Fan and Ventilation Rate Monitoring of Cage-Free Layer Houses in California

X. Lin, R. Zhang, S. Jiang, H. M. El-Mashad, H. Xin

Abstract. *Ventilation rates were continuously monitored from 1 March 2012 to 13 May 2013 in two cage-free layer houses in California. The average number of brown Lohmann laying hens in each house was 33,300. Temperature, relative humidity, static pressure, and running status of 48 ventilation fans were continuously monitored and recorded every minute. Regression models were developed to relate house temperature and ventilation rate to inlet air temperature and to relate airflow rate to building static pressure (R^2 = 0.98). Results showed that the daily mean ventilation rate per hen ranged from 1.91 to 8.72 m^3 h^{-1} hen^{-1}, averaging 4.49 ±1.53 m^3 h^{-1} hen^{-1}. The standard uncertainty of daily mean ventilation rate was determined to be 3.7%. The 91 cm and 130 cm fans were found to perform at 82% and 63% of the manufacturer-rated airflow rates, respectively. Minimum and maximum static pressures were 11.0 and 50.6 Pa, respectively, corresponding to 2 and 16 running tunnel fans. When the house temperature exceeded 30°C, an evaporative cooling system was activated, which could reduce the inlet air temperature by 6.3°C and concurrently increased the indoor air humidity ratio by 3.4 g per kg dry air. Cooling pad efficiency was 66%. The sidewall fans and tunnel fans were operated at 65% and 20%, respectively, of the total time when layers occupied the houses. A new rational formula for calculating dry base ventilation rate was developed based on the ratio of water vapor volume to moist air volume. The developed models and data collected in this research can be used to calculate the ventilation rates in cage-free layer houses to ensure the healthy conditions needed for laying hens. The models and data can also be used in the design of cage-free houses and in calculating emissions of air pollutants from these houses.*

Keywords. *Cage-free laying hen house, Fan curve, Static pressure, Ventilation.*

Cage-free egg production houses have received a great deal of interest in California and in many parts of the world. Increasing the living space for each hen in a layer house improves the welfare of laying hens. California issued Proposition 2 in 2008 that obliges farmers to provide enough living space for laying hens to freely stand up, lie down, turn around, and extend their wings without interrupting other hens. The new Shell Egg Food Safety Regulations in Title 3 of the California Code of Regulations require a minimum living space of at least 748 cm^2 (116 $in.^2$) for each hen in cages that hold nine hens or more (CDFA, 2013). The California egg industry was required to implement Proposition 2 by 1 January 2015. As a result, it is expected that cage-free housing system will be widely adopted in California in the near future to comply with Proposition 2 requirements. The European Union (EU) has banned conventional cages and has widely used cage-free houses since 2013 for the welfare of laying hens (Appleby, 2003).

Ventilation in animal housing is an important parameter that affects animal welfare and productivity. In high-density poultry houses, fresh air should be mechanically provided using fans. The fans are controlled by timers and thermostats to deliver the ventilation rates needed for poultry houses. Proper determination of ventilation rates is important to ensure adequate temperature and relative humidity (RH) in poultry houses (Wathes and Charles, 1994). Moreover, ventilation rates need to be accurately measured to quantify air emissions from animal houses (Calvet et al., 2010).

Ventilation rates can be estimated by measuring carbon dioxide concentration and heat balance in animal houses (Chepete et al., 2004; Li et al., 2005; Liang et al., 2005; Xin et al., 2006; Zhao et al., 2015) or by directly measuring fan airflow rates (Wheeler et al., 2002; Li et al., 2005; Chai et al., 2009; Cortus et al., 2010; Li et al., 2009; Lin et al., 2011, 2012). For direct measurements, such as in long-period air emission monitoring research, one practice is to monitor the operating status (on/off) of ventilation fans, fan rotational speed, and building differential static pressure (DSP) (Lin et al., 2012). The DSP across a house is defined as the pressure outside the house minus the pressure inside the house (BESS, 1996a, 1996b) and is normally positive. The airflow rates of fans are measured and assessed with a portable Fan Airflow Numeration System (FANS, fig. 2d), as described by Gates et al. (2004), Lin et al. (2011), and Lin et al. (2012).

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The fan tester method has been widely applied in animal houses, including poultry houses (Lin et al., 2011, 2012; Chen et al., 2014; Shepherd et al., 2015). The airflow rate measured with a fan tester can be used to develop mathematical models of airflow rate as a function of house static pressure. Several studies have been published on the determination of ventilation rates in mechanically ventilated commercial poultry buildings to determine air emissions rates (Wheeler et al., 2006; Calvet et al., 2010; Lin et al., 2011, 2012; Wang-Li et al., 2013; Chen et al., 2014; Shepherd et al., 2015). Zhao et al. (2015) reported the ventilation rates in aviary houses. However, measurements of ventilation rates in cage-free houses are seldom reported. Hence, it is necessary to determine the ventilation rates in cage-free houses in order to quantify the air pollutant emission rates from these houses (Lin et al., 2017).

The objectives of this research were to: (1) continuously measure the ventilation rates in two cage-free layer houses in California, (2) develop airflow models for two kinds of fans used in cage-free layer houses, and (3) determine the effects of the inlet air temperature and the number of operating fans on the temperature of layer houses.

Methodologies

Monitored Site Description

Ventilation rates were measured in two cage-free layer houses. Both houses were located on a ranch in the San Joaquin Valley, California. The two houses were built in 2009 and 2008 and are denoted H1 and H2, respectively. The two houses were built in two stories following the standards of the American Humane Association for cage-free houses in compliance with California's Proposition 2. Figure 1 shows the monitoring locations for the two houses in plan and endwall views. The two houses were oriented N-S and spaced 15.3 m apart. Each house was 135 m L × 17 m W × 4 m H (at eave), and the ridge height was 6.9 m. The first and second floor heights were 1.8 and 2.1 m, respectively. The service areas in the north and south ends of the houses were 6.0 m (20 ft) and 5.5 m (18 ft) deep along the house length. Each floor had four nesting rows with feed, water supply, nests, perches, and manure belts to remove manure three times a week. Each hen had an average usable area of 1161 cm^2 (180 $in.^2$) and could access nests, perches, and the litter floor. Each house could hold about 38,000 brown Lohman hens (fig. 2c). Single-cycle production was practiced for 55 weeks. At the beginning of each flock, the house floors were covered with a 5 cm thick layer of new rice hulls. The mixture of rice hulls and manure was cleaned out at the end of the flock. Monitoring equipment was installed in December 2011, and data were collected from 1 March 2012 to 13 May 2013. The numbers of complete data days (CDD) for ventilation rate measurements were 391 and 396 for H1 and H2 respectively, representing 94% and 95% of the total number of laying hen occupation days from 1 March 2012 to 13 May 2013. A CDD is defined as a day with more than 1080 (75% of 1440) records of daily 1 min data.

