7-29-2019

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Abstract

The environment inside laying hen houses has an important effect on hen productivity, health, and well-being. Heat exchangers (HEs) can recover waste heat in ventilation exhaust to reduce supplemental heating needs while maintaining a greater fresh air exchange rate. For laying hen houses, there is limited information on the effect of heat recovery ventilation (HRV). Thus, the objective was to evaluate an air-to-air HE for manure belt drying ventilation in aviary laying hen housing. Temperature (T), relative humidity, ammonia, and manure dry matter (DM) content were characterized during a 4-wk period in October 2018. In weeks 2 and 4, the HRV was shut down and compared to weeks 1 and 3 when the HRV was operational. Average (±SD) ambient T was 10.6°C ± 4.0°C, similar for the 4-wk period. Heat exchanger efficiency was 75.07% ± 9.4% with the average supply temperature increased by 10.0°C ± 3.4°C and an average of 93.94 ± 31 kW heat recovered. Average indoor T (23.1°C ± 0.5°C) was warmer as a function ambient T and daily average T range was lower with HRV (1.8°C ± 0.7°C) compared to without HRV (22.2°C ± 1.2°C; 3.1°C ± 1.1°C). Seven days after manure removal, final average manure DM was 40.6% ± 3.1% (without HRV) and 60.0% ± 3.3% (with HRV). Implementation of HRV positively influenced indoor thermal environment by maintaining less dynamic diurnal fluctuations and greater temporal T uniformity.

Keywords

heat exchanger, indoor environment, poultry, cage-free, manure dry matter

Disciplines

Agriculture | Bioresource and Agricultural Engineering | Poultry or Avian Science

Comments

This is a pre-copyedited, author-produced version of an article accepted for publication in *The Journal of Applied Poultry Research* following peer review. The version of record--Goselink, Y. S. M., and B. C. Ramirez. "Characterization of an Air-to-Air Heat Exchanger for Manure Belt Drying Ventilation in an Aviary Laying Hen House." *The Journal of Applied Poultry Research* (2019): pfz075--is available online at DOI: 10.3382/japr/pfz075. Posted with permission.

Characterization of an air-to-air heat exchanger for manure belt drying ventilation in an aviary laying hen house

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Primary audience: flock supervisors, researchers, engineers, producers, equipment

SUMMARY

The environment inside laying hen houses has an important effect on hen productivity, health, and well-being. Heat exchangers (**HE**s) can recover waste heat in ventilation exhaust to reduce supplemental heating needs while maintaining a greater fresh air exchange rate. For laying hen houses, there is limited information on the effect of heat recovery ventilation (**HRV**) on indoor environment and management considerations. Thus, the objective of this study was to evaluate an air-to-air HE for manure belt drying ventilation in aviary laying hen housing. Temperature (**T**), relative humidity, ammonia, and manure dry matter (**DM**) content were characterized during a 4-week period in October 2018. In week 2 and 4, the HRV was shut down and compared to week 1 and 3 when the HRV was operational. Number of hens housed, laying percentage, number of floor and system eggs, and mortality were similar for both treatments. Average (±SD) ambient T was XX°C ±XX°, similar for the 4-week period. HE temperature-transfer efficiency was 75.07% ±9.4% with an average supply temperature increased by 10.0°C ±3.4°C and an average of 93.94 ±31 kW heat recovered. Average indoor T (23.1°C ±0.5°C) was warmer as a function ambient T and daily average T range was lower with HRV (1.8°C ±0.7°C) compared to without HRV (22.2°C ±1.2°C; 3.1°C ±1.1°C). Seven days after manure removal, final average manure DM was 40.6% ±3.1% (without HRV) and 60.0% ±3.3% (with HRV). Implementation of HRV positively influenced indoor thermal environment by maintaining less dynamic diurnal fluctuations and greater temporal T uniformity.

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Key words: heat exchanger, indoor environment, poultry, cage-free, manure dry matter

DESCRIPTION OF PROBLEM

Poultry house indoor environment has an important effect on the productivity, health, and welfare of laying hens [1, 2, 3]. The thermal environment (**TE**; air and surface temperatures, relative humidity, and airspeed) and air quality (**AQ**; particulate matter and gas concentrations) can be used to describe the indoor environment and have been associated with various productivity responses [4, 5]. Mechanical ventilation systems are often used to control the indoor TE and AQ by removing heat, moisture, and other gases generated by hens, equipment, manure, drinkers, etc. [2, 5, 6]. Generally, ventilation systems are designed to remove sensible heat in mild to hot weather and control moisture as well as other gases in cold weather [7]. Air temperature (**T**) is the main component of the TE that influences laying hen feed intake and feed conversion ratio [8, 9]. Laying hens increase feed intake in cold T to compensate for elevated heat loss [10, 11]. Air quality is mainly assessed by ammonia (**NH_3**), carbon dioxide (**CO_2**), and particulate matter (**PM**) concentrations [12, 13, 14]. Factors influencing NH_3 levels include ventilation rate, water vapor, hen density and activity, manure handling and removal times, and manure characteristics (pH, moisture, and surface area) [5, 9, 12, 15, 16]. When ventilation rate is reduced, indoor NH_3 and other gas concentrations increase [5, 15]. Elevated NH_3 levels can have a negative effect on the productivity, health, and well-being of the birds [9, 14, 17]. Also, wet and fresh manure emits greater NH_3 than dry manure; therefore, NH_3 emissions can be reduced by drying the manure [15, 18, 19]. The indoor environment must be managed correctly to promote high levels of laying hen productivity, health, and welfare.

