Heat stress alleviation for dairy cows housed in an open-sided barn by cooling fan and perforated air ducting (PAD) system

Xie Lina[1,2,3], Wang Chaoyuan[1,2,3*], Ding Luyu[1,2,3], Gui Zhiyuan[1,2,3], Zhang Lu[1,2,3], Shi Zhengxiang[1,2,3], Li Baoming[1,2,3], Jia Chuntao[4]

(1. *Department of Agricultural Structure and Bioenvironmental Engineering, College of Water Resources and Civil Engineering, China Agricultural University, Beijing 100083, China*; 2. *Key Laboratory of Agricultural Engineering in Structure and Environment, Ministry of Agriculture, China Agricultural University, Beijing 100083, China*; 3. *Engineering Research Center on Animal Healthy Environment, Beijing 100083, China;* 4. *Hailin Dairy Farm, Shigezhuang Town, Tianjin 301718, China*)

Abstract: Curtain-sided barns with circulation fans above stall are commonly used to house dairy cows in China. Many farms equipped with circulation fans are unable to provide appropriate cooling, especially for the naturally ventilated shed, which can result in decreasing feed intake and milk production. For alleviating heat stress and improving animal comfort, a system consisting of an air cooler and a 30 m perforated air duct (PAD) was integrated to evenly distribute cooling air. The air was cooled by underground water and delivered to targeted zones above stall bed. The system was evaluated in an open sided dairy barn in Tianjin, China. For the stalls equipped with PAD system, air velocity reached above 1.1 m/s at 0.5 m height plane of the stall space, and was more uniformly distributed. Compared to the stalls equipped with circulation fans, the PAD system lowered air temperature by 1.5 ℃, and increased relative humidity by 8.1%. On average, Temperature Humidity Index (THI) and Equivalent Temperature Index (ETI) were decreased by 0.5 and 0.6, respectively. After a 15 days' operation of the system, rectal temperatures of the treated dairy cows were significantly lowered. The results also showed that the cows under PADs had a higher milk production. These findings suggest the PAD can be an effective cooling alternative for naturally ventilated dairy barns to alleviate heat stress.

Keywords: dairy cow, heat stress, perforated air duct, cooling fan, naturally-ventilated barn

DOI: 10.25165/j.ijabe.20171006.3135

Citation: Citation: Xie L N, Wang C Y, Ding L Y, Gui Z Y, Zhang L, Shi Z X, et al. Heat stress alleviation for dairy cows housed in an open-sided barn by cooling fan and perforated air ducting (PAD) system. Int J Agric & Biol Eng, 2017; 10(6): 1–10.

1 Introduction

Milking dairy cows can adapt to a wide range of climatic condition without significant decline in milk production. However, hot and humid climate easily leads to heat stress for dairy cows, which typically increases respiration rate, decreases feed intake and alters feeding behavior, and ultimately results in declines of milk yield with reduced production efficiency[1-6]. Furthermore, heat stress in summer lowers the fertility

---

Received date: 2016-12-14 **Accepted date:** 2017-07-28

Biographies: Xie Lina, Research Assistant, research interests: dairy environmental control, Email: xlina@cau.edu.cn; **Ding Luyu,** PhD, Assistant Professor, research interests: dairy environment and welfare, Email: ding8877@126.com; **Gui Zhiyuan,** Graduate candidate, research interest: animal environmental control technique, Email: gzy@guoxn.com; **Zhang Lu,** Graduate candidate, research interests: thermal environment of dairy housing, Email: 1032076033@qq.com; **Shi Zhengxiang,** PhD, Professor, research interests: dairy environment and management, Email: shizhx@cau.edu.cn; **Li Baoming,** PhD, Professor, research interests: animal housing, environment and equipment, Email: libm@cau.edu.cn; **Jia Chuntao,** Farm Manager, research interest: dairy production management, Email: hailinyangzhichang@126.com.

***Corresponding author: Wang Chaoyuan,** PhD, Associate Professor, research interest: animal environment control and welfare. Key Laboratory of Agricultural Engineering in Structure and Environment, Ministry of Agriculture, China Agricultural University, Beijing 100083, China. Tel: +86-10-62736698; Email: gotowchy@cau.edu.cn.

rate and consequently affects the reproductive performance of dairy cows as well[7-9].

In order to relieve heat stress, strategies from primary non-evaporative cooling (conductive, convective and radiation) to evaporative cooling are widely investigated and applied to different housing system in varied climates[10-16]. Tucker et al.[17] found a positive relationship between shade usage and ambient solar radiation in all treatments, and a significant reduction of body temperature of dairy cows under shading. Compared to conventional fans, high volume low speed fans were estimated to be more effective in saving the energy in a freestall barn[18]. With the increasing of ambient temperature, non-evaporative cooling becomes less effective. Thus the cooling system combining mixing fans and sprinklers or foggers is broadly applied in dairy barns, and has been proved to be one of the most effective methods in alleviating heat stress for dairy cows[14,19-24]. However, cooling efficiency of the system strongly depends on the relative humidity (RH) of the ambient air, and its effectiveness is compromised under humid climate. Brouk et al.[25] reported that temperature humidity index (THI) could be only lowered by less than 10% with an evaporation cooling system under high RH conditions.

