

A Re-evaluation of the Impact of Temperature Humidity Index (THI) and Black Globe Humidity Index (BGHI) on Milk Production in High Producing Dairy Cows

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Introduction

The temperature humidity index (THI) was originally developed for humans by Thom (1958) and extended to cattle by Berry et al (1964). It is currently used to estimate cooling requirements of dairy cattle in order to improve the efficiency of management strategies to alleviate heat stress. The Livestock Conservation Institute evaluated the biological responses to varying THI values and categorized them into mild, moderate and severe stress levels for cattle (Whittier, 1993; Armstrong, 1994). However, as pointed out by Berman (2005) the supporting data for these designations are not published. In addition, the index is based on a retrospective analysis of studies carried out at The University of Missouri in the 1950's and early 1960's on a total of 56 cows averaging 15.5 kg/d, (range 2.7-31.8 kg/d). In contrast, average production per cow in the United States is presently over 30 kg/d with many cows producing above 50 kg/d at peak lactation. The sensitivity of cattle to thermal stress is increased when milk production is increased thus reducing the "threshold temperature" when milk loss begins to occur (Berman, 2005). This is due to the fact that metabolic heat output is increased as production levels of the animal increase. For example, the heat production of cows producing 18.5 and 31.6 kg/d of milk has been shown to be 27.3 and 48.5% higher than non-lactating cows (Purwanto et al., 1990). Research has shown that when milk production is increased to from 35 to 45 kg/d the threshold temperature for heat stress is reduced by 5°C (Berman, 2005). The physiological effects based on THI predictions on milk yield are currently underestimating the severity of heat stress on Holstein cattle. Radiant heat load and/or convection effects were not evaluated by Berry et al., (1964) and the majority of dairy cows care currently housed under a shade structure during heat stress months. Shade structures alleviate some of the radiant heat load there is still a conducive effect coming from the metal shade structure. In Israel, a typical shade structure is estimated to add 3°C to the effective ambient temperature surrounding the animals (Berman, 2005). The use of fans for cooling management systems causes varying convection levels under shade structures as well.

An additional factor in utilizing THI values is the management time interval. In past research, the milk yield response to a given THI was the average yield in the second week at a given environmental heat load therefore milk yield measurements were not recorded until two weeks

after experiencing the environment (Berry et al., 1964). In order to avoid economic production losses dairy producers need to be informed of the level of cooling to be implemented immediately when heat stress occurs. Research has indicated that the effects of a given temperature on milk production are maximal between 24 and 48 hours following heat stress (Collier et al., 1981; Spiers et al., 2004). It has also been reported that ambient weather conditions two days prior to milk yield measurement had the greatest correlation to decreases in milk production and dry matter intake (West et al., 2003). Research has shown that the total number of hours when THI is greater than 72 or 80 over a 4 day interval had the highest correlation with milk yield (Linville and Pardue, 1992). Collectively, these findings indicate that current THI values for lactating dairy cows underestimate the impact of a given thermal load on animal productivity and have an inappropriate time interval associated with a cooling management decisions. Avoiding a decline in milk production over a 48 hour period will automatically prevent a decrease in lactation persistency two weeks later. Utilizing the THI in order to reduce milk production losses has been effective however; the current THI is in need of updating on an appropriate time scale with data from higher producing animals. The pattern of stress application is a final component of the THI to be considered. In the research conducted for the current THI, animals were exposed to given THI conditions continuously meaning, with no daily circadian environmental fluctuations, for the entire two week period (Berry et al., 1964). Under natural dairy management conditions, temperatures are not kept constant rather they follow a circadian pattern which rises and falls during a normal 24 hour day. It is important to establish THI under conditions normally experienced by lactating dairy cows. In addition, the most appropriate parameters need to be identified. For example, average, minimum, maximum, and hours above a certain THI all need to be examined. Research has reported that minimum THI is more highly correlated with a reduction in feed intake compared to maximum THI (Holter et al., 1996). When evaluating test day yields results showed a decrease of 0.2 kg per unit of THI increase above 72 when THI was composed of maximum temperature and minimum humidity (Ravagnolo et al., 2000).

