Introduction of backgrounds and approach in reducing heat stress of dairy cattle from an environmental engineering point of view

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Abstract

To reduce heat stress in dairy cattle required multi-disciplinary approach, such as breeding, nutrition, structural design, environmental control, management, etc. This report will focus on introduction of engineering fundamental related to moist air and water and some proven technologies can be used to reduce heat stress of dairy cattle. A software, can be downloaded from the Internet, was introduced. Equations, Tables, Figures were provided for the users to aid in the design process of their approach in reducing heat dress in dairy cattle.

Introduction

The impacts of thermal (heat) stress to the estrous behavior, conception rate and lactation of dairy cattle are huge. Many research have been done to emphasize the importance of reducing such stress to the animal. The great financial loss of farmers due to heat stress in cattle is also well known. Research suggested that integrated approach is required to successfully reducing the heat stress.

This report will firstly focus on the engineering backgrounds related to moist air and water and secondly, introduce some personal observations on means to reduce heat stress in dairy cattle. Some newly developed methods will be introduced.

Part I. Engineering fundamentals related to moist air and water

Engineering fundamentals related to moist air and water were categorized into 7 parts including: 1. psychrometric properties of moist air, 2. pad efficiency at various facing velocity, 3. pad efficiency and pressure drop at various thickness, 4. efficiency of the nozzle in misting/fogging system , 5. temperature humidity index, 6. black globe temperature, and 7. wet bulb globe temperature.

1. Psychrometric properties of moist air

Psychrometric charts are tools for engineers to derive thermodynamic properties of moist air. Such properties including dry bulb, wet bulb and dew point temperatures, absolute and relative humidity, specific volume, enthalpy, vapor pressure and saturated vapor pressure, etc. At a given atmosphere pressure, other properties can be derived with given two independent properties. Charts with only three atmospheric pressures are available. They are: at sea level (1 atmospheric pressure), middle altitude and high altitude.

A software, entitled 'Psychart' as shown in Figure 1,.was developed to replace the chart method. The software allows users to assign different atmospheric pressure, thus, making it more accurate in practical applications. As shown in Figure 2, users can enter either the pressure value or altitude in English or metric units.

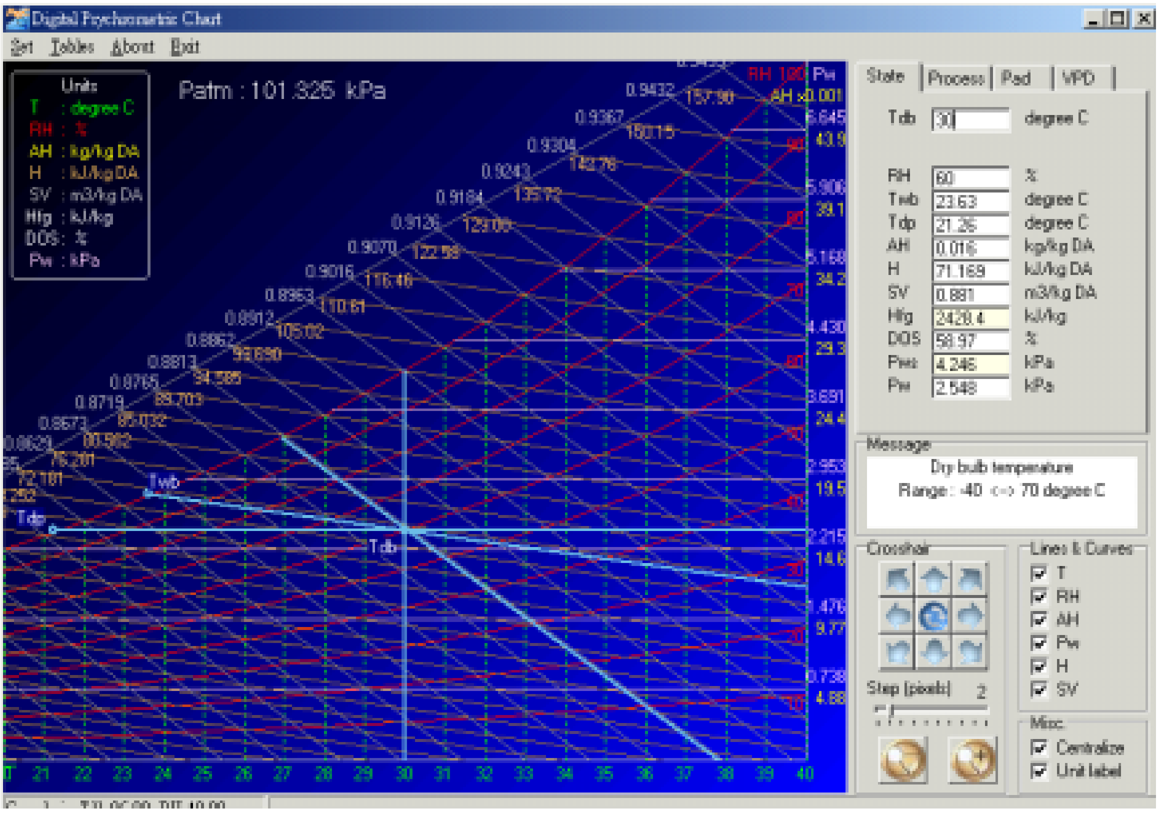


Figure 1. Digital psychrometric chart

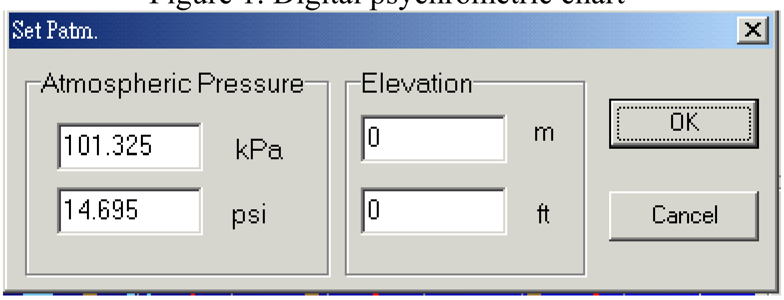


Figure 2. Pop-up window for users to assign atmospheric pressure.

Tables below provide users easy access to the thermodynamic properties in regular summer conditions of tropical and subtropical climates under 1 atmospheric pressure. Under other pressure condition, please re-run the program.

Table 1 shows wet bulb temperatures (Twb) with given ranges of dry bulb temperature (Tdb) and relative humidity (RH) and Table 2 shows RH with given ranges of Tdb and Twb.

