EVALUATING NEW VENTILATION RATE AND EVAPORATIVE COOLING FOR MODERN SWINE PRODUCTION

BY

YANXI LU

THESIS

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Adviser:

Clinical Assistant Professor Morgan Hayes

Abstract

Heat and moisture production (HMP) rates of animals are used for calculation of ventilation rate (VR) in animal housing. New swine HMP data revealed considerable differences from previously reported data. This project determined new design VR for swine barn and evaluated differences from previously recommended VRs. The phases of swine production evaluated included gestation, farrowing, nursery, growing and finishing. The ranges of ambient temperature and ambient relative humidity (RH) evaluated for minimum VR were -25 to 15°C at 10°C increment and 15% to 75% at 15% increment, respectively. Indoor set points for temperature and RH were, respectively, 15, 20, 25°C and 60%, 70%, 80% for all five ambient conditions. The results showed that the old VR for moisture control was 54.2%, 30.0%, 69.3%, 31.4% and 52.8% lower than the new VR in gestation, farrowing, nursery, growing and finishing stages, respectively. For hot weather conditions, there is an additional concern that the higher HMP of the pigs could increase the occurrence of heat stress if VR recommendations are not increased. Heat stress reduction by using evaporative cooling and maximum VR were estimated based on long term weather data generated by a stochastic model for locations including Sioux City, IA, Fayetteville, NC and Texas, OK. Temperature-Humidity Index (THI) was used as an indicator to evaluate animal heat stress. Effects of operating a barn with and without evaporative cooling and using different maximum VR on indoor THI were studied. The results indicated that pigs went through longer time periods and higher intensity of conditions above a critical THI threshold when not using evaporative cooling. July showed the greatest opportunity for reducing critical THI conditions using evaporative cooling, especially the period from 15:00-17:00. Evaporative cooling can substantially reduce the heat stress duration during evening through the midnight and also relieve the magnitude of heat stress during afternoon. Maximum rate of ventilation and evaporative cooling were recommended to be used jointly during July especially for gestation and farrowing stages.

To my adviser, parents and grandparents

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Chapter 1. General Introduction and Literature Review

1.1 Introduction

For the past sixty years, pigs have been predominantly raised indoors for better food safety, management and performance (Brown-Brandl et al., 2004). It is critical to have adequate control of temperature and humidity for animals raised in barns to maintain high levels of animal well-being and productivity (Zhang, 1994). During summer, high temperature and high relative humidity contribute to heat stress, which has very board effects on animal behavior and physiology. Pigs are relatively sensitive to high environmental temperature comparing with other species of livestock (Panagakis and Axaopoulos, 2006), so it is necessary to reduce the potential of heat stress during summer. During winter, the primary goal of environmental control is to remove excessive moisture of barns, which results in the growth of disease microorganisms and degrades the structural integrity (Albright, 1990).

The ventilation design is an important part of strategy used to control indoor climate for swine (Zhang, 1994). Rates of sensible heat production (SHP) and latent heat production (LHP) or moisture production (MP) from animals and their housing environmental conditions are important (W/kg, W/kg and $g/hr^{-1}kg^{-}$ for SHP, LHP and MP respectively) in swine housing design since they can be used for calculation of design VR. Most of the VR designs for swine housing have been based on SHP and MP rates from studies conducted in the 1950s and 1970s (Stinn and Xin, 2014; Brown-Brandl et al., 2004). Since there has been a great deal of changes in genetics, nutrition/feeding, and production methods (Brown-Brandl et al., 2004), SHP and MP for both the swine and their modern facilities have changed and VR is expected to be different from previously recommended VR. Updated recommendations for ventilation are necessary for designing and managing modern swine.

During summer, the heat stress reduction is main goal for indoor climate control. Evaporative cooling is a strategy that has long been recommended to increase swine comfort under hot weather condition (Gunhan, 2006). While the ventilation system can limit the rise in temperature of the barn, evaporative cooling can reduce the temperature by the process of adiabatic saturation. Evaporative cooling had been commonly used in the Southwest and is becoming popular in the Midwest. Comparing with simple tunnel ventilation system, combinations of the ventilation system and evaporative cooling are believed to effectively reduce heat stress of pigs (Stinn and Xin, 2016). Misting and cooling pad were two most popular strategies in evaporative cooling (Bridges et al 1992). Both systems were used to minimized the inside temperature humidity index (THI). Misting systems were found to be efficient in broiler and turkey houses in the Southeast. It has low initial investment comparing with traditional pad system (Bridges et al 1992). However, pad system was found to be more effective for resulting in smaller daily inside dry-bulb temperature variation, maximum reduction of apparent heat intensity and lower total consumption of water (Panagakis, 2005). Strategy of evaporative cooling is referred as cooling pad in this study.

1.2 Literature Review

1.2.1 Updated Heat Production Rate and Moisture Production Rate

Research about HMP update was accomplished for other species of farm animal. Total THP was 12% to 37% higher for pullets and 12% higher for lay hens than that recommended by CIGR (Chepete et al, 2004) and both SHP and LHP indicated significant difference from the old value. The new HMP provided basis of updating design and operation of poultry housing ventilation systems (Chepete et al, 2004). In the article published by Chepete and Xin (2004), newly collected data showed SHP and MP were 8.0% lower and 22% higher than the old bird-level values, which had previously been the basis for evaluating the design and operation of laying-hen house ventilation system. VR based on old SHP and MP values were 10% higher and 18% lower, respectively, for temperature control and moisture control than the new VR. The paper closely evaluated how balance temperature was influenced by indoor temperature and RH set points (Chepete and Xin, 2004).

Similarly, higher SHP and MP have recently been published in two papers on swine production. Advancements in animal genetics, nutrition and management practices have led changes in HMP rates of modern swine and housing systems (Stinn and Xin, 2014). The article from Brown-Brandl et al. (2014) provides recently collected HMP data for all phases of modern swine production. HMP at both calorimeter-level and facility-level were studied. Heat and moisture production of swine were compared at different stages, including nursery piglets, growing pigs, early finishing pigs, late finishing pigs, gestating gilts and farrowing sows. Calorimeter-level THP and LHP were described by linear regression equations based on ambient temperature and animal weight. The results indicated that the facility-level THP agreed with the calorimeter data except for the nursery piglets, but LHP values at the calorimeter-level were less than those observed at the facility level. THP of modern pigs is higher than the current standards except for nursery stage. Updated THP and MP values were recommended by the authors to design VR for existing swine facilities. In the article published by Stinn and Xin (2014), facility-level THP and MP rates of modern U.S breeding swine in gestation and farrowing were studied. Comparing with old data from ASABE standard, THP, LHP and SHP were 35%, 72% and 19% higher than the old values of early gestation stage and 12%, 34%, and 3% higher than the old values for late gestation. Values for farrowing stage showed increases of 29%, 52% and 6% in THP, LHP, and SHP compared to ASABE Standard (ASABE, 2013). Updating of standards used in the design and operation of ventilation systems for swine barn was also recommended (Stinn and Xin, 2014).

1.2.2 Swine Heat Stress

Farm animals are known to have a thermal comfort zone, which varies based on the species, the physiological status of animals, the size, and weather conditions (St-Pierre et al., 2003). The animals can acclimate to meet the thermal challenges to some extent. Exceeding of thermal zone of the animal due to environmental conditions can cause heat stress (Nardone et al., 2010). Heat stress results from the imbalance between the net amount of energy from surrounding environment, which flows from the animal and the amount of heat produced absorbed by the animal (St-Pierre et al., 2003) which results in heat storage in the animal and subsequent core body temperature rise. The detrimental effects of heat stress include feed intake reduction, increase of respiration rates and rectal temperature, slower growth, and poor reproduction efficiency (Bull et al., 1997). The productivity of swine can be negatively affected due to the physiological change mentioned above. For sows, heat stress has consistently reduced the milk yield, increasing the lactation weight loss for both sow and litter and piglet mortality. In addition, heat stress affects fertility of both male and female pigs (St-Pierre et al., 2003). For growing pigs, growth rates and resulting feed conversions of swine were dramatically reduced by exposing to moderate heat stress (Brown-Brandl et al., 1998). Annual losses averaged $299 million for swine industries due to heat stress and the losses mainly accounted in Texas, California, Oklahoma, Nebraska and North Caroline (St-Pierre et al., 2003).

1.2.3 Temperature-Humidity Index

Many stress indicators have been used to quantitatively evaluate the heat stress on animals: respiration rate, respiratory volume, pulse rate, skin temperature and other physiological characteristic (Bull, 1997). Thermal indices can develop relationships between animal stress and multiple environmental factors, which can serve as guidelines of decision-making for environmental control (Lucas, 2000). Currently, many thermal indices have been used to estimate the degree of thermal stress by animals. Thermal indices typically include temperature and a least one other environmental factor like humidity, wind speed, or solar radiation. The common thermal indices used in heat stress evaluation are the temperature-humidity index (THI). Each thermal index was based on certain biological consequences such as skin temperature, rectal temperature, and respiration rate etc (Gates et al, 1991). Moreover, the sensitivity of different species to same environmental factor can vary. For example, the moisture content of air has less effect on non-sweating species such as swine and poultry than those sweating species such cattle (Hahn et al, 2009). Thermal indices should be carefully examined based on objectives of the study and species of interest. Ideally, "each index value will always result in a unique thermophysiological effect, regardless of the combination of the input meteorological input value" (Hahn et al, 2009). In this study, concerns of body temperature altering by ambient temperature and humidity in summer should be regarded as a priority comparing with other biological indicators. Study by Tompkins (1967) showed increasing ambient temperature elevated rectal temperature of the sows resulting in reduced of embryonic survival. Heitman et al. (1958) found the high body temperature contributed to the low weight gain of animals especially for pigs in the growing and finishing stage. To account for differences in reproductive and growth efficiency for all stages for swine production, the selected thermal index used in this study should be correlated with core body temperature (Ingram, 1964).

1.2.4 Maximum and Minimum Ventilation Rate

Steady-state sensible heat and moisture balance can be used to determine VR as a function of building thermal properties, stocking density and outdoor condition. VR for humidity control can be calculated by following equation (Albright 1990):

$$V_{H_2O} = \frac{MP \times M}{\rho \times (W_i - W_o) \times 1000} \tag{2}$$

where is V_{H2O} for moisture control (m^3hr^{-1}), M is total body mass of animals in facility (kg); MP is moisture production ($ghr^{-1}kg^{-1}$); ρ is the density of air (kg m^{-3}) based on outside temperature and is the inverse of specific volume; W_i and W_o are inside and outside humidity ratio (kg H_2O/kg dry air), respectively.

VR for temperature control can be calculated by the following equation (Albright, 1990):

$$V_{temp} = \frac{SHP \times M \times N - (\sum UA + FP)(t_i - t_o)}{C_p \times \rho \times (t_i - t_o)} \times \frac{3600}{N} \qquad (7)$$

where V_{temp} is VR for temperature control (m^3 hr^{-1} hd^{-1}); N is number of animals; U is thermal conductance of each building component in the summation (W m^{-2} °C^{-1}); A is the area of the building component (m^2); FP is the perimeter heat loss factor; t_i is inside air temperature (°C); t_o is outside air temperature; C_p is specific heat of air (J $kg^{-1}K^{-1}$). The contribution of solar heat and heat from lights are ignored and only heat production from animal was considered as indoor heat source based on assumption that the swine building is well-insulated and the low-wattage lights were used (Chepete and Xin, 2004). If evaporative pad is applied, the t_o should be substituted by t_{oe} which is temperature of air as it exits the cooling pad (Albright, 1990).

Minimum VR is determined by comparing the ventilation curves based on the design for temperature control, humidity control and CO_2 control. The criterion for selecting minimum VR at a certain temperature is to choose the maximum ventilation among these three rates (Albright, 1990). It is generally found the CO_2 dominant VR for very cold conditions, which will not be discussed in this study; moisture control governs VR for very cold condition and as ambient temperature exceeds a certain value (balance temperature) the VR for temperature control becomes the dominant (Albright, 1990).

The maximum VR is based on temperature control during warm conditions and issued to limit the rise of indoor temperature above the outdoor temperature. Certainly, in animal barns the rise of indoor temperature is a dominant factor for selecting VR. It can be noted from equation that "temperature rise halved when the ventilation rate doubles" which means the return on increasing ventilation is less for each decrease in temperature rise (Albright, 1990). Albright (1990) suggested that an appropriate air temperature rise is about 1.5°C to 2°C during warmest weather without using evaporative cooling.

1.2.5 Stochastic Weather Model:

Outdoor climatic data are needed to project changes in indoor temperature and humidity due to HMP of pig at different phases of production. Currently, local design air temperatures and humidity are based on historical conditions in the locations listed. These design conditions are published by technical societies like American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) and updated regularly, with various software tool available (e.g Design weather sequence viewer, ver 2.1(ASHRAE, 1997), Weather Data Viewer, Ver 5.0 (ASHRAE, 2013), and International Weather for Energy Calculations, from ASHRAE (Colliver et al, 1995; Colliver et al, 1998). However, evaluating the effects of changing of climates variables on agricultural production should base on a longer period of time, which means more detailed data are needed (Semenov, 1993). Fehr (1983) suggested that using of long-term weather data for calculation could provide a more accurate method of determining the frequency of occurrence of the THI exceeding the specific threshold. Stochastic weather models have been extensively used to generate long time series of weather data, which can construct scenarios of meteorological change to apply to agricultural analysis.

Stochastic weather models and laying hen models were combined to predict the net cost/benefits of evaporative cooling. Two models combined to evaluate the feasibility of the evaporative cooling for animal barn by Gates and Timmons (1988). The daily temperature change was based on a sinusoidal relationship, as given by the following equation

$$OT_{mean} = [(OT_{max} - OT_{min})/2]*[1+\sin((day-100)*\boldsymbol{\pi}/180)]+OT_{min} \quad (1)$$

where OT_{max} and OT_{min} are the maximum and minimum of 12 monthly mean temperature in ^{o}C and “day” is Julian Date. In this case, the model simulated the mean daily temperatures for 200 years to ensure the true population mean can fall into the 95% confident interval. In Semenov (1993), a crop simulation model was incorporated with climate model to predict crop growth influenced by climatic variability. A relatively complex stochastic weather model was introduced. Variables such as maximum temperature and solar radiation were conditioned on the wet-day or dry-day, so precipitation occurrences were first generated in the model. The amount of precipitation was estimated according to a mixed exponential distribution (Johnson, 1996). Other weather generation models may use different distributions. The weather generation model Mearns (1997) simulated precipitation occurrence by using two-state first-order Markov Chain model. Once the condition of wet and dry was determined, daily temperature and sunshine-hours can be simulated based on some statistical distributions such as normal distribution. The seasonal variations of the parameters including precipitation and temperature were analyzed by Fourier series (Johnson, 1996). Mearns (1997) also compared the actual data and results of simulated weather model and found “good agreement between historical and generated data” in both precipitation and temperature data. These researches demonstrated the utilities of using stochastic model for those agricultural studies addressing extreme climate condition. Since the indoor microclimatic change of animal barn was strongly impacted by the outdoor conditions, weather data generated from stochastic model were valuable for predicting heat stress events.

Weather generator used in this study is AgGEM which can be downloaded freely from NRSC website (www.nrcs.usda.gov). It was originally published in Agricultural Research Service Report in 1984 known as “WGEM” written by Richardson, C.W, and Wright, D.A. The more recent version is named as GEM6 (NRCS, 2016). A Study from Johnson (1996) showed that “WGEM” had been extensively applied to many agricultural researches projects such as wheat simulation model which tests the climatic variability on wheat yields in different locations. The author claimed that data generated by GEM6 could closely mimic most aspects of the true climate of many locations (Johnson, 1996). The latest version GEM6 was known as AgGEM and can do everything that GEM6 did (NRCS, 2016).

Input files containing historical weather data are needed by AgGEM. 233 US Stations had been already developed statistical parameter files, which can be used as input the file of AgGEM, so AgGEM can only be directly applied if the locations are near enough to any one of the 233 stations. To obtain the climatic information of locations other than the 233 stations, users were recommended to develop their own input file based on at least 20-year historical data without any missing data, however, access to obtain weather stations without any missing data is challenging.

1.2.6 Evaporative Cooling Efficiency and Applications:

The most common method for evaporative cooling in swine housing is the fan and cooling pad system, which is used to enhance swine comfort during summer. Generally, the components of cooling pad systems include water supply, distribution pipe for water circulating, pad media and water collecting tank (Gunhan et al., 2007). Dry-bulb temperature reduction by evaporative cooling is through the process of adiabatic saturation. As warm air is drawn through the evaporative cooling medium, the humidity of air increases while the temperature reduced because of the evaporation of the water in the cooling pad. The web-bulb temperature of the air was constant during the cooling process (Dağtekin et al, 2009). The most common material used to make cooling pad by manufacturers is cellulose paper. Gunhan et al (2006) tested the efficiencies of evaporative cooling pads made of common materials including fine pumice stones, volcanic tuff, coarse pumice stone, commercial cellulose pads and shading net. The author found that commercial cellulose pad is optimal pad media, which can approximately achieve up to 80% of evaporative efficiencies. The efficiency defined as the difference between inlet dry bulb temperature and outlet dry bulb temperature divided by the difference between inlet dry bulb temperature and wet bulb temperature of inlet air. Malli et al (2010) investigated the overall pressure drop, humidity variation, evaporated water and effectiveness under different inlet air velocities. The author found the amount of evaporated water increase by increasing the inlet air velocity and the thickness of the pad. The effectiveness decreased with greater inlet air velocity.

Currently there have been numerous published studies the feasibility of using evaporative cooling to reduce heat stress in animal barn. Lucas et al (2000) characterized the heat stress situation with and without using evaporative cooling in hourly level during summer in Portugal. Temperature and relative humidity data from four locations were analyzed for the period 1995-1997. THIs were calculated and compared under conditions of with and without using evaporative cooling. The efficiency of evaporative cooling was assumed to be 80%. Lucas (2000) found days with high outdoor temperature tend to have relatively low RH in studying locations suggesting the potential for using evaporative cooling. Moreover, many hours with THI fall into emergency categories (THI $\geq$83) could be eliminated by using evaporative cooling. Lucas (2000) claimed evaporative cooling is a feasible and cost-effective option of reducing heat stress of animal. The indoor humidity and temperature for THI calculations in this study were based on the assumption of not considering conduction heat loss of the building and animal heat production. Fehr (1983) assumed the rise of dry-bulb and wet-bulb temperature resulted from animal heat and moisture production to be 2^{o}C and 1^{o}C, respectively. This assumption was based on the condition of proper ventilation of animal barn. In the study of Fehr (1983), three-hourly weather data for 7 locations in the Southern and Central United States were used to evaluate the heat stress reduction by evaporative cooling. The minimum percent reduction exceeding the THI of 85 using evaporative cooling was 89.6%, which indicates evaporative cooling can substantially reduce the frequency of occurrence of danger level (THI ≥85) of heat stress. In most cases, although the evaporative cooling would not be able to eliminate heat stress, it can reduce the heat stress below the certain level. Besides determining the feasibility from the perspective of THI reduction, the economic benefit of using evaporative cooling was quantified by Gates et al (1988). Laying model based on the relationship for laying hen performance and surrounding temperature were applied to estimate the egg production at different thermal conditions. A stochastic model was used to provide sufficient data about ambient temperature and humidity changes that influence on the indoor thermal conditions. Gates et al (1988) found even considering the marginal cost and installation cost using evaporative cooling can significantly enhance the net return. It was noted that since heat stress is seasonal, the optimal starting date of flock placement is from January to June, which can realize a greater return. Panagakis and Axopoulis (2006) compared evaporative pads and fogging on air in change of indoor temperature and reduction of heat stress in growing swine building by simulation. Indoor temperature and humidity ratio were calculated from ordinary differential equations based on energy balances. The terms of the energy balance included animal sensible and latent heat production, structural heat losses, pen floor heat losses, heat losses from evaporative pad cooling or fogging air. Real hourly data included dry-bulb temperature, relative humidity, solar irradiance and wind speed from May through September in Athens, Greece. THI, the hours that the THI exceeded 85, duration and intensity of heat stress were used as comparison criterions for comparison. During the five-month period, the evaporative cooling pad was found to be more efficient than fogging in reducing heat stress intensity and also made the indoor temperature more stable. It was found that indoor temperature could be up to 7.3°C lower than the outdoor temperature by employing evaporative cooling. Also, to result in the same reduction of heat stress, evaporative cooling used 19.5 times less water than fogging air.

1.3 Objectives.

The overall goal of this study is to update ventilation rates and evaluate the effect of evaporative cooling and ventilation system on indoor environmental control for swine based on new heat and moisture production rates. This study aimed to provide specific guidelines for VR based on varied outdoor and indoor condition and recommendation on evaporative cooling operation for heat stress reduction.

To fulfill the goal, the followed tasks will be accomplished:

1. Calculate new VR for moisture and temperature control based on new HMP.
2. Compare new VR with old VR recommendations.
3. Develop modeling for evaporative cooling evaluation on heat stress reduction.
4. Evaluate effect of evaporative cooling on heat stress with different VR.

Chapter 2. Evaluating Ventilation Rates Based on New Heat and Moisture Production Data

2.1 Introduction

THP can be partitioned into SHP and LHP or MP. Animal-level sensible heat is lost mainly from the animal body while latent heat is dissipated through the pig's breathing and by evaporation from its skin (Zhang, 1994). An ideal ventilation system should reduce the potential for heat stress during hot weather and remove excessive moisture of barns in the winter. During cold weather, under-ventilation would result in high RH, which would poorly affect air quality and be favorable to the growth to disease microorganisms. Also, higher RH leads to excessive moisture building up and condensation in walls during cold weather, which degrades the structural integrity prematurely. In contrast, over-ventilation contributes to a dusty environment, which results in respiratory concerns for the animals and uses excessive fuel to run the supplemental heat (Brown-Brandl, et al., 2014).

With the differences in HMP noted in chapter 1, and similar VR evaluations for other species based on new HMP, the expectation is that the recommended VR for swine housing would increase appreciably. Therefore, the objectives of this chapter were to use the updated HMP values to provide new swine VR and to compare these to previously published recommendations.

2.2 Methods

2.2.1 Data Source in facility and animal level for VR Calculation

Typical THP and SHP values for nursery, growing and finishing stages were from the calorimeter equations while the LHP were from the facility level measurements (Brown-Brandl et al., 2014). Values for the gestation and farrowing stage were from Stinn and Xin (2014) at the facility level. All comparative heat production rates between recent studied and ASABE standards are organized in Table 1. The contribution of solar gain and heat from typically fluorescent lights was ignored, hence animal heat was considered as the only sensible heat source (Chepete and Xin, 2004). LHP or MP at facility level instead of the animal level was used in this study because MP from unvented heaters, water wastage, sprinkle-cooling systems and waste-handling systems was the significant contribution in an empty barn (Brown-Brandl et al., 2014).

Accounting for this facility-level MP would lead to increase in the recommended minimum ventilation.

Table 1. Summary of updated THP, SHP and MP values of swine at different production stages. (Study is new HMP data and ASABE standard is old HMP data)

	Gestation		Farrowing		Nursery		Growing		Finishing	
	Study	ASABE	Study	ASABE	Study	ASABE	Study	ASABE	Study	ASABE
Mass(kg)	204	200	175	177	16.7	17.5	34.0	40.0	117	100
THP(W/kg)	1.86	1.40	3.28	2.60	4.83	5.00	4.04	3.10	2.07	1.90
SHP(W/kg)	0.95	0.97	1.66	1.30	2.85	3.50	2.29	1.60	1.27	1.10
LHP(W/kg)	0.91	0.43	1.62	1.30	5.35	1.50	1.94	1.50	0.82	0.80
MP(g/hr^{1}kg^{-1})	1.34	0.70	2.38	1.80	7.86	2.20	2.85	2.20	1.20	1.20

2.2.2 Ventilation Rate for Moisture Control

Methods of determining minimum VR for moisture control from Chepete and Xin (2003) and Albright (1990) was applied. Minimum VR was calculated as:

$$V_{H_2O} = \frac{MP \times M}{\rho \times (W_i - W_O) \times 1000} \quad (2)$$

where is V_{H2O} is VR for moisture control (m^{3}hr^{-1}); M is mass (kg); MP is moisture production (ghr^{-1}kg^{-1}); ρ is the density of air (kg m^{-3}) based on outside temperature and is the inverse of specific volume; W_i (kg H_2O/kg dry air) and W_o (kg H_2O/kg dry air) are inside and outside humidity ratio, respectively.

$$V_{moisture} = \frac{\frac{1}{P_a} \times R_a \times T \times (1 + 1.6078W)}{1 + W} \quad (3)$$

where is $V_{moisture}$ specific volume of moist air (m^{3}kg^{-1}); Pa is barometric pressure of the inside or outside air, Pa; Ra is dry air gas constant, 287.055(J kg^{-1}K^{-1}); T is absolute dry bulb temperature (K); W(kg H_2O/kg dry air) is humidity ratio for indoor or outdoor air of the following form:

$$W = 0.62198\left(\frac{P_w}{P_a - P_w}\right) \quad (4)$$

where P_w is partial vapor pressure of the indoor or outdoor air of the following form:

$$P_w = RH \times P_{ws} \quad (5)$$

where P_{ws} is saturation vapor pressure of inlet or outlet air of the following form:

$$P_{ws}(t) = e^{\left[\frac{C_1}{t} + C_2 + C_3 \times t + C_4 \times t^2 + C_5 \times t^3 + C_6 \times t^4 + C_7 \times \ln(t)\right]} \quad (6)$$

For -100 ⩽ t < 0ºC, the coefficients are:

C_1= -5.6745359$\times 10^3$, C_2 = 6.3925247, C_3= -9.677843$\times 10^{-3}$, C_4= 6.22157$\times 10^{-7}$, C_5= 2.0747825 $\times 10^{-9}$, C_6 = -9.484024$\times 10^{-13}$, C_7 = 4.1635019.

For 0⩽ t ⩽ 200ºC, the coefficients are:

C_1 = -5.8002206$\times 10^3$, C_2=1.3914993, C_3 = -4.8640239$\times 10^{-2}$, C_4= 4.1764768$\times 10^{-5}$, C_5= -1.4452093$\times 10^{-8}$, C_6=0, C_7 = 6.5459673.

2.2.3 Ventilation Rate for Temperature Control

Methods of determining the VR for temperature control as described by Chepete and Xin (2003) and Albright (1990) were applied. Animal heat was considered as the only heat source. The structure of sidewalls for all the studied barns was assumed to be concrete knee walls with insulated studs above. Insulation R-value of cooling pads, curtain or fans used in the gestation, farrowing, and wean to finish barns were assumed to be negligible; also all buildings were over at least a shallow pit leading to negligible perimeter heat loss factor. VR for temperature control was calculated as:

$$V_{temp} = \frac{SHP \times M \times N - (\sum UA + FP)(t_i - t_o)}{C_p \times \rho \times (t_i - t_o)} \times \frac{3600}{N} \quad (7)$$

where V_{temp} is VR for temperature control (m3 hr^{-1} hd^{-1}); N is number of animals; U is thermal conductance of the building component (W m^{-2} °C^{-1}); A is the area of the building component (m^2); $\sum UA$ term included the constituent components of the wall $(UA)_W$, ceiling $(UA)_c$,and floor $(UA)_f$; FP is the perimeter heat loss factor; t_i is inside air temperature (°C); t_o is outside air temperature; C_p is specific heat of air (J $kg^{-1}K^{-1}$).

2.2.4 Balance Temperature

Balance temperature t_{bal} is the temperature at which ventilation rate for temperature control equals ventilation rate for moisture control, below which supplemental heat is needed to maintain the set-point temperature. This can be determined by plotting V_{temp} and V_{H2O} based on outside temperature and seeing where the lines intersect; it can also be determined by the following equation:

$$t_{bal} = t_i - \frac{3.6 \times 10^6 \times (W_i - W_o) \times X}{MP \times M \times N \times C_p + 3.6 \times 10^6 \times Y} \tag{8}$$

where $X = SHP \times M \times N + (UA)_f \times 5$ $\quad Y = (W_i - W_o) \times [(UA)_W + (UA)_c]$

Balance temperature can be used to estimate the heating degree days or hours and therefore the total amount of fuel or energy needed to heat a space throughout a typical winter.

2.2.5 Facility Description

Building dimensions and capacities for farrowing, gestation, and wean to finish barns are described below. All VR scenarios were run with the assumption that the barns were at full capacity.

The farrowing site is assumed to be a barn with nine farrowing rooms. The farrowing rooms each had a dimension of 15.5 m x 13.9 m with a shallow manure pit of 0.61m deep. Each farrowing room had 40 farrowing crates. A hallway with an evaporative pad provided a shared inlet for the nine rooms and approximately 55% of the side wall. Each room was equipped with two 0.3m diameter pits fans, two 0.6m diameter variable-speed fans, one 0.91m diameter fan, and one 1.2m diameter fan to provide the ventilation needs (Stinn and Xin, 2014). The capacity of the farrowing barn was assumed to be 360 sows/litters for all nine rooms.

The gestation barn was assumed to be 121.9m x 30.5m with mechanical ventilation year round and a capacity of 1800-head gestation sows. The barn had a total of twelve 0.61m diameter pit fans, 6 on each of the south and north sides, and fifteen, 1.37m diameter tunnel fans on the west end walls. Evaporative cooling pads were on the east end wall and the middle section of each sidewall for summer cooling (Stinn and Xin, 2014).

The nursery, growing and finishing phases were accommodated with one wean to finish barn, which was double-stocked except during the finishing stage. The barn had a dimension of 25 x 57m with a deep-pit manure storage and a holding capacity of 2400 pigs (single-stocking). The barn had four 0.6m diameter pit fans, two 0.6m diameter end-wall fans providing the minimum ventilation. Sidewall curtains on both the north and south walls of the barn were used to provide natural ventilation during the summer (Pepple, 2011). Basic dimensions of three sites were summarized in table 2.

The sidewalls for all barns were assumed to be concrete block and stud wall insulation, which is popular for housing large swine (Jones and Friday, 1995). The Upper wall assumed to be 2 x 4 studs (R = $13m^2$•K/W) while lower wall assumed to be standard blocks (R = $12m^2$•K/W). Ceiling was assumed to be the structure of ceiling with rigid insulation (R = $16m^2$•K/W) (Jones and Friday, 1995). The floor was assumed to be slatted (R = $6.813616m^2$•K/W) (ASHRAE, 2013).

Table 2: Dimensions of barn and cooling pad across five phases.

	Dimension of cooling pad (Length X Height)	Dimension of animal barn (Length X Width X Height)	Number of Animals
Gestation Stage	30.5m X 1.83m	121.9m X 30.5m X 1.83m	1800
Farrowing Stage	15.5m X 1.83m X 9 X 55%	15.5m X 13.9m X 1.83m X 9	360
Nursery Stage, Growing Stage and Finishing Stage	12.5m X 1.83m X 2	12.5m X 57m X 1.83m	2400/2400 /1200

2.3 Result and Discussion

Tables A1-A5 listed the summaries V_{H2O} under typical indoor and outdoor environmental conditions by production phases. These tables provide specific V_{H2O} guidance based on specific ambient environment and management's set point choices. Overall, increasing indoor RH or temperature (RH_i and t_i) reduced V_{H2O} at a given outdoor RH and temperature (RH_o and t_o)

across all five stages. For instance, as Figure E1 shows increasing t_i from 15°C to 20°C in the gestation phase reduced V_{H2O} by 37% (at RH_o = 15% and RH_i = 60% across t_o). The line with 15°C indoor set point shows higher VR needed to remove the excess moisture as compared with the other two set points. Figure E2 shows that increasing RH_i from 60% to 80% reduced V_{H2O} by approximately 26% (at t_i = 15°C and RH_o = 15%, growing stage). RH_o had minor effects on V_{H2O} when compared to RH_i. Increasing RH_i setpoint results in the drop of t_{bal}. Chepete and Xin (2004) pointed out that even small magnitude of rising of supplemental heat can cause formidable practical challenge to distribute space heat in the large area. When the t_o is below t_{bal}, the t_{bal} can be reduced by increasing RH_i setpoint. However, as noted earlier, unmanaged high RH_i may result in the growth of microorganisms or barn degradation.

Figure E3 evaluates the effect of single vs. double stocking on V_{temp} (RH_o = 15% and t_i =15°C). Weaned pigs were double-stocked when they entered the wean-to-finish barn. As they continued growing, half of the pigs were moved to a second room while the rest of pigs remained in the room, which is now described as single-stocked. As the graph shows, V_{temp} for the single stock barn is higher than the V_{temp} for double stock, which is due to the greater total mass of the finishing pigs in single stock phase. The total weight of animal has a dominant effect on V_{temp} which causes the finishing stage to have a higher design V_{temp}. To include proper fan capacity, the V_{temp} for finishing stage instead of growing stage should be the VR design criteria of the wean-finish barn. In the Figure E3 shows VR in $m^3hr^{-1}kg^{-1}$; without the effect of total animal mass of animal, both V_{temp} and V_{H2O} (RH_i=60% and RH_i = 80%) for growing stage are higher than those for finishing stage, resulting from higher specific SHP and MP for the growing stage (2.29W kg^{-1} and 2.85 g $h^{-1}kg^{-1}$, respectively) compared to the finishing stage (1.1 W kg^{-1} and 1.2 g $h^{-1}kg^{-1}$, respectively). The t_{bal} for finishing stage and growing stage are -28°C and -5°C, respectively, at RH_o = 50%. In the winter, the supplemental heat was on until the barn reached t_{bal}. Since nursery, growing and finishing pigs are all reared in the same barn, it is necessary to have the ventilation capacity and supplemental heat requirement for all stages. The ability to control minimum VR based on animal weight and barn stocking rate would provide opportunities to optimize fuel use.

Figure E4-E8 show typical V_{H2O} versus outside temperature by production phases for both moisture and temperature control. VRs calculated based on new HMP values and old ASABE

HMP values were compared in these graphs. In general, increasing outdoor temperature would elevate VR across all five stages; and VR for temperature control increased faster than the VR for moisture control under the same environmental conditions, which had agreement with Albright (1990) that moisture control dictated the minimum VR at very cold region, and temperature control started to dictated the minimum VR when temperature had exceeded a point. Overall, ventilation rates from new HMP rates are higher than the ventilation rates from ASABE standards across all five phases. The t_{bal} for gestation, farrowing, nursery, growing and finishing are -5°C, -4°C, 11°C, -15°C and -28°C respectively. The t_{bal} of finishing stage is lower than t_{bal} of growing stage. Determining the set-point temperature of supplemental heat should consider condition for both growing and finishing stage for wean-finishing barn. In practice, Zhang (1994) recommended that the heat deficit temperature can be altered to be lower than t_{bal} if the room is full of animal, for example, double stock for growing stage. These t_{bal} values suggest a need for supplemental heat in barns of many regions.

The 99% design temperature of Central Illinois Region was -15.1°C according to ASHRAE (2013), and the balance temperature for nursery stage is determined to be 11°C. The set point of indoor condition was assumed to be 20°C and 60% for RH_i and 45% for RH_o. The corresponding VR based on the assumption above is $8.4m^3hr^{-1}hd^{-1}$. As the outdoor temperature increased to balance temperature, which is 11°C, RH_o is increased and result in elevation of RH_i which ultimately altering the VR needed for moisture control. However, when the outdoor temperature is below or equal to balance temperature, the VR is expected to remain in the first stage. The unchanging of VR might contributed to under ventilation for moisture control. For example, if RH_o increased to 75% while RH_i increased to 80%, the new requiring VR for moisture control is $8.7m^3hr^{-1}hd^{-1}$, which is higher than the VR for the condition based on the 99% design temperature ($8.4m^3hr^{-1}hd^{-1}$). In conditions when outdoor conditions approach balance temperature if the outside humidity is higher, VR for moisture control at design conditions may not be adequate. Determining set-point temperature for the first stage of VR should consider design temperature and balance temperature and the corresponding relative humidity change.