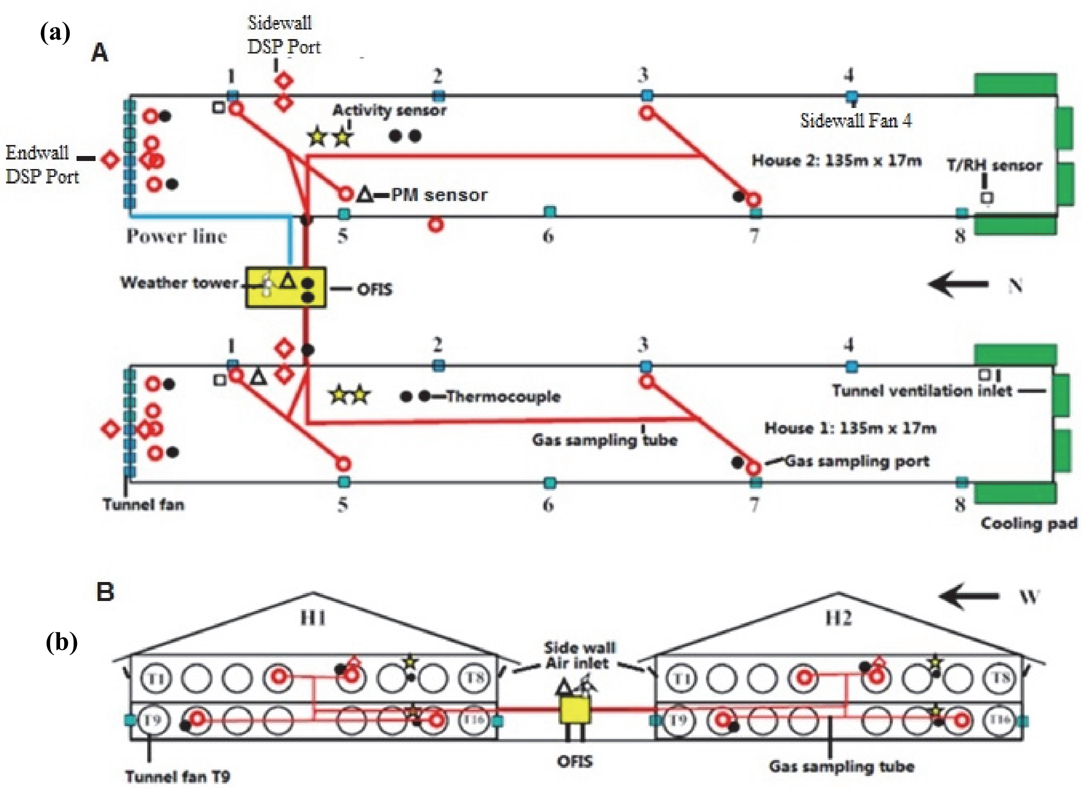

Figure 1. Schematic of measurement and sampling locations: (a) plan view and (b) endwall view.

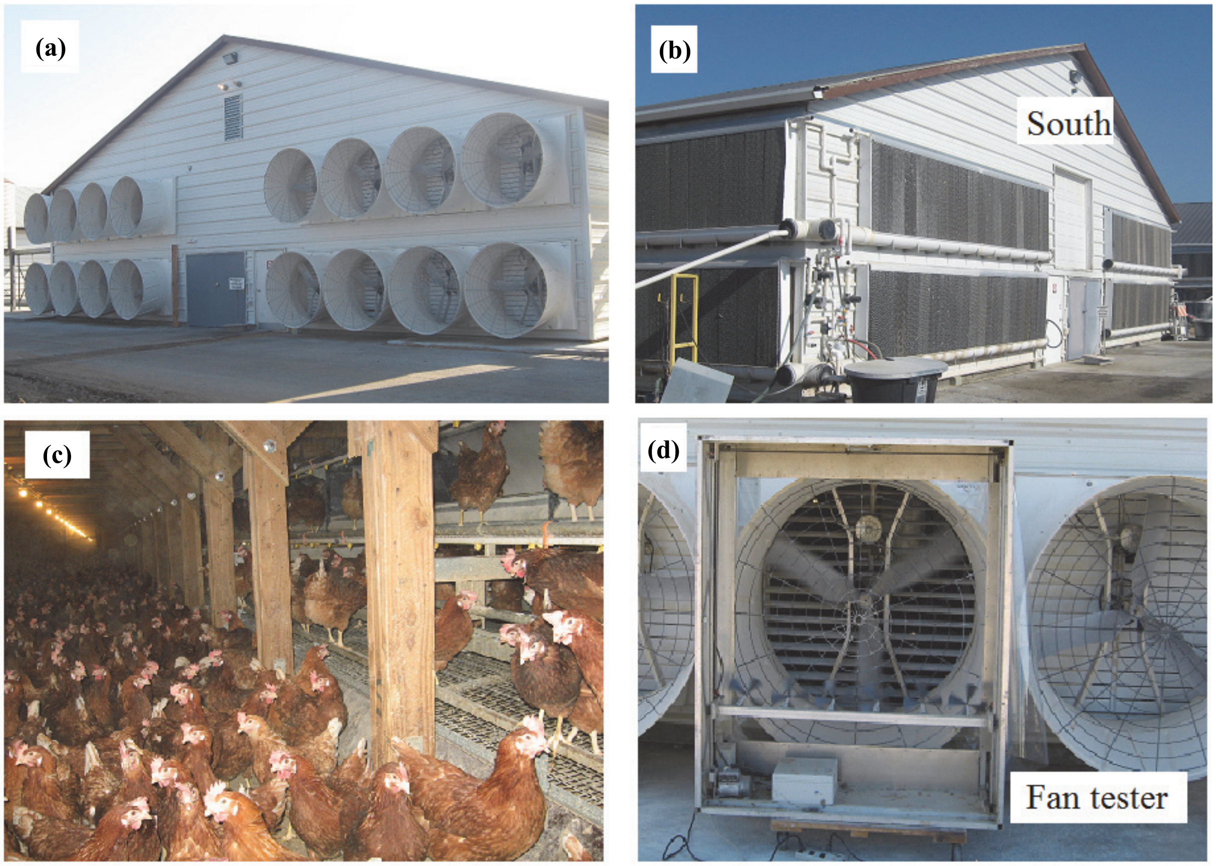

Figure 2. (a) Layer house north endwall with 16 tunnel fans, (b) south endwall and west sidewall with cooling pads, (c) inside of layer house, and (d) fan tester being used to test the airflow rate of a tunnel fan.

The inside temperature of the layer houses was maintained between 22.2°C and 25.6°C. Each house had eight 91 cm (36 in.) single-speed sidewall fans (AT36Z1, Aerotech, Mason, Mich.) installed on the sidewalls of the first floor, sixteen 130 cm (51 in.) single-speed tunnel fans (VX511F1CR, Aerotech, Mason, Mich.) installed on the north endwall in two rows (fig. 1 and fig. 2a), and eight evaporative cooling pads (fig. 2b) installed on the south endwall and the two sidewalls. The evaporative cooling pads were used in conjunction with the tunnel fans to provide the cooling air needed during warm weather. Ventilation air entered the second floor through 66 sidewall inlets (33 inlets on each side, each 122 cm L × 18 cm H) with a total area of 14.49 m^2. The tunnel fan air inlets were comprised of four sidewall inlets (12.01 m L × 1.17 m H) and four south endwall inlets (5.51 m L × 1.14 m H) with a total area of 81.35 m^2. There were four sidewall cooling pads (12.04 m L × 1.22 m H × 0.15 m D) and four south endwall cooling pads (6.02 m L × 1.22 m H × 0.15 m D) (fig. 2b) with a total volume of 13.42 m^3. The air inlets were controlled by the DSP measured near the north endwall.

The 24 fans were operated in 12 stages (table 1) and three ventilation modes (VM1, VM2, and VM3). In VM1, the sidewall fans were operated to maintain the air quality and temperature at a set point of 23.9°C. In stage 1, sidewall fans 1, 3, 5, and 7 were operated. In stage 2, when the house temperature increased, sidewall fans 2, 4, 6, and 8 were added. In VM2, when the house temperature reached 1.1°C higher

Table 1. Ventilation stages, modes, inside temperature set points, inlet, and cooling pad operation for both houses.

