Spatial Analysis of Air Velocity, Air Temperature, and Humidity in Natureform Single-Stage Incubators Using Simulated Eggs

by

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Abstract

Spatial variation of the thermal environment within incubators has been a critical concern for the optimal development of egg embryos. Variations in air velocity, temperature, and humidity can alter embryonic mortality, egg moisture loss, hatchability, and post-hatch growth. Researchers are also concerned with minimizing the variation within small research incubators to reduce the within-treatment variation in order to compare thermal treatments. Therefore, the objective of this study was to quantify the spatial variation of air velocity, temperature, and humidity within a single-stage incubator using simulated eggs for both setter-phase incubation (SPI) and hatcher-phase incubation (HPI). Eight small Natureform incubators capable of holding 1080 eggs were used. Air velocity was measured using a hot-wire anemometer at 60 Hz for both SPI and HPI. Two readings, perpendicular and parallel to the mixing fan, were taken at each of 25 locations across six levels. The 25 locations were combined into five zones for comparison. The incubator was set to 37.5 °C and 65 % RH for SPI and 36.7 °C and 60 % RH for HPI for a test period of three days. During SPI, air temperature (16 locations) and relative humidity (2 locations) was measured across six levels with self-contained (iButton) data loggers attached to 3D-printed eggs. During HPI, air temperature (9 locations) and relative humidity (2 locations) was measured across six levels with iButtons attached within wiffle balls attached to chick baskets. Relative humidity was converted to vapor pressure deficit (VPD). The main effects of location and level were analyzed with two-way ANOVA with the GLIMMIX procedure (SAS ver. 9.4) for air velocity, temperature, and humidity. During SPI, mean air velocity by zone was highest near the fan (1.8 m per s) and lowest at the front of the incubators (0.6 m per s). During HPI, mean

air velocity was highest outside the chick baskets and lowest within the chick basket. During SPI, mean air temperature ranged between a low of 37.3 °C towards the front to a high of 38.2 °C near the back left corner. During HPI, air temperature ranged between a low of 36.7 °C towards the front, to a high of 37.5 °C near the left and right side of the basket. During SPI, VPD ranged from 2.0 kPa and 2.05 kPa. For HPI, VPD ranged between 1.99 kPa and 2.05 kPa. 3D-printed eggs with iButtons can effectively capture air temperature and relative humidity near the egg surface during incubation. This study characterized air velocity patterns in a Natureform single-stage incubator and provided a methodology to measure temperature and relative humidity variation during research studies involving live embryos.

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Thank you from the bottom of my heart for your invaluable contributions to this accomplishment.

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List of Abbreviations

SPI Setter-phase Incubation

HPI Hatcher-Phase Incubation

VPD Vapor Pressure Deficit

AIC Akaike Information Criterion

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Introduction

There are an estimated 109.5 billion eggs set in hatcheries in the United States annually (USDA, 2023). It is common knowledge that the proper thermal environment around each egg in an incubator directly affects the percentage of eggs hatched and the quality of the chick at placement. The growth and development of the embryo inside the egg is dependent on several thermal parameters, such as temperature and humidity, that are driven by proper airflow.

Air temperature directly influences embryo homeostasis (Magli et al., 2008); hence proper temperature regulation is essential. Significant variations in incubation temperature during the embryonic stages usually result in unfavorable effects on post-hatch growth and alter embryo development (Tong et al., 2013, Walker et al., 2013). However, maintaining a constant internal egg temperature to meet embryonic needs throughout incubation is challenging (Gigli et al., 2009, Adewumi, & Atanda, 2016). It is important to note that even when the incubator is calibrated to meet the required temperature for embryonic development, temperature is not static and can be influenced by various external factors that can lead to a higher rate of embryonic mortality, poor chick quality, and reduced growth efficiency and meat yields (Tejeda et al., 2021).

Three factors determine the temperature of the developing embryo: 1) the temperature of the incubator, 2) the metabolic heat output of the embryo itself, and 3) the capacity of heat to travel between the incubator and the embryo (French, 1997). The influence of incubation temperature on egg hatchability and chick quality might be connected to its impact on heat and water loss, incubation time, and airflow rate. However, such effects depend on how long and substantial the deviation from optimal temperature is (Okpagu, 2016, Sozcu and Ipek, 2015).