VR from Zhang (1994) and MWPS (1990) were compared with the new VRs. The V_{H2O} recommended by Zhang (1994) were 54%, 30%, 69%, 31% and 53% lower than the new V_{H2O} for gestation, farrowing, nursery, growing and finishing respectively, which is due to the higher

LHP or MP of the animals plus the inclusion of MP from the surroundings. In these comparisons the same outdoor temperature of -25°C was used, providing minimum VRs for extreme winter conditions. For example, in farrowing stage (175kg), the new MP (2.38 g $h^{-1}kg^{-1}$) is 78% higher than the old MP value (1.34 g $h^{-1}kg^{-1}$) for a given room temperature leading to a 30% increase in V_{H2O}. Comparing to VR recommended in MWPS (1990), old VR were 40%, 34%, 56%, 2% and 3% lower than the new VR for gestation, farrowing, nursery, growing, and finishing stages, respectively. It is important to note that for the winter condition used in the comparison with MWPS, the finishing phase minimum VR might be controlled by V_{temp} due to very low t_{bal}, while the remaining phases were managed for V_{H2O}. In comparison with both sets of recommendations, elevations of V_{H2O} in the gestation and nursery phases were highest. This agreed with the greatest increase in LHP or MP shown in Table 1. The increase in LHP or MP in nursery is the largest determined from the HMP data, and may need further investigation. Some of this high facility level MP may be due to the undeveloped urination/defecation patterns in the piglets on partially slatted floors, leading to increased washing or higher than average evaporation of urine (Brown-Brandl et al., 2014). It may also be typical of commercial barns. Further validation of these data would be valuable prior to increasing V_{H2O} for the nursery phase.

2.4 Conclusion and Recommendations

This study demonstrates why updating the VR recommendations is needed. Phases of swine production evaluated in this study included gestation, farrowing, nursery, growing and finishing. Overall previous VR recommendations or VR based on old HMP values substantially underestimate the need for both moisture and temperature control. This study provides usable lookup tables of VR needed for moisture control based on indoor and ambient conditions. The tables provide a useful tool for evaluating V_{H2O} based on local conditions. Since the design of swine barns varies from region to region, VR's based on the new HMP rates for different types and scales of swine barns warrant further work. The balance temperature for the phases of gestation, farrowing, nursery, growing, finishing for typical housing in the Midwest USA are -5°C, -4°C, 11°C, -15°C and -28°C respectively. These balance temperatures suggest a need for supplemental heat in barns, especially the early (nursery) stage in wean-to-finish barn for many regions.

Chapter 3. Evaluating the Effect of Evaporative Cooling on Heat Stress Reduction of Swine

3.1 Introduction

It is well known that the high environmental temperature causes heat stress, which can reduce production and reproductive efficiency of pigs. Ventilation designed for temperature control in warm conditions is more than adequate for moisture and air quality control, so the primary goal for summer ventilation is reduce indoor air temperature. Ideally, the maximum ventilation rate will limit the rise in temperature and humidity above the ambient conditions. Evaporative cooling has been recommended as an effective means to reduce heat stress and improve the animal comfort (Lucas et al., 2000; Fehr et al., 1983; Panagakis et al., 2006). The most common method for evaporative cooling is the fan and cooling pad system. Panagakis et al. (2006) compared evaporative pads and fogging on air in the change of indoor temperature and reduction of heat stress in growing swine building by simulation; during the five-months period of summer, evaporative cooling pad was found to be more efficient than fogging in reducing heat stress intensity and also led to less fluctuation in indoor temperature. Morales et al. (2013) compared three environmental temperature control strategies including the system of evaporative cooling combined with negative of curtains, snout cooler, and management of curtain and found that evaporative cooling was more efficient than the other two strategies to reduce the room temperature and resulted in better feed intake by sows.

Temperature alone is not always an ideal measure for predicting heat stress; factors like solar load, air speed, and relative humidity also affect heat stress (Lucas et al., 2000). Thermal indices can develop a relationship between animal stress and the environmental factor, which can serve as guideline of decision-making for the environmental control. Currently, many thermal indices, like the temperature humidity index (THI), have been used to estimate the degree of heat stress by animals. Some response indicators have been used to quantitatively evaluate the heat stress on animal including respiration rate, respiratory volume, pulse rate, skin temperature and other physiological characteristics (Lucas et al., 2000). A study by Tompkins (1967) showed increasing ambient temperature elevated the rectal temperature of animal, which resulted in reduction of embryonic survival. Heitman (1958) found the high body temperature could contribute to low weight gain of animals. In order to reduce the mortality of embryos in gestation stage and increase the rate of gain for grow-finish swine, a THI that was proven to be a good indicator of core body temperature was sought.

Stochastic weather models have been extensively used to generate long time series of weather data, which can construct scenarios of meteorological change to apply to agricultural analysis (Johnson 1996; Mearns, 1997; Gates and Timmons, 1988). Gates and Timmons (1988) summarized following advantages of stochastic weather data over those from historical data as 1) avoiding tedious and storage-intensive computer operation 2) input files were more accessible 3) more extreme situations of temperatures can be covered by the results from the weather generator model. Mearns (1997) also compared the actual data and results of simulated weather model and found "good agreement between historical and generated data" in both precipitation and temperature data. These studies demonstrated the utility of using stochastic model for those agricultural studies linked to extreme climate events. Since the indoor microclimatic change of swine barn is strongly impacted by the outdoor conditions, weather data generated from stochastic model are very appropriate to use.

Compared to previous studies on the feasibility of evaporative cooling, the analysis of evaporative cooling on the reduction of heat stress in this study is based on more comprehensive information including newer heat and moisture production rates of the pigs and three locations with high concentrations of swine production each with different typical weather patterns. Moreover, the efficiency of evaporative cooling pad was assumed to be constant in most literature while this study adjusts pad efficiency by pad area and face velocities expected based on description of commercial farms.

The objectives of this chapter were 1) Determining maximum VR of animal barn under different temperature condition. 2) Calculating THI value of exhaust air with known VR under the condition of not using evaporative cooling 3) Evaluating potential benefits of using evaporative cooling for reducing THI conditions below critical threshold for swine barns during summer.

3.2 Methods

3.2.1 Model of Evaluation Evaporative Cooling.

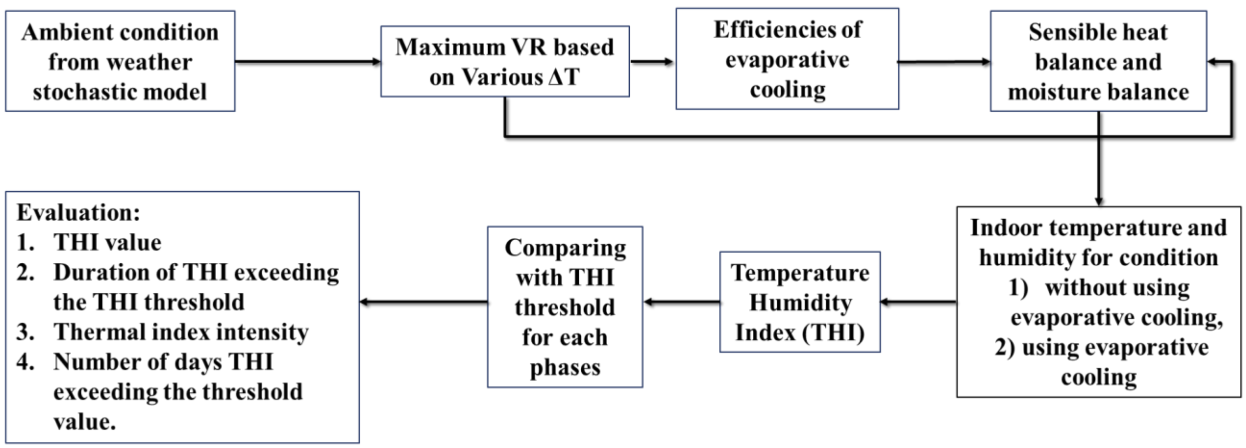

Figure 1. Model of evaluating evaporative cooling.

Figure 1 shows the process of evaluating the evaporative cooling in term of heat stress reduction. First, the daily weather variables including maximum and minimum dry-bulb and wet-bulb temperatures, dew point were extracted from stochastic weather model for 50 years and were converted into hourly dry-bulb and wet-bulb temperature. Maximum VR based on ΔT = 2°C, 3°C and 5°C. VR can affect efficiencies of cooling pad by altering the face velocities. Under constantly assumed thickness of cooling pad and water flow rate, the efficiencies of evaporative pads corresponding to different VR were determined. Indoor temperature and humidity ratio for conditions of w/o and w/ using evaporative cooling were calculating by incorporating different efficiencies of evaporative cooling and VR. The same SHP and LHP values used in chapter 2 were used in this model. It is assumed that the model does not adjust heat production by ambient temperature. The THI threshold for emergency conditions was used as indicator of heat stress of animal. Effect of evaporative cooling on heat stress was evaluated by comparing hourly THI value with threshold value for each swine production stage.

3.2.2 Weather Data Generation.

Weather data including maximum temperature, minimum temperature and dew point of Sioux City (IA), Texas (OK) and Fayetteville (NC) were generated by AgGEM. These counties were in top counties in hog and pig sales and each has a different climate pattern (USDA, 2016). Since the input file of Texas and Fayetteville were not developed, the already developed input file for

Amarillo and Raleigh, which are nearby the two locations above were used instead. The output of AgGEM contained 1) daily maximum air temperature 2) daily minimum air temperature 3) daily average dew-point temperature 4) daily wind speed in miles/hour 5) total solar radiation in BTU/hour*ft^2.

The number of year for simulation necessarily related to the allowable error to be accepted in the estimation. Gates and Timmons (1988) suggested that the number of years used for replication should predict true mean response, which defined as the production response expected if infinite replications were made. In this study, 500 years of replications were assumed to properly predict the true means for the variables (maximum dry-bulb temperature, minimum dry-bulb temperature and dew-point), which were regarded as the "population". It should be ensured that the estimation is within a specified percent of the true mean in certain confidence interval. In this study, the mean and standard deviation of 500 years were first determined. Then, 95% confidence interval (CI) were determined for randomly samples with sample sizes of increasing number of the year (starting with n =1) until the CI containing the mean of 500 years was found. The years included in each sample were randomly selected from the 500-year replication by random number generator. A period of fifty years was selected by the above method and was used for all simulations in this study. Results of maximum and minimum temperature from weather generator were compared with the ASHRAE (2013) climatic design information. For the weather data from Sioux City, average dry-bulb temperature based on 50 year-simulation were 16.1^{0}C, 22^{0}C, 24.3^{0}C, 23^{0}C and 17.6^{0}C for May through September respectively, and the differences were less than 5% comparing the data from ASHRAE (2013). Moreover, the standard deviation of dry-bulb temperature was 4.8, 3.4, 2.9, 3.13 and 4.6 for May through September indicating less fluctuation of dry-bulb temperature during July, which was agreed by the weather data from ASHRAE (2013). The comparison between stochastic weather data and ASHRAE climatic design condition validated the reliability of stochastic weather data used in the following calculation.

Daily temperature is the minimum unit AgGEM can generate. Hourly outdoor dry-bulb and wet-bulb temperatures were needed to perform the calculation of the diurnal change of indoor temperature and humidity. ASHRAE (2013) provided the procedures of developing a daily profile, which can describe the variation of dry and wet-bulb temperature on design days. Table

3 is normalized daily temperature profile in the fraction of the daily temperature range. Fraction corresponding with the time of Table 3 is in term of solar time. However, the difference between local and solar time can be between 1 hr and 2 hr, which affected by site longitude and daylight saving time indicated by apparent solar time (AST). AST is the time with reference to the sun's actual position in the sky, which depends on local standard time (LST):

$$AST = LST + ET/60 + (LON\text{-}LSM)/15 \quad (9)$$

where LST is local standard time, decimal hours; ET is equation time in minutes in Table 4; LSM is longitude of local standard time meridian, ^{0}E; LON is longitude of Site, ^{0}E.

Table 3. Fraction of Daily Temperature Range.

AST(hour)	Fraction	Time(hour)	Fraction	Time(hour)	Fraction
1	0.88	9	0.55	17	0.14
2	0.92	10	0.38	18	0.24
3	0.95	11	0.23	19	0.39
4	0.98	12	0.13	20	0.5
5	1.00	13	0.05	21	0.59
6	0.98	14	0.00	22	0.68
7	0.91	15	0.00	23	0.75
8	0.74	16	0.06	24	0.82

Table 4. Equation of Time (ET), min.

Month	May	June	July	August	September
ET(min)	3.7	-1.3	-6.4	-3.6	6.9

Every hourly temperature can be calculated by subtracting the fraction corresponding certain hour of the temperature range (dry-bulb and wet-bulb) from daily maximum temperature (ASHRAE, 2013). Dry-bulb temperature range can be retrieved from the results of AgGEM since the maximum and minimum dry-bulb temperatures were known. Daily wet-bulb temperature range could be calculated following Bridges and Gates (1992). The maximum relative humidity (RH_{max}) of the day is assumed to occur at the minimum dry bulb temperature (Tdb_{min}) and minimum dew point temperature (Tdp_{min}). Tdp_{min} is assumed to 1^0C less than Tdb_{min}. RH_{max} can be obtained from the state point of (Tdp_{min}, Tdb_{min}) in psychrometrics chart. Humidity ratio (W) is assumed to be constant over the day. Since temperature and RH change inversely within the day, the minimum relative humidity (RH_{min}) occurs at the highest dry-bulb temperature, RH_{min} can be calculated from the state point of (Tdb_{max}, W).

3.2.3 Maximum Ventilation Rate

The maximum VR are based on warm weather condition. The maximum ventilation rate is dictated by the temperature control and is assumed to provide adequate moisture control. In the condition without evaporative cooling, the sensible energy balance was given from (Albright, 1990):

$$q_s + q_m + q_{so} + q_h = \sum UA(t_i - t_o) + FP(t_i - t_o) + 1006\rho V(t_i - t_o) \qquad (10)$$

where q_s is sensible heat production of animal (Wkg^{-1}), q_m is sensible heat emission from facilities which is negligible in this case, q_{so} is sensible heat gained from the sun which is negligible in this case, q_h is sensible heat gained from supplemental heat which is negligible during summer, U is thermal conductance of the building component ($Wm^{-2}{}^\circ C^{-1}$); A is the area of the building component (m^2), V is VR ($m^3\ hr^{-1}$) per animal.

The maximum VR can be calculated using the following equation:

$$V = \frac{qs * M * N - (UA_w + UA_c) * (T_i - T_o)}{1006 * \rho * (T_i - T_o)} * \left(\frac{3600}{N}\right) \qquad (11)$$

The unit of q_s used in this paper is W per kg and N is the number of animals. Maximum VR is determined based on the temperature difference between indoor and outdoor conditions. Temperatures are assumed to rise 2 ^{0}C, 3^0C and 5^0C respectively in three scenarios, because these increases in indoor temperature reflect condition which frequently occur in swine barns (Lucas, 2000). The 5^0C difference between indoor and outdoor condition reflects the worst-case scenario for heat stress potential, which may happen when the ventilation systems have been maintained improperly or are worn out.

3.2.4 Efficiency of Evaporative Cooling

Gunhan and Demir (2007) developed an equation to determine the evaporative saturation efficiency by linear regression analysis:

$$\eta = -2.45Q - 5.71v + 0.32h + 41.78 \quad (12)$$

where Q is water flow rate in l min^{-1}, v is air “face” velocity in m s^{-1} which is VR divided by the area of cooling pad, and h is the thickness of pad in mm. The face velocity is varied between the phases of production (barn) and with VR. In the study, water flow and thickness are assumed to be 1.75 l min^{-1} and 152 mm and remain constant for each calculation. The dimension of the evaporative cooling pad and animal barn for four production stages are shown in table 2.

By the adiabatic process, temperature air is reduced with increases of relative humidity. The cooler air from evaporative cooling can be determined by following equation (Dagtekin et al. 2009):

$$T_{oe} = T_{amb} - (T_{wet} - T_{amb})\,\eta \quad (13)$$

where T_{oe} is cooled air from the evaporative cooling, T_{amb} is outdoor dry-bulb temperature and T_{wet} is outdoor wet-bulb temperature. All the temperature variables were in ^{0}C.

The air is moved into indoor environment by ventilation and sensible heat and latent heat is added by animal heat production. The indoor temperature is also affected by the insulation of the building. These factors led to the indoor dry bulb temperature being determined by following equation:

$$T_i = \frac{q_s*M*N+(UA_W+UA_c+1006*\rho*V)*T_o}{UA_W+UA_c+1006*\rho*V} \quad (14)$$

U is thermal conductance of the building component (W m^{-2} °C^{-1}); A is the area of the building component (m^2); UA_w is the component of wall and UA_c is component of ceiling; V is ventilation rate (m^3 hr^{-1}) per animal; In condition 2, T_o was substituted by T_{oe} which is temperature of cooled air from evaporative cooling.

Indoor moisture ratio is determined by the following equation:

$$W_i = \frac{Mp*M+V*\rho*W_O}{V*\rho} \quad (15)$$

where W_i and W_o are indoor and outdoor moisture ratio (m^3hr^{-1}); M_p is moisture production ($ghr^{-1}kg^{-1}$) of animals; In condition 2, W_o is substituted by W_{oe} which is moisture ratio of cooled air from evaporative cooling.

3.2.5 THI and Thermal Index Intensity

In Lucas (2000), following equation for calculating temperature-humidity index (THI) was used to reflect the rate of rise of deep-body temperature in swine as a measure of physiological stress. This equation was used in all scenarios the thermal index for evaluation.

$$THI = 0.63t_w + 1.17t_d + 32. \tag{16}$$

where t_w and t_d are the wet-bulb and dry-bulb temperature in °C. The range of THI values can be divided into four categories: normal, alert, danger and emergency for each production stage as displayed in table 5 (Sales, 2008; Fehr, 1983). The threshold of THI in this study for growing and finishing is 83 and 79 while for farrowing and gestation the THI is 73 for emergency level.

Table 5: THI categories for swine based on response to heat stress.

Stage	Normal	Alert	Danger	Emergency
Growing and Finishing	THI ≤ 74	75 ≤ THI ≤ 78	79 ≤ THI ≤ 82	THI ≥ 83
Farrowing and Gestation	65 ≤ THI ≤ 69	N/A	69 ≤ THI ≤ 73	THI ≥ 73

Four comparing criterions were used to comparing the conditions of using evaporative and condition without using evaporative cooling: THI based on the equation 17 (Criterion 1), duration of THI exceeding the threshold value (Hr) (Criterion 2), thermal index intensities (I*Hr) (Criterion 3) which calculated by the following equation:

$$I*Hr=\sum_T \sum_t \Delta THI * \Delta t \tag{17}$$

where ΔTHI is the difference between the calculated indoor THI value and the threshold THI value, and Δt is time interval corresponding to the exceeding THI which is calculated in 1 hr intervals for this study.

Number of day in a month THI exceeding the threshold value during certain time period (Criterion 4) were also used as comparing criterions and counted based on the average of 50 years data. Criterion 4 can not only be used for evaluating evaporative cooling on heat stress reduction but also estimate about the periods with high THI value during a day.

3.3 Results and Discussion

3.3.1 Outdoor Weather Condition in a Typical Year.

Hourly and daily weather data based on fifty-year simulation are used in the study. Figure 2 depicted the outdoor temperature fluctuant based on 50-year data within summer (May through September). Outdoor temperature for a summer period (May through September) based on maximum value of 50-year data, minimum value of 50-years data, average value of 50-years data and typical year data were compared. "Average of 50 year data" is the average value based on 50-year data, namely, 50 daily temperatures from the same date were extracted and the average was taken. "Max of 50 year data" is maximum value among the temperatures from the same date based on 50-year data, namely, 50 daily temperatures from the same date were extracted and the maximum value were chosen. "Min of 50 year data" is minimum value among the temperatures from same date, namely, 50 daily temperatures from the same date were extracted and the minimum values were chosen. "Typical year" is daily temperature data from a year randomly chosen from 50 years.

The data based on average value can roughly depicted the daily temperature change during summer, however comparing with typical year data, it insufficiently represents the real fluctuation of outdoor temperature which partially due to the average value avoiding all the extreme values of temperature. The yearly data based on neither maximum value and minimum value for 50-year data can represent the real situation due to large standard deviation (The standard deviations for each day among 50 years were all above 5).

The ways of dealing with 50-year data should accord the corresponding comparing criterion used to evaluate performance of evaporative cooling. I*Hr, Hr and THI for whole summer period were generally recommended to calculate based on the sum of 50 years data to cover more comprehensive weather data. If fluctuation for only diurnal pattern of THI was studied, the data was recommended extracted from typical year data.

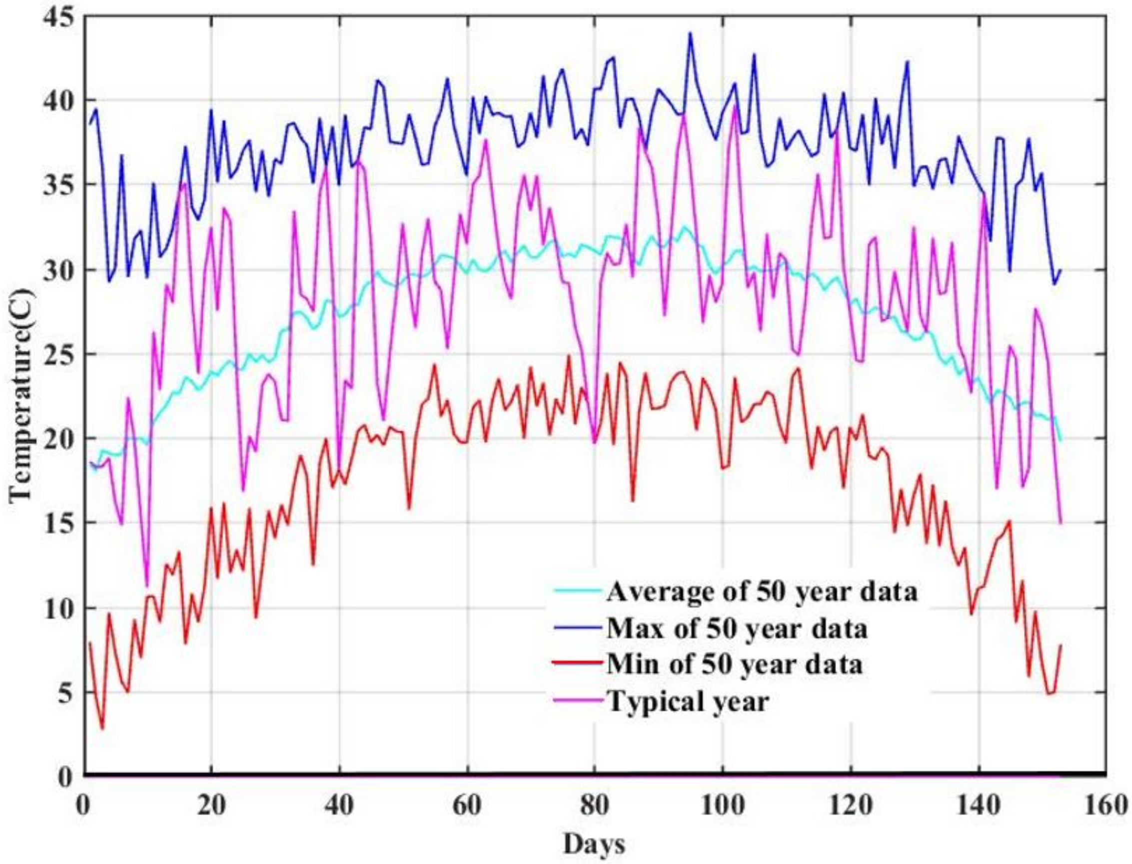

Figure 2. Outdoor temperature for Sioux City. ("Average of 50 year data" is the average value based on 50-year data, "Max of 50 year data" is maximum value among the temperature from the same date based on 50 years data, "Min of 50 year data" is minimum value among the temperatures from the same date. "Typical year" is daily temperature data from a year randomly chosen from 50 years.)

Figure F1-F3 showed the outdoor hourly temperature fluctuation during summer of a typical year for Sioux City, IA, Fayetteville, NC and Texas, OK. Evaporative cooling was operated as the outdoor temperature exceeded 22ºC for growing and finishing stage and 20ºC for gestation and farrowing stage. The number of operating hours for evaporative cooling was approximately 42% of summer time for growing and finishing and 54% for gestation stage and finishing stage of summer for Sioux City, 52% and 66% for Fayetteville and 51% and 64% for Texas. Overall, the pigs in Fayetteville received the longest period of potential heat stress if no cooling treatments were applied compared with other two locations. In July, the numbers of operating hours for evaporative cooling were all above 80% for all three locations for gestation and farrowing stage. In June, July and August, evaporative cooling operated for above half number of time. Since cooling pads are recommended to be shut off each day as part of proper maintenance, in months like July it is critical to understand which hours the pads should be shut off without creating likely heat stress conditions.

Outdoor temperature in more than 90% days in early May and late September are below the set point of evaporative cooling, which confirmed using meteorological data from May through September in this study is reasonable for evaluating the whole season when heat stress is expected to be a concern.

For each month May through September, the percentage of hours the cooling pads operated in the gestation barn were 13%, 54%, 85%, 79% and 36% for Sioux City, 28%, 64%, 89%, 86% and 33% for Fayetteville, and 36%, 67%, 83%, 72% and 36% for Texas. All values indicate that sows need to tolerate the greatest number of hours of potential for heat stress in July compared to other months. Figure F4-F6 depicts the hourly fluctuation of dry-bulb temperature and relative humidity in July for three locations. Overall, lowest relative humidity occurs when the temperature peaked, which shows the potential of using evaporative cooling.

3.3.2 Maximum Ventilation Rate During Summer

Maximum VR (m^3hr^{-1}) across growing, finishing, gestation and farrowing stage are tabulated in table 6 based on differences between indoor and outdoor temperature (ΔT) in condition 1 (without evaporative cooling). The maximum VRs are applied to the calculation across three locations. Overall, maximum ventilation rate decreases with increasing of ΔT. VRs needed by sow and piglets in farrowing stage were higher than these for the growing/finishing stage. The maximum VR for growing and finishing are based on same dimension of barn. VRs for finishing stage are approximately twice as much as these for growing stages. Comparing with old VR for temperature control, new VRs were 14% and 15% higher than old value for finishing and gestation (MWPS, 1990). It was found that increase in VR from old recommendations for temperature control is less than increased VR for moisture control, partially because the increase of SHP from old values is less than the increase of LHP.

Table 6. Maximum ventilation rate (m^3hr^{-1}) per animal across four phases based on the difference between indoor and outdoor temperature (ΔT) without evaporative cooling.

Production Stage	$VR_{\Delta T = 2^oC}$	$VR_{\Delta T = 3^oC}$	$VR_{\Delta T = 5^oC}$
Growing	121	81	48
Finishing	231	154	92
Gestation	296	197	118
Farrowing	450	300	179

According to Equation 12, ventilation rate can alter the retention time of air as it flows through the cooling pad and ultimately affect the efficiencies of cooling pads. Figure F7 shows that efficiencies of cooling pad based on VR set with ΔT = 2ºC, 3ºC and 5ºC without evaporative cooling ($VR_{\Delta T = 2^oC}$, $VR_{\Delta T = 3^oC}$and $VR_{\Delta T = 5^oC}$). Decreasing the VR can elevate efficiencies of evaporative cooling by slowing face velocity. Similarly, the area of cooling pad can be increased to improve the efficiency. Evaporative cooling in farrowing stage with highest VR has highest efficiencies due to largest area of cooling pad per volume of air moved compared with other phases. Beside the ventilation rate, Stinn and Xin (2014) pointed out that maintenance is critical to the pad efficiencies; efficiencies reduce if the pad is not receiving adequate water due to clogging or poor pump performance.

3.3.3 Indoor THI Based on Overall 50-year Data

Table B1-B3 show the I*Hr and Hr (criterion 2&3) values based on 50-year data for three locations at different VR. In Sioux City, under $VR_{\Delta T = 2^oC}$, $VR_{\Delta T = 3^oC}$ and $VR_{\Delta T = 5^oC}$ without evaporative cooling, Hr are approximately 38%, 43% and 55% of total hours for the 50 years for gestation stage and 10%, 13% and 20% of total hour for finishing stage. The results suggest that more than half summer sows in gestation were exposed to the high potential for heat stress if the barn lacked of evaporative cooling and ventilation was operated poorly, which might cause reduced fertility and higher abortion rates. The situation is even worse in Fayetteville where the Hr is up to 71% of total hours for the 50 years under $VR_{\Delta T = 5^{o}C}$ without using evaporative cooling for gestation stage. In addition, I*Hr and Hr of gestation stage are slightly higher than these in farrowing stage followed by the levels recorded in the finishing and growing stage. With the operation of evaporative cooling in Sioux City, Hr are approximately 23%, 28% and 41% of total hours for the 50 years for gestation stage and 1%, 2% and 4% for finishing stage under $VR_{\Delta T = 2^{o}C}$, $VR_{\Delta T = 3^{o}C}$ and $VR_{\Delta T = 5^{o}C}$. I*Hr were reduced by 65%, 62% and 55% for gestation and 95%, 94% and 89% for finishing stage under $VR_{\Delta T = 2^{o}C}$, $VR_{\Delta T = 3^{o}C}$ and $VR_{\Delta T = 5^{o}C}$. Dagtekin (2009) concluded "it is impossible to reach the optimal temperature requirement… evaporative cooling may help reduce the negative effects of heat stress." Figure F8 and Figure F9 show the I*Hr and Hr for each month with two conditions for gestation stage with $VR_{\Delta T = 5^{o}C}$ in Sioux City; the percentages of I*Hr reduction were all above 50% across five months.

According to table B1, without evaporative cooling, under $VR_{\Delta T} = 2^{\circ}C$, I*Hr of gestation was slightly higher than farrowing (approximately 1%). By using evaporative cooling, I*Hr of farrowing stage is 20% less than farrowing, which is due to higher evaporative cooling efficiency of farrowing resulting from its larger active cooling area. Table B4-B12 indicated I*Hr and Hr in two conditions in each month during summer based on 50-year data for three locations under different VR. Overall, I*Hr and Hr peaked in July, followed by August, June, September and May respectively for three locations.

3.3.4 Indoor THI of a Typical Year or an Average Year Based on 50-year Data

Table C1-C9 show the I*Hr and Hr (criterion 2 & 3) in a typical year for all three locations and have agreement with 50-year level data mentioned above. Since the table B4-B12 for I*Hr and Hr for sum of 50 years data can indirectly provide information of the average variables, typical year data instead of average value of 50 years data was used for calculation for providing extra information. Under $VR_{\Delta T = 5^{o}C}$, Hr are approximately 89% and 49% of July hour for gestation and finishing stage in condition 1 and are reduced to 80% and 21% in condition 2 for Sioux City. Figure F10-F21 depict the THI change (criterion 1) during whole summer for a typical year for three different locations for gestation stage or finishing stage, which have the similar fluctuation of outdoor temperature. Under $VR_{\Delta T = 2^oC}$, the THI that exceeds the threshold value for finishing stage can be essential eliminated by using evaporative cooling.

The tables D1-D18 summarize the number of days in each month that indoor THI value exceeds the threshold (criterion 1 and 4) for each hour in two conditions for all three locations for gestation stage and finishing stage. Overall, THI peaks at 15:00-16:00 in Sioux City, Fayetteville and 16:00-17:00 in Texas.

In Sioux city, without evaporative cooling, under $VR_{\Delta T = 5^oC}$, for most day sows in gestation stage were exposed to THI values above critical threshold in emergency level almost every hour in July, more than 20 hours within a day in June and August, more than 10 hours within a day during May and September. At $VR_{\Delta T = 2^oC}$, for most days in June, July and August, heat stress still existed in more than 8 hours, especially during the hours from of 12:00 -19:00.

Figure F22-F27 depicted the indoor THI by month and diurnal pattern. THI values were calculated based on the average of 50-year data. Figure F24 depicted the THI change under $VR_{\Delta T =5^oC}$ for gestation stage in Sioux City without using evaporative cooling and Figure F27 were same scenarios but with using evaporative cooling. Thermal intensity can be reduced by 48%, and occasional heat stress intensity from the time period of midnight to morning in June, July and August can be eliminated by using evaporative cooling. Figure F22 and F24 depicted the indoor THI under $VR_{\Delta T = 5^oC}$ and $VR_{\Delta T = 2^oC}$ respectively for gestation stage in Sioux City without using evaporative cooling. By altering $VR_{\Delta T = 5^oC}$ to $VR_{\Delta T = 2^oC}$, heat stress intensity can be reduced by 41% and occasional heat stress from the time period of midnight to morning in June, July and August can be eliminated as well. Table D19 showed the number of days in a month that THI exceeded the threshold for each hour under different VR for gestation stage in July in Sioux City which had agreement with the discussion above. By altering $VR_{\Delta T = 5^oC}$ to $VR_{\Delta T = 2^oC}$, heat stress from 22:00-9:00 the next day can be substantially relieved. Increasing the ventilation or using other complementary cooling treatment to further relieve the heat stress targeting the period of afternoon was needed. Table D20 compared the number of days in a month that THI exceeded the threshold for each hour under $VR_{\Delta T = 2^oC}$ for Sioux City, Fayetteville and Texas for gestation stage in July. Fayetteville has longer period time of heat stress than other two locations.

Evaporative cooling barely impacts the number of days above threshold for the period 10:00am-22:00pm in July for all locations, but it can largely eliminate the occasional heat stress in the afternoon in May and September. Figure F28 and Figure F29 show the number of days that THI is above the threshold for gestation stage at $VR_{\Delta T = 5°C}$ in Sioux City for two condition. By using evaporative cooling, number of days with high THI in May and September can be substantially reduced to fewer than 10 days during the hours 10:00 – 20:00, but no distinct reduction were found in June, July and August during the hours 10:00 – 20:00. Figure F30 indicated the THI value for a typical day in July and number of days with THI value within 24 hours in $VR_{\Delta T = 5°C}$ are both high. Even though fewer days with high THI value are removed from 10:00-20:00, greater intensity of THI value are reduced during the time. Lesser intensities of THI are also reduced in the period from midnight to 10:00. Evaluating effect of evaporative cooling on heat stress varied based on the criterions used to comparison.

The information above about counting the number of days for each month that THI exceeding the threshold can provide references for farmer about managing the operation time of evaporative cooling and potentially alter maximum VR by month or environmental condition.

3.3.5 Indoor THI Value of a Typical Day in the Summer

Figures F31 and F32 depict the effect of using evaporative cooling on indoor THI value (criterion 1) on July 22nd of a typical day which has highest average outdoor temperature during summer in a typical year for gestation stage and finishing stage. The percentage of THI reduction under $VR_{\Delta T = 5°C}$ are found to be slightly higher than those under $VR_{\Delta T = 2°C}$ (9.7% *vs*. 9% when temperature peaked) during afternoon, which is due to lower face velocity and higher efficiency of evaporative cooling in $VR_{\Delta T = 5°C}$. However the overall magnitude of THI and Hr are both greater in $VR_{\Delta T = 5°C}$ than in $VR_{\Delta T = 2°C}$. In finishing stage, even at $VR_{\Delta T = 5°C}$, THI value for most hours can be reduced below the threshold by using evaporative cooling.

Figure F33 depicts the THI and RH fluctuation on 22nd July for gestation stage. Before approximately 10:00, indoor RH for both two conditions were lower than outdoor temperature because higher of the indoor temperature. After 10:00, indoor RH in condition 2 has slower decline than outdoor RH and RH in condition 1 while THI in condition 2 do show less increase. By using evaporative cooling, temperature can be reduced significantly, but indoor RH has less variability and is maintained at relatively high level. Huynh et al (2007) observed that at high temperature and humidity condition (indoor temperature is above 28°C and RH is above 80%), pigs have inclination of moisturizing their skin by wallow in mud and water in order to increase evaporation to lose heat rather than increasing breathing frequency. Wetting the skin may still allow a difference in water vapor pressure between skin and air and thus enabling evaporative cooling even at high humidity (Huynh, 2007). When using evaporative cooling resulting in high indoor humidity, the effectiveness of different heat reduction strategies from the instinct behavior of pigs needs to be observed and quantified.