Ventilation capacity is determined to limit the difference between ambient to indoor T (warm/hot weather) and maintain acceptable moisture and AQ levels (cold weather) [7,20]. For aviary style housing, colder climates commonly require supplemental heat to maintain both the T and AQ at the desired level. This can result in additional operational costs and CO_2 emissions

[6, 21]. Heat recovery ventilation (**HRV**) regains residual heat in the exhaust ventilation air and transfers it to the fresh air (tempering) supplied to the house [22, 23, 24]. This may be a sustainable, alternative solution to maintain a high level of AQ, while concurrently maintaining the desired room T [6]; however, implementation has been challenging in poultry houses due to elevated dust levels in exhaust air that reduces ventilation capacity by obstructing airflow in the heat exchanger (**HE**) and degrades efficiency by accumulating on the HE fins. New materials and HE designs have promoted implementation in poultry houses; thus, creating opportunities to explore impact on indoor TE and AQ as well as management practices.

HRV systems for broiler houses are better studied compared to laying hen houses, with results showing reduced energy consumption and operating costs [6,22,25]. Further, HRV was found to improve broiler weight gain, feed conversion ratio, and was generally perceived to improve the indoor environment by surveyed producers [6, 26]. If no supplemental heating or HRV is present, lower indoor T could increase feed intake and reduce feed efficiency, as previously noted. The addition of HRV could lead to reduced heating fuel usage, if supplemental heating is present or a greater minimum ventilation rate with the same heating fuel usage Similarly, the environment in laying hen houses could be also improved because the tempered air is distributed evenly across the manure-belts throughout the house; hence, a more uniform temperature distribution. Additionally, this contributes to drying the manure and subsequently reducing manure NH_3 emissions [15, 18, 19]. These numerous impacts of HRV are often found with greater magnitude during cold ambient T.

Application and management strategies associated with HRV for manure belt drying ventilation in cage-free (aviary) laying hen houses are generally unknown. The objective of this study is to evaluate an air-to-air HE for manure belt drying ventilation in aviary laying hen housing.

MATERIALS AND METHODS

Housing and Management

This field study was performed in an aviary laying hen house with outdoor access located near Hamilton, Washington, USA (48.526, -121.988). The house contained 39,187 laying hens (78 weeks of age) at the start of the experiment. Hens were housed in four rows of an aviary system [26] that featured two vertical tiers and opposing nestboxes between tiers. Hens were fed a standard diet, supplemented with oyster shells in the floor area. Light period began at 04:30 and transitioned to the dark period with dimming from 21:00 to 21:30. Outdoor access was automatically provided between 10:00 and 21:20 every day by opening eight hen doors (1.80 × 0.40 m; 70.9 ×15.7 in.) on both sides of the building. Manure was removed weekly on Friday, between 10:00 and 13:00. A scraper under each row of the aviary system removed excess litter daily between 23:00 and 23:55. Feed intake was estimated from automatic, continuous weighing of feed bins and mortality, floor/system eggs, egg production, and mortality were recorded daily by the caretaker.

The fully-mechanical, house ventilation system comprised of five variable speed fans (20,800 m^3/h; 12,242 ft^3/min, Ø 0.81 m; 32 in.) and nine single-speed fans (16,990 m^3/h; 10,000 ft^3/min, Ø 0.76 m; 30 in.) mounted in the roof ridge. There were 41 (east) and 37 (west) sidewall inlets to distribute fresh air. Inlets (1.2 × 0.3 m; 46.1 ×12.2 in. each) were controlled based on negative pressure when hen doors were closed and temperature controlled when hen doors were open. Four wall fans (Ø 1.52 m; 60 in.; hot weather) were located along the north endwall but were non-operational in this study. There was no supplemental heating inside the house. The ventilation system controller [27] automatically operated and recorded the status of fans, HE, actuators, lights, feed delivery, dampers, hen doors, etc. In addition, ventilation rate was estimated from the fan stage multiplied by the rated capacity.

Heat Recovery Ventilation

In addition to the house ventilation, a HRV system comprised of a counter-flow HE [28] (L×W×H; 3.3 × 10.1 × 1.8 m; 10.8 × 33.1 × 5.9 ft) with two pre-heaters [29] that supplied tempered, fresh air via a round, 13 m (42.6 ft) long insulated duct (Ø 1.02 m; Ø 3.35 ft) to the manure belt drying system (part of the aviary system; Figure 1) by a 7 kW (9.4 HP) variable frequency blower. Indoor air was extracted through a 3 m (9.8 ft) long insulated duct by a 4 kW (5.4 HP) variable frequency blower. The HE was a fraction of the total house ventilation for minimum to mild weather ventilation with a rated capacity of 32,145 m^3/h (18,920 ft^3/min). The total HE surface area was approximately 1,365 m^2 (14,693 ft^2).

Supply air flowrate (Figure 1) decreased when supply air temperature was ≤20.1°C (68°F), to increase heat transfer rate and subsequently increase supply air temperature. When the supply air was ≤17.7°C (64°F), the pre-heaters were operational with a 1.1°C (2°F) differential; however, the pre-heaters did not operate during this study. Extraction air flow (Figure 1) reduced when the supply air temperature reached 23.3°C (74°F), this reduced the efficiency of the HE and prevented increasing the temperature in the house. An automatic washing cycle operated every day between 12:30 and 13:00 to remove accumulated PM from the HE fins. During washing, supply and extraction flows were reduced to 11% of capacity. In addition, the fresh air intake (Figure 1) pre-filter was cleaned twice a week.