Target temperatures of 37.5 °C to 37.8 °C recommended by several researchers (Ipek et al. 2014, Sgavioli. et al. 2016, Jonathan et al. 2020, Agyekum et al. 2022, Avsar et al. 2022, Bahram et al. 2022) resulted in optimal utilization of yolk, shorter pipping time, decreased feed intake, lower embryonic mortality, and higher body weight, indicating the significance of precise temperature control during incubation. According to Phillip (2004), the incubator's temperature should be between 37.2 °C and 37.8 °C. Embryonic mortality may occur if the temperature is below 35.6 °C or increases beyond 39.4 °C for several hours. Exposure to these extreme temperatures, due to either overheating or underheating, can critically compromise the hatching process, posing a severe threat to the embryos (Cartwright, 2000).

Several studies (Morita et al. 2016, Almeida et al. 2016, Jonathan et al. 2020, Bahram et al. 2022) have shown that lower incubator temperatures (36.0 °C to 36.7 °C) as compared to 37.5 °C during incubation caused lower metabolism and growth, higher yolk utilization, slowed fetal development, increased incubation duration, lower chick weight, shorter hatching time, lower hatchability, increased feed consumption, higher cholesterol levels in hatchlings, and delays in growth and lower utilization of yolk. Similarly, researchers (Morita et al. 2016, Almeida et al. 2016, Leksrisompong et al. 2009, Jonathan et al. 2020, Tesarova et al. 2021, Bahram et al. 2022) have shown that incubator temperatures (39°C to 39.4°C) as compared to 37.5 °C can negatively impact chick development, embryonic mortality, decreased food consumption, bone development, higher mortality with a higher incidence of malposition and decrease chick quality. These findings emphasize that accurate temperature control during incubation is crucial for achieving optimal hatchability and survival rates of healthy chicks.

Relative humidity plays a crucial role in the water vapor pressure gradient between the egg and the environment, influencing its weight loss during incubation. Higher relative humidity

levels decrease the water pressure deficit, reducing egg weight loss. Low egg weight loss corresponds to low latent heat loss, as evaporative heat loss is minimized (Lourens 2008).

Maintaining appropriate relative humidity levels during incubation to optimize incubation conditions and improve hatchery performance is important. A slightly higher relative humidity level (63%) can significantly impact the incubation process by positively influencing chick growth and placement body weight, and a lower relative humidity level may negatively affect embryo survival leading to higher mortality rates and delayed development, extended hatch times, and decreased hatchability but has little effect on chick quality or post-hatch performance (Bruzual et al. 2000, Van der Pol et al. 2013). According to Bruzual et al. (2000), fertile hatchability increased, and placement body weight improved at a relative humidity of 53%. Maintaining relative humidity within the recommended range, which may vary depending on specific conditions, can positively impact fertile hatchability and chick body weight.

According to Lourens (2001), air velocity is crucial in incubation, hatchability, and controlling the temperature of embryos. He reported that a minimum of 0.25 m per s air velocity was necessary to effectively control incubation temperature and maximize hatchability. Proper airflow aids mixing in the incubator. When the air velocity is low, the temperature will typically increase from embryo heat production, which may lead to decreased hatchability, increased late embryonic mortality, and chick culling (Joseph, 2006). Another study by Kaltofen (2007), investigated the relationship between air velocity and percentage hatch in two cabinet-type incubators and reported air velocities ranged from 0.08 to 3.00 m per s. He showed that the highest fan speed yielded the best hatching results.

French (2009) reported that the greater the airflow over the egg, the more efficiently heat is transferred to or from the egg and the airflow rate over the eggs significantly impacts how

successfully heat is transported. Variations in airflow rates are a significant reason for temperature variations within incubators. Temperature fluctuations of up to 1.2 °C have been discovered in commercial incubators (French, 2009), and minimizing this variation requires more consistent airflow over the eggs in all areas throughout the incubator. Deviations of one degree from the optimum temperature can significantly impact the hatchability of eggs and embryo development (Lourens, 2008).

Understanding the variation of these thermal parameters within an incubator is important for researchers when designing thermal treatments comparisons for hatching studies. Natureform single-stage incubators have been used by researchers to evaluate the effects of high incubation temperatures (Bruzual et al., 2000; Joseph et al., 2006; Leksrisompong et al., 2009; Oviedo-Rondon et al., 2009; and Shim and Pesti, 2011) as well as low incubation temperatures (Joseph, Lourens, and Moran, 2006; and Shim and Pesti, 2011) compared to a control. Bruzual et al., (2000) also evaluated the effect of humidity on hatching parameters in Natureform incubators. The assumption being made in all these studies was that eggs within incubator treatments were held at the prescribed temperature and humidity set on the process controllers. There was no quantification of thermal variation within incubators for these studies.