Climates in China vary greatly from different zones. It is typically characterized by hot and humid weather in summer even in northern China, which represents a really big challenge for dairy production. In China, open or curtain sided barn with outdoor excising yard where the animals may freely access to is very typical for housing dairy cows. A cooling system combining sprinklers or foggers and circulation fans above stall is currently used, which is normally unable to provide appropriate cooling in hot and humid days, and can result in a fairly big reduction in feed intake and milk production[24].

Dairy cows usually rest for around 10-14 h a day on the beds in the freestall system. In order to improve the thermal condition for comfort and alleviate heat stress of the animals, a cooling system consisting of an air cooler and a perforated air duct (PAD) was integrated to directly distribute cooled air into the stall space. In this paper, a field test on such cooling system was conducted, and its performance was evaluated via thermal environment assessment and the cow production performance investigation.

2 Materials and methods

2.1 Dairy cow barn

Field tests of the cooling system were carried out in a commercial dairy farm during the period of July 27 to August 20, 2013 in Tianjin City, China. The farm had two naturally ventilated barns to house milking cows, and a milking parlor was located in between the two barns. The tests were conducted in the northern barn, which was 174 m in length, 27 m in width, and oriented east-west. An opening was set along the ridge of the curtain-sided barn, and the height of the curtain was adjustable depending on the climates to regulate indoor thermal environment. During the experimental period, the curtains in the sidewalls were all rolled up, making the barn fully open in two sides. The barn was connected to a fully open exercising yard with a width of 10.0 m in the south, where the cows may have a free access to it. The barn was divided into four sections by the central feeding (drive-through) alley and a cross alley to milking parlor, which was perpendicular to the feeding alley (Figure 1). In each section, two-row head to head freestalls were equipped, and the size of the stall was 1.2 m (width) by 2.4 m (length).

The experiment was conducted in the southwestern section (Section I) of the barn with a total of 90 freestalls, and 86 Holstein milking cows were housed during the test. There were two groups of freestalls in this section, which were separated by a 12 m cross alley. Two water troughs were placed on the cross alley for the cows. The west one, where 50 stalls were placed, was installed with the air cooler and perforated air duct cooling system as a treatment area, and the east with 40 stalls was as a control area.

In the control area, circulation fans were hung about 2.5 m above the floor surface at an interval of 18 m to accelerate the air speed for the resting cows on the stalls (Figure 1). Sprinklers mounted on the feeding fences combining the circulation fans hanging above were applied to cool all the animals during feeding.

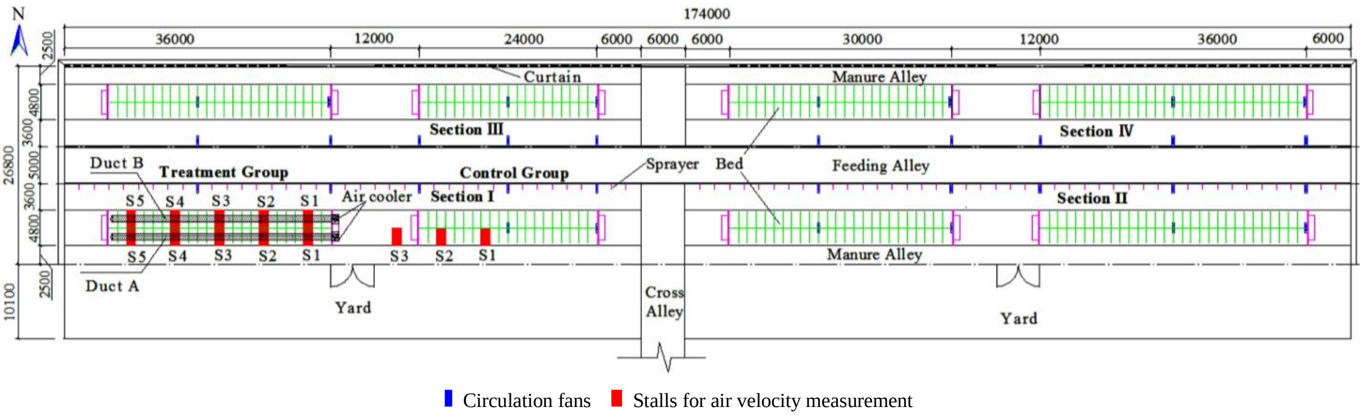
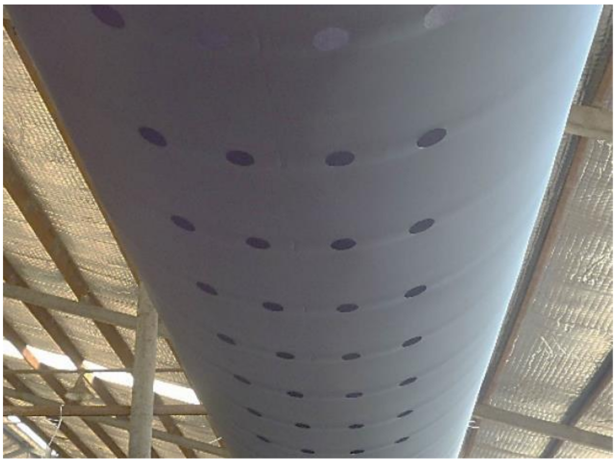


Figure 1 Layout of the open-sided dairy barn surveyed, being divided by the feeding alley and pathway to milking parlor into 4 sections (All dimensions are in mm)