The effects of radiant heat load can be evaluated using the BGHI ($BGHI = t_{bg} + .36t_{dp} + 41.5$ where t_{bg} = black globe temperature °C and t_{dp} = dew point temperature, °C), developed by Buffington et al. (1981). Research has demonstrated that BGHI had increased correlations to rectal temperature increases and milk yield decreases compared to THI (Buffington et al., 1981). It has also been shown that the correlation of BGHI to milk yield is greater ($r^2 = .36$) under conditions of high solar radiation (no shade) than under a shade structure ($r^2 = .23$; Buffington et al., 1981). However, milk production in this study was considered to be low (average 15 kg/cow). Therefore, correlations of BGHI to milk yield under shade structures might be higher with higher producing dairy cows (which are more sensitive to increased heat loads). It is also apparent a great deal of variation is not explained by BGHI. This might be improved by determining the impact of an additional factor like skin temperature.

Another option in measuring radiant environmental temperature is by using infrared technology to measure skin surface temperature. In doing this we can account for differences in microenvironment around the animals and have a greater accuracy of measuring environmental heat load. Creating a skin temperature humidity index ($STHI = t_s + .36 t_{dp} + 41.5$ where t_s = infrared skin surface temperature $^{\circ}C$ and t_{dp} = dew point temperature, $^{\circ}C$), might allow for greater prediction of an animal's heat stress compared to BGHI or THI. Using infrared thermography guns it is possible obtain rapid and reliable skin surface temperatures. These parameters would be best to evaluated under controlled environmental conditions and confirmed under practical management conditions. Under commercial dairy conditions vaginal temperatures can be used to continuously record core body temperatures as other researchers have conducted (Araki et al., 1985; Ominski et al., 2002). Obtaining core body temperature in addition to simultaneous recording of black globe and dry bulb temperatures and humidity as well as milk yield will permit determining relationships between ambient heat load, core body temperature and subsequent milk yields.

Conducting studies where temperature and humidity are controlled in a circadian manner, in order to mimic natural environmental conditions, has not been conducted. Feed intake and milk yield under natural conditions has resulted in mean THI two days prior to milk production to have the greatest effect on both intake and yield (Collier et al., 1981, West et al., 2003). Unfortunately, because these results were not obtained in controlled environment researchers were unable to quantify the relationship between THI and milk yield.

The goal of this study was to utilize high producing dairy cows and including radiant energy impacts on animal performance. Specific objectives were to determine the effects of minimum, maximum, average THI and the number of hours at a given THI on milk production of high producing dairy cows.

Materials and Methods

The data analyzed in this study was taken from 8 different studies over the course of three years. One hundred multiparous Holstein cows were housed in individual tie stalls in one of two environmentally controlled chambers in the William Parker Agricultural Research Center at the University of Arizona. The University of Arizona's Institute of Animal Care and Use Committee approved all protocols and use of animals in the current study. Temperature humidity Index (THI) was calculated using dry bulb temperature (T_{db} , $^{\circ}F$) and relative humidity (RH), ($T_{db} - (0.55 - (0.55 * RH / 100)) * (T_{db} - 58)$; Buffington et al., 1977). Black globe humidity index was calculated by using black globe temperature (T_{bg} , $^{\circ}C$) and RH (Buffington et al., 1981). Milk yields, feed intake, water intake, skin temperature, rectal temperature, respiration rate and sweating rate was measured in all cows daily.

