due to ventilation, and these concepts are addressed throughout ventilation design options used in the dairy industry. This article highlights the difference between barn-level ventilation and cow-level ventilation, and various system design parameters for typical ventilation systems are addressed. Finally, the challenges and costs of maintaining a ventilation system, as well as the estimated costs of installing and operating typical ventilation designs are described.

The most common point of confusion in the dairy industry is the difference between recirculation and ventilation. Ventilation is when fresh air enters the barn whereas recirculation is when the same air in the barn is sped up, typically through the use of a fan. Circulation fans are commonly found in dairy barns to mix air within the

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barn and/or provide fast-moving air for summertime cooling, but they do not provide ventilation.

Another point of confusion is the difference between ventilation and cooling. Cooling is the transfer of thermal energy via sensible or latent heat transfer processes. A sensible heat transfer process is one in which heat transfer occurs due to a temperature gradient without a change in phase, like cold water running on your hand, while a latent heat transfer process occurs due to change in phase, such as sweat evaporating off skin.

Because sensible heat requires a gradient of temperature to cool or heat the animal, if the air is the same temperature as the cow, it will not be cooled or warmed. Meanwhile, latent heat needs a humidity gradient to occur because most latent heat is removed through evaporation of water (eg, animal panting, cooling wet-pads, soakers, foggers). If the air is saturated with water, meaning the relative humidity is very high, the potential temperature reduction is only 30% to 40% that of dry environments.[4]

The most a ventilation system can achieve alone is to have the temperature, humidity, and gas inside the building reach the same levels as the outside air.

OVERALL VENTILATION DESIGN

Natural ventilation depends on the natural wind speed and direction, and temperature differences in the air to create the pressure differentials that drive air in and out of the barn. Openings in a natural barn can be either inlets or outlets depending on the direction of the air and the pressure gradients generated at the openings.

Mechanical ventilation uses positive pressure, negative pressure, or a combination of both. Negative-pressure ventilation uses exhaust fans to draw air out of the barn, creating a negative pressure inside compared with the outside.

A positive-pressure system pushes air into the barn, creating a positive pressure inside when compared with the outside. Positive-pressure tube ventilation systems are an example of such a system, and some versions are beginning to combine a positive-pressure system with a matching negative-pressure system, creating a so-called "neutral-pressure" barn.

Mechanical ventilation systems are typically defined using 3 key design metrics: air changes per hour (ACH), barn cross-sectional area airspeed, and air flow per animal unit (Fig. 1). They each address a different aspect of the ventilation design, and all 3 should be considered when evaluating a system.

Natural ventilation systems are not easily defined, although some studies have attempted to quantify natural ventilation rates.[5–7] Instead, natural systems rely on

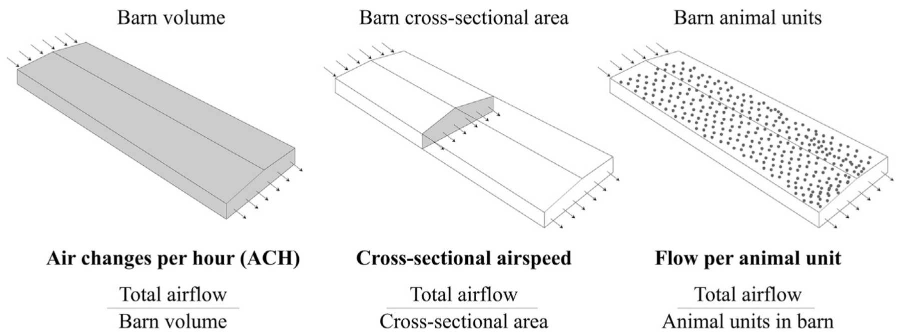

Fig. 1. Three key ventilation parameters comparing the total flow to the barn's volume, cross-sectional area, and number of animals.

the barn dimensions, orientation, and spacing to capitalize on ventilation created by thermal buoyancy and natural wind patterns.

VENTILATION SYSTEMS

Natural Ventilation

Natural ventilation is the most common system on mid-size to small-size farmsteads.[8] Natural ventilation relies on 2 main factors to provide ventilation in a building. One is the thermal buoyancy created by the warm air around the animals, which rises and exits through an open ridge, which is called the “chimney” or “stack” effect. Hotter air has a lower density and tends to rise, whereas colder air drops. This creates a natural flow pattern that is mainly temperature driven. During cold temperatures, the stack effect is the main driver of ventilation.

The force of the wind into the building openings creates wind gusts and the air passing over the open ridge creates a lifting force inside the building. During warmer temperatures, large open curtain sidewalls will allow for natural wind forces to enter the barn. Although the stack effect will still occur during the summer, the large openings will be the main ventilation driver. For this reason, naturally ventilated barns need to be oriented perpendicular to prevailing summer winds. Because the air typically enters through the sidewall and exits through the ridge, it is also a benefit for airflow if the winter prevailing winds hit the eave openings.[1]

The main characteristics of naturally ventilated barns are an open ridge, open eaves, adequate interior roof slope, freedom from wind shadows, and an east to west orientation. To maximize natural ventilation, it is important to have an insulated smooth ceiling with a 3:12 or 4:12 pitch and an open ridge of 2 inches (5 cm) for every 10 ft (3 m) of barn width, with a minimum ridge opening of 6 inches (15 cm). The eave openings on each sidewall should be half of the ridge opening, ensuring the total sidewall opening is the same as the ridge during cold temperatures. Sidewalls are usually 13 to 16 ft (4–5 m) high fitted with curtains that are completely opened in the summer to capture as much of the prevailing winds as possible. The eave openings can be either built into the barn’s structure or be controlled with a split curtain sidewall.

The provision of adequate ventilation and cooling in naturally ventilated buildings that house dairy cattle is challenged by the wide variety of different building structures in the farmstead. Wind shadows refer to areas of disturbed airflow downstream of an obstruction, such as an adjacent building structure. A common source of wind shadows in large naturally ventilated facilities is another barn in an H-configuration (**Fig. 2**). As seen in **Fig. 2**, the barn downstream receives a much lower airflow than the one directly facing the incoming winds. It takes approximately 5 to 10 times the height of the obstruction for the airflow to return to their original airspeeds.

Practically, most natural ventilated facilities are being constructed at 100 ft (30 m) separation distance to prevent as much wind shadow as possible. Although recommendations on separation distances are higher than that,[1] 100 ft (30 m) or shorter are commonly found because of limited space on the farmstead, and how far cows, workers, and manure have to travel between buildings.

