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# New control strategy against temperature sudden-drop in the initial stage of pad cooling process in poultry houses

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**Abstract**

Preliminary field measurements have shown substantial temperature sudden-drop (ΔTsd) at bird level in the initial stage of pad cooling process in arid regions of China. Such sudden temperature fluctuation can cause thermal stress to laying hens and this problem is attracting increasing concerns. The purpose of this study was to develop a new control strategy (NCS) to avoid or minimize ΔTsd while simplify the operational process. Theoretical calculation and field test were conducted in this study. The key ambient thermal factor affecting ΔTsd was analysed by calculating temperature drop of cooled air existing the cooling pad (ΔTd). A countermeasure was applied by controlling the wetted pad area at each startup of the water supply pump. Field test was carried out to demonstrate application of the NCS in a poultry house. The theoretical arithmetic results showed that ambient relative humidity (RHo) was the main factor affecting ΔTd, and ΔTsd occurred when RHo ≤ 60%. Temperature fluctuation at the bird level (Tdb,b) could be controlled within 4°C when the wetted pad area increased by 25%. The NCS operated based on RHo that was divided into three regions. For RHo > 80%, the pump would not be turned on because of poor cooling effect. For 60% < RHo < 80%, no ΔTsd would occur and the pump would be controlled by "on-off" regulation. For RHo ≤ 60%, ΔTsd occurred and the pump was turned on intermittently. Then, 4-stage cooling would be applied. Results of the field test were generally consistent with the theoretical simulation with regards to alleviation of ΔTsd that was controlled within 3.5°C. Further field verification of the NCS on the flock health and production performance is warranted.

**Keywords**

evaporative cooling, poultry housing, temperature fluctuation, thermal stress

**Disciplines**

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**Comments**

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# New control strategyagainst temperature sudden-drop in the initial stage of pad cooling process in poultry houses

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**Abstract:** Preliminary field measurements have shown substantial temperature sudden-drop ($\Delta T_{sd}$) at bird level in the initial stage of pad cooling process in arid regions of China. Such sudden temperature fluctuation can cause thermal stress to laying hens and this problem is attracting increasing concerns. The purpose of this study was to develop a new control strategy (NCS) to avoid or minimize $\Delta T_{sd}$ while simplify the operational process. Theoretical calculation and field test were conducted in this study. The key ambient thermal factor affecting $\Delta T_{sd}$ was analysed by calculating temperature drop of cooled air existing the cooling pad ($\Delta T_d$). A countermeasure was applied by controlling the wetted pad area at each startup of the water supply pump. Field test was carried out to demonstrate application of the NCS in a poultry house. The theoretical arithmetic results showed that ambient relative humidity ($RH_o$) was the main factor affecting $\Delta T_d$, and $\Delta T_{sd}$ occurred when $RH_o \leq 60\%$. Temperature fluctuation at the bird level ($T_{db,b}$) could be controlled within 4℃ when the wetted pad area increased by 25%. The NCS operated based on $RH_o$ that was divided into three regions. For $RH_o > 80\%$, the pump would not be turned on because of poor cooling effect. For $60\% < RH_o < 80\%$, no $\Delta T_{sd}$ would occur and the pump would be controlled by “on-off” regulation. For $RH_o \leq 60\%$, $\Delta T_{sd}$ occurred and the pump was turned on intermittently. Then, 4-stage cooling would be applied. Results of the field test were generally consistent with the theoretical simulation with regards to alleviation of $\Delta T_{sd}$ that was controlled within 3.5℃. Further field verification of the NCS on the flock health and production performance is warranted.

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## 1 Introduction

Fan and pad cooling system is widely used for animal production in hot climate[1,2]. Because of its low energy cost, higher ventilation rate and good cooling efficiency[3-8], the cooling system has become a standard configuration for commercial poultry houses in hot regions[9]. For most laying-hen houses in China, operation of the pad cooling systems is decided by the farm operators according to their experiences or best judgment. In general, when the indoor average temperature ($T_{average}$) reaches 30℃, the pad cooling system is activated manually. The pump will then be turned off when there is no need for cooling. This simple “on-off” regulation (OOR) involves full wetting of the pads, which leads to large, abrupt temperature drops. Preliminary studies showed that when the temperature drop at bird-level reached 5℃ within 20 min, acute cold stress could occur to the birds which in turn adversely affect their health and production performance[10,11]. This temperature drop is referred to as temperature sudden-drop ($\Delta T_{sd}$) in this article. The problem of $\Delta T_{sd}$ is widespread, especially in the areas north of the Yangtze River, and is attracting increasing concerns in China.

Good cooling effect is what we are pursuing, but $\Delta T_{sd}$ is undesirable. In order to slow down the cooling rate in the initial stage of pad cooling process, intermittent operation of the water supply pump is practiced at some poultry farms. On these farms, operators need to preset a series of complex parameters, such as the ventilation level in different temperature regions, the time to start and stop the pad cooling process, switch time interval of the pump’s operation in different time periods, and so on. Some studies showed that temperature fluctuation at bird-level ($T_{db,b}$) could be kept within 2℃-4℃ if the relevant parameters were set properly[10,12]. However, this is difficult for operators due to the continental climates in China. The climate varies greatly among different regions and even in the same region, the day-to-day variations in climate is unpredictable. Therefore，it is impossible for users to find out the suitable and pre-set parameters. Frequent adjustments to the pad cooling operation has necessitated in the cooling process. Needless to say, such a practice is both labor-intensive and unreliable. In fact, users often set the