During the days with extreme weather (mostly occurring in June, July and August), evaporative cooling does not eliminate all the hours with danger or emergency level of THI. Some other measures and strategies can be taken to reduce the heat stress. Huynh (2004) pointed out that pigs became uncomfortable and inactive, and avoiding physical contact with other pigs with increasing temperature. Huynh suggested that physical space for animal should increase with increasing of temperature based on the thermoregulatory behavioral changes. Comparing with the sows in gestation stage, sows and piglets in farrowing stage have more spaces, which allow sufficient air flowing and heat dissipation in the surrounding, which can relieve heat stress to some degree. This certainly leads to the need for further investigation on how stocking density may influence THI thresholds.

3.4 Conclusion and Recommendations

More than half of summer sows in gestation are exposed to high THI if only ventilation is provided for all three locations. The situation becomes even worse in Fayetteville due to the higher overall temperature in the summer. Pigs needed to tolerate longer periods of high THI in July comparing with other months, so July has longer periods operation time for evaporative cooling system. The highest I*Hr and Hr tend to occur in the period of 15:00-16:00 in Sioux City, Fayetteville and 16:00-17:00 in Texas. By using evaporative cooling, many hours of emergency conditions are completely removed or substantially relieved especially during 2:00-7:00. Occasional heat stress in the afternoon in May and September can also be largely eliminated. During July, especially in from 12:00-19:00, evaporative cooling fails to significantly to reduce the number of hour with high THI, particularly in gestation. However, the intensity of heat stress indicated by THI can be relieved. In addition, the reduction in the nighttime THI may be just as critical for handling heat stress. Stinn (2014) suggested the evaporative cooling can not only use for heat stress reduction during the day based on temperature change but also cool the barn down quickly in the evening in order to achieve the maximum recovery time for animals before the next heat stress period. For example, at $VR_{\Delta T} = 2^oC$, even though table 43 indicates that THI from 22:00-9:00 the next day were below the threshold, evaporative cooling is suggested to operate until midnight in order to give sows extra ‘cooling’. The operation of both maximum ventilation and evaporative cooling is likely needed for all 24hr during the hottest days of summer. Moreover, efficiencies are found to be slightly higher in relatively lower ventilation rates. Results of limiting the rise of indoor temperature by using maximum ventilation rate is distinct, however, as mentioned in Chapter 1, temperature rise is halved when the VR doubles, so increased maximum ventilation often involves causes high cost for operation. The efficiencies of evaporative cooling pads enhanced by slightly decreased the ventilation rate might be feasible strategies. Otherwise, additional pad area in new designs will also provide better cooling efficiency. The “trade off” of decreasing or increasing ventilation rate to achieve optimum indoor temperature can be considered as feasible strategies based on the given circumstances.

Chapter 4. General Conclusion and Future Work

This study provides a lookup table of updated VR for moisture control based on indoor and ambient conditions including the barns for gestation, farrowing, nursery, growing and finishing stage. Previous VR recommended were found to substantially underestimate VR for both moisture and temperature control and 54%, 30%, 69%, 31% and 53% lower than the new value for gestation, farrowing, nursery, growing and finishing stage. The balance temperatures related to the supplement heat set point were also recommended for typical housing in the Midwest USA. The balance temperature for the phases of gestation, farrowing, nursery, growing, finishing for typical swine housing in the Midwest USA are -5°C, -4°C, 11°C, -5°C and -28°C respectively. These balance temperatures suggest a need for supplemental heat in barns, especially the early (nursery) stage in wean-to-finish barn for many regions.

Without evaporative cooling, pigs have high possibility of exposure to heat stress during July especially for gestation and farrowing stage even with maximum VR. THI peaks in the period of 15:00-17:00 in the studied locations. Evaporative cooling can substantially reduce the heat stress duration during evening and nights and extensively relieve the magnitude of heat stress during afternoon. Operation of both maximum VR and evaporative cooling was recommended to work jointly for 24 hr during the July for gestation and farrowing stage. However, according to Zulovich (2009), it was suggested that evaporative cooling pads should be allowed to dry for at least four hours each night in order to control the algae growth within the pad and maintain pad life. To increase the effectiveness of cooling pad, more installation of cooling pad was recommended especially for the gestation barn due to their higher sensitivity to heat stress. Moreover, a slightly decreased ventilation rate to achieve higher cooling efficiencies for heat stress reduction can be consider as a feasible strategy in some circumstances. Since sows in gestation and farrowing stage have higher sensitively to high heat stress, lower stocking density may also be effective.

Future work recommendations:

1. The nursery MP in facility level was high, which might due to the undeveloped urination/defecation patterns in the piglets on partially slatter floor. Further validation of VR for moisture control based on the MP is recommended.
2. Calculation of VR based on other type of design of swine barn is recommended.
3. The model of predicting indoor THI can be improved by considering more factors:
    a. Gradient of temperature could result in uneven spatial distribution of THI value in the barn. Transient model to predict temperature can be incorporated to the current steady-state model to obtain more comprehensive information about indoor THI.
    b. Time-dependent simulation were recommended for the model
    c. Ventilation stage should be considered based on indoor temperature instead of constant VR.
    d. Heat and moisture model corresponding to temperature and growth of animal can be incorporated to the current model.

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Appendix A: Moisture Control Ventilation

Table A1. Moisture control ventilation rate ($m^3\ hr^{-1}\ hd^{-1}$) for typical indoor and outdoor conditions for gestation barn (Average pig weight = 204 kg and MP = 1.34 g $hr^{-1}kg^{-1}$).

		t_i = 15 °C			t_i = 20°C			t_i = 25 °C		
t_o	RH_o (%)	RH_i = 60%	RH_i = 70%	RH_i = 80%	RH_i = 60%	RH_i = 70%	RH_i = 80%	RH_i = 60%	RH_i = 70%	RH_i = 80%
-25		30.6	26.1	22.8	22.1	18.9	16.5	16.2	13.9	12.1
-15		32.3	27.5	24.0	23.3	19.9	17.3	17.0	14.5	12.6
-5	15	34.8	29.5	25.6	24.8	21.1	18.3	18.0	15.3	13.3
5		38.9	32.6	28.0	27.2	22.9	19.8	19.4	16.4	14.2
15		46.8	38.3	32.3	31.2	25.9	22.1	21.6	18.1	15.5
-25		30.9	26.3	23.0	22.3	19.0	16.6	16.3	13.9	12.1
-15		33.1	28.1	24.4	23.7	20.2	17.5	17.3	14.7	12.8
-5	30	37.1	31.1	26.8	26.0	21.9	19.0	18.6	15.8	13.6
5		45.5	37.1	31.3	30.3	25.1	21.4	21.0	17.5	15.0
15		70.1	52.5	37.1	40.1	31.7	26.2	25.6	20.8	17.5
-25		31.1	26.5	23.1	22.5	19.1	16.7	16.4	14.0	12.2
-15		34.0	28.7	24.9	24.2	20.5	17.8	17.5	14.9	12.9
-5	45	39.7	33.0	28.2	27.3	22.8	19.6	19.3	16.2	14.0
5		54.9	43.2	35.5	34.2	27.7	23.2	22.8	18.8	15.9
15		N/A	83.9	59.8	56.1	40.9	32.2	31.3	24.4	20.0
-25		31.4	26.8	23.3	22.6	19.3	16.8	16.5	14.0	12.2
-15		34.9	29.4	25.4	24.6	20.8	18.0	17.7	15.0	13.0
-5	60	42.7	35.0	29.7	28.7	23.8	20.3	20.0	16.7	14.4
5		69.3	51.6	41.0	39.2	30.9	25.5	24.9	20.2	17.0
15		N/A	N/A	N/A	93.7	57.9	41.8	40.4	29.6	23.3
-25		31.7	27.0	23.4	22.8	19.4	16.8	16.6	14.1	12.3
-15		35.8	30.1	25.9	25.1	21.2	18.3	18.0	15.2	13.2
-5	75	46.3	37.4	31.3	30.2	24.9	21.1	20.7	17.2	14.7
5		93.8	64.0	48.6	46.0	35.0	28.2	27.5	21.9	18.1
15		N/A	N/A	N/A	286.4	99.1	59.8	56.9	37.6	28.0

Table A2. Moisture control ventilation rate (m3 hr^{-1} hd^{-1}) for typical indoor and outdoor conditions for gestation barn (Average pig weight = 175 kg (farrowing stage) and MP = 2.38 g $hr^{-1}kg^{-1}$)

		t_i = 15 °C			t_i = 20°C			t_i = 25 °C		
t_o °C	RH_o (%)	RH_i = 60%	RH_i = 70%	RH_i = 80%	RH_i = 60%	RH_i = 70%	RH_i = 80%	RH_i = 60%	RH_i = 70%	RH_i = 80%
-25	15	46.6	39.8	34.7	33.7	28.8	25.1	24.7	21.1	18.4
-15		49.2	41.9	36.5	35.5	30.3	26.4	25.9	22.1	19.3
-5		53.0	44.9	39.0	37.8	32.1	27.9	27.5	23.4	20.3
5		59.3	49.7	42.7	41.4	34.9	30.1	29.6	25.0	21.7
15		N/A	N/A	N/A	47.5	39.4	33.6	33.0	27.6	23.7
-25	30	47.0	40.1	35.0	34.0	29.0	25.3	24.9	21.2	18.5
-15		50.4	42.8	37.2	36.1	30.7	26.7	26.3	22.4	19.5
-5		56.5	47.4	40.9	39.6	33.4	28.9	28.4	24.0	20.8
5		69.4	56.6	47.8	46.1	38.2	32.6	31.9	26.7	22.9
15		N/A	N/A	N/A	61.1	48.3	39.9	39.0	31.6	26.6
-25	45	47.5	40.4	35.2	34.2	29.2	25.4	25.0	21.3	18.5
-15		51.7	43.8	37.9	36.8	31.2	27.1	26.6	22.6	19.7
-5		60.5	50.2	42.9	41.5	34.8	29.9	29.4	24.7	21.3
5		83.7	65.8	54.1	52.0	42.2	35.4	34.7	28.6	24.3
15		N/A	N/A	N/A	85.5	62.4	49.0	47.7	37.2	30.4
-25	60	47.9	40.8	35.5	34.4	29.3	25.5	25.1	21.4	18.6
-15		53.1	44.8	38.7	37.5	31.7	27.5	27.0	22.9	19.8
-5		65.1	53.4	45.2	43.7	36.3	31.0	30.4	25.5	21.9
5		105.6	78.6	62.5	59.7	47.1	38.8	37.9	30.8	25.8
15		N/A	N/A	N/A	142.8	88.2	63.7	61.5	45.0	35.5
-25	75	48.4	41.1	35.7	34.7	29.5	25.7	25.2	21.5	18.7
-15		54.6	45.8	39.4	38.2	32.2	27.9	27.4	23.2	20.0
-5		70.5	57.0	47.7	46.0	37.9	32.2	31.5	26.2	22.5
5		142.9	97.6	74.0	70.1	53.3	43.0	41.9	33.3	27.6
15		N/A	N/A	N/A	436.3	151.0	91.1	86.6	57.2	42.6

Table A3. Moisture control ventilation rate ($m^3\ hr^{-1}\ hd^{-1}$) for typical indoor and outdoor conditions for gestation barn (Average pig weight = 16.7 kg (nursery stage) and MP = 7.86 $ghr^{-1}kg^{-1}$).

		t_i = 15 °C			t_i = 20°C			t_i = 25 °C		
t_o °C	RH_o (%)	RH_i = 60%	RH_i = 70%	RH_i = 80%	RH_i = 60%	RH_i = 70%	RH_i = 80%	RH_i = 60%	RH_i = 70%	RH_i = 80%
-25	15	10.6	9.1	7.9	7.8	6.7	5.8	5.8	4.9	4.3
-15		11.2	9.5	8.3	8.2	7.0	6.1	6.0	5.1	4.5
-5		11.9	10.1	8.8	8.7	7.4	6.4	6.4	5.4	4.7
5		13.0	11.0	9.5	9.3	7.9	6.8	6.8	5.8	5.0
15		N/A	N/A	N/A	10.4	8.7	7.5	7.4	6.2	5.4
-25	30	10.7	9.1	8.0	7.8	6.7	5.8	5.8	4.9	4.3
-15		11.4	9.7	8.4	8.3	7.1	6.1	6.1	5.2	4.5
-5		12.5	10.5	9.1	8.9	7.6	6.6	6.5	5.5	4.8
5		14.5	12.0	10.3	10.1	8.4	7.2	7.2	6.0	5.2
15		N/A	N/A	N/A	12.3	10.0	8.4	8.3	6.9	5.8
-25	45	10.8	9.2	8.0	7.9	6.7	5.8	5.8	5.0	4.3
-15		11.6	9.8	8.5	8.4	7.1	6.2	6.2	5.2	4.5
-5		13.1	11.0	9.4	9.3	7.8	6.7	6.7	5.6	4.9
5		16.4	13.3	11.2	10.9	9.0	7.6	7.6	6.3	5.4
15		N/A	N/A	N/A	15.0	11.7	9.6	9.5	7.6	6.4
-25	60	10.9	9.2	8.0	7.9	6.7	5.9	5.8	5.0	4.3
-15		11.8	10.0	8.7	8.5	7.2	6.3	6.2	5.3	4.6
-5		13.8	11.4	9.8	9.6	8.0	6.9	6.9	5.8	5.0
5		18.8	14.8	12.2	12.0	9.7	8.1	8.1	6.7	5.6
15		N/A	N/A	N/A	19.4	14.2	11.2	11.1	8.6	7.1
-25	75	10.9	9.3	8.1	8.0	6.8	5.9	5.9	5.0	4.3
-15		12.0	10.2	8.8	8.6	7.3	6.3	6.3	5.3	4.6
-5		14.5	11.9	10.1	9.9	8.3	7.1	7.0	5.9	5.1
5		22.1	16.8	13.5	13.2	10.5	8.7	8.6	7.0	5.9
15		N/A	N/A	N/A	27.3	18.0	13.4	13.3	9.9	7.9

Table A4. Moisture control ventilation rate ($m^3\ hr^{-1}\ hd^{-1}$) for typical indoor and outdoor conditions for a wean to finish barn (average pig weight = 34kg (Growing stage) and MP = 2.85 g $h^{-1}kg^{-1}$)

		t_i = 15 °C			t_i = 20°C			t_i = 25 °C		
t_o °C	RH_o (%)	RH_i = 60%	RH_i = 70%	RH_i = 80%	RH_i = 60%	RH_i = 70%	RH_i = 80%	RH_i = 60%	RH_i = 70%	RH_i = 80%
-25	15	10.9	9.3	8.1	7.9	6.7	5.9	5.8	4.9	4.3
-15		11.5	9.8	8.5	8.3	7.1	6.2	6.1	5.2	4.5
-5		12.4	10.5	9.1	8.8	7.5	6.5	6.4	5.4	4.7
5		13.8	11.6	10.0	9.7	8.1	7.0	6.9	5.8	5.1
15		N/A	N/A	N/A	11.1	9.2	7.8	7.7	6.4	5.5
-25	30	11.0	9.4	8.2	7.9	6.8	5.9	5.8	4.9	4.3
-15		11.8	10.0	8.7	8.4	7.2	6.2	6.1	5.2	4.5
-5		13.2	11.1	9.5	9.2	7.8	6.7	6.6	5.6	4.9
5		16.2	13.2	11.1	10.8	8.9	7.6	7.5	6.2	5.3
15		N/A	N/A	N/A	14.2	11.3	9.3	9.1	7.4	6.2
-25	45	11.1	9.4	8.2	8.0	6.8	5.9	5.8	5.0	4.3
-15		12.1	10.2	8.9	8.6	7.3	6.3	6.2	5.3	4.6
-5		14.1	11.7	10.0	9.7	8.1	7.0	6.9	5.8	5.0
5		19.5	15.4	12.6	12.1	9.8	8.3	8.1	6.7	5.7
15		N/A	N/A	N/A	20.0	14.6	11.4	11.1	8.7	7.1
-25	60	11.2	9.5	8.3	8.0	6.8	6.0	5.9	5.0	4.3
-15		12.4	10.4	9.0	8.8	7.4	6.4	6.3	5.3	4.6
-5		15.2	12.5	10.5	10.2	8.5	7.2	7.1	5.9	5.1
5		24.6	18.3	14.6	13.9	11.0	9.1	8.9	7.2	6.0
15		N/A	N/A	N/A	33.3	20.6	14.9	14.3	10.5	8.3
-25	75	11.3	9.6	8.3	8.1	6.9	6.0	11.3	9.6	8.3
-15		12.7	10.7	9.2	8.9	7.5	6.5	12.7	10.7	9.2
-5		16.5	13.3	11.1	10.7	8.8	7.5	16.5	13.3	11.1
5		33.3	22.8	17.3	16.4	12.4	10.0	33.3	22.8	17.3
15		N/A	N/A	N/A	101.8	35.2	21.3	-49.6	148.6	148.3

Table A5. Moisture control ventilation rate ($m^3\ hr^{-1}\ hd^{-1}$) for typical indoor and outdoor conditions for a wean-finish barn (average pig weight = 117 kg (Finishing stage) and MP = 1.2 $gh^{-1}kg^{-1}$)

		t_i = 15 °C			t_i = 20°C			t_i = 25 °C		
t_o °C	RH_o (%)	RH_i = 60%	RH_i = 70%	RH_i = 80%	RH_i = 60%	RH_i = 70%	RH_i = 80%	RH_i = 60%	RH_i = 70%	RH_i = 80%
-25	15	15.8	13.5	11.8	11.4	9.8	8.5	8.4	7.2	6.2
-15		16.7	14.2	12.4	12.0	10.3	8.9	8.8	7.5	6.5
-5		18.0	15.2	13.2	12.8	10.9	9.5	9.3	7.9	6.9
5		20.1	16.8	14.5	14.0	11.8	10.2	10.0	8.5	7.3
15		N/A	N/A	N/A	16.1	13.4	11.4	11.2	9.3	8.0
-25	30	15.9	13.6	11.9	11.5	9.8	8.6	8.4	7.2	6.3
-15		17.1	14.5	12.6	12.3	10.4	9.1	8.9	7.6	6.6
-5		19.2	16.1	13.9	13.4	11.3	9.8	9.6	8.1	7.1
5		23.5	19.2	16.2	15.6	12.9	11.0	10.8	9.0	7.8
15		N/A	N/A	N/A	20.7	16.4	13.5	13.2	10.7	9.0
-25	45	16.1	13.7	11.9	11.6	9.9	8.6	8.5	7.2	6.3
-15		17.5	14.8	12.9	12.5	10.6	9.2	9.0	7.7	6.7
-5		20.5	17.0	14.6	14.1	11.8	10.1	10.0	8.4	7.2
5		28.4	22.3	18.4	17.6	14.3	12.0	11.8	9.7	8.2
15		N/A	N/A	N/A	29.0	21.1	16.6	16.2	12.6	10.3
-25	60	16.2	13.8	12.0	11.7	9.9	8.7	8.5	7.3	6.3
-15		18.0	15.2	13.1	12.7	10.8	9.3	9.2	7.8	6.7
-5		22.1	18.1	15.3	14.8	12.3	10.5	10.3	8.6	7.4
5		35.8	26.6	21.2	20.3	16.0	13.2	12.9	10.4	8.8
15		N/A	N/A	N/A	48.4	29.9	21.6	20.9	15.3	12.0
-25	75	16.4	13.9	12.1	11.8	10.0	8.7	8.6	7.3	6.3
-15		18.5	15.5	13.4	13.0	10.9	9.4	9.3	7.9	6.8
-5		23.9	19.3	16.2	15.6	12.8	10.9	10.7	8.9	7.6
5		48.5	33.1	25.1	23.8	18.1	14.6	14.2	11.3	9.4
15		N/A	N/A	N/A	148.0	51.2	30.9	29.4	19.4	14.5

Appendix B. Sum of I*Hr and Hr accumulated in 50 years.

Table B1. I*Hr and Hr in different conditions in Sioux City, IA accumulated in 50 years under $VR_{\Delta T = 2^oC}$, $VR_{\Delta T = 3^oC}$ and $VR_{\Delta T = 5^oC}$ (Condition I is environmental control without using evaporative cooling and Condition II is with using evaporative cooling.)

	$VR_{\Delta T = 2^oC}$				$VR_{\Delta T = 3^oC}$				$VR_{\Delta T = 5^oC}$			
	Condition I		Condition II		Condition I		Condition II		Condition I		Condition II	
Production Stage	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*
Growing	80069	19228	4100	1979	112704	24717	6927	3147	208566	38094	22471	8778
Finishing	78798	18964	3890	1900	110734	24405	6606	3017	201269	37132	20842	8224
Gestation	501881	69791	175850	42300	618868	80326	229751	51799	900494	101755	406413	76507
Farrowing	498795	69485	133615	36467	612581	79834	194517	47349	888777	100979	374244	72697

Table B2. I*Hr and Hr in different conditions in Fayetteville, NC accumulated in 50 years under $VR_{\Delta T = 2^oC}$, $VR_{\Delta T = 3^oC}$ and $VR_{\Delta T = 5^oC}$ (Condition I is environmental control without using evaporative cooling and Condition II is with using evaporative cooling.)

Production Stage	$VR_{\Delta T = 2^oC}$				$VR_{\Delta T = 3^oC}$				$VR_{\Delta T = 5^oC}$			
	Condition I		Condition II		Condition I		Condition II		Condition I		Condition II	
	I*Hr	Hr	I*Hr	Hr	I*Hr	Hr	I*Hr	Hr	I*Hr	Hr	I*Hr	Hr
Growing	102416	27099	5072	2945	148508	35059	9770	5271	284495	54148	36964	15515
Finishing	100674	26760	4786	2804	145792	34607	9263	5047	274368	52838	34133	14539
Gestation	695932	95732	282386	65701	853764	107963	368221	78591	1221421	130660	628044	106959
Farrowing	691711	95377	224300	58337	845338	107288	320257	73401	1206372	129955	585891	103910

Table B3. I*Hr and Hr in different conditions in Taxes, OK accumulated in 50 years under $VR_{\Delta T = 2^oC}$, $VR_{\Delta T = 3^oC}$ and $VR_{\Delta T = 5^oC}$ (Condition I is environmental control without using evaporative cooling and Condition II is with using evaporative cooling.)

Production Stage	$VR_{\Delta T = 2^oC}$				$VR_{\Delta T = 3^oC}$				$VR_{\Delta T = 5^oC}$			
	Condition I		Condition II		Condition I		Condition II		Condition I		Condition II	
	I*Hr	Hr	I*Hr	Hr	I*Hr	Hr	I*Hr	Hr	I*Hr	Hr	I*Hr	Hr
Growing	141038	29533	4813	2651	190147	36153	8416	4326	324871	51440	29780	12205
Finishing	139038	29223	4502	2497	187171	35755	7938	4127	314832	50373	27449	11417
Gestation	695912	84636	233380	52799	836803	95592	296209	63174	1167622	117975	506001	90088
Farrowing	692155	84337	171154	45040	829296	95058	246010	57641	1153999	117122	462963	86659

Table B4. I*Hr and Hr in different conditions in Sioux City, IA accumulated in 50 years under $VR_{\Delta T = 2^oC}$ (Condition I is environmental control without using evaporative cooling and Condition II is with using evaporative cooling.)

Production Stage	*May*				*June*				*July*				*August*				*September*			
	Condition I		*Condition II*		*Condition I*		*Condition II*		*Condition I*		*Condition II*		*Condition I*		*Condition II*		*Condition I*		*Condition II*	
	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*
Growing	2709	707	97	44	16977	4255	964	425	33631	7580	1706	890	22630	5579	1141	548	4128	1108	193	72
Finishing	2659	694	92	43	16694	4201	921	407	33137	7501	1610	847	22261	5485	1082	533	4051	1084	185	70
Gestation	25916	4950	5445	1614	114012	16112	38216	9394	182043	22813	73842	17165	142155	19192	49980	12423	37756	6724	8759	2580
Farrowing	25697	4908	3773	1235	113299	16039	28793	7966	181035	22735	57305	14868	141306	19116	37738	10754	37458	6687	6174	2028

Table B5. I*Hr and Hr in different conditions in Sioux City, IA accumulated in 50 years under $VR_{\Delta T = 3^oC}$ (Condition I is environmental control without using evaporative cooling and Condition II is with using evaporative cooling.)

Production Stage	*May*				*June*				*July*				*August*				*September*			
	Condition I		*Condition II*		*Condition I*		*Condition II*		*Condition I*		*Condition II*		*Condition I*		*Condition II*		*Condition I*		*Condition II*	
	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*
Growing	3970	986	159	71	24266	5549	1568	662	46304	9460	2996	1446	32098	7180	1908	848	6081	1542	296	120
Finishing	3886	962	151	68	23818	5478	1502	638	45560	9362	2847	1383	31520	7094	1822	814	5951	1509	283	114
Gestation	34755	6268	7558	2208	140968	18463	50181	11624	219533	25567	95010	20386	174043	21762	65370	15190	49567	8266	12011	3376
Farrowing	34264	6206	5996	1863	139522	18355	42183	10480	217536	25435	81927	19234	172340	21641	55167	13898	48919	8197	9656	2915

Table B6. I*Hr and Hr in different conditions in Sioux City, IA accumulated in 50 years under $VR_{\Delta T = 5^oC}$ (Condition I is environmental control without using evaporative cooling and Condition II is with using evaporative cooling.)

	May				*June*				*July*				*August*				*September*			
Production	*Condition I*		*Condition II*		*Condition I*		*Condition II*		*Condition I*		*Condition II*		*Condition I*		*Condition II*		*Condition I*		Condition II	
Stage	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	I*Hr	Hr
Growing	8288	1869	527	214	46121	8793	4824	1852	81771	13721	10049	3938	59805	10943	6157	2411	12648	2796	913	363
Finishing	7913	1800	487	196	44431	8554	4482	1726	79191	13437	9316	3703	57706	10680	5710	2260	12090	2690	846	339
Gestation	59169	9410	15722	4157	205675	23360	90493	17491	305772	30395	159735	26608	249101	26829	115706	21789	88147	12587	27337	6508
Farrowing	58089	9284	14299	3798	202984	23195	82964	16760	302270	30231	148832	26023	246011	26643	106492	21032	79423	11626	21731	5421

Table B7. I*Hr and Hr in different conditions in Fayetteville, NC accumulated in 50 years under $VR_{\Delta T = 2^oC}$ (Condition I is environmental control without using evaporative cooling and Condition II is with using evaporative cooling.)

	May				*June*				*July*				*August*				*September*			
Production	*Condition I*		*Condition II*		*Condition I*		*Condition II*		*Condition I*		*Condition II*		*Condition I*		*Condition II*		*Condition I*		*Condition II*	
Stage	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*
Growing	5366	1722	103	83	22297	6161	1026	652	39651	9509	2293	1305	27446	7394	1040	698	7656	2313	610	207
Finishing	5250	1699	94	79	21901	6078	963	623	39048	9400	2164	1249	26972	7311	973	653	7503	2272	592	200
Gestation	60569	10722	15599	4661	158501	21823	64402	15528	219131	26606	103392	21614	181449	23809	76940	17787	76282	12772	22053	6111
Farrowing	60094	10660	11265	3759	157540	21750	50845	13764	217960	26524	84575	19988	180400	23730	61177	15896	75717	12713	16438	4930

Table B8. I*Hr and Hr in different conditions in Fayetteville, NC accumulated in 50 years under $VR_{\Delta T = 3^oC}$ (Condition I is environmental control without using evaporative cooling and Condition II is with using evaporative cooling.)

Production Stage	*May*				*June*				*July*				*August*				*September*			
	Condition I		*Condition II*		*Condition I*		*Condition II*		*Condition I*		*Condition II*		*Condition I*		*Condition II*		*Condition I*		*Condition II*	
	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*
Growing	8105	2004	269	101	32317	6782	1082	581	51840	10050	2117	1242	37719	7898	1200	644	11057	2799	145	83
Finishing	7960	1972	257	96	31859	6725	1014	542	51178	9970	1973	1176	37186	7808	1123	611	10855	2748	135	72
Gestation	60198	9374	11457	3268	159211	19005	53731	12268	220225	24168	89734	18521	179310	20847	62553	14129	76967	11242	15905	4613
Farrowing	59781	9329	7298	2375	158367	18936	39195	10416	219155	24084	68983	16665	178385	20785	45694	12188	76467	11203	9983	3396

Table B9. I*Hr and Hr in different conditions in Fayetteville, NC accumulated in 50 years under $VR_{\Delta T = 5^oC}$ (Condition I is environmental control without using evaporative cooling and Condition II is with using evaporative cooling.)

Production Stage	*May*				*June*				*July*				*August*				*September*			
	Condition I		*Condition II*		*Condition I*		*Condition II*		*Condition I*		*Condition II*		*Condition I*		*Condition II*		*Condition I*		*Condition II*	
	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*
Growing	8501	2490	228	150	32800	8013	2063	1153	55411	11773	4322	2291	27446	7394	1040	698	11783	3284	936	339
Finishing	8297	2434	213	133	32179	7907	1953	1109	54517	11651	4100	2198	26972	7311	973	653	11519	3232	906	327
Gestation	78988	12775	21811	6086	194258	24372	84867	18641	262065	29174	131247	24791	181449	23809	76940	17787	98065	15079	30180	7929
Farrowing	77988	12659	17826	5281	192356	24260	73637	17496	259793	29006	116457	23758	180400	23730	61177	15896	96885	14955	25053	6938

Table B10. I*Hr and Hr in different conditions in Texas, OK accumulated in 50 years under $VR_{\Delta T = 2^oC}$ (Condition I is environmental control without using evaporative cooling and Condition II is with using evaporative cooling.)

Production Stage	*May*				*June*				*July*				*August*				*September*			
	Condition I		*Condition II*		*Condition I*		*Condition II*		*Condition I*		*Condition II*		*Condition I*		*Condition II*		*Condition I*		*Condition II*	
	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*
Growing	11667	2709	391	140	43618	8323	1878	977	68221	11888	3808	1995	50746	9550	2087	1074	15896	3678	252	140
Finishing	11423	2666	375	136	42936	8216	1770	926	67277	11799	3590	1902	49965	9451	1967	1029	15570	3623	236	134
Gestation	76445	11136	15223	4189	190695	21301	68375	14780	259693	26738	112092	21542	213769	23371	79348	16870	96201	13046	21170	5793
Farrowing	75568	11045	11506	3411	189022	21193	56602	13451	257598	26620	96005	20387	211935	23232	65906	15550	95173	12968	15991	4842

Table B11. I*Hr and Hr in different conditions in Texas, OK accumulated in 50 years under $VR_{\Delta T = 3^oC}$ (Condition I is environmental control without using evaporative cooling and Condition II is with using evaporative cooling.)

Production Stage	*May*				*June*				*July*				*August*				*September*			
	Condition I		*Condition II*		*Condition I*		*Condition II*		*Condition I*		*Condition II*		*Condition I*		*Condition II*		*Condition I*		Condition II	
	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	I*Hr	Hr
Growing	19372	4711	1140	605	64095	12477	8029	3396	98988	16731	15771	6340	76312	14285	9445	4205	25727	5944	2580	696
Finishing	18451	4540	1028	553	61764	12168	7409	3180	95930	16417	14614	5971	73656	13964	8678	3928	24578	5749	2405	907
Gestation	125560	17301	44077	10193	276390	28969	146265	25104	357905	33265	209625	30815	309268	31208	168840	27727	152298	19917	59237	13120
Farrowing	123568	17156	39689	9510	273054	28837	136537	24466	354070	33131	197834	30367	305672	31096	158084	27169	150007	19735	53747	12398

Table B12. I*Hr and Hr in different conditions in Texas, OK accumulated in 50 years under $VR_{\Delta T = 5^oC}$ (Condition I is environmental control without using evaporative cooling and Condition II is with using evaporative cooling.)

	May				*June*				*July*				*August*				*September*			
Production	*Condition I*		*Condition II*		*Condition I*		*Condition II*		*Condition I*		*Condition II*		*Condition I*		*Condition II*		*Condition I*		Condition II	
Stage	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*
Growing	22817	4574	1070	422	74737	11870	6808	2778	110691	15763	13197	5175	85961	13289	7629	3268	30665	5944	1077	562
Finishing	21868	4408	989	381	72430	11632	6273	2624	107709	15516	12211	4871	83387	13034	7005	3045	29439	5783	970	496
Gestation	117189	14900	30539	7367	263998	26070	117521	21048	349626	31679	181059	28286	293728	28390	135068	23743	143081	16936	41814	9644
Farrowing	115468	14759	26509	6691	260987	25891	107505	20324	345970	31494	168461	27704	290451	28180	123917	23021	141123	16798	36570	8919

Appendix C. I*Hr and Hr for a typical year.

Table C1. I*Hr and Hr in different conditions in Sioux City, IA in a typical year under $VR_{\Delta T = 2^oC}$ (Condition I is environmental control without using evaporative cooling and Condition II is with using evaporative cooling).

Production Stage	*May*				*June*				*July*				*August*				*September*			
	Condition I		*Condition II*		*Condition I*		*Condition II*		*Condition I*		*Condition II*		*Condition I*		*Condition II*		*Condition I*		*Condition II*	
	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*
Growing	0	0	0	0	272	58	8	6	1039	221	31	28	601	157	24	18	200	29	52	13
Finishing	0	0	0	0	269	58	7	6	1025	218	29	25	590	156	22	18	199	29	51	13
Gestation	85	32	0	0	1923	280	660	164	4804	535	2287	428	3550	466	1399	331	1139	175	516	100
Farrowing	83	32	0	0	1911	281	508	147	4780	534	1874	401	3529	465	1075	299	1131	175	441	94

Table C2. I*Hr and Hr in different conditions in Sioux City, IA in a typical year under $VR_{\Delta T = 3^oC}$ (Condition I is environmental control without using evaporative cooling and Condition II is with using evaporative cooling).

Production Stage	*May*				*June*				*July*				*August*				*September*			
	Condition I		*Condition II*		*Condition I*		*Condition II*		*Condition I*		*Condition II*		*Condition I*		*Condition II*		*Condition I*		*Condition II*	
	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*
Growing	0	0	0	0	379	90	16	10	1395	266	83	59	856	188	48	27	254	45	68	16
Finishing	0	0	0	0	372	85	15	10	1375	264	78	56	841	184	46	26	251	44	66	15
Gestation	144	42	0	0	2404	334	881	211	5674	593	2836	505	4321	529	1833	405	1430	202	655	125
Farrowing	141	42	0	0	2372	331	751	189	5628	590	2515	486	4279	527	1568	379	1414	201	591	113

Table C3. I*Hr and Hr in different conditions in Sioux City, IA in a typical year under $VR_{\Delta T = 5^oC}$ (Condition I is environmental control without using evaporative cooling and Condition II is with using evaporative cooling).

Production	*May*				*June*				*July*				*August*				*September*			
	Condition I		*Condition II*		*Condition I*		*Condition II*		*Condition I*		*Condition II*		*Condition I*		*Condition II*		*Condition I*		*Condition II*	
Stage	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*
Growing	6	6	0	0	736	149	66	29	2358	363	406	165	1551	267	164	67	446	81	130	31
Finishing	5	6	0	0	708	144	60	28	2290	361	375	159	1500	266	151	64	431	80	124	30
Gestation	343	83	17	12	3531	412	1594	294	7607	669	4419	619	6101	631	3202	561	2147	264	1074	166
Farrowing	334	83	11	9	3507	417	1471	285	7530	665	4169	610	6028	628	2978	550	2116	262	1012	160

Table C4. I*Hr and Hr in different conditions in Fayetteville, NC in a typical year under $VR_{\Delta T = 2^oC}$ (Condition I is environmental control without using evaporative cooling and Condition II is with using evaporative cooling)

Production	*May*				*June*				*July*				*August*				*September*			
	Condition I		*Condition II*		*Condition I*		*Condition II*		*Condition I*		*Condition II*		*Condition I*		*Condition II*		*Condition I*		*Condition II*	
Stage	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*
Growing	2	2	0	0	590	147	22	19	1050	241	34	36	992	206	76	42	18	12	0	0
Finishing	1	2	0	0	581	147	20	17	1035	241	31	33	979	206	71	40	17	12	0	0
Gestation	296	86	9	6	3612	469	1767	357	5032	570	2467	488	4773	564	2493	473	875	191	111	72
Farrowing	292	85	2	4	3591	467	1479	336	5007	568	2026	458	4748	560	2111	455	867	189	42	49

Table C5. I*Hr and Hr in different conditions in Fayetteville, NC in a typical year under $VR_{\Delta T = 3^oC}$ (Condition I is environmental control without using evaporative cooling and Condition II is with using evaporative cooling).