Groups 1-4

Forty-eight multiparous lactating Holstein cows were balanced for parity and stage of lactation and assigned to an incomplete crossover design involving two levels of radiant heat load, 2 levels of dry bulb temperature, and two levels of humidity. These parameters were then combined to produce eight experimental environments. Each of these eight environments have a range of dry bulb temperature, radiant energy, relative humidity, and THI values mimicking a possible 24 hour period under shade structures during summer months in the southern part of the United States. Cows were housed at the University of Arizona, William J. Parker Research Complex, in two environmental chambers, with only one room capable of producing radiant heat load. Six cows were housed in each environmental chamber, each group consisted of 12 cows therefore, four groups of animals (n=12) were brought to the facilities at separate times in order to reproduce eight environments. Each group of animals experienced a minimum of two and a maximum of three environments over a 22 d period. Animals entering the facility were provided seven days to acclimate to the chambers in a thermal neutral environment (Environment #3). Followed by a four day experimental environment, then cow's switched environmental chambers and were provided seven days to acclimate to the new chamber in a thermal neutral environment (Environment #3). After seven days, cows experienced the opposite experimental environment for four days. Cows were milked and fed twice daily with orts measured once a day prior to the morning milking. During adjustment periods, respiration rates (RR), surface temperatures (ST), evaporative heat loss (EVHL), rectal temperatures (RT), and heart rate (HR) were measured. Skin temperatures and sweating rates were measured from the shoulder, ribs, and rump of the animal twice a day (0500 and 1700 h). These same heat parameters were measured four times a day (0500, 1000, 1400, and 1700 h) during the four day experimental periods. On the 3rd d of each 4 d period a 24 h recording of these same observations were made every hour on the hour. Skin temperatures were measured with an infrared temperature gun (Raynger® MX™ model RayMX4PU Raytek C, Santa Cruz, CA). Rectal temperatures were measured using a digital thermometer (GLA M700 Digital Thermometer, San Luis Obispo, CA). Respiration rates were obtained by visually counting flank movements during a 15 sec interval and multiplying by 4 and evaporative heat loss was measured using an evapometer (Delfin Technologies, LTD., Finland). Heart rate was measured by cardiac auscultation. Environmental parameters recorded hourly and used for calculations of BGHI and THI are ambient temperature (T_{db}), relative humidity (RH), black globe temperature (T_{bg}), and radiant energy.

Group 5

Twelve multiparous mid lactation cows were assigned to one of two studies in January or June of 2004. Animals were balanced for parity and assigned to one of two environmental chambers at the University of Arizona, William J. Parker Research Complex. Environmental treatments consisted of one thermal neutral environment (8-15°C, 8-40% humidity) and two heat stressed environments 1) 30-40°C, 8-40% humidity and 2) the same heat stress conditions with the addition 4 h of solar radiation at 600 watts/h/m² from 1100 to 1500 h). Animals were provided

seven days to adjust to the facilities and then experienced 3 14 d periods in an incomplete, crossover design. Solar lamps were only available in one of the environmental chamber rooms; cows had to switch rooms prior to the third period so that all animals experienced all environments. Once animals switched rooms they were provided 7 d to re-adjust to their new environmental chamber prior to period 3. Cows were milked two times a day (0600 and 1800 h) and milk weights recorded at each milking. Animals were fed a total mixed ration two times a day (0700 and 1700 h) and orts were weighed and recorded prior to the morning feeding.

Heat parameters were measured bihourly on d 6 of each period. Skin temperatures were measured with an infrared temperature gun on the right and left side of the animal on the middle of the rump and loin (Raynger® MX™ model RayMX4PU Raytek C, Santa Cruz, CA). Rectal temperatures were measured using a digital thermometer (GLA M700 Digital Thermometer, San Luis Obispo, CA). Respiration rates were obtained by visually counting flank movements during a 15 sec interval and multiplying by 4 and evaporative heat loss was measured using an evapometer (Delfin Technologies, LTD., Finland). Heart rate was measured by cardiac auscultation.

Group 6

A total of twelve lactating multiparous Holstein cows averaging 140 ± 13 DIM were assigned randomly to one of two environmental chambers at the William J. Parker Agricultural Research Complex at The University of Arizona. Cows were milked twice a day and recorded for daily milk yield. A total mixed ration was fed twice daily and weigh backs were measured once a day prior to the morning feeding. Dairy Nutrition Services (Chandler, AZ) formulated the TMR to meet or exceed energy requirements according to NRC, 2001. All studies were approved by the University of Arizona Institutional Animal Care and Use Committee. Cows were given seven days to acclimate in the environmental chambers and both groups regardless of treatment were exposed to thermal neutral conditions (20°C, 20% humidity, THI = 64). Following acclimation, cows continued to experience the same thermal neutral conditions for an additional 9 d and allowed to eat ad libitum (Period 1; P1). Period 1 and period 2 (P2) were separated by a 7 d where cows remained in the same thermal neutral condition. During P2, cows in group 1 remained in the same thermal neutral condition while cows in group 2 experienced heat stress (HS) and were fed ad libitum. In order to mimic daily variations, during HS cyclical temperatures ranged from 29.4 to 38.9°C with humidity held constant at 20%, THI ranged from 73 to 82 daily. Respiration rate (RR), skin temperatures (ST) and rectal temperatures (RT) were measured and recorded four times daily (0600, 1000, 1400, and 1800 h). Measuring RR was done by counting flank movements for 60 sec. On a shaved section on the shoulder of the cow skin temperatures were measured with an infrared temperature gun (Raynger® MX™ model RayMX4PU Raytek C, Santa Cruz, CA). Rectal temperatures were measured using a digital thermometer (GLA M700 Digital Thermometer, San Luis Obispo, CA).