Mechanical Ventilation

Mechanical ventilation relies on exhaust fans, intake fans, or both to provide fresh air in the facility. A significant advantage over natural systems is that the barn orientation and layout are not as limited by the surrounding structures. Mechanical systems also have a lower ceiling than natural systems and can be placed closer together to a minimum of 60 ft (18 m) for proper water drainage. A drawback to fully mechanical

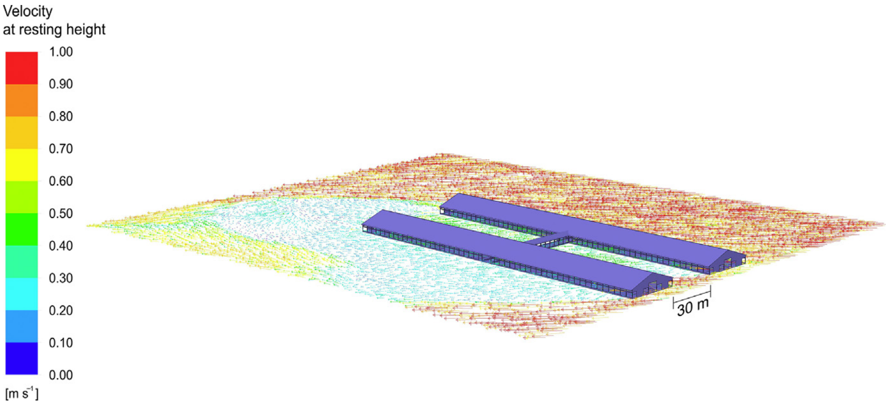

Fig. 2. Computational fluid dynamics results of natural ventilated barns separated by 30-m distance and the resulting velocity vectors at 1 m s^{-1} in a 45° direction.

systems is that there is no natural ventilation option, so a backup generator is necessary in case of emergency.

There are 2 main types of mechanical ventilation systems currently in use in the dairy industry: tunnel and cross ventilation. In general, tunnel ventilation is when the air flows parallel to the feed lane, and cross ventilation is when the air flows perpendicular to the feed lane (Fig. 3).

Tunnel-ventilated barns

The main changes implemented in tunnel barns compared with natural barns are a reduction in roof pitch and changes to the sidewalls. Typically the pitch will be half or one-third of that used in natural barns, often 1:12 or 2:12. Some systems are also designed with a false ceiling, giving the inside structure a flat ceiling almost flush with the sidewall height to reduce the flow area and increase airspeed. Depending on where the feed lanes are, the sidewalls may be a few ft lower than natural barns and only a small section of the barn will have curtain sidewalls, enough to provide inlet airspeeds of at least 500 ft min^{-1} (2.5 m s^{-1})[9] at the maximum ventilation rate.

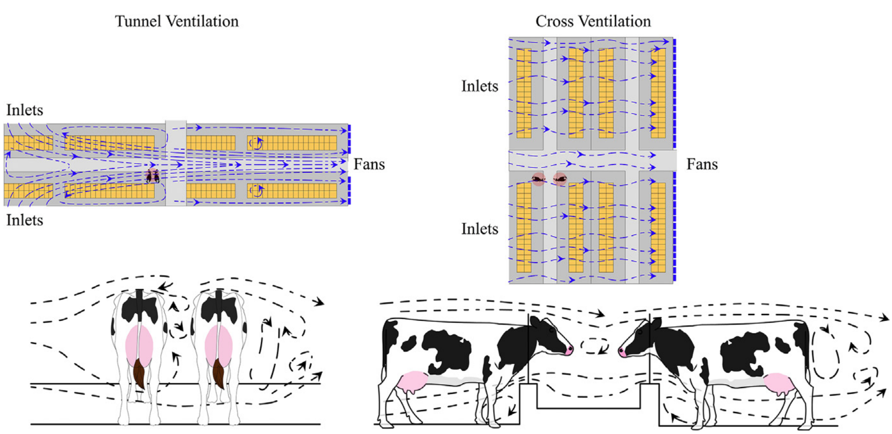

Fig. 3. Typical flow profiles for tunnel-ventilation (*left*) and cross-ventilation (*right*) systems; tunnel ventilation flows (*left*) parallel to the feed lane. Cross-ventilation (*right*) flows perpendicular to the feed lane.

In tunnel-ventilated barns, the fastest airspeeds will be at the feed lane, followed by the pen alleys, and then the stall microenvironment. Achieving appropriate air speeds in the stall microenvironment is difficult if only exhaust fans are used. This is due to a number of structural components that restrict and redirect the airflow away from the stalls; mainly walls or waterers at the cross-overs. These effects can be demonstrated using a computational fluid dynamics model (**Fig. 4**) of a tunnel barn.

The dark blue areas in the model have airspeeds below 200 ft min^{-1} (1 m s^{-1}) and are typically found at the end of the barn farther from the fans, after the inlets, and in the stalls behind the cross-over walls.

Hybrid barns

Although technically hybrid barns refer to any barn with a combination of natural and mechanical ventilation, most hybrid barns refer to tunnel-style barns with either an adjustable ridge or ridge cupola fans. The idea behind these systems is to have a mechanical system during the summer to provide a consistent supply of fresh air and heat abatement, and an ability to switch to a natural-style ventilation system during the winter months, capitalizing on the sidewalls for even distribution of fresh air. In hybrid barns, the roof may be pitched as a tunnel barn, with cupola fans used to assist air movement up toward the ridge.

Cross-ventilated barns

Cross-ventilated barns have the lowest roof pitch: typically 0.5:12. The sidewalls are often higher, especially if the feed lanes are located on the edges of the barn, to allow for overhead doors and feed trucks. When cows are feeding or resting, their orientation is such that the cows do not block the airflow from each other because of the air traveling perpendicularly to the feed lanes. One sidewall holds the fans and the opposite sidewall is an adjustable curtain or a wet-pad to serve as an inlet.

Cross-ventilated barns are commonly designed for 2 main reasons: lower cost and lower barn footprint per stall. Cross barns have the benefit of economies of scale, as most of the herd is housed under a single facility, which saves both space and building materials. Cross-ventilated barns work well with 8 to 12 rows of stalls, but air quality issues can arise as more rows of stalls are added.