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parameters according to their experiences or 'best judgment'. When the parameters are set improperly, large temperature fluctuations will occur. The intermittent on/off operation - will also shorten the service life of the pump[10]. Investigations have revealed that this problem is wide spread in most farms with this control method. According to the personal communication with farm veterinarians, the negative impact on bird's production in summer is significantly. Furthermore, indoor average temperature, usually collected at different areas of the house, is used to control the operation of pump. Although $\Delta T_{sd}$ may not appear according to the data displayed on the control computer, the $\Delta T_{sd}$ may have occurred indeed because it usually occurs in the area near the cooling pad rather than in the central part of the house. Therefore, a new control strategy (NCS) of pad cooling systemis is urgently needed for these regions in China. The criteria for a successful NCS consists of appreciable alleviation of $\Delta T_{sd}$ and the ease of on-farm operation.

For a modern poultry house, the current regulation of automatic environmental control system is mainly based on indoor micro-environment. For the pad cooling system, the efficiency of its operation depends on the difference between the dry-bulb temperature ($T_{db,o}$) and wet-bulb temperature ($T_{wb,o}$) of ambient air[13]. Therefore, it is reasonable to consider the outside climate as well as indoor temperature when controlling indoor temperature fluctuation.

The objectives of this study were: (1) to identify the main source of ambient thermal factor causing $\Delta T_{sd}$ in the initial stage of pad cooling process, and to seek an effective and workable counter-method to avoid or alleviate $\Delta T_{sd}$; (2) to develop a new control strategy for pad cooling system that incorporates the dynamic ambient thermal factors and features ease of operation and (3) to test application and performance of the NCS in a commercial poultry house.

## 2 Materials and methods

### 2.1 Development of the NCS

The purpose for developing the NCS is to avoid $\Delta T_{sd}$ in the initial stage of pad cooling process and simplify the operation of users. The approach consists of three steps: (1) determine $\Delta T_d$ –the key ambient thermal factor affecting $\Delta T_{sd}$ under various climatic conditions, (2) find the practical measure against $\Delta T_{sd}$ controlling the amount of wetted pad area at the start-up of the water-supply pump to avoid the maximum potential dry-bulb temperature drop and (3) incorporate the calculations into the control algorithm through programming.

2.1.1 Determination of $\Delta T_d$

According to the cooling efficiency of the pad cooling system[13-18], $\Delta T_d$ can be calculated by the Equation (1):

$$\Delta T_d = T_{db,o} - T_{db,i} = (T_{db,o} - T_{wb,o}) \times \eta_c \tag{1}$$

where, $\Delta T_d$ is reduction or drop in air temperature after going through the cooling pad, ℃; $T_{db,o}$ and $T_{wb,o}$ are the ambient dry-bulb and wet-bulb temperature, ℃, respectively; $T_{wb,i}$ is the temperature of cooled air existing the cooling pads, ℃; $\eta_c$ is the cooling efficiency of the pad cooling system.

The $T_{wb,o}$ can be obtained from a psychrometric chart based on $T_{db,o}$, and ambient relative humidity ($RH_o$) for a given altitude (i.e., barometric pressure) or measured with a psychrometer. However, continuous measurement of $T_{wb,o}$ with electronic sensors poses challenges, albeit possible[19]. In comparison, dry-bulb temperature and RH can be more readily measured with electronic sensors. For practical purposes, the relatively small influence of barometric pressure fluctuations at a given altitude on the calculation of $T_{wb,o}$ can be neglected. The following calculations of $T_{wb,o}$ assume the standard sea level barometric pressure of 101.325 kPa which is used in this article. Given $T_{db,o}$ (℃) and $RH_o$ (%), $T_{wb,o}$ (℃) can be determined using the following empirical Equation (2)[20]:

$$\begin{aligned} T_{wb,o} = T_{db,o} atan[0.15(RH_o + 8.31)^{\frac{1}{2}} + atan(T_{db,o} + RH_o) - \\ atan(RH_o - 1.70) + 0.0039(RH_o)^{\frac{3}{2}} atan(0.023RH_o) - 4.69] \end{aligned} \tag{2}$$

The error of $T_{wb,o}$ is −0.1 ℃-0.6 ℃, when −20 ℃ ≤ $T_{db,o}$ ≤ 45 ℃ and 5% ≤ $RH_o$ ≤ 100%. When Equation (2) is substituted into Equation (1), $\Delta T_d$ is only related with $T_{db,o}$ and $RH_o$.

2.1.2 Counter-measure against $\Delta T_{sd}$

At the initial stage of cooling process, when some part of the pad is wetted and the other part is still dry, only the air going through the wetted part can be cooled. The air going through the dry area is still warm and can be considered having $T_{db,o}$. The drop of $T_{db,b}$ will be reduced if cooled and warm air can be completely mixed before the fresh air enters the birds area, then $\Delta T_{sd}$ will be avoided.

The temperature of the mixed air and the temperature drop of mixed air after existing cooling pads can be estimated by Equations (3) and (4), respectively.

$$T_{mix} = a_w \times (T_{db,i} - T_{db,o}) + T_{db,o} \tag{3}$$

$$\Delta T_{mix} = T_{db,o} - T_{mix} = a_w (T_{db,o} - T_{db,i}) \tag{4}$$

where, $T_{mix}$ is the mixed air temperature of cooled and warm air, ℃; $\Delta T_{mix}$ is the temperature drop of mixed air after existing cooling pad, ℃; $T_{db,i}$ is the dry-bulb temperature of the cooled air gonging through the wetted area of pad, ℃; $a_w$ is the percentage of wetted area occupied in total area of pad, %.