Group 7

Ten lactating multiparous Holstein cows averaging 99.8 ± 20.2 DIM were randomly assigned to one of two environmental treatments over the course of three experimental periods. All animals were housed at The University of Arizona, William J. Parker Research Complex in tie-stall stanchions in the environmental chambers. Animals were exposed to three experimental periods, period 1 (P1), 7 d of thermal neutral conditions, period 2 (P2), 7 d of heat stress, and period 3 (P3), 7 d of heat stress; totaling 21 d to complete the entire study. Period 1 consisted of thermal neutral conditions (20°C, with humidity held constant at 20% with a 12 and 12 h light and dark cycle). Period 2 and P3 environments consisted of heat stress with cyclical daily temperatures in order to mimic daily variations (ranging from 29.4 to 38.9°C with humidity being held at 20%, THI = 72.4 to 82.2, with a 12 and 12 h light and dark cycle). All cows were fed a total mixed ration three times a day (0500, 1200, and 1700 h) and orts were recorded once a day prior to the morning feeding. All cows were allowed to eat ad libitum. All cows were milked two times a day (0500 and 1700h) and recorded at each milking.

Heat parameters such as respiration rate, surface temperature (from the shoulder, rump, and tail head), and rectal temperatures were measured four times a day (0600, 1000, 1400, and 1800 h). Surface temperatures were measured using an infrared temperature gun (Raynger[®]MX[™] model RayMX4PU Raytek C, Santa Cruz, CA). Rectal temperatures were obtained using a standard digital thermometer (GLA 525/550 Hi-Performance Digital Thermometer, San Luis Obispo, CA).

Group 8

Eighteen second lactation Holstein cows averaging $89.2 (\pm 8.1)$ DIM were randomly assigned to an environmental chamber room into individual tie stalls located at the University of Arizona William J. Parker Research Complex. The chamber rooms only house six cows at a time therefore the study was replicated three times and one cow was removed from the study due to temperament issues in the facilities. All cows were milked two times a day and milk weights were recorded at each milking (0500, 1700 h). All cows were fed a totally mixed ration (TMR) two times day at milking times and orts were recorded prior to the morning feeding. Cows were housed at the University of Arizona dairy for 19 days prior to entering the environmental chambers. While at the dairy, cows received one of two dietary treatments 1) Control diet with 0 g/ton Rumensin or 2) the control diet top dressed with Rumensin at 450 mg/cow/d. Once they entered the facility they were provided 3 d to adjust however, continued on their dietary treatment. All cows regardless of dietary treatment experienced a constant thermal neutral environment (20% humidity, THI = 64, with 14 h light and 10 h dark cycles) and allowed to eat ad libitum for 9 d (experimental period [P] 1). They were then given 2 d in the same thermal neutral environment prior to experiencing P2 (experimental period [P] 2) which consisted of cyclical temperatures (29.4 to 38.9°C with constant 20% humidity, $\text{THI} \geq 73, \leq 82$ and 14 h light and 10 h dark cycles) and were fed ad libitum. This environment was made to replicate daily

variations in temperatures throughout the day. Heat parameters were collected three times a day (0600, 1500 and 1800 h). Respiration rates were obtained by counting flank movements for 15 sec and multiplied by 4 for a total of breaths per minute. Surface temperatures were measured on a shaved patch (~5 cm²) of skin on the shoulder of the animal using an infrared temperature gun (Raynger[®]MX[™] model RayMX4PU Raytek C, Santa Cruz, CA). Using a standard digital thermometer (GLA M700 Digital Thermometer, San Luis Obispo, CA) rectal temperatures were measured. Environmental parameters recorded hourly and used for calculations of THI are ambient temperature (T_{db}) and relative humidity (RH).

Statistics

Data was analyzed using ANOVA and REGRESSION procedures of SAS (SAS, 1999). Milk yields were recorded during the acclimation periods and prior to environment initiation and were included as a covariate in the analysis. The dependent variable analyzed was milk yield, RR, ST, RT, HR, and EVHL. The independent variables included daily THI, ST, STHI and BGHI. The level of significance was set at P < 0.05 for all main effects and interactions and the LSMEANS test was conducted when significance was detected.