	May				*June*				*July*				*August*				*September*			
Production	*Condition I*		*Condition II*		*Condition I*		*Condition II*		*Condition I*		*Condition II*		*Condition I*		*Condition II*		*Condition I*		*Condition II*	
Stage	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*
Growing	7	4	0	0	839	186	62	48	1430	274	87	61	1333	251	137	66	44	24	0	0
Finishing	7	4	0	0	825	185	57	46	1409	273	81	60	1315	248	130	64	42	24	0	0
Gestation	452	115	17	12	4376	515	2245	418	5946	619	3083	546	5675	604	3116	536	1215	248	211	103
Farrowing	443	113	9	6	3591	467	1479	336	5898	614	2745	529	5628	603	2820	519	1196	242	142	89

Table C6. I*Hr and Hr in different conditions in Fayetteville, NC in a typical year under $VR_{\Delta T = 5^oC}$ (Condition I is environmental control without using evaporative cooling and Condition II is with using evaporative cooling).

	May				*June*				*July*				*August*				*September*			
Production	*Condition I*		*Condition II*		*Condition I*		*Condition II*		*Condition I*		*Condition II*		*Condition I*		*Condition II*		*Condition I*		*Condition II*	
Stage	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*
Growing	37	20	0	0	1552	282	288	116	2424	372	404	158	2231	351	427	167	176	72	0	0
Finishing	33	20	0	0	1501	272	267	112	2357	363	375	151	2168	342	397	153	162	66	0	0
Gestation	960	209	110	58	6078	589	3564	516	7982	711	4798	675	7641	679	4758	636	2175	374	651	233
Farrowing	936	207	82	52	6010	585	3375	504	7900	710	4538	669	7562	678	4523	630	2132	369	558	217

Table C7. I*Hr and Hr in different conditions in Texas, OK in a typical year under $VR_{\Delta T = 2^{o}C}$ (Condition I is environmental control without using evaporative cooling and Condition II is with using evaporative cooling.)

	May				*June*				*July*				*August*				*September*			
Production	*Condition I*		*Condition II*		*Condition I*		*Condition II*		*Condition I*		*Condition II*		*Condition I*		*Condition II*		*Condition I*		*Condition II*	
Stage	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*
Growing	113	31	0	0	1552	282	288	116	1274	237	23	25	554	143	4	10	315	74	0	0
Finishing	111	30	0	0	1501	272	267	112	1258	233	20	22	545	141	3	9	310	74	0	0
Gestation	1041	176	205	64	6078	589	3564	516	5008	525	2083	426	3247	421	1361	313	1654	213	472	117
Farrowing	1033	174	123	50	6010	585	3375	504	4985	522	1599	386	3229	419	1066	282	1645	212	315	93

Table C8. I*Hr and Hr in different conditions in Texas, OK in a typical year under $VR_{\Delta T = 3^{o}C}$ (Condition I is environmental control without using evaporative cooling and Condition II is with using evaporative cooling.)

	May				*June*				*July*				*August*				*September*			
Production	*Condition I*		*Condition II*		*Condition I*		*Condition II*		*Condition I*		*Condition II*		*Condition I*		*Condition II*		*Condition I*		*Condition II*	
Stage	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*
Growing	178	49	0	0	1768	255	155	64	1659	274	59	45	789	167	23	26	441	89	0	0
Finishing	174	49	0	0	1749	251	148	64	1638	273	54	43	776	167	21	24	433	88	0	0
Gestation	1350	211	288	88	5678	544	2637	447	5861	573	2589	486	3938	477	1756	366	2024	255	609	145
Farrowing	1333	210	213	71	5636	542	2301	423	5816	571	2219	470	3901	474	1523	344	2004	253	481	130

Table C9. I*Hr and Hr in different conditions in Texas, OK in a typical year under $VR_{\Delta T = 5^0C}$ (Condition I is environmental control without using evaporative cooling and Condition II is with using evaporative cooling).

Production Stage	*May*				*June*				*July*				*August*				*September*			
	Condition I		*Condition II*		*Condition I*		*Condition II*		*Condition I*		*Condition II*		*Condition I*		*Condition II*		*Condition I*		*Condition II*	
	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*	*I*Hr*	*Hr*
Growing	372	80	2	4	2664	324	449	149	2625	351	284	125	1427	246	145	69	773	124	25	20
Finishing	356	78	1	2	2603	323	420	146	2559	346	259	120	1382	239	132	62	748	121	21	19
Gestation	2122	282	606	150	7491	624	4058	572	7765	663	4108	608	5545	569	2948	486	2940	344	1068	197
Farrowing	2089	282	531	141	7418	623	3801	564	7688	660	3831	602	5480	567	2754	475	2901	337	963	187

Appendix D. Number of days that THI exceeding threshold.

Table D1. Number of days that THI exceeding threshold (THI = 73) in a month in different conditions for gestation stage in Sioux City, Iowa under $VR_{\Delta T = 2^oC}$ (Condition I is environmental control without using evaporative cooling and Condition II is with evaporative cooling

	May		*June*		*July*		*August*		*September*	
	Condition I	*Condition II*	*Condition I*	*Condition II*	*Condition I*	*Condition II*	*Condition I*	*Condition II*	*Condition I*	*Condition II*
1:00	0	0	0	0	0	0	0	0	0	0
2:00	0	0	0	0	0	0	0	0	0	0
3:00	0	0	0	0	0	0	0	0	0	0
4:00	0	0	0	0	0	0	0	0	0	0
5:00	0	0	0	0	0	0	0	0	0	0
6:00	0	0	0	0	0	0	0	0	0	0
7:00	0	0	0	0	0	0	0	0	0	0
8:00	0	0	0	0	0	0	0	0	0	0
9:00	0	0	0	0	0	0	5	0	0	0
10:00	0	0	11	0	11	1	10	3	0	0
11:00	0	0	22	3	22	18	31	6	7	0
12:00	1	0	30	10	31	31	31	17	10	0
13:00	1	0	30	17	31	31	31	25	13	0
14:00	8	0	30	18	31	31	31	27	15	0
15:00	11	0	30	18	31	31	31	29	15	0
16:00	11	0	30	18	31	31	31	29	13	0
17:00	7	0	30	17	31	31	31	27	10	0
18:00	1	0	30	17	31	31	31	25	6	0
19:00	1	0	30	9	31	31	31	17	0	0
20:00	0	0	21	1	21	20	21	5	0	0
21:00	0	0	17	0	17	8	14	4	0	0
22:00	0	0	6	0	6	0	4	3	0	0
23:00	0	0	0	0	0	0	0	0	0	0
0:00	0	0	0	0	0	0	0	0	0	0

Table D2. Number of days that THI exceeding threshold (THI = 73) in a month in different conditions for gestation stage in Sioux City, Iowa under $VR_{\Delta T = 3^oC}$ (Condition I is environmental control without using evaporative cooling and Condition II is with evaporative cooling).

	May		*June*		*July*		*August*		*September*	
	Condition I	*Condition II*	*Condition I*	*Condition II*	*Condition I*	*Condition II*	*Condition I*	*Condition II*	*Condition I*	*Condition II*
1:00	0	0	0	0	5	0	4	0	0	0
2:00	0	0	0	0	0	0	1	0	0	0
3:00	0	0	0	0	0	0	0	0	0	0
4:00	0	0	0	0	0	0	0	0	0	0
5:00	0	0	0	0	0	0	0	0	0	0
6:00	0	0	0	0	0	0	0	0	0	0
7:00	0	0	0	0	0	0	0	0	0	0
8:00	0	0	0	0	0	0	0	0	0	0
9:00	0	0	3	0	27	0	6	0	0	0
10:00	0	0	17	0	31	12	27	19	4	0
11:00	0	0	29	6	31	29	31	31	10	0
12:00	1	0	30	17	31	31	31	31	14	0
13:00	9	0	30	18	31	31	31	31	17	0
14:00	15	0	30	23	31	31	31	31	18	2
15:00	16	0	30	25	31	31	31	31	18	2
16:00	16	0	30	25	31	31	31	31	16	0
17:00	13	0	30	22	31	31	31	31	14	0
18:00	9	0	30	18	31	31	31	31	10	0
19:00	1	0	30	17	31	31	31	31	2	0
20:00	0	0	28	6	31	29	31	30	0	0
21:00	0	0	18	3	31	19	29	27	0	0
22:00	0	0	17	0	31	5	24	14	0	0
23:00	0	0	6	0	30	0	11	1	0	0
0:00	0	0	1	0	25	0	5	0	0	0

Table D3. Number of days that THI exceeding threshold (THI = 73) in a month in different conditions for gestation stage in Sioux City, Iowa under $VR_{\Delta T = 5^oC}$ (Condition I is environmental control without using evaporative cooling and Condition II is with evaporative cooling)

	May		*June*		*July*		*August*		*September*	
	Condition I	*Condition II*	*Condition I*	*Condition II*	*Condition I*	*Condition II*	*Condition I*	*Condition II*	*Condition I*	*Condition II*
1:00	0	0	10	1	31	24	17	5	0	0
2:00	0	0	5	0	29	15	7	5	0	0
3:00	0	0	3	0	26	7	6	4	0	0
4:00	0	0	1	0	18	4	5	4	0	0
5:00	0	0	0	0	9	1	4	3	0	0
6:00	0	0	0	0	4	0	4	3	0	0
7:00	0	0	0	0	9	1	4	3	0	0
8:00	0	0	4	0	28	9	6	5	0	0
9:00	0	0	17	5	31	29	25	7	4	0
10:00	0	0	29	15	31	31	31	23	10	0
11:00	3	0	30	18	31	31	31	28	17	2
12:00	15	0	30	27	31	31	31	31	20	7
13:00	18	0	30	30	31	31	31	31	25	8
14:00	19	1	30	30	31	31	31	31	29	10
15:00	21	1	30	30	31	31	31	31	29	10
16:00	21	1	30	30	31	31	31	31	25	8
17:00	19	1	30	30	31	31	31	31	20	6
18:00	18	0	30	30	31	31	31	31	17	3
19:00	13	0	30	26	31	31	31	31	10	1
20:00	1	0	30	18	31	31	31	28	6	0
21:00	1	0	30	17	31	31	31	25	2	0
22:00	0	0	27	12	31	31	31	19	0	0
23:00	0	0	18	6	31	30	28	11	0	0
0:00	0	0	17	5	31	29	24	7	0	0

Table D4. Number of days that THI exceeding threshold (THI = 83) in a month in different conditions for finishing stage in Sioux City, Iowa under $VR_{\Delta T = 2^oC}$ (Condition I is environmental control without using evaporative cooling and Condition II is with evaporative cooling)

	May		*June*		*July*		*August*		*September*	
	Condition I	*Condition II*	*Condition I*	*Condition II*	*Condition I*	*Condition II*	*Condition I*	*Condition II*	*Condition I*	*Condition II*
1:00	0	0	0	0	0	0	0	0	0	0
2:00	0	0	0	0	0	0	0	0	0	0
3:00	0	0	0	0	0	0	0	0	0	0
4:00	0	0	0	0	0	0	0	0	0	0
5:00	0	0	0	0	0	0	0	0	0	0
6:00	0	0	0	0	0	0	0	0	0	0
7:00	0	0	0	0	0	0	0	0	0	0
8:00	0	0	0	0	0	0	0	0	0	0
9:00	0	0	0	0	0	0	0	0	0	0
10:00	0	0	0	0	0	0	0	0	0	0
11:00	0	0	0	0	24	0	5	0	0	0
12:00	0	0	14	0	31	0	23	0	0	0
13:00	0	0	18	0	31	0	28	0	2	0
14:00	0	0	26	0	31	0	31	0	4	0
15:00	0	0	28	0	31	1	31	2	4	0
16:00	0	0	28	0	31	1	31	3	2	0
17:00	0	0	24	0	31	0	29	3	0	0
18:00	0	0	18	0	31	0	27	2	0	0
19:00	0	0	13	0	31	0	22	0	0	0
20:00	0	0	0	0	20	0	5	0	0	0
21:00	0	0	0	0	0	0	2	0	0	0
22:00	0	0	0	0	0	0	0	0	0	0
23:00	0	0	0	0	0	0	0	0	0	0
0:00	0	0	0	0	0	0	0	0	0	0

Table D5. Number of days that THI exceeding threshold (THI = 83) in a month in different conditions for finishing stage in Sioux City, Iowa under $VR_{\Delta T = 3^oC}$ (Condition I is environmental control without using evaporative cooling and Condition II is with evaporative cooling).

	May		*June*		*July*		*August*		*September*	
	Condition I	*Condition II*	*Condition I*	*Condition II*	*Condition I*	*Condition II*	*Condition I*	*Condition II*	*Condition I*	*Condition II*
1:00	0	0	0	0	0	0	0	0	0	0
2:00	0	0	0	0	0	0	0	0	0	0
3:00	0	0	0	0	0	0	0	0	0	0
4:00	0	0	0	0	0	0	0	0	0	0
5:00	0	0	0	0	0	0	0	0	0	0
6:00	0	0	0	0	0	0	0	0	0	0
7:00	0	0	0	0	0	0	0	0	0	0
8:00	0	0	0	0	0	0	0	0	0	0
9:00	0	0	0	0	0	0	0	0	0	0
10:00	0	0	0	0	31	0	3	0	0	0
11:00	0	0	7	0	31	0	14	0	0	0
12:00	0	0	18	0	31	0	27	0	2	0
13:00	1	0	26	0	31	0	31	0	4	0
14:00	4	0	30	0	31	10	31	3	7	0
15:00	9	0	30	0	31	17	31	5	7	0
16:00	9	0	30	0	31	17	31	5	4	0
17:00	4	0	29	0	31	7	31	5	2	0
18:00	1	0	26	0	31	0	30	5	0	0
19:00	0	0	18	0	31	0	27	2	0	0
20:00	0	0	6	0	31	0	13	0	0	0
21:00	0	0	0	0	31	0	5	0	0	0
22:00	0	0	0	0	29	0	1	0	0	0
23:00	0	0	0	0	10	0	0	0	0	0
0:00	0	0	0	0	0	0	0	0	0	0

Table D6. Number of days that THI exceeding threshold (THI = 83) in a month in different conditions for finishing stage in Sioux City, Iowa under $VR_{\Delta T = 5^oC}$ (Condition I is environmental control without using evaporative cooling and Condition II is with evaporative cooling).

	May		*June*		*July*		*August*		*September*	
	Condition I	*Condition II*	*Condition I*	*Condition II*	*Condition I*	*Condition II*	*Condition I*	*Condition II*	*Condition I*	*Condition II*
1:00	0	0	0	0	0	0	0	0	0	0
2:00	0	0	0	0	0	0	0	0	0	0
3:00	0	0	0	0	0	0	0	0	0	0
4:00	0	0	0	0	0	0	0	0	0	0
5:00	0	0	0	0	0	0	0	0	0	0
6:00	0	0	0	0	0	0	0	0	0	0
7:00	0	0	0	0	0	0	0	0	0	0
8:00	0	0	0	0	0	0	0	0	0	0
9:00	0	0	0	0	0	0	3	0	0	0
10:00	0	0	0	0	31	0	14	0	0	0
11:00	0	0	0	0	31	3	28	0	4	0
12:00	0	0	12	3	31	26	31	3	10	0
13:00	1	0	18	6	31	29	31	5	12	0
14:00	4	0	22	11	31	31	31	11	14	0
15:00	9	0	26	14	31	31	31	18	14	0
16:00	9	0	26	14	31	31	31	23	11	0
17:00	4	0	22	10	31	31	31	23	10	0
18:00	1	0	18	6	31	29	31	17	4	0
19:00	0	0	10	0	31	24	31	9	0	0
20:00	0	0	0	0	31	2	27	5	0	0
21:00	0	0	0	0	31	0	19	3	0	0
22:00	0	0	0	0	29	0	7	0	0	0
23:00	0	0	0	0	10	0	5	0	0	0
0:00	0	0	0	0	0	0	1	0	0	0

Table D7. Number of days that THI exceeding threshold (THI = 73) in a month in different conditions for gestation stage in Fayetteville, NC under $VR_{\Delta T = 2^oC}$ (Condition I is environmental control without using evaporative cooling and Condition II is with evaporative cooling).

	May		*June*		*July*		*August*		*September*	
	Condition I	*Condition II*	*Condition I*	*Condition II*	*Condition I*	*Condition II*	*Condition I*	*Condition II*	*Condition I*	*Condition II*
1:00	0	0	1	0	11	0	4	0	0	0
2:00	0	0	0	0	2	0	0	0	0	0
3:00	0	0	0	0	0	0	0	0	0	0
4:00	0	0	0	0	0	0	0	0	0	0
5:00	0	0	0	0	0	0	0	0	0	0
6:00	0	0	0	0	0	0	0	0	0	0
7:00	0	0	0	0	0	0	0	0	0	0
8:00	0	0	0	0	0	0	0	0	0	0
9:00	0	0	10	0	31	3	13	0	0	0
10:00	0	0	26	7	31	31	31	7	2	0
11:00	7	0	30	17	31	31	31	26	13	0
12:00	16	0	30	25	31	31	31	31	21	2
13:00	21	0	30	27	31	31	31	31	27	4
14:00	24	0	30	29	31	31	31	31	30	10
15:00	26	2	30	30	31	31	31	31	30	13
16:00	26	4	30	30	31	31	31	31	30	13
17:00	24	4	30	29	31	31	31	31	30	8
18:00	21	2	30	26	31	31	31	31	27	3
19:00	15	0	30	24	31	31	31	31	21	2
20:00	6	0	30	17	31	31	31	25	13	0
21:00	0	0	27	12	31	31	31	14	3	0
22:00	0	0	21	6	31	27	31	6	0	0
23:00	0	0	17	0	31	7	21	3	0	0
0:00	0	0	9	0	31	2	9	0	0	0

Table D8. Number of days that THI exceeding threshold (THI = 73) in a month in different conditions for gestation stage in Fayetteville, NC under $VR_{\Delta T = 3^oC}$ (Condition I is environmental control without using evaporative cooling and Condition II is with evaporative cooling)

	May		*June*		*July*		*August*		*September*	
	Condition I	*Condition II*	*Condition I*	*Condition II*	*Condition I*	*Condition II*	*Condition I*	*Condition II*	*Condition I*	*Condition II*
1:00	0	0	16	1	31	21	15	5	0	0
2:00	0	0	6	0	25	9	5	3	0	0
3:00	0	0	0	0	9	3	4	1	0	0
4:00	0	0	0	0	5	1	2	0	0	0
5:00	0	0	0	0	2	0	0	0	0	0
6:00	0	0	0	0	0	0	0	0	0	0
7:00	0	0	0	0	2	0	0	0	0	0
8:00	0	0	1	0	13	0	4	0	0	0
9:00	0	0	18	0	31	2	26	0	0	0
10:00	1	0	29	6	31	23	31	5	8	0
11:00	10	0	30	17	31	31	31	21	16	0
12:00	20	0	30	23	31	31	31	31	27	2
13:00	23	0	30	27	31	31	31	31	30	5
14:00	29	5	30	30	31	31	31	31	30	11
15:00	30	7	30	30	31	31	31	31	30	13
16:00	30	9	30	30	31	31	31	31	30	15
17:00	27	9	30	30	31	31	31	31	30	15
18:00	23	7	30	30	31	31	31	31	30	13
19:00	20	3	30	30	31	31	31	31	26	11
20:00	10	0	30	27	31	31	31	31	16	4
21:00	5	0	30	21	31	31	31	31	13	0
22:00	0	0	27	18	31	31	31	26	3	0
23:00	0	0	21	16	31	31	31	17	0	0
0:00	0	0	18	9	31	31	26	8	0	0

Table D9. Number of days that THI exceeding threshold (THI = 73) in a month in different conditions for gestation stage in Fayetteville, NC under $VR_{\Delta T = 5^oC}$ (Condition I is environmental control without using evaporative cooling and Condition II is with evaporative cooling)

	May		*June*		*July*		*August*		*September*	
	Condition I	*Condition II*	*Condition I*	*Condition II*	*Condition I*	*Condition II*	*Condition I*	*Condition II*	*Condition I*	*Condition II*
1:00	0	0	26	18	31	31	31	30	2	0
2:00	0	0	19	18	31	31	30	26	0	0
3:00	0	0	18	17	31	31	27	18	0	0
4:00	0	0	17	16	31	31	22	15	0	0
5:00	0	0	16	16	31	31	17	15	0	0
6:00	0	0	16	10	31	31	15	12	0	0
7:00	0	0	16	9	31	29	17	10	0	0
8:00	0	0	18	10	31	31	29	12	0	0
9:00	1	0	28	16	31	31	31	17	8	0
10:00	12	0	30	19	31	31	31	30	19	0
11:00	23	0	30	27	31	31	31	31	30	3
12:00	30	5	30	30	31	31	31	31	30	12
13:00	31	10	30	30	31	31	31	31	30	15
14:00	31	13	30	30	31	31	31	31	30	20
15:00	31	18	30	30	31	31	31	31	30	23
16:00	31	19	30	30	31	31	31	31	30	25
17:00	31	19	30	30	31	31	31	31	30	25
18:00	31	17	30	30	31	31	31	31	30	22
19:00	29	13	30	30	31	31	31	31	30	20
20:00	22	10	30	30	31	31	31	31	27	15
21:00	16	5	30	30	31	31	31	31	21	12
22:00	11	0	30	28	31	31	31	31	15	7
23:00	6	0	30	26	31	31	31	31	11	2
0:00	0	0	28	21	31	31	31	31	6	1

Table D10. Number of days that THI exceeding threshold (THI =83) in a month in different conditions for finishing stage in Fayetteville, NC under $VR_{\Delta T=2^oC}$ (Condition I is environmental control without using evaporative cooling and Condition II is with evaporative cooling).

	May		*June*		*July*		*August*		*September*	
	Condition I	*Condition II*	*Condition I*	*Condition II*	*Condition I*	*Condition II*	*Condition I*	*Condition II*	*Condition I*	*Condition II*
1:00	0	0	0	0	0	0	0	0	0	0
2:00	0	0	0	0	0	0	0	0	0	0
3:00	0	0	0	0	0	0	0	0	0	0
4:00	0	0	0	0	0	0	0	0	0	0
5:00	0	0	0	0	0	0	0	0	0	0
6:00	0	0	0	0	0	0	0	0	0	0
7:00	0	0	0	0	0	0	0	0	0	0
8:00	0	0	0	0	0	0	0	0	0	0
9:00	0	0	0	0	0	0	0	0	0	0
10:00	0	0	0	0	3	0	1	0	0	0
11:00	0	0	17	0	31	0	21	0	0	0
12:00	0	0	26	0	31	0	31	0	2	0
13:00	4	0	30	0	31	0	31	0	12	0
14:00	9	0	31	1	31	0	31	2	15	0
15:00	12	0	31	6	31	5	31	3	15	0
16:00	12	0	31	6	31	6	31	3	15	0
17:00	8	0	31	1	31	6	31	2	15	0
18:00	3	0	30	0	31	5	31	0	12	0
19:00	0	0	26	0	31	0	31	0	2	0
20:00	0	0	17	0	31	0	19	0	0	0
21:00	0	0	1	0	15	0	5	0	0	0
22:00	0	0	0	0	1	0	0	0	0	0
23:00	0	0	0	0	0	0	0	0	0	0
0:00	0	0	0	0	0	0	0	0	0	0

Table D11. Number of days that THI exceeding threshold (THI = 83) in a month in different conditions for finishing stage in Fayetteville, NC under $VR_{\Delta T = 3^oC}$ (Condition I is environmental control without using evaporative cooling and Condition II is with evaporative cooling).

	May		*June*		*July*		*August*		*September*	
	Condition I	*Condition II*	*Condition I*	*Condition II*	*Condition I*	*Condition II*	*Condition I*	*Condition II*	*Condition I*	*Condition II*
1:00	0	0	0	0	0	0	0	0	0	0
2:00	0	0	0	0	0	0	0	0	0	0
3:00	0	0	0	0	0	0	0	0	0	0
4:00	0	0	0	0	0	0	0	0	0	0
5:00	0	0	0	0	0	0	0	0	0	0
6:00	0	0	0	0	0	0	0	0	0	0
7:00	0	0	0	0	0	0	0	0	0	0
8:00	0	0	0	0	0	0	0	0	0	0
9:00	0	0	0	0	0	0	0	0	0	0
10:00	0	0	7	0	30	0	6	0	0	0
11:00	0	0	21	0	31	0	30	0	1	0
12:00	3	0	29	0	31	7	31	3	12	0
13:00	10	0	30	6	31	29	31	6	16	0
14:00	14	0	30	9	31	31	31	13	18	0
15:00	18	0	30	15	31	31	31	17	23	0
16:00	18	0	30	15	31	31	31	17	23	0
17:00	13	0	30	8	31	31	31	11	17	0
18:00	8	0	30	6	31	26	31	5	16	0
19:00	2	0	29	0	31	7	31	1	9	0
20:00	0	0	19	0	31	0	30	0	1	0
21:00	0	0	13	0	31	0	16	0	0	0
22:00	0	0	2	0	15	0	5	0	0	0
23:00	0	0	0	0	1	0	0	0	0	0
0:00	0	0	0	0	0	0	0	0	0	0

Table D12. Number of days that THI exceeding threshold (THI = 83) in a month in different conditions for finishing stage in Fayetteville, NC under $VR_{\Delta T = 5^oC}$ (Condition I is environmental control without using evaporative cooling and Condition II is with evaporative cooling).

	May		*June*		*July*		*August*		*September*	
	Condition I	*Condition II*	*Condition I*	*Condition II*	*Condition I*	*Condition II*	*Condition I*	*Condition II*	*Condition I*	*Condition II*
1:00	0	0	0	0	3	0	1	0	0	0
2:00	0	0	0	0	0	0	0	0	0	0
3:00	0	0	0	0	0	0	0	0	0	0
4:00	0	0	0	0	0	0	0	0	0	0
5:00	0	0	0	0	0	0	0	0	0	0
6:00	0	0	0	0	0	0	0	0	0	0
7:00	0	0	0	0	0	0	0	0	0	0
8:00	0	0	0	0	0	0	0	0	0	0
9:00	0	0	6	0	27	0	5	0	0	0
10:00	0	0	21	0	31	6	30	0	0	0
11:00	5	0	30	7	31	31	31	2	12	0
12:00	13	0	30	17	31	31	31	9	18	0
13:00	20	0	30	19	31	31	31	23	24	0
14:00	24	0	30	26	31	31	31	30	30	3
15:00	25	0	30	26	31	31	31	31	30	4
16:00	25	0	30	26	31	31	31	31	30	4
17:00	24	0	30	25	31	31	31	31	29	3
18:00	20	0	30	19	31	31	31	31	24	1
19:00	13	0	30	17	31	31	31	30	16	1
20:00	4	0	30	7	31	31	31	23	11	0
21:00	0	0	26	0	31	9	31	7	2	0
22:00	0	0	18	0	31	2	27	4	0	0
23:00	0	0	15	0	31	0	16	0	0	0
0:00	0	0	6	0	21	0	5	0	0	0

Table D13. Number of days that THI exceeding threshold (THI = 73) in a month in different conditions for gestation stage in Texas, OK under $VR_{\Delta T = 2^oC}$ (Condition I is environmental control without using evaporative cooling and Condition II is with evaporative cooling).

	May		*June*		*July*		*August*		*September*	
	Condition I	*Condition II*	*Condition I*	*Condition II*	*Condition I*	*Condition II*	*Condition I*	*Condition II*	*Condition I*	*Condition II*
1:00	0	0	0	0	19	0	3	0	0	0
2:00	0	0	0	0	0	0	0	0	0	0
3:00	0	0	0	0	0	0	0	0	0	0
4:00	0	0	0	0	0	0	0	0	0	0
5:00	0	0	0	0	0	0	0	0	0	0
6:00	0	0	0	0	0	0	0	0	0	0
7:00	0	0	0	0	0	0	0	0	0	0
8:00	0	0	0	0	0	0	0	0	0	0
9:00	0	0	0	0	0	0	0	0	0	0
10:00	0	0	1	0	25	0	5	0	0	0
11:00	0	0	22	0	31	17	27	1	0	0
12:00	4	0	30	12	31	31	31	16	10	0
13:00	14	0	30	22	31	31	31	26	22	0
14:00	21	0	30	24	31	31	31	30	27	3
15:00	25	1	30	30	31	31	31	30	30	7
16:00	27	2	30	30	31	31	31	30	31	9
17:00	27	2	30	30	31	31	31	30	31	9
18:00	24	1	30	29	31	31	31	30	30	6
19:00	20	0	30	23	31	31	31	30	27	3
20:00	14	0	30	20	31	31	31	26	19	0
21:00	3	0	30	10	31	31	31	15	10	0
22:00	0	0	23	3	31	29	29	7	3	0
23:00	0	0	18	0	31	3	25	0	0	0
0:00	0	0	9	0	31	0	12	0	0	0

Table D14. Number of days that THI exceeding threshold (THI = 73) in a month in different conditions for gestation stage in Texas, OK under $VR_{\Delta T = 3^oC}$ (Condition I is environmental control without using evaporative cooling and Condition II is with evaporative cooling).

	May		*June*		*July*		*August*		*September*	
	Condition I	*Condition II*	*Condition I*	*Condition II*	*Condition I*	*Condition II*	*Condition I*	*Condition II*	*Condition I*	*Condition II*
1:00	0	0	9	0	31	0	13	0	0	0
2:00	0	0	0	0	24	0	4	0	0	0
3:00	0	0	0	0	0	0	0	0	0	0
4:00	0	0	0	0	0	0	0	0	0	0
5:00	0	0	0	0	0	0	0	0	0	0
6:00	0	0	0	0	0	0	0	0	0	0
7:00	0	0	0	0	0	0	0	0	0	0
8:00	0	0	0	0	0	0	0	0	0	0
9:00	0	0	0	0	0	0	0	0	0	0
10:00	0	0	10	0	31	0	14	0	0	0
11:00	1	0	26	8	31	31	31	10	4	0
12:00	8	0	30	18	31	31	31	25	14	0
13:00	18	0	30	23	31	31	31	31	26	2
14:00	25	1	30	30	31	31	31	31	29	7
15:00	28	3	30	30	31	31	31	31	30	9
16:00	31	3	30	30	31	31	31	31	30	11
17:00	31	3	30	30	31	31	31	31	30	11
18:00	28	2	30	30	31	31	31	31	30	9
19:00	24	1	30	30	31	31	31	31	29	6
20:00	18	0	30	23	31	31	31	30	24	2
21:00	7	0	30	18	31	31	31	24	14	0
22:00	3	0	30	10	31	31	31	14	7	0
23:00	0	0	23	4	31	30	28	7	0	0
0:00	0	0	18	0	31	10	22	0	0	0

Table D15. Number of days that THI exceeding threshold (THI = 73) in a month in different conditions for gestation stage in Texas, OK under $VR_{\Delta T = 5^oC}$ (Condition I is environmental control without using evaporative cooling and Condition II is with evaporative cooling).

	May		*June*		*July*		*August*		*September*	
	Condition I	*Condition II*	*Condition I*	*Condition II*	*Condition I*	*Condition II*	*Condition I*	*Condition II*	*Condition I*	*Condition II*
1:00	0	0	23	11	31	31	28	14	0	0
2:00	0	0	18	6	31	31	23	9	0	0
3:00	0	0	13	3	31	27	16	5	0	0
4:00	0	0	9	0	31	18	11	2	0	0
5:00	0	0	4	0	28	8	6	0	0	0
6:00	0	0	0	0	20	3	3	0	0	0
7:00	0	0	0	0	8	0	0	0	0	0
8:00	0	0	0	0	20	3	3	0	0	0
9:00	0	0	9	0	31	20	12	3	0	0
10:00	0	0	23	13	31	31	29	16	0	0
11:00	5	0	30	22	31	31	31	27	12	0
12:00	18	2	30	30	31	31	31	31	26	5
13:00	27	4	30	30	31	31	31	31	30	11
14:00	31	8	30	30	31	31	31	31	30	15
15:00	31	14	30	30	31	31	31	31	30	19
16:00	31	16	30	30	31	31	31	31	30	23
17:00	31	16	30	30	31	31	31	31	30	23
18:00	31	14	30	30	31	31	31	31	30	18
19:00	31	8	30	30	31	31	31	31	30	15
20:00	26	4	30	30	31	31	31	31	30	11
21:00	18	2	30	29	31	31	31	31	25	5
22:00	12	0	30	23	31	31	31	28	16	0
23:00	4	0	30	18	31	31	31	26	11	0
0:00	1	0	29	18	31	31	31	21	5	0

Table D16. Number of days that THI exceeding threshold (THI = 83) in a month in different conditions for finishing stage in Texas, OK under $VR_{\Delta T = 2^oC}$ (Condition I is environmental control without using evaporative cooling and Condition II is with evaporative cooling).

	May		*June*		*July*		*August*		*September*	
	Condition I	*Condition II*	*Condition I*	*Condition II*	*Condition I*	*Condition II*	*Condition I*	*Condition II*	*Condition I*	*Condition II*
1:00	0	0	0	0	0	0	0	0	0	0
2:00	0	0	0	0	0	0	0	0	0	0
3:00	0	0	0	0	0	0	0	0	0	0
4:00	0	0	0	0	0	0	0	0	0	0
5:00	0	0	0	0	0	0	0	0	0	0
6:00	0	0	0	0	0	0	0	0	0	0
7:00	0	0	0	0	0	0	0	0	0	0
8:00	0	0	0	0	0	0	0	0	0	0
9:00	0	0	0	0	0	0	0	0	0	0
10:00	0	0	0	0	0	0	0	0	0	0
11:00	0	0	0	0	0	0	0	0	0	0
12:00	0	0	15	0	31	0	20	0	0	0
13:00	0	0	24	0	31	0	31	0	4	0
14:00	3	0	30	0	31	0	31	0	9	0
15:00	7	0	30	0	31	17	31	3	14	0
16:00	12	0	30	3	31	27	31	7	17	0
17:00	12	0	30	3	31	27	31	7	17	0
18:00	6	0	30	0	31	14	31	1	14	0
19:00	2	0	30	0	31	0	31	0	9	0
20:00	0	0	24	0	31	0	29	0	4	0
21:00	0	0	13	0	31	0	17	0	0	0
22:00	0	0	0	0	16	0	1	0	0	0
23:00	0	0	0	0	0	0	0	0	0	0
0:00	0	0	0	0	0	0	0	0	0	0

Table D17. Number of days that THI exceeding threshold (THI = 83) in a month in different conditions for finishing in Texas, OK under $VR_{\Delta T = 3^oC}$ (Condition I is environmental control without using evaporative cooling and Condition II is with evaporative cooling).