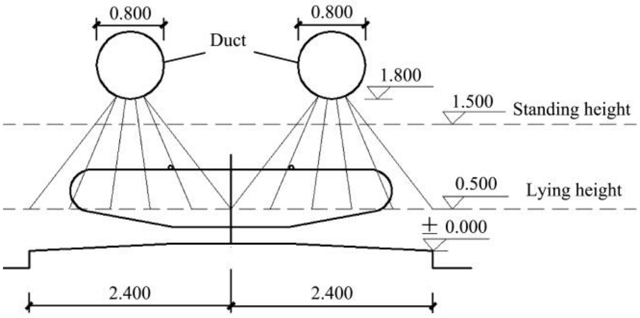
2.2 Air cooler and PAD cooling system

A unit of the surveyed cooling system mainly consisted of a PAD and an air cooler, which worked under a similar mechanism of the evaporative pad cooling system. The configuration of the air cooler was 1.17 m (width) ×1.17 m (length) ×0.96 m (height), with a power of 1.5 kW, and its maximum airflow rate was 20 000 m^3/h at zero static pressure. Underground water from a well in the farm was pumped and circulated inside the air cooler. The PAD made by permanent flame retardant polyester (Figure 2), a light-weighted material, was 30 m long and 0.8 m in diameter, connected to the outlet of the air cooler for conveying and dispersing cooling air to body surfaces of the dairy cows when resting on the stalls. Each row of the stalls in the treatment area was installed with a PAD, and the lower edge of the duct was 2.0 m above the bedding surface.

In each PAD (Duct A and Duct B), four-row of orifices with different diameters along the length of the duct were designed. Distributions of the orifices and its specification as well as the airflow rate of the system are shown in Figure 2 and Table 1, respectively. For Duct A, the diameter of the outer orifice was 3.5 cm, and 3.2 cm for inner orifice, while they were 2.6 cm and 2.3 cm for Duct B. Theoretical airflow rates were around 14 680 m^3/h and 14 050 m^3/h for the two PADs, respectively. The designed air velocities at 0.5 m height above the bedding, which was documented as the height of the milking cows when lying down[26], were 1.0 m/s and 1.5 m/s for PADs A and B, respectively. And the cooling air jetted from the duct was expected to cover the entire area of the bedding surface (Figure 2).



a. Distribution of the orifices



b. Air jetting from the duct to the resting spaces of the head to head stalls for dairy cows (dimension in m)

Figure 2 Schematics of the PAD system

Table 1 Specifications of the orifices, theoretical jetted air velocity and airflow rates of two PADs

PAD	Jetted air velocity /m·s^{-1}	Orifice diameter /mm	Orifice numbers	Orifice spacing /m	Airflow per orifice /m³·h^{-1}	Airflow /m³·h^{-1}
A	8.25	35	140	0.214	28.6	14 680
		32	140	0.214	23.9	
		32	140	0.214	23.9	
		35	140	0.214	28.6	
B	8.25	26	250	0.120	15.8	14 050
		23	250	0.120	12.3	
		23	250	0.120	12.3	
		26	250	0.120	15.8	

2.3 Data collection

2.3.1 Temperature, RH and air velocity measurement

Temperature and RH inside the barn were automatically monitored at an interval of 1 min by using HOBO data loggers (Model U14-001, Onset Computer Corporation, MA, USA), which were installed on the neck rails of the stalls, and 1.2 m above the bedding. Measurement range and accuracy of the sensor were -20℃ to 50℃, 0.2℃ for temperature, and 0 to 100%, ±2.5% for RH, respectively. Air velocities of the stall space and inside PAD as well as the air temperature inside PAD were measured by using a handled anemometer (Model KA41L, Kanomax, Japan). The accuracy for temperature and RH measurement were 0.5℃ and ±3% measured value, respectively.

In order to specify spatial distribution of air velocities, thirteen stalls (S1-S5, Figure 1) were selected for measurement including five under each PAD in treatment area and three under the circulation fans in the control area. The measured stall was at an interval of 6 m. For each of the stall, air velocity distributions were determined at three planes at the height levels of 0.5 m (lying height of the cow), 1.0 m and 1.5 m (standing height) above the bedding. At each plane, air velocities at 28 locations were sampled in a stall area of 1.2 m by 2.4 m. The measurements were replicated three times at each sampling location, and the values were averaged as the air velocity of each point.

Water temperature in air cooler was measured using a thermometer (Model Temp-5, Oakton, USA) with a measuring accuracy of 0.2℃. Air temperature, RH and velocity outside the barn were automatically recorded at an interval of 1 min using a HOBO weather station (Model U21, Onset, MA, USA), and the accuracy were ±0.2℃, ±3.5% and ±0.5 m/s, respectively.

2.3.2 Rectal temperature and respiration rate measurement

For each area, five dairy cows resting on the stall for more than 10 min were selected to measure the rectal temperature (*Tr*) and respiration rate (*RR*), and the measurement started at 16:00. *Tr* was sampled using a handled thermometer (Model Temp-5, Oakton, USA), and *RR* was artificially determined.

2.3.3 Milk yield recording

Milk yield of the cows was automatically recorded by the milking system (Afimilk Ltd., Israel), and the data was used for production comparison.