Results

As expected, as THI values increased the rectal temperatures and respiration rates of cows increased, (figures 1 and 2)

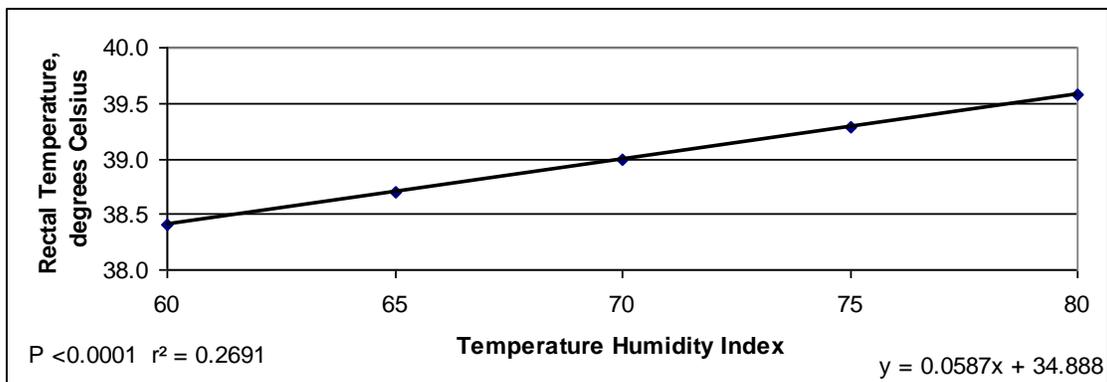


Figure 1. Effect of increasing temperature humidity index on rectal temperatures in lactating Holstein cows.

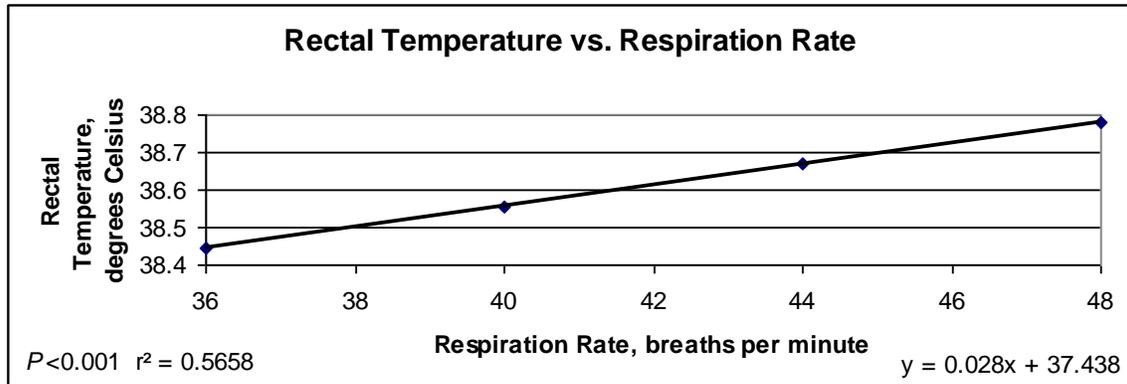


Figure 2. Rectal temperature vs. respiration rate.

Respiration rates increased by 2.0 breaths per minute per increase in THI unit ($P < 0.001$; $r^2 = 0.4343$). Evaporative heat loss at the skin was also found to increase as rectal temperatures were increased (Figure 3, $P < 0.001$; $r^2 = 0.0556$). These increases in evaporative heat loss indicate that the cow is at or above its upper critical temperature.

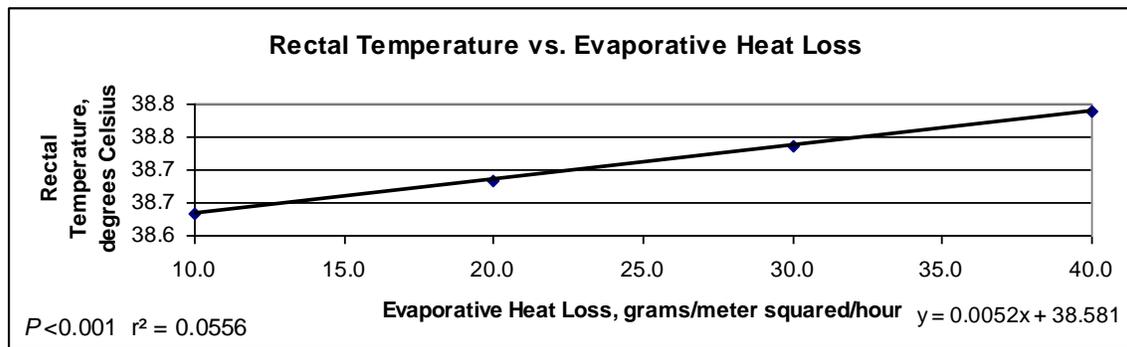


Figure 3. Rectal temperature vs. evaporative heat loss.