Ventilation Mode and Stage[a]	Temperature (°C)	Total Fans	Added Fans	Open Inlets	Cooling Pad	Timer
VM1S1	24.4	4	Sidewall fans 1, 5, 3, 7	Sidewall	-	-
VM1S2	25	8	Sidewall fans 2, 6, 4, 8	Sidewall	-	-
VM2S3	25.6	2	Tunnel fans 10, 15	Tunnel	-	Used
VM2S4	26.1	4	Tunnel fans 11, 14	Tunnel	-	-
VM2S5	26.7	6	Tunnel fans 4, 5	Tunnel	-	-
VM2S6	27.2	8	Tunnel fans 1, 8	Tunnel	-	-
VM2S7	27.8	12	Tunnel fans 3, 6, 9, 16	Tunnel	-	-
VM2S8	28.9	16	Tunnel fans 2, 7, 12, 13	Tunnel	-	-
VM3S9	>28.9	18	Sidewall fans 1, 5	Tunnel	Water on[b]	-
VM3S10	>28.9	20	Sidewall fans 2, 6	Tunnel	Water on	-
VM3S11	>28.9	22	Sidewall fans 3, 7	Tunnel	Water on	-
VM3S12	>28.9	24	Sidewall fans 4, 8	Tunnel	Water on	-

[a] For example, VM1S1 stands for ventilation mode 1 and stage 1.
[b] Water supply to cooling pad is turned on when the temperature is greater than the set point.

than the set point, the sidewall inlets were closed, the sidewall fans were turned off, the tunnel inlets at the south endwalls and sidewalls were opened, and tunnel fans 10 and 15 in the north endwall were turned on. A timer was used to operate tunnel fans 10 and 15 for 1 min every 6 min. As the house temperature increased, the tunnel fans were operated in stages 3 through 8. VM3 was applied when the house temperature continued to increase. In VM3, the sidewall fans were turned on again by four thermostats in the house, and the cooling pads were watered. VM3 was applied until the inside temperature was reduced below the set point.

MONITORING METHOD

An on-farm instrument shelter (OFIS) was located between H1 and H2 (fig. 1). Temperatures at one gas sampling probe of nine sampling lines were measured with a thermocouple (type T, TE Wire and Cable, Saddle Brook, N.J.) and relative humidity and temperature (RHT) probe sensors (RHT-WM, Novus, Sao Paulo, Brazil). Thermocouples were installed at sidewall fan 7 and tunnel fans 5 and 10 in both houses to measure exhaust air temperatures. Three RHT sensors were installed on a weather tower on the roof of the OFIS and at sidewall fan 1 in both houses to monitor the temperature and relative humidity of the ambient air and in the two houses. Two more RHT sensors were installed in the houses close to the evaporative cooling pads to monitor the temperature and relative humidity of the air coming from the pads. Furthermore, four thermocouples, two in each house, were used to monitor the inside temperatures of the houses in the first and second floors. The locations of the sensors are shown in figure 1.

DSP in both houses was measured with four static pressure sensors (model 2301002PD2F11B, Setra, Boxborough, Mass.) that were installed across the east sidewall and north endwall of both houses (fig. 1). All four static pressure sensors were installed inside the OFIS to prevent zero shift by maintaining a stable temperature around them. Each sensor was composed of two tubes, one inside the house and the other outside the house, at the specified locations. The DSP measured at the sidewall close to fan 1 was used to calculate the sidewall fan airflow rate. The DSP measured at the north endwall was used to calculate the tunnel fan airflow rate.

Each pair of sidewall fans (fans 1 and 5, fans 2 and 6, fans 3 and 7, and fans 4 and 8) was controlled by a relay. Each of the 16 tunnel fans was controlled by a relay. Therefore, the 24 fans in each house were controlled by 20 relays, for total of 40 relays in the two houses. The relays were monitored by 40 current sensors to determine the on/off times of the fans. The evaporative cooling pads on the first and second floors were controlled by four relays, and a total of eight current sensors were used to monitor the on/off times of the evaporative cooling pads.

A portable fan tester (FANS) was used to test the sidewall and tunnel fans and measure actual fan airflow rates. During the tests, the house DSP was also measured. The measured fan airflow rates were correlated with the DSP. Two airflow rate curves in the form of equation 1 were generated for the sidewall and tunnel fans and used to calculate the fan airflow rates:

$$Q = f\left(\Delta p\right) \tag{1}$$

where

Q = fan airflow rate (m^3 s^{-1})

Δp = differential static pressure (DSP) (Pa).

The actual airflow rate of an installed fan is commonly lower than that of a new fan (Lin et al., 2012). Therefore, the fans that were operated in the two houses were evaluated by the fan performance coefficient (k, dimensionless) as follows:

$$k = \frac{Q}{Q_N} \tag{2}$$

where Q_N is the airflow rate of a new fan as certified by the manufacturer or by the Bioenvironmental and Structural Systems (BESS) Laboratory at the University of Illinois.

Table 2 lists the airflow rates of new sidewall fans (91 cm diameter) and new tunnel fans (130 cm diameter) at different DSP values. Using the data in table 2, regression equations 3 and 4 were derived for calculating the new sidewall fan airflow rate (Q_{NS}, m^3 s^{-1}) and the new tunnel fan airflow rate (Q_{NT}, m^3 s^{-1}) using house DSP (Δp, Pa):

$$Q_{NS} = 5.90 - 0.01446\Delta p - 0.0004863\Delta p^2 \quad (R^2 = 1.0,\ p < 0.01,\ n = 7) \tag{3}$$

$$Q_{NT} = 13.27 - 0.001794\Delta p^2 \quad (R^2 = 0.98,\ p < 0.01,\ n = 7) \tag{4}$$

Equation 1 determines the airflow rates at actual conditions, which can be converted into standard temperature, pressure, and dry (STPD) airflow rates. STPD is defined at 20°C, standard atmosphere pressure (1 atm), and zero relative humidity. The conversion of actual Q to Q at STPD was calculated as follows:

$$Q_{DS} = Q\left(1 - \frac{Q_W}{Q}\right)\left(\frac{293.15p}{273.15 + T}\right) \tag{5}$$

where

Q_{DS} = STPD airflow rate of a fan (m^3 s^{-1})

p = fan outlet air pressure (atm)

T = outlet air temperature (°C)

Q_W = water vapor flow rate (m^3 s^{-1}) of the fan.

Chen et al. (2014) used the humidity ratio to calculate the ratio of water vapor flow rate to the moist airflow rate (Q_w/Q), and this method was widely used as a standard operation procedure for calculating and reporting air emissions

Table 2. Airflow rates of new fans with diameters of 91 and 130 cm (BESS, 1996a, 1996b).

Differential Static Pressure (Pa)	Fan Airflow Rate (m^3 s^{-1}) New Sidewall Fan (91 cm diameter)	New Tunnel Fan (130 cm diameter)
0	5.96	13.64
12.4	5.6	12.79
24.9	5.15	11.75
37.3	4.7	10.52
49.8	4.03	9.06
62.2	3.19	7.17
74.7	2.04	2.69

from barns (Lim and Bogan, 2006). The humidity ratio of a given moist air sample is defined as the ratio of the mass of water vapor to the mass of dry air contained in the sample (Wessel, 2001). Therefore, the humidity ratio cannot be used to calculate the ratio of water vapor flow rate to the moist airflow rate. According to the ideal gas law and Wessel (2001), the ratio of Q_W/Q is equal to the ratio of the partial pressure of water vapor (p_W) to the total mixture pressure (p), as expressed by equation 6:

$$\frac{Q_W}{Q} = \frac{p_w}{p} \tag{6}$$

where p_W is the partial pressure of water vapor (Pa).