2.4 Data treatment and analysis

2.4.1 Distribution of air velocity at different height planes

In order to assess the uniformity and distribution of air velocities in the stall spaces, coefficient of non-uniformity (K_v) was applied in this project. A smaller K_v indicates that air velocity is more evenly distributed in the plane. K_v is determined by using the following equation[27]:

$$K_v=\frac{\sigma_i}{\bar{v}}=\left.\frac{\sqrt{\sum(v_i-\bar{v})^2}}{n}\middle/\frac{\sum v_i}{n}\right. \tag{1}$$

where, σ_i is root mean square error of air velocity, m/s; $\bar{v}$ is average air velocity of all the locations measured in the plane, m/s; v_i is air velocity at a location, m/s; and n is the number of the locations for air velocity measurement.

2.4.2 THI and equivalent temperature index (ETI)

THI and ETI predicted by meteorological variables are the common indicators to evaluate the degree of thermal stress for animals, and both indexes were also applied in this research to assess the performance of cooling effect of PAD system. THI calculation is based on[28]:

$$THI=0.81t+(0.99t-14.3)RH+46.3 \tag{2}$$

where, THI is temperature and humidity index, dimensionless; t is the dry bulb temperature, ℃; and RH is the relative humidity, %.

Compared to THI, ETI is a commonly less used alternative, while it incorporates the effect of air velocity along with air temperature and RH. ETI is considered to have outperformance in evaluating heat stress for dairy under hot and humid climates[29]. Baeta et al.[30] gave the following equation to calculate *ETI* by using dry bulb temperature (t, ℃), RH (%) and air velocity (v, m/s) as:

$$ETI=27.88-0.456t+0.010754t^2-0.4905RH+0.00088(RH)^2 +1.1507v-0.126447v^2+0.019876tRH-0.046313tv \tag{3}$$

Baeta et al.[30] reported the alert levels of dairy cattle based on *ETI* were safe (16-26.5), caution (26.5-31.5), extreme caution (31.5-37.5), danger (37.5-43.5) and extreme danger (>43.5). While based on a survey carried out in Brazil, Silva et al.[29] suggested four alert categories using *ETI*, including safe (<30), caution (30-34), extreme caution (34-38) and danger (>38) for dairy cattle in tropical regions.

2.4.3 Statistical analysis

Statistical analyses were conducted using SPSS software (version 20.0; IBM, Armonk, NY, USA). Results were expressed as Mean±SD, and statistical significance was based on $p<0.05$.

3 Results and discussion

3.1 Performance of the PAD system

3.1.1 Temperature of the air jetted from PAD

Before being pumped into the air cooler, underground water from a well was stored in an outside tank, and the water temperature in air cooler changed within 20℃-27℃ during the experimental period. Results showed that the temperature of the air emitted from the duct was significantly correlated with water temperature ($R^2>0.87$). During the test, water temperatures of air coolers A and B were slightly different, resulting in a difference of the air temperature going throw the PADs. In summer time, relative lower air temperature of PAD system was able to achieve a better cooling effect and increased thermal condition of the animals conform. Normally, the temperature of the air emitted from the duct increased as increasing of the distance from the air cooler (Figure 3). Air temperatures from the beginning to the end of the duct, were averagely raised by 1.7℃ and 2.2℃ for PADs A and B, respectively.

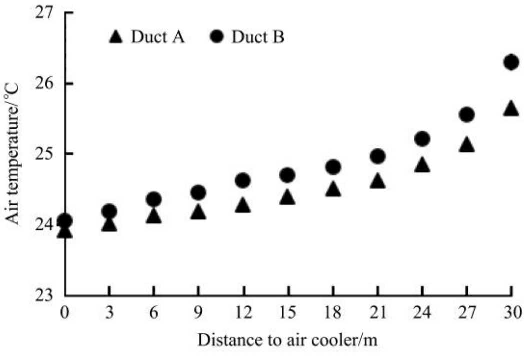


Figure 3 Temperature of the jetted air from the Ducts A and B, increased as the increasing of the distance to air coolers

In general, lower temperature of the incoming water to the air cooler was helpful in having a better cooling effectiveness. As the jetted air temperature increased along the length of the duct, the cooling effect was compromised at the end of the PAD, which constrains the length of the PAD system. At the end of the system, both the airflow rate and air temperature were adversely affected, making the system could not achieve the expected cooling effect.

3.1.2 Velocity of the air jetted from and inside the Ducts

Air velocities in the center of the ducts and jetted from orifices versus the distance to the air cooler were plotted in Figure 4. Longitudinal air velocities in the center of the ducts decreased from 10-12 m/s to less than 0.5 m/s from the beginning to the end. Air velocities of the air jetted from PAD systems were kept relatively stable, varying from 11 m/s to 15 m/s. The size of the orifice impacted the jetted air velocity, while no significant difference was found. Commonly, jetted air velocity from the ducts was related with the arrays and sizes of the orifices. The smallest orifice had the highest jetted speed, and vice versa.

