Dairy Cooling: The Benefits and Strategies

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Summary

Heat stress adversely affects dairy cows in a variety of ways. A cow suffering from heat stress, for example, produces less milk, conceives less often, and is at a greater risk of contracting a range of debilitating and even deadly diseases. The severity of the effects directly related to heat stress vary significantly by climate, with estimated production losses at dairies without cooling ranging from 403 pounds per cow per year in Wisconsin to almost 4,000 pounds per cow per year in Florida. Heat stress can also have a major effect on reproduction cycles. For example in Florida, cows not subjected to cooling measures have an estimated 59.2 additional days open.[1] In periods of extreme heat, the resultant heat stress has even led directly to animal deaths. During a 2006 heat wave in California, 25,000 cattle perished.[2] In 2010, economic losses resulting from heat stress were estimated to be $1.2 billion across the entire US dairy sector, an average of $39,000 per dairy.[3] Clearly, as global temperatures increase and dairies expand to meet a growing demand, the costs of heat stress and the need to mitigate it will increase as well. Fortunately, the effects of heat stress can be reduced by implementing properly designed and operated ventilation systems and employing effective cow cooling strategies. A 2003 analysis found that providing dairy cows with an optimal level of cooling reduces the total cost of heat stress and its mitigation by an average of 43% across the US, as compared to if no cooling measures were taken.[1] To help producers better understand the costs associated with heat stress and the measures that can be taken to alleviate it, this summary discusses heat stress characteristics and their effects in more detail and also the various systems and strategies now available for heat stress relief. To aid in selecting the system best suited to a particular herd, production operation, and existing infrastructure, companion Climate-Specific Guides, *Dairy Cooling in Humid Continental Climates*, *Dairy Cooling in Arid and Semi-Arid Climates*, and *Dairy Cooling in Humid Subtropical Climates*, provide design guidelines and discussion of these strategies as they relate to the local climate and available resources.

Heat stress

Animal heat balance

Both normal metabolism and the conversion of nutrients into milk generate heat. A cow becomes heat stressed when she is producing more heat than can passively dissipate from her body to the surrounding environment. As temperatures exceed 68 - 80 °F (depending on the humidity), active physiological and behavioral responses are necessary to avoid overheating.[4] A heat stressed cow increases her sweating and respiration rates to transfer more heat to the environment through evaporation. However, these responses divert energy from the milk production process, decreasing feed efficiency.[5] She also stands for longer periods as a way to increase her surface area for maximum heat dissipation, but excessive standing disrupts her resting patterns and can contribute to lameness.[6] In addition, she reduces her dry matter intake (DMI) and milk production to reduce the quantity of heat she generates.

Temperature humidity index (THI) as an indicator of heat stress

The rate at which heat can be transferred sensibly through convection depends on the temperature difference between the air and the hide, while the rate at which evaporation can transfer heat also depends on the relative humidity (RH). Consequently, not only high temperatures but also high humidities slow the dissipation of heat from the cow and contribute to heat stress. At 100% RH, no evaporation can occur and the effects of heat stress can set in at temperatures as low as 68 °F. At lower levels of RH, minimal sweating can help dissipate heat during periods of high temperature up to about 80 °F.[4] To quantify the level of heat stress caused by the combined effects of temperature and RH, the temperature humidity index or THI (see equation 1 and figure 1) was developed as a function of both temperature and RH.

Equation 1:

$$THI = T - (0.55 - 0.0055 \times RH) \times (T - 58) \quad [7]$$

where T is temperature (°F) and RH is relative humidity (%). Note that although air velocity reduces heat stress, this THI index does not include air velocity as a variable.

Temperature	Relative humidity [%]																				
°F	0	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
72	64	65	65	65	66	66	67	67	67	68	68	69	69	69	70	70	70	71	71	72	72
74	65	66	66	67	67	67	68	68	69	69	70	70	70	71	71	72	72	73	73	74	74
76	66	67	67	68	68	69	69	70	70	71	71	72	72	73	73	74	74	75	75	76	76
78	67	68	68	69	69	70	70	71	71	72	73	73	74	74	75	75	76	76	77	77	78
80	68	69	69	70	70	71	72	72	73	73	74	75	75	76	76	77	78	78	79	79	80
82	69	69	70	71	71	72	73	73	74	75	75	76	77	77	78	79	79	80	81	81	82
84	70	70	71	72	73	73	74	75	75	76	77	78	78	79	80	80	81	82	83	83	84
86	71	71	72	73	74	74	75	76	77	78	78	79	80	81	81	82	83	84	84	85	86
88	72	72	73	74	75	76	76	77	78	79	80	81	81	82	83	84	85	86	86	87	88
90	72	73	74	75	76	77	78	79	79	80	81	82	83	84	85	86	86	87	88	89	90
92	73	74	75	76	77	78	79	80	81	82	83	84	85	85	86	87	88	89	90	91	92
94	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94
96	75	76	77	78	79	80	81	82	83	85	86	87	88	89	90	91	92	93	94	95	96
98	76	77	78	79	80	82	83	84	85	86	87	88	89	90	91	93	94	95	96	97	98
100	77	78	79	80	82	83	84	85	86	87	88	90	91	92	93	94	95	97	98	99	100
102	78	79	80	81	83	84	85	86	87	89	90	91	92	94	95	96	97	98	100	101	102
104	79	80	81	82	84	85	86	88	89	90	91	93	94	95	96	98	99	100	101	103	104
106	80	81	82	84	85	86	88	89	90	91	93	94	95	97	98	99	101	102	103	105	106
108	81	82	83	85	86	87	89	90	92	93	94	96	97	98	100	101	103	104	105	107	108
110	82	83	84	86	87	89	90	91	93	94	96	97	99	100	101	103	104	106	107	109	110
112	83	84	85	87	88	90	91	93	94	96	97	99	100	102	103	105	106	108	109	111	112
114	84	85	86	88	89	91	92	94	96	97	99	100	102	103	105	106	108	109	111	112	114

- Stress threshold
- Mild-moderate stress
- Moderate-severe stress
- Severe stress

FIG. 1. THI index. Adapted from [4].