Sampling and Instrumentation

The study was performed over a four-week period, beginning Oct 5, 2018 and concluding Nov 3, 2018. In week 1 and 3, the HRV operated normally. Conversely, in week 2 and 4, the HRV was non-operational and the HE sealed to prevent air exchange possibly induced by the house ventilation. An experimental week was determined to begin on the day the manure was removed. The day the HE was turned on or off was excluded because of the resulting transient house environment from the change in ventilation and adjustments. The ventilation system controller had two versions of the ventilation controller software: 1) to operate the HRV and 2) house ventilation without HRV. The same settings (i.e., desired room T, ventilation settings, combi-table, etc.) were identical in both versions of software, except the settings that are unique to the HRV.

Ambient T/relative humidity (**RH**) were monitored near the house (Figure 2) at 5 min intervals [30]. Indoor dry-bulb T and RH [31] were measured at four locations (wirelessly connected to the external monitoring station). The ventilation control computer software [32] recorded six T sensors used for ventilation system (Figure 2) and three T sensors at fresh air intake, extraction, and supply of HE as well as house and HE ventilation capacity. Indoor AQ was assessed by measuring the gaseous NH_3 concentration at six locations (1.5 m above the floor; Figure 2) between 08:00 and 09:00 every day with a handheld sensor [33]. At each location, measurements were made in triplicate, with a 3 min interval between replicates.

Four manure samples were taken daily from the manure belt from both the lower and the top level from poultry house (Figure 2) between 08:00 and 09:00 to quantify DM [34].

Data and Statistical Analysis

For quality control, data were parsed to remove outliers or any erroneous/incorrect values. The HE efficiency was assessed by calculating the temperature-transfer efficiency (Equation 1; adapted from Allen and Payne [20]).

$$\mu_T = \frac{T_s - T_a}{T_e - T_a} \tag{1}$$

Where,

μ_T = temperature-transfer efficiency (dimensionless)
T_s = supply air temperature (°C)
T_a = ambient air temperature (°C)
T_e = extraction air temperature (°C)

In addition, temperature rise ($\Delta T = T_s - T_a$; °C) was calculated. Total sensible heat recovery (Equation 2) was estimated (adapted from DLG Test Report 6140 [35]) and provides insight to potential supplemental heating requirements.

$$q_r = c_p \, m \, (T_s - T_a) \qquad (2)$$

Where,

q_r = sensible heat recovered (kW)
c_p = specific heat capacity of air (assumed constant; 1.006 kJ/kg/K)
m = HRV mass flow rate (kg/s)

The HRV mass flow was estimated from the ventilation capacity (percentage logged by controller), manufacturer's rated maximum fan flow, and moist air density. Average daily efficiency of the HE, ventilation rate, house T, ambient T, pressure and opening of the inlets was calculated for the two weeks with and without HRV. Daily averages were at 5 min intervals for the 12 d of data with and without HRV.

Ambient T was compared for each 12 d period by randomly subsampling (n = 60) from each day [36]. Statistical analysis was performed to determine the effect of ambient T on the indoor T for the 12 d with and without HRV [37]. This was assessed from the average of ten indoor T sensors and the ambient T sensor. Ambient T measurements were divided in five bins: <6°C, 6°C to 9°C, 9°C to 12°C, 12°C to 15°C, and >15°C (<42.8°F, 42.8°F to 48.2°F, 48.2°F to 53.6°F, 53.6°F to 59°F, and >59°F). Also, statistical analysis was performed to explain the effect of the number of days after manure removal (day) for the 12 d with and without HRV on manure DM [38]. High variability existed among NH_3 concentration measurements and were therefore omitted from statistical analysis. Ventilation rate was increased on d 5 of week 2 (no HRV) by the farm staff in response to elevated NH_3.

RESULTS AND DISCUSSION

Each 6 d period (i.e., HRV and no HRV), during the four-week experimental period experienced similar ambient conditions (P = 0.51; Table 1); hence, allowing for a reasonable comparison of the impact of ventilation parameters on the indoor environment. During the experiment, ambient T was not sustained below 0°C (as commonly experienced for major laying hen production areas during winter), so this study can provide good insight to the capabilities and operating conditions of utilizing HRV for these moderate ambient conditions. In colder ambient conditions, heat recovery and efficiency are expected to increase, based on the trends and operation of the HE. Further, productivity (number of hens housed, laying percentage, and number of floor and system eggs) were similar for both treatments (Table 1). While differences in productivity were not anticipated in the relatively short, 7 d experimental period, this does suggest no major management or ventilation issues were encountered during the experiment. Albeit, feed intake was 3.2 g/d different between treatments, this may be attributed to the lower house T experienced without HRV. Mortality was on an average two dead birds greater with HRV compared to without HRV; however, average mortality for this month was 3 to 4 dead birds per day lower compared to the previous month. This maybe have been attributed to increasing bird age and poor weather. Floor litter depth was ~3 cm and considered rather dry (not measured); however, more caking was noticed near the open popholes. The HRV supply air was blowing on the manure belts, so the greatest difference in DM would be observed in the manure on the belts with minimal impact on litter DM.

The HE operation was managed by the ventilation controller and prior to start of the experimental period, the settings (preheater offset and differential, ventilation curve, etc.) required intensive and iterative adjustment to optimize HE operation. It is important to note, initial settings resulting from installation often need alteration to meet producer specific needs and account for local climate, house age, ventilation style, etc. Additional management and training are typically needed when new mechanical equipment is added poultry facilities.