Table 1. Twb (in ^{o}C) at various Tdb (20 – 44 ^{o}C) and RH (50 – 100%)

	20	22	24	26	28	30	32	34	36	38	40	42	44
50	13.79	15.39	17	18.61	20.22	21.84	23.46	25.09	26.73	28.38	30.04	31.7	33.38
55	14.47	16.12	17.77	19.43	21.08	22.75	24.42	26.09	27.78	29.47	31.18	32.89	34.62
60	15.15	16.84	18.53	20.23	21.93	23.63	25.34	27.06	28.79	30.53	32.28	34.04	35.81
65	15.81	17.54	19.27	21.01	22.75	24.49	26.25	28.01	29.78	31.56	33.35	35.16	36.97
70	16.45	18.22	19.99	21.77	23.55	25.33	27.13	28.93	30.74	32.56	34.39	36.24	38.09
75	17.09	18.9	20.7	22.51	24.33	26.15	27.99	29.83	31.67	33.53	35.4	37.28	39.17
80	17.71	19.56	21.4	23.25	25.1	26.96	28.82	30.7	32.59	34.48	36.39	38.3	40.23
85	18.33	20.2	22.08	23.96	25.85	27.74	29.64	31.56	33.48	35.41	37.35	39.3	41.26
90	18.93	20.84	22.75	24.67	26.59	28.51	30.45	32.39	34.35	36.31	38.28	40.27	42.26
95	19.53	21.47	23.41	25.36	27.31	29.27	31.24	33.21	35.2	37.19	39.2	41.21	43.24
100	20	22	24	26	28	30	32	34	36	38	40	42	44

Table 2. RH (in %) at various Tdb and Twb (20 – 44 ^{o}C)

	20	22	24	26	28	30	32	34	36	38	40	42	44
20	100	82.63	69.02	57.61	48.01	39.89	33	27.14	22.14	17.89	14.26	11.17	8.55
22	N/A	100	83.49	70.48	59.48	50.13	42.16	35.35	29.52	24.52	20.24	16.57	13.42
24	N/A	N/A	100	84.34	71.84	61.18	52.06	44.23	37.49	31.69	26.69	22.38	18.67
26	N/A	N/A	N/A	100	85.17	73.11	62.75	53.83	46.12	39.45	33.68	28.67	24.34
28	N/A	N/A	N/A	N/A	100	85.98	74.3	64.21	55.45	47.85	41.24	35.49	30.48
30	N/A	N/A	N/A	N/A	N/A	100	86.78	75.43	65.56	56.95	49.44	42.88	37.13
32	N/A	N/A	N/A	N/A	N/A	N/A	100	87.56	76.49	66.81	58.33	50.89	44.36
34	N/A	N/A	N/A	N/A	N/A	N/A	N/A	100	88.32	77.49	67.96	59.58	52.19
36	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	100	89.03	78.39	68.99	60.68
38	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	100	89.67	79.18	69.87
40	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	100	90.19	79.82
42	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	100	90.57
44	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	100

Table 3. WBD at various Tdb (20 – 44 ^{o}C) and RH (50 – 100%).

	20	22	24	26	28	30	32	34	36	38	40	42	44
50	6.21	6.61	7	7.39	7.78	8.16	8.54	8.91	9.27	9.62	9.96	10.3	10.62
55	5.53	5.88	6.23	6.57	6.92	7.25	7.58	7.91	8.22	8.53	8.82	9.11	9.38
60	4.85	5.16	5.47	5.77	6.07	6.37	6.66	6.94	7.21	7.47	7.72	7.96	8.19
65	4.19	4.46	4.73	4.99	5.25	5.51	5.75	5.99	6.22	6.44	6.65	6.84	7.03
70	3.55	3.78	4.01	4.23	4.45	4.67	4.87	5.07	5.26	5.44	5.61	5.76	5.91
75	2.91	3.1	3.3	3.49	3.67	3.85	4.01	4.17	4.33	4.47	4.6	4.72	4.83
80	2.29	2.44	2.6	2.75	2.9	3.04	3.18	3.3	3.41	3.52	3.61	3.7	3.77
85	1.67	1.8	1.92	2.04	2.15	2.26	2.36	2.44	2.52	2.59	2.65	2.7	2.74
90	1.07	1.16	1.25	1.33	1.41	1.49	1.55	1.61	1.65	1.69	1.72	1.73	1.74
95	0.47	0.53	0.59	0.64	0.69	0.73	0.76	0.79	0.8	0.81	0.8	0.79	0.76
100	0	0	0	0	0	0	0	0	0	0	0	0	0

Pad and fan system, misting, fogging are cooling methods based on evaporative cooling. The limitation of this approach is the wet bulb depression (WBD) of the air condition. WBD is the difference between Tdb and Twb. Table 3 shows WBD at various Tdb and RH.

Efficiency of the pad and fan system is defined as the (Tdb_outdoor – Tdb_after pad) over WBD. In Figure 3, the assigned Tdb_outdoor equals 26 °C and RH equals 45 %, the derived Twb is 17.77 °C, thus, WBD equals 8.23 °C. An 80% efficiency pad means the Tdb_after pad equals 26 – 0.8 * WBD = 26 – 0.8 * 8.23 = 19.41 °C.

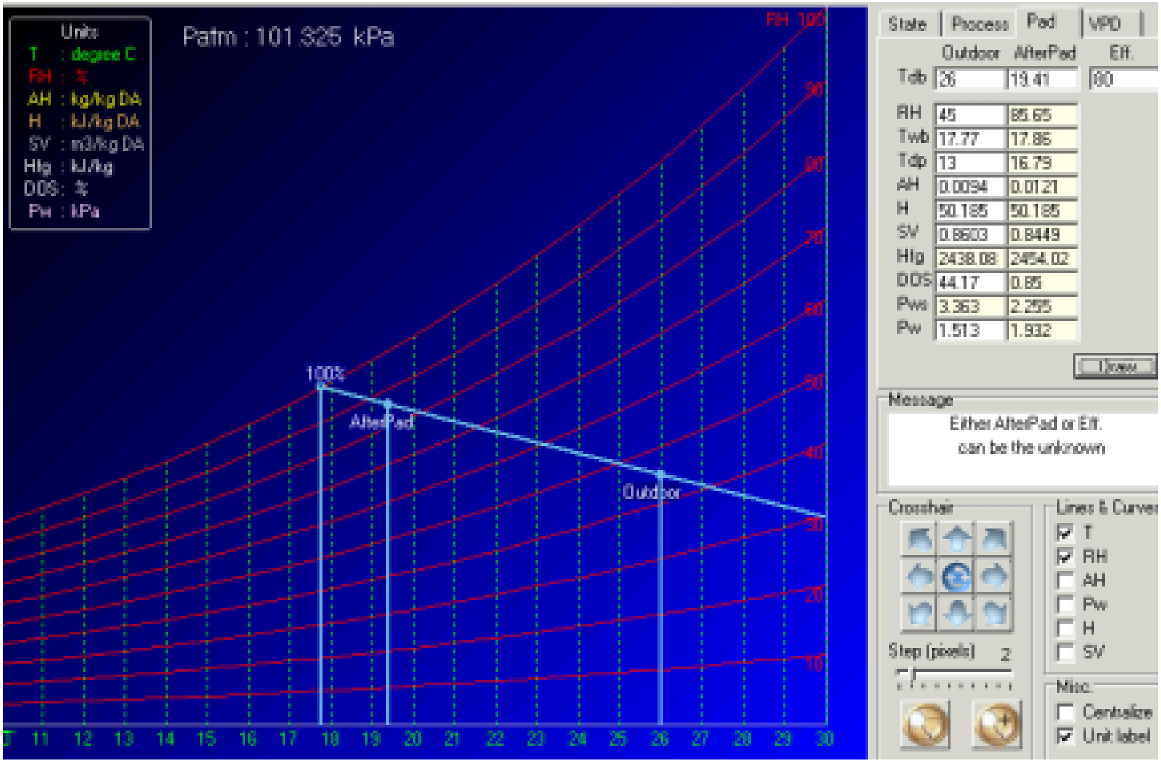


Figure 3. Output of pad and fan system in Psychart software.