Immediate effects of THI on milk production and dry matter intake

Over the past several decades, a number of research studies have measured milk production and DMI as a function of THI. Older studies and THI charts indicate that the negative effects of heat stress can manifest at THI values of 70 and 72, but because high-producing dairy cows generate more heat than their ancestors, the maximum THI at which they can maintain optimal performance is lower. The most recent research places the threshold THI at 68.[4] The results of a number of these studies were combined to facilitate an estimate of the average daily reduction in milk production and DMI due to heat stress in pounds per cow per day, as shown in equations 2 and 3.[1]

Equation 2:

$$MILK_{loss}\ [lb/cow\text{-}day] = 0.00638 \times (THI_{max} - THI_{threshold})^2 \times (\text{heat stress hours})$$

Equation 3:

$$DMI_{loss}\ [lb/cow\text{-}day] = 0.003169 \times (THI_{max} - THI_{threshold})^2 \times (\text{heat stress hours})$$

where THI_{max} is the highest THI experienced during a day and the number of heat stress hours is the amount of time the THI is greater than the $THI_{threshold}$. On a day with a peak temperature of 81 °F and 50% RH, for example, THI_{max} would be 75 (refer to figure 1). If the THI remained above the $THI_{threshold}$, (currently set at 68) for 8 hours, then $MILK_{loss} = 0.00638 \times (75 - 68)^2 \times (8 \text{ hours}) = 2.5$ pounds of lost milk production per cow for that day. On the other hand, if the cow only suffers heat stress in the holding area and can begin to cool down once she is in the barn, the duration of heat stress might be closer to 2 hours. The results from equations 2 and 3 as a function of THI_{max} for 2 to 16 heat stress hours are shown in figure 2 below.

	Milk loss (lb/cow-day)								Reduced DMI (lb/cow-day)							
Max THI	**Heat stress hours**															
	2	4	6	8	10	12	14	16	2	4	6	8	10	12	14	16
68	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
72	0	0	1	1	1	1	1	2	0	0	0	0	1	1	1	1
76	1	2	2	3	4	5	6	7	0	1	1	2	2	2	3	3
80	2	4	6	7	9	11	13	15	1	2	3	4	5	5	6	7
84	3	7	10	13	16	20	23	26	2	3	5	6	8	10	11	13
88	5	10	15	20	26	31	36	41	3	5	8	10	13	15	18	20
92	7	15	22	29	37	44	51	59	4	7	11	15	18	22	26	29
96	10	20	30	40	50	60	70	80	5	10	15	20	25	30	35	40

FIG. 2. Losses in milk production and DMI for varying THI_{max} and heat stress hours without heat abatement from equations 2 and 3.

Delayed effects of heat stress on milk production

Heat stress will affect a lactating cow not only on the day she suffers such stress but also in the days following. In fact, the reduction in milk production from a lactating cow is greater two days after a heat stress event than during the time of heat stress.[8] A number of studies have also shown that heat stressed dry cows suffer reduced performance during their next lactation due to reduced mammary gland development, especially those in late gestation. For example, in a 2011 study conducted at the University of Florida, a group of cows subjected to heat stress during their dry period produced an average of 11 pounds per cow per day less during the subsequent lactation than those that received cooling.[9]

Effect of heat stress on reproduction

The negative effects of heat stress on reproduction are both immediate and delayed. Decreased fertility is apparent during times of heat stress, as well as into the fall months after the heat stress season has passed.[10] Heat stress causes the rate of successful inseminations to fall, thus negatively affecting a herd’s average number of days open per year, which is defined as the average number of days between calving and conception. The costs of additional days open include increased breeding costs, increased culling and replacement costs, and reduced milk production. Including reproductive culling, the cost of a day open was recently estimated between $3.19 and $5.41.[11] When the cost of reproductive culling is accounted for separately, lower values, such as $2.50 per day open have been employed.[1] The estimated increase in average number of days open due to heat stress is shown in Table 1 for several of the major dairy states.