I hypothesize that the airflow, air temperature, and humidity is similar across all levels (1 – 6) of the egg trays during setter-phase incubation in Natureform single-stage incubators and the airflow, air temperature, and humidity is similar across all levels (1 – 6) of egg baskets during hatcher-phase incubation in Natureform single-stage incubators Therefore, the objective of this study was to quantify the spatial variation of temperature, humidity, and air velocity within a Natureform single-stage incubator using simulated eggs for both setter-phase incubation (SPI) and hatcher-phase incubation (HPI).

Materials and Methods

Thermal parameters of air velocity, air temperature, and humidity were measured in two separate studies for eight incubators during (1) setter-phase incubation (egg trays) which is approximately between 0 – 15 days and (2) hatcher-phase incubation (chick baskets) which is approximately between 16 – 21 days. These studies were performed with simulated eggs to remove the effect of heat production from the embryo or chick.

Incubators

The spatial variation of the thermal environment was evaluated in eight Natureform single-stage incubators (NMC 2000; Natureform, Inc., Jacksonville, Florida). The incubators had internal dimensions of 104.5 ×116.8 ×119.4 cm with a mixing fan fixed in the center of the back wall (Fig. 1e). Air entered the unit through the intake vent (Fig. 1b) and humidity duct (Fig. 1d) on the back wall and exited through an adjustable slide vent in the ceiling (Fig. 1a). Heat was provided through heating bars (Fig. 1f) that were controlled by a temperature process controller. Humidity was provided through cooling coils (Fig. 1c) that were controlled by a humidity process controller. During the setter-phase, the system was designed with a rack holding twelve egg trays in six levels for a total of 1,080 eggs (90 eggs per tray). During the hatcher-phase, hatching chicks would be transferred to a trolley stacked with six chick baskets. There were four of the eight incubators located in the same room. The incubators were run in pairs, with two being used at a time. Each incubator was set to run for 12 hours before data collection.

Figure 1. Incubator showing (a) Adjustable slide vent, (b) intake vent, (c) cooling coils, (d) humidity duct, (e) mixing fan, (f) heating bars, (g) relative humidity probe, (h) temperature probe

Air Temperature and Relative Humidity

Logger Selection and Calibration

Air temperature and relative humidity were measured and recorded in the incubators using two types of data loggers. Due to supply chain issues, few relative humidity sensors to spread across incubators. The self-contained relative humidity iButton (DS1923-F5#, embedded data systems, Lawrenceburg, Kentucky) measured both air temperature and relative humidity and had an accuracy of 0.5 °C, 0.6% RH, and a resolution of 0.1 increments. A second self-contained iButton (DS1922L-F5#, embedded data systems, Lawrenceburg, Kentucky) measured only air temperature and had an accuracy of ±0.5 °C, a resolution of 0.1 increments.

The iButtons were calibrated in an environmental chamber (ESL-2H, ESPEC North America, Inc, Hudsonville, Michigan) at the Auburn University Biosystem Engineering Research Laboratory. The chamber temperature and relative humidity parameters were set at 10°C:50%, 30°C:30%, and 50°C:10% during the temperature iButton calibration. The humidity iButtons were calibrated at adjusted levels of 17°C:80%, 30°C:50%, and 50°C:20% as the high (90%) and low (10%) humidities were hard to maintain consistency. Temperature calibrations were performed with a temperature probe (1551A STIK Thermometer, Fluke, Everett, Washington). Relative humidity was calibrated with a dew point chilled mirror hygrometer (DEWTRAK II SN 53596, Edgetech Instruments, Hudson, Michigan) along with the temperature probe and atmospheric pressure from a weather station. Relative humidity was calculated from dew point using a psychometric equation (ASABE, 2021).

Setter-Phase Incubation

A plastic egg was 3D-printed to hold an iButton data logger to measure the air temperature and humidity at the egg surface (Figure 2). The eggs were created with two matching halves and together measured 54.8 ± 1.3 mm in length, 43.1 ± 0.1 mm in width, and 46.5 ± 0.4 mm in diameter based on dimensions given in Altuntas & Sekeroglu (2010). The 3D eggs were printed with PLA Prusa Blue filament (PRM-PLA-PRO-1000, Prusament, Prague) in a 3D printer (i3 MK3S+, Prusa, Czech Republic) at the National Poultry Technology Center at Auburn University. The data loggers were fastened to the top surface with a metal ring (DS1922L-F5#, Embedded Data Systems, Lawrenceburg, Kentucky).