Heat Exchanger Performance

For week 1 and 3 (i.e., HRV), extraction ventilation capacity was always at 100% (estimated 32,146.8 m^3/h; 18,921 ft^3/min) and only reduced during daily washing. Average supply ventilation capacity to the manure belt was 93.7% ±9.1% (estimated 30,124.6 m^3/h; 17,730 ft^3/min) and only typically decreased for ambient T <10°C (50°F). Average temperature-transfer efficiency (μ_T; Equation 1) was 75.07% ±9.4% (Figure 3; washing time excluded) and tempered supply air by an average 10.0°C ±3.4°C (18.0°F ±6.2°F). The μ_T increased as ambient and house T difference increased. Compared to a cross-flow HE [27], the tested HE exceeded μ_T (57%) but showed a lower temperature gain (12.6°C; 22.7°F). Two types of counter flow HE tested by Selders et al. [38] showed a μ_T of 62% and 71%, with an average 14°C (25°F) and 15°C (27°F) temperature increase, respectively. These results were found for broiler house applications, which may explain the higher increase in T due to the higher desired house T for broilers and at slightly lower ambient T compared to this study. The higher efficiency during this experiment may be due to the counterflow design compared to the more common crossflow, larger thermal transfer surface area (i.e., greater area for heat transfer), and minor factors, such as, thermal insulation and minimal leakage in the HE construction.

Average heat recovery (equation 2; Figure 3) was 93.94 ±31 kW (320,529 BTU/h), with greater heat recovery found when the ambient and house T difference increased. Greater ambient and house T difference reduced heat recovery because fresh air intake flow was reduced at colder ambient T. Overall heat transfer coefficient was 6.92 W/m^2/K. This is lower than the 21 W/m^2/K for a parallel flow HE found by Kennedy et al. [22] and most likely attributed to the large surface of the HE used in this study; however, the efficiency was found to be greater in this study compared to Kennedy et al. [22].

Washing

Intake and extraction ventilation were reduced during the daily washing. As a result, μ_T decreased during washing and for several hours after washing has finished (Figure 4). This reduction in μ_T is due to the supply air T less than mean house T and the subsequent evaporation of any water remaining on the fins. Typically, about 3.75 h were required to return to the average μ_T (~75%). This information is important for improving the control of the unit to avoid supplying air that could possibly chill the birds or decrease the house T.

Labor to clean this HE was minimal. Washing the inlet air filter was performed by spraying with water and took approximately 15 min (performed twice per week). Thorough cleaning the whole HE could require several hours with two people (approximately twice a year) with a pressure washer to wash restricted spaces.

Ventilation

Estimated house ventilation capacity was generally greater with HRV (22.5% ±8.5%). At this capacity, ventilation rate is estimated to be 1.68 m^3/h (0.99 ft^3/min) per hen (Figure 5). House ventilation capacity without HRV was 20.1% ±12.6%, or an estimated 1.50 m^3/h (0.88 ft^3/min) per hen. Only during and after washing the HE, ventilation rate was found to be lower when HRV was operational – most likely due to the decreased μ_T.

House static pressure was lower during the night when HRV was nonoperational, because the HE supplies and extracts air (neutral ventilation) from the house (Figure 6). During daytime, this effect disappears, because the inlets are opened less during HRV and house ventilation rate is greater. House static pressure reduced between 10:00 and 21:20, because the pop-holes for outdoor access were opened (Figure 6).

Thermal Environment

Overall average (±SD) ambient T was 10.2°C ±4.0°C (with HRV) and 10.9°C ±4.2°C (without HRV) during the study period (Table 1). The overall (10 T sensors) average house T was warmer with HRV (23.1°C ±0.5°C) compared to without HRV (22.2°C ±1.2°C). For each day, average T range (daily maximum – minimum) was less with HRV (1.8°C ±0.7°C) compared to without HRV (3.1°C ±1.1°C). This suggests laying hens with HRV were exposed to less dynamic diurnal fluctuations and greater temporal T uniformity.

Ambient T impacted indoor T with and without HRV (Figure 7), as expected; however, ambient T effects on indoor T were greater without HRV ($P < 0.001$). For ambient T <6°C (42.8°F), spatial and temporal average indoor T was 2.3°C (4.1°F) lower without HRV. Due to the lack of supplemental heating without HRV, indoor T decreased with colder ambient T conditions (Figure 7).

Overall average (±SD) ambient RH was 89.9% ±10.7% (with HRV) and 83.3% ±18.2% (without HRV) during the study period. Overall average indoor RH (4 RH sensors) were 59.5% ±3.6% (with HRV) and 59.7% ±7.7% (without HRV). Overall average indoor dewpoint T was greater with HRV (14.5°C ±0.8°C) compared to without HRV (13.8°C ±1.6°C). This was most likely attributed to the greater ambient dewpoint T, higher average indoor T and extra evaporation of water from manure experienced during weeks with HRV.

Manure and Ammonia

Average manure DM was 38.8% ±3.1% (without HRV) and 53.8% ±5.7% (with HRV). On the days when manure was removed from the belts (7 d from previous removal), average manure DM was 40.6% ±3.1% (without HRV) and 60.0% ±3.3% (with HRV; Figure 8). Increased DM content per day, effect of HRV, and the interaction between day and HRV operation were all significant ($P < 0.001$). Manure with a greater DM content required less hauling capacity for transportation and is preferable for land application. A potential limitation of this study is the lack of comparison between HRV and recirculated house air for manure belt drying.