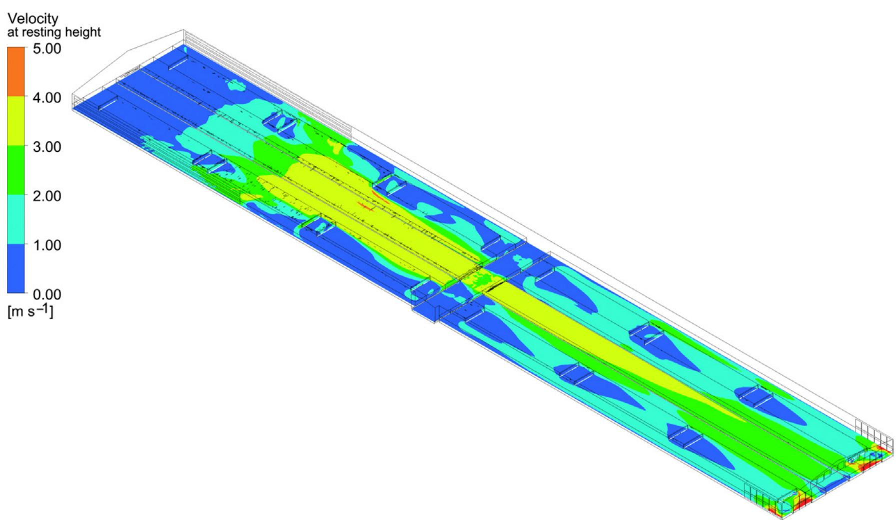

Fig. 4. Computational fluid dynamics model of a tunnel-ventilated barn at 41 ACH.

The key design features of the ventilation systems described in this article are summarized in **Fig. 5**.

Based on the wide variation in barn design and the challenges of providing fresh air at an appropriate speed for the climate, ventilation and cooling systems should be designed to also meet the following more general priorities:

1. Provide air movement at the appropriate speed in the stall microenvironment
2. Provide sufficient air exchange to remove heat, noxious gases, and moisture from the barn
3. Ensure that the system works well across all seasons

PROVIDE AIR MOVEMENT AT THE APPROPRIATE SPEED IN THE STALL MICROENVIRONMENT

The barn can be split into 3 key microenvironments that need to be ventilated: the overall barn, the pen, and the stall (**Fig. 6**).

The priority under conditions of heat stress is to provide fast-moving air within the stall microenvironment because the increased airspeed at the cow's body improves both sensible and latent heat transfer by mixing the air in the stall.[10,11] When heat stressed, adult cows lying in freestalls undergo body temperature increases of approximately 1.1°F (0.6°C)[12] per hour and soon reach body temperatures at which the cow must stand to cool, reducing resting time and putting the cow at increased risk for lameness and other health challenges.[13] Furthermore, cows prefer fast-moving air when they are hot,[14] and for cow barns we have traditionally failed to provide sufficient fast-moving air to help keep the cow cool in her resting space.[15]

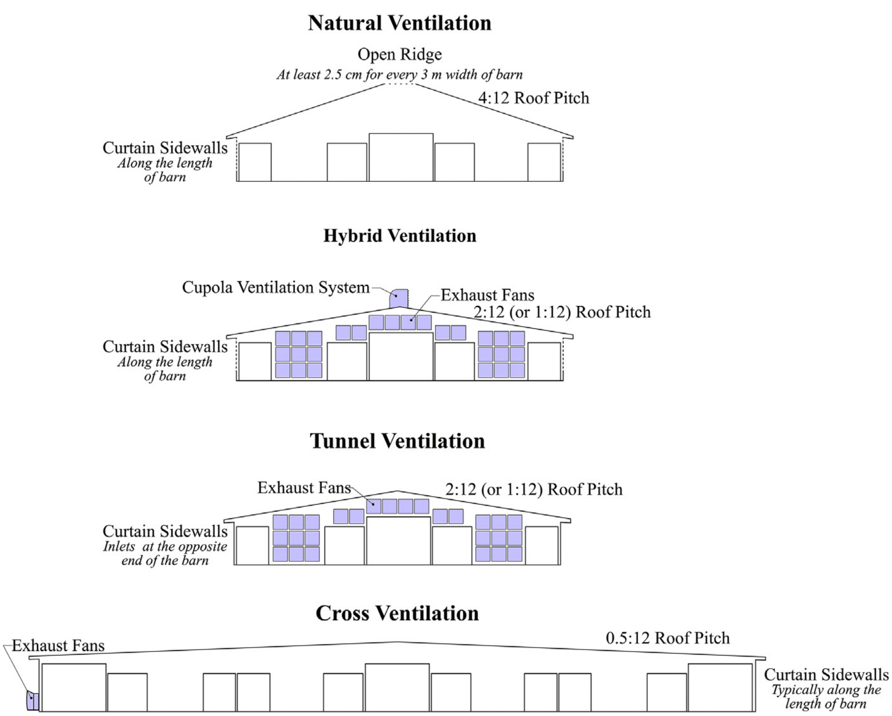

Fig. 5. Four main types of ventilation systems and their key design features.

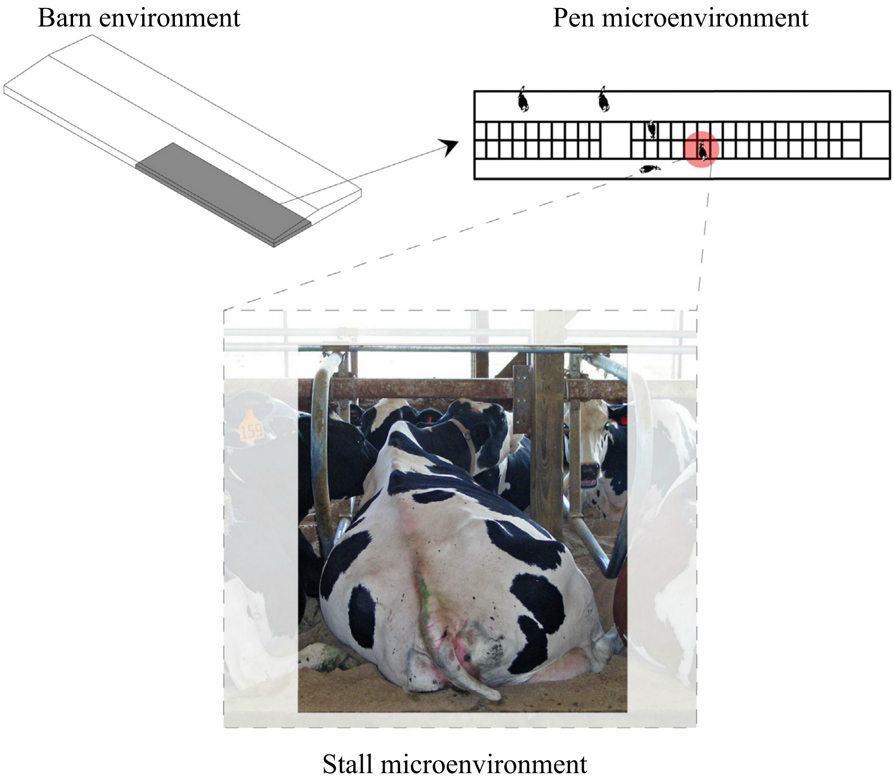

Fig. 6. Various environments within the dairy barn: barn-level environment, pen microenvironment, and stall microenvironment.