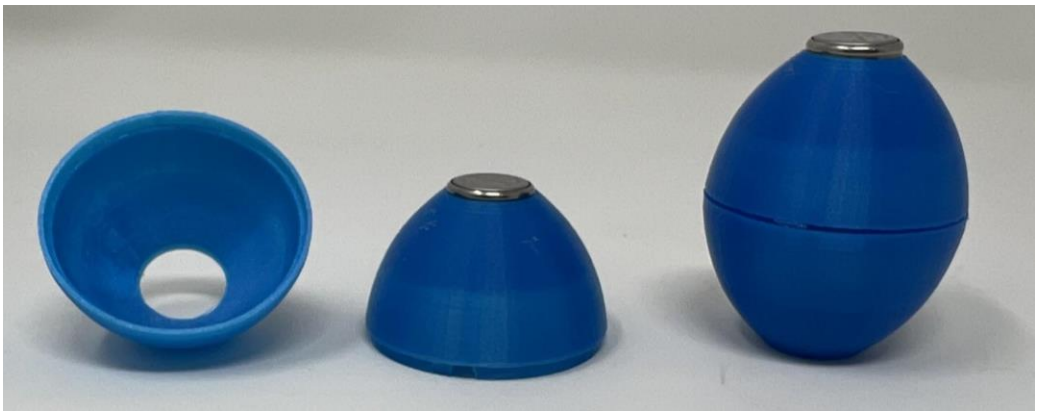


Figure 2. Self-contained iButton dataloggers were mounted in the top of a 3D-printed egg to measure air temperature and/or humidity at the egg surface. Two matching halves were pressed together to create a whole egg.

Sixteen temperature dataloggers were spatially arranged across two egg trays (Figure 3) at each of the six levels in the incubator (Figure 4). Locations 5 and 12 were fitted with loggers that measured both air temperature and relative humidity. The remaining egg locations were filled with 164 simulated eggs (Dreidel, China) with an average weight of 14.15 ± 3.47 g and dimensions of 56.1 mm in length, 40.9 mm in width, and 38.1 mm in diameter. A total of 96 dataloggers were used in each incubator.

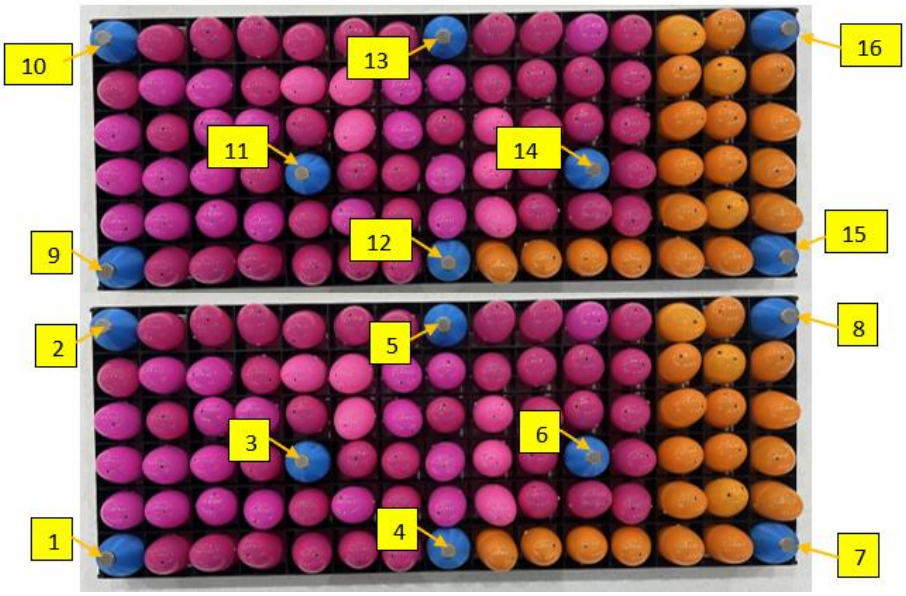


Figure 3. Spatial arrangement and labeling of 3D-printed eggs (blue egg with iButton) across two black trays on each level. Locations 5 and 12 measured humidity in addition to temperature.

Figure 4. Arrangement of the twelve egg trays at the six levels within the incubator. Level 1 is at the top and Level 6 is at the bottom.