Because p_W is equal to relative humidity (RH) times the saturation partial pressure of water vapor (Wessel, 2001), the dry airflow rate can be calculated using equation 7:

$$Q_{DS} = Q\left(1 - \frac{\mathrm{RH}p_{ws}}{P}\right)\left(\frac{293.15p}{273.15+T}\right) \tag{7}$$

where

RH = relative humidity (dimensionless and decimal)

p_{WS} = saturation partial pressure of water vapor (Pa).

The p_{ws} for the temperature range of 0°C to 200°C is given by equation 8 (Wessel, 2001):

$$p_{ws} = e^{\left(\frac{C_1}{T}+C_2+C_3T+C_4T^2+C_5T^3+C_6\ln T\right)} \tag{8}$$

where

p_{ws} = saturation partial water vapor pressure (Pa)

T = temperature (K)

C_1 = -5.800 E+3

C_2= 1.391

C_3 = -4.864 E-2

C_4 = 4.176 E-5

C_5 = -1.445 E-8

C_6 = 6.546.

The ventilation rate of a house is the sum of the airflow rates from all operating sidewall and tunnel fans, as expressed in equation 9:

$$VR_H = F_S Q_S + F_T Q_T \tag{9}$$

where

VR_H = ventilation rate of layer house (m^3 s^{-1})

F_S and F_T = numbers of operating sidewall and tunnel fans, respectively

Q_S and Q_T = sidewall and tunnel fan airflow rates (m^3 s^{-1}), respectively.

The hen-specific ventilation rate (m^3 h^{-1} hen^{-1}) was calculated by dividing the ventilation rate (m^3 h^{-1}) by the number of laying hens in the house.

Uncertainty of Ventilation Rate

Assuming that the airflow rates of individual fans in each house are independent variables, the uncertainty of the VR is composed of the errors from the 24 fans. The standard uncertainty of VR for each house was calculated as follows (Formasini, 2008), and the relative uncertainty was then expressed as $\sigma_{VR}/VR \times 100$:

$$\sigma_{VR} = \sqrt{\sum_{i=1}^{F} \sigma_i^2} \tag{10}$$

where

σ_{VR} = standard uncertainty of house VR (m^3 s^{-1} house^{-1})

F = number of operating fans

σ_i = standard error of the airflow rate of ith fan (m^3 s^{-1}) that was calculated using equations 12 or 13 and measured fan airflow rates (Lin et al., 2012).

The estimated standard error of a single fan airflow rate was the difference between the *in situ* measured airflow for a particular fan and the calculated value from a fan model for all fans of the same diameter. The 91 cm and 130 cm fans were tested 42 and 34 times, respectively. The standard error for each fan model (91 cm and 130 cm diameters) is expressed by equation 11:

$$\sigma = \sqrt{\frac{\sum_{j=1}^{Nt}\left(Q_j - Q_{Mj}\right)^2}{N_t - 1}} \tag{11}$$

where

σ = standard error of fan airflow rate (m^3 s^{-1})

N_t = total number of fan tests

Q_{Mj} = airflow rate measured in the jth fan test (m^3 s^{-1})

Q_j = airflow rate estimated by equation 12 for sidewall fan or by equation 13 for tunnel fan for the jth fan test (m^3 s^{-1}).

The standard errors were calculated for the 130 cm fans (tunnel fans 1 to 16) and the 91 cm fans (sidewall fans 1 to 8) using the test data from both houses and over all fan test events.

Results and Discussion

Fan Airflow Rates

The airflow rates were measured using the fan tester for nine of the sixteen 91 cm fans in both houses. Airflow rates were measured 42 times on 11 and 13 September 2012. The sidewall DSP ranged from 13.7 to 52.4 Pa, and the corresponding fan airflow rates ranged from 2.83 to 4.65 m^3 s^{-1}. Fan airflow rate is expressed as a function of sidewall DSP as follows:

$$Q_s = 5.04 - 0.0345\Delta p_S \quad (R^2 = 0.59,\ p < 0.01,\ n = 41) \tag{12}$$

where

Q_s = airflow rate of sidewall fan (m^3 s^{-1})

Δp_S = DSP measured across sidewall (Pa).

Figure 3a shows measured airflow rates for new and in-operation 91 cm fans (eq. 3). The measured airflow rates of the in-operation fans were lower than those of new fans. The airflow rate decreased with an increase of DSP. The low measured airflow rates for the in-operation fans might be attributed to accumulated dirt on the fan blades, dirty shutters,

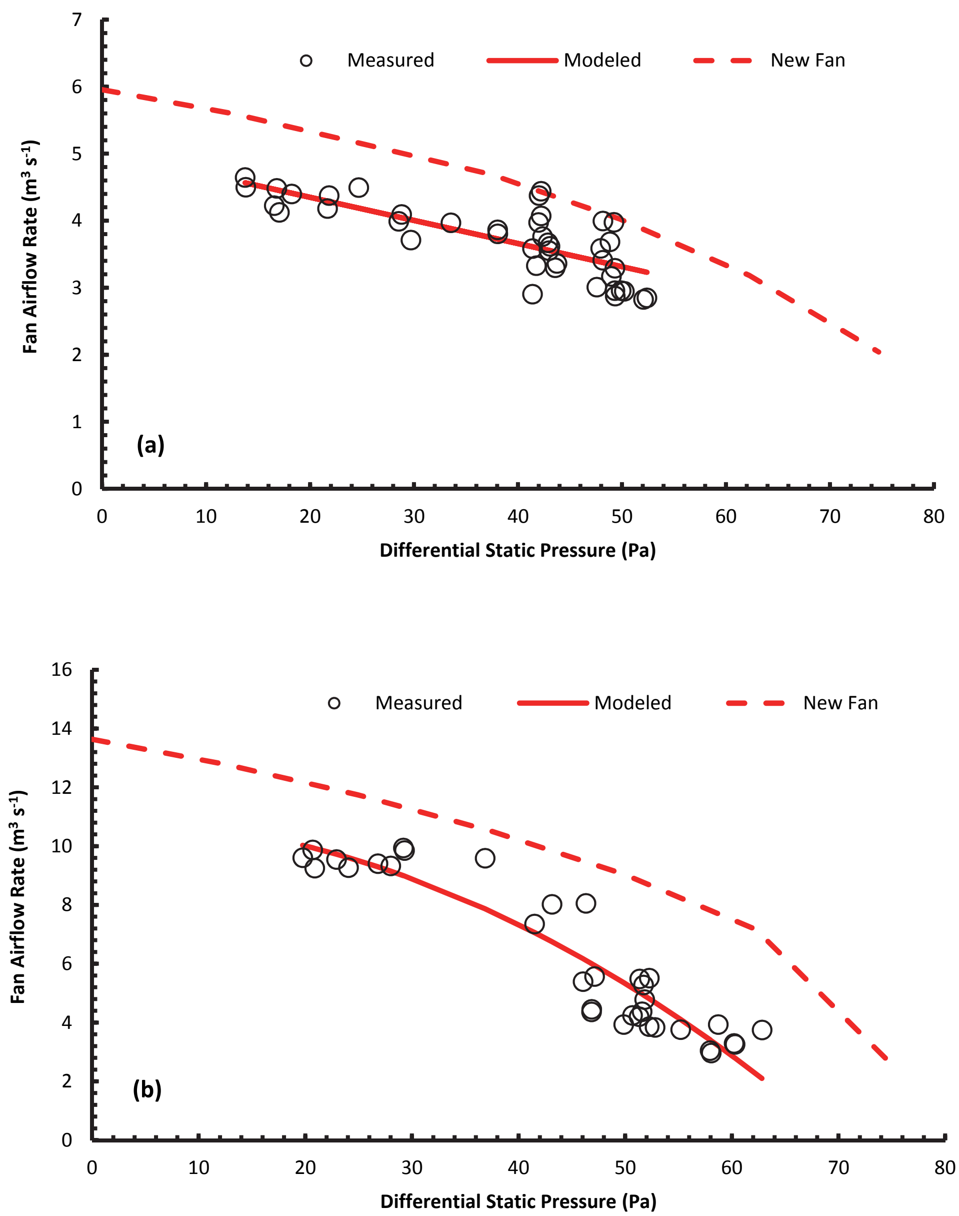

Figure 3. Airflow rates for fans with diameters of (a) 91 cm and (b) 130 cm.

and/or loose belts (Casey et al., 2008). The fan performance factor (k, eq. 2) ranged from 0.65 to 1.00 and averaged at 0.82, which was higher than that (0.75) reported by Lin et al. (2012). The standard error (eq. 11) between modeled and measured airflow rates was 0.35 $m^3 s^{-1}$, which represented 9.3% of the measured average airflow rate.