2. Pad efficiency at various facing velocity

Trumbull, et al. (1986) developed equations to predict the efficiency as a function of the air velocity (V, in m/s) for three commercially available pads. Although no thickness information available in the report, educated guess is that they are all in 10 cm thickness. The equations are as follows:

$Eff = 86.62 - 20.787 * V + 2.755 * V^2$	for Kool-Cel pad
$Eff = 91.034 - 17.91 * V + 5231 * V^2$	for CELdek pad
$Eff = 76.055 + 2.909 * V - 17.414 * V^2$	for Excelsior pad

Mannix (1981) found that the water flow rate through a pad had no effect on the evaporator pad performance, as long as the water is evenly distributed and the pad was fully saturated. However, Trumbull, et al. (1986) found that the efficiency of the pads vary due to different water flow rates. At low water flow rates (0.57 – 1.53 L/s), the efficiency decrease when face velocity increase from 0.2 to 1 m/s. At high water flow rates (2.16 – 3.33 L/s), the efficiency remain the same when face velocity increase from 0.2 to 1 m/s.

Blow-off of water from the pad occurring at 1 m/s for the excelsior pad, 1.6 m/s for the Kool-Cel pad and 2 m/s for the CELdek pad (Trumbull, et al., 1986).

3. Pad efficiency and pressure drop at various thickness

The thicker the pad, the higher the efficiency and pressure drop at given face velocity of air as shown in Figures 4a and 4b (Munters Corp., USA). Increase face velocity of air (V, in m/s) will also increase the pressure drop (in Pa) of the system. The equations to derive following figures are listed below.

Efficiency for 20 cm pad $=-0.404*V^3+1.6017*V^2-5.4791*V+97.821$

Efficiency for 10 cm pad $= -1.4545*V^3+6.3377*V^2-16.801*V+89.857$

Pressure Drop for 20cm pad $=-2.7475*V^3+24.987*V^2-3.1053*V$

Pressure Drop for 10cm pad $= 1.5084*V^3+3.6479*V^2+6.2665*V-0.3838$

Pressure drop of the system affect the volumetric flow rate of the fans as shown in Figure 5, which is the fan curves of Euromme fans, which is quite popular in Taiwan.

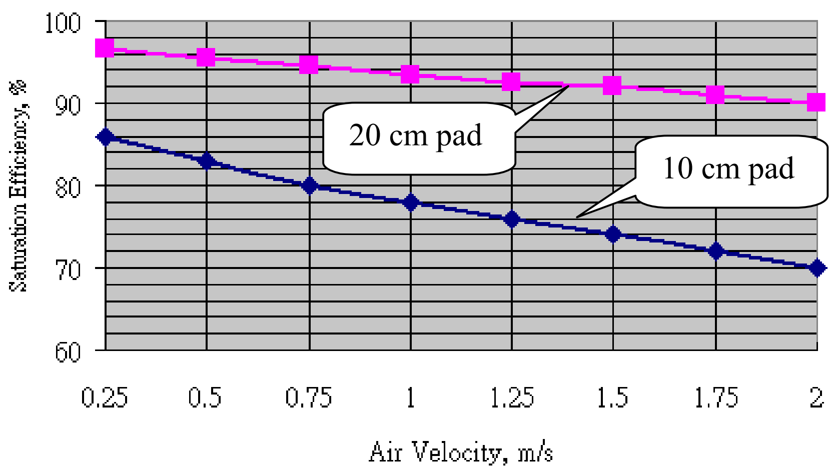


Figure 4a. pad efficiency at various air velocity and thickness.

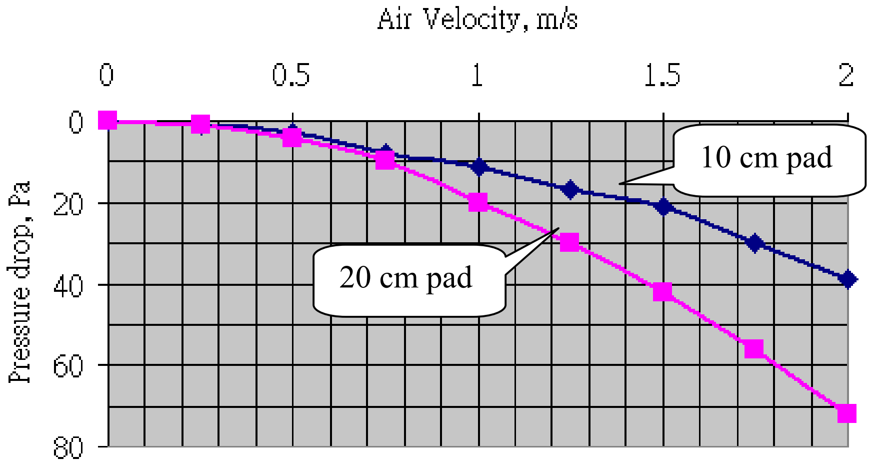


Figure 4b. Pressure drop at various air velocity and thickness.