	May		*June*		*July*		*August*		*September*	
	Condition I	*Condition II*	*Condition I*	*Condition II*	*Condition I*	*Condition II*	*Condition I*	*Condition II*	*Condition I*	*Condition II*
1:00	0	0	0	0	0	0	0	0	0	0
2:00	0	0	0	0	0	0	0	0	0	0
3:00	0	0	0	0	0	0	0	0	0	0
4:00	0	0	0	0	0	0	0	0	0	0
5:00	0	0	0	0	0	0	0	0	0	0
6:00	0	0	0	0	0	0	0	0	0	0
7:00	0	0	0	0	0	0	0	0	0	0
8:00	0	0	0	0	0	0	0	0	0	0
9:00	0	0	0	0	0	0	0	0	0	0
10:00	0	0	0	0	0	0	0	0	0	0
11:00	0	0	1	0	25	0	5	0	0	0
12:00	0	0	21	0	31	0	26	0	0	0
13:00	2	0	30	0	31	1	31	0	10	0
14:00	7	0	30	1	31	24	31	4	15	0
15:00	13	0	30	6	31	31	31	11	22	0
16:00	16	0	30	10	31	31	31	14	25	0
17:00	16	0	30	10	31	31	31	14	25	0
18:00	12	0	30	6	31	31	31	10	20	0
19:00	6	0	30	1	31	20	31	4	15	0
20:00	2	0	30	0	31	0	31	0	8	0
21:00	0	0	18	0	31	0	26	0	0	0
22:00	0	0	8	0	31	0	12	0	0	0
23:00	0	0	0	0	6	0	0	0	0	0
0:00	0	0	0	0	0	0	0	0	0	0

Table D18. Number of days that THI exceeding threshold (THI = 83) in a month in different conditions for finishing in Texas, OK under $VR_{\Delta T = 5°C}$ (Condition I is environmental control without using evaporative cooling and Condition II is with evaporative cooling)

	May		*June*		*July*		*August*		*September*	
	Condition I	*Condition II*	*Condition I*	*Condition II*	*Condition I*	*Condition II*	*Condition I*	*Condition II*	*Condition I*	*Condition II*
1:00	0	0	0	0	1	0	0	0	0	0
2:00	0	0	0	0	0	0	0	0	0	0
3:00	0	0	0	0	0	0	0	0	0	0
4:00	0	0	0	0	0	0	0	0	0	0
5:00	0	0	0	0	0	0	0	0	0	0
6:00	0	0	0	0	0	0	0	0	0	0
7:00	0	0	0	0	0	0	0	0	0	0
8:00	0	0	0	0	0	0	0	0	0	0
9:00	0	0	0	0	0	0	0	0	0	0
10:00	0	0	0	0	4	0	0	0	0	0
11:00	0	0	18	0	31	0	25	0	0	0
12:00	3	0	30	1	31	25	31	4	8	0
13:00	12	0	30	11	31	31	31	16	16	0
14:00	18	0	30	18	31	31	31	25	24	0
15:00	22	0	30	22	31	31	31	28	27	0
16:00	25	1	30	23	31	31	31	28	29	1
17:00	25	1	30	23	31	31	31	28	29	1
18:00	22	0	30	22	31	31	31	27	27	0
19:00	18	0	30	18	31	31	31	25	24	0
20:00	10	0	30	11	31	31	31	15	16	0
21:00	3	0	30	1	31	23	31	4	7	0
22:00	0	0	23	0	31	0	28	0	0	0
23:00	0	0	17	0	31	0	21	0	0	0
0:00	0	0	4	0	29	0	7	0	0	0

Table D19. Number of days that THI exceeding threshold (THI = 73) in different conditions for gestation stage under $VR_{\Delta T = 2^oC}$, $VR_{\Delta T = 3^oC}$ and $VR_{\Delta T = 5^oC}$ in Sioux City, IA (Condition I is environmental control without using evaporative cooling and Condition II is with evaporative cooling.)

	ΔT = 2		*ΔT = 3*		*ΔT = 5*	
	Condition I	*Condition II*	*Condition I*	*Condition II*	*Condition I*	*Condition II*
1:00	0	0	5	0	31	24
2:00	0	0	0	0	29	15
3:00	0	0	0	0	26	7
4:00	0	0	0	0	18	4
5:00	0	0	0	0	9	1
6:00	0	0	0	0	4	0
7:00	0	0	0	0	9	1
8:00	0	0	0	0	28	9
9:00	0	0	27	0	31	29
10:00	11	1	31	12	31	31
11:00	22	18	31	29	31	31
12:00	31	31	31	31	31	31
13:00	31	31	31	31	31	31
14:00	31	31	31	31	31	31
15:00	31	31	31	31	31	31
16:00	31	31	31	31	31	31
17:00	31	31	31	31	31	31
18:00	31	31	31	31	31	31
19:00	31	31	31	31	31	31
20:00	21	20	31	29	31	31
21:00	17	8	31	19	31	31
22:00	6	0	31	5	31	31
23:00	0	0	30	0	31	30
0:00	0	0	25	0	31	29

Table D20: Number of days that THI exceeding threshold (THI = 73) in July for gestation stage under $VR_{\Delta T = 2^oC}$ (Condition I is environmental control without using evaporative cooling and Condition II is with evaporative cooling).

	Sioux City		*Fayetteville*		*Texas*	
	Condition I	*Condition II*	*Condition I*	*Condition II*	*Condition I*	*Condition II*
1:00	0	0	11	0	19	0
2:00	0	0	2	0	0	0
3:00	0	0	0	0	0	0
4:00	0	0	0	0	0	0
5:00	0	0	0	0	0	0
6:00	0	0	0	0	0	0
7:00	0	0	0	0	0	0
8:00	0	0	0	0	0	0
9:00	0	0	31	3	0	0
10:00	11	1	31	31	25	0
11:00	22	18	31	31	31	17
12:00	31	31	31	31	31	31
13:00	31	31	31	31	31	31
14:00	31	31	31	31	31	31
15:00	31	31	31	31	31	31
16:00	31	31	31	31	31	31
17:00	31	31	31	31	31	31
18:00	31	31	31	31	31	31
19:00	31	31	31	31	31	31
20:00	21	20	31	31	31	31
21:00	17	8	31	31	31	31
22:00	6	0	31	27	31	28
23:00	0	0	31	7	31	2
0:00	0	0	31	2	31	0

Appendix E. Ventilation rate curve.

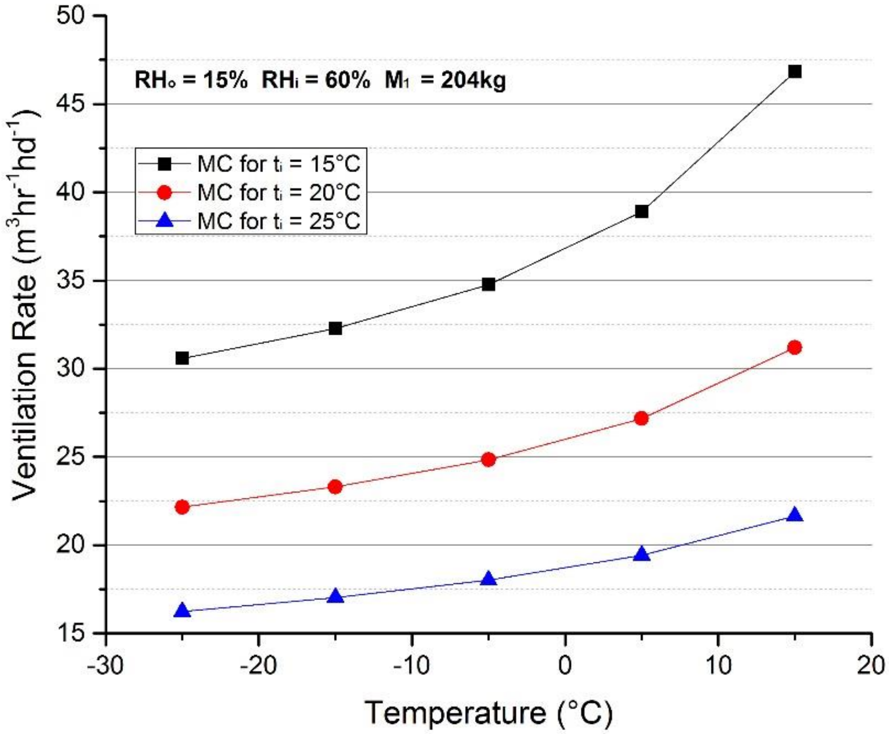

Figure E1. Minimum ventilation rate for moisture control (MC) required for gestation stage for three indoor set point temperatures (M_1 is mass of sow in gestation stage, t_i is indoor temperature, RH_i is indoor relative humidity, RH_o is outdoor relative humidity)

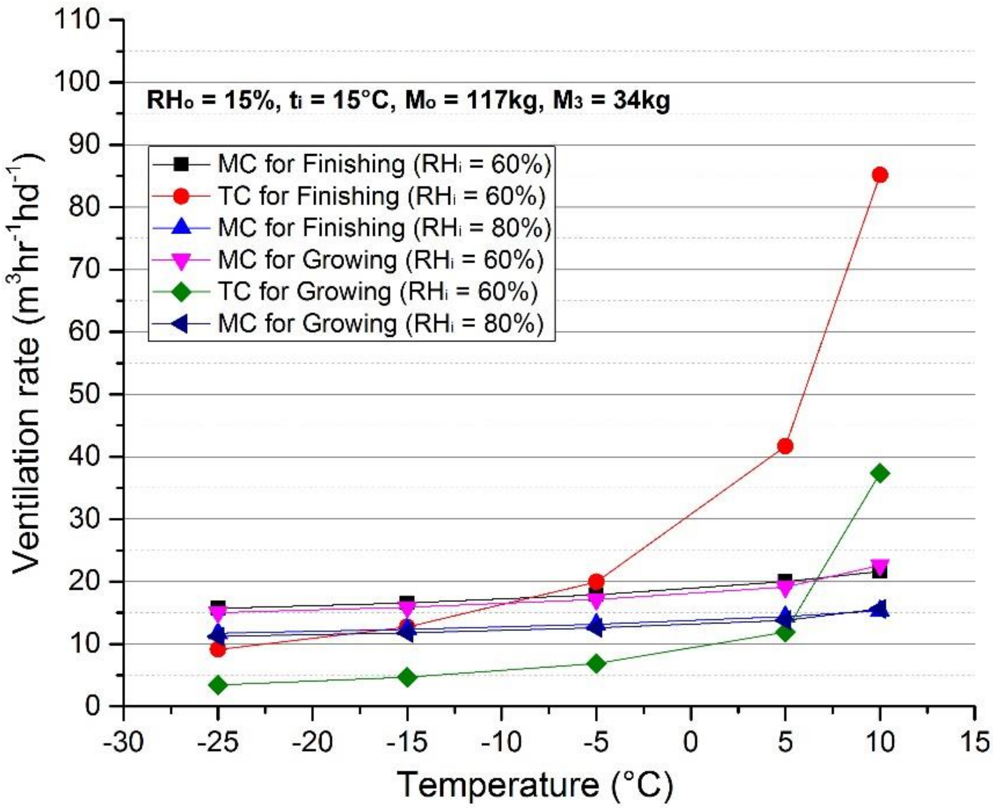

Figure E2. Typical ventilation rates ($m^3\,hr^{-1}hd^{-1}$) for moisture control (MC) and temperature control (TC) for single stocked (finishing) and double stocked (growing) periods in a grow-finish barn. MC is labeled based on two indoor RH set points 60 and 80%. (M_2 is mass of pig in finishing stage and M_3 is mass of pig in growing stage, t_i is indoor temperature, RH_i is indoor relative humidity, RH_o is outdoor relative humidity)

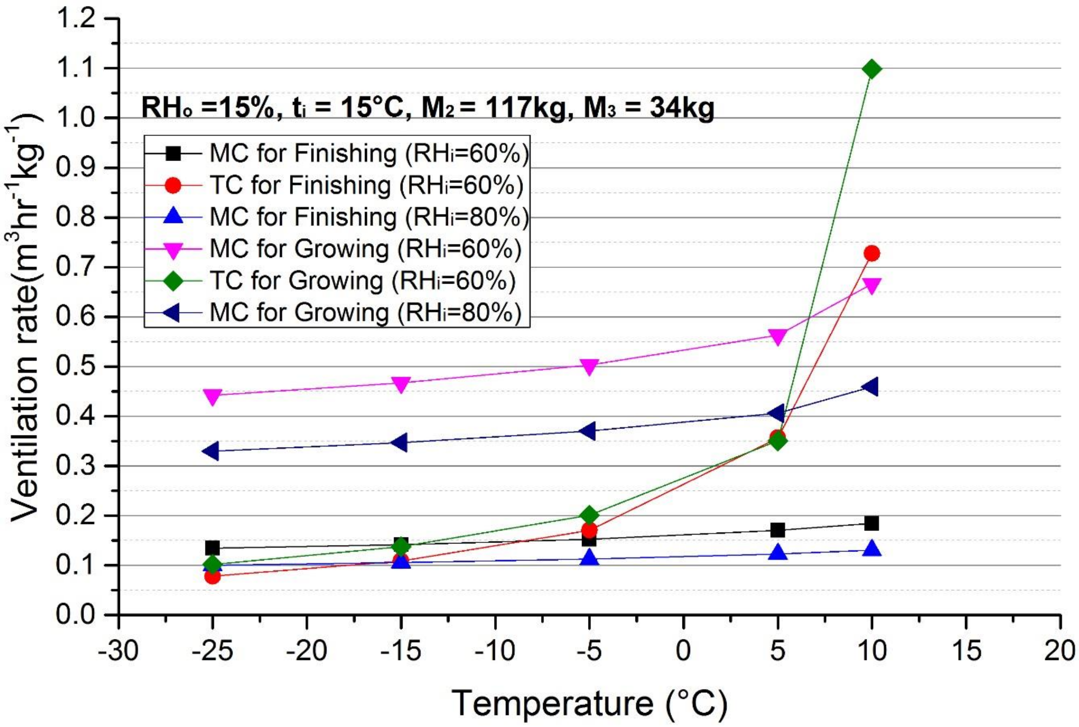

Figure E3. Typical ventilation rates($m^3\,hr^{-1}kg^{-1}$) for moisture control (MC) and temperature control (TC) for single stocked (finishing) and double stocked (growing) periods in a grow-finish barn. MC is labeled based on two indoor RH set points 60% and 80%. (M_2 is mass of pig in finishing stage and M_3 is mass of pig in growing stage, t_i is indoor temperature, RH_i is indoor relative humidity, RH_o is outdoor relative humidity)

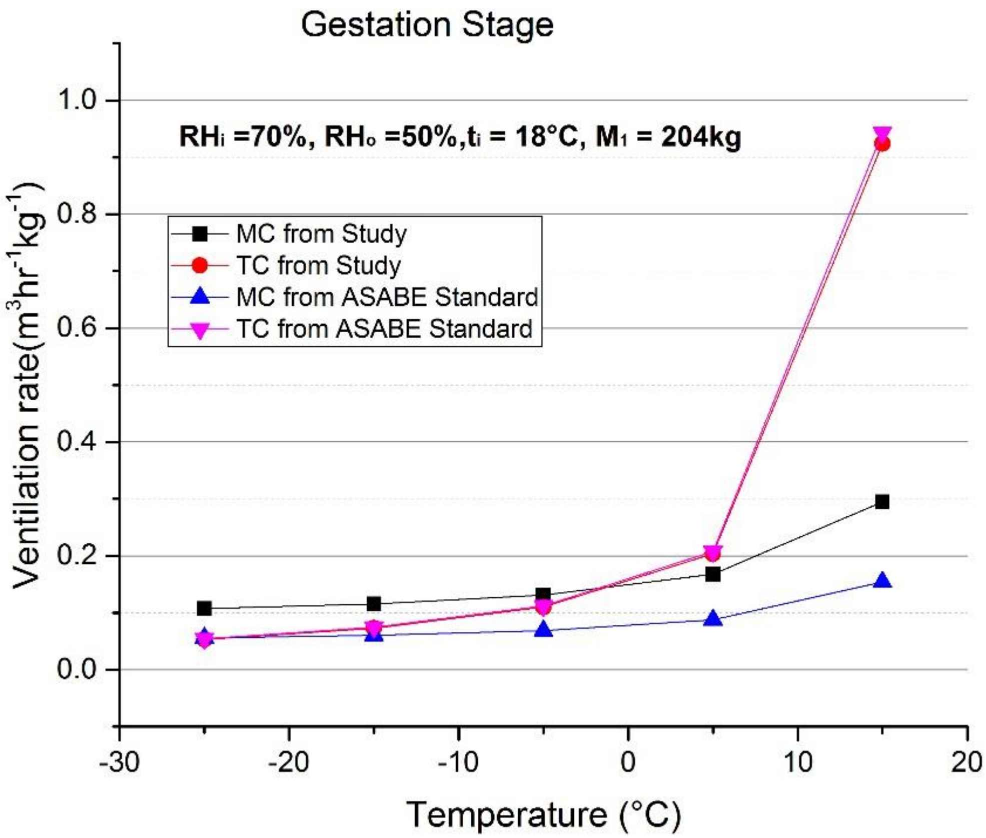

Figure E4. Typical ventilation rate for moisture control (MC) and temperature control (TC) for gestation stage. (M_1 is mass of pig in gestation stage, t_i is indoor temperature, RH_i is indoor relative humidity, RH_o is outdoor relative humidity.)

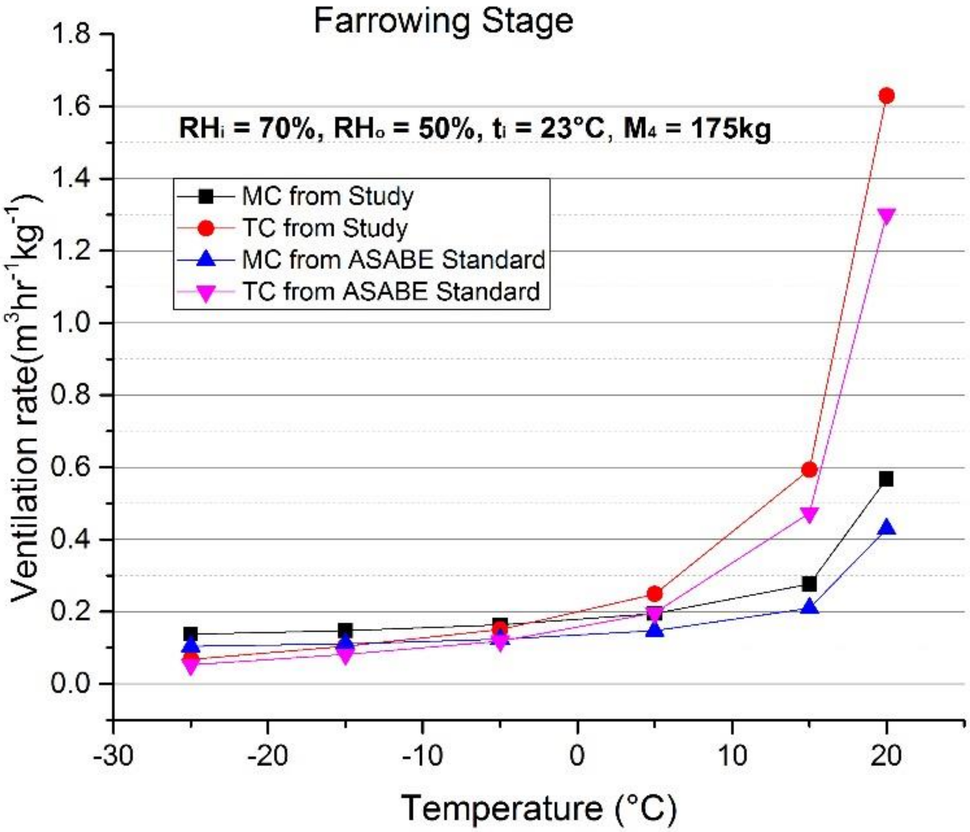

Figure E5. Typical ventilation rate for moisture control (MC) and temperature control (TC) for farrowing stage. (M_4 is mass of sow in farrowing stage, t_i is indoor temperature, RH_i is indoor relative humidity, RH_o is outdoor relative humidity)

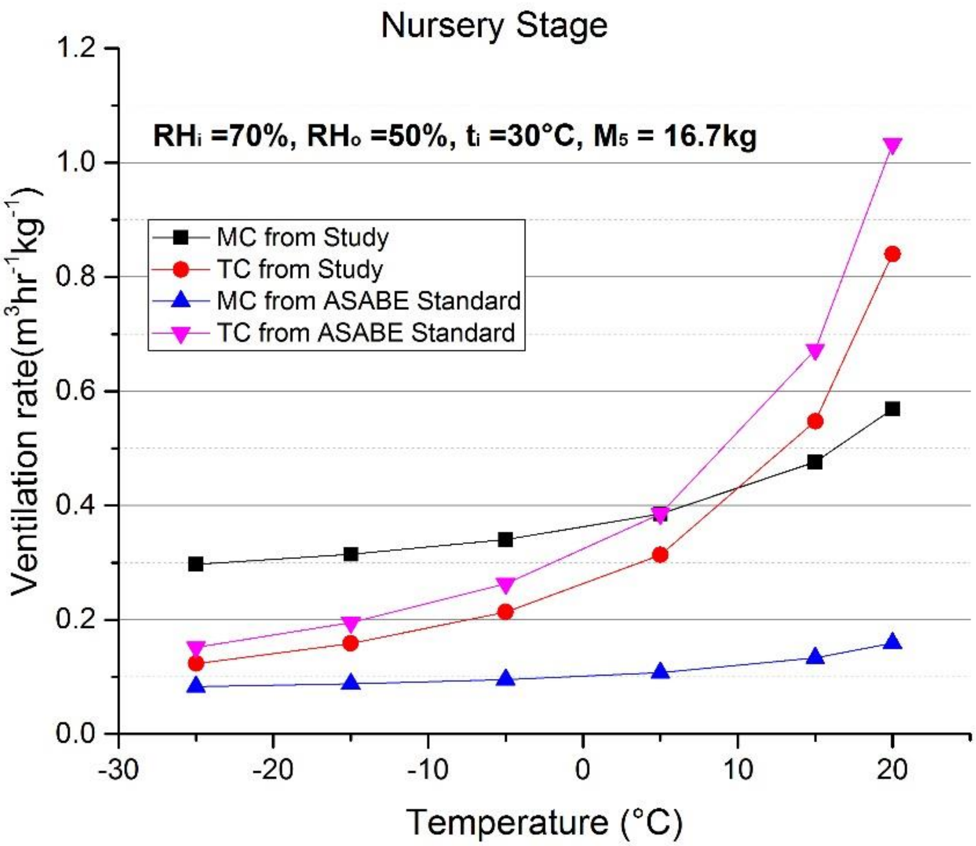

Figure E6. Typical ventilation rate for moisture control (MC) and temperature control (TC) for nursery stage. (M_5 is mass of pig in nursery stage, t_i is indoor temperature, RH_i is indoor relative humidity, RH_o is outdoor relative humidity)

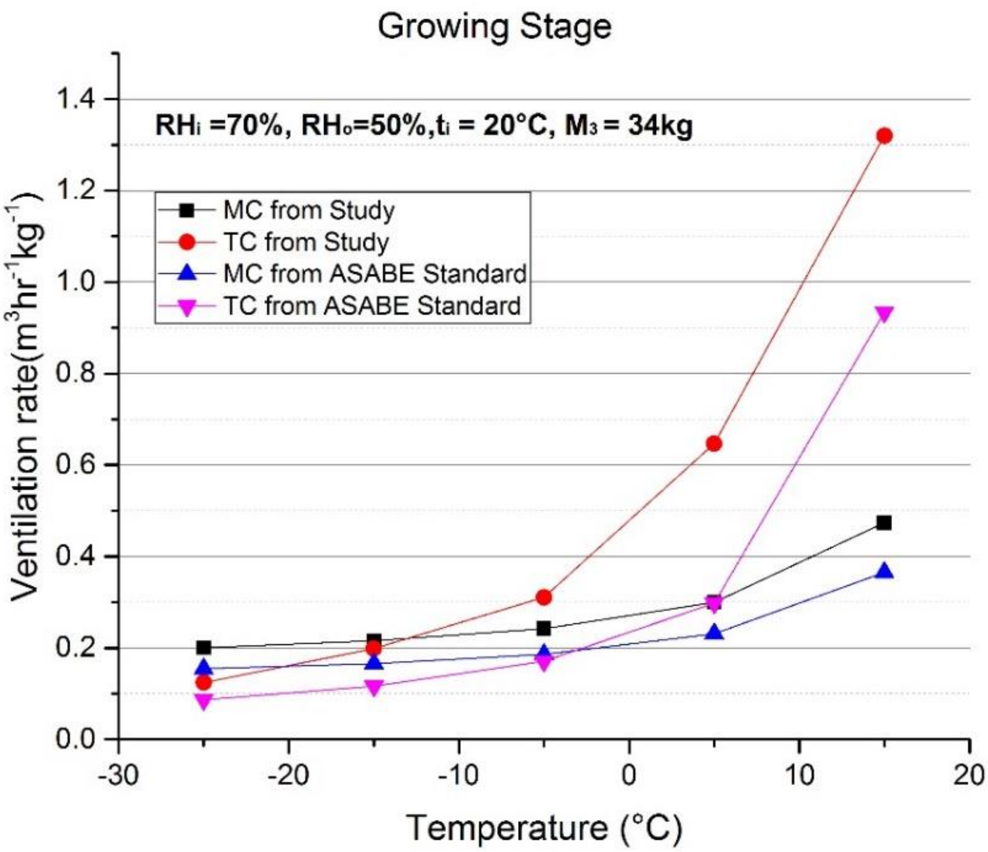

Figure E7. Typical ventilation rate for moisture control (MC) and temperature control (TC) for growing stage. (M_3 is mass of pig in growing stage, t_i is indoor temperature, RH_i is indoor relative humidity, RH_o is outdoor relative humidity.)

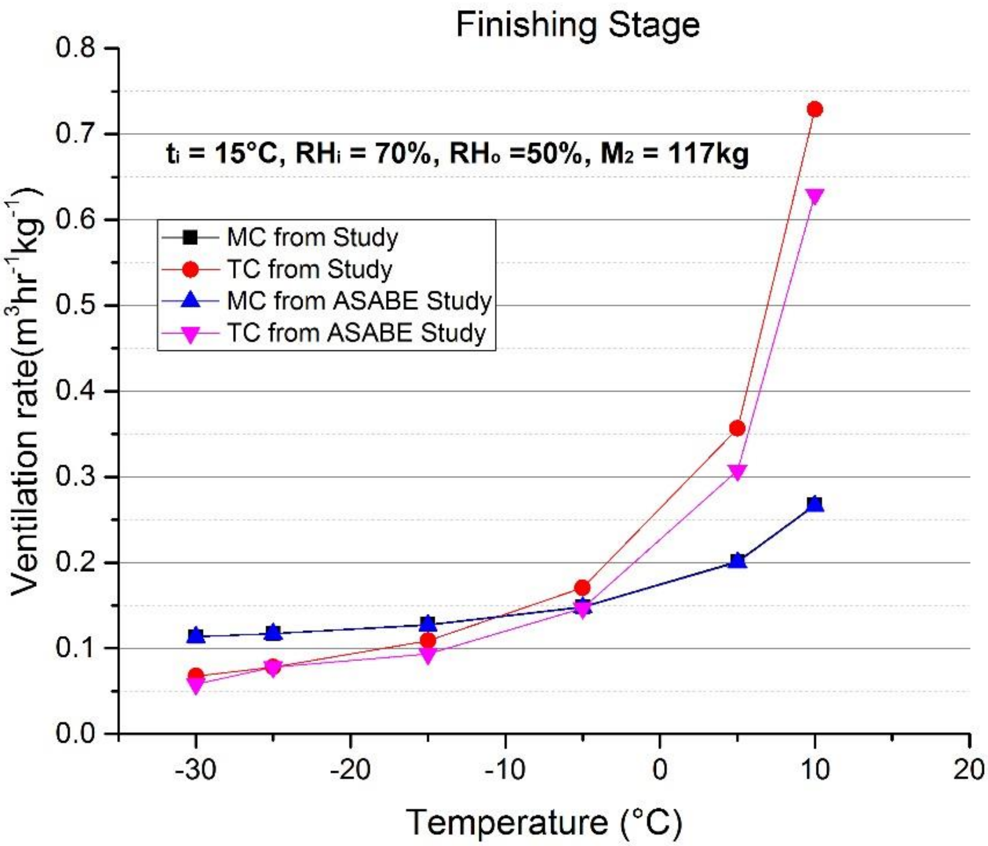

Figure E8. Typical ventilation rate for moisture control (MC) and temperature control (TC) for finishing stage. (M_2 is mass of pig in finishing stage, t_i is indoor temperature, RH_i is indoor relative humidity, RH_o is outdoor relative humidity.)

Appendix F. Outdoor condition, THI values etc.

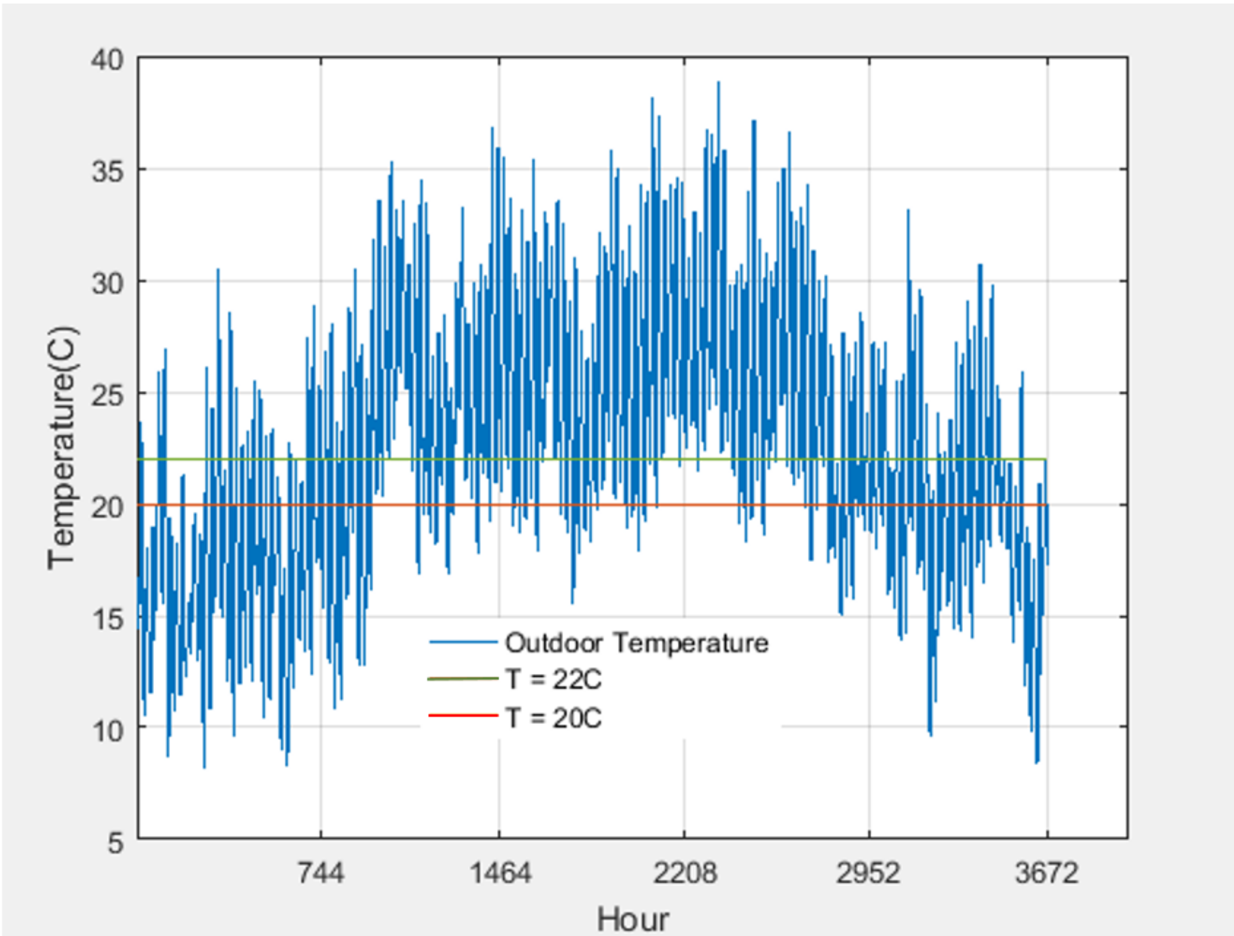

Figure F1. Outdoor hourly temperature during summer of a typical year for Sioux City.

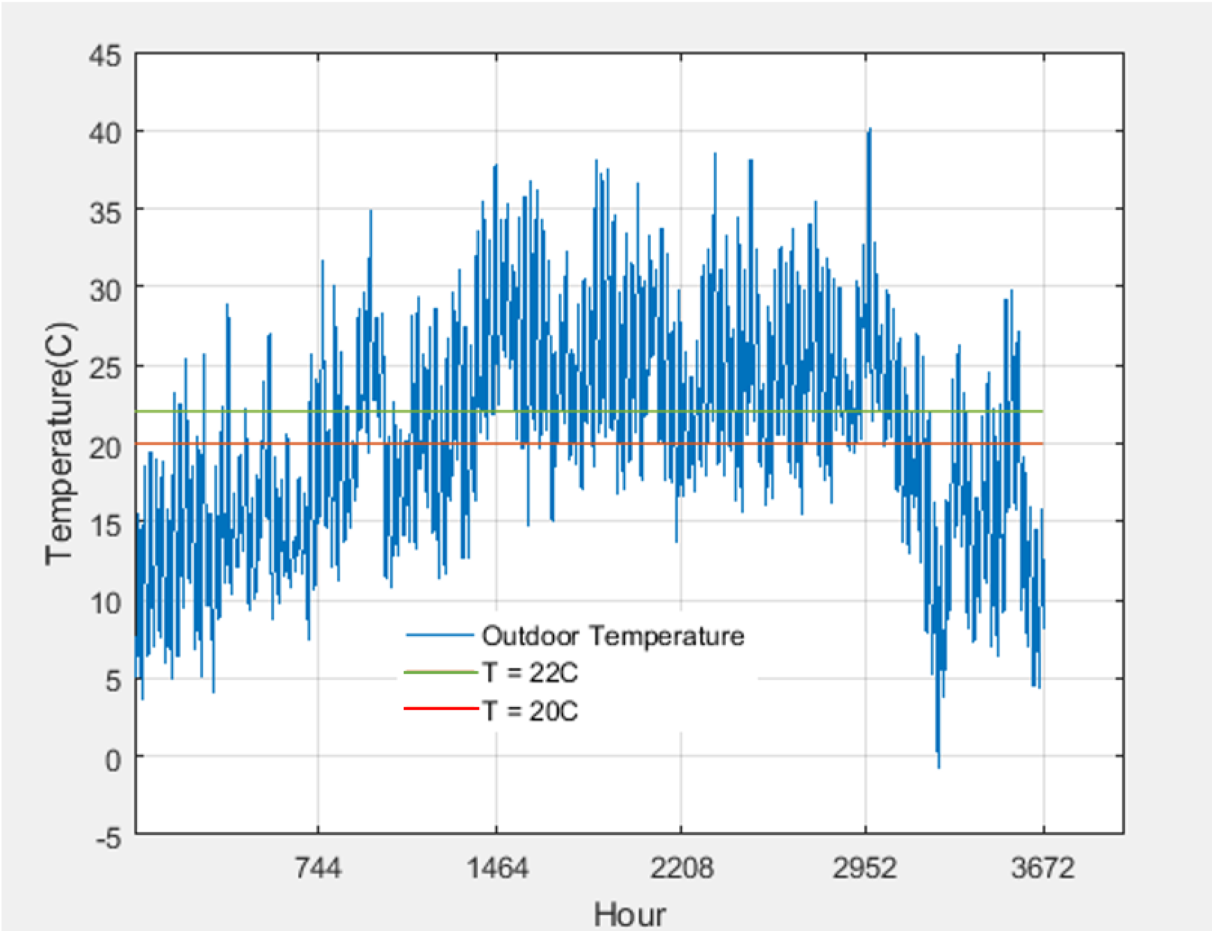

Figure F2. Outdoor hourly temperature during summer of a typical year for Fayetteville, NC.