An additional benefit of increased DM content, is lower NH_3 emissions [15,18,19]. Elevated NH_3 concentrations can have negative effects on hen productivity, health, and well-being [9,14,17] and working conditions for animal caretaker. With HRV, average NH_3 was 2.6 ppm, compared to 9.1 ppm without HRV. Ammonia concentration was found to increase with the number of days after manure removal. This finding agrees with Groot Koerkamp et al., [18] and Liang et al., [14]. It was especially evident in week 2 (no HRV), as shown by the rapid NH_3 concentration increase. On day 5 after manure removal in week 2 (no HRV), NH_3 concentration exceeded 25 ppm, the permissible exposure limit [40]; therefore, ventilation was increased to reduce the NH_3 concentration in the house. As expected, NH_3 concentrations (as well as other gases) were most likely influenced by low air exchange rates and the lack of air velocity directly above the manure belt in the treatment without HRV, lower manure DM content, and more days after manure removal as previously described by [15,18,19]. Further, in week 2 (without HRV), an increase in manure T was anecdotally observed, indicating more bacterial activity. These bacteria convert uric acid and urea to NH_3 [15]. Due to the relatively high minimum house ventilation rate and colder house T, NH_3 concentration did not increase to expected levels; thus, statistical inferences were inconclusive. Further, this minimum house ventilation rate may also have affected other measured parameters like the house T and manure DM. Nevertheless, this parameter was not observed to have a substantial impact on the results.

CONCLUSION AND APPLICATIONS

1. Heat recovery ventilation (HRV) had an overall positive effect on the indoor thermal environment, reduced NH_3 emission, and manure dry matter content.

2. Heat exchanger (HE) operation is managed by the ventilation controller settings and for optimum operation, requires iterative management strategies and manipulation of these settings.
3. Routine maintenance on HE, such as daily washing of accumulated particulate matter and weekly cleaning of fresh air intake prefilter, is of paramount importance to achieve high efficiency.
4. The addition of HRV can increase fresh air exchange while reducing the capacity of supplemental heating; however, proper ventilation system design considerations must be simultaneously integrated with the HE to achieve desired performance.

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26. Bolegg Terrace, Vencomatic Group

27. Lumina 38, Fancom B.V.

28. Clima Unit 1000, Agro Supply, Vencomatic Group

29. Guardian 325, L.B. White

30. Accuracy: ±0.21°C; ±2.5% RH; S-THB, Onset Computer Corp.

31. Accuracy: ±0.2°C; ±2.5% RH; RXW-THC, Onset Computer Corp.

32. FarmManager; F–Central, Fancom B.V.

33. 0 – 100 ppm; BW GasAlert NH3, BW Technologies

34. After collection, the manure was placed in aluminum cups and weighed, each cup containing approximately 100 g of fresh manure. Samples were placed in a 1,000 W electric oven at 105°C (221°F) for 24 h and weighed again to calculate the DM.

35. DLG Test Report 6140. 2009. “Heat Exchanger Earny Type 40.000 (Efficiency of Heat Recovery under Practical Conditions).” 1–12.

36. A generalized linear model (ambient T = HRV + day + HRV × day) was used compared average daily ambient T for 12 d when HRV was operational and nonoperational (SAS Institute. 2012. SAS 9.4 for Windows. SAS Institue Inc., Cary, NC). Significance implies $P < 0.05$.

37. A generalized linear model (indoor T = HRV + ambient T + HRV × ambient T) was used to explain the effect of the ambient T on inside T for the 12 d with and without HRV. Where HRV was operation (0) or nonoperation (1) for that time point. Significance implies $P < 0.05$.

38. A generalized linear model (manure DM = HRV + day + HRV × day) was used to explain the effect of the number of days after manure removal (day) for the 12 d with and without HRV. Significance implies $P < 0.05$..

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Acknowledgements

This research was supported with funding provided by Vencomatic Inc. and Vencomatic Group (Eersel, The Netherlands). The authors would like to acknowledge the contributions and support of Wilcox Family Farms as well as Jim and Caye during the preparation and completion of this work.

Table 1. Descriptive statistics for average daily productivity and ambient conditions with and without heat recovery ventilation (n = 12).

	HRV (±SD)	Without HRV (±SD)
Ambient T (°C)	10.2 ±4.0 (1.2, 19.6) [1]	10.9 ±4.2 (2.8, 23.5) [1]
Ambient RH (%)	89.9 ±10.7 (56.3, 100.0) [1]	83.3 ±18.2 (28.7, 100.0) [1]
Ambient dewpoint (°C)	8.5 ±2.8 (0.9, 13.1) [1]	7.7 ±2.8 (-0.5, 13.9) [1]
Number of hens	39,091 ±69	39,020 ±74
Laying percentage (%)	90.3 ±0.9	90.2 ±1.3
Feed intake (g)	112.6 ±4.9	115.8 ±4.5
Feed conversion ratio (g/g) [2]	2.1 ±0.1	2.1 ±0.1
Floor and system eggs	164 ±24	164 ±23
Mortality (number of birds)	11 ±2	9 ±2

[1] (minimum, maximum)

[2] FCR = Feed intake / (Egg weight × Laying percentage × Number of hens)