Table 1. Increase in average days open caused by heat stress compared to unstressed cows.[1]

State	Increase in average days open	State	Increase in average days open
California	12.1	Minnesota	10.0
Wisconsin	8.7	New Mexico	23.0
New York	7.3	Michigan	7.8
Pennsylvania	13.2	Texas	53.9
Idaho	8.8	Washington	7.0
Arizona	25.6	Florida	59.2

Heat stress also affects the fetal development and postnatal health of calves. Another study performed at the University of Florida in 2012 found the average birth weight of calves born to heat stressed mothers was 80.5 pounds, as compared to 93.7 pounds for those from mothers that had received cooling. The difference in weights also continued through the weaning period, after which the calves from heat stressed mothers averaged 322.8 pounds compared to 340.8 pounds for calves whose mothers had received cooling.[12]

Additional effects of heat stress on overall health

- Impaired immune system
- Acidosis due to slug feeding
- Lameness due to increased standing

Income lost as a result of heat stress

Before investing in a cooling system, a dairy producer should try to estimate the amount of money that will likely be saved. Typically, the greatest loss caused by heat stress is reduced milk production. The DMI will also decrease as a function of heat stress, saving money on feed. Values for reduced milk production and DMI can be estimated using equations 2 and 3, if the number of heat-stress days, the *duration* of heat stress on those days, and the *maximum* heat stress on those days are all known. Because historical weather data is not always readily available for a given site and processing it can take a significant amount of time, estimates of the average total economic costs of heat stress per dairy cow without cooling are presented in Table 2.[1] These estimates include decreased milk production and DMI, as well as increased days open, reproductive culls, and deaths resulting from heat stress. (Note: although heat stress negatively affects animal health and calf weight, this analysis did not attempt to quantify direct costs of these effects.)

Table 2. Losses from heat stress for dairy cows without cooling in Wisconsin, Arizona, and Florida.[1]

	Reduced milk production (lbs)	Reduced DMI (lbs)	Additional days open	Additional reproductive culls (per 1000)	Additional deaths (per 1000)	Average cost per cow
Wisconsin	403	201	8.7	6.3	1.3	$72
Arizona	1607	798	25.6	24.7	5.2	$265
Florida	3974	1971	59.2	79.9	17.2	$676

Assumptions include $MILK_{loss}$ value = $0.13 / lb, DMI_{loss} value = $0.059 / lb, Day open value = $2.50, Reproductive cull value = $1,200 and Death value = $1,800.

Heat Abatement Strategies

To reduce the risk of heat stress, dairy producers can either alter the cow's environment, the cow's diet or the genetic make-up of the herd. To alter the environment, for example, the producer can provide shade and drinking water or introduce measures that will artificially lower the temperature and augment the air velocity. Because the benefits of shade and water are well known, this series of guides will only focus on comparing various ventilation and cow cooling strategies.

Ventilation

Maintaining a healthy building environment requires ventilation, which is a matter of exchanging the air inside the building with air outside the building. The "fresh" outside air must be allowed to flow into the barn to replace the "stale" inside air, which contains heat, moisture, ammonia, and pathogens (see figure 3). During the summer, air exchange is especially important to remove the heat generated by the herd and prevent the warming of the barn. During hot weather, the air-exchange rate should be a minimum of 1,000 CFM per cow.[13] In practice, many mechanically ventilated buildings significantly exceed this guideline to provide adequate air velocity for heat stress relief. During the winter, a 50 CFM per cow minimum air exchange rate is required to remove the noxious gases, moisture, and other contaminants that build up inside the barn. Alternatively, the ventilation rate can be determined by

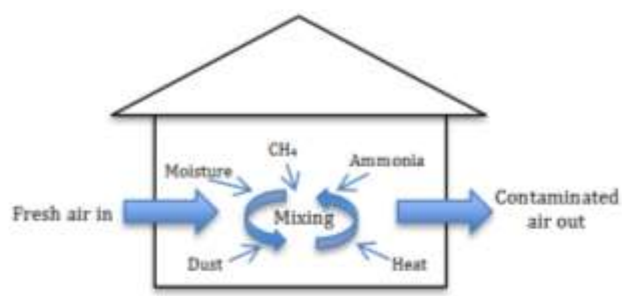

FIG. 3. Fresh air dilutes the concentration of heat, moisture, and contaminants.

calculating the recommended number of air changes per minute, which are 0.07 air changes per minute in winter and 1 air change per minute in summer.[14]

Air velocity

Higher air velocities produce higher rates of convective heat transfer. This effect, most commonly known as “wind chill,” reduces the apparent THI and the effects of heat stress. In naturally ventilated barns and holding areas, circulation fans (also known as “panel” or “basket” fans) aimed at the cows, are often added to increase the velocity of the air passing over the animals. In cross- and tunnel-ventilated barns, ventilation fans can both ventilate and cool the cows if the barn design allows for a relatively high velocity in the animal occupied zones. An air velocity of 400 to 600 fpm has been shown to reduce heat stress and is often used as a design specification.[13] The Facility and Ventilation Design section provides more information concerning the various systems, and how they increase air velocity at cow level depending on the type of building being conditioned.

Cooling cows with water

Water works in several ways to cool cows. The cow herself uses water when panting and sweating, thereby producing an evaporative cooling effect. Heat dissipation through evaporation can be enhanced by applying water directly to the cow using soakers and sprinklers. Additionally, water can be used to indirectly cool cows by evaporating it into the ventilation air (which lowers the air’s temperature) before the air is blown onto the cows.

Direct cooling with sprinklers, soakers, and showers

Soakers, sprinklers, and showers wet the cow’s hide, providing cooling due to the water being cooler than her hide, and then through evaporation as she drys. Soakers are usually placed along the feedline, sprinklers over the holding area, and showers at the parlor exit. These systems should be oriented to avoid getting bedding or feed wet. It is also important to actually soak the hide as opposed to just the hair (in which case an insulating layer of air will be trapped between the film of water on the hair coat and the hide). Low-pressure (20 - 40 psi) sprinklers produce large droplets that can penetrate the hair coat more effectively than small droplets.