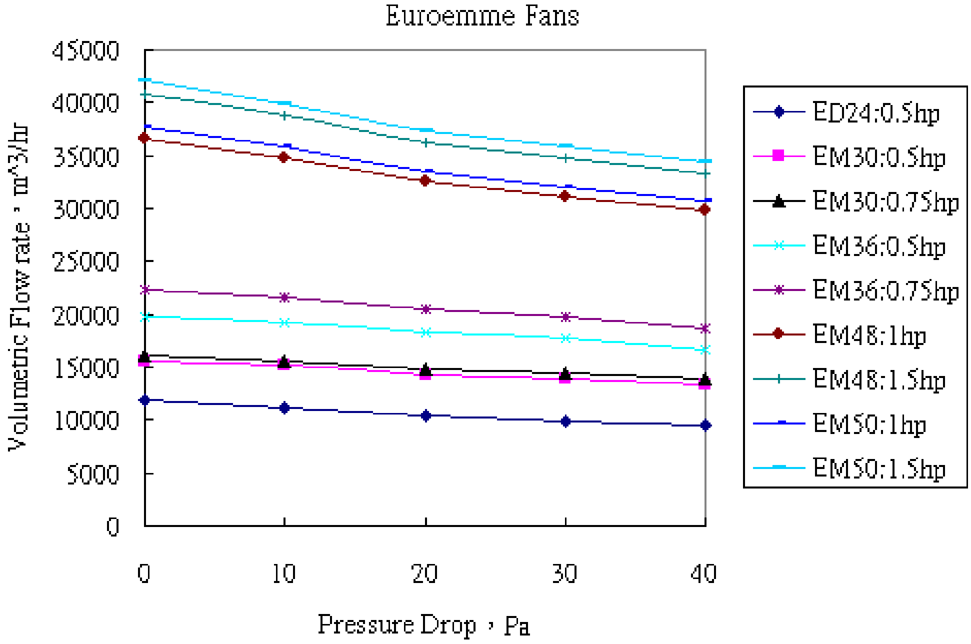


Figure 5. Fan curves of various models of Euroemme fans

4. Efficiency of the nozzle in misting/fogging system

The efficiency of the misting/fogging system will be less than or equal to the efficiency of the nozzle depends on number of nozzle used in the system and the rate of water sprayed per nozzle. Bottcher et al. (1991) developed an equation to estimate the efficiency (β) of the nozzle for misting (large droplet due to low pressure or large hole in nozzle) and fogging (small droplet due to high pressure and small hole in nozzle) with respect to water pressure (P, in kPa). The equation is listed below.

$$\beta = 0.124 + 1.35 * 10^{-4} * P$$

At 35 atmospheric pressure, the efficiency is around 60%. When P equals 64.888 atmospheric pressure (64.888 * 100 kPa), the nozzle efficiency (β) reaches 100%

assuming 1 atmospheric pressure equals 0.1 MPa. Considering some friction loss, a 70 atmospheric pressure was suggested by the author in high pressure fogging related research.

5. Temperature Humidity Index (THI)

Rectal temperature and milk production are in direct proportion to the THI (Igono et al., 1985; Knapp and Grummer, 1991). Dairy cattle at THI higher than 70 – 72.°C is considered under heat stress (Ingraham et al., 1974; Johnson, 1985; Stott, 1981). Successful conception rate will be decreased when the monthly average of THI is greater than 62 (du Preez et al, 1991). Below listed two equations to calculate THI.

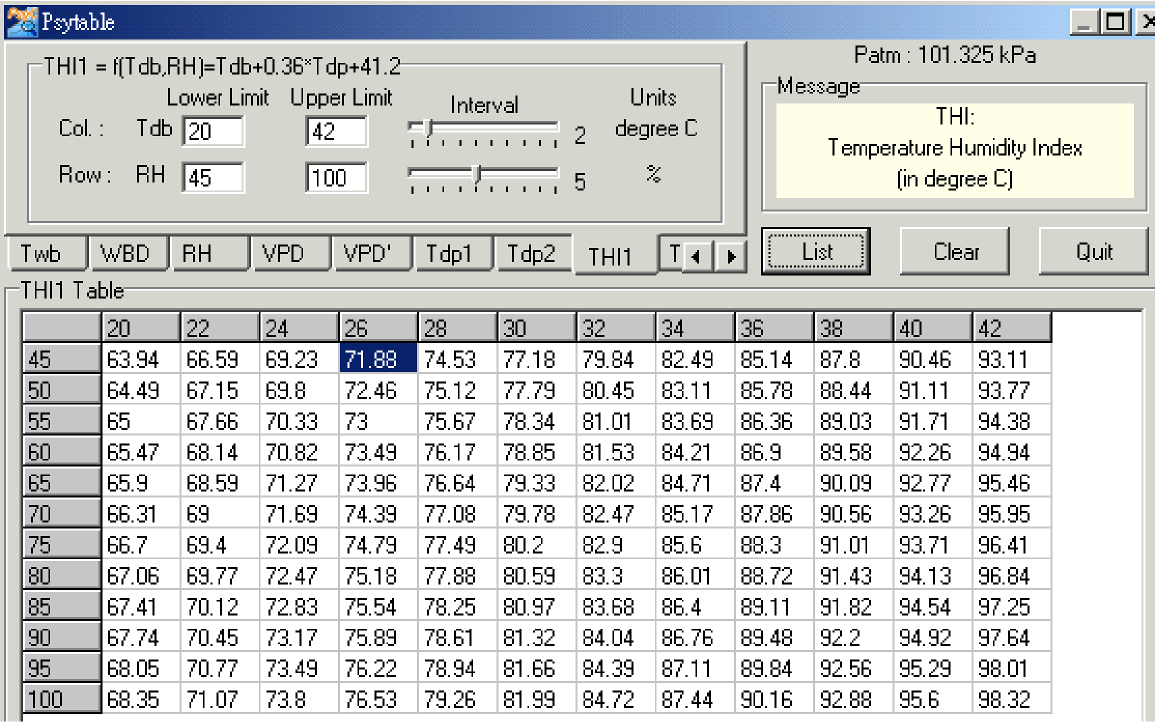
$$THI = T \text{ (in } ^oF) - 0.55 * (100\text{-}RH\%)/100 * (T - 58) \quad \text{(Ingraham et al., 1974)}$$
$$THI = Tdb \text{ (in } ^oC) + 0.36 * Tdp \text{ (in } ^oC) + 41.2 \quad \text{(Armstrong, 1994)}$$

Both equations required two environmental factors: the 1st eq. requires dry bulb temperature (in degree F) and relative humidity (in percentage) and the 2nd eq. requires dry bulb and dew point temperatures both in degree C. Please noted that the THI should have no unit, neither ^oF nor ^oC. The results of above equations were not consistent as listed below. THI values of Ingraham’s equation are always bigger than values calculated using Armstrong’s equation. The difference get bigger when THI values become larger as shown below:

Table 4. Comparisons of THI equations

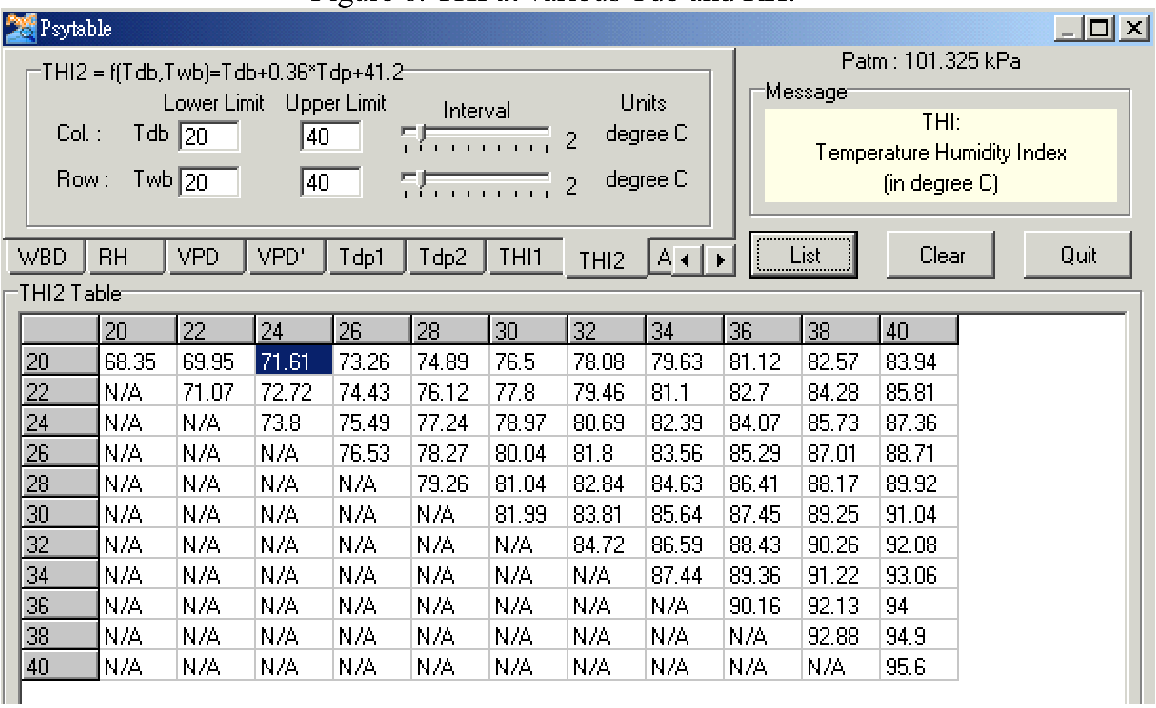
T, Tdb	RH%	Twb	Tdp	THI
78.8 ^oF= 26 ^oC	45%	17.7 ^oC	13 ^oC	THI=72.50 (Ingraham’s eq) THI=71.88 (Armstrong’s eq.)
104 ^oF= 40 ^oC	100%	40 ^oC	40 ^oC	THI=104 (Ingraham’s eq) THI=95.6 (Armstrong’s eq.)

Armstrong’s equation was used in the software developed as shown in Figures 6 and 7. Two Tables can be found in these two figures showing calculated results of THI with given ranges of Tdb and RH and with given ranges of Tdb and Twb, respectively. THI does not consider the effects of radiation and wind velocity.



	20	22	24	26	28	30	32	34	36	38	40	42
45	63.94	66.59	69.23	71.88	74.53	77.18	79.84	82.49	85.14	87.8	90.46	93.11
50	64.49	67.15	69.8	72.46	75.12	77.79	80.45	83.11	85.78	88.44	91.11	93.77
55	65	67.66	70.33	73	75.67	78.34	81.01	83.69	86.36	89.03	91.71	94.38
60	65.47	68.14	70.82	73.49	76.17	78.85	81.53	84.21	86.9	89.58	92.26	94.94
65	65.9	68.59	71.27	73.96	76.64	79.33	82.02	84.71	87.4	90.09	92.77	95.46
70	66.31	69	71.69	74.39	77.08	79.78	82.47	85.17	87.86	90.56	93.26	95.95
75	66.7	69.4	72.09	74.79	77.49	80.2	82.9	85.6	88.3	91.01	93.71	96.41
80	67.06	69.77	72.47	75.18	77.88	80.59	83.3	86.01	88.72	91.43	94.13	96.84
85	67.41	70.12	72.83	75.54	78.25	80.97	83.68	86.4	89.11	91.82	94.54	97.25
90	67.74	70.45	73.17	75.89	78.61	81.32	84.04	86.76	89.48	92.2	94.92	97.64
95	68.05	70.77	73.49	76.22	78.94	81.66	84.39	87.11	89.84	92.56	95.29	98.01
100	68.35	71.07	73.8	76.53	79.26	81.99	84.72	87.44	90.16	92.88	95.6	98.32

Figure 6. THI at various Tdb and RH.



	20	22	24	26	28	30	32	34	36	38	40
20	68.35	69.95	71.61	73.26	74.89	76.5	78.08	79.63	81.12	82.57	83.94
22	N/A	71.07	72.72	74.43	76.12	77.8	79.46	81.1	82.7	84.28	85.81
24	N/A	N/A	73.8	75.49	77.24	78.97	80.69	82.39	84.07	85.73	87.36
26	N/A	N/A	N/A	76.53	78.27	80.04	81.8	83.56	85.29	87.01	88.71
28	N/A	N/A	N/A	N/A	79.26	81.04	82.84	84.63	86.41	88.17	89.92
30	N/A	N/A	N/A	N/A	N/A	81.99	83.81	85.64	87.45	89.25	91.04
32	N/A	N/A	N/A	N/A	N/A	N/A	84.72	86.59	88.43	90.26	92.08
34	N/A	N/A	N/A	N/A	N/A	N/A	N/A	87.44	89.36	91.22	93.06
36	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	90.16	92.13	94
38	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	92.88	94.9
40	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	95.6

Figure 7. THI at various Tdb and Twb.

Linvill and Pardue (1992) developed equation to predict milk production based on previous 4 days THI information as shown below.

MP (in kg/day/cow) = 21.48 – 0.051 * HD74 – 0.0099 * HA80S

where, 21.48: regular milk production in kg per day per cow

HD74: total hours of THI > 74 for the last 4 days

HA80S: square of total hours of THI > 80 for previous day

A different equation, developed by Berry (1964), listed in ASAE standards (1988) is listed below:

$$MPD = 1.08 - 1.736\ NL + 0.02474\ (NL)\ (THI)$$

where, MPD: milk production decrease per cow per day, in kg/day/cow
NL: daily production quantity under no heat stress, in kg/day/cow
THI: Temperature humidity index

Table 5 shows the MPD values for 3 level of NL values assuming daily production amount is 20, 25 and 30 kg/day/cow. It is quite obvious to observe that at fixed THI, MPD increase with NL increase, which indicated that heat stress affect high yielding cow most in term of milk production decrease (MPD). Also, MPD increase when THI increase for same level of NL.

Table 5. Various MPD for 3 levels of NL at various environmental conditions

MPD, kg/ cow /day	Tdb=36°C RH=90% THI =89.5	Tdb=36°C RH=50% THI =85.9	Tdb=30°C RH=70% THI =79.9	Tdb=24°C RH=90% THI =73.2
NL =20 kg/cow/day	MPD=10.6	MPD=8.8	MPD=5.9	MPD=2.6
NL = 25	MPD=13	MPD=10.8	MPD=7.1	MPD=3.0
NL = 30	MPD=15.4	MPD=12.7	MPD=8.3	MPD=3.3

6. Black globe temperature (BGT)

The black globe temperature (BGT) represents the combine effect of dry bulb temperature, average radiation and average wind velocity. It is normally used to quantify the effect of shading. The black globe temperature did not consider the effect of humidity. When BGT <=25 °C, forced ventilation has no effect on reducing body and rectal temperature of cattle. When the temperature of the surrounding environment (below 1.8 m inside dairy barn) of cattle reaching 36 °C, forced ventilation can reduce the increase rate of rectal temperature by half when the BGT increase (Berman, 1985).