Unfortunately, air is "lazy" in that it will follow the path of least resistance. The barn is littered with potential obstructions, such as feed curbs, stall loops, waterers, other cows, and concrete walls, which will redirect the flow away from the cow's resting space. The challenge is using barn-level design numbers (ACH, cross-sectional airspeed, and flow/animal, see **Fig. 1**) to evaluate the different pen and stall microclimates (see **Fig. 4**).

Minimum Cooling Airspeed

Although the temperature humidity index (THI) is a good measure of the heat stress a cow might experience,[7] it does not include an airspeed effect. There is surprisingly little information on what airspeed is necessary to provide adequate cooling. A series of psychroenergetic studies[16] published as bulletins at the University of Missouri evaluated the heat and mass transfer for various breeds of cattle. In bulletin 552,[17] the respiration rate of Holstein cattle was found to decrease with increasing airspeeds. At temperatures below 95°F (35°C), increasing airspeed resulted in a lower respiration rate, but the decrease in respiration rate when increasing airspeed from 40 to 433 ft min^{-1} (0.2–2.2 m s^{-1}) was much higher than the decreased respiration rate when airspeed was further increased from 433 to 787 ft min^{-1} (2.2–4.0 m s^{-1}). Findings from these series of experiments are still being used as a reference for heat generation for adult lactating cows in standards,[18] even though milk production per cow has dramatically increased since 1959. Similar diminishing returns of faster-moving air were found on cows with wetted skin under various airspeeds.[11] There was a significant difference in respiration rate and temperature between cows cooled with fans and water to the control, but no significant difference was found between the cows cooled at different airspeeds. The benefits of increasing from still air to 200 ft min^{-1} (1 m s^{-1}) appear much greater than the benefits of increasing airspeeds beyond 400 ft min^{-1} (2 m s^{-1}).

A heat stress model designed for cattle[19] was modified to consider Holstein cows. The new heat stress model[10] found that air velocities of 167 ft min^{-1} (0.85 m s^{-1}) can help cows increase their threshold temperature (temperature at which the respiration rate rose above 53% of the maximal respiratory rate). Further increasing airspeed to 295 ft min^{-1} (1.5 m s^{-1}) increased the threshold temperatures and reduced the negative effects of high humidity to practically zero. Similarly, there was a significant difference of air temperature between still air and 200 ft min^{-1} (1 m s^{-1}) but no significant difference between 200 ft min^{-1} (1 m s^{-1}) and 400 ft min^{-1} (2 m s^{-1}).[11]

Although the specifics of the heat and mass balance between the cow and its environment have changed significantly since 1959, the underlying diminishing returns between airspeed and heat stress markers (respiration rate, vaginal temperature, and skin temperature) have remained a constant finding in the limited studies performed. Therefore, we define the minimum cooling airspeed (MCAS) required for cows as 200 ft min^{-1} (1 m s^{-1}). Airspeeds should be at a minimum 200 ft min^{-1} (1 m s^{-1}) with little reported benefit of exceeding 400 ft min^{-1} (2 m s^{-1}), and be evenly distributed through the microenvironment of the stall, particularly in high humidity environments.

Achieving Minimum Cooling Airspeed

Panel fans

Panel, or recirculation fans, are great options for providing MCAS in the stall's microenvironment. These fans are typically 48 to 54 inches (1.2–1.4 m) in blade diameter and are recommended to be spaced at approximately 24-ft (7.3-m) intervals. The traditional recommendations of spacing fans 10 blade diameters apart are erroneous, as MCAS is not achieved for a sufficient proportion of the resting area.[15] The stalls immediately after a fan are commonly the areas with the lowest airspeed. It is the area farthest from the previous fan that does not receive the MCAS of the fan directly above them (Fig. 7).

The fan's air jet will not reach the cows immediately (see Fig. 7). This means that when fans are 48 ft (14.6 m) apart, the fan has to cover 68 ft (20.6 m): the distance between fans plus the first 20 ft (6 m) of the next fan. At 24 ft (7.3 m) apart (approximately 5 diameters of the fan in Fig. 7), the fan has to provide fast-moving air for 43 ft (13.3 m) (∼50 ft [15 m] before the jet billows in Fig. 7).

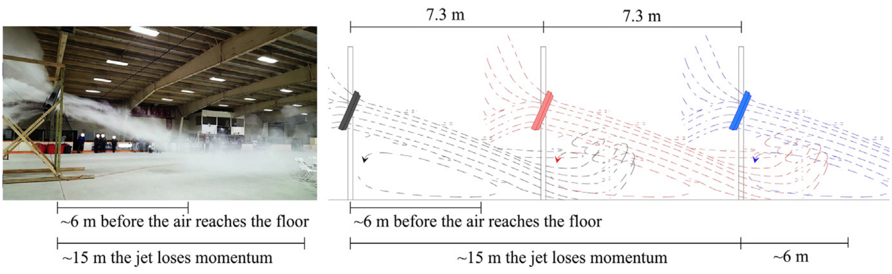

Fig. 7. A 54-inch fan smoking trial (*left*) and fans installed at 7.3 and 14.6 m from each other (*right*). If the red fan was not included, the black fan's jets would not reach the 6-m zone of still air in front of the blue fan.

This is all dependent on the fan angle and size, which should be aimed toward the resting space enough to increase the airspeed. With so many variations in barn, stall, and fan design, this angle is best determined by aiming the previous fan toward the space underneath the next fan. An anemometer could be used to measure the airspeeds at the resting height, particularly a few stalls after the fan to ensure there is overlap between them and most cows have proper airflow while resting. Another option is large, louvered fans commonly known as “cyclone” fans. These are 72 inches (1.8 m) in diameter and usually provide good results when installed at 60-ft (18.3-m) intervals.

There is some debate as to how to position the recirculation fans. All of the options shown in Fig. 8 provide adequate airspeeds at the resting area, but there are pros and cons. More frequent fan installation provides a more even distribution of airspeeds, but at the cost of doubling the necessary wiring for installation.

A similar trade-off exists when considering panel fans against larger cyclone fans (Fig. 9). One large cyclone fan covers a similar number of stalls compared with 2-panel to 3-panel fans. This reduces the wiring costs and maintenance by two-thirds, although the panel fans will likely achieve more evenly distributed resting airspeeds, and depending on fan choice, operate at similar running cost. Whatever the fan chosen, however, they are typically turned on at 65 to 68°F (18.3–20.0°C).

In many naturally ventilated barns, producers have installed circulation fans (typically panel fans) to consistently improve the airspeed at the resting area. Due to the significant consequences of heat stress,[13,20] the number of recirculation fans used in a natural ventilation system is similar to those found in mechanical ventilation systems.