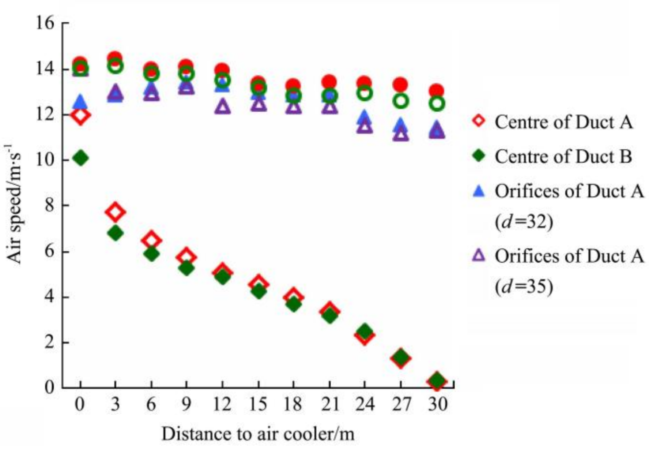


Figure 4 Velocities of the air inside and jetted from Ducts A and B, decreased along the length of the ducts

3.2 Spatial distribution of air velocities above the stalls

3.2.1 Air velocity distribution

As reported, dairy cows rest 12 h a day or even longer[26], among which the majority is for lying on the stalls. Thus a good spatial thermal environment at the stall space, air velocity at lying height level in particular, is critical in improving thermal comfort of the animals, and consequently beneficial to milk production. Air velocities at three different height levels (0.5 m, 1.0 m and 1.5 m) of the stalls in the control and treatment areas are shown in Table 2. In hot climates, recommended minimum wind speed cross the body surface of the dairy was 1 m/s. At the lying height of 0.5 m, air velocities in the stall space under the Duct A and Duct B were averaged at 1.1 m/s and 1.3 m/s, which were close to theoretical values and satisfied the minimum requirements recommended. The velocities distributed above the stall were slightly bigger than the control area with circulation fans (p>0.05). Field test also found that air velocity above the bedding was easily affected by the wind outside the barn because of the open system, and Duct B, closer to the feeding fence, was also impacted by the circulation fans hung above.

Table 2 Air velocities at three different heights above stalls in treatment and control areas, m/s

Stall #	1.5 m height			1.0 m height			0.5 m height		
	Duct A	Duct B	Control	Duct A	Duct B	Control	Duct A	Duct B	Control
S1	0.9 ± 0.3^{ab}	1.8±0.3	0.8±0.5	0.9±0.2	1.4±0.3	0.8±0.2	0.9±0.3	0.9 ± 0.1^{b}	0.7±0.4
S2	1.4 ± 0.1^{a}	1.6±0.1	1.0±0.5	1.3±0.0	1.4±0.1	1.2±0.6	1.0±0.1	1.4 ± 0.0^{a}	1.8±1.1
S3	1.1 ± 0.0^{ab}	1.7±0.2	1.0±0.1	1.1±0.1	1.5±0.4	0.7±0.2	1.0±0.1	1.5 ± 0.1^{a}	0.4±0.1
S4	1.1 ± 0.0^{b}	1.8±0.0	-	1.1±0.1	1.4±0.1	-	1.2±0.3	1.3 ± 0.0^{a}	-
S5	0.9 ± 0.1^{b}	1.5±0.2	-	1.2±0.1	1.3±0.2	-	1.2±0.3	1.2 ± 0.1^{a}	-
Mean ± SD	1.1±0.2	1.7±0.1	0.9±0.1	1.1±0.1	1.4±0.1	0.9±0.3	1.1±0.2	1.3±0.2	1.0±0.7

Note: In the same column, values with different superscripts are significant difference at p<0.05 level.

Compared to Duct A, air velocities at both heights of 1.0 m and 1.5 m were greater for the stalls under Duct B, due to the difference in array and size of orifices. At these two heights, air velocities were also significantly different from the control area (p<0.05). Generally, air velocities of Duct A were all approximately 1.1 m/s at the three different heights, which were relatively stable in the space, while for Duct B they gradually decreased from 1.7 m/s to 1.3 m/s at the heights from 1.5 m to 0.5 m.

3.2.2 Air velocity uniformity

Table 3 shows the coefficient of non-uniformity (K_v) of the air velocities in the spaces of the stalls investigated. Duct B had the smallest K_v, while it was the biggest for the stalls equipped with circulation fans in the control area, representing Duct B had the best uniformities of air velocity and the control had the lowest. At the heights of 1.0 m and 1.5 m, no significant difference was found for the treatment and the control. While at the lying height of milking cows (0.5 m), K_v for Duct B was dramatically smaller, compared to Duct A and circulation fans, indicating the air velocities for the stall spaces underneath Duct B was much more uniformly distributed.

Table 3 Coefficient of non-uniformity (K_v) of different height levels above stalls under Duct A, Duct B (treatment) and circulation fans (control)

Stall #	1.5 m height			1.0 m height			0.5 m height		
	Duct A	Duct B	Control	Duct A	Duct B	Control	Duct A	Duct B	Control
S1	0.60±0.23	0.36 ± 0.03^{ab}	0.44 ± 0.16^{b}	0.51±0.14	0.47 ± 0.01^{a}	0.44 ± 0.11^{b}	0.33±0.08	0.34 ± 0.07^{a}	0.41±0.06
S2	0.46±0.50	0.43 ± 0.02^{a}	0.50 ± 0.07^{a}	0.37±0.03	0.32 ± 0.06^{bd}	0.39 ± 0.12^{b}	0.36±0.02	0.22 ± 0.01^{bc}	0.32±0.26
S3	0.60±0.06	0.32 ± 0.04^{b}	0.82 ± 0.12^{a}	0.50±0.11	0.36 ± 0.08^{b}	0.83 ± 0.28^{a}	0.40±0.12	0.24 ± 0.06^{bc}	0.51±0.04
S4	0.70±0.05	0.32 ± 0.04^{b}	-	0.50±0.11	0.26 ± 0.01^{cd}	-	0.33±0.05	0.18 ± 0.03^{c}	-
S5	0.69±0.13	0.42 ± 0.09^{a}	-	0.40±0.03	0.39 ± 0.04^{ab}	-	0.27±0.05	0.30 ± 0.06^{ab}	-
Mean ± SD	0.61±0.10	0.37±0.05	0.59±0.20	0.46±0.07	0.36±0.08	0.55±0.24	0.34 ± 0.05^{A}	0.26 ± 0.06^{B}	0.42 ± 0.10^{A}

Note: Values with different superscripts are significant difference at p<0.05 level.