2.1.3 Water demand to wet a particular area of pad

When only some parts of the pad are wetted in the initial stage of pad coolling process, the wetted pad area is determined by water supplied at each startup of pump. The water demand for maximal cooling efficiency has been recommended[6], but water demand to wet a partial area of pad ($Q$) has not been reported. As far as honeycomb fiber paper pad is concerned, $Q$ is related to pad type, height, length, thickness and et al., and can be estimated as:

$$Q = V_w \cdot H \cdot L \cdot T \tag{5}$$

where, $Q$ is the water demand to wet a particular area of pad, L; $V_w$ is the estimated water demand to wet per unit volume of pad, L/m$^3$; $H$, $L$, and $T$ are height, length, and thickness of the portion of cooling pad which is wetted, m, respectively.

To estimate $V_w$, ten pieces of fiber paper pad (7090 type, Munters Air Treatment Equipment (Beijing) Co., LTD) were chosen for test. Five of them were 0.60 m $L$×1.50 m $H$×0.10 m $T$, and the other five were 0.60 m $L$×1.5 m $H$×0.15 m $T$. All pieces were set up vertically on the floor of the lab. Each piece was sprayed 1.5 L of water, as evenly as possible, on the top of the pad. The wetted area of each piece was measured through image analysis (Figure 1), and $V_w$ was calculated. The estimated $V_w$ value was 18.9 L/m$^3$ to 20.4 L/m$^3$, averaging 19.8 L/m$^3$. Then, Equation (5) can be rewritten as follow:

$$Q = 19.8 \cdot H \cdot L \cdot T \tag{6}$$

Cooling pad has become a standard product with fixed size. For the sake of application convenience, the water damand needed to wet per-linear meter of pad ($Q_{pL}$) is introduced to the NCS.

Rewriting Equation (6), $Q_{pL}$ becomes:

$$Q_{pL} = Q / L = 19.8 \cdot H \cdot T \tag{7}$$

The value of $Q_{pL}$ (7090 type) is calculated and listed in Table 1, and NCS will be programmed based on it.

Figure 1 Evaluation of pad wetted area and specific water volume of the pad

**Table 1 Water demand to wet per-linear meter of cooling pad ($Q_{PL}$)**

| Pad size | | $Q_{pL}$/L m$^{-1}$ | | | |
|---|---|---|---|---|---|
| Thickness/m | Height/m | 1/4 $H$ | 1/2 $H$ | 3/4 $H$ | $H$ |
| 0.15 | 2 | 1.49 | 2.97 | 4.46 | 5.94 |
| | 1.8 | 1.34 | 2.67 | 4.01 | 5.88 |
| | 1.5 | 1.11 | 2.23 | 3.34 | 4.46 |
| 0.1 | 2 | 0.95 | 1.98 | 2.97 | 3.96 |
| | 1.8 | 0.86 | 1.78 | 2.67 | 3.56 |
| | 1.5 | 0.74 | 1.49 | 2.23 | 2.97 |

Note: $Q_{pL}$=19.8·$H$·$T$, $Q_{pL}$ is the water demand to wet per-unit length of cooling pad (L/m); $H$ and $T$ are height and thickness of the portion of cooling pad which is wetted (m), respectively.

### 2.2 Development of software and field demonstration

The software of NCS was developed in LabVIEW12 graphical programming language, and the database MySQL was used. To test the NCS, a field demonstration was carried out during June and July of 2014 (a total of 45 d) in Hebei Province, China. Two similar tunnel-ventilated conventional cage layer houses were chosen for the test. The dimensions of the houses were 90 m ($L$) × 12 m ($W$) × 3.6 m ($H$), each holding 14 000 W-36 laying hens at 30 weeks of age. The cooling pad measuring 14.4 m ($L$) × 2.50 m ($H$) × 0.15 m ($T$) was installed at one end of the house. An air deflector was installed at rear side of the pad to mix the cooled and warm air (Figure 2). Eight 1.38-m diameter exhaust fans (TUHE-S1, Tuhe Equipment Industrial Co., Ltd., China) were located in the opposite end wall. Each ventilation fan had a nominal airflow rate of approximately 22 500 m$^3$/h. All fans were turned on during the test, and controlled manually.

The pad cooling system in the experimental house was controlled by NCS. Four sensors were used in NCS and the installation and connection with control computer are shown in Figure 2. The function of each sensor was described as following: sensor 1 (P-RTS-2, Rotem Control and Management, Israel), sensor 2 (P-RHS-10PL, Rotem Control and Management, Israel), and sensor 3 (P-RTS-2, Rotem Control and Management, Israel) were used to collect $T_{db,o}$, $RH_o$ and $T_{outlet}$, respectively. Sensor 4 was a volumetric flow meter (DMF-1-3-A, Beijing Sincerity Automatic Equipment Co., LTD) installed in the water supply pipeline and it was used to collect the volume of water at each start of pump. The data of $T_{db,o}$, $T_{db,i}$ and $RH_o$ were recorded at 10 min intervals. The volume of water was collected every 30 s. $T_{max}$ was set at 30 ℃ according to the farm operator.