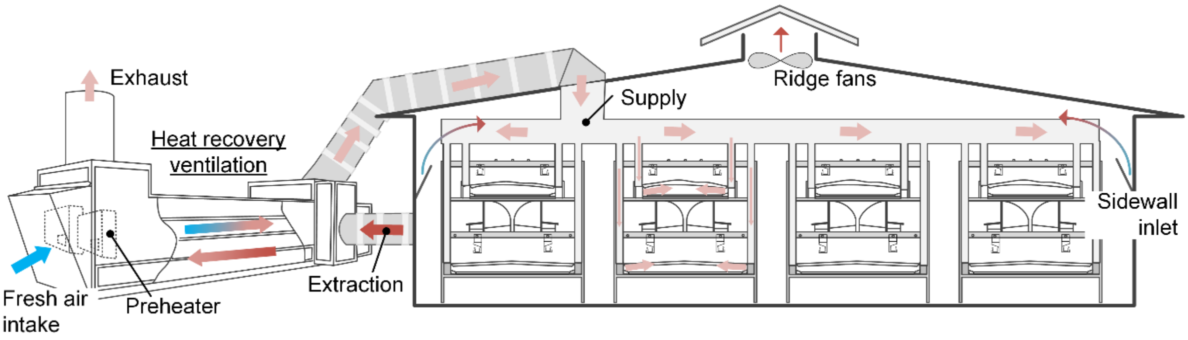


Figure 1. Overview house and heat recovery ventilation systems. Pre-heated fresh air is tempered by an air-to-air, counterflow heat exchanger and supplied to the manure belt drying system. House ventilation consisted of ridge-mounted single and variable speed fans with sidewall inlets for distribution. *Not to scale.*

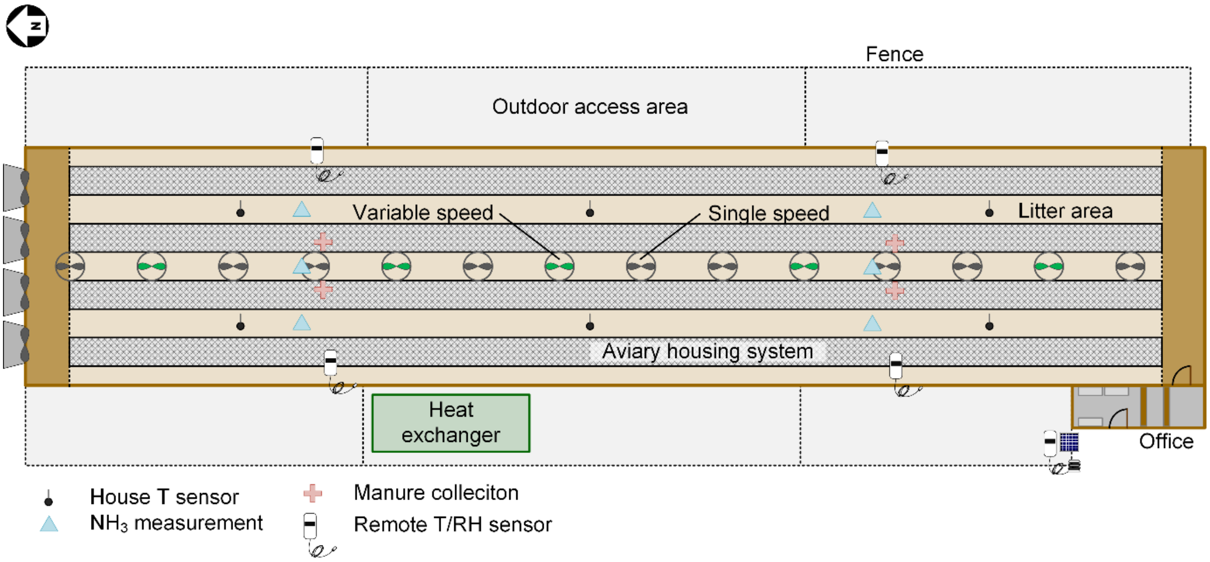


Figure 2. Overview of house layout and locations of T, RH, NH_3, and manure sampling locations. *Not to scale*.