The airflow rates for nine 130 cm fans were measured with the fan tester 34 times on 11 September 2012 (fig 2d). The measured endwall DSP ranged from 19.7 to 62.8 Pa and averaged 44.5 Pa. The measured airflow rate is expressed as a function of the endwall DSP as follows:

$$Q_T = 10.9 - 0.00223\Delta p_T^2 \quad (R^2 = 0.87, p < 0.01, n = 34) \tag{13}$$

where

Q_T = airflow rate of tunnel fan ($m^3 s^{-1}$)

Δp_T = DSP measured across north endwall (Pa).

Figure 3b shows airflow rates for new and in-operation 130 cm fans. The measured airflow rates ranged from 2.97 to 9.94 $m^3 s^{-1}$ and averaged at 6.13 $m^3 s^{-1}$. The fan performance factor (k) ranged from 0.41 to 0.89 and averaged at 0.63. The lower values of k may be due to the fact that the tunnel fans were working at high pressures (50 to 60 Pa) compared to the sidewall fans, which were working at low pressures (<30 Pa). The standard error between the modeled and measured airflow rates was 0.91 $m^3 s^{-1}$, which represented 14.8% of the average measured airflow rate. The high DSP for the tunnel fans means that the tunnel inlet opening area is too small for the number of fans. The farm should enlarge the tunnel inlet opening.

House Ventilation Rates

Monthly mean ventilation rates, as calculated using equation 9, for both houses are shown in figure 4. As can be seen, the ventilation rates increased during warm months (April to October) as compared with cool months (November to March).

Figure 5 shows the daily mean VR as a function of daily mean inlet air temperature. The VR increased with an increase in inlet temperature, and the maximum VR was achieved at 31°C because all 24 fans were operating at their maximum capacity. The following regression was derived to calculate the daily mean VR as a function of inlet temperature (in the range of 3°C to 31°C):

$$VR = 2.87 - 0.0569T_a + 0.00740T_a^2 \quad (R^2 = 0.98,\ p < 0.001,\ n = 29) \tag{14}$$

where

VR = daily mean hen-specific ventilation rate (m^3 h^{-1} hen^{-1})

T_a = daily mean temperature of inlet air (°C).

The VR in both houses ranged from 15 to 82 m^3 s^{-1} and averaged 39 and 45 m^3 s^{-1} at STPD for H1 and H2, respectively (table 3). The minimum hourly mean VR at STPD was 15.2 m^3 s^{-1} or 1.91 m^3 h^{-1} hen^{-1}, which corresponded to the airflow rate delivered by four 91 cm fans (table 3). The maximum hourly VR at STPD was 82.3 m^3 s^{-1} or 8.72 m^3 h^{-1} hen^{-1}. According to Lohmann (2011), the recommended minimum ventilation rates for 1.73 kg laying hens are 2.6 and 10.4 m^3 h^{-1} hen^{-1} in cold and hot weather, respectively. The overall specific average VR in both houses was 4.46 m^3 h^{-1} hen^{-1}, which was 1.3 times higher than that (1.9 m^3 h^{-1} hen^{-1}, varied from 0.3 to 7.5 m^3 h^{-1} hen^{-1}) reported by Zhao et al. (2015) for aviary houses. The higher overall specific average VR in the current study was attributed to the higher daily mean inlet temperature (17.4°C) than that (8.9°C) reported by Zhao et al. (2015). The measured specific VR in this study was lower than that (5.02 m^3 h^{-1} hen^{-1}) of high-rise layer houses, which was measured on the same farm before switching to cage-free housing (Lin et al., 2012). This was attributed to the lower bird density in the cage-free housing, which allows easier heat removal than high-rise houses. The living area for each bird was 1161 and 729 cm^2 in cage-free and high-rise houses, respectively. However, Zhao et al. (2015) did not find a difference in ventilation rates between conventional belt manure house and aviary houses.

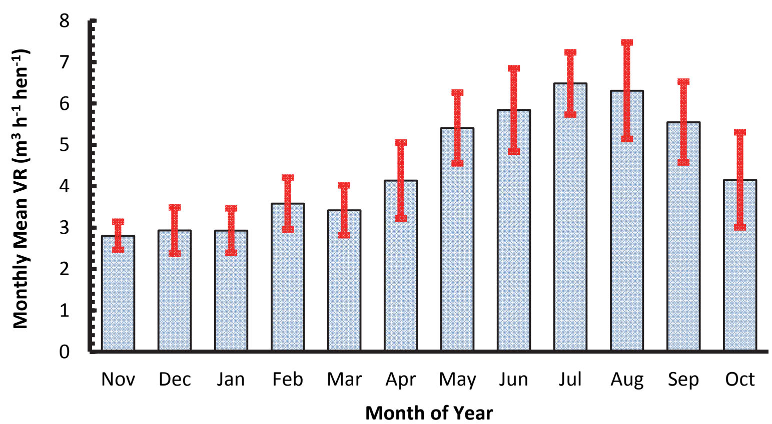

Figure 4. Monthly mean ventilation rates with standard deviations measured in houses 1 and 2 in 14 months. Y error bars are standard deviations.

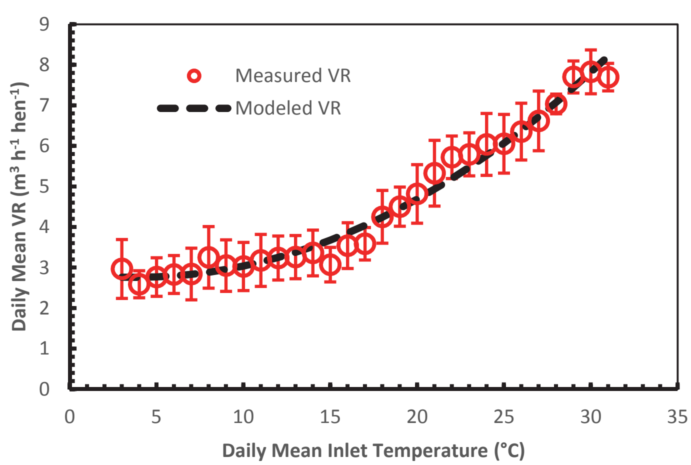

Figure 5. Relationship between daily mean ventilation rate and inlet temperature for houses 1 and 2. Y error bars are standard deviations.

Table 3. Daily mean statistics of house inventories, environmental variables, and ventilation rates with complete data days (CDD).