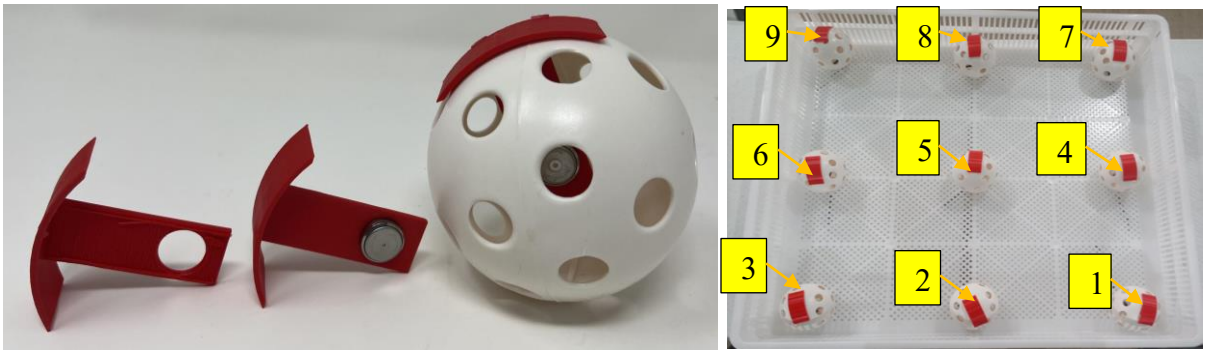
The incubators were set to 37.5 °C and 65% relative humidity and monitored two at a time over a 72-hr period and for 14 days during fall. Air temperature and relative humidity were measured at a 5-min sampling rate. A temperature and relative humidity datalogger same as the iButtons located within the incubators was placed in the room that housed the incubators to monitor room air temperature. The data were downloaded using a computer and a serial 1-Wire protocol (DS9490R#. maxim integrated, Philippines).

Hatcher-phase Incubation

A second system was designed to hold the self-contained dataloggers in the chick baskets (Natureform 180 egg hatch basket ,Natureform, Inc., Jacksonville, Florida) as the 3D-printed eggs could roll and touch each other. A 44 mm T-shaped tab was 3D-printed to hold an iButton

in the center of a wiffle ball (PPB-6M, Hot Glove Inc, Taiwan) (Fig. 5a). The function of the wiffle ball was to provide physical separation of the data logger from any eggs or chicks within the hatch basket if eggs were incubated with this data logging system. The t-holders were printed with a PLA Prusa Red filament (PRM-PLA-PRO-1000, Prusament, Prague) in a 3D printer (i3 MK3S+, Prusa, Czech Republic) at the National Poultry Technology Center at Auburn University. The wiffle balls were fixed to the basket floor with zip ties 28.5 x 31.5 cm apart in 9 locations (3 rows of three) inside the chick crates of dimension 71.0 x 71.5 cm (Figure. 5b) and stacked inside the incubator (Fig. 6).

Nine dataloggers were installed in the 3D-printed t-holders and spatially arranged across the chick basket (Figure 5b) at each of the six levels in the incubator (Fig. 6). Locations 1 and 9 were fitted with loggers that measured both air temperature and relative humidity at each level. The baskets were filled with 164 simulated eggs, with weights and dimensions described previously. A total of 42 temperature dataloggers and 12 temperature/relative humidity loggers were used in each incubator.



(a) (b)

Figure 5. (a) The 3-D printed t-holder were fixed to a wiffle ball with a temperature/relative humidity iButton logger within (b) the chick baskets to capture temperature relative humidity.

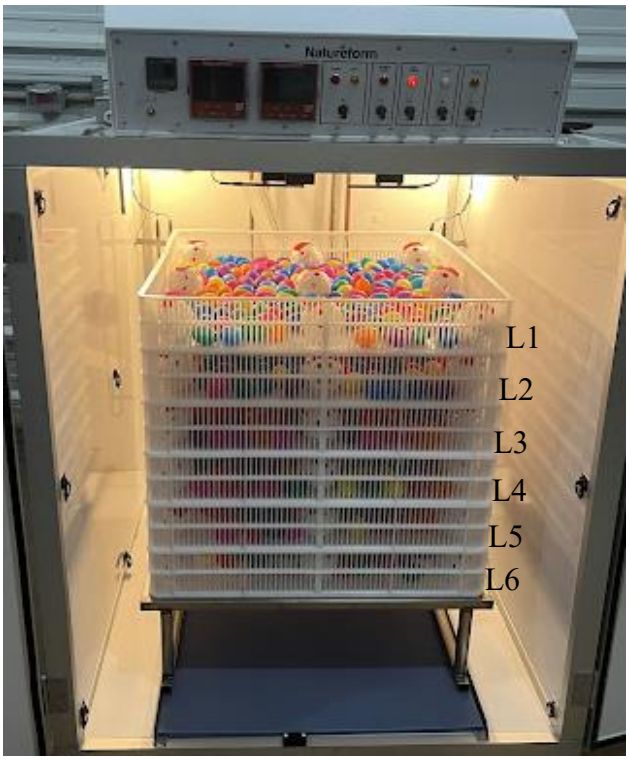


Figure 6. Arrangement of chick baskets at six levels of the rack in the incubator. Level 1 is on top, and Level 6 is on bottom.