For tunnel-ventilated barns, there are 3 main zones where airspeeds in the resting area tend to be low: the end-wall opposite to the exhaust fans, the area after the inlets, and the stalls after the cross-overs (see Fig. 4). Increasing the ventilation rate has diminishing returns for improving the airspeeds in these areas and there is a recent trend for tunnel ventilation to use fans over the stalls similar to natural ventilation systems to provide fast-moving air. The concept is to have the exhaust fans provide enough ventilation to remove excess heat while the fans over the stalls provide MCAS (see Fig. 9).

In cross-ventilated barns, using panel fans is a relatively new idea, although some systems have begun using variable frequency drives (VFDs) combined with panel fans as a replacement for baffles to improve the airflow distribution during the winter and provide cooling in the summer.

High-volume low-speed fans

There is little information about the use of high-volume low-speed (HVLS) fans in dairy barns to provide fast-moving air. As their name implies, these systems move large volumes of air at low speeds. The lack of information on their performance in dairy barns makes it difficult to recommend specific design choices. However, through clinical

Fig. 8. Natural ventilation barns equipped with a panel fan every support post (*left*), 2 panel fans side by side over head-to-head stalls and a panel fan over single-row stalls every other support post (*middle*), and alternating fans every other support post over head-to-head stalls (*right*).

Fig. 9. Hybrid-ventilated barn with cyclone fans over the stalls to provide fast-moving air in the stall microenvironment and a closed ridge with a cupola system.

experience, we have found that 20-ft (6-m) HVLS fans should be installed at a 40-ft (12.2-m) spacing interval. Installations at 60 ft (18.3 m) do not provide MCAS throughout the resting area. These fans, however, are a good choice to de-stratify the environment within the barn (useful during cold winters).

Positive-pressure tube ventilation systems

More commonly considered a winter ventilation system for calf barns, some producers have used the idea of installing positive-pressure tube ventilation systems (PPTV) above the stalls to direct fresh air and MCAS over the cows (Fig. 10). Similar to the HVLS fans, they provide a good distribution and help de-stratify the air, but unlike the HVLS fans, this system also ventilates. Unfortunately, the air jets from these systems are extremely susceptible to any wind pressure and there is very little research on their potential use for heat abatement.

PPTV systems are not recommended for typical freestall facilities, but are a good choice for retrofitted stanchion, tie stall, or other systems in which ventilation is severely limited.

Baffles

Baffles are devices used to redirect the flow of air from the headspace above the cows toward the microenvironment of the stall (Fig. 11) and are generally considered a staple in cross-ventilated barns. Although variation exists, baffles are typically located along the building support posts, which are usually along the middle of head-to-head stalls. Baffles work well to provide MCAS at the stall level, but have issues during the winter months, as warmer air tends to get trapped in-between the baffles, accumulating humidity and heat. To prevent trapping of air, retractable baffles that can be adjusted in the winter are a potential solution, or circulation fans can be used to help mix the air. Baffles are designed at a minimum height of 7 ft (2.1 m) from the stall surface to avoid animals and machinery from reaching and damaging them.

The airspeed increase due to baffles tends to be short-lived and is generally easily disrupted by other restrictions to the airflow created by cows, concrete curbs, and so forth. This means tunnel-ventilated barns require a much higher number of baffles to provide MCAS in the cow resting area. Each time the flow is redirected, it is also

Fig. 10. PPTV system for adult cows.

restricted, and pressure is added to the system,[21] lowering exhaust efficiency. For this reason, baffles are typically not recommended for tunnel-ventilation systems. In cross systems, the ideal baffle placement is over the inlet side of the head-to-head stall platform, or the middle of the platform.

Although designs vary from barn to barn, baffle opening height is typically designed to generate 510 ft min^{-1} (2.6 m s^{-1}) in the area underneath the baffle.[22]

PROVIDE SUFFICIENT AIR EXCHANGE TO REMOVE HEAT, NOXIOUS GASES, AND MOISTURE FROM THE BARN

The main purpose of a ventilation system is to maintain harmful gases, moisture, and temperature at safe levels throughout the year (**Fig. 12**). The minimum ventilation

Fig. 11. Baffles installed in a cross-ventilated (*left*) and a tunnel-ventilated (*right*) retrofit barn.

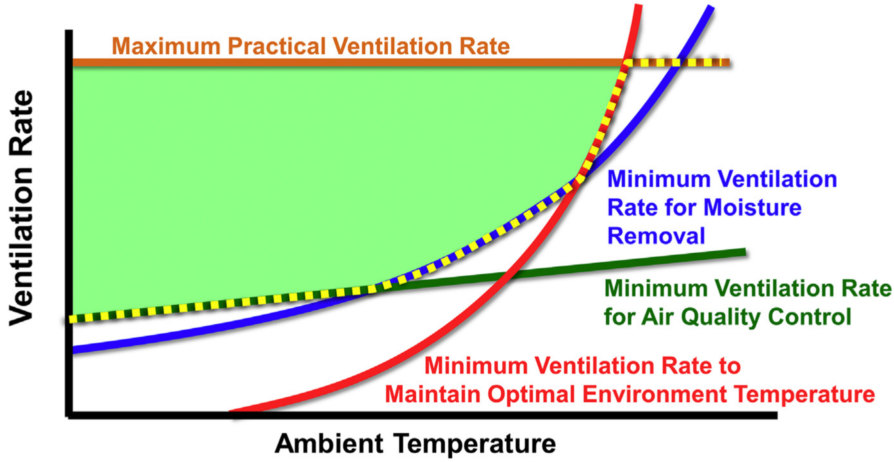

Fig. 12. The ideal ventilation design curve. (*Adapted from* Christianson LL. Ventilation - energy and economics - Figure 14.2. In: Hellickson MA and Walker JN, editors. Ventilation of agricultural structures. St. Joseph (MI): American Society of Agricultural Engineers; 1983. p. 336; with permission.)

required to maintain each of these factors changes with the seasons. Typical design values for mechanical ventilation are 4 ACH during the winter and 40 to 60 ACH, 500 ft min^{-1} (2.54 m s^{-1}) cross-sectional area airspeeds, and 1500 ft^3 min^{-1} (2550 m^3 h^{-1}) per cow during the summer. However, some producers are designing systems up to 100 ACH[18] for summertime cooling.