Directly wetting the cow is most effective when combined with fans because air velocity increases the rate of evaporation from the hide. A study performed at Kansas State in 2003 tested several sprinkling frequencies (5, 10, and 15 minutes) with and without fans on respiration rates and body temperature. They found that only sprinklers are more effective than only fans, but that the combination of sprinklers and fans is most effective.[15]

Indirect cooling with misters and cooling pads

High pressure (> 200 psi) misters, which produce very small droplets, and also evaporative cooling pads, (corrugated membranes through which the water drips) are commonly used to cool the air before it reaches the cows.[14] The cooling effect these systems can provide is limited by the quantity of water they can evaporate into the incoming air before the air is saturated (i.e. RH = 100% and the dry- and wet-bulb temperatures are equal). Therefore, the lower the RH of the incoming air, the more water can be evaporated into it and the greater the cooling potential, making evaporative cooling particularly effective in arid climates. Evaporative cooling can also be effective in humid climates during the hottest part of the day, which is when RH is lowest.

Evaporative cooling lowers both the temperature and THI. However, because moisture is added to the air, which raises the RH, the reduction in THI is not as great as the reduction in temperature. For example, assuming 75% evaporation efficiency, air entering at a temperature of 90 °F and 30% RH undergoes a temperature reduction of approximately 17 °F and a THI reduction of approximately 6.3 units. However, entering air at 90 °F and 70% RH undergoes a temperature reduction of approximately 6.2 °F and a THI reduction of only about 2.6 units. Note that evaporation efficiency is defined as the percent of the difference between the incoming air's dry- and wet-bulb temperatures that is achieved through evaporative cooling. For example, if the incoming air's dry-bulb temperature were 90 °F and wet-bulb temperature were 80 °F, an evaporative cooling system operating at 75% efficiency would lower the air by 7.5 °F to 82.5 °F.

Control of evaporative cooling systems

Evaporative systems should always be closely monitored to make sure the optimal amount of water is being used. Too little will reduce the effectiveness of the cooling system; too much will create unhealthily wet conditions in resting areas and contribute to mastitis, and excess water from sprinklers will ultimately end in the manure management system.[14] Because cooling pads self-regulate in this respect, they offer a distinct advantage: the drier and hotter the entering air, the more water will evaporate. Conversely, the flow rate through a mister will not change unless directed to by the control system.

Facility and ventilation design

Dairy facilities are designed with both ventilation and air velocity in mind, and in general a dairy barn's design can be categorized as either being naturally or mechanically ventilated. The particular type of barn in any region is often determined by climate and herd. In hot climates, for example, where cows do not need protection from the elements during winter months, a naturally ventilated structure, such as an open walled, shade ramada will suffice, as will another natural design called a "Saudi-style" barn. The type of building best suited to a particular region is usually dependent in part on the type of ventilation and cooling system employed; thus, the two should be considered together.

Natural ventilation

Naturally ventilated buildings rely on wind and thermal buoyancy to provide fresh air to the cows and at the same time remove the stale air. Typically, the naturally driven current of air will enter through a sidewall and exit through an opening along the ridge of the roof and the downwind sidewall. Guidelines for sizing sidewall openings are provided in Table 3. Ridge openings should be at least 2 inches wide per 10 feet of building width for an open ridge and 3 inches per 10 feet of building width if a covered or overshot ridge is used. Openings at both ends of the barn also allow wind to blow through the barn. The expulsion of air through the opening along the ridge (which works on the principle of thermal buoyancy) is called the chimney effect and can usually provide some ventilation when wind speed is minimal. However, this effect is relatively small during the summer when the temperature difference between inside and outside the barn is maintained as low as possible (usually only a degree or two). A relatively steep roof pitch (between 4/12 and 6/12) produces a greater chimney effect than a roof with a shallower slope.[14]

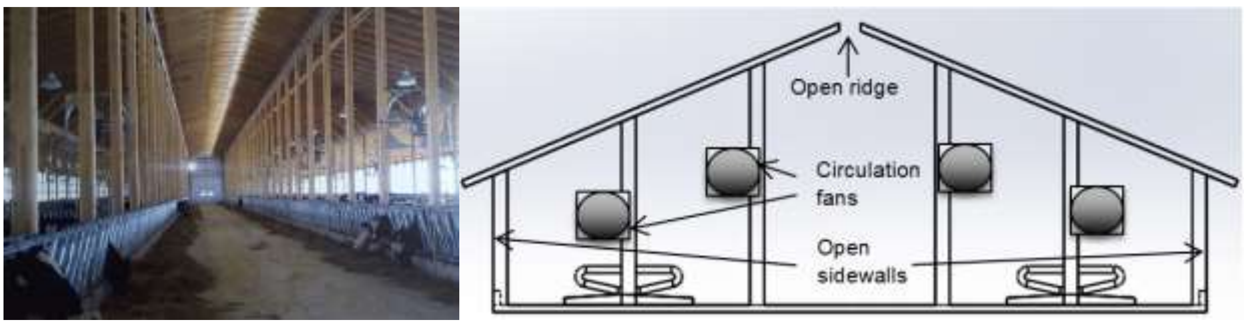

FIG. 4. Photo and diagram of 4-row naturally ventilated barns.