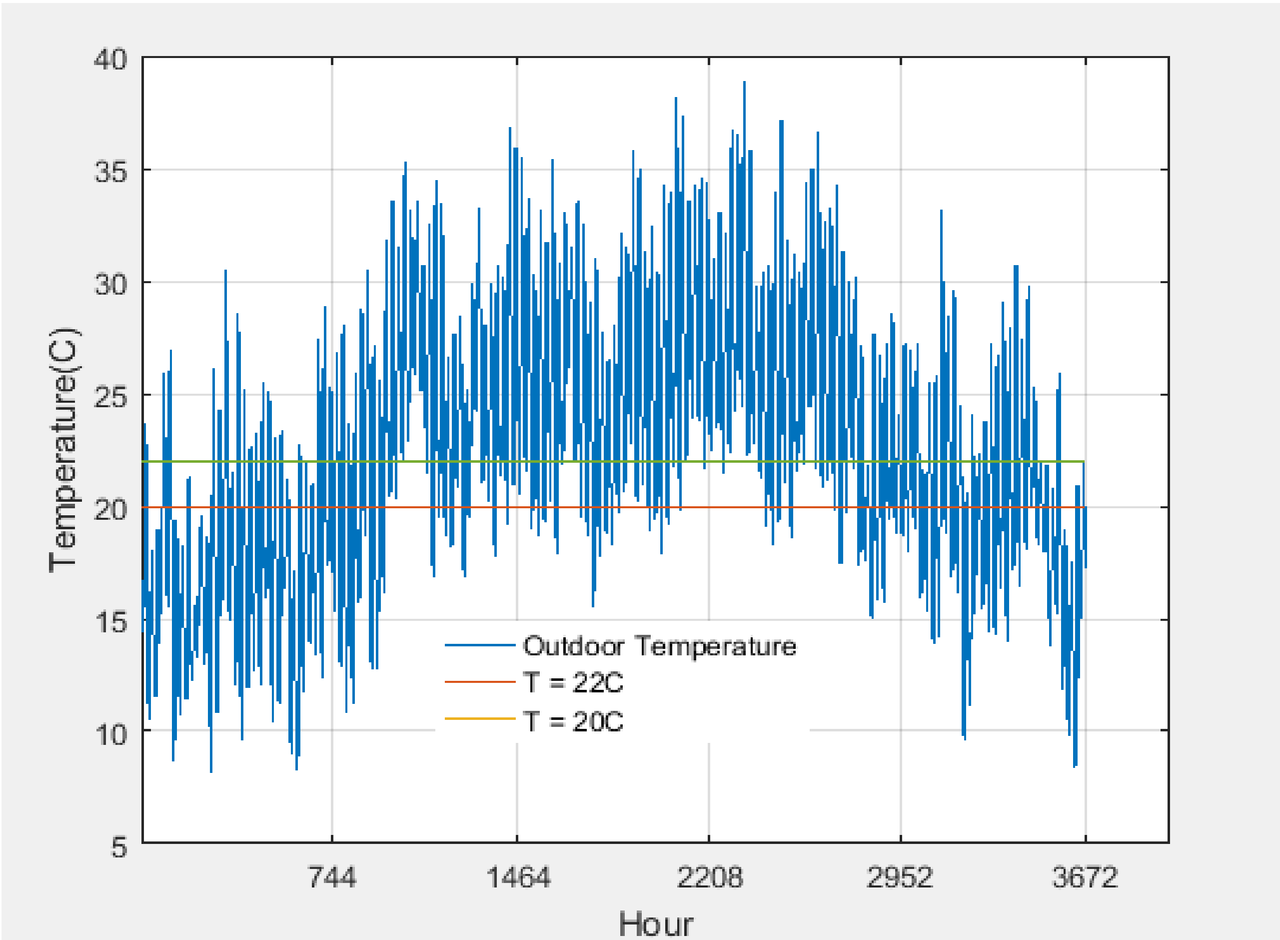

Figure F3. Outdoor hourly temperature during summer of a typical year for Texas, OK.

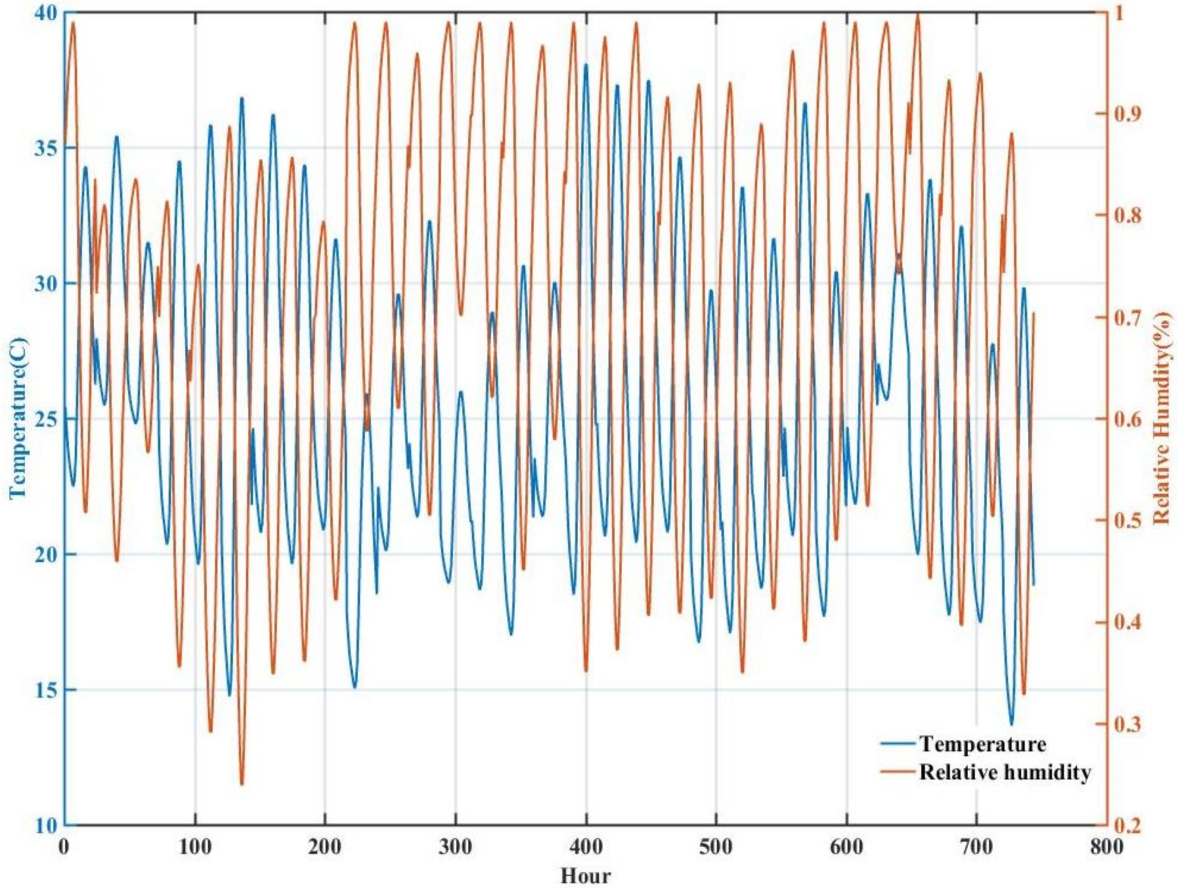

Figure F4. Outdoor hourly temperature and relative humidity during July of a typical year in Sioux City, IA.

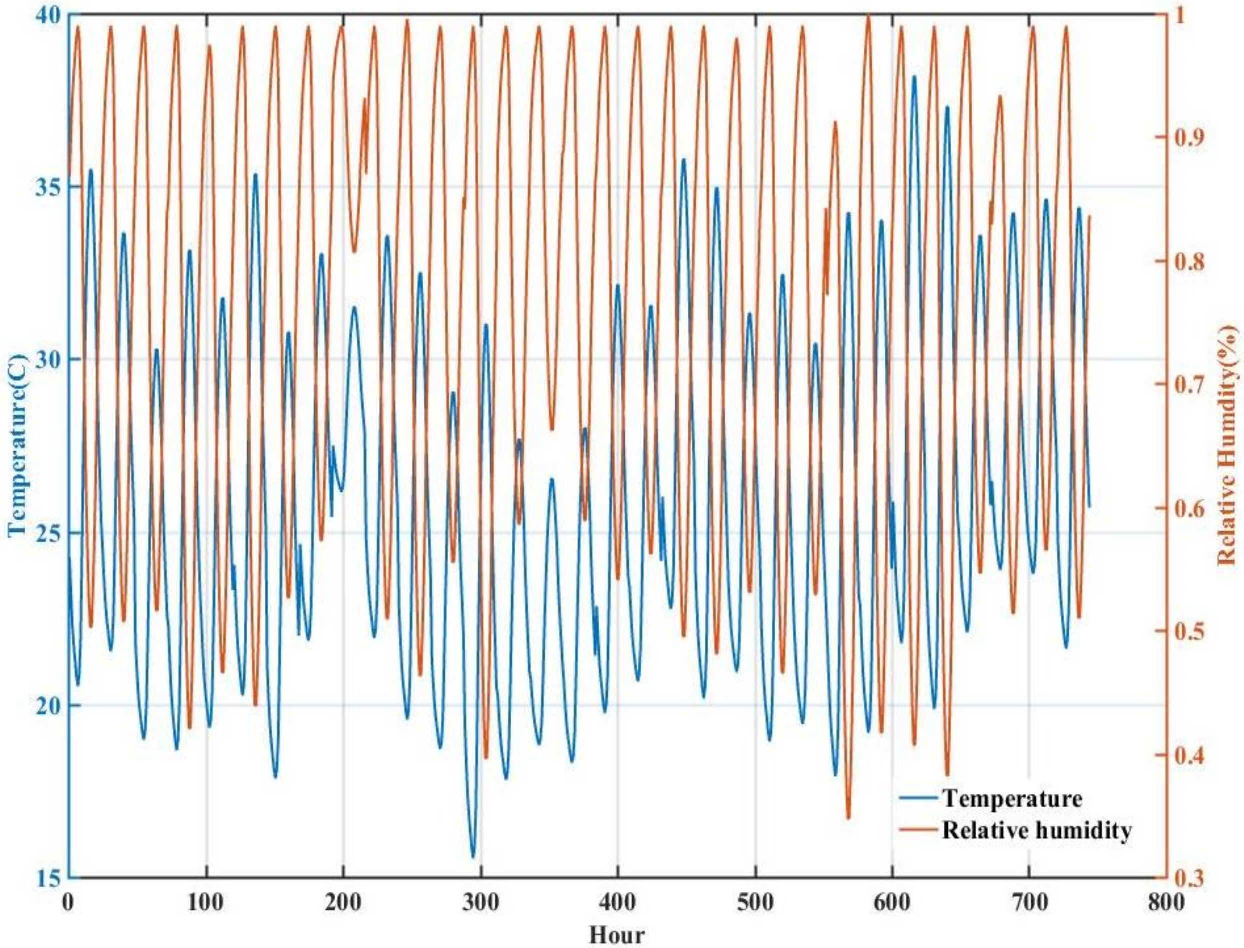

Figure F5. Outdoor hourly temperature and relative humidity during July of a typical year in Fayetteville, NC.

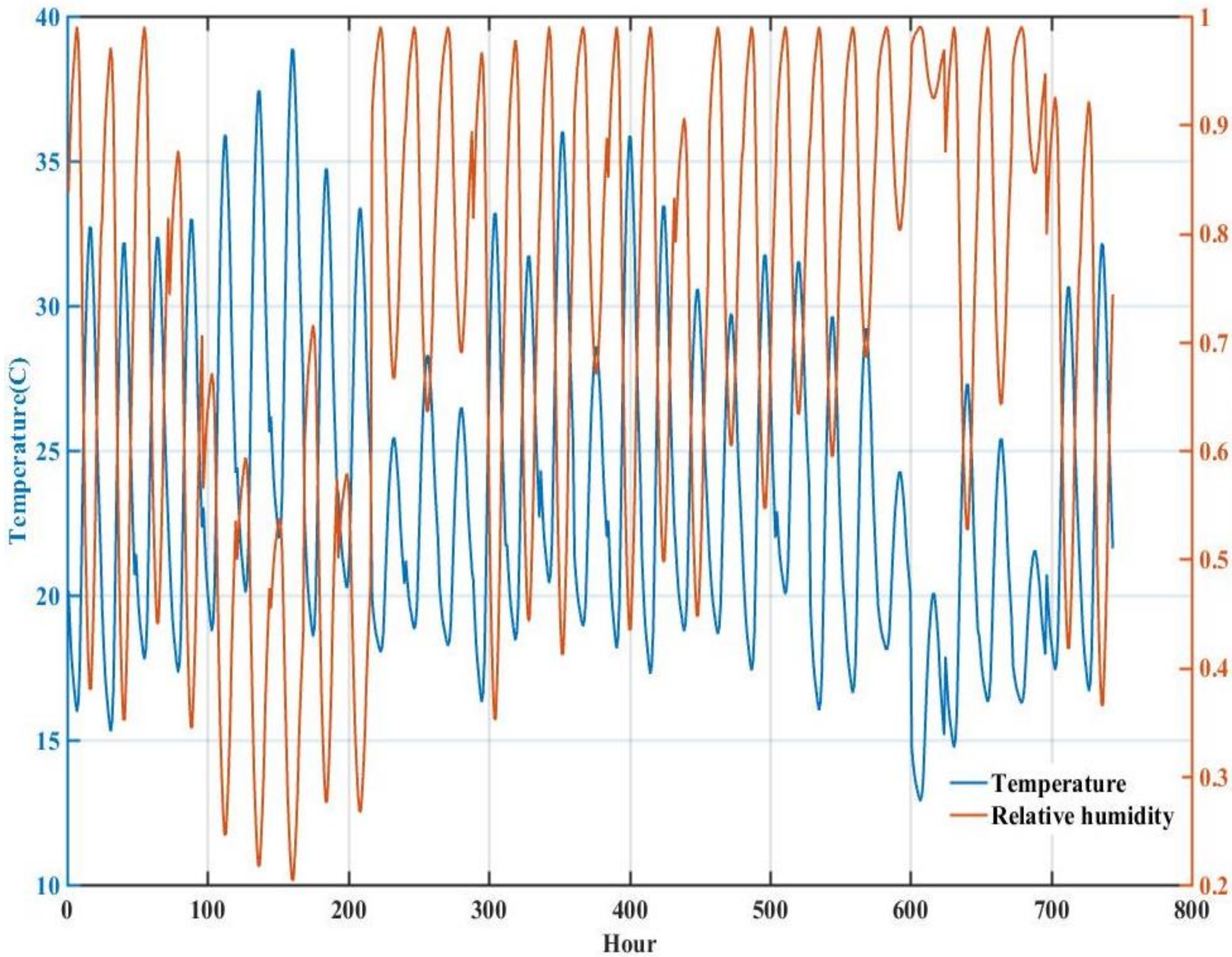

Figure F6. Outdoor hourly temperature and relative humidity during July of a typical year in Texas, OK.

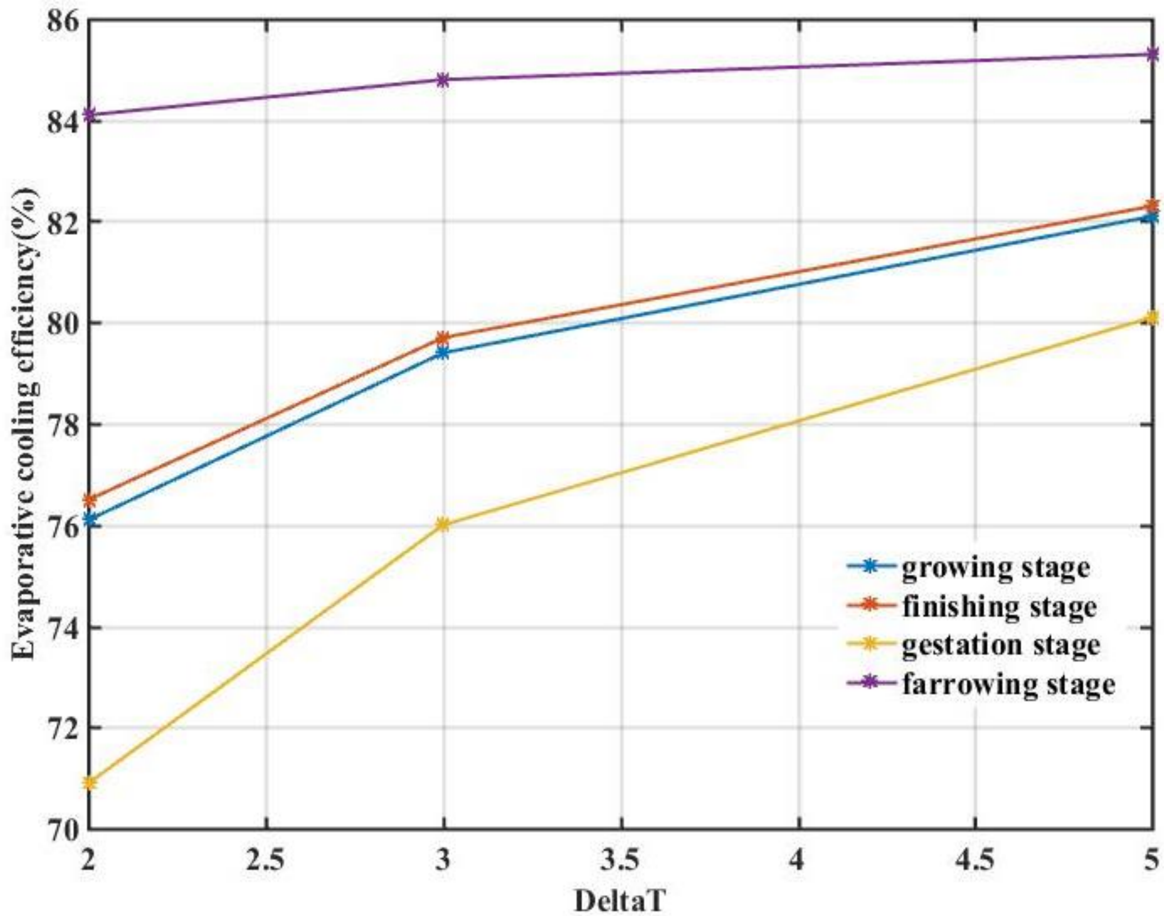

Figure F7. Efficiencies of cooling pad under $VR_{\Delta T=2}$, $VR_{\Delta T=3}$, $VR_{\Delta T=5}$ for growing stage, finishing stage, gestation stage and farrowing stage.

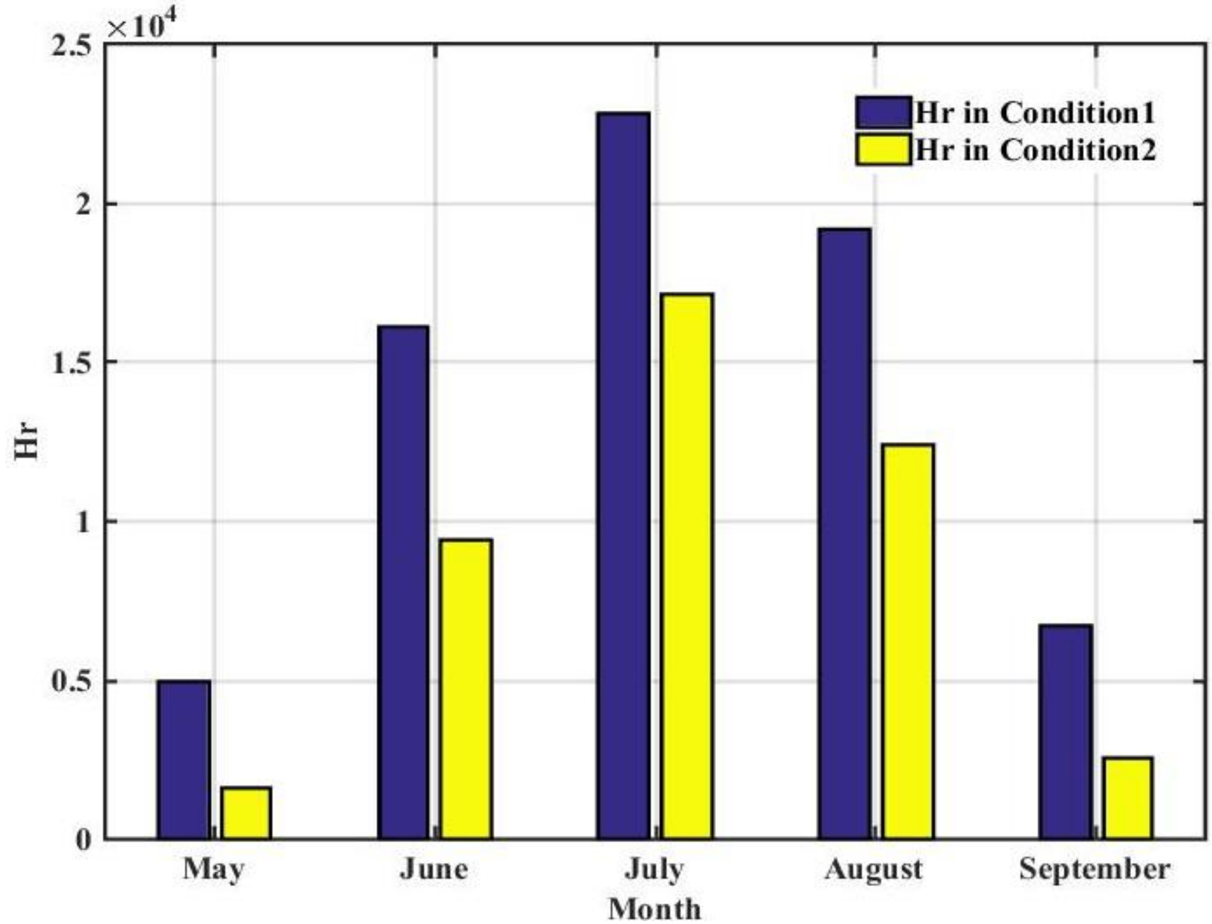

Figure F8. Hr in two conditions (Condition I is environmental control without using evaporative cooling and Condition II is with evaporative cooling) comparing with danger THI threshold for gestation stage (THI = 73) at $VR_{\Delta T=5}$ in Sioux, City based on 50-year data.

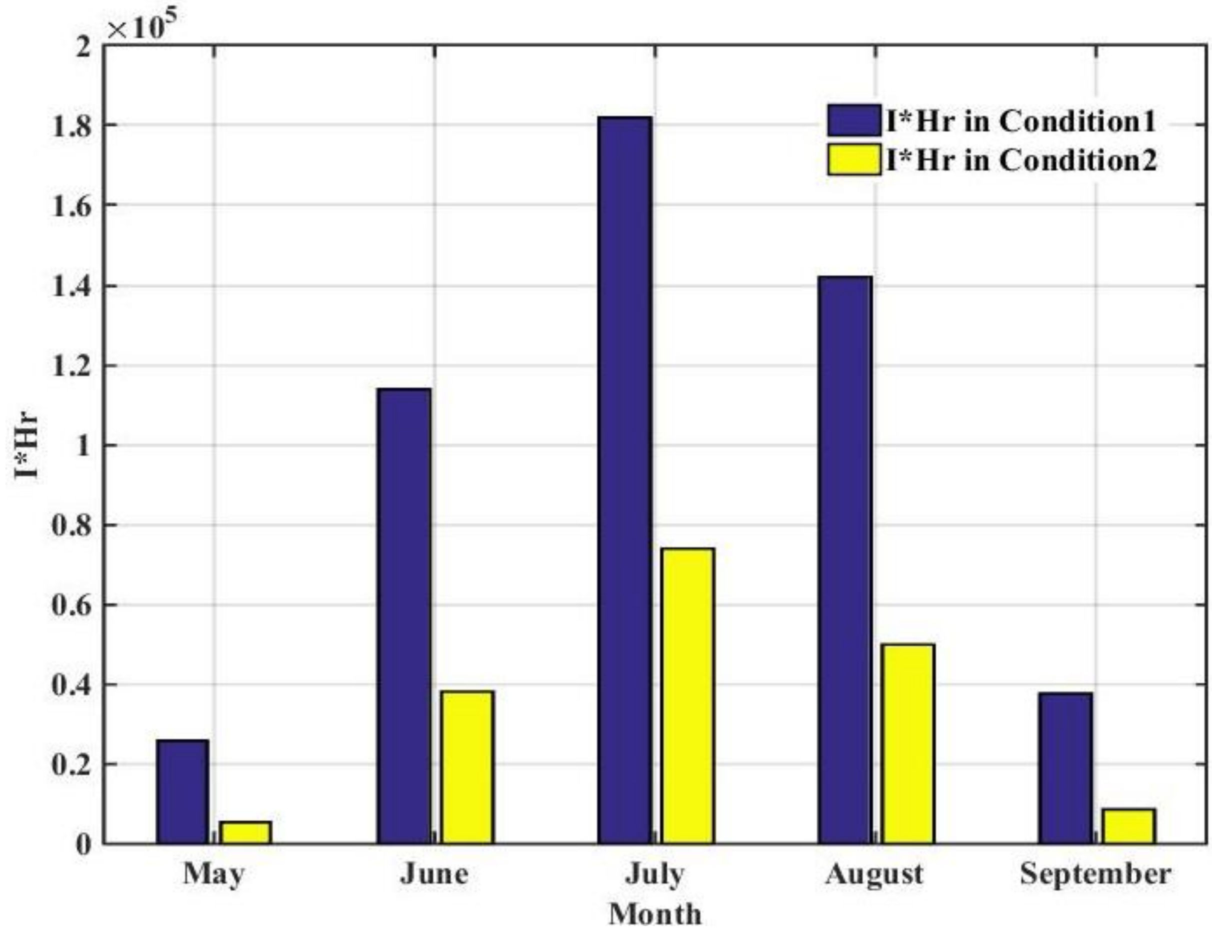

Figure F9. I*Hr in two conditions (Condition I is environmental control without using evaporative cooling and Condition II is with evaporative cooling) comparing with danger THI threshold for gestation stage (THI = 73) at $VR_{\Delta T=5}$ in Sioux, City based on 50-year data.

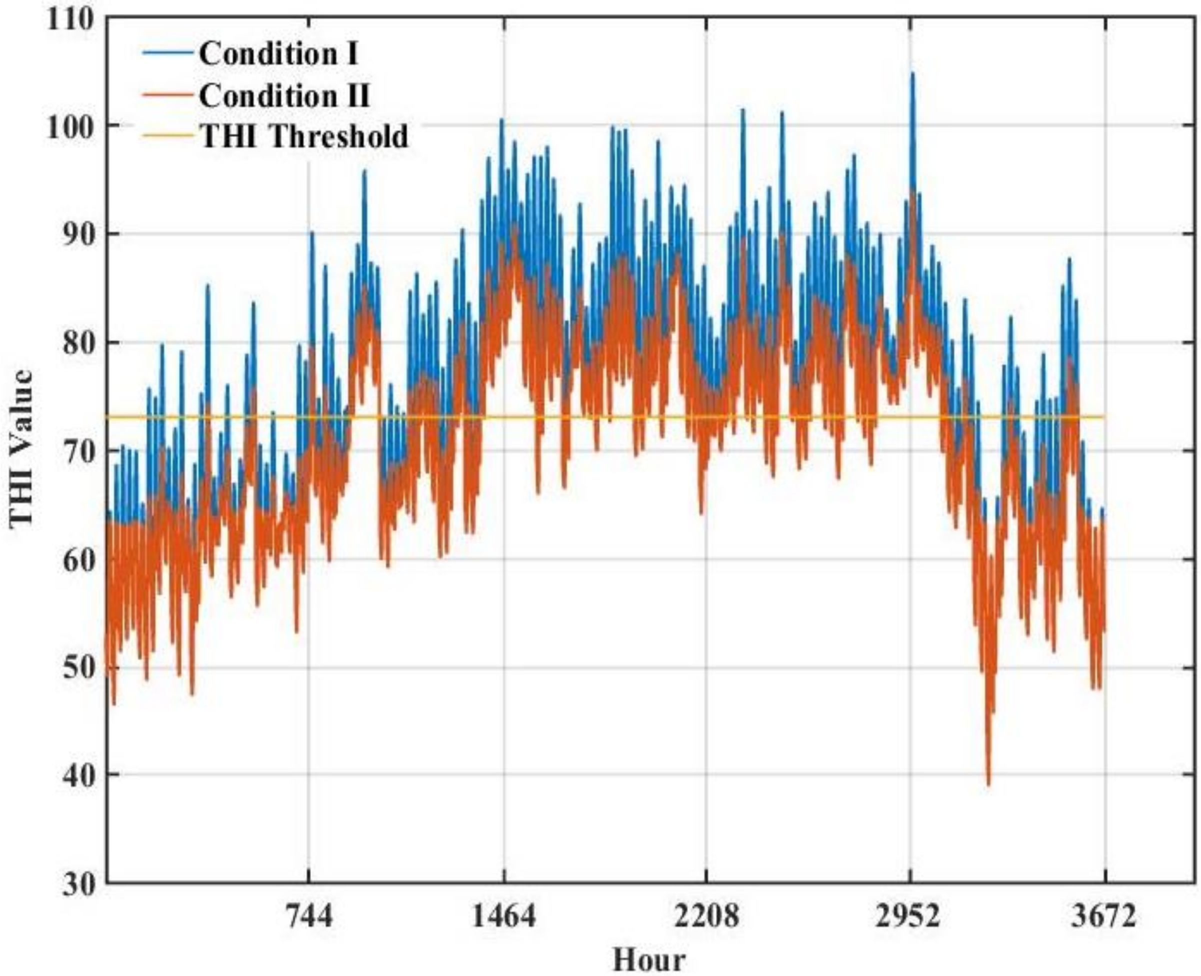

Figure F10. Hourly THI from May to September in two conditions (Condition I is environmental control without using evaporative cooling and Condition II is with evaporative cooling) comparing with danger THI threshold for gestation stage (THI = 73) under $VR_{\Delta T=5°C}$ in Sioux City IA for a typical year.

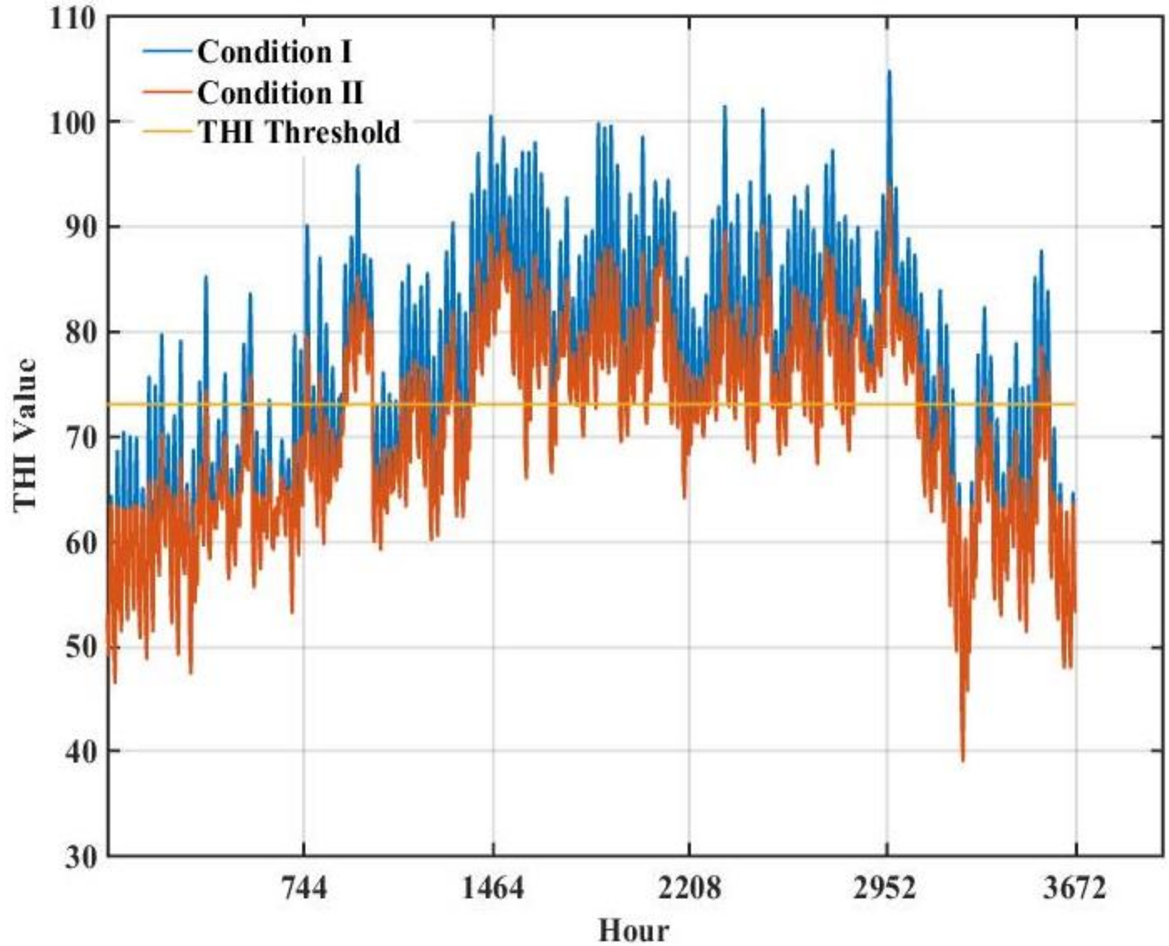

Figure F11. Hourly THI from May to September in two conditions (Condition I is environmental control without using evaporative cooling and Condition II is with evaporative cooling) comparing with danger THI threshold for gestation stage (THI = 73) under $VR_{\Delta T=3°C}$ in Sioux City IA for a typical year.

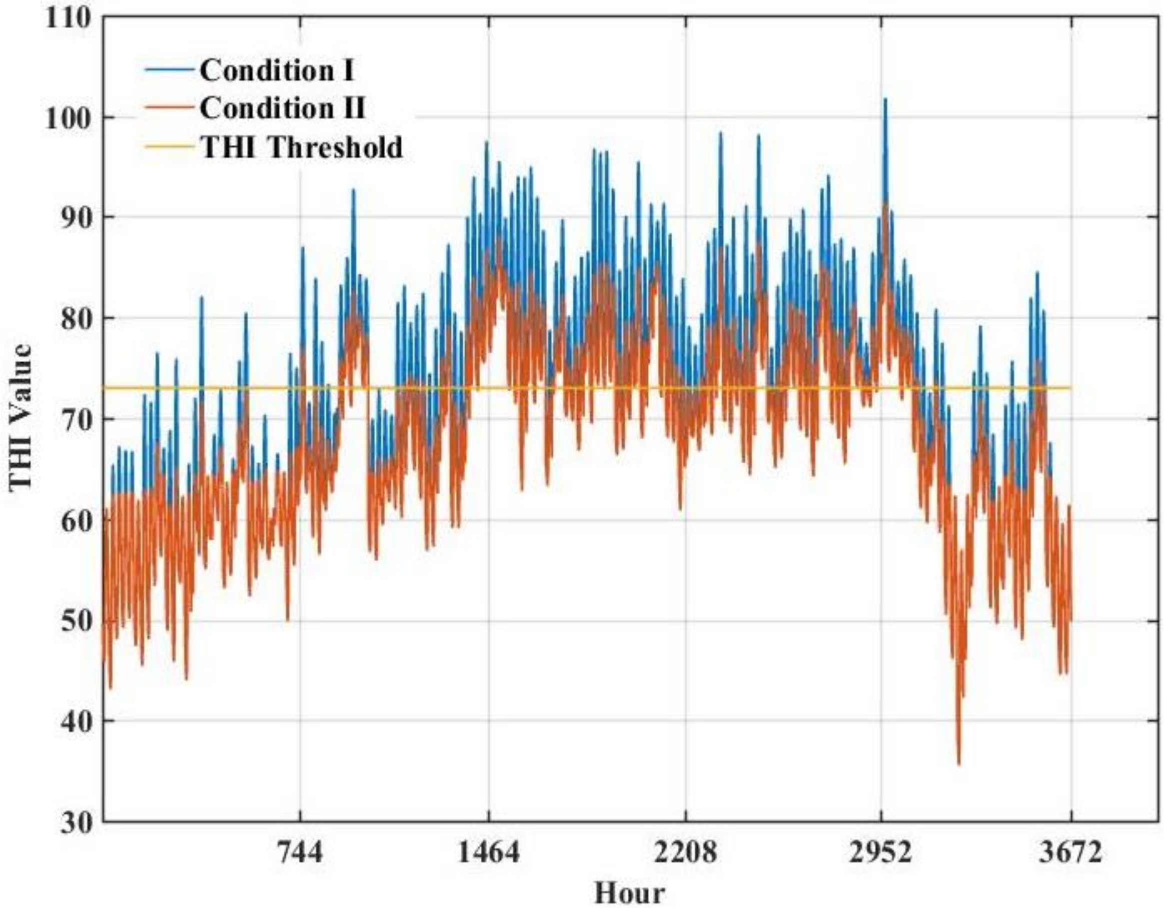

Figure F12. Hourly THI from May to September in two conditions (Condition I is environmental control without using evaporative cooling and Condition II is with evaporative cooling) comparing with danger THI threshold for gestation stage (THI = 73) under $VR_{\Delta T=2°C}$ in Sioux City IA for a typical year.