The pad cooling system in the control house was regulated by OOR. The water supply pump was turned on manually, as soon as the pad cooling system in the NCS or experimental house started operating. Then it was turned off at 18:00 according to the operator of the house in the control house.

A portable temperature and RH logger (HOBO U23-001, Onset Computer Corporation Pocasset, MA, USA) was located at the test point near the birds in each house (Figure 2). The logger was put into a hard cover to avoid birds pecking. It was used to collect $T_{db,b}$ at 10 min intervals.

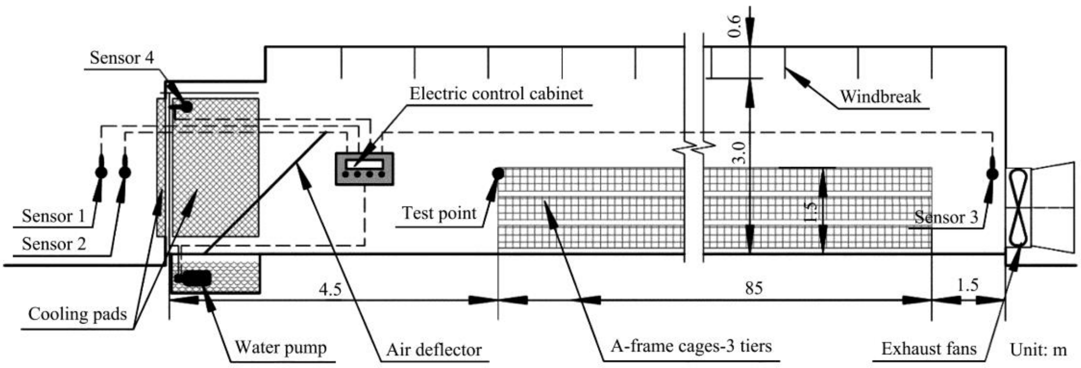


Figure 2 Diagram of experimental houses

## 3 Results and discussion

### 3.1 Construction of NCS

3.1.1 $\Delta T_d$ and the ambient thermal parameters

Efficiency of pad cooling system has been reported to reach above 80% when the face velocity is 1.0 m/s to 1.5 m/s in hot and dry regions in China[8,21,22]. According to Equations (1) and (2), $\Delta T_d$ was calculated when pad was fully wetted (Table 2). The results indicated that there was a good linear relation between $\Delta T_d$ and ambient thermal parameters. Namely, $\Delta T_d$ increased with decreasing $RH_o$ or / and $T_{db,o}$, in addition, $RH_o$ was the main factor affecting $\Delta T_d$. The results also showed that $\Delta T_{sd}$ occurred when $RH_o \leq 60\%$, which necessitates use of counter-measures to avoid it. The magnitude of $\Delta T_d$ can be reduced by running pump earlier or lowering the temperature set-point for activating the cooling system. For example, $\Delta T_d$ decreased 1℃ when activating the cooling system at $T_{db,o}$ of 25℃ *vs*. 30℃ when $RH_o \leq 60\%$. However, $\Delta T_{sd}$ could not be eliminated by this method alone. When $60\% < RH_o < 80\%$, $\Delta T_d$ was 3℃ to 4℃, indicating that $T_{db,b}$ would be less than 5℃, and no $\Delta T_{sd}$ appeared. When $RH_o \geq 80\%$, the cooling effect was no more than 2℃. When the pad cooling system was in operation, the indoor *RH* would climb to near saturation quickly. In this situation, birds' natural ability to dissipate latent heat would be greatly reduced, likely resulting in severe heat stress[2,25]. Therefore, increasing air velocity over birds may be a better method to cool them when $RH_o \geq 80\%$, rather than to operate pad cooling system[23,24]. In general, $RH_o$ was the key thermal factor affecting $\Delta T_{sd}$, and the NCS will be constructed based on $RH_o$.

3.1.2 Counter-measure against $\Delta T_{sd}$

In tunnel-ventilated poultry houses, indoor temperature increases gradually from the cooling pad end to the exhaust fans end. The air temperature ($T_{max}$) at the exhaust end for laying hen houses is suggested to be no more than 28℃[25]. Furthermore, the longitudinal (end-to-end) temperature gradient should be less than 3℃[25,26], which depends on the ventilation rate, length of the building and arrangements of the air inlets and fans. Based on these recommendations, for $T_{max}$ of 28℃ at the exhaust end, air temperature at the pad end should be 25℃ to 27℃. When the pad is completely dry, the temperature near the pad can be regarded same as $T_{db,o}$. Therefore, if $T_{max}$ was used to operate pad cooling system, the pump should be turned on when $T_{db,o}$ rose to 25-27℃.

The $\Delta T^*_d$ was calculated theoretically when the pad was wetted for different percentages in the initial stage of cooling process. The results indicated that $\Delta T^*_d$ increased with the increasing wetted area of pad, and it could be controlled within 4℃ when the wetted area gradually increased by 25%, as shown in Figures 3 and 4. The results also demonstrated that controlling the wetted area of pad at each start-up of pump was an effective method against $\Delta T_{sd}$ in the initial stage of cooling process. Hence, the NCS was developed and programmed to avoid $\Delta T_{sd}$ accordingly.