3.3 Effects of PADs on thermal environment of stall spaces

3.3.1 Air temperature, RH and THI

Field test was carried out in the hottest days in the summer of 2013. Usually, THI inside the barn reached above 80 before 10:00 and lasted around 10 h a day to 20:00, suggesting heat stress for the cows was under a danger level during the period[28]. The highest THI commonly occurred at 14:00-16:00, while it was seldom excess 90, which was treated as the critical point of an emergency state.

Average thermal indexes (air temperature, RH and THI) for the period of 0:00 to 20:00 inside the barn during the field test are shown in Table 4. Results showed that the ambient temperature averaged at 28.1℃ during the test, which were greatly higher than air temperature of the treated stall spaces under the Ducts A and B. Compared to the control area, air temperatures of the stall spaces equipped with Ducts A and B were decreased by 0.6℃ and 0.9℃, respectively. Average RH (75.5%, 75.8%) was approximately increased by 6% because of the evaporative cooling process via the air coolers, while no significant difference was observed (p>0.05). THI for the treated stall spaces was significantly lowered by 1.4 compared to ambient air (p<0.05). Although air temperature was reduced, no difference on THI was found for the treatment and control areas due to the offset of RH increasing. Cooling effect and animal comfort were also compromised.

Table 4 Average temperature, RH and THI of stall spaces under Duct A, Duct B (treatment)and circulation fans (control)

Index	Outdoor	Circulation Fan (control)	Duct A (treatment)	Duct B (treatment)
Temperature/℃	28.1±0.7	27.5±0.6	26.9±0.5	26.6±0.6
RH/%	71.9±6.0	69.7±5.7	75.5±5.5	75.8±4.9
THI	78.0±0.3	77.1±0.3	77.0±0.4	76.6±0.4

As the increase of air temperature in the afternoon, dairy cows are usually more stressful. Thermal indexes, including air temperature, RH and THI, are illustrated in Table 5 for the mostly challenged period of 12:00 to 18:00. In this period, the average outdoor temperature reached 35.3℃, and air temperature of the stall spaces in PAD system was substantially decreased by some 4℃ to 31.4℃, which was also 1.5℃ lower than that of the control area (under circulation fans). Comparing the stall space under circulation fans, RH was raised by 8.1% to 52.3% for the PAD stall space (p<0.05). THI of the stall spaces in both the treatment and control areas were much lower than outside, which were reduced by 2.9 and 2.3, respectively. Compared to the daily average THI reduction (1.2), it suggested that the air cooler and PAD system had a better cooling efficiency in the hottest period of a day, during which the outdoor RH was relatively smaller.

Table 5 Average temperature, RH and THI of stall spaces under Duct A, Duct B (treatment) and circulation fans (control) for the period of 12:00 to 18:00

Thermal index	Outdoor	Circulation Fan (control)	Duct A (treatment)	Duct B (treatment)
Temperature/℃	35.3±1.2^{a}	32.9±1.7^{b}	31.3±1.1^{b}	31.4±1.1^{b}
RH/%	41.3±3.6^{c}	44.3±4.2^{b}	52.3±2.7^{a}	52.4±3.0^{a}
THI	83.3±0.6^{a}	81.0±1.3^{b}	80.4±1.1^{b}	80.5±1.0^{b}

Note: Values with different superscripts are significant difference at p<0.05 level.

Yan et al.[24] assessed the effect of sprinkler and fan cooling system on alleviating heat stress of dairy in eastern China, and found the inside THI of naturally ventilated barns was slightly lowered by the system. Due to the differences on cooling systems and tested ambient environment (RH in particular), the PAD system surveyed in this paper showed a better result in THI reduction.

3.3.2 Equivalent temperature index (ETI)

Although ETI is commonly less used, it incorporates the effect of air temperature, RH along with air velocity. Based on a survey of 413 dairy cows in tropical regions, Silva et al.[29] concluded that ETI had significant correlations with rectal temperature and respiratory rate of the animals, while the correlation for THI was the lowest, and ETI was suggested to be a best thermal stress indicator among five indexes for dairy in hot climates. It also categorizes dairy cow in a safe state when ETI is less 30, while in a caution state when it is 30-34.

In the period of 12:00-18:00, average ETI for the treatment area was majorly within the range of 30-31, showing that the dairy cow was still under a slight heat stress even with the air cooler and PAD system. Average ETI reached 31.1 for the control area with circulation fans, which was 0.6 higher than the treatment area (Figure 5), while no statistical difference was found (p>0.05). ETI peak typically occurred around 13:00-14:00, and dramatically decreased after 17:00, stating the thermal comfort of the cows increasing afterwards.