Variable	Overall					House 1					House 2				
	Mean	SD	Min	Max	CDD	Mean	SD	Min	Max	CDD	Mean	SD	Min	Max	CDD
Laying hens															
Number of hens	33,894	2661	28,490	38,139	835	34,295	2451	30,576	38,139	416	33,496	2800	28,490	37,820	419
Mean hen mass (kg)	1.7	0.1	1.3	1.9	835	1.8	0.1	1.3	1.9	416	1.7	0.1	1.3	1.9	419
Temperature (°C)															
Inlet air	17.4	6.4	3.3	30.6	381	-	-	-	-	-	-	-	-	-	-
Layer room	22.2	3.7	11.3	30.7	835	22.3	3.6	11.5	30.7	418	22.1	3.9	11.3	27.4	417
Exhaust air	20.3	4.7	8.3	28.6	836	20	4.5	8.8	28.6	418	20.5	4.8	8.3	28.1	418
Relative humidity (%)															
Inlet air	60	13	37	88	381	-	-	-	-	-	-	-	-	-	-
Layer room	62	10	36	85	764	61	9	36	84	418	62	11	36	85	346
Exhaust air	55	9	30	76	836	52	9	30	66	418	58	8	39	76	418
Humidity ratio (g kg^{-1})															
Inlet air	7.4	2.0	2.7	13.3	381	-	-	-	-	-	-	-	-	-	-
Layer room	8.7	2.3	3.9	15.1	764	9.1	2.3	4.3	15.1	418	8.2	2.2	3.9	13.6	346
Exhaust air	9.2	2.5	4.5	16.0	836	8.4	2.4	4.6	15.3	418	10.1	2.2	4.5	16.0	418
DSP (Pa)	24.8	6.7	6.2	45.9	793	24.8	6.5	13.6	45.9	395	24.9	7.0	6.2	45.9	398
Ventilation rate															
As found (m^3 s^{-1} house^{-1})	43.7	16.0	15.3	87.7	787	40.0	12.7	20.9	68.9	391	47.3	18.0	15.3	87.7	396
STPD (m^3 s^{-1} house^{-1})	41.9	14.6	15.2	81.7	787	38.6	11.6	20.7	64.1	391	45.2	16.4	15.2	81.7	396
STPD (m^3 h^{-1} hen^{-1})	4.46	1.52	1.91	8.65	787	4.11	1.34	2.04	7.46	391	4.80	1.60	1.91	8.65	396

Layer House Temperature and Ventilation Stages

The target temperatures of the layer houses could be achieved by operating eight sidewall fans and 16 tunnel fans in 12 stages at various inlet air temperatures. To evaluate the layer house temperatures associated with the ventilation stages, the continuously monitored data were classified into 12 ventilation stages. It was found that 43,865 of the observations, or 63.3% of the total, exactly followed the 12 ventilation stages. Table 4 shows the distribution of ventilation observations across the 12 stages. For example, at stage 1, there were 33,905 observations, which represented 77% of the total number of observations. For each ventilation stage, the layer house temperature increased with the increase in inlet air temperature. For example, in stage 1 with four operating sidewall fans, the layer house temperature increased from 12.8°C to 24.4°C as the inlet air temperature increased from 1°C to 23°C. When the inlet air temperature was 15°C, the layer house temperature was 21.7°C, and the observations were 19% of the subtotal of 33,905 observations at this stage. Table 4 also shows that the layer house temperature ranged from 8.9°C to 30°C and averaged 24.8°C.

Figure 6 shows the ventilation system capacity required to maintain the layer house temperature below 30°C as the inlet air temperature increased from 1°C to 39°C. The ventilation system was able to maintain the house temperature below 30°C despite the hot inlet temperature of 39°C because the evaporative cooling pads effectively reduced the incoming air temperature. Table 4 shows that the ventilation system operated mostly in stages 1 and 2, which represented 77% and 12%, respectively, of the total operating time. The other ten stages accounted for 11% of the total operating time. However, based on the total 69,328 sets of 15 min average data, the sidewall fans operated for 65% of the total time, and the tunnel fans operated for 20% of the total time when layers occupied the houses.

Equation 15 correlates the layer house temperature with the inlet air temperature and the number of operating fans using a total of 69,328 sets of 15 min average data and reflects the fact that layer room temperature increased with the increase in inlet air temperature and decreased with the number of operating fans:

$$T_h = 14.42 + 0.537T_a - 0.185F \quad (R^2 = 0.79,\ p < 0.001,\ n = 69328) \tag{15}$$

where =

T_h = layer house 15 min average temperature (°C)

T_a = 15 min average of inlet air temperature (°C)

F = number of operating fans including sidewall and tunnel fans.

Based on equation 15, three additional fans must be operated to maintain the layer room at a constant temperature when the inlet air temperature increases by 1°C. Similarly, the layer room temperature can be expressed by the hen-specific ventilation rate and inlet temperature, as shown by equation 16:

$$T_h = 14.49 + 0.608T_a - 0.654\text{VR} \quad (R^2 = 0.80,\ p < 0.001,\ n = 69328) \tag{16}$$

where VR is the hen-specific ventilation rate (m^3 h^{-1} hen^{-1}) at dry standard condition.

Ventilation Stage and Differential Static Pressure

The average daily DSP measured across the sidewalls and endwalls was 24.8 Pa. The 15 min mean DSP reached a maximum of 64 Pa at ventilation stage 12. Table 5 shows the measured 15 min mean sidewall and endwall DSP in the 12 ventilation stages. In ventilation mode 1, the sidewall DSP was 17.2 Pa at stage 1 with four sidewall fans operating and increased to 19.6 Pa at stage 2 with eight sidewall fans operating (table 5). In ventilation mode 2, the endwall DSP was 13.5 Pa at stage 3 with only two operating tunnel fans and increased to 50.8 Pa at stage 8 with 16 operating tunnel fans. In mode 3, the sidewall DSP was 40.6 Pa at stage 9 with two sidewall fans and 16 tunnel fans and reached 50.3 Pa at stage 12 with all 24 fans operating. The endwall DSP was 49.0 Pa at stage 9 and increased to 56.9 Pa at stage 12. After corre-

Table 4. Average layer room temperature (°C) and percentage of time at each ventilation stage.

	Ventilation Mode and Stage[a]											
	VM1S1	VM1S2	VM2S3	VM2S4	VM2S5	VM2S6	VM2S7	VM2S8	VM3S9	VM3S10	VM3S11	VM3S12
Number of operating fans[b]	4 SF	8 SF	2 TF	4 TF	6 TF	8 TF	12 TF	16 TF	16 TF + 2 SF	16 TF + 4 SF	16 TF + 6 SF	16 TF + 8 SF
Number of observations[c]	33,905	5321	51	119	258	752	837	1528	161	464	99	370
Fraction of total observations[d]	77%	12%	0.1%	0.3%	0.6%	1.7%	1.9%	3.5%	0.4%	1.1%	0.2%	0.8%
Inlet air temperature[e]												
1°C	12.8 (1)	-	-	-	-	-	-	-	-	-	-	-
3°C	13.8 (3)	8.9 (2)	-	-	-	-	-	-	-	-	-	-
5°C	15.2 (5)	10.8 (6)	-	-	-	-	-	-	-	-	-	-
7°C	17.1 (8)	12.4 (10)	-	-	-	-	-	-	-	-	-	-
9°C	18.2 (11)	14.0 (10)	-	-	-	-	-	-	-	-	-	-
11°C	19.2 (15)	15.4 (9)	-	-	-	-	-	-	-	-	-	-
13°C	20.4 (17)	16.5 (7)	16.7 (6)	-	-	-	-	-	-	-	-	-
15°C	21.7 (19)	17.7 (7)	23.0 (4)	-	-	-	-	-	-	17.7 (3)	-	-
17°C	22.5 (12)	19.6 (5)	25.1 (16)	24.0 (5)	-	-	-	-	-	18.9 (3)	-	-
19°C	23.0 (6)	22.3 (11)	25.9 (20)	23.6 (17)	-	-	21.2 (1)	-	-	20.7 (11)	-	-
21°C	23.8 (2)	23.9 (15)	22.0 (4)	24.6 (14)	24.1 (3)	-	22.4 (2)	-	-	22.3 (18)	23.7 (3)	-
23°C	24.4 (1)	25.1 (11)	26.0 (2)	25.5 (21)	25.4 (17)	25.6 (2)	22.9 (1)	23.3 (1)	-	23.2 (16)	24.4 (18)	25.0 (2)
25°C	-	26.1 (7)	26.8 (8)	26.0 (23)	26.2 (38)	26.1 (23)	25.4 (3)	24.9 (2)	-	23.9 (7)	25.3 (43)	26.2 (22)
27°C	-	26.8 (1)	28.4 (20)	28.3 (5)	27.1 (19)	26.9 (32)	27.4 (8)	26.5 (5)	26.5 (2)	24.1 (5)	25.8 (5)	27.2 (34)
29°C	-	-	27.9 (16)	28.3 (8)	26.9 (13)	27.0 (22)	28.1 (24)	28.1 (16)	28.4 (27)	27.6 (4)	27.7 (11)	28.0 (28)
31°C	-	-	29.0 (6)	29.0 (3)	27.1 (5)	26.9 (18)	27.6 (20)	27.9 (22)	28.9 (30)	29.1 (7)	29.0 (4)	28.8 (11)
33°C	-	-	-	28.7 (3)	28.0 (1)	27.2 (2)	27.4 (23)	27.5 (24)	28.6 (17)	28.4 (5)	30.0 (9)	29.8 (2)
35°C	-	-	-	-	-	27.4 (1)	-	27.7 (17)	28.7 (7)	28.3 (9)	-	-
37°C	-	-	-	-	-	-	-	28.2 (10)	28.6 (14)	28.4 (9)	-	-
39°C	-	-	-	-	-	-	-	29.1 (3)	28.0 (3)	29.5 (3)	-	-