The incubator air temperature and relative humidity were set on the controllers to 36.67 ^{o}C and 60%, respectively, and monitored two at a time over a 72-hr period at a 5-min sampling rate.

Air temperature and relative humidity were measured in each incubator on a spatial grid at six levels that corresponded to the air space among the eggs in the basket (32.0, 42.5, 54, 66.5, 77.0, and 88.5.0 cm from the bottom). At each level, air temperature and relative humidity were measured at 9 locations (three horizontal × three depths) for a total of 54 measurements. Horizontal locations were 6.5, 33.5, and 64.5 cm from the left of the basket wall. Depth locations were 7.5, 36.5, and 64.0 cm from the front of the basket wall. A temperature and relative humidity data logger was placed in the room that housed the incubators to monitor room air temperature.

Air Velocity

Setter-Phase Incubation

Each incubator was individually set up with a rack and twelve egg trays filled with 1,080 simulated eggs. The incubator air temperature and relative humidity were set on the process controllers to 37.5 ^{o}C and 65%, respectively. The air velocity was measured in each incubator on a spatial grid at seven levels that corresponded to the air space above each egg tray or basket and at the bottom of the incubator (16.5, 36.8, 49.5, 61.0, 72.4, 87.0, 95.3 cm from the bottom). At each level, velocities were measured at 25 locations (five horizontal by five depths) for a total of 175 measurements. Horizontal locations were 12.7, 40.6, 58.4, 74.9, and 100.3 cm from the left wall. Depth locations were 23.5, 37.5, 52.7, 66.7, and 81.3 cm from the front wall interior surface.

Air velocity was measured with a hot-wire anemometer (9535-A, TSI Incorporated, Minnesota USA) at 60 Hz with a 10 s average per reading. Two velocity measurements were taken for each location: perpendicular and parallel to the mixing fan. A maximum stable reading was recorded at each location. To allow the use of the meter across the 175-point grid, a clear plastic 113.0 by 134.6 cm wall was constructed from plexiglass and extruded aluminum framing (1515, 8020, Columbia City, IN) and clamped in place of the incubator doors (Fig. 7-left). Expandable foam weather stripping was used to create an airtight seal. Slots were cut in the plexiglass to allow the meter to easily access each grid location. Slots were sealed with tape except for the sample location. Small foil streamer sections were taped on each wall in a grid to qualitatively visualize air flow patterns.

(a) (b)

Figure 7. A constructed plastic wall was clamped to the front of the incubator to allow measurements and visualization of air velocity with the incubator doors open while maintaining air patterns during (a) setter-phase incubation using a rack and twelve egg trays, and (b) hatcher-phase incubation using a rack and six chick baskets. Streamers were taped in a grid to visualize airflow around the perimeter of the incubator.

Hatcher-phase Incubation

Each incubator was individually set up with a rack and six chick baskets filled with the same 1,080 simulated eggs. The incubator air temperature and relative humidity were set on the process controllers to 37.5 ºC and 65%, respectively. The air velocity was measured in each incubator following the same process used for setter-phase incubation. To allow the hot-wire anemometer to enter the chick baskets, three small rib sections were removed from the face of each chick basket (Fig 7b). Small foil streamer sections were taped on each wall in a grid to qualitatively visualize air flow patterns.

Statistical Analysis

Calibrations were performed with a linear regression analysis using the PROC REG procedure in SAS (SAS 9.4, SAS Institute Inc, Cary, North Carolina) which was used to generate a linear regression model (Eqn 1.). Transfer functions (Eqn 2.) were used to calibrate each logger similar to Chesser et al. (2012).

$$Y = mx + b \quad \text{(Eqn. 1)}$$

$$X = \frac{1}{m(y)} - \frac{1}{m(b)} \quad \text{(Eqn. 2)}$$

where y is the uncalibrated iButton (dependent variable), m is the slope, x is the independent variable (temperature probe), b is the offset, and X is the calibrated output.

The eight incubators were considered the experimental unit in a completely randomized design. Air velocity was organized into five linear zones starting from the back (Zone 1) to the front (Zone 5) for comparison (table 1). The GLIMMIX procedure in SAS (Version 9.4, SAS Institute, 2016) was used to conduct a 2-way ANOVA to assess the fixed effects of measurement location, incubator level, and the interaction of measurement location and level on air temperature and air velocity for both SPI and HPI. Room air temperature and relative humidity were included as a covariate to account for differences in days of measurement. Least squares means were separated at $\alpha = 0.05$. The Akaike information criterion (AIC) was used to find the optimal covariance structure, and Gaussian was used for the response distribution. The mean air temperature and mean air velocity in the incubator were interpolated and mapped using the kriging method in the GSTAT package (1.1.423; RStudio, Vienna, Austria), similar to Luck et al., 2014, Linhoss et al., 2017, and Falana et al., 2023. A 0.25 cm by 0.25 cm cell size was used for data interpolation.