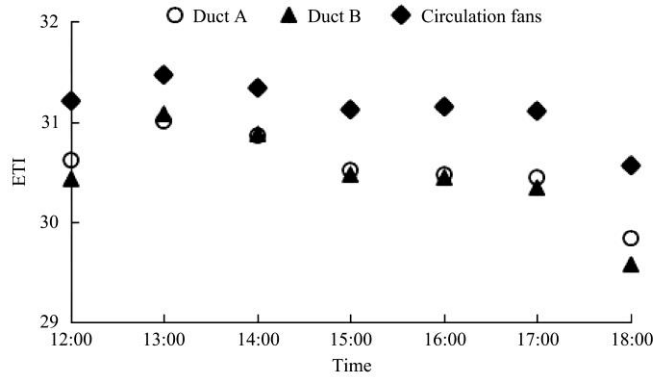


Figure 5 Average ETI for the treatment (Duct A and Duct B) and control (circulation fans) areas for the period of 12:00-18:00

3.4 Effects of PAD system on respiration rate and rectal temperature

Compared to the control, respiration rate (RR) for the treatment cows was about 67 bpm (breaths per minute) (Table 6), which was 6 bpm less and showed no significant difference. Rectal temperatures (*Tr*) of the dairy cattle rested on the stalls under Duct A and Duct B were 38.7°C, and 38.8°C, respectively, which were lowered by 0.3°C and 0.2°C. Significant difference on *Tr* was observed for the control and treatment cows ($p<0.05$), shown in Table 6.

Table 6 RR and Tr of the cows in treatment and control areas

Areas	Respiration rate /bpm	Rectal temperature / ℃
Treatment, Duct A	67±6	38.7 ± 0.2^{b}
Treatment, Duct B	67±6	38.8 ± 0.1^{b}
Control, Circulation Fan	73±4	39.0 ± 0.1^{a}

Note: Values with different superscripts are significant difference at $p<0.05$ level.

Because the system was installed in a naturally ventilated barn with fully open sides, the jetted velocity of the cooling air was affected by the wind speed of the outdoor ambient air, and drifting may happen. Furthermore, constrained by the underground water temperature and capacity of the air coolers, the cooler and PAD system was unable to significantly cool down the entire spatial environment of the barn. The system provided a better resting environment for the cows by retaining the ‘cooling properties’ and relative evenly distributing the cooler air to the body surfaces and hence to improve thermal comfort of the cows.

3.5 Effects of PAD system on milk yield

Milk yield of the cows housed in Section I and Section II (Figure 1) was recorded and analyzed during the experiment. In Section I, air cooler and PAD systems were installed and 86 milking cows were housed, while there were 70 cows in section II. Prior to the field test, 3 d average milk yields were 24.0 kg/d·cow and 21.6 kg/d·cow in Section I and Section II, respectively. After a 15 d operation of the air cooler and PAD system, milk yield for the cows in Section I increased to 24.7 kg/d·cow, while it was almost unchanged in Section II.

4 Conclusions

A cooling system consisting of an air cooler and a perforate air duct was developed to evenly distribute cooling air to the dairy cattle on the stalls, in order to alleviate heat stress. Field experiment showed that air velocity reached 1.1 m/s and 1.3 m/s for Duct A and Duct B at the 0.5 m height plane above the bedding, and was more uniformly distributed for the stalls equipped with PAD system. Compared to the stalls equipped with circulation fans, the PAD system averagely lowered air temperature by 1.5°C, and increased RH by 8.1%. During the period of 12:00-18:00, THI of the treatment area was decreased by 2.9 compared to outdoor ambient air, which was also 0.6 lower than control area. Average ETI for the treatment area was majorly within the range of 30-31, about 0.6 lower compared to the control, and no significant difference was found. After a 15 d operation of the system, rectal temperatures of the treated dairy cows were significantly lowered. The result also showed that the treated area had a higher milk production. These findings suggest the PAD can be an effective cooling alternative for naturally ventilated dairy barns.

Acknowledgments

This study was funded by National High Technology Research and Development Program (2013AA10230602), and China Agricultural Research System (CARS-36). A special thank for all the help from Hailin Dairy Farm, Tianjin, China, where the field evaluation was conducted.

[References]

[1] McDowell R E, Hooven N W, Camoens J K. Effects of climate on performance of Holsteins in first lactation. Journal of Dairy Science, 1976; 59(5): 965–971.

[2] Collier R J, Beede D K, Thatcher W W, Israel L A, Wilcox C J. Influences of environment and its modification on dairy animal health and production. Journal of Dairy Science, 1982; 65(11): 2213–2227.

[3] Schneider P L, Beede D K, Wilcox C J. Nycterohemeral patterns of acid-base status, mineral concentrations and digestive function of lactating cows in natural or chamber heat stress environments. Journal of Animal Science, 1988; 66(1): 112–125.

[4] Holter J B, West J W, McGilliard M L, Pell A N. Predicting ad libitum dry matter intake and yields of Jersey cows. Journal of Dairy Science, 1996; 79(5): 912–921.

[5] Holter J B, West J W, McGilliard M L. Predicting ad libitum dry matter intake and yield of Holstein cows. Journal of Dairy Science, 1997; 80(9): 2188–2199.

[6] Nienaber J A, Hahn G L, Brown-Brandl T M, Eigenberg R A. Heat stress climatic conditions and the physiological responses of cattle. In: ASAE Annual Meeting, 2003. Paper No. 701P0203. St. Joseph, Mich., ASAE.

[7] De Rensis F, Scaramuzzi R J. Heat stress and seasonal effects on reproduction in the dairy cow: a review. Theriogenology, 2003; 60(6): 1139–1151.