7. Wet bulb globe temperature (WBGT)

The wet bulb globe temperature (WBGT) is an improved index over THI and BGT. It takes into consideration of dry bulb temperature, humidity, radiation and wind velocity. A heat stress monitor (hs-3600, Metrosonics, INC., Figure 8) calculated WBGT using separate equations depends on whether the device is under shade or not. The equations are listed below.

WBGT_indoor = 0.7 * Twb + 0.3 * BGT
WBGT_outdoor = 0.7 * Twb + 0.2 * BGT + 0.1 * Tdb
where, WBGT, Twb, Tdb, BGT are in ^{o}C.

The WBGT was used in the studies of suggested length of “stay-time” for an individual performing various tasks, under various physiological heat exposure limits (PHEL) and the studies of permissible heat exposure threshold limit values by U.S. Navy, Heat Stress Division at the Naval Medical research institute.

Figure 8. The heat stress monitor (hs-3600, Metrosonics, INC.). From the left, there are dry bulb, black globe and wet bulb temperature probes.

Part II. An Integrated Approach

There is no single mean to reduce heat stress in cattle as well as other animal. An successful approach will be an integrated approach. The following contents, divided into 7 categories, contains personal observations from the environmental control point of view. They are: 1. structure, 2. natural ventilation, 3. forced ventilation, 4. pad and fan system, 5. Fogging multi-layer net and fan system, 6. Intermittent spraying and forced ventilation and 7. drinking water temperature.

1. Structure

The longer side of the house should be constructed in the east-west orientation to reduce the .amount of direct sunlight shine upon the side walls or enter the house as shown in Figure 9.

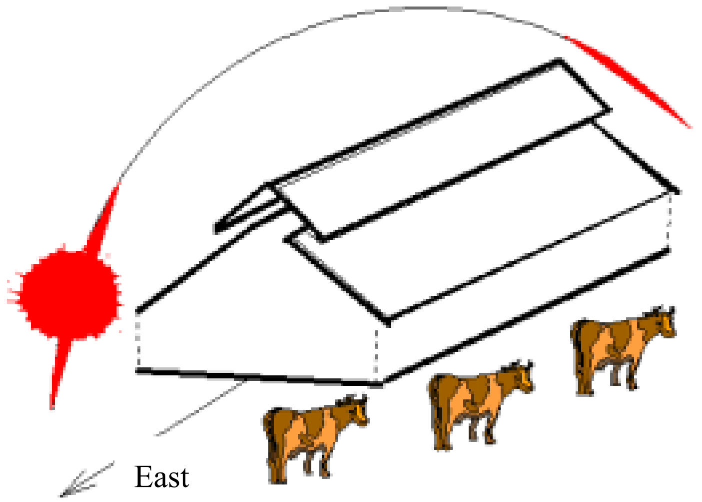


Figure 9. Proper orientation of the dairy barn.

Painted white on roof can increase the amount of reflective sunlight, thus reducing the amount of absorbed solar energy. The summation of reflectivity and absorptivity of a material at the same wavelength equals unity as shown below.

$$1 = \text{Reflectivity} + \text{Absorptivity}$$

For an open type dairy barn, reduced the amount of direct sunlight as much as possible by means of side curtains. As shown in Figure 10, tall building allows more direct sunlight to enter the house.

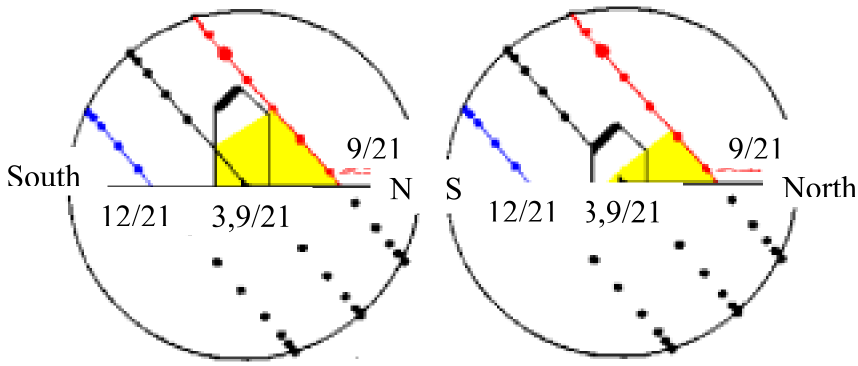


Figure 10. Tall building allows more direct sunlight to enter the house.

Side shading curtain is the cheapest mean to prevent sunlight entering the house. Install the side curtain at the post as shown in Figure 11a provide little protection when curtains were rolled up. However, as shown in Figure 11b, an extend length of eave with shading material was installed and the vertical shading was moved outside. The new shading system performed much better than the old system.

Figure 11a. Original side curtains Figure 11b. Improved side curtains

The west side of the barn can also installed a side and vertical curtains as shown in the following before and after photos.

Figure 12a. West side of the dairy barn before renovation

Figure 12b. West side of the dairy barn after renovation (view 1)

Figure 12c. West side of the dairy barn after renovation (view 2)

Tall structure (eave height > 3.5 m) is not economically viable. There are other means to remove hot air on top layer inside the building. Outside covering, outside shading and outside shading with roof-spray are proven/popular greenhouse technologies and can be applied in structural design of dairy barn to reduce the height of the eave. Various roof system with improved performance in natural ventilation by providing enough roof opening, enhance solar chimney effect, etc. can be other alternatives.

For a close type dairy barn, besides pad and fan installed in both ends, my design is to install an extra layer at the other two ends with no pad or fans installed. Fixed, nontransparent curtain can be used as the outside layer. Outside layer and inside wall keep at 10 cm apart and with openings at both ends in vertical direction on outside layer. The bottom opening provides entrance for the cold air and the upper openings allows heated air to exit. Ten cm of air layer provides thermal barrier to prevent conductive thermal energy from entering the house through vertical walls. From my point of view, this is the cheapest double wall approach which is a proven technology in structural design.