Table 1. Zoning of air velocity for the early and late stages.

Zone	Early Stage	Late Stage
1	5, 10, 15, 20, 25	5, 10, 15, 20, 25
2	4, 9, 14, 19, 24	4, 9, 14, 19, 24
3	3, 8, 13, 18, 23	3, 8, 13, 18, 23
4	2, 7, 12, 17, 22	2, 7, 12, 17, 22
5	1,6 11, 16, 21	1,6 11, 16, 21

For statistical comparison, relative humidity was converted to vapor pressure deficit (VPD) using equation 3 (ASABE, 2019).

$$VPD = e^{o}(1 - RH/100) \quad (3)$$

where:

VPD = vapor pressure deficit (kPa)

RH = relative humidity (%)

e^{o} = saturation vapor pressure (kPa)

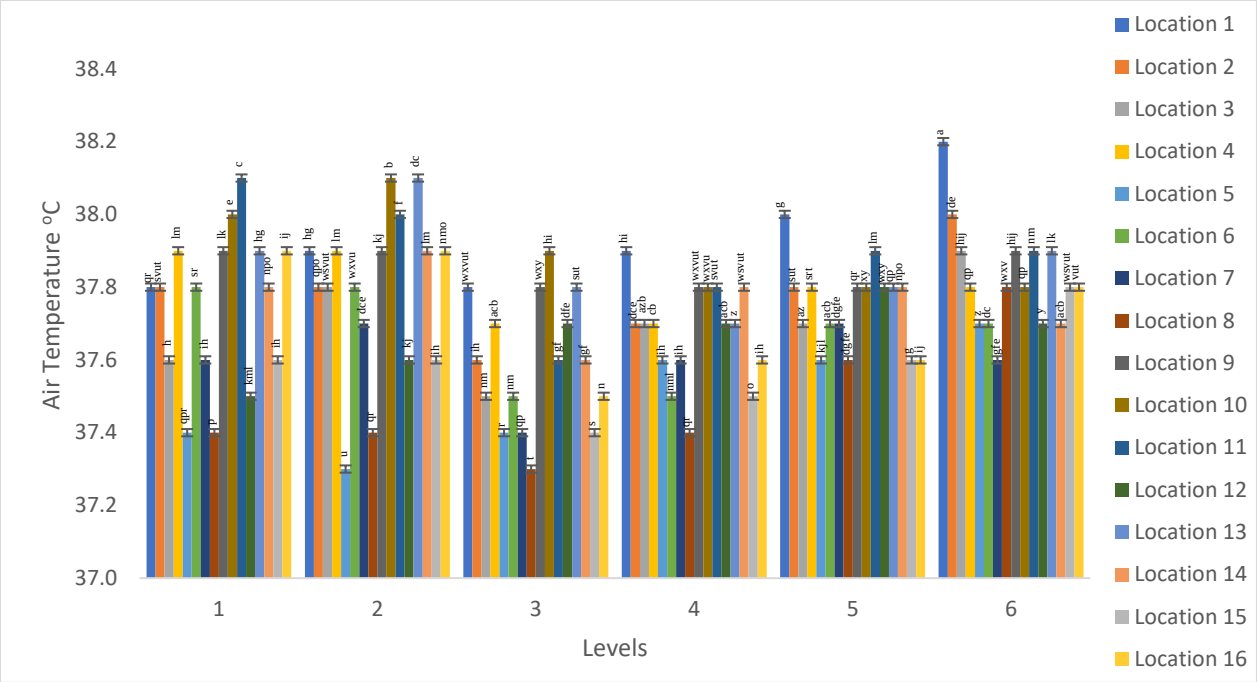
The GLIMMIX procedure was used to compute the fixed effects of incubator level on vapor pressure deficit for both the setter-phase and hatcher-phase. Room VPD was included as a covariate to account for differences in days of measurement. Least Squares Means were separated at $\alpha = 0.05$.