**Table 2 $\Delta T_d$ of the air through the evaporative cooling pads/℃**

| $T_{db,o}$ | $RH_o$/% | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 10 | 15 | 20 | 25 | 30 | 35 | 40 | 45 | 50 | 55 | 60 | 65 | 70 | 75 | 80 | 85 | 90 | 95 |
| 25 | 12 | 11 | 10 | 9 | 8 | 8 | 7 | 6 | 6 | 5 | 4 | 4 | 3 | 3 | 2 | 1 | 1 | 0 |
| 26 | 12 | 11 | 10 | 9 | 9 | 8 | 7 | 6 | 6 | 5 | 4 | 4 | 3 | 3 | 2 | 2 | 1 | 1 |
| 27 | 12 | 11 | 11 | 10 | 9 | 8 | 7 | 7 | 6 | 5 | 5 | 4 | 3 | 3 | 2 | 2 | 1 | 1 |
| 28 | 13 | 12 | 11 | 10 | 9 | 8 | 8 | 7 | 6 | 5 | 5 | 4 | 3 | 3 | 2 | 2 | 1 | 1 |
| 29 | 13 | 12 | 11 | 10 | 9 | 9 | 8 | 7 | 6 | 5 | 5 | 4 | 3 | 3 | 2 | 2 | 1 | 1 |
| 30 | 13 | 12 | 11 | 10 | 10 | 9 | 8 | 7 | 6 | 6 | 5 | 4 | 3 | 3 | 2 | 2 | 1 | 1 |
| 31 | 14 | 13 | 12 | 11 | 10 | 9 | 8 | 7 | 6 | 6 | 5 | 4 | 4 | 3 | 2 | 2 | 1 | 1 |
| 32 | 14 | 13 | 12 | 11 | 10 | 9 | 8 | 7 | 7 | 6 | 5 | 4 | 4 | 3 | 2 | 2 | 1 | 1 |

Note: It was calculated at the cooling efficiency of 80% and the standard sea level pressure of 101.325 kPa.

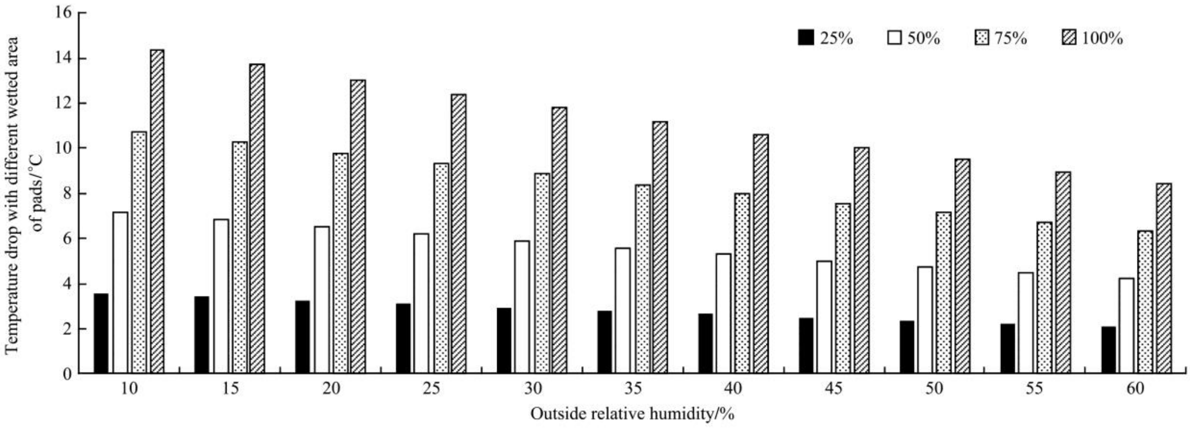


Figure 3 Estimated temperature drop of mixed air with different amount of wetted pad area when ambient temperature is 25°C

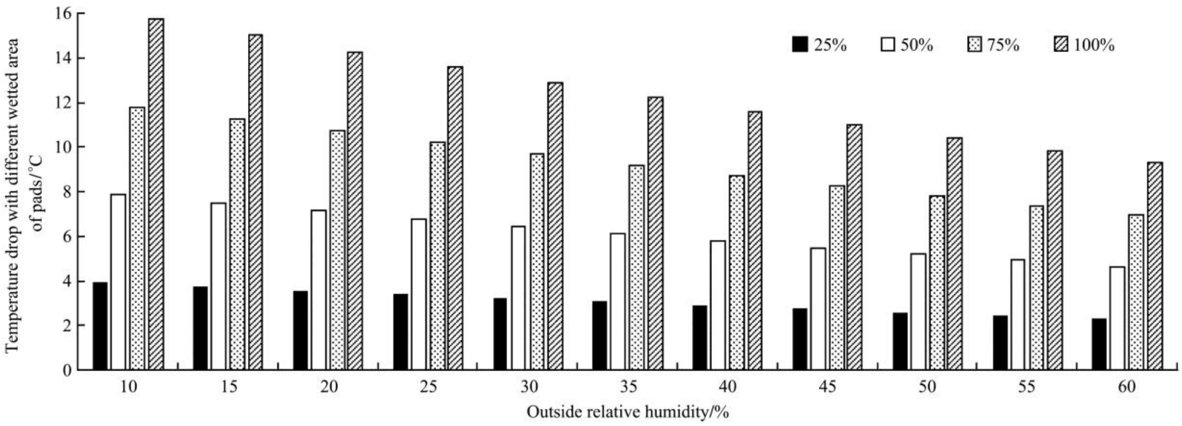


Figure 4 Estimated temperature drop of mixed air for different amount of wetted pad area when ambient temperature is 27°C