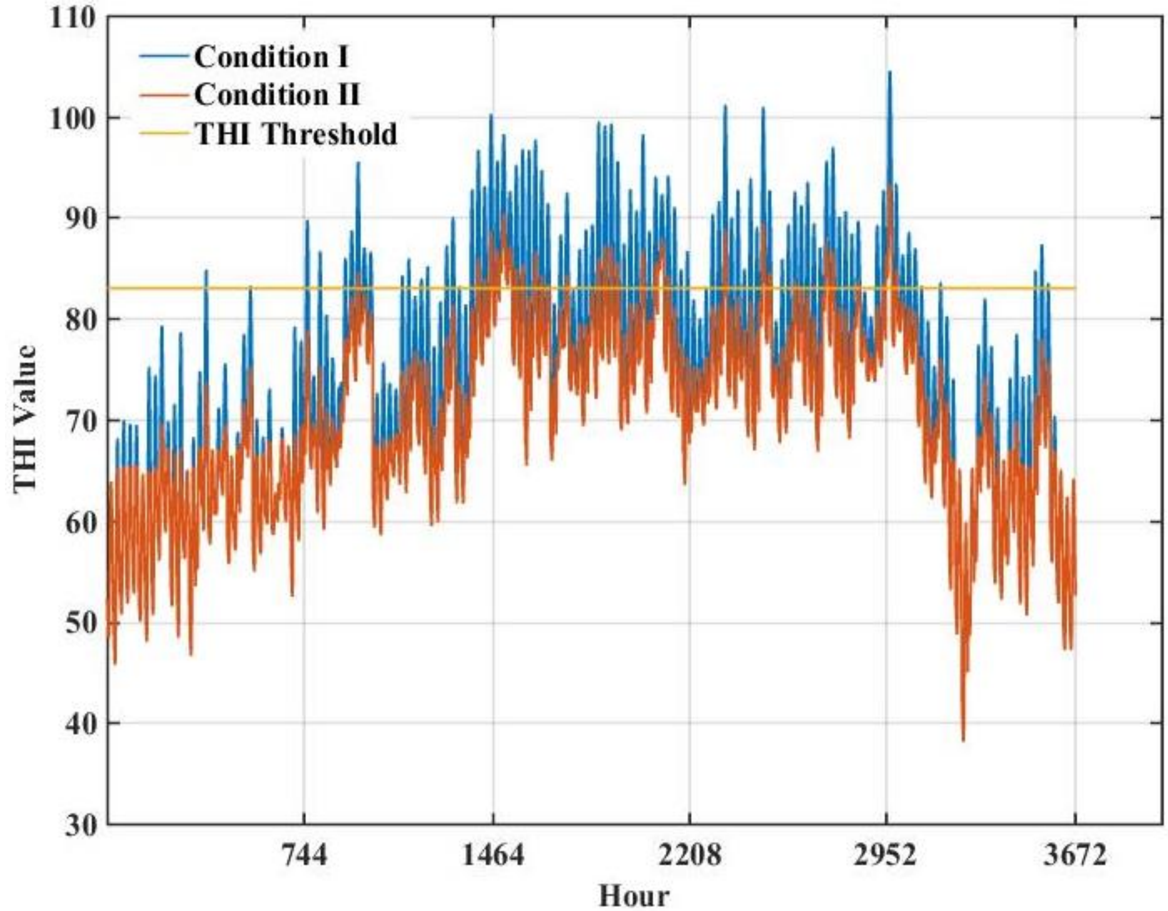

Figure F13. Hourly THI from May to September in two conditions (Condition I is environmental control without using evaporative cooling and Condition II is with evaporative cooling) comparing with danger THI threshold for finishing stage (THI = 83) under $VR_{\Delta T=5°C}$ in Sioux City IA for a typical year.

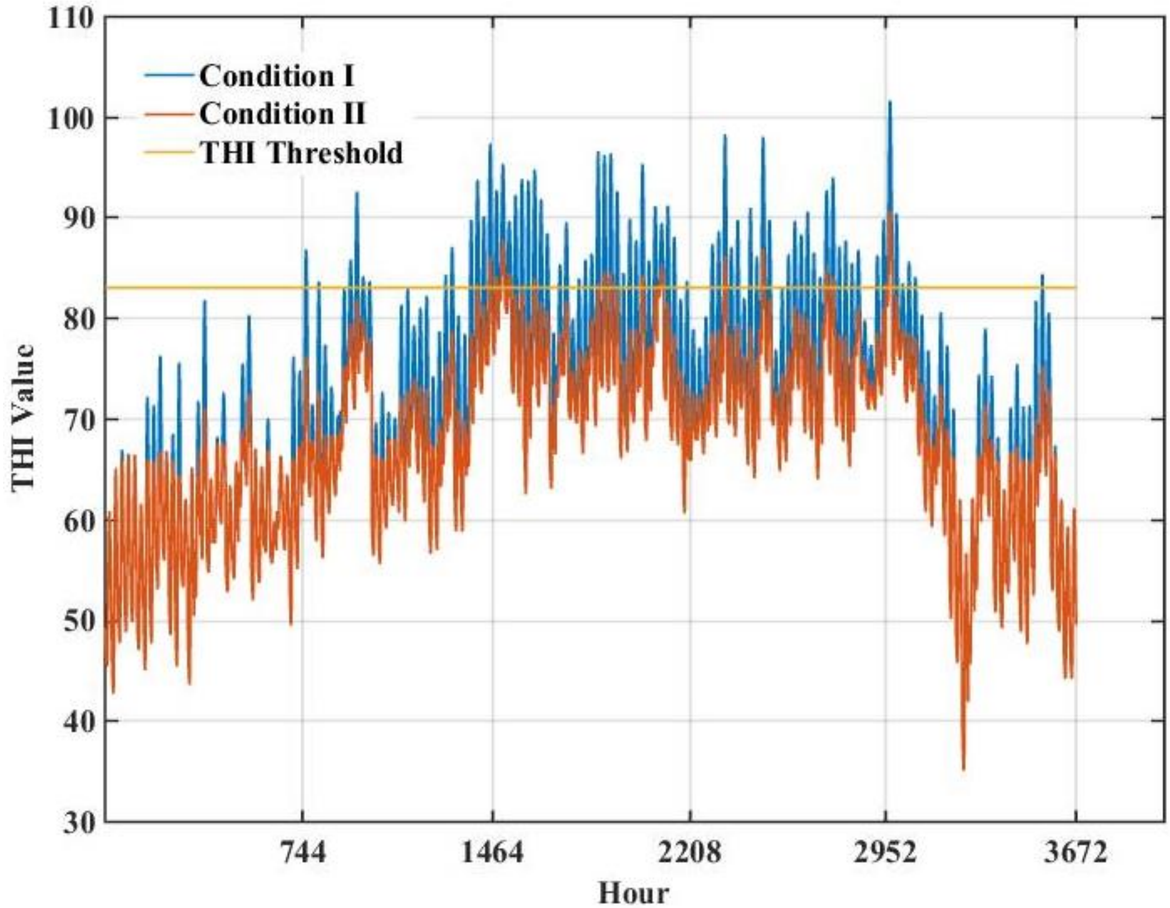

Figure F14. Hourly THI from May to September in two conditions (Condition I is environmental control without using evaporative cooling and Condition II is with evaporative cooling) comparing with danger THI threshold for finishing stage (THI = 83) under $VR_{\Delta T=3^{\circ}}$ in Sioux City IA for a typical year.

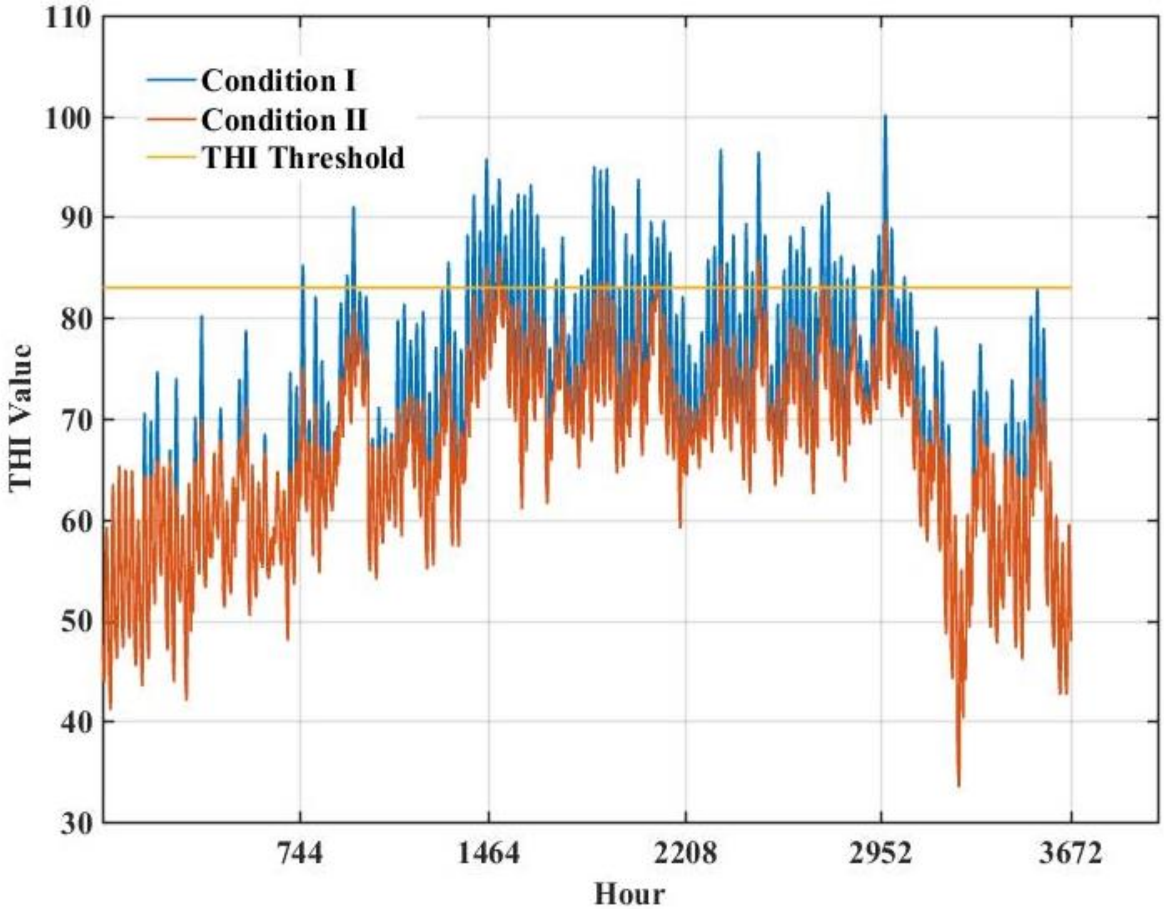

Figure F15. Hourly THI from May to September in two conditions (Condition I is environmental control without using evaporative cooling and Condition II is with evaporative cooling) comparing with danger THI threshold for finishing stage (THI = 83) under $VR_{\Delta T=2°C}$ in Sioux City IA for a typical year.

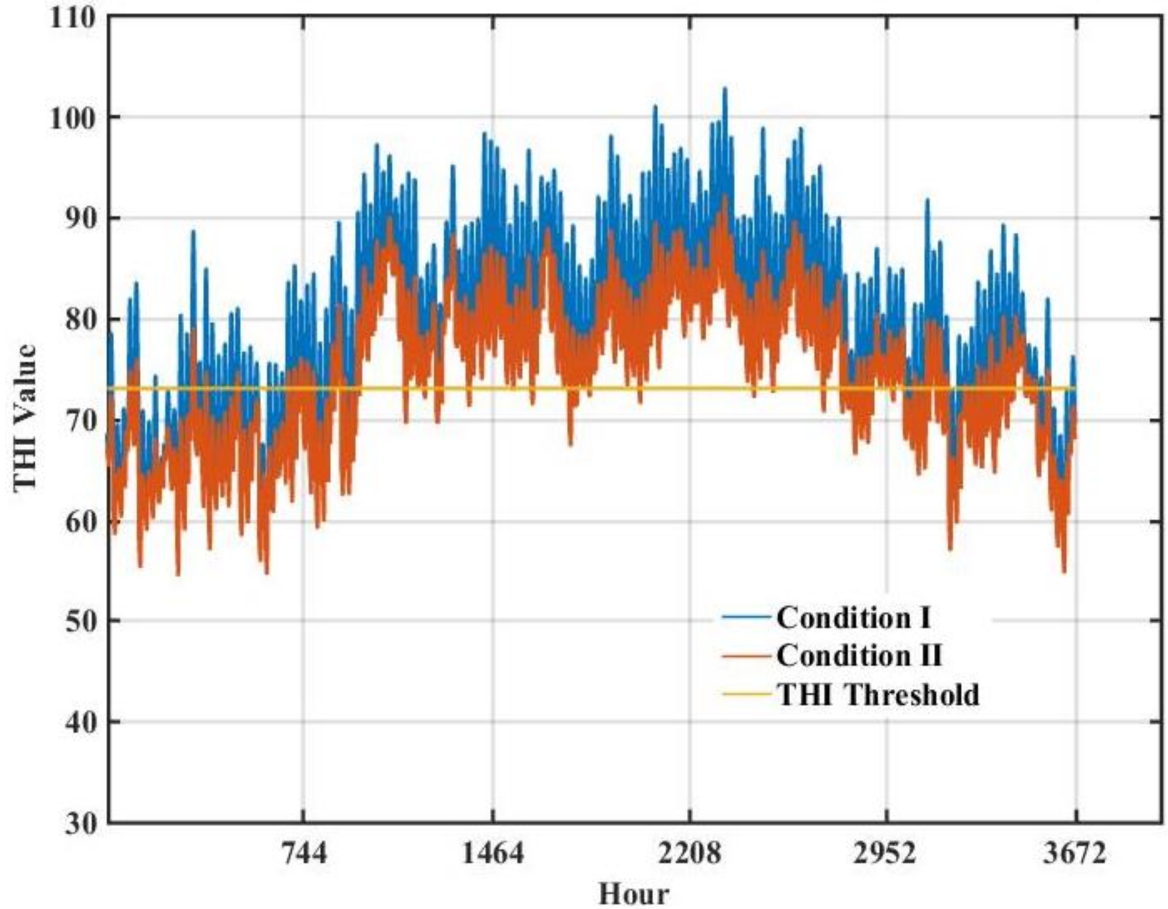

Figure F16. Hourly THI from May to September in two conditions (Condition I is environmental control without using evaporative cooling and Condition II is with evaporative cooling) comparing with danger THI threshold for gestation stage (THI = 73) under $VR_{\Delta T=5°C}$ in Fayetteville, NC for a typical year.

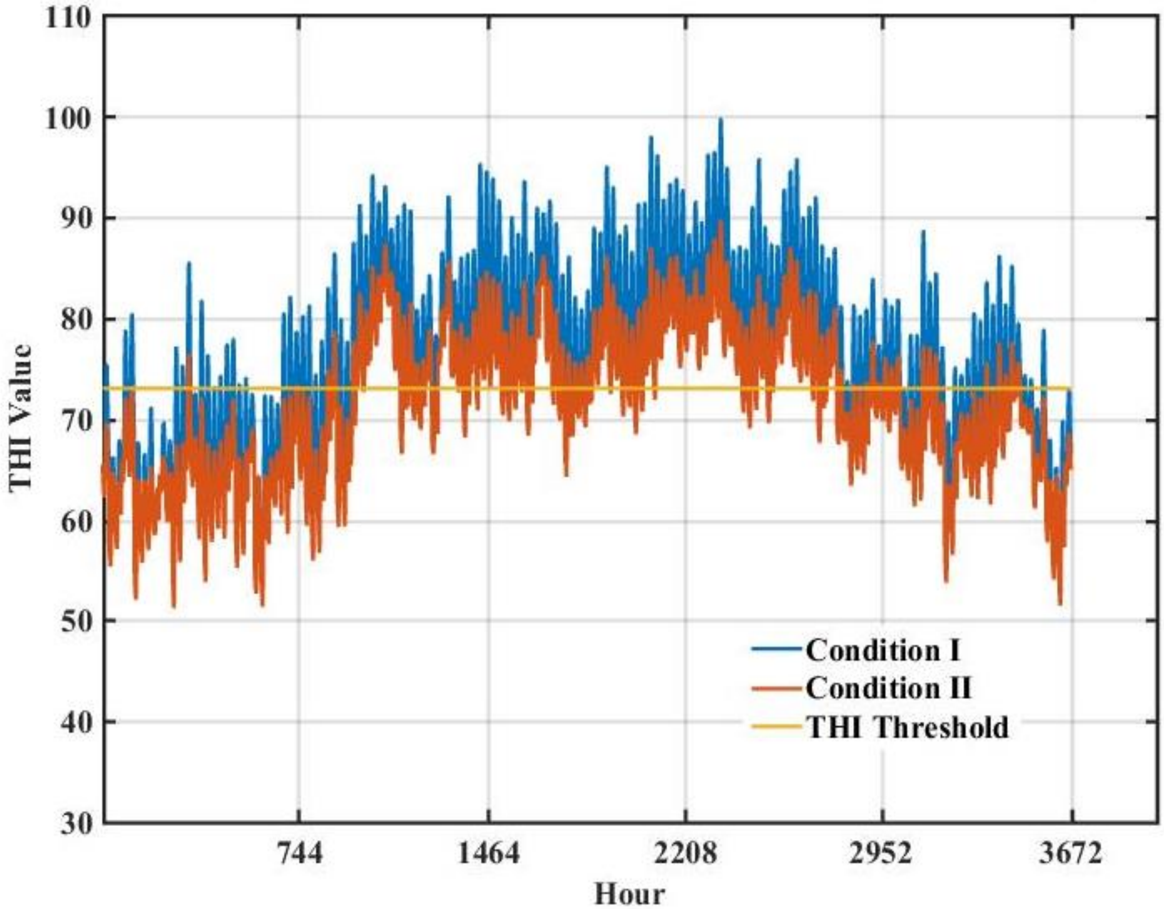

Figure F17. Hourly THI from May to September in two conditions (Condition I is environmental control without using evaporative cooling and Condition II is with evaporative cooling) comparing with danger THI threshold for gestation stage (THI = 73) under $VR_{\Delta T=3°C}$ in Fayetteville, NC for a typical year.

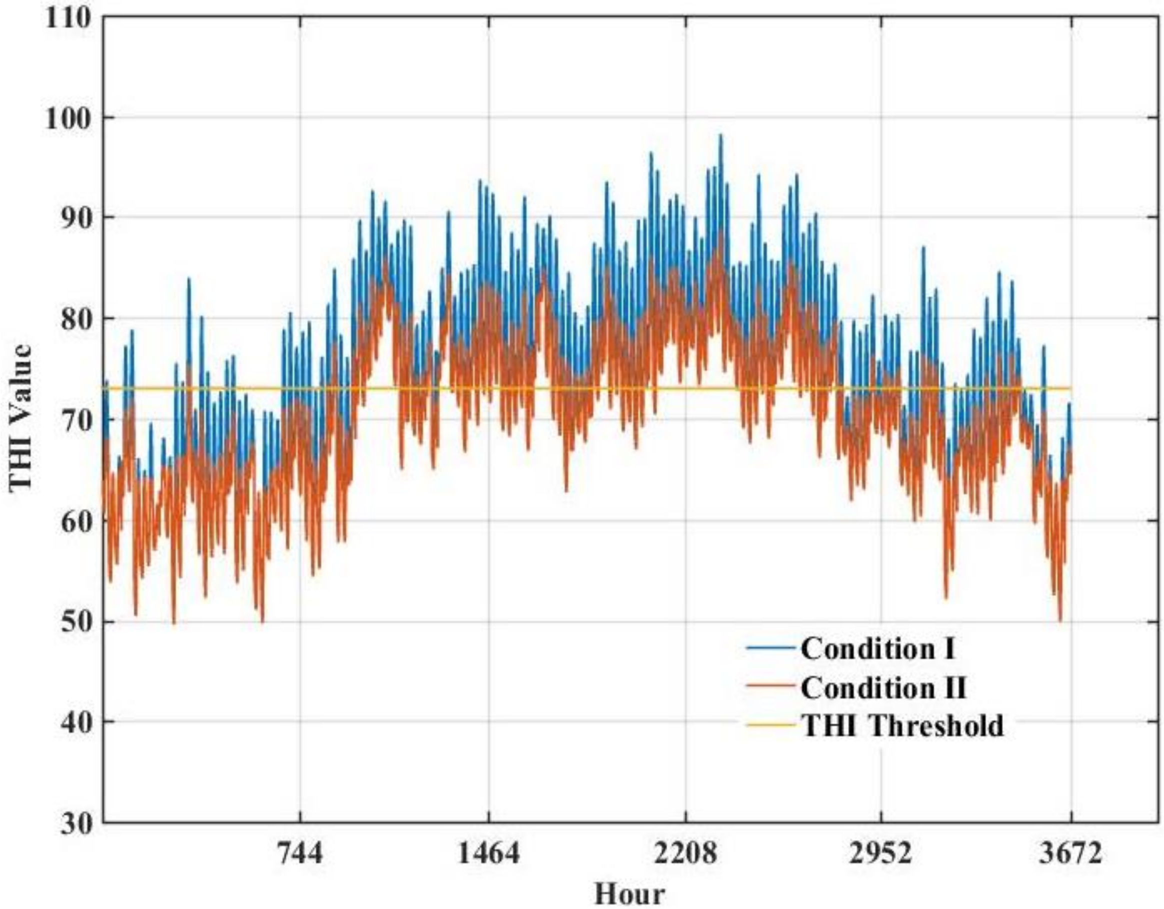

Figure F18. Hourly THI from May to September in two conditions (Condition I is environmental control without using evaporative cooling and Condition II is with evaporative cooling) comparing with danger THI threshold for gestation stage (THI = 73) under $VR_{\Delta T=2°C}$ in Fayetteville, NC for a typical year.

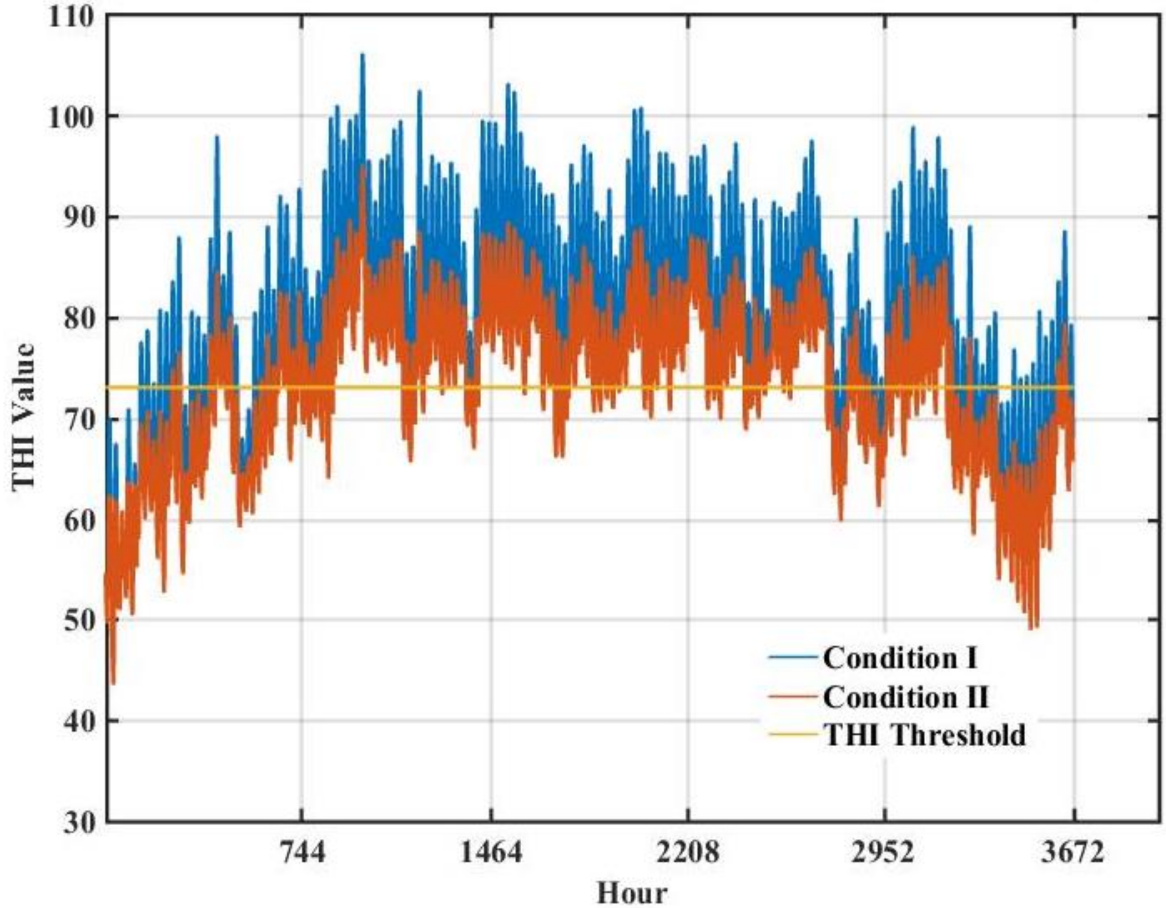

Figure F19. Hourly THI from May to September in two conditions (Condition I is environmental control without using evaporative cooling and Condition II is with evaporative cooling) comparing with danger THI threshold for gestation stage (THI = 73) under $VR_{\Delta T=5°C}$ in Texas, OK for a typical year.

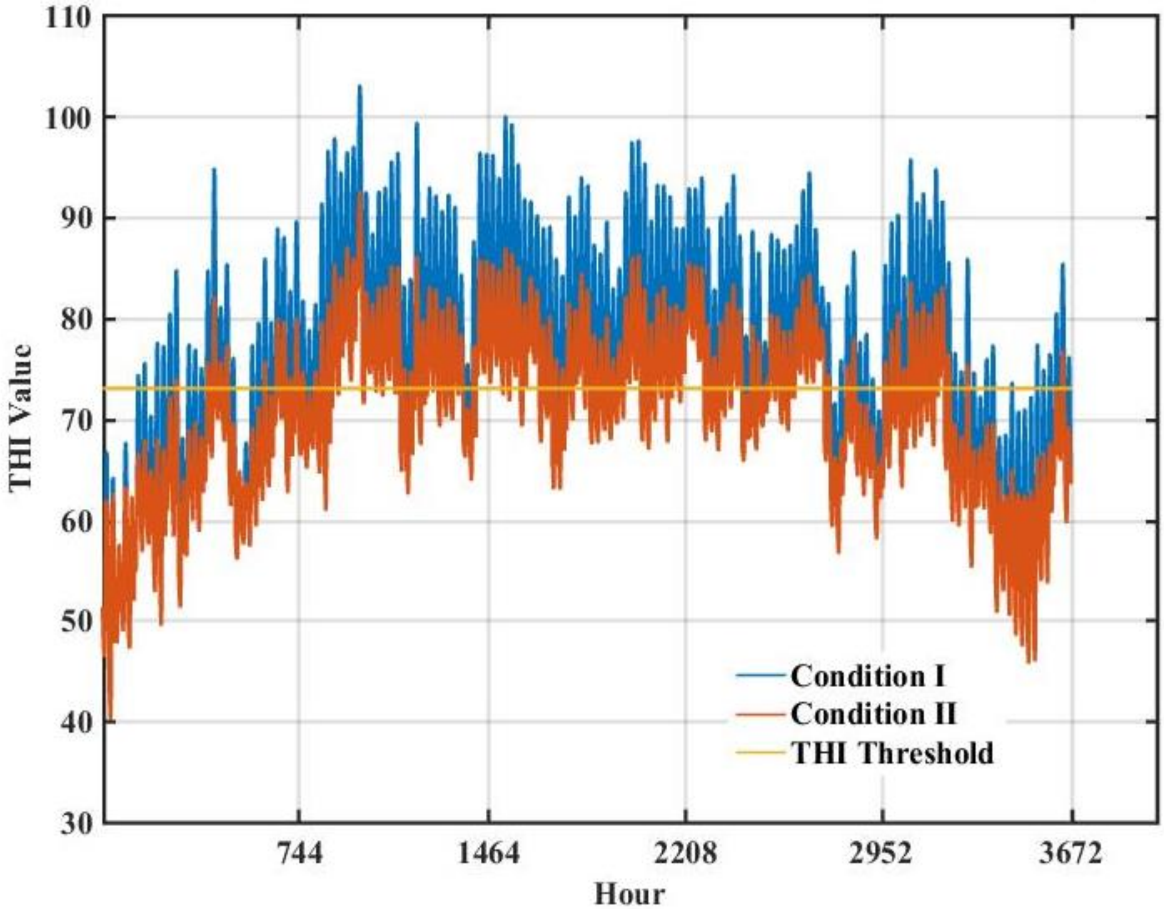

Figure F20. Hourly THI from May to September in two conditions (Condition I is environmental control without using evaporative cooling and Condition II is with evaporative cooling) comparing with danger THI threshold for gestation stage (THI = 73) under $VR_{\Delta T=3°C}$ in Texas, OK for a typical year.

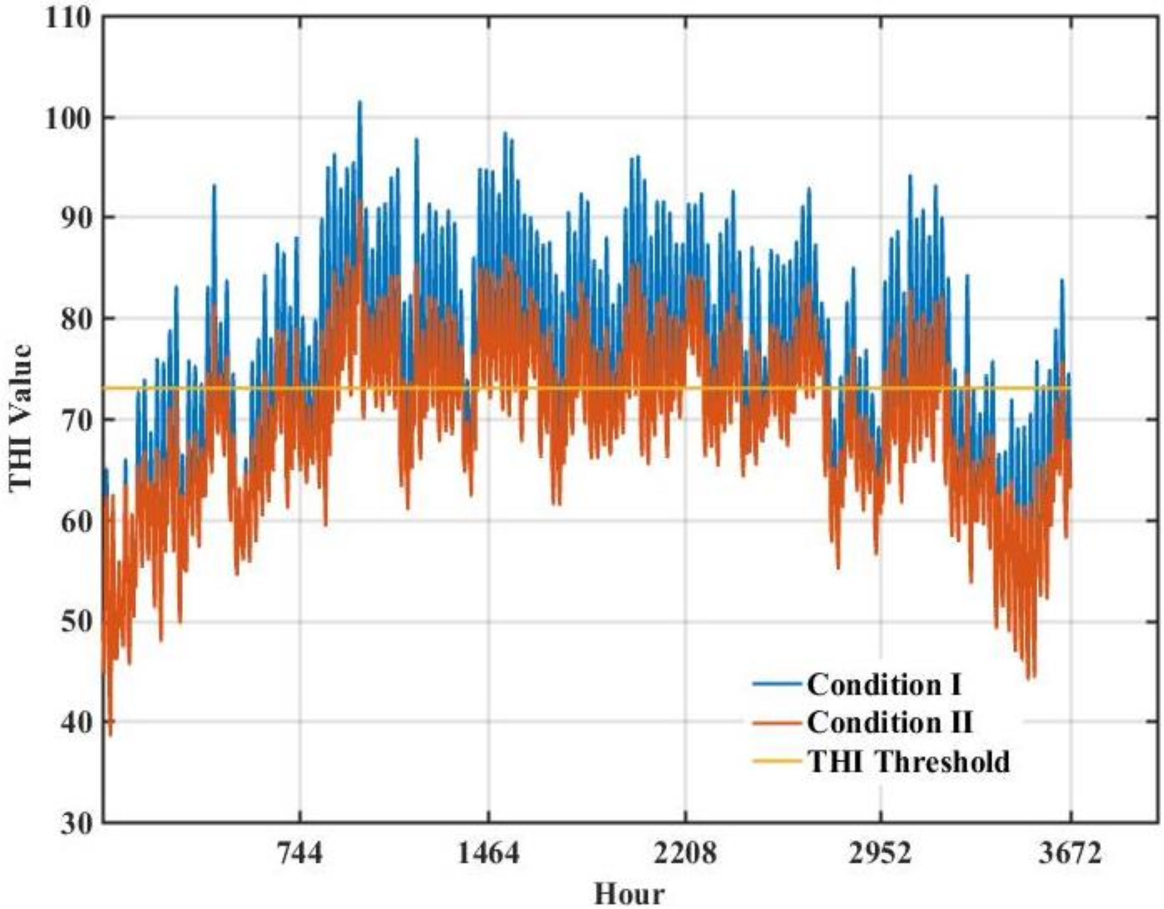

Figure F21. Hourly THI from May to September in two conditions (Condition I is environmental control without using evaporative cooling and Condition II is with evaporative cooling) comparing with danger THI threshold for gestation stage (THI = 73) under $VR_{\Delta T=2°C}$ in Texas, OK for a typical year.

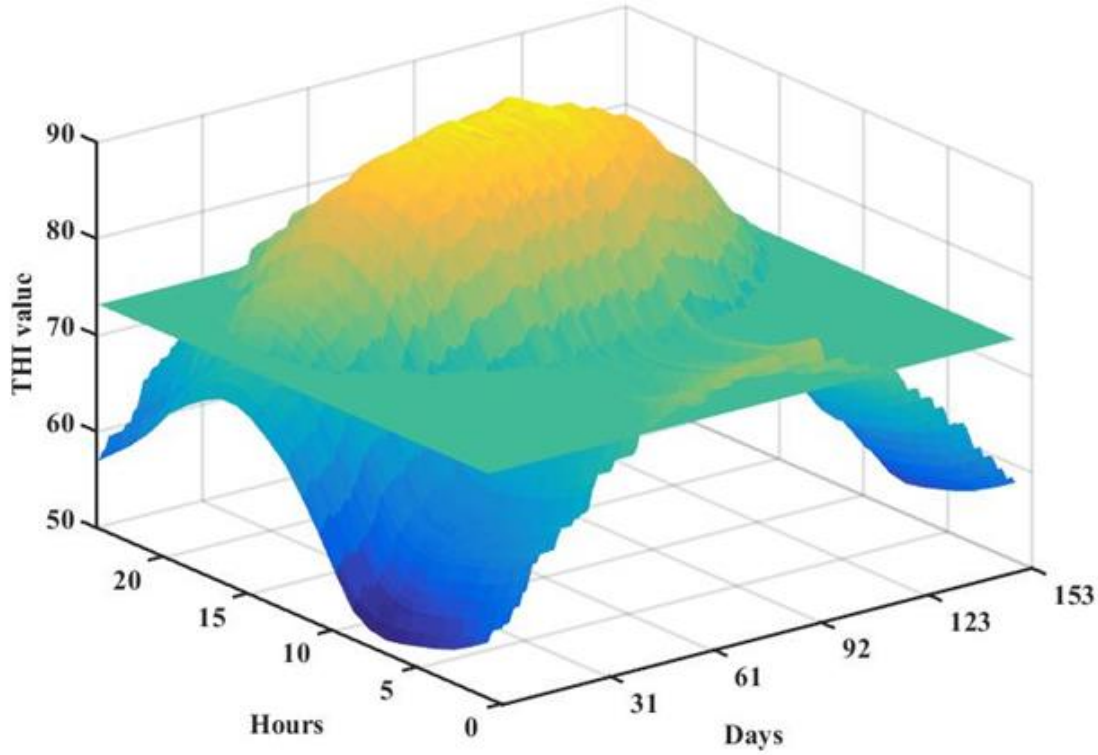

Figure F22.THI value for a year without using evaporative cooling for gestation stage in Sioux City under $VR_{\Delta T=5°C}$.