Table 3. Size sidewall openings based on building width and stocking density. Adapted from [14].

Building width (feet)	Stocking density (ft^2/1,000 lbs)	Sidewall opening height (feet)
40	75	10
60	75 (55)	10 (12)
80	75	12
100	75 (55)	12 (14)
120	75 (60)	14 (16)

Because natural ventilation relies primarily on wind for air exchange, it is best to orient the barn so its sidewalls are perpendicular to the prevailing summertime winds. Naturally ventilated barns do not work well if they are built in an area of low wind or to the lee of other buildings or topographic features that obstruct the wind. Obstacles, such as silos, trees, fences, and even certain kinds of crops, disrupt airflow for downwind distances of up to 5 to 10 times their height. In addition, a naturally ventilated barn should be at least 75 feet away from any other building and even farther, depending on the size of the adjacent buildings.[14] Building on a knoll is better than building in a hole as wind tends to blow more frequently on a hill top.

Air velocity in naturally ventilated barns

To increase velocity of the air passing over the cows, circulation fans are often installed in the holding areas, milking stalls, resting stalls and along the feed lines and are usually activated at temperatures above 68 °F. Generally, circulation fans will be placed at every 10 fan diameters, at a minimum of 8 feet above the floor of the holding pen or barn, and at a 25- to 35-degree angle. It should be noted that circulation fans do not typically bring in fresh air, and therefore do not provide a significant amount of ventilation.

High volume, low speed (HVLS) fans are of a larger diameter and mounted on the ceiling. These typically serve as an alternative to smaller high-speed circulation fans and can move a large volume of air very efficiently. However, because of their relatively large size (up to 24 feet), the locations where they can be installed are limited.[14] A study conducted at the University of Wisconsin-Madison found that a 20-foot fan mounted at 16 feet above the feed lane in a 4-row barn could achieve velocities of 200 to 299 fpm over the feed lines, but less than 200 fpm over the stalls.[16] When considering cooling fans, one should design their installation to ensure the air they deliver reaches the cows at the target velocity.

Evaporative cooling in naturally ventilated barns

To enhance the cooling effect fans can produce, low-pressure sprinklers can be added in naturally ventilation barns and holding areas. Sprinklers are often installed at intervals of 6 to 8 feet along the feed lines, as well as overhead in naturally ventilated holding areas. Feedline soakers deliver around 0.35 gal per cycle per position at the feed line[14], and sprinklers apply around 0.025 gal per square foot per cycle in the holding area[17], although these values can vary significantly depending on available water and lagoon space. Half-circle (typically 135-degree) nozzles are best for the feed line to avoid wetting the feed, and 360-degree nozzles are most commonly used in the holding area. High capacity nozzles (such as i-Wobs) reduce the number of nozzles needed in the holding area and therefore are often preferable if there is adequate headroom.[18] Sprinklers should be activated at temperatures above 68 °F and set to run from 1 to 3 minutes every 15 minutes. The time lapse between runs should be reduced by 5 minutes for every 10 °F increase in temperature. The duration of the sprinkler cycle depends on the type of the nozzle and its flow rate.[14] Because the application of water will increase the humidity, it is especially important to maintain high levels of air exchange in areas with these systems.

Mechanical ventilation

Unlike naturally ventilated barns, which rely on wind and thermal buoyancy for air exchange, mechanically ventilated barns rely solely on fans. Such systems provide more consistency and control because the fans and other components are available when needed unlike natural airflow, which can be variable and unpredictable. Another advantage of mechanical ventilation as compared to natural ventilation is that the higher wind speed virtually eliminates flies.[18] However, because mechanical ventilation relies on fans for ventilation during hot, as well as cold periods, it typically consumes more electricity.

Mechanical ventilation systems can either operate under positive pressure, in which fans blow air into the building, or negative pressure, in which fans suck air out of the building. The milking parlor is an interior space that is often ventilated under positive pressure to keep stale air from entering from the holding pen. Otherwise, most systems rely on exhaust fans to move air out of the building. The resulting negative pressure within the barn causes air to enter through the inlets, which are often located on the wall opposite the exhaust fans. In tunnel-ventilated barns (see figure 5a), the air flows parallel to the ridge and perpendicular to the cow (when she is in the stall). In cross-ventilated barns (see figure 5b), the air flows perpendicular to the ridge and parallel to the cow (when in the stall).