Similar to the MCAS, the required ventilation rate for adult cows is not well defined. A wide range of recommendations and standards exists (Table 1). The standards[18]

Table 1
Mechanical ventilation summer recommendations

m^3 h^{-1} per Animal Unit	ft^3 m^{-1} per Animal Unit	Source	Animal Unit	Specified For	ACH
113	66	Shen et al,[32] 2013	600 kg cow	Humidity balance	2
463	272	Shen et al,[32] 2013	625 kg cow	dT <3°C in 27°C outside conditions	8
535	315	MWPS-1,[33] 1983	453 kg cow	Hot weather rate	9
798	470	Holmes et al,[34] 2013	635 kg cow	Hot weather rate	13
1700	1000	Tyson et al,[35] 2014; Gooch & Stowell,[36] 2003	—	Summer rate	29
2549	1500	Tyson et al,[35] 2014	—	Summer rate	43
1787	1052	MWPS-1,[33] 1983	453 kg cow	Alternative hot weather rate	30
2383	1403	Nordlund[37]	—	Minimum hot weather rate	40
3574	2104	Holmes et al,[34] 2013	635 kg cow	Alternative hot weather rate	60
5957	3506	Stowell et al,[38] 2003	—	Hot weather rate	100

Abbreviation: ACH, air changes per hour.

use a heat and mass balance methodology to avoid a 1.8 to 3.6°F (1–2°C) increase in temperature between the inlet and outlet of the barn. The relative humidity should be below 80% and the inside surfaces should have enough insulation to avoid reaching dew-point temperatures at 80% relative humidity to avoid condensation.

Each ventilation system should be individually evaluated, as average recommendations make assumptions of production, weight, location, and flow distribution that will not accurately represent every microclimate.[23] Unfortunately, these recommendations and standards are all at a barn-level resolution, which has not been properly related to the microenvironment of the pen or the microenvironment of the stalls.

One of the main reasons for these discrepancies is that freestall barns tend to have a tall ceiling and ridge. It is not uncommon for ceilings to go as high as 26 ft (8 m) or higher, meaning the stall microclimate is limited to approximately 20% of the total flow area, depending on the pen location. Because most heat and mass transfer processes (eg, cow panting, sweating, ammonia from manure) occur within the microenvironment of the pen, it is important that the ventilation system is able to reach these areas.

A recent trend for tunnel-ventilation systems is to use a ventilation rate of 40 ACH, as it is usually enough to meet the temperature difference standards in mild climates. Regardless of the ventilation rate, it is recommended that local sources of airspeed, like fans over the stalls, are used in tunnel ventilation because the ventilation rate has diminishing returns on minimizing low airspeed areas after 40 ACH.

Unlike mechanical ventilation, it is difficult to estimate and control specific ventilation rates for natural barns. Instead, if the building is located, oriented, and designed with the overall recommendations, the system should perform well, although inconsistencies are common due to natural wind patterns.

ENSURE THAT THE SYSTEM WORKS ACROSS ALL SEASONS

A ventilation system needs to be designed so that it performs well across all seasons. This will vary significantly between climatic regions because the ventilation system needs to serve the workers, the facility, and the cows equally. Improper management of the system through the various climatic changes is the most common issue with ventilation systems in the dairy industry. It is very common to find excellent winter systems that perform poorly during the heat of the summer, particularly in natural systems without fans over the stalls. Meanwhile, large mechanically ventilated facilities face the opposite problem where summer ventilation is optimal, but there are significant distribution and condensation issues during the winter.

Because dairy cattle are cold tolerant, the goal in the winter is to maintain adequate moisture and gas concentration levels in the air to avoid respiratory disease rather than keeping the animals warm. The ventilation rate must be high enough to ensure adequate air quality but low enough to prevent as much freezing and condensation within the barn as possible. Typically, producers use 4 ACH as the minimum winter ventilation rate and 40°F (4.4°C) as the winter temperature set-point for minimum ventilation, but some producers use 8 ACH at 40°F (4.4°C) and 4 ACH farther down at 20°F (−6.6°C). As ambient temperature increases, the minimum ventilation rate required to maintain adequate environmental temperature and moisture levels increases and eventually, the maximum practical ventilation rate is achieved, typically at 40 to 60 ACH (see **Fig. 12**).

In the summer, the main goal of ventilation is to ensure that natural and manmade cooling processes are occurring as efficiently as possible by exhausting excess heat and preventing thermal buildup in the facility. In general, cows are considered to be in a comfortable environment in temperatures between 40 and 68°F (4.4 and

20°C), and the most common set-point for the ventilation system to operate at the maximum summer rate is 68°F (20°C); however, some producers are beginning to shift the set-point to 65 °F (18.3 °C) because of the high costs associated with heat stress.[24] The THI, which is a number that combines temperature and humidity impact on the cow, is the most commonly used measure of heat stress for dairy cows. A THI of 68 is where cows typically begin to show signs of heat stress.[25]

One of the most important factors for adequate natural ventilation a producer can control is having a well-insulated barn. During cold temperatures, a well-insulated barn will conserve heat and maintain warmer surface temperatures on the inside, improving the stack effect and preventing condensation. During hot temperatures, a well-insulated barn will reduce heat gain from solar radiation and convection effects, reducing the ventilation needed to maintain a comfortable environment.

Almost every newly installed mechanical ventilation system now includes a transition methodology between the summer and winter conditions. A mechanical ventilation system uses a combination of temperature, and more recently humidity, sensors, and a controller that operates fans and adjusts the sidewall curtain openings to ensure adequate inlet openings during the various ventilation stages.

Fans should be operated from a control system that monitors temperature within the barn (pen), and inlets and fans should be evenly distributed to equalize airflow patterns between regions of the barn as much as possible. This should be planned with a detailed wiring and control map of which fans are used and that are switched off at various intervals across the seasons. The advent of VFDs has allowed even natural ventilation systems to include a transition methodology in which the circulation fans will operate at minimum speeds to mix the air in the winter and speed up as temperature increases to provide cooling.

There is little information on what the ventilation rate should be during mild weather. It is recommended to stage the ventilation system every 3.6°F (2°C),[7] but the ramping functions are more usually dependent on the number of fans and how the fans were wired during installation. The most commonly found methodology to stage the ventilation system from winter to summer is to use a linear ramping function. Once a minimum and maximum ventilation rate is designed, a straight line is drawn between them to determine the different stages. The specifics of how many stages and whether VFDs are used depend on the fan manufacturer, builder, and producer.

Each ventilation system has different challenges as the seasons change. One issue with tunnel barns is the temperature and humidity difference between the inlet and the outlet of the barn, which is influenced by barn length. Barns should be no longer than 600 ft (183 m) long because a significant drop in air quality can be observed after 600 ft (183 m), particularly in the winter. A similar problem is found in cross-ventilated barns that are too wide.

Hybrid systems provide the most flexibility across seasons, but tend to have the highest installation cost due to combining 2 or more ventilation systems, as well requiring curtain sidewalls along the length of the barn. Because the whole sidewall can be opened in these systems, they can ventilate in emergency situations (**Fig. 13**).