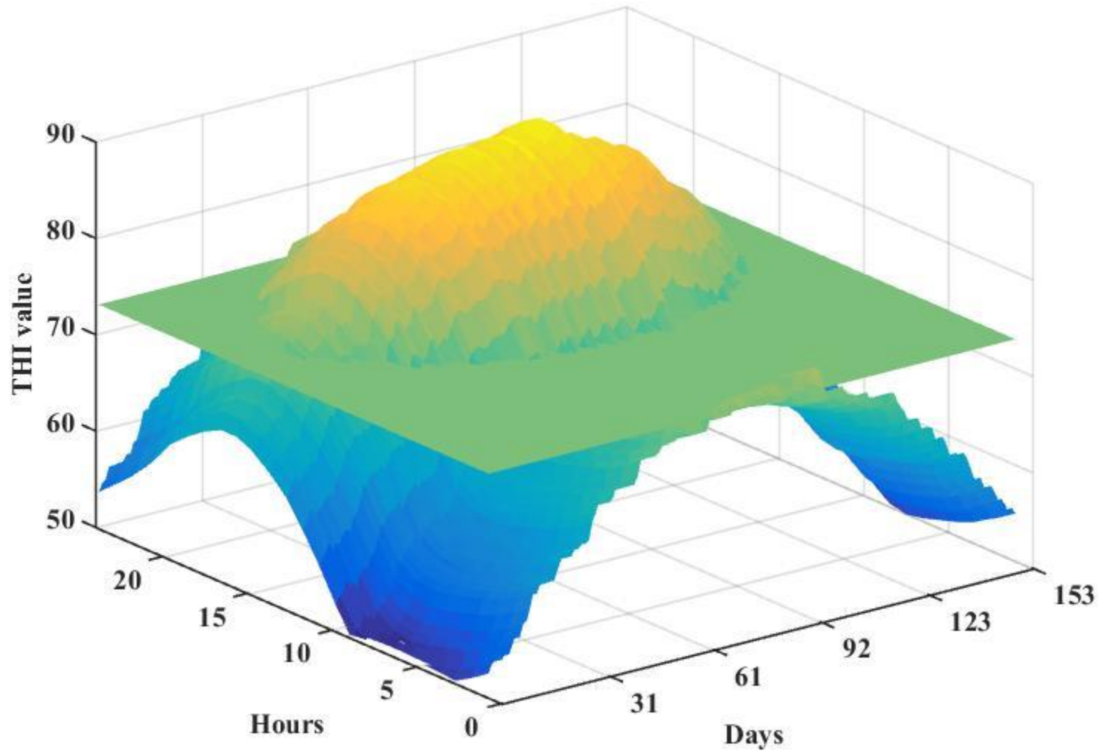

Figure F23.THI value for a year without using evaporative cooling for gestation stage in Sioux City under $VR_{\Delta T=3°C}$.

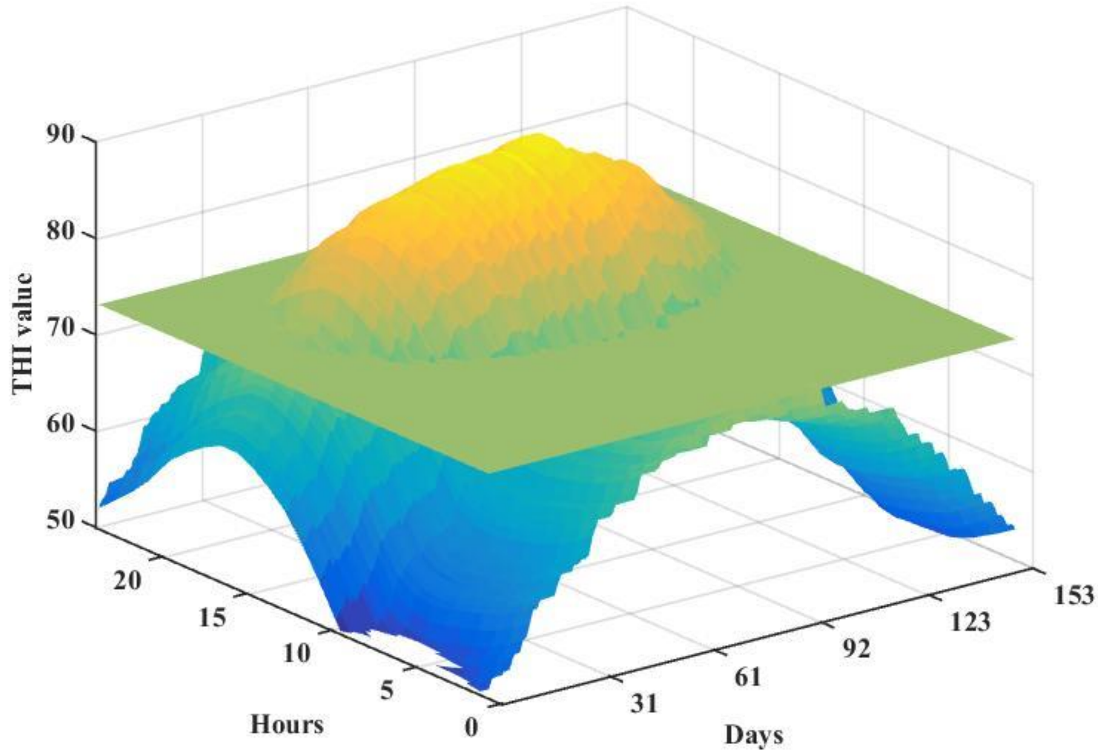

Figure F24.THI value for a year without using evaporative cooling for gestation stage in Sioux City under $VR_{\Delta T=2°C}$.

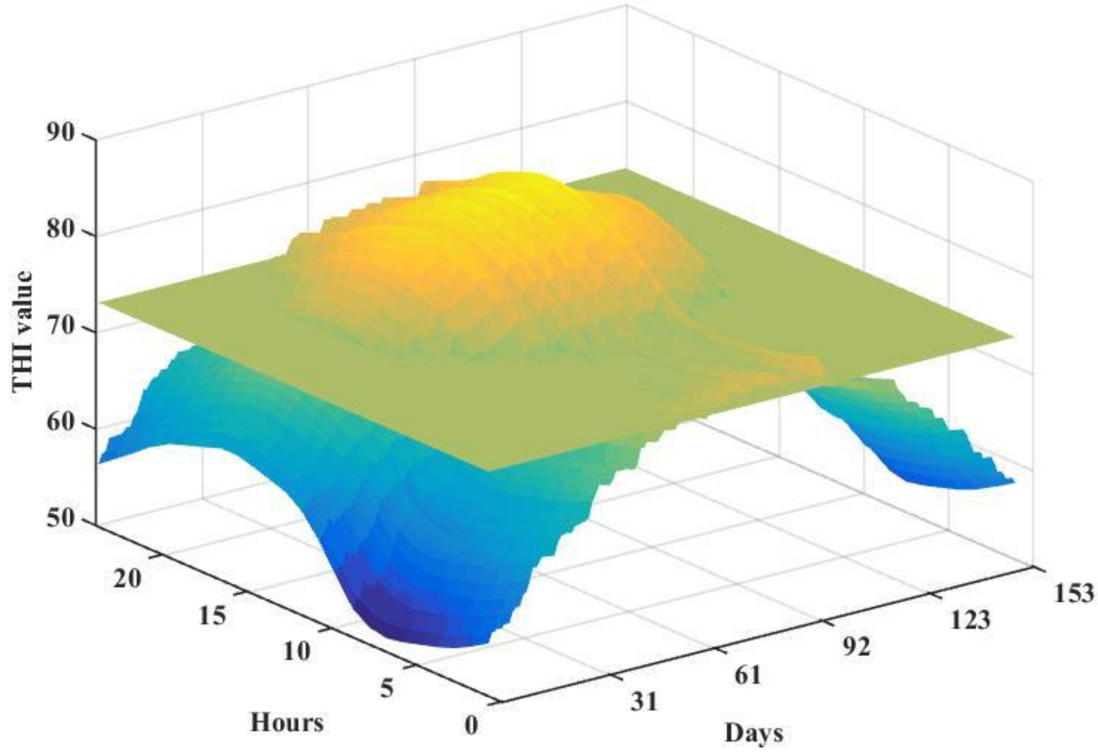

Figure F25. THI value for a year using evaporative cooling for gestation stage in Sioux City under $VR_{\Delta T=5°C}$.

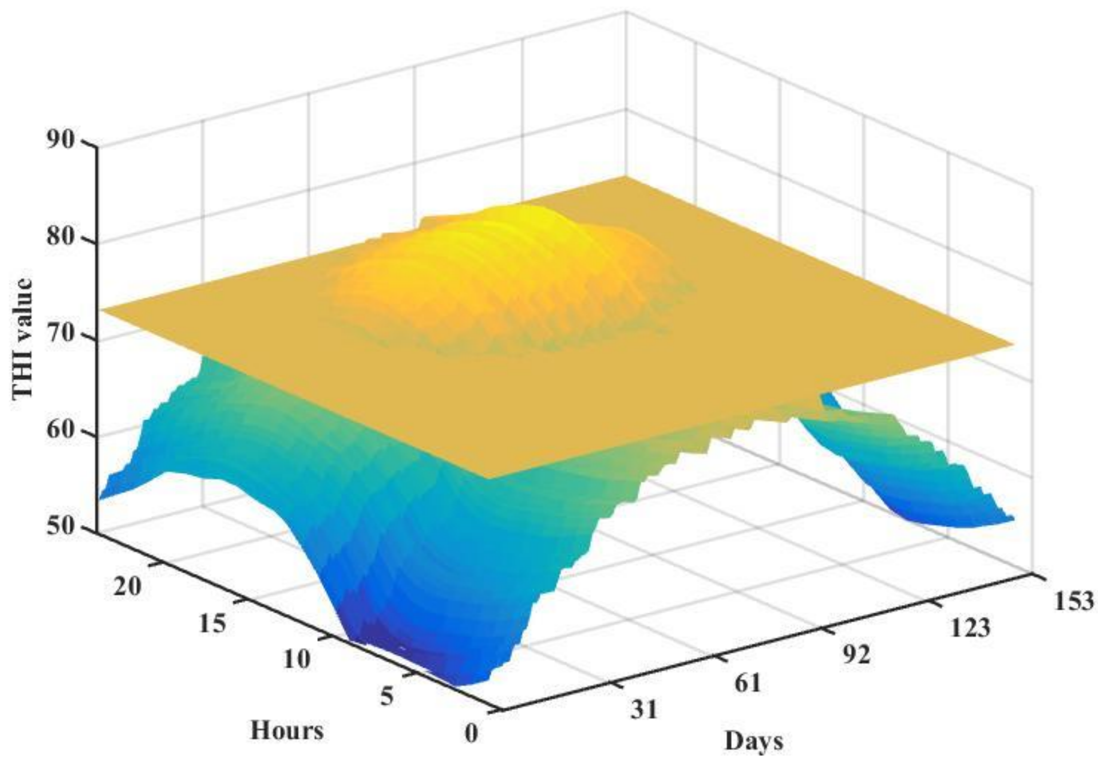

Figure F26. THI value for a year using evaporative cooling for gestation stage in Sioux City under $VR_{\Delta T=3°C}$.

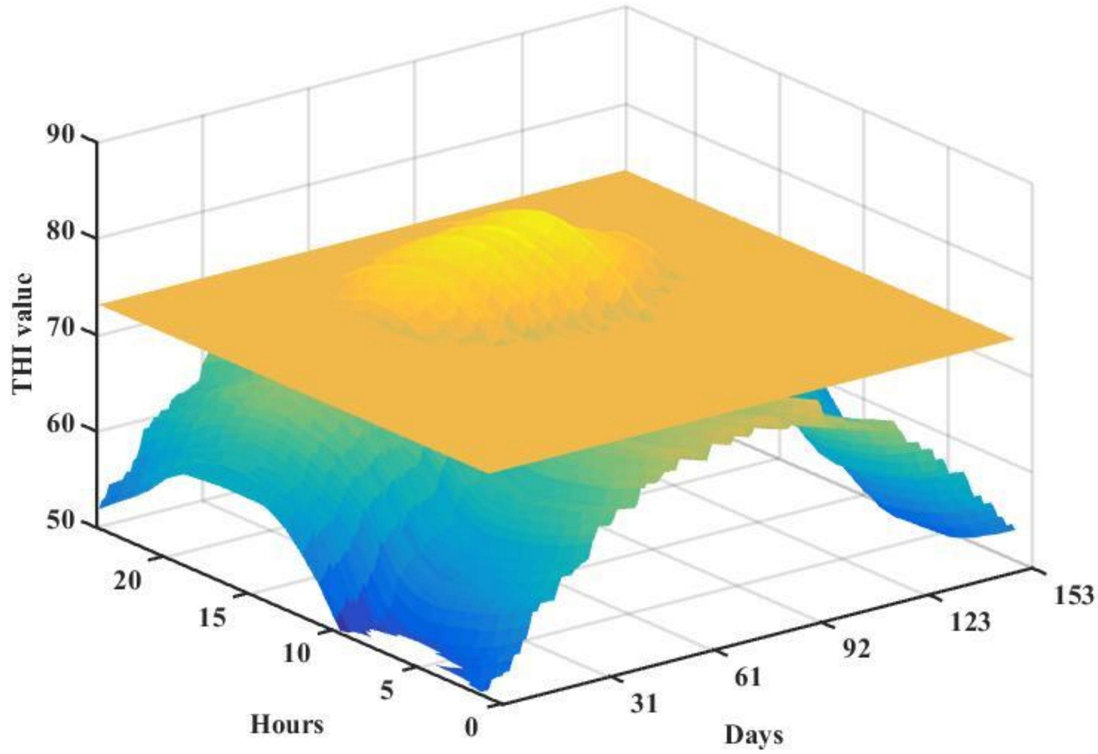

Figure F27. THI value for a year using evaporative cooling for gestation stage in Sioux City under $VR_{\Delta T=2°C}$.

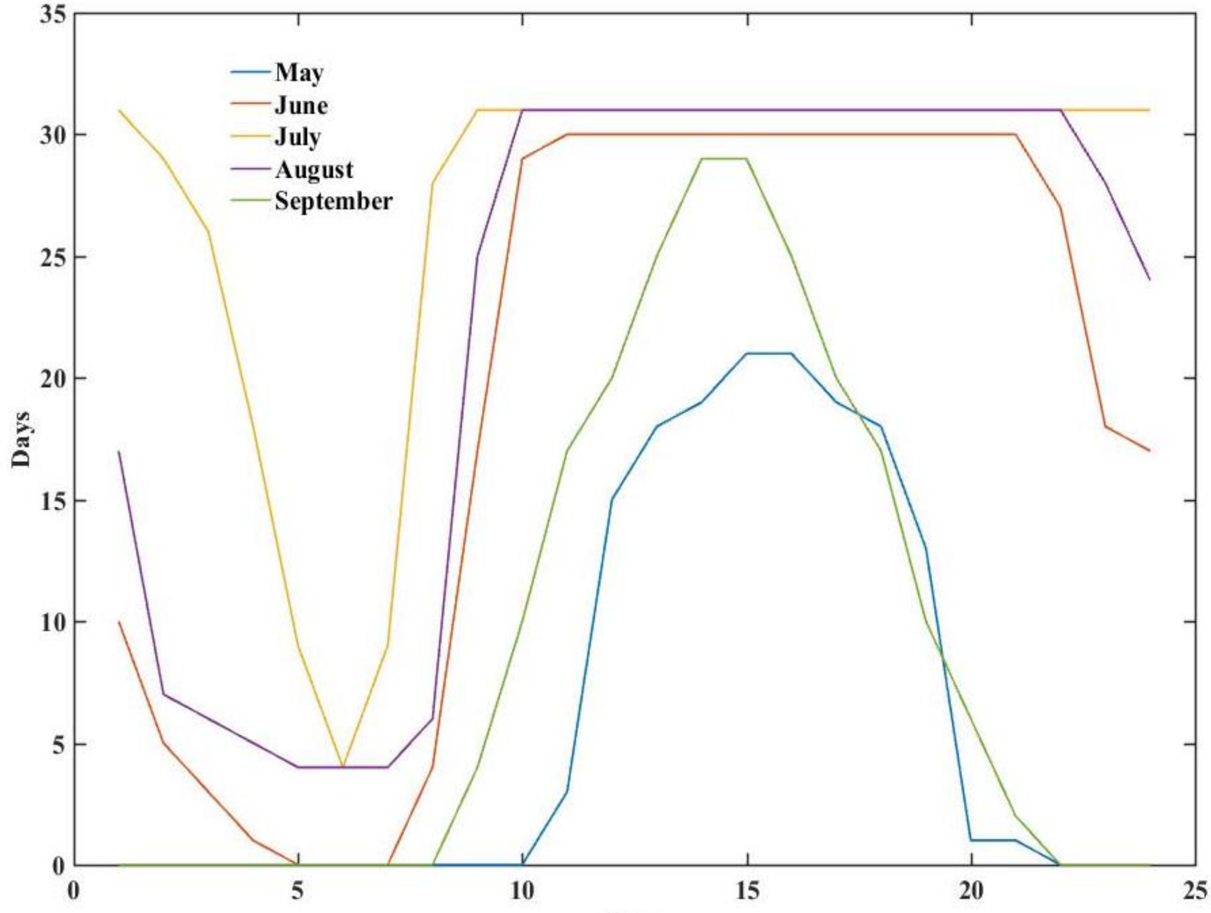

Figure F28. Number of Days that THI exceeded the threshold for gestation stage under $VR_{\Delta T = 5°C}$ without evaporative cooling in Sioux City.

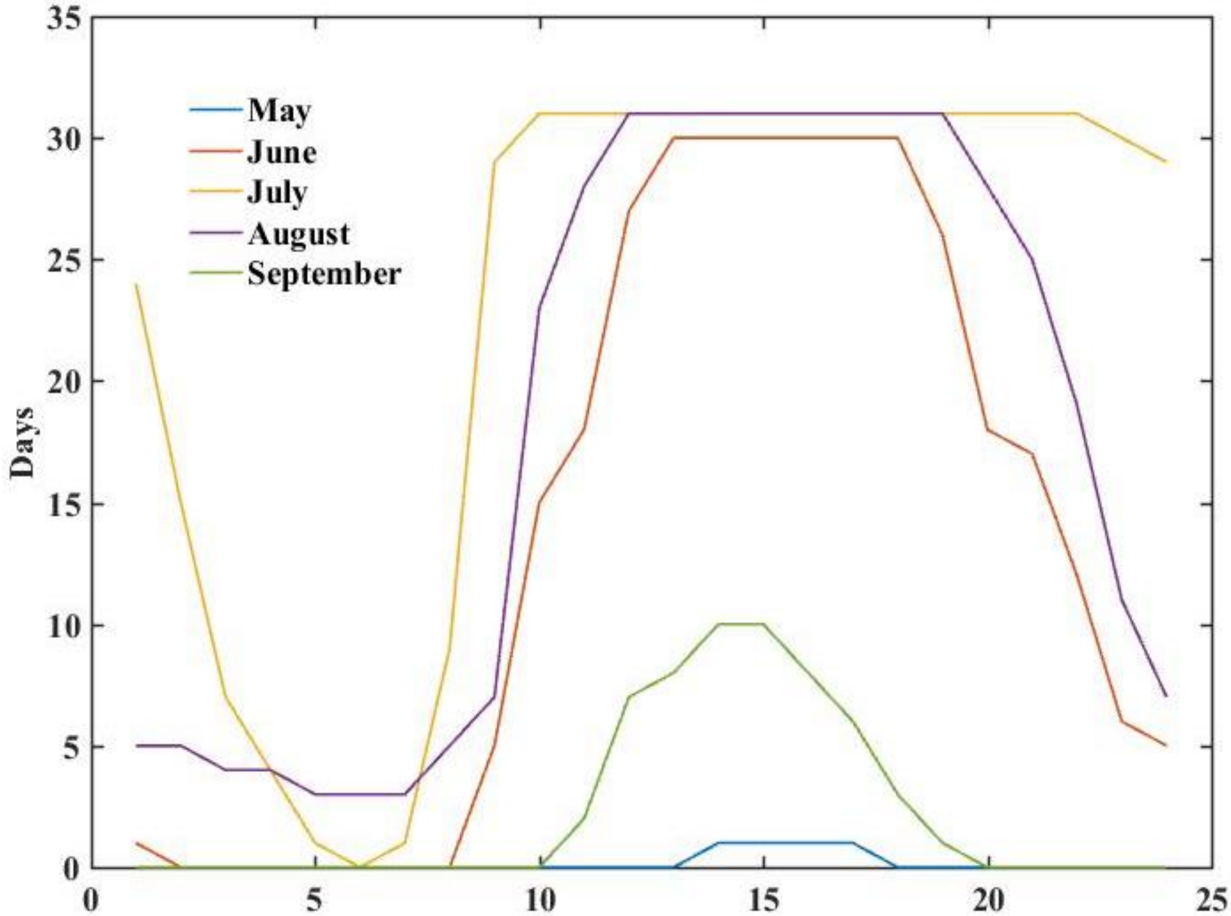

Figure F29. Number of Days that THI exceeded the threshold for gestation stage under $VR_{\Delta T = 5^0C}$ with evaporative cooling in Sioux City.

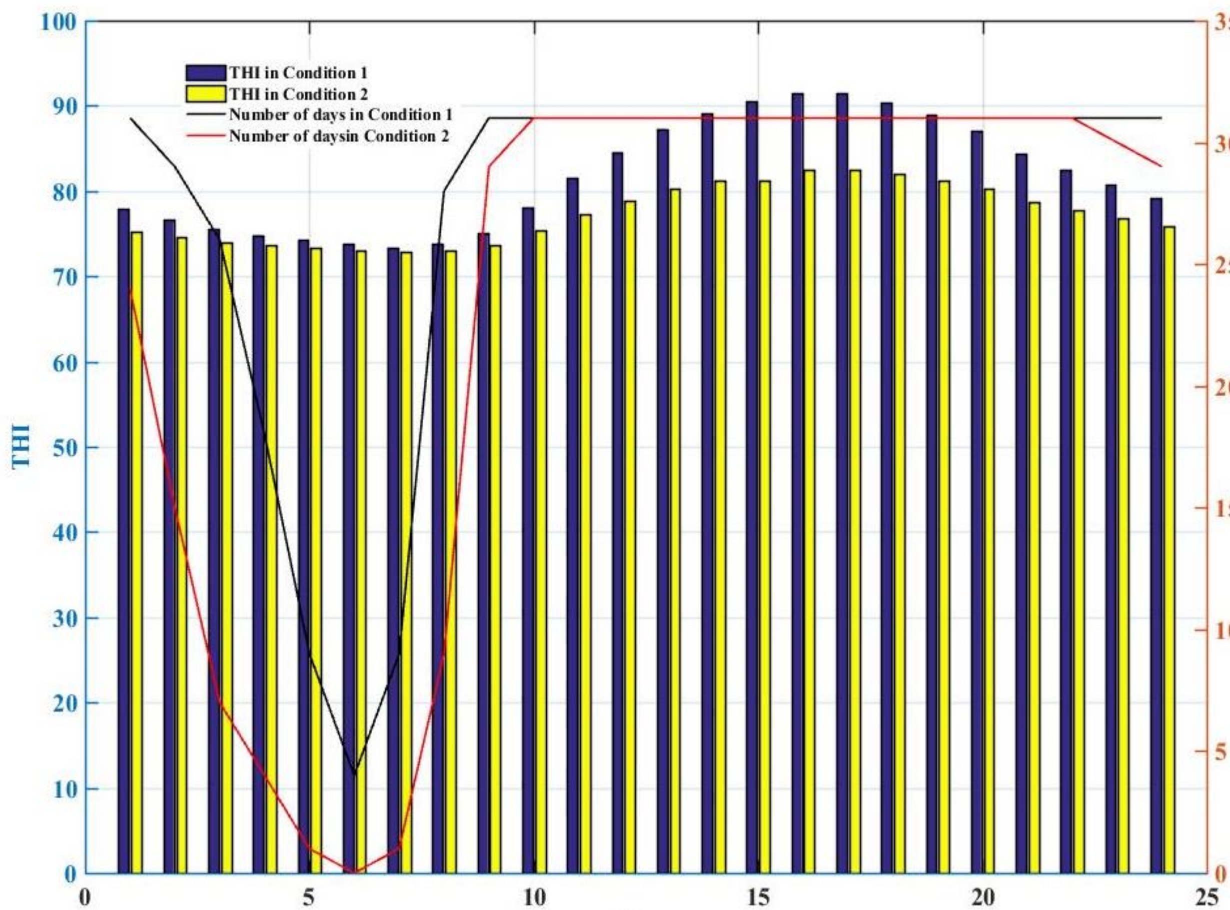

Figure F30. THI value in a typical day and number of days that THI exceeded the threshold for gestation under $VR_{\Delta T = 5°C}$ in Sioux City.

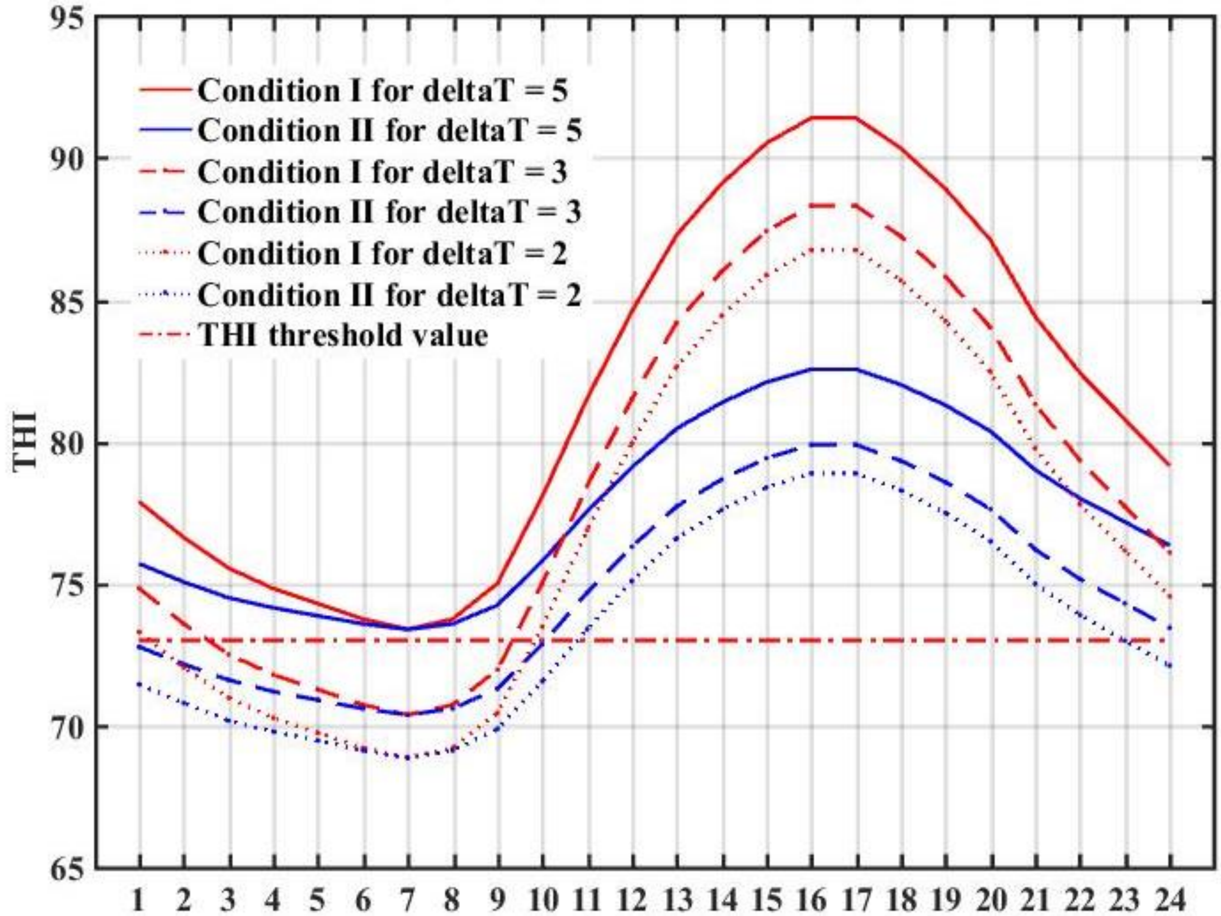

Figure F31. THI value change during a 22ed, July in different condition for gestation stage under $VR_{\Delta T = 2^oC}$, $VR_{\Delta T = 3^oC}$ and $VR_{\Delta T = 5^oC}$ in Sioux City, Iowa (Condition I is environmental control without using evaporative cooling and Condition II is with evaporative cooling.)

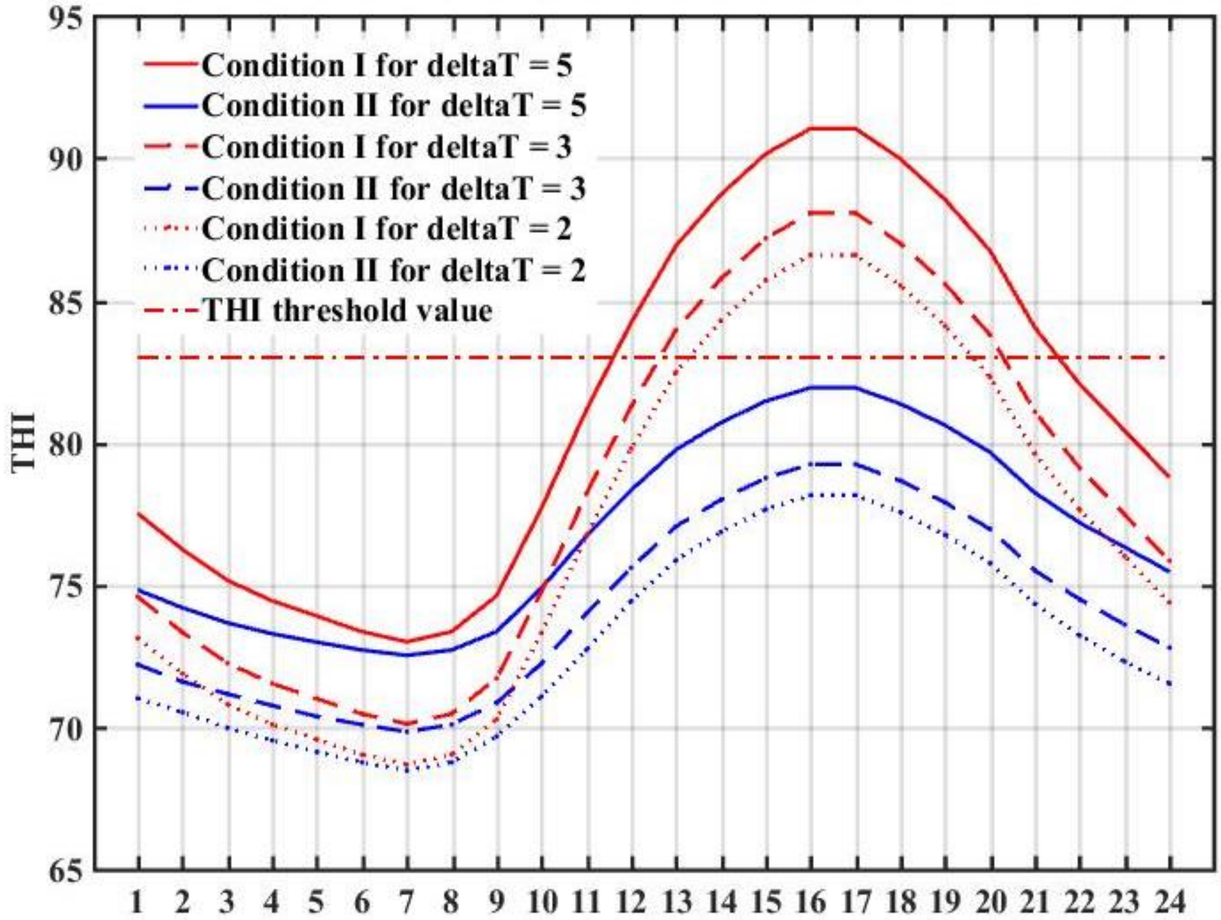

Figure F32. THI value change during 22ed, July in two condition for finishing stage under $VR_{\Delta T = 2^oC}$, $VR_{\Delta T = 3^oC}$ and $VR_{\Delta T = 5^oC}$ in Sioux City, Iowa (Condition I is environmental control without using evaporative cooling and Condition II is with evaporative cooling.)

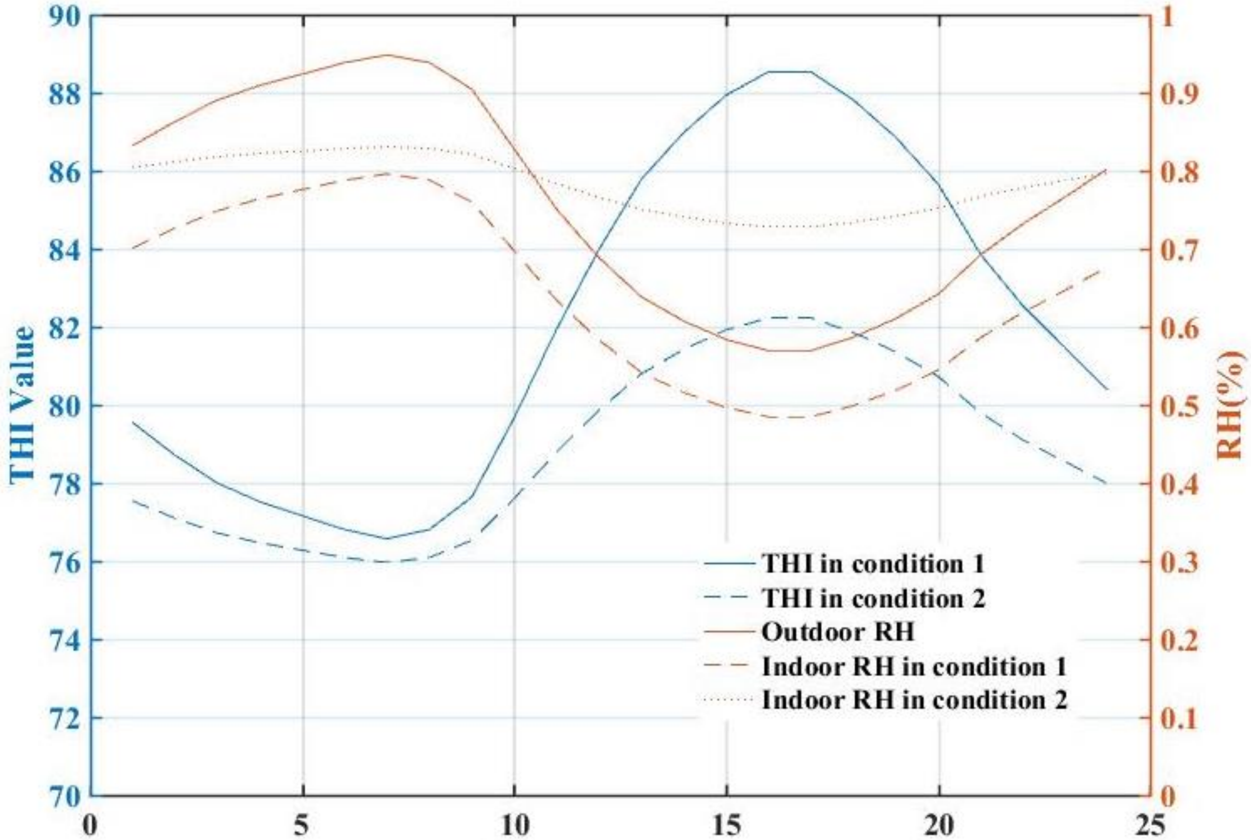

Figure F33. THI and RH in a typical day in two condition for gestation stage under $VR_{\Delta T = 3^oC}$ in Sioux City, Iowa (Condition I is environmental control without using evaporative cooling and Condition II is with evaporative cooling.)