As THI, rectal temperatures and evaporative heat loss increased milk yields were shown to decrease linearly (Figures 4 and 5). This decrease in milk yield was linear between THI values of 60 and 80 indicating that milk yield losses were occurring well below a THI threshold of 72.

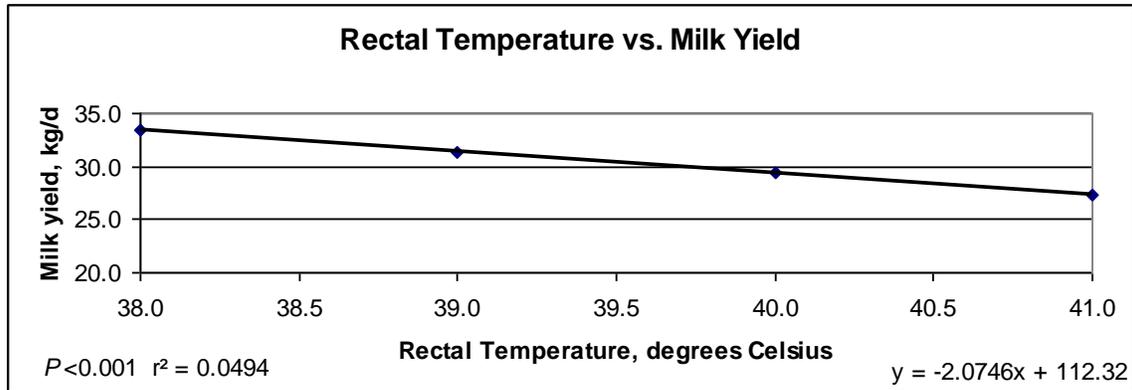


Figure 4. Rectal temperature vs. milk yield.

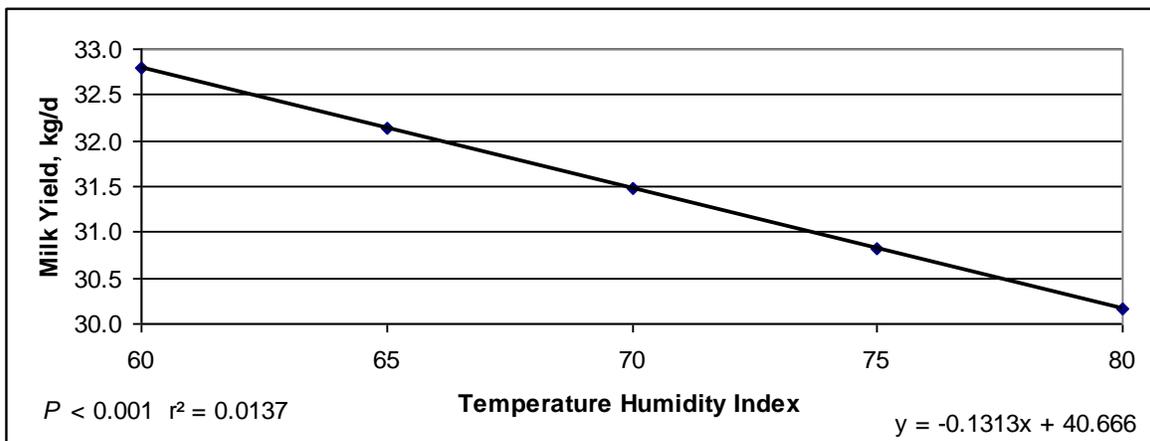


Figure 5. Effect of increasing temperature humidity index on milk yield in lactating Holstein cows.

Evaluation of data on minimum THI indicates that milk yield losses become significant when minimum THI on any given day is 65 or greater. Average losses in milk yield per day were 2.2 kg per day between a minimum THI of 65 and 73. Thus suggests that cooling of dairy cows should be initiated anytime minimum THI is 65 or above or when average THI is 68.