[a] For example, VM1S1 stands for ventilation mode 1 and stage 1.
[b] SF and TF stand for sidewall fan and tunnel fan, respectively.
[c] Each observation represents a period of 15 min.
[d] Values are percentages of 43,875 total observations.
[e] Inlet air temperature is T_a ±1 (°C). For each inlet air temperature, the values for each stage are the average room temperature (and the percentage of the observations at this temperature in parentheses). Empty cells in each stage indicate no observations or less than 1% of the observations.

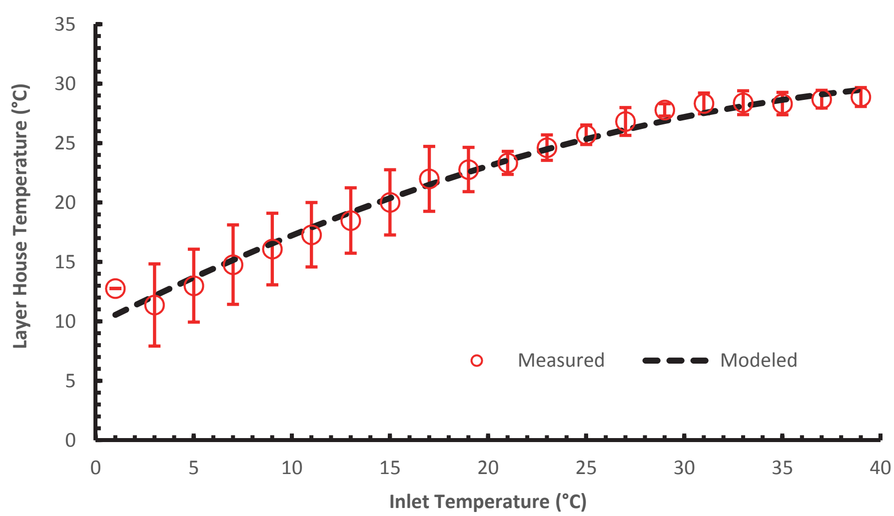

Figure 6. Measured layer house temperature and modeled temperature using 15 min data. Y error bars are standard deviations.

lating the 69,328 pairs of 15 min average sidewall and endwall DSP data with the number of operating fans, equation 17 was obtained:

$$\Delta p = 4.26 + 2.41F$$
$$(R^2 = 0.81,\ p < 0.001,\ n = 69328) \quad (17)$$

where

Δp = average of layer house sidewall DSP and endwall DSP (Pa)

F = number of operating fans.

Table 5. Single house VR uncertainty and relative uncertainty as influenced by ventilation stage.

Ventilation Mode and Stage[a]	Number of Operating Fans		Measured DSP (Pa)		Ventilation Rate (m^3 s^{-1} $house^{-1}$)			Standard Uncertainty (m^3 s^{-1} $house^{-1}$)	Relative Standard Uncertainty (%)
	Sidewall	Tunnel	Sidewall	Tunnel	Total	Sidewall Fans	Tunnel Fans		
VM1S1	4	0	17.2	18.3	17.8	17.8	0	0.70	3.9
VM1S2	8	0	19.6	22.0	34.9	34.9	0	0.99	2.8
VM2S3	0	2	9.4	13.5	21.0	0	21.0	1.29	6.1
VM2S4	0	4	13.7	19.6	40.2	0	40.2	1.82	4.5
VM2S5	0	6	19.2	24.1	57.6	0	57.6	2.23	3.9
VM2S6	0	8	25.3	30.9	70.1	0	70.1	2.57	3.7
VM2S7	0	12	35.2	42.9	81.5	0	81.5	3.15	3.9
VM2S8	0	16	41.3	50.8	82.4	0	82.4	3.64	4.4
VM3S9	2	16	40.6	49.0	96.2	7.3	88.9	3.67	3.8
VM3S10	4	16	44.5	52.1	91.6	14.0	77.5	3.71	4.0
VM3S11	6	16	48.1	55.6	84.5	20.3	64.2	3.74	4.4
VM3S12	8	16	50.3	56.9	85.3	26.4	58.9	3.77	4.4

[a] For example, VM1S1 stands for ventilation mode 1 and stage 1.

Ventilation Stage and House Ventilation Rates

Table 5 also shows the house ventilation rates calculated with equation 9 for stages 1 through 12. The house ventilation rates increased with stage number in ventilation modes 1 and 2. However, in mode 3, the total ventilation rate decreased from stage 9 to stage 12 because the ventilation rate of the tunnel fans sharply decreased with increased endwall DSP (table 5). This indicates that the tunnel ventilation inlets are too small and should be enlarged. In the current condition, stages 10, 11, and 12 should not be used because their ventilation rates did not increase with more operating fans.

Uncertainty of Ventilation Rates

The standard error of the airflow rate for the individual sidewall and tunnel fans was 0.35 and 0.91 m^3 s^{-1}, respectively. Table 5 shows the house VR, house VR standard uncertainty, and relative standard uncertainty for the 12 ventilation stages. The house VR ranged from 17.8 to 96.2 m^3 s^{-1} $house^{-1}$ for stages 1 through 12 (table 5), and the standard uncertainty increased from 0.70 to 3.77 m^3 s^{-1} $house^{-1}$, as calculated by equation 10. The relative standard uncertainty varied from 2.8% for stage 2 to 6.1% for stage 3. The relative standard uncertainty decreased from 3.9% for stage 1 to 2.9% for stage 2. In ventilation mode 2, the relative standard uncertainty decreased for the initial stages (stages 3 to 7) and slightly increased at stage 7 because the VR increased by 0.9 m^3 s^{-1} from stages 7 to 8 with the addition of four tunnel fans. In ventilation mode 3, the relative standard uncertainty increased from stages 9 to 12 due to the increased standard uncertainty, but the VR decreased. This decrease in relative standard uncertainty is not normal and is different from the findings of Lin et al. (2012), who reported that the relative standard uncertainty in a high-rise layer house decreased with more operating fans.