2. Natural ventilation

For an open type dairy barn, roof vent is required to allow upper heat to escape. In the traditional open-roof structure, size of roof opening vs. floor area and vertical distance between air inlet and outlet are the key factors for natural ventilation. Suggested width of roof opening is that house with 6 m wide required roof opening at with at least 30 cm in width and increase 5 cm in width for every 3 meter house width as shown in the following equation:

$$W_{ro} = 30 + 5 * (W_h - 6)/3$$

where, W_{ro}: width of roof opening, in centimeter

W_h: width of dairy house, in meter

A simple model exists to predict thermally-induced natural ventilation where there is one inlet and one outlet, but its use should be limited to making initial or field estimates. If the areas of inlet and outlet are equal, and there is no wind, airflow can be estimated by the equation listed below (Albright, 1990).

$$V = 2 * A * (C/0.65) * [g * \Delta h * (Ti - To)/Ti]^{1/2}$$

where V is in m^3/s, g is the gravitational constant, A is the area of one of the openings, C is the coefficient of discharge of each opening, Δh is the distance, m, between the two openings, and Ti and To are indoor and outdoor air temperature, K, respectively. When the two openings are not equal, the smaller of the two is used in above equation and V is adjusted by multiplying (1+ % increase in flow). The % increase in flow can be calculated using the regression equation shown in Figure 13.

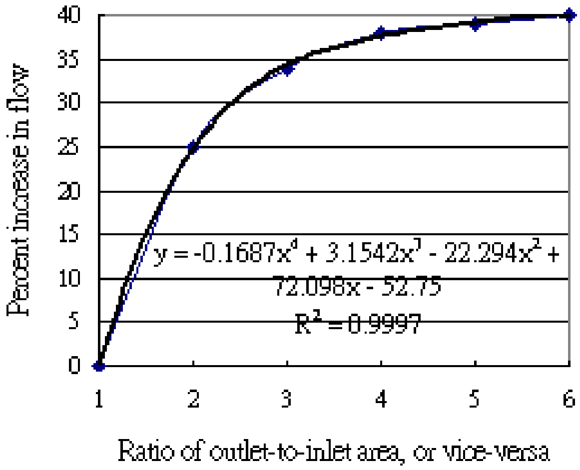


Figure 13. Percent increase in flow vs. ratio of outlet-to-inlet area

Various roof vent methods are available such as double-roof with tiny holes and wind driven rotating roof vent as shown in Figures 14a and 14b, respectively. Both were patented technologies. The later approach is quite popular in Taiwan, however, some manufactures does not understand the principle of solar chimney, thus the system performance varied within different manufactures .

Figure 14a. One layer of the double layer roof with small holes.

Figure 14b. Wind driven rotating roof vent.

3. Forced ventilation

For an open type dairy barn, fans can be installed along the house and tilted at no more than 30 degree. Please noted that, inside a building, the temperature at upper layer will be higher than lower area due to the fact that the density of the air decreased when the temperature increased. If the fans tilted too much, the heated air at upper layer will be brought down to the surrounding of dairy cattle. One way to prevent this undesired situation and still using the large angle tilted fan is to install high pressure fogging system under the roof with fogger facing down or horizontally. The fog will be evaporated thus reducing the temperature of the air at upper part without increasing the humidity of the surrounding of the cattle.

Figure 15. Movable fan installed with fogging on upper part of the dairy barn.

A movable fan system was developed to provide back and forth wind to the cattle at meal time and sometimes at all time. Two fans per set was installed per 10 meter with one fan facing feeds and one fan facing the neck of the cattle as shown in Figure 15. One motor was used to pull 4 sets of fans subject to the dimension of the dairy barn. In other applications, the same motor can drive up to 10 sets. The system have been worked started from 1995 and no failure was found up to now in 2002.

4. Pad and fan system

For a close type dairy barn, evaporative cooling system is required in the tropical and subtropical climate zones. Pad and fan system is one of the alternatives. The usefulness of the pad system depends on local climate and the efficiency of the pad. For a traditional pad system utilize expensive imported pad, the efficiency is 80% for 10 cm pad at 1.5 m/s suggested face velocity and is about 90 % efficiency for 15 cm pad at 2.5 m/s suggested face velocity. The potential of the pad was investigated by the author based on local climate using 10 years of hourly weather data as shown below (Fang, 1994).

Table 6. Probability of RH and Tdb data of various locations in Taiwan (Fang, 1994)

	RH < 65%		65% ≤ RH ≤ 85%		RH > 85%	
	Tdb<27	Tdb≥27	Tdb<27	Tdb≥27	Tdb<27	Tdb≥27
Taipei	8.05%	8.75%	34.64%	16.19%	30.21%	2.16%
HuaLian	7.35%	1.78%	43.28%	20.47%	25.67%	1.45%
Ilan	3.01%	1.36%	27.63%	17.22%	47.90%	2.86%
Tainan	5.93%	5.80%	32.16%	24.27%	28.11%	3.72%
Kaoshung	7.99%	3.94%	38.67%	30.51%	15.31%	3.57%
ChaI	3.71%	3.65%	23.23%	18.29%	47.62%	3.47%

Taichung	9.10%	8.83%	35.64%	16.80%	28.60%	1.02%
Taidong	9.72%	4.25%	46.96%	25.67%	12.29%	1.09%
WuChi	7.74%	2.90%	40.14%	22.49%	24.00%	2.72%

From the first column from the right of Table 6, one can observed that high humidity does not come together with high temperature. It is true in Taiwan as well as elsewhere. That is the reason why evaporative cooling system is still useful in some so called hot, humid area such as Taiwan. But, how good is the evaporative cooling system? What can we expect in reducing the air temperature through the pad? As shown in Figure 16 which is rather misleading. Firstly, in Taiwan, we don't have humidity reaching 30% and our highest temperature is more than 35 ^{o}C. Table 7 shows the probability of WBD of various locations in Taiwan. From Table 7, one can realized that expecting a temperature drop of 'pad efficiency * 5 ^{o}C' is reasonable. For example, in Tainan, 92.25% of the year, one should not expect the air temperature drop passing the pad to exceed 4 ^{o}C assuming 80% efficiency.

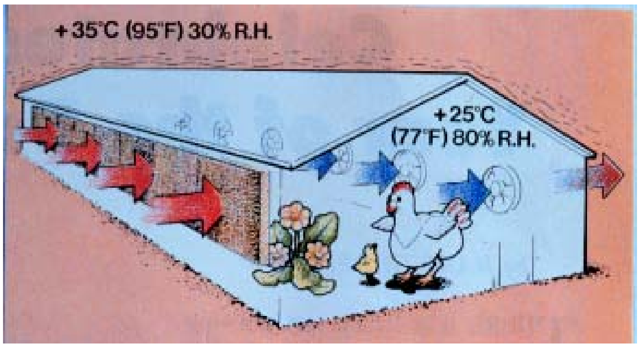


Figure 16. Misleading schematic diagram of pad and fan system provided by manufacturer.

Table 7. Probability of WBD in Taiwan (Fang, 1994)

	WBD = Tdb – Twb		
	WBD <= 3 ^{o}C	WBD <= 4 ^{o}C	WBD <= 5 ^{o}C
Taichung	6.28%	77.73%	87.43%
Taipei	8.35%	80.76%	88.84%
Tainan	9.01%	82.39%	92.25%
Taidong	8.39%	81.37%	93.29%
KaoShung	2.39%	81.83%	93.51%
CharI	9.14%	88.13%	94.68%
WuChi	2.12%	87.12%	95.33%
HuaLian	2.78%	89.05%	96.45%
I-Lan	4.82%	93.53%	97.92%

Lowing water temperature for pad system has little effect on the air temperature passing through the pad.