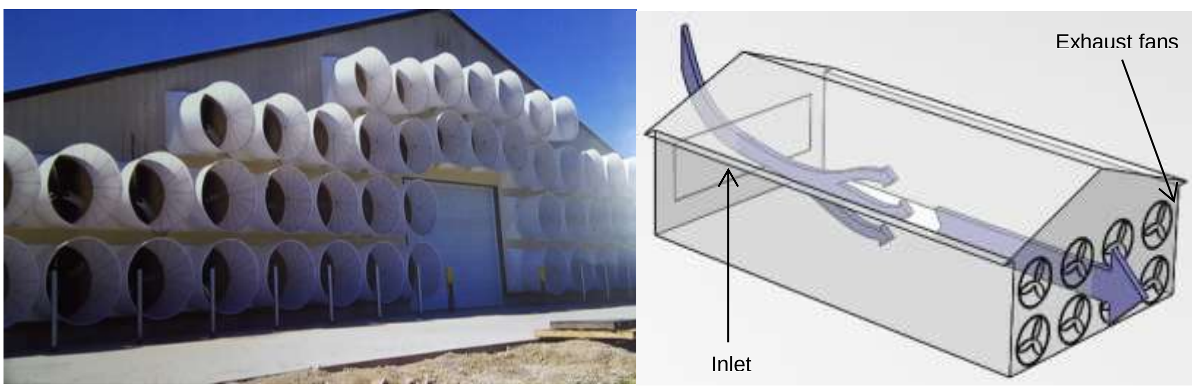

FIG. 5a. Tunnel-ventilated barns

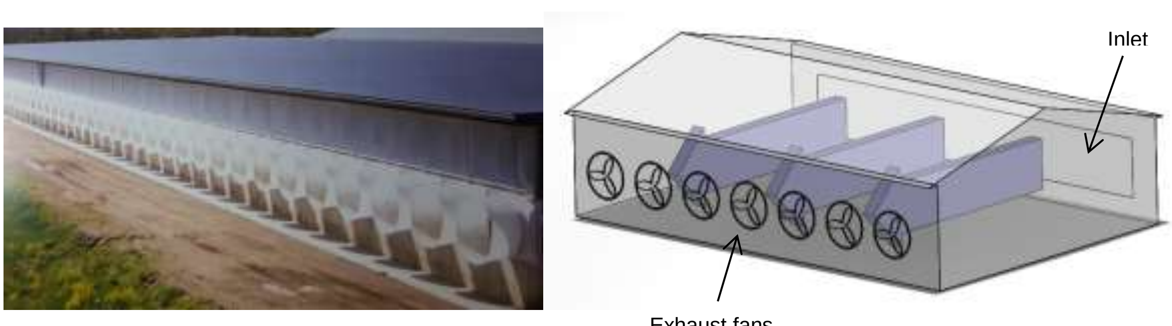

FIG. 5b. Cross-ventilated barns

Air velocity in mechanically ventilated barns

Mechanical ventilation is most effective when the barn’s design produces a high air velocity at cow level. This effect can be difficult to achieve, however, because air always takes the path of least resistance, and in a dairy barn such a path is not through row after row of cows and stalls, but rather through walkways and equipment lanes or through the space above cow level. Thus, to direct air back down toward the animals, baffles should be placed at optimal locations in the open upper spaces of the barn and perpendicular to airflow. Each baffle should span from one sidewall to the other; otherwise, much of the air pushed through the space by the fans simply passes around the ends rather than under the baffle. The lower the baffle, the more effectively it increases the velocity of the air flowing under it. However, the height at which the baffle is installed is limited by the height of equipment that must pass below, especially the feed mixer. The relationship between baffle height, cumulative fan capacity, and air velocity is shown in equation 4.

Equation 4:

$$Q = V_{baffle} \text{ x } length_{baffle} \text{ x } height_{baffle}$$

where Q is the cumulative fan capacity (CFM), $length_{baffle}$ (ft) is the length of the baffle, $height_{baffle}$ (ft) is the height of the baffle above the floor, and V_{baffle} (fpm) is the air velocity under the baffle. Note that if there is no baffle, $height_{baffle}$ is replaced with the height of the ceiling, and a much higher flow rate will be necessary to move air at the target velocity through the entire cross-section of the barn.

FIG. 6. Slanted baffle in cross-ventilated barn. Higher air velocity is often observed in cross alleys where baffles are higher to allow equipment to pass underneath.

Tunnel or cross

Cross ventilation has become the preferred system in newly constructed barns housing large herds. Baffles are more effective in cross-ventilated barns than in tunnel-ventilated barns because they are placed over the rows (as opposed to perpendicular to the rows), more effectively directing air to cow level. Another advantage of cross ventilation is that because the cows are oriented parallel to the airflow, upstream cows block less air from reaching downstream cows than in tunnel-ventilated barns. On the other hand, tunnel ventilation is a good choice when an existing, naturally ventilated barn does not meet the ventilation requirements by depending on wind alone. Tunnel ventilation can provide air velocity more economically than a cross ventilation system in barns of fewer than 8 rows because there is a smaller cross-sectional area (unless the barn is shorter than it is wide), and fewer fans are needed.

Evaporative cooling in mechanically ventilated barns

Evaporative cooling the air before it reaches the cow (indirect cooling) is a relatively common way to augment the system used to mechanically ventilate a barn, employing cooling pads or high-pressure misters. Both systems vaporize water into the entering air before it reaches the cow, thus cooling the air and increasing its RH. Feedline soakers can also be used in mechanically ventilated barns, but special care must be taken so the airflow does not blow the water droplets onto the feed.