During the summer, the hybrid system will have mechanical ventilation combined with circulation fans to provide sufficient fresh air and MCAS. As the temperature drops, the mechanical system will decrease the ventilation rate until a determined set-point at which the system will transition to a natural or assisted natural ventilation system. In the assisted natural system, the exhaust system shuts off, but a series of cupola fans will turn on. Depending on the design, the cupola system will cover more than the minimum winter ventilation rate, with 1 or 2 more ventilation stages. These systems can excel in climates where temperatures fluctuate significantly

Fig. 13. A hybrid ventilation system with fans at the end-wall for summer ventilation and cupola fans for winter ventilation.

throughout the year, but are not necessary in locations with more consistent temperatures; like arid climates or year-round temperate regions.

VENTILATION SYSTEM MAINTENANCE

Proper system maintenance is just as important as proper design. Fans with poor maintenance can lose 30% to 50% of their efficiency.[26] Reactive maintenance can be costly and dangerous, as it can quickly degrade ventilation performance, degrading the cow's microenvironment along with it. Evaporative cooling systems using wet-pads require significant maintenance, as they can clog up quickly with water residue. For fans, belts should be inspected for tightness, and blades and louvers should be inspected for buildup and dust. Ideally, the farm will maintain fans that operate year-round at least twice a year and summer fans at least once a year, but these schedules should be considered the bare minimum.

ECONOMICS OF VENTILATION SYSTEMS

There is little information on the costs of ventilation systems in the dairy industry. In a survey of energy use in dairy farms,[27] ventilation was shown to account for 20% of the total energy use on farm.

A facility designed for 1008 cows housed in 4 pens was quoted by a building company and 7 ventilation designs were evaluated for operating costs. The 7 systems consisted of 2 natural barns with fans every 48 ft (14.6 m) (NAT1), every 24 ft (7.3 m) (NAT2); 2 tunnel-ventilated barns designed at 60 ACH (TUN60) and 40 ACH (TUN60) with panel fans every 24 ft (7.3 m); a hybrid system designed at 40 ACH with cyclone fans every 60 ft (18.3 m) (HYB40) and a cupola system; and 2 cross-ventilated barns, an 8-row (8CRO) and a 16-row (16CRO) barn. Previous economic models and surveys[28–30] have quoted the cost of building a new facility at $2500 per stall without including electrical costs. The total costs before including the cost of financing showed a similar range of $2300 to $2700 per stall depending on the ventilation system and layout (Table 2).

Overall, construction costs are similar across the range of different designs. Therefore, other factors, such as herd size, location, barn orientation, footprint per stall, cow flow, lighting, manure handling, and owner preference should be considered over the capital costs of building and installing a specific type of barn ventilation system. In general, it costs approximately twice as much to operate a mechanical system per year than a natural system, and approximately double to operate it in a hot climate as opposed to a temperate climate. However, as variable speed fans become more

Table 2
Capital costs of 7 ventilation systems amortized over 10 years, cost in USD

Ventilation System	Building Cost	Ventilation Installation Cost	Total Costs (+5% Fee)	Total Financed Cost (4.25% APR)	Total Capital Cost Per Stall Per Year
NAT1	2,156,432	62,860	2,330,257	2,902,862	289
NAT2	2,156,432	125,720	2,396,260	2,991,254	287
TUN60	2,145,902	182,095	2,444,397	3,051,344	303
TUN40	2,145,902	247,682	2,513,263	3,137,310	311
HYB40	2,309,893	273,732	2,712,806	3,386,399	336
8CRO	2,099,789	171,110	2,384,444	2,976,504	295
16CRO	3,611,588	171,110	3,971,833	4,958,044	246

common, the operating costs can be reduced by optimizing the operating schedules of the variable speed fans.[31] Fan selection has the largest effect on the cost of operating ventilation systems. Therefore, fans with a higher ventilation efficiency rating should be selected whatever the system used.

SUMMARY

A wide variety of ventilation systems can provide an excellent environment for the cow within a barn, provided they meet 3 critical design criteria; the provision of appropriate air speeds in the stall microenvironment defined as a minimum air speed of at least 200 ft min^{-1} (1 m s^{-1}); the provision of sufficient air exchange to effectively remove heat, noxious gases, and moisture from the barn, typically at least 4 ACH in the winter and 40 to 60 ACH; and the system must be designed to function well across all seasons with an effective transition methodology. Once these criteria are met, it is further essential to perform at least bi-annual fan maintenance for year-round systems.

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REFERENCES

1. Midwest Plan Service. MWPS-33. Natural ventilating systems for livestock housing. 1st edition. Ames (IA): Midwest Plan Service; 1989. Available at: https://www-mwps.sws.iastate.edu/catalog/ventilation-livestock-housing/natural-ventilating-systems-livestock-housing. Accessed August 30, 2018.
2. Callan RJ, Garry FB. Biosecurity and bovine respiratory disease. Vet Clin North Am Food Anim Pract 2002;18(1):57–77.
3. Nardell EA, Keegan J, Cheney SA, et al. Airborne infection: theoretical limits of protection achievable by building ventilation. Am Rev Respir Dis 1991;144:302–6.
4. Berman A. Extending the potential of evaporative cooling for heat-stress relief. J Dairy Sci 2006;89(10):3817–25.
5. Bruce JM. Natural convection through openings and its application to cattle building ventilation. J Agric Eng Res 1978;23(2):151–67.
6. Wu W, Zhai J, Zhang G, et al. Evaluation of methods for determining air exchange rate in a naturally ventilated dairy cattle building with large openings using computational fluid dynamics (CFD). Atmos Environ 2012;63:179–88.