Table 1. Effect of minimum temperature humidity index (THI) on milk yield in lactating Holstein Cows producing greater than

35 Kg milk per day

<u>Min THI</u>	<u>Slope</u>	<u>P-value</u>
49	-1.01	0.26
50	0.55	0.72
51	0.21	0.52
55	-0.28	0.76
63	-0.09	0.86
64	-0.04	0.91
65	-2.63	0.0007
66	-2.04	<0.0001
70	-3.250	0.006
73	-1.08	0.015

We also investigated the time interval required at an average THI of 68 before milk yield losses became significant. This data indicated that milk yield losses became significant after 17 hours of exposure to an average THI of 68 and equated to a 2.2 kg per day loss in milk yield. Thus, our data indicates that for dairy cows producing more than 35 kg/day need additional cooling when minimum THI is 65 or greater or when average THI is 68 for more than 17 hours per day.

Discussion

Although current cooling standards utilize a THI thresh hold of 72 before initiation of cooling, our research indicates that adverse affects can be shown as early as a THI of 68. During this study we found that physiological parameters and milk yields were affected at THI values well below 72. When analyzing the data it was observed that between a THI of 64 and 72 there were large reduction in milk yields therefore chose to analyze hours above a given THI between 65 and 72 to get a more precise estimate of the threshold and subsequently arrived at a threshold of 68. When researchers analyzed data of on farm studies they have also concluded that at an average THI of 68 milk production begins to decline however, based on entire analysis of the data they still summarize that a THI of ≥ 72 is when adverse affects are seen (Ravagnolo et al., 2000). Our results indicate that a daily THI equal to 68 results in a milk loss of 2.2 kg/day for each 24 hours. Another study reported milk yield decreases by 0.2 kg per day per unit of THI as THI increased above 72 (Ravagnolo et al., 2000). In the current study milk yield decreases averaging 2.2 kg were observed when animals experienced a minimum THI of 65 or greater ($P <$

0.05). Johnson et al., (1963) summarized that DMI and milk yield were shown to decrease significantly when maximum THI reached 77, this was later re-assessed and values of 64, 72, and 76 for minimum, average, and maximum THI were given respectively (Igono et al., 1992).

The black globe humidity index may perhaps be a more ideal measurement of heat stress due to the fact that solar radiation is incorporated. When calculating the black globe humidity index from these studies, only four out of the eight studies actually recorded the appropriate values in order to produce the BGHI. Therefore, small numbers of observations are attributed to the lower values and correlations observed were very small. Thus, we did not produce evidence that BGHI was superior to THI for estimating the threshold temperatures for milk yield loss.

The next question is a practical one. What is the cost return to the producer for cooling beginning at an average THI of 68 versus 72? If we use an example employing 100 dairy cows which are being cooled by a Korral Kool cooler we should expect a milk yield gain of 2.2 kg of milk per day beginning cooling at 68 versus 72. For 100 dairy cows, that would equate to a milk yield gain of 4.84 CWT's. Using a milk price of \$17.00 and a feed price of \$14.00 the income above feed costs would be \$14.52. The cost of using the coolers is shown in Table 2 from Burgos et al. 2007. Using a variable cost of \$0.14 per cwt of milk produced and assuming each cooler would cool 10 cows the total cooler variable cost would be \$6.8 producing an income of \$7.09 per 100 cows or \$0.071 per cow per day. In a herd of 3000 lactating dairy cows the potential income would equate to \$213 per day or \$1491 per week. This does not take into account any beneficial effects on reproductive performance in these cows.

However, the cost of cooling could be reduced dramatically by using geothermal conductive cooling of cows. Bastian and co-workers 2003 demonstrated that waterbeds filled with chilled water offered an alternative cooling method for dairy cows. However, there was considerable condensation on the surface of the cooled waterbed which would represent a mastitis risk to dairy cows. Recently collaborative work by Agriaire Industries and the University of Arizona has demonstrated that heat exchangers could be buried 12 inches below the surface of a freestall bed and still provide significant conductive cooling to dairy cows. Geothermal cooling would represent significant cost reduction in reducing heat stress on dairy cows and offers the additional opportunity of using the same approach to warm cows during cold winter months in northern dairy locations. Field testing of this concept is currently underway.