Static pressure

Static pressure refers to the difference between the pressure within the dairy housing produced by fans and the pressure of the surrounding atmosphere. This pressure difference is due to the friction created by the molecules of air as they move along the barn's walls and around other obstacles in their path, and it is usually measured in inches of water. Inlets, baffles, cows, stalls, and shutters all contribute to produce a greater resistance to airflow and thus a greater static pressure. As static pressure increases, each fan has to move air against a greater resistance, and the fan's capacity decreases. Consequently, to avoid installing an undersized ventilation system, ventilation fans should be selected based on their performance at the pressure they will be operating. Typically, 0.1 inches (of water) of static pressure is used as a baseline when selecting fans for average sized tunnel-ventilated buildings, while 0.15 inches should be used for larger tunnel-ventilated barns[13] and 8-row (4-baffle) cross-ventilated barns.[19]

The actual static pressure of a ventilation system may be significantly higher depending on the specifics of a design, with measurements around 0.25 inches not uncommon in large barns with baffles and evaporative pads.[18] Evaporative pads alone can add a significant amount of static pressure, often between 0.05 to 0.10 inches, depending on the velocity of the air passing through them.[20] Higher velocity through the inlet results in higher static pressure. If evaporative pads are used, airflow through the inlets should be limited to 300 to 400 fpm to limit static pressure, but the airflow can be as high as 600 to 800 fpm if no pads are used.[21] Because baffles restrict airflow (to increase air velocity over the cows), they are often responsible for the bulk of the static pressure inside a barn. The higher the air velocity under the baffle, the greater the drop in pressure across it. The static pressure per baffle can be estimated using equation 5.[19]

Equation 5:

$$S.P._{baffle} = (V_{baffle} / 4000)^2$$

where $S.P._{baffle}$ (inches of water) is the static pressure drop resulting from the baffle and V_{baffle} (fpm) is the velocity under the baffle.

The total static pressure can then be estimated by summing the static pressure of the inlet (including the cooling pads) and all of the downstream baffles. For example, if the velocity under the baffle is 600 fpm, then from equation 5, the static pressure per baffle equals 0.0225 inches. If we assume the cooling pad adds 0.05 inches of static pressure, a barn with 4 baffles would have a static pressure drop of 0.14 inches and a barn with 8 baffles would have a static pressure drop of 0.23 inches. This method can, however, underestimate the total static pressure because it does not include the resistance produced by the cows, stalls, dirty shutters, wind blowing against the fan or other obstructions.

Short circuiting

If there is any opening closer to the exhaust fans than the inlets on the opposite side of the barn, some air will preferentially enter through the closer opening, leaving zones of low-velocity airflow between the opening and the designated inlets (see figure 7). This is known as "short circuiting," and it is often caused by open doors, breezeways, open shutters on non-operating fans, and other design issues.

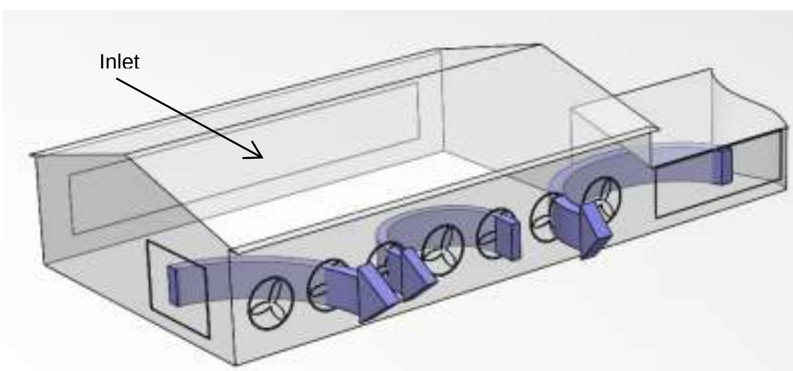

FIG. 7. Short circuiting caused by an open door (left), non-operating fan with open shutters (center), and breezeway (right), resulting in minimal ventilation for cows in the stalls.

Milking center ventilation and cooling

Parlor

Parlor ventilation usually employs positive pressure to keep stale air from entering the parlor from the holding area. The air-exchange rate in mechanically ventilated parlors is often higher than in the barn to remove excess moisture, improve hygiene, and provide air velocity, often on the order of 3,000 to 4,000 CFM per cow. In addition, high ventilation rates in the parlor also provide additional fresh air to cows in the holding area. Circulation fans are commonly used to provide additional mixing and air velocity, especially in larger parlors. Some parlors are naturally ventilated with large sidewall openings that serve as inlets and outlets. However, this option should only be applied at sites with consistent wind.

FIG. 8. Positive pressure fans blowing air into milking parlor.

Holding area

The holding area is typically considered a priority for cooling because of the high animal density, resulting in higher temperatures and humidities than in the barn. The majority of holding areas are naturally ventilated and provide supplemental cooling by means of circulation fans and low-pressure sprinklers. Circulation fans are placed in rows facing away from the parlor to avoid blowing hot, dirty air into the parlor (see figure 9 below). Due to intense cooling needs in the holding area, fans are spaced closer together than over the stalls or feedlines. For example, rows of 36-inch fans should be spaced every 15 to 20 feet, and 10 feet side by side, and rows of larger panel fans (52 to 54 inches) should be spaced every 25 to 30 feet and 15 feet side by side.[18] In naturally ventilated holding areas with poor wind, circulation fans can be placed along an open sidewall and angled into the holding area to provide additional fresh air. For guidelines on water application in the holding area, see the section on naturally ventilated buildings. Because cows do not spend much time in the rear portion of the holding area, priority should be given to the three-fourths closest to the parlor. In addition to providing cooling, it is always important to try to minimize the time cows spend in the holding area. As seen in Table 1, holding cows for even a relatively brief amount of time in a high THI environment can reduce milk production significantly.

FIG. 9. Circulation fans and sprinklers over holding area.