[8] Moghaddam A, Karimi I, Pooyanmehr M. Effects of short-term cooling on pregnancy rate of dairy heifers under summer heat stress. Veterinary Research Communications, 2009; 33(6): 567–575.

[9] Boni R, Perrone L L, Cecchini S. Heat stress affects reproductive performance of high producing dairy cows bred in an area of southern Apennines. Livestock Science, 2014; 160(1): 172–177.

[10] Shanklin M D, Stewart R E. Radiation cooling of dairy cattle. Transaction of the ASAE, 1960: 3(2): 52–56.

[11] Roman-Ponce H, Thatcher W W, Buffington D E, Wilcox C J, van Horn H H. Physiological and production responses of dairy cattle to a shade structure in a subtropical environment. Journal of Dairy Science, 1977; 60(3): 424–430.

[12] Strickland J T, Bucklin R A, Nordstedt R A, Beede D K, Bray D R. Sprinkler and fan cooling system for dairy cows in hot, humid climates. Applied Engineering in Agriculture, 1989; 5(2): 231–236.

[13] Means S L, Bucklin R A, Nordstedt R A, Beede D K, Bray D R, Wilcox C J, et al. Water application rates for a sprinkler and fan dairy cooling system in hot, humid climates. Applied Engineering in Agriculture, 1992; 8(2): 375–379.

[14] Turner L W, Chastain J P, Hemken R W, Gates R S, Crist W L. Reducing heat stress in dairy cows through sprinkler and fan cooling. Applied Engineering in Agriculture, 1992; 8(2): 251–256.

[15] Kadzere C, Murphy M, Silanikove N, Maltz E. Heat stress in lactating dairy cows: a review. Livestock Production Science, 2002; 77(1): 59–91.

[16] Gebremedhin K G, Lee C N, Larson J E, Davis J. Alternative cooling of dairy cows by udder wetting. Transaction of the ASABE, 2013; 56(1): 305–310.

[17] Tucker C B, Rogers A R, Schütz K E. Effect of solar radiation on dairy cattle behavior, use of shade and body temperature in a pasture-based system. Applied Animal Behavior Science, 2008; 109(2-4): 141–154.

[18] Worley J W, Bernard J K. Use of high volume low speed (HVLS) fans for cooling dairy cows in a freestall barn in a hot humid climate. In: ASAE Annual Meeting, 2005. Paper No. 054112. St. Joseph, Mich., ASAE.

[19] Calegari F, Calamari L, Frazzi E. Effects of ventilation and misting on behaviour of dairy cattle in the hot season in South Italy. In: Proceedings of 5th International Dairy Housing Conference, St. Joseph, Mich., ASAE, 2003; pp. 303–311.

[20] Avendaño-Reyes L, Alvarez-Valenzuela F D, Correa-Calderón A, Saucedo-Quintero J S, Robinson P H, Fadel J G. Effect of cooling Holstein cows during the dry period on postpartum performance under heat stress conditions. Livestock Science, 2006; 105(1): 198–206.

[21] Khongdee S, Chaiyabutr N, Hinch G, Markvichitr K,Vajrabukka C. Effects of evaporative cooling on reproductive performance and milk production of dairy cows in hot wet conditions. International Journal of Biometeorology, 2006; 50(5): 253–257.

[22] Arbel A, Barak M, Shklyar A. Dairy barns cooling: integrated high pressure fogging system with air ventilation and circulation systems. In: ASABE Annual Meeting, 2007. Paper No. 074123. St. Joseph, Mich.: ASABE.

[23] Matarazzo S V, Perissinotto M, SilvaI J O, Moura D J, FernandesS A A. Electronic monitoring of behavioral patterns of dairy cows in a cooling freestall. In: Proceedings of 6th International Dairy Housing Conference, St. Joseph, Mich.: ASABE, 2007; pp.235–238.

[24] Yan Z , Wang C, Li B, Zhang G, Shi Z, Li H, et al. Influence of water temperature and spraying interval on cooling effect of sprinkler system in dairy barns. Applied Engineering in Agriculture, 2014; 30(4): 611–617.

[25] Brouk M J, Smith J F, Harner J P. Efficiency of modified evaporative cooling in Midwest dairy freestall barns. In: Proceedings of 6th International Livestock Environment Symposium, St. Joseph, Mich. ASAE, 2001; pp. 412–418.

[26] The Danish Agricultural Advisory Center (DAAC). Interdisciplinary report "Housing Design for Cattle-Danish Recommendations". Third edition. Copenhagen, Denmark: The Danish Agricultural Advisory Center, 2002.

[27] Deng S, Shi Z, Li B, Zhao S, Ding T, Zheng W. CFD simulation of airflow distribution in low profile cross ventilated dairy cattle barn. Transactions of the CSAE, 2014; 30(6): 139–146. (in Chinese)

[28] National Research Council. A guide to environmental research on animals. Washington DC, National of Academy Science, 1971.

[29] Silva R G D, Morais D A E F, Guilhermino M M. Evaluation of thermal stress indexes for dairy cows in tropical regions. Revista Brasileira de Zootecnia, 2007; 36(4): 1192–1198.

[30] Baeta F C, Meador N F, Shanklin M D, Johnson H D. Equivalent temperature index at temperatures above the thermoneutral for lactating dairy cows. In: ASAE Annual Meeting, 1987.Paper No. 874015. St. Joseph, Mich., ASAE.