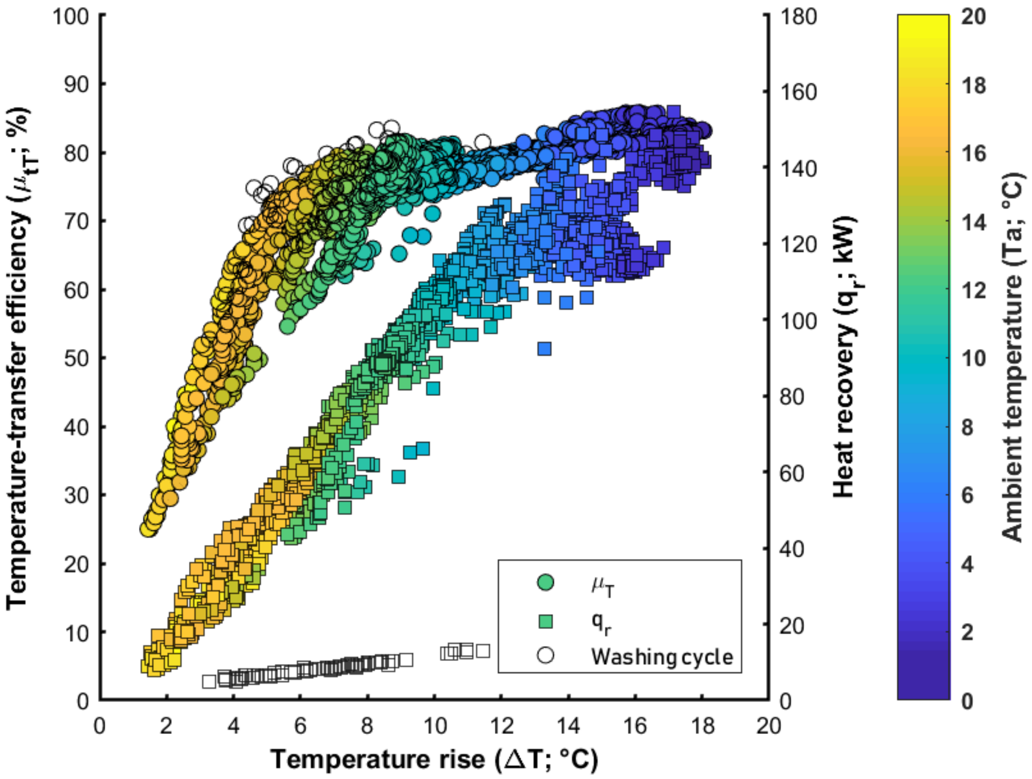


Figure 3. Effect of the difference between ambient and house temperature (∆T) on temperature-transfer efficiency and heat recovery. Markers colored by ambient temperature and empty markers are during washing cycle.

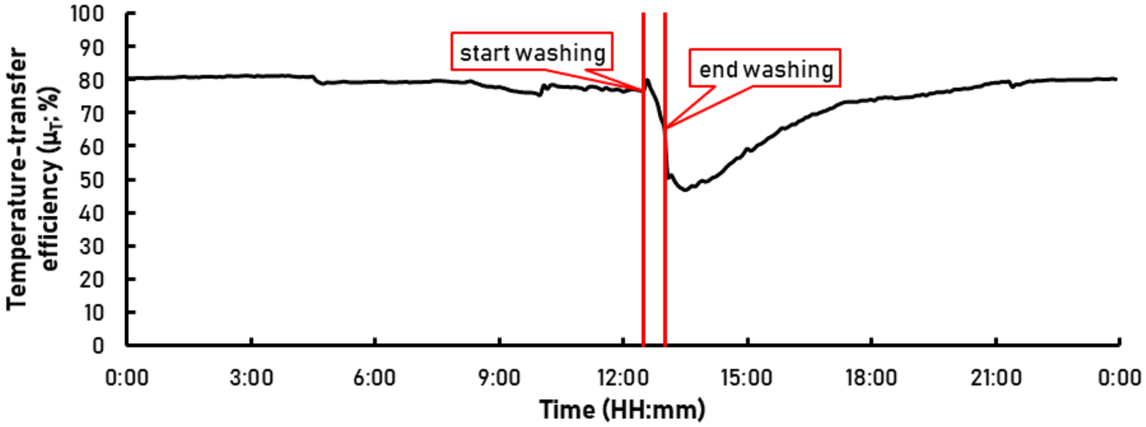


Figure 4. Example of one day to demonstrate the impact of the diurnal washing cycle on temperature-transfer efficiency.

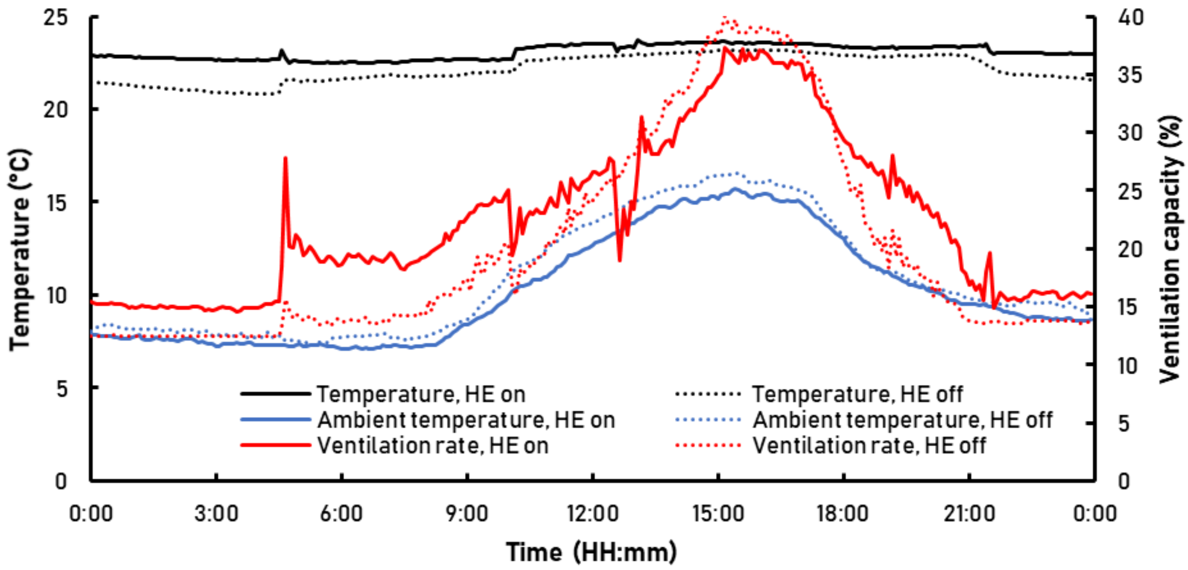


Figure 5. Example ambient temperature, house temperature, and ventilation rate for a day. Ventilation depends mainly on outside temperature, but peaks when the lights are turned on and birds become active; thus, increasing heat production. Ventilation decreases when pop holes open and when HE is washing.