Table 2. Summary of investment and operating costs KK system.¹

Variable	
Cooling System Investment, \$ ²	118,067.5
Cooling System Investment, \$/cow	472.00
Electrical Usage, KWh/d	723
Electrical Cost, \$/d	32.33
Electrical Cost, \$/cow/d	0.13
Water Usage, L/d	305
Water Cost, \$/d	4.03
Water Cost, \$/cow/d	0.016
Variable Cost, \$/d ³	36.36
Variable Cost, \$/cow/d	0.15
Variable Cost, \$/cwt/d	0.14

¹Adapted from Burgos et al. 2007. Daily computations were divided by 119 days and per cow computation were divided by 250,

²Seventeen 0.72m ADS-ST fans and twenty 1.2m KK coolers (curtains included),

³Water (\$0.01/liter) and electrical (0.0446/KWh) rates were calculated from Stotz Dairy, Buckeye, AZ.

Conclusion

Re-evaluation of the temperature humidity index provides the industry with solutions for tomorrow. Through this study it proved to be underestimated for current high producing dairy cows. Results show that THI beginning at 68 affect dairy cows adversely during heat stress. Therefore, cooling methods on commercial dairy farms should be implemented earlier to prevent these effects. Parameters indicative of heat stress were also shown to be correlated with THI and therefore are measurements that can be obtained to evaluate the degree of heat stress in the animal. Further research should be conducted to evaluate the relationship between BGHI and physiological parameters as with the addition of solar radiation effects perhaps the correlations would be greater; especially after arithmetic means demonstrate strong correlations between BGHI or THI to skin surface temperature and respiration rate.

References

- Araki, C.T., R.M. Nakamura, L. W. Kam and N.L. Clark. 1985. Diurnal temperature patterns of early lactating cows with milking parlor cooling. *J. Dairy Sci.* 68:1496-1501
- Armstrong, D.V. 1994. Heat stress interactions with shade and cooling. *J. Dairy Sci.* 77:2044-2050.
- Bastian, K.R., K.G. Gebremedhin and N.R. Scott. 2010. A finite difference model to determine conduction heat loss to a water-filled mattress for dairy cows. *Trans ASAE* 46:773-780.
- Berry I.L, M.D. Shanklin and H.D. Johnson. 1964. Dairy shelter design based on milk production decline as affected by temperature and humidity. *Trans. Am. Soc. Ag. Eng.* 7:329-331.
- Berman, A. J. 2005. Estimates of heat stress relief needs for Holstein dairy cows. *J. Anim. Sci.* 83:1377-1384.
- Collier, R.J., R.M. Eley, A.K. Sharma, R.J. Pereira and D.E. Buffington. 1981. Shade management in subtropical environment for milk yield and composition in Holstein and Jersey Cows. *J. Dairy Sci.* 64: 844-849.
- Igono, M. O., G. Bjotvedt, and H. T. Sanford-Crane. 1992. Environmental profile and critical temperature effects on milk production of Holstein cows in desert climate. *Int. J. Biometeorol.* 36:77-87.
- Linville, D.E., and F.E. Pardue. 1992. Heat stress and milk production in the South Carolina coastal plains. *J. Dairy Sci.* 75:2598-2604.
- Ominkski, K.H., A. D. Kennedy, K. M. Wittenberg and S.A. Moshtaghi Nia. 2002. Physiological and production responses to feeding schedule in lactating dairy cows exposed to short-term, moderate heat stress. *J. Dairy Sci.* 85:730-737.
- Purwanto, B.P., Y. Abo, R. Sakamoto, F. Furumoto, and S. Yamamoto. 1990. Diurnal patterns of heat production and heart rate under thermoneutral conditions in Holstein Friesian cows differing in milk production. *J. Agric. Sci.* 114:139-142.
- Ravagnolo, O and I. Miztal. 2000. Genetic component of heat stress in dairy cattle, parameter estimation. [J Dairy Sci.](#) 83:2126-30.
- Spiers, D.E., J.N. Spain, J.D. Sampson and R.P. Rhoads. 2004. Use of physiological parameters to predict milk yield and feed intake in heat-stressed dairy cows. *J. Thermal Biol.* 29:759-764.
- Thom, E.C. 1958. Cooling degree days. *Air Conditioning, Heating and Ventilating* 55:65-69.