### 3.2 The NCS applied for pad cooling system

#### 3.2.1 Principle of NCS

The NCS for pad cooling system was proposed based on $RH_o$, and the detail is described in Figure 5. The $RH_o$ was divided to three regions in NCS. The computer would analyze the real-time $RH_o$ when the pump is activated. When $RH_o \geq 80\%$, the pump will not be turned on because of poor cooling effect. When $60\% < RH_o < 80\%$, the pump was controlled by OOR. When $RH_o \leq 60\%$, four-stage control measure for pump will be taken, level-I, level-II, level-III and level-IV. Twenty-five percent (25%) of the cooling pad area is wetted at level-I in the initial stage of cooling process, then increases by 25% to the next level. Water is supplied continuously at level-IV until the cooling is no longer needed.

The $T_{max}$ in the NCS is set by the operator. When air temperature near the exhaust fans ($T_{outlet}$) reaches $T_{max}$, the water pump will be turned on automatically, and the corresponding $T_{db,o}$ ($T^*_{db,o}$) will be recorded at the first startup of pump for the day. The cooling process will be stopped when $T_{db,o}$ drops to $T^*_{db,o}$ again. The volume of water needed at each level can be estimated by the control computer based on Table 1. A volumetric flow meter is used to monitor the volume of water supply at each startup of the pump. Once water supply reaches the demand, the pump will be turned off. The process repeats itself, as needed.

Compared with the existing control method for pad cooling system, the pump is turned on based on $T_{outlet}$ in NCS, rather than the average indoor temperature. As such NCS is expected to more effectively keep all the birds, especially those near the exhaust end, in the thermal comfort zone. In addition, it keeps the longitudinal (end-to-end) air temperature gradient to a narrow range. The operating process of pump is controlled by real-time $RH_o$ automatically in NCS, rather than the switch time interval input by operators according to their experiences or "best judgment". The $RH_o$ is divided into three ranges. The pump is controlled by a particular method in each range. When $RH_o \leq 60\%$, -stage cooling is used to avoid $\Delta T_{sd}$. The $\Delta T_d$ can be theoretically controlled within 4 ℃ when the wetted pad area is increased by 25% from this level to the next. Moreover, NCS is user friendly. All of the required input parameters of basic housing information can be set easily by the operators. Once the parameters are set, the control system will run automatically according to the dynamic ambient thermal factors. It is readily adaptable to users in different climatic regions.

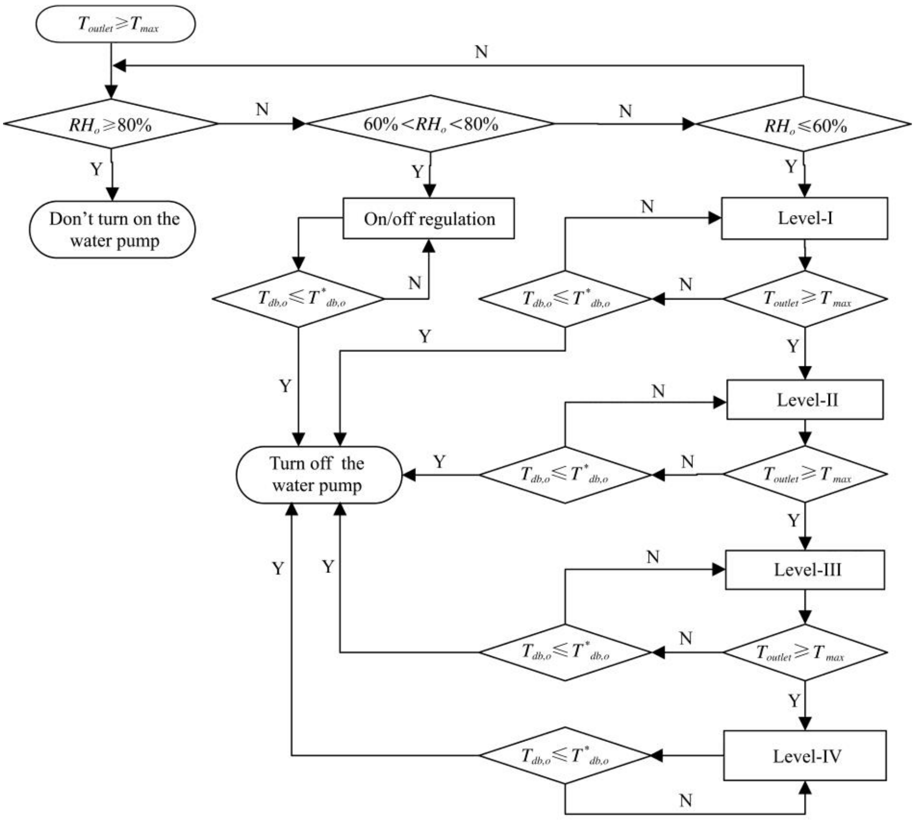


Figure 5 Schematic diagram of the new control strategy (NCS) for pad cooling system

#### 3.2.2 Software of NCS

The software of NCS is developed in LabVIEW 12 graphical programming language, and the database uses MySQL. There are two operating modules, pre-set parameters module and real-time information display module, corresponding to the pre-set parameters interface and the real-time information display interface, respectively. In the pre-set parameters interface, operators only need to input the basic information of the poultry houses, such as the dimensions of the house and cooling pad, total number of fans and air-flow of fan, and the maximum temperature, as shown in Figure 6. After setting the parameters, the system will automatically run according to the real-time ambient thermal factors collected and the preset maximum temperature. Daily updating of the bird age (d) will be done automatically. In the real-time information display interface, some closely related information will be presented, such as $T_{db,o}$, $RH_o$, and running conditions of the pad cooling system (Figure 7).