7. Bjerg B, Cascone G, Lee IB, et al. Modelling of ammonia emissions from naturally ventilated livestock buildings. Part 3: CFD modelling. Biosyst Eng 2013. https://doi.org/10.1016/j.biosystemseng.2013.06.012.
8. Brotzman R, Cook N, Nordlund K, et al. Cluster analysis of Dairy Herd Improvement data to discover trends in performance characteristics in large Upper Midwest dairy herds. J Dairy Sci 2015;98(5):3059–70.
9. Hellickson MA, Walker JN. Ventilation of agricultural structures. Monograph no. 6. St. Joseph (MI): American Society of Agricultural Engineers; 1983. Available at: https://books.google.com/books/about/Ventilation_of_Agricultural_Structures.html?id=ML9NP-RaRX4C. Accessed August 24, 2018.
10. Berman A. Estimates of heat stress relief needs for Holstein dairy cows. J Anim Sci 2005;83:1377–84. Available at: https://academic.oup.com/jas/article-abstract/83/6/1377/4803167. Accessed August 24, 2018.
11. Berman A. Increasing heat stress relief produced by coupled coat wetting and forced ventilation. J Dairy Sci 2008;91(12):4571–8.
12. Hillman PE, Lee CN, Willard ST. Thermoregulatory responses associated with lying and standing in heat-stressed dairy cows. Trans ASAE 2005;48(2):795–801.
13. Cook NB, Mentink RL, Bennett TB, et al. The effect of heat stress and lameness on time budgets of lactating dairy cows. J Dairy Sci 2007;90(4):1674–82.
14. Calegari F, Calamari L, Frazzi E. Fan cooling of the resting area in a free stalls dairy barn. Int J Biometeorol 2014;58(6):1225–36.
15. The Dairyland Initiative. Ventilation and Heat Abatement – The Dairyland Initiative. 2018. Available at: https://thedairylandinitiative.vetmed.wisc.edu/home/housing-module/adult-cow-housing/ventilation-and-heat-abatement/. Accessed August 24, 2018.
16. Yeck RG, Stewart RE. A ten-year summary of psychroenergetic laboratory dairy cattle research at the University of Missouri. Trans ASAE 1959;2(1):71–7.
17. Kibler H, Brody S. Environmental Physiology With Special Reference to Domestic Animals. 1951. Available at: http://www.asrc.agri.missouri.edu/research/bec/MO Ag Exp Bulletins/Bulletin 552 - Influence of wind on heat exchange and body temperature regulation in jersey holstein brown swiss and brahman cattle.pdf. Accessed August 24, 2018.
18. American Society of Agricultural Engineers. ASAE EP270.5 DEC1986 (R2017) Design of Ventilation Systems for Poultry and Livestock Shelters. 2017. Available at: https://elibrary.asabe.org/azdez.asp?JID=2&AID=24432&CID=s2000&T=2. Accessed August 24, 2018.
19. McGovern RE, Bruce JM. A model of the thermal balance for cattle in hot conditions. J Agric Eng Res 2000;77(1):81–92.
20. West JW. Effects of heat-stress on production in dairy cattle. J Dairy Sci 2003;86(6):2131–44.
21. Harner JP, Smith JF. “Let it flow, let it flow” moving air into the freestall space. In: Housing of the future. Sioux Falls (SD). 2008. Available at: https://www.asi.k-state.edu/doc/dairy/moving-air-into-the-freestall-space.pdf. Accessed August 30, 2018.
22. Smith JF, Bradford BJ, Harner JP, et al. Short communication: effect of cross ventilation with or without evaporative pads on core body temperature and resting time of lactating cows. J Dairy Sci 2016;99(2):1495–500.
23. Seedorf J, Hartung J, Schröder M, et al. A survey of ventilation rates in livestock buildings in Northern Europe. J Agric Eng Res 1998;70(1):39–47.
24. St-Pierre NR, Cobanov B, Schnitkey G. Economic losses from heat stress by US livestock industries. J Dairy Sci 2003;86:E52–77.

25. Collier RJ, Zimbelman RB, Rhoads RP, et al. A re-evaluation of the impact of temperature humidity index (THI) and black globe humidity index (BGHI) on milk production in high producing dairy cows. In: Western Dairy Management Conference . Reno, Nevada. 2011. p. 113–25. Available at: http://wdmc.org/2011/A Re-Evaluation of the Impact of Temperature Humidity Index %28THI%29 and Black Globe Humidity Index %28BGHI%29 on Milk Production in High Producing Dairy Cows pg 113-126.pdf. Accessed August 30, 2018.
26. Bodman GR, Shelton DP. G95-1242 Ventilation Fans: Performance. 1995. Available at: http://digitalcommons.unl.edu/extensionhisthttp://digitalcommons.unl.edu/extensionhist/600. Accessed August 30, 2018.
27. Ludington D, Johnson E. Dairy farm energy audit summary. New York: New York State Energy Res Dev Authority; 2003. Available at: https://www.nyserda.ny.gov/-/media/Files/Publications/Research/Energy-Audit-Reports/dairy-farm-energy.pdf.
28. Ferreira FC, Gennari RS, Dahl GE, et al. Economic feasibility of cooling dry cows across the United States. J Dairy Sci 2016. https://doi.org/10.3168/jds.2016-11566.
29. Kammel DW. Building cost estimates-dairy modernization. Madison. 2015. Available at: https://fyi.uwex.edu/dairy/files/2015/11/Building-Cost-Estimates-Dairy-Modernization.pdf. Accessed August 30, 2018.
30. Tyson JT. Heat abatement techniques in dairy housing in the northeast. 2008. Available at: https://etda.libraries.psu.edu/files/final_submissions/3034. Accessed August 30, 2018.
31. Atkins I, Mondaca M, Choi C. Energy efficiency and air distribution of VFD-driven mechanical ventilation systems. In: 2016 American Society of Agricultural and Biological Engineers Annual International Meeting, ASABE, Orlando, Floria, July 17–20, 2016. https://doi.org/10.13031/aim.20162461516.
32. Shen X, Zhang G, Wu W, et al. Model-based control of natural ventilation in dairy buildings. Comput Electron Agric 2013;94:47–57.
33. Midwest Plan Service, Structures and Environment Subcommittee. MWPS-1. Structures and environment handbook. Ames (IA): Midwest Plan Service; 1983. Available at: https://www-mwps.sws.iastate.edu/catalog/construction-farm/structures-and-environment-handbook. Accessed August 30, 2018.
34. Holmes BJ, Cook NB, Funk T, et al. Dairy freestall housing and equipment. Midwest Plan Service; 2013. Available at: https://www-mwps.sws.iastate.edu/catalog/livestock/dairy/dairy-freestall-housing-and-equipment. Accessed August 24, 2018.
35. Tyson JT, McFarland DF, Graves RE. Tunnel ventilation for tie stall dairy barns. PennState Extension 2016. Available at: https://extension.psu.edu/tunnel-ventilation-for-tie-stall-dairy-barns.
36. Gooch CA, Stowell RR. Tunnel ventilation for freestall facilities – design, environmental conditions, cow behavior, and economics. In: Janni K, editor. Fifth international dairy housing. Fort Worth (TX). 2003. p. 227–34. Available at: https://elibrary.asabe.org/azdez.asp?JID=1&AID=11626&CID=dhc2003&T=2. Accessed August 30, 2018.
37. Nordlund K. Ventilating existing buildings. In Preconvention Seminar 7: Dairy Herd Problem Investigation Strategies American Association of Bovine Practitioners 36th Annual Conference, Columbus, OH, September 15–17, 2003. Available at: https://www.vetmed.wisc.edu/dms/fapm/fapmtools/9ventilation/VetsVent.pdf.
38. Stowell RR, Gooch CA, Bickert WG. Design parameters for hot-weather ventilation of dairy housing: a critical review. In: Janni K, editor. Fifth international dairy housing. Fort Worth (TX). 2003. p. 218–26. Available at: https://elibrary.asabe.org/azdez.asp?AID=11625&t=2. Accessed August 30, 2018.