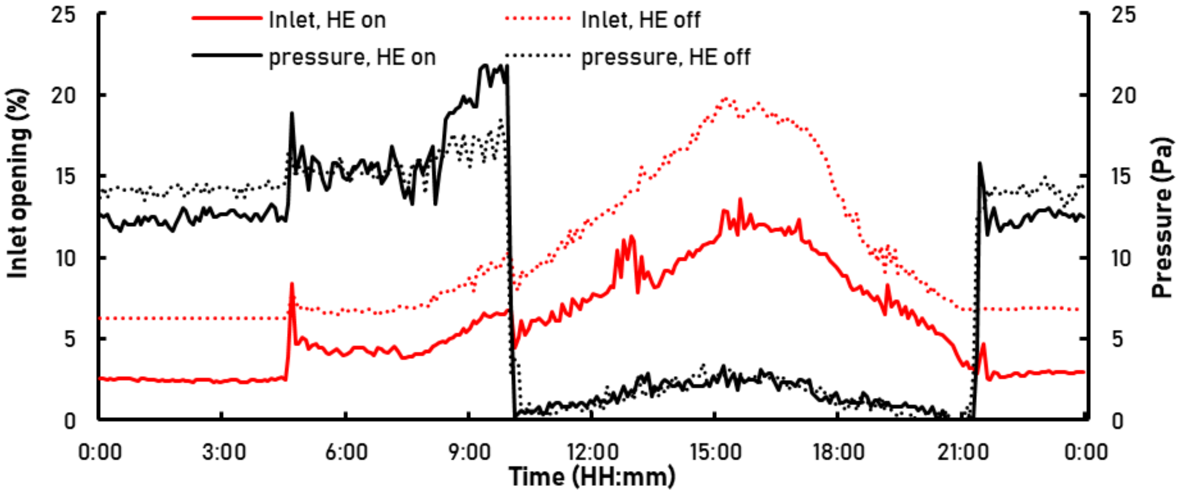
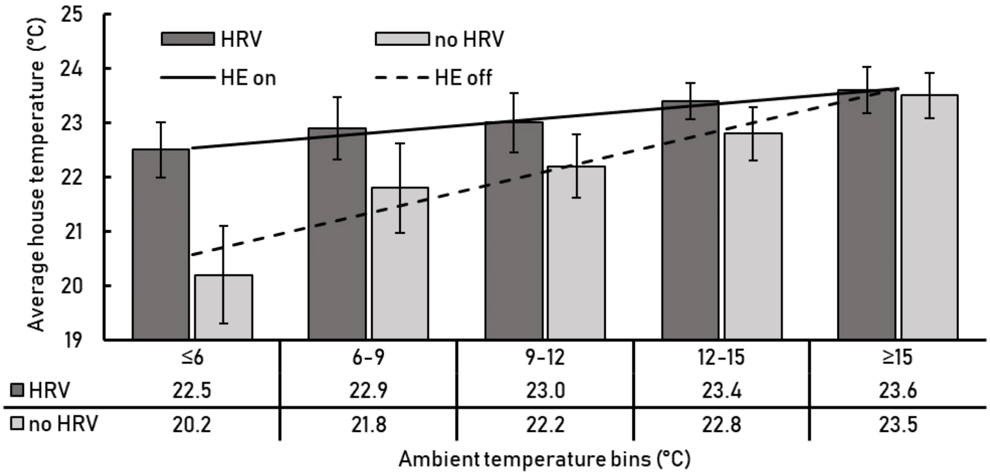


Figure 6. Example diurnal ventilation and sidewall inlet operation to demonstrate the impact of opening the doors for outdoor access on static pressure.



	≤6	6-9	9-12	12-15	≥15
▨ HRV	22.5	22.9	23.0	23.4	23.6
☐ no HRV	20.2	21.8	22.2	22.8	23.5

Figure 7. The effect of the ambient temperature on the temperature in the house. Ambient temperature is divided into five bins. The difference in linear regression coefficients was 0.124°C greater for HE on than HE off significantly different (P<0.001).

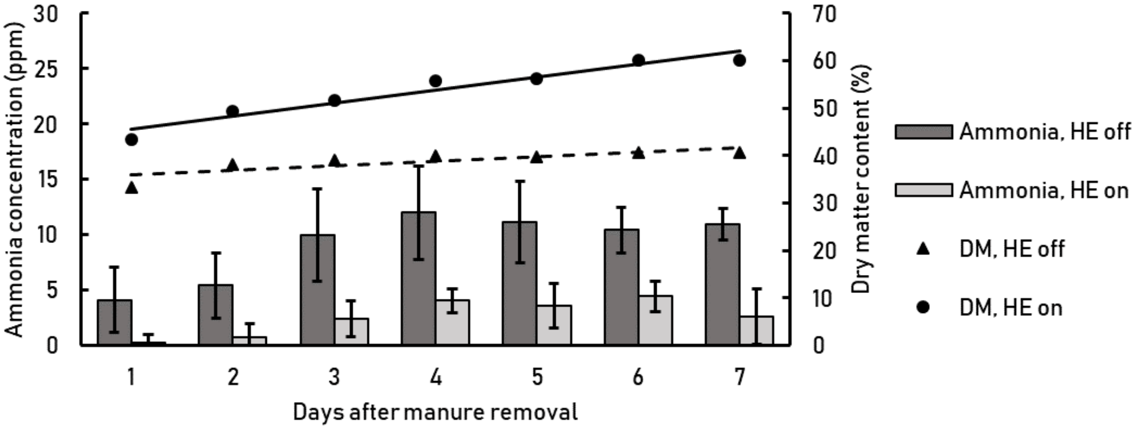


Figure 8. The ammonia concentration (ppm) 1 to 7 d after manure removal on the left y-axis and the DM content (%) of the manure on the secondary y-axis. The linear regression coefficients for the effect of the number of days and HE on/off are 0.59 ppm (HE off) and 3.60 ppm (HE on).