5. Fogging multi-layer net and fan system

In Taiwan, we have tried different materials to replace expensive imported pad. Among several trials, a promising system entitled fogging multi-layer net and fan system, developed by the author, was patented in 2001.

The efficiency of the system reaches 92.5%, which is higher than 80% of the traditional 10cm pad and 90% of the 15 cm pad system. The fogging multi-layer net and fan system can be used in both negative pressure type and positive pressure type as shown in Figure 17. The positive pressure type system was installed in the dairy barn of a private company located in Tainan and the negative pressure type systems have been successfully installed in chicken houses, greenhouses, etc.

Figure 17a. Misting multi-layer net and fan system used in greenhouse (Fang and Lai, 2001).

Figure 17b. Fogging multi-layer net and fan system used in dairy barn (Fang and Lai, 2001).

Berman et al (1985) suggested that 25 to 26 ^{o}C is the upper critical temperature for high yielding dairy cows. Close type dairy barn equipped with pad and fan or fogging multi-net and fan systems are two systems having the potential to maintain the environment of cows below 26 ^{o}C throughout the day.

6. Intermittent spraying and forced ventilation

Fogging and movable fan system can increase lactation but has little effect on rectal temperature. Direct spraying on the body is the cheapest mean to reduce the rectal temperature, thus reducing the heat stress in cattle. Many research has proof that this system is effect to improve lactating and reproductive performance of dairy cows (Wang, et al., 1993; Berman, 1995).

Figures 18a and 18b show the infrared image of the cattle before and after spraying. An intermittent timer control system was installed to control the on/off of the sprayer and fans. The best cooling effect can be achieved by setting the system at 1:9 interval per cycle and 5 to 6 cycles per treatment. Berman (1985; 1995) and Wang et al. (1993) suggested that spraying for 0.5 minute and turn on the fan for 4.5 minutes. Totally 5 minutes per cycle and 30 minutes per treatment can have 6 cycles.

The author used 1 minute spraying and 9 minutes for fan per period and treated for 50 minutes (5 cycles) using different types of nozzle and fan (Fang, 1998). The exact setting should depends on the local situation and the water flow rate, the volumetric flow rate of the fan and the number of fans installed. The key is to wet the cattle thoroughly and dry it again totally. The major cooling effect lies in the period from wet to dry.

The cooling effect lasts for 30 – 45 minutes using Berman's approach (0.5 min spraying, 4.5 min forced ventilation, 6 cycles per period, 30 minutes per period) and the cooling effect lasts for 60 – 90 minutes using author's approach (1 min spraying, 9 min forced ventilation, 5 cycles per period, 50 minutes per period).

Berman (1985) suggested that spraying plus forced ventilation treatment should be conducted every two hours for 30 minutes, thus, requiring 7 to 8 treatments per day. The improvement of this cooling treatment is significant. Conception rate can be increased from 20% to 30 % and the steady estrous behavior increase from 45% to 70%, without estrous behavior decrease from 33% to 12%, length of estrous period increase from 11.5 to 16 hours during the summer time.

Wang et al (1993) tested sprinkling followed by forced ventilation 5 times per day between 10:00 am to 4:30 pm. During the experiment, the rectal temperature of the cows was significantly reduced by 0.2 ^{o}C. In Author's experiment, we found the rectal temperature reduced by 0.4 ^{o}C (Fang, 1998). Wang et al (1993) also conducted same cold treatment 9 times per day between 5 am to 9 pm for 10 days and found that the amount of lactation increased by 2.6 kg/day/cow in treatment group over control group.

The intermittent spraying and forced ventilation can be conducted at the holding location before milking as shown in Figure 19 or a separated location. The place should have good drainage.

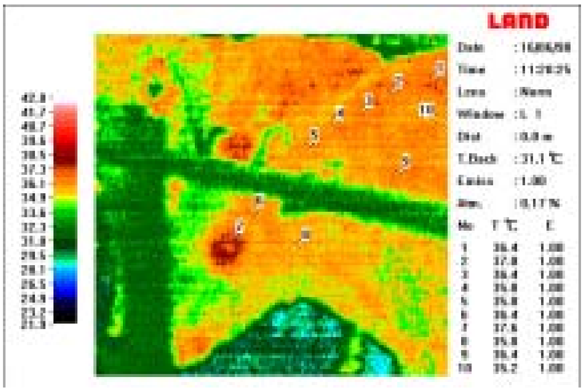


Figure 18a .Body temperatures before spraying.

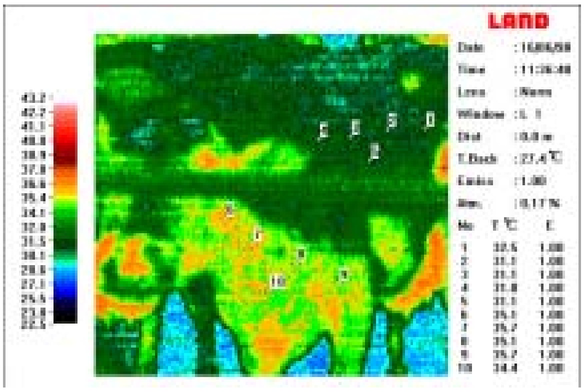


Figure 18b .Body temperatures after spraying.

Figure 19. Intermittent spraying and forced ventilation.

7. Drinking water temperature

Stermer et al. (1986) conduct experiments on releasing heat stress by lowering drinking water temperature. Results shown that water temperature at 22 ^{o}C is significantly better than water temperatures at 10, 16 and 28 ^{o}C. The body temperature decrease 0.6 ^{o}C and respiration rate reduced 12 times per minute.

Conclusions

One method proved successful does not guarantee elsewhere. One method proved non-feasible might become highly successful in another time, in another place and sometimes conducted by another person. One must realized that there are conditions required to guarantee the success and there are limitations to all methods subject to the local climate, availability of resource, people, etc. Even in the same method, there are various approach and in the same approach there are different settings of operating conditions.

In this report, engineering fundamentals related to moist air and water were reviewed. Equations, Tables and Figures were provided as the reference for further studies of readers. The 'Psychart' software developed by the author can be downloaded from http://ecaaser3.ecaa.ntu.edu.tw/weifang/psy/cea2-5.htm.

The listed web-site contains DOS based and WINDOWS based programs developed by the author throughout the years. To download the software mentioned in this report, please click on the newest version.

Many methods in reducing heat stress in dairy cattle were introduced. They are all proven technologies but some have not been applied to dairy cattle. It is our wishes to prove the usefulness of the systems, such as double wall, double roof with small holes, negative pressure type fogging multi-net and fan system, etc. in the near future.

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