### 3.3 Field demonstration of NCS

The daily thermal data were continually collected for a 45-day field test and the cooling pad system was not operated in 12 d because of raining or high $RH_o$ during the test. The temperature sudden drop occurred in 20 d total and the variation of temperature and $RH_o$ in these 20 d were analyzed and the statistical data was summarized as following. The max and mean values of outside temperature were 41.2℃ and 20.9℃, respectively. The mean and minimum values of $RH_o$ were 55% and 6%, respectively. The maximum difference between $T_{outlet}$ and $T_{db,b}$ in NCS and OOR were 3.5℃ and 7.1℃ in the initial stage of pad cooling process, and the mean values were 2.8℃ and 6.3℃, respectively. In these 20 d, the maximum and mean $T_{outlet}$ in NCS and OOR during light time were 28.5℃ and 27.4℃, respectively.

During this test period, the new control system ran stably, and the actual cooling effect was generally consistent with the expected performance. The fluctuation of $T_{db,b}$ was maintained within 3.5℃. The driest day (1st July 2014 with a minimum $RH_o$ of 6%) was selected and the cooling process was analyzed during the light period. If the $\Delta T_{sd}$ could be eliminated when $RH_o$ is the lowest, it would not occur during the rest of the days.

In the chosen days, the first time of pump running was at 8:10 automatically in experimental house with NCS. The $RH_o$ and $T^*_{db,o}$ were 12% and 27.5℃ at that moment respectively. Then, the pump was turned on manually as soon as possible in the control house with OOR. The fluctuation of $T_{db,b}$ in the two houses were shown in Figure 8.