Results and Discussion

Air Temperature

Setter-Phase Incubation

There was a location, level, and location-by-level interaction for air temperature ($P < 0.0001$). Least squares means for each location by level combination are summarized in Fig. 8. The overall mean air temperature in the incubator was 37.7 ºC. The minimum air temperature of 37.3 ºC occurred at location 5 on level 2 and location 8 on level 3. The maximum air temperature of 38.2 ºC occurred at location 1 on level 6. The maximum range of air temperature across the incubators during the setter-phase incubator was 0.9 ºC. For each level 1 through 6, the maximum range of air temperature were 0.7 ºC, 0.8 ºC, 0.6 ºC, 0.5 ºC, 0.4 ºC, and 0.6 ºC, respectively. Fig. 9 illustrates the mean air temperature map across each of the six levels during SPI. The dimensions of the incubator and fan location are included for reference. The white dashed line indicates the perimeter of each egg tray at each level. In general, air temperature was generally warmer near the back of the incubator near the fan and colder at the front of the incubator near the doors.



Means with different superscripts differ P < 0.05.

Figure 8. Least square means and air temperature for location and level for setter-phase (egg trays).

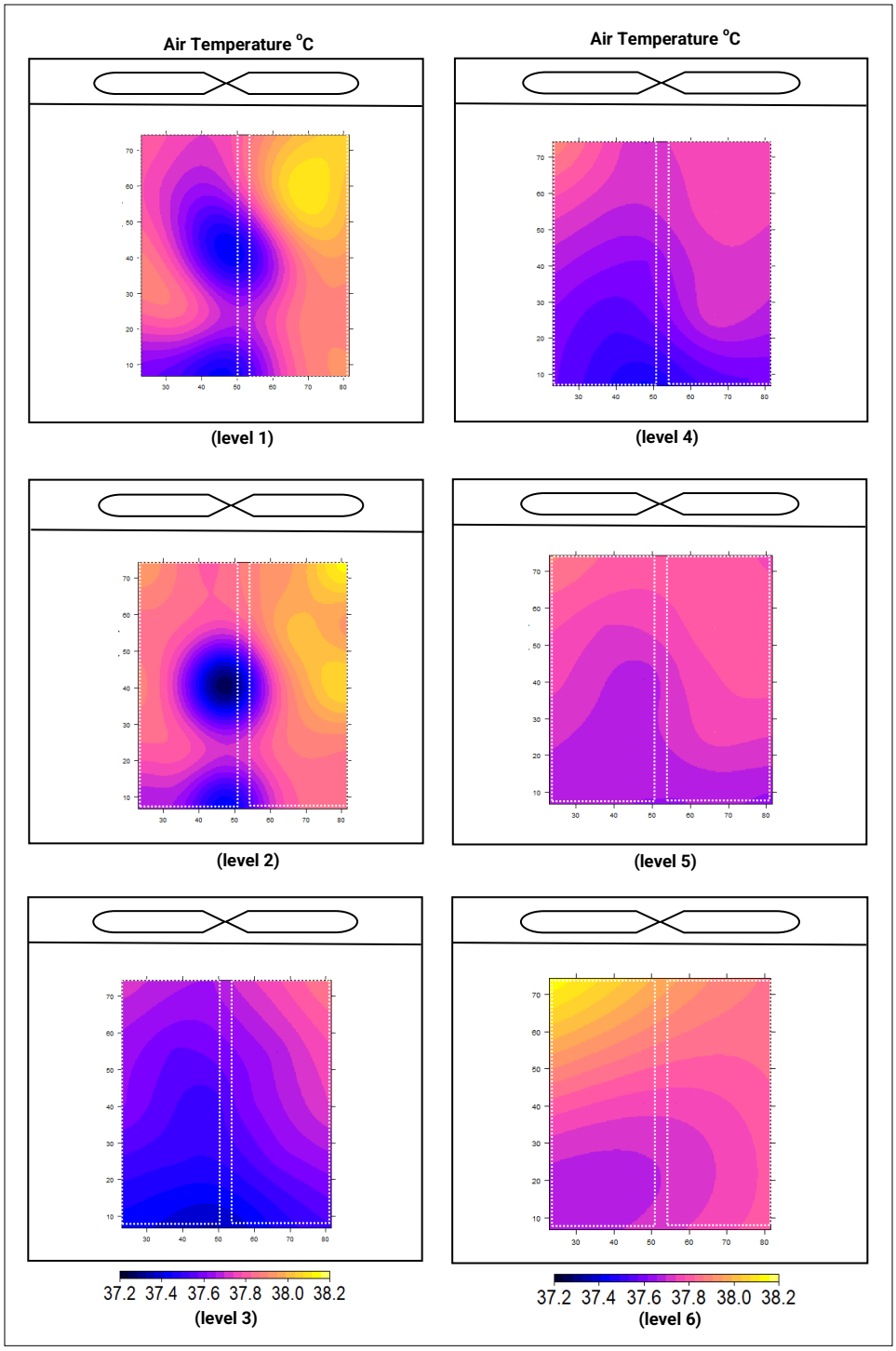