Fan selection

Regardless of the type of ventilation system implemented, it is important to use efficient fans and maintain them with regular service. The efficiency of a fan is the volume of air it moves per unit of electricity, which is usually measured in CFM per watt. This standard performance metric is commonly obtained by testing the fan at the Bioenvironmental and Structural Systems Laboratory (BESS Lab), located at the University of Illinois.[22] BESS Lab results are accredited and provide a non-biased comparison of the performance of fans built by different manufacturers. When choosing exhaust fans, the static pressure at which they will be operating should always be considered. Some fans perform much better at higher static pressures than others. In general, larger fans are more efficient and fans with a smaller tip clearance perform better against static pressure. Poor maintenance can also reduce a fan's efficiency to anywhere from 40% to 80% of the BESS lab tested performance values.[23] To avoid poor performance, belts and bearings should be serviced regularly. Consider whether these components are easily accessible when selecting fans. Belt tensioners can also help to reduce belt maintenance.

In recent years, variable-frequency drives (VFDs) have been installed in many HVAC systems to improve energy efficiency. A number of agricultural fans are VFD compatible, and thus the producer intending to install a ventilation or cooling system is often faced with the question of whether or not VFD drives are worthwhile. VFDs save energy by running at a lower speed at conditions where the motor's full capacity is not needed. In dairy barns, this would be under relatively low heat stress conditions (i.e. THI < 75). For tunnel- and cross-ventilated barns, the air velocity can be adjusted without VFDs by turning strategically selected fans off based on the desired airflow rate. Circulation fans, on the other hand, should not be selectively turned off and require VFDs to adjust the air velocity at cow level. VFDs also place less stress on the motor during start up, which is an advantage because it results in less mechanical wear.

Economics of cow cooling

One approach to assessing the economics of cow cooling is to minimize the total costs of heat stress, including the cost of mitigation. A 2003 economic analysis[1] used weather data for each dairy region of the continental United States to estimate the total costs of heat stress under several intensities of heat abatement: minimal, representing shade and ventilation without air velocity on the cow; moderate, representing ventilation and circulation fans only; high, representing ventilation, circulation fans and sprinklers; and intense, representing ventilation and high-pressure evaporative coolers mounted on fans. Each cooling intensity was assigned a capital cost (which was annualized) and an operating cost for each heat stress hour, as well as a function to estimate the reduction in apparent THI it would provide at varying levels of temperature and RH. The results indicated that fans and sprinklers would reduce the total costs of heat stress to the greatest extent in all states besides Arizona, Kansas, New Mexico, Oklahoma, and Texas, where the additional costs of the intensive heat abatement strategy were determined to be worthwhile. The study presents the total economic losses from heat stress under optimal heat abatement intensity and the total economic losses under minimum heat abatement for dairy cows. Table 4 presents the optimal cooling method for several dairy states and the percent savings from implementing that method as compared to the estimated costs of heat stress under minimal heat abatement, where savings is defined by equation 6.

Equation 6:

Savings [%] = 100 – [(cost with optimal heat abatement)/(cost under minimal heat abatement)] x 100

Table 4. Reduction in annual total costs of heat stress under the optimal heat abatement intensity compared to under minimal heat abatement [1].

State	Optimal Strategy*	Annual Savings (%)	State	Optimal Strategy*	Annual Savings (%)
California	High	31	Minnesota	High	40
Wisconsin	High	41	New Mexico	Intense	48
New York	High	39	Michigan	High	38
Pennsylvania	High	43	Texas	Intense	46
Idaho	High	42	Washington	High	31
Arizona	Intense	60	Florida	High	52

*Of the strategies that the study considered

Research and Emerging Technology

While the economic data in the previous section shows investments in cooling generally yield quite high returns, the results for each cooling system and herd will vary. For example, this analysis did not consider the various types of ventilation systems discussed in this paper (i.e. tunnel, cross, natural), the settings of the control system, the costs of the housing needed for each type of system, or choice of higher versus lower quality fans. These areas require further research.

In addition, none of the systems currently available completely eliminate the threat of heat stress, especially in hot, humid climates where evaporative cooling has a low cooling potential and air velocity alone cannot sufficiently dissipate heat. Therefore, research aimed at developing new cow-cooling methods is underway. One alternative, as an example, involves using conductive cooling mattresses upon which a cow can recline and dissipate excess body heat. The system, which is being developed at University of Wisconsin-Madison, uses ground water or chilled water circulated through a mattress located in the stall. When the cow is reclining, the relatively cool water passing through the mattress draws heat away from the animal's body through the thin rubber layer on top of the mattress.[24]

It is also apparent that much of the energy used to operate mechanical ventilation systems is wasted because the air flows across spaces not occupied by the cows, such as walkways, equipment lanes, and all the space above cow level. Improvements in system and structure design could improve the overall efficiency of these systems (some dairies have placed freezer strip curtains in equipment lanes to partially block airflow). A garage-style door installed or curtain above the lane could lower to produce the same effect and be raised to allow equipment to pass.

Conclusions

Heat stress is an important financial consideration for dairy farmers and heat stress mitigation has proven to be worthwhile across the United States. Certainly, if global temperatures and dairy productivity continue to increase, the costs of heat stress and need to mitigate it will also increase. The guidelines herein should help producers estimate the costs of heat stress relative to various states within the US and give an overview of the available heat abatement options. While it is clear that investments in cooling are economic, the challenge becomes how to best select and design a system. The companion Climate-Specific Guides are intended to describe best practices for choosing the most adequate system and optimizing its functionality for a particular herd in that climate.

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