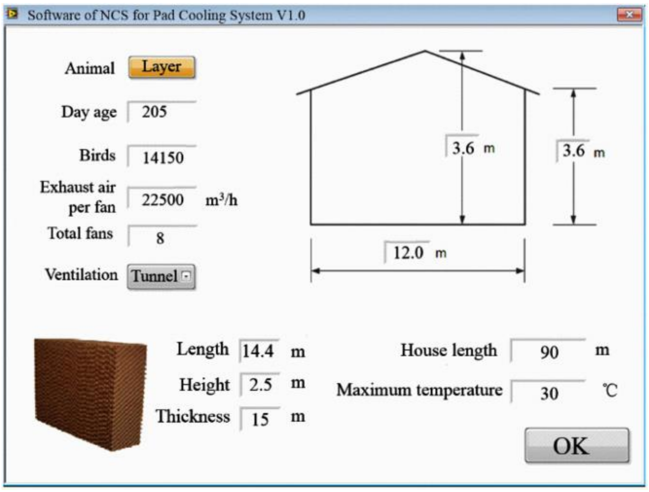


Figure 6 Pre-set parameters interface

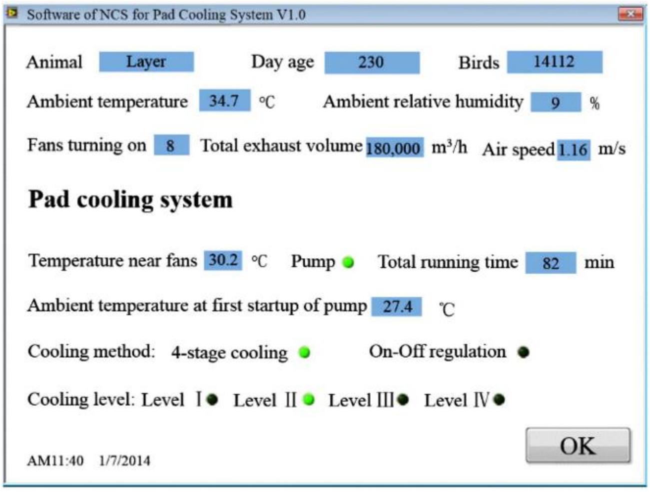


Figure 7 Real-time information display interface

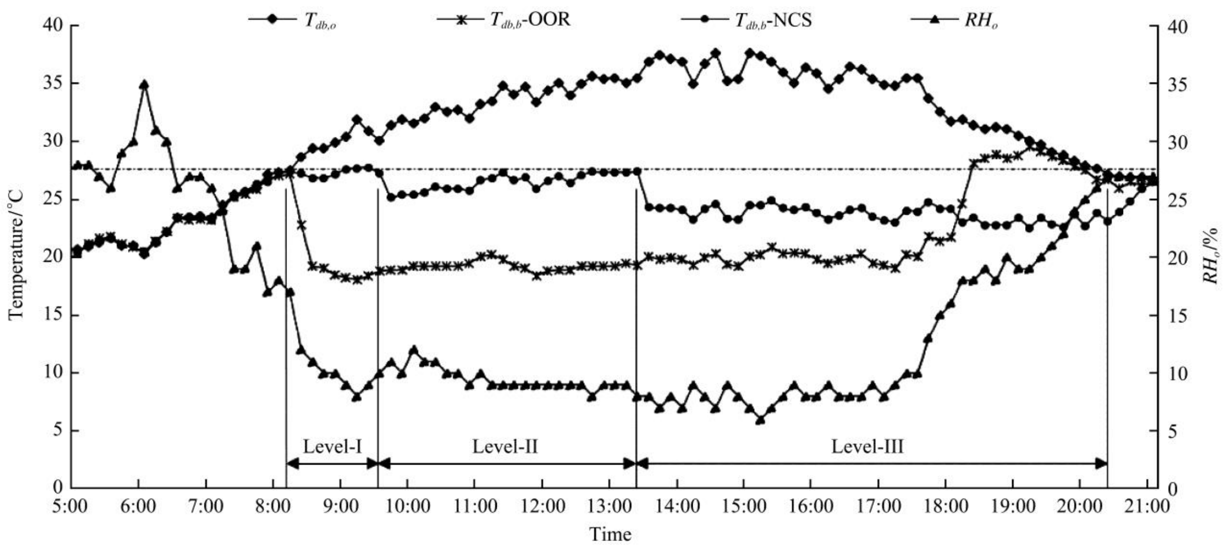


Figure 8 Temperature fluctuation at bird level with two kinds of control system for pad cooling system

As shown in Figure 8, there was a sudden drop of $T_{db,b}$ with OOR. The drop of $T_{db,b}$ reached 7℃ within 20 min of cooling initiation, causing occurrence of $\Delta T_{sd}$. As the pad was fully wetted as soon as the pad cooling system was operated, the maximum cooling effect was achieved quickly. When pump was turned off by the operator at 18:00, $T_{db,b}$ rose to 28℃ within 20 min, then it remained above 28℃ until 19:50. On the contrary, the fluctuation of $T_{db,b}$ was relatively gradual and slow in the experimental house with NCS. The drop of $T_{db,b}$ was controlled within 3℃ from this level to the next. The $T_{outlet}$ rose to $T_{max}$ at 08:10. The corresponding $RH_o$ and $T^*_{db,o}$ were 12% and 27.5℃, respectively. The operation of pump was controlled by 4-stage control approach with NCS. The cooling stage of Level-Ⅰ to Level-Ⅲ were applied on this day. The proportions of wetted areas of cooling pad were 25%, 50% and 75% in Level-I, Level-II and Level-III, respectively. Photographs of the wetted area of cooling pad for different cooling levels are shown in Figure 9. The wetted area of cooling pad roughly increased at 25% increments from Level-I to Level-III, which was consistent with the calculations. The pad cooling process was stopped automatically when $T_{db,o}$ dropped to 27.5℃ at 20:20. In addition, $T_{db,b}$ was maintained around 23℃ in NCS, rather than sudden rise to 28℃ or above in OOR. The results support the expectation that NCS provides an effective method to eliminate $\Delta T_{sd}$ in the initial stage of pad cooling process.

Level-I Level-II Level-III

Figure 9 Photographes of different cooling level in OCS

## 4 Conclusions

In this study, the main ambient thermal parameter affecting $\Delta T_{sd}$ in the initial stage of pad cooling system was analyzed, and the counter-measure to avoid $\Delta T_{sd}$ was proposed by controlling the wetted area of pad at each start-up of pump. Then the NCS was constructed and programmed. Finally, the field application of NCS vs. traditional on-off-regulation (OOR) method was demonstrated in commercial poultry houses. The conclusions are as follows:

1) Outside $RH_o$ is the main factor affecting the temperature reduction by the cooling system ($\Delta T_d$) in the initial stage of pad cooling process. To a certain extent, $\Delta T_d$ can be reduced by running pump earlier or lowering the maximum temperature, but excessive sudden drop in temperature ($\Delta T_{sd}$) could not be eliminated by this method alone.

2) The $\Delta T_{sd}$ can be eliminated effectively by controlling the wetted area of pad at each start-up of pump if the cooled air and warm air are well mixed once leaving the cooling pad. The resultant temperature drop of the mixed air ($\Delta T_{mix}$) can be controlled within 4℃ according to theoretical calculation when the wetted pad area is increased gradually at 25% increments.

3) The NCS is constructed based on $RH_o$ and the software is developed. The $RH_o$ is divided into three regions in NCS. Different control systems are used in each range. For $RH_o$ > 80%，the pump will not be turned on because of poor cooling effect. For 60% < $RH_o$ < 80%, no $\Delta T_{sd}$ will occur and the pump will be controlled by “on-off” regulation. For $RH_o \leq 60\%$, $\Delta T_{sd}$ occurs and count-measures are needed. Then, 4-stage cooling level is used to avoid $\Delta T_{sd}$. $\Delta T_d$ can be controlled within 4℃ theoretically when wetted area of cooling pad is increased by 25% gradually. In addition, input the parameters needed to run the NCS controller are the basic information of the poultry houses and can be readily entered by the operator.

4) A field testing was carried out to demonstrate the application of NCS in actual production. The results demonstrated stable operation of the NCS and generally consistent cooling effect as predicted in the theoretical calculations. Specifically, the fluctuation of $T_{db,b}$ was maintained within 3.5℃ and $\Delta T_{sd}$ was successfully avoided. The temperature at the bird level ($T_{db,b}$) downstream from the cooling pad in NCS showed a gradual transition in temperature, where as it had a sudden drop for the OOR method in the initial stage of cooling process.

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