Evaporative Cooling System

Evaporative cooling pads are an effective practice in hot climates to decrease the layer house temperature. Figure 7 shows the inlet air temperature, layer house air temperature, and moist air temperature from the cooling pads for a typical day in California. Figure 7 also shows the effects of operating the cooling pads during two periods (from 12:15 to 13:30 and from 14:30 to 18:15 on 15 July 2012). The average inlet air temperature was 34.8°C. The measured air temperature from the cooling pad was 25°C, and the average layer room temperature was 27.3°C. This means that the cooling pads decreased the house temperature by 7.5°C as compared to the inlet air temperature. The measured ambient relative humidity was 32%. The cooling efficiency of the cooling pad system was calculated to be 76% (Ahmed et al., 2011).

Furthermore, the humidity ratio in the layer houses increased when the cooling pads were watered during the two periods (fig. 8). After ambient air passed through the evaporative cooling pads, the average humidity ratio of the air increased from 11.2 to 14.3 g kg^{-1}. The average humidity ratio continued to increase and reached 15.3 g kg^{-1} due to the water vapor produced by hen respiration and by evaporation from the manure.

Based on analysis of the 2685 sets of 15 min average data when the evaporative cooling pads were being watered, the temperatures at the inlet, after the cooling pads, and in the layer room were 33.7°C, 25.5°C, and 27.4°C, respectively, which demonstrates that the evaporative cooling pads decreased the inlet air temperature by 8.2°C and decreased the layer room temperature by 6.3°C. Similarly, the humidity ratio of the inlet air passing through cooling pads increased by 3.4 g kg^{-1} (from 10.9 to 14.3 g kg^{-1}) and reached 15.4 g kg^{-1} in the layer room. Because the average relative humidity was 33%, the minimum temperature that the cooling pads can reach (i.e., thermodynamic wet bulb temperature) was calculated to be 21.3°C. This means that the maximum temperature decrease was 12.4°C (from 33.7°C to 21.3°C). Therefore, the average cooling efficiency of the cooling pad system was 66%.

Conclusions

Fan airflow regression equations were developed based on fan test data for 91 cm and 130 cm fans. The fan performance factors were 82% and 63% for the 91 cm and 130 cm fans, respectively. For a cage-free layer house with 33,394 laying hens, the daily mean hen-specific ventilation rate (VR) ranged from 1.91 to 8.72 m^3 h^{-1} hen^{-1} and averaged 4.49 ±1.53 m^3 h^{-1} hen^{-1}. The relative standard uncertainties of daily mean VR ranged from 2.3% to 6.1% and averaged 3.7%. There was a positive correlation between layer room temperature, inlet

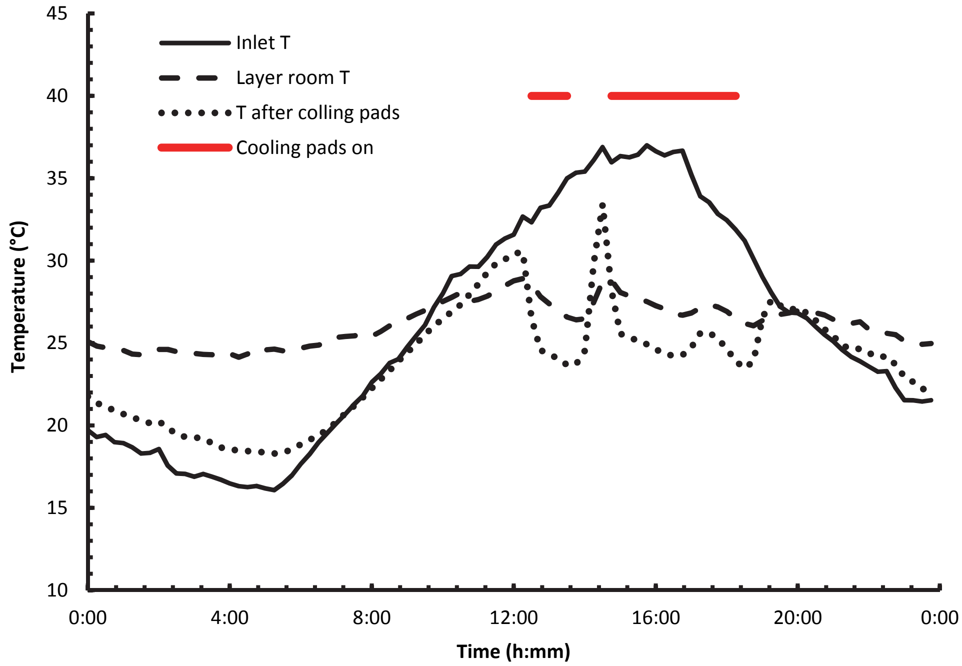

Figure 7. Effects of evaporative cooling pads on house temperature as measured in house 2 on 15 July 2012.

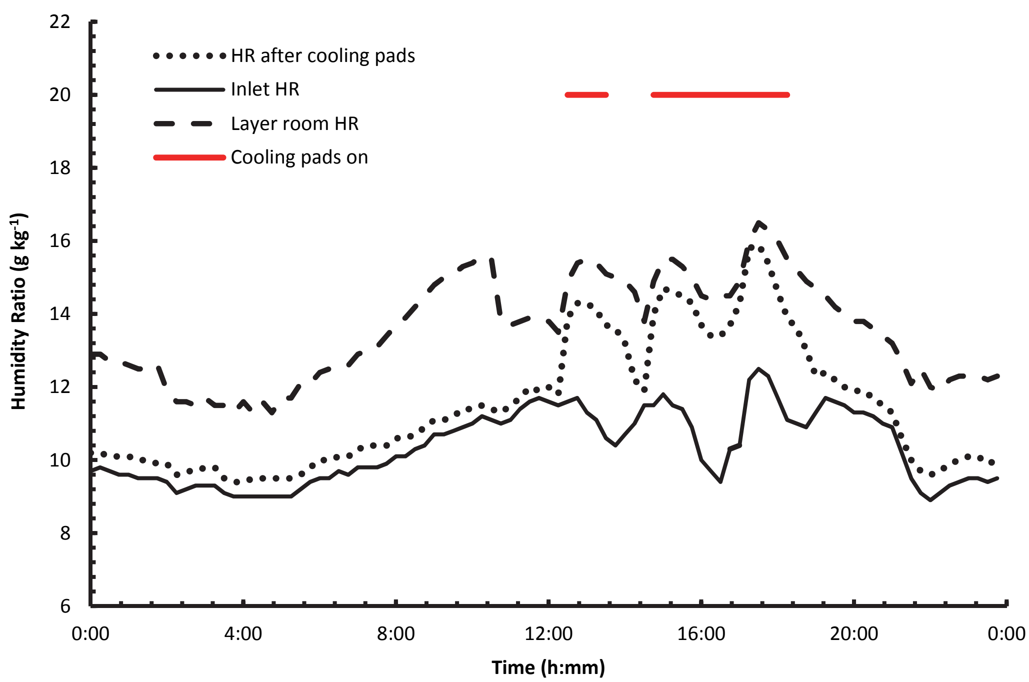

Figure 8. Effects of evaporative cooling pads on humidity ratio as measured in house 2 on 15 July 2012.

air temperature, and VR or number of operating fans. The daily average house DSP was 24.8 Pa and varied from 6.2 to 45.9 Pa. During summer when the inlet air temperature exceeded 30°C, the evaporative cooling system could decrease the inlet air temperature by 6.3°C and increase the house humidity ratio by 3.4 g kg^{-1}. The average cooling efficiency of the cooling pad system was 66%. The sidewall fans operated 65% of the total time when layers occupied the houses, and the tunnel fans operated 20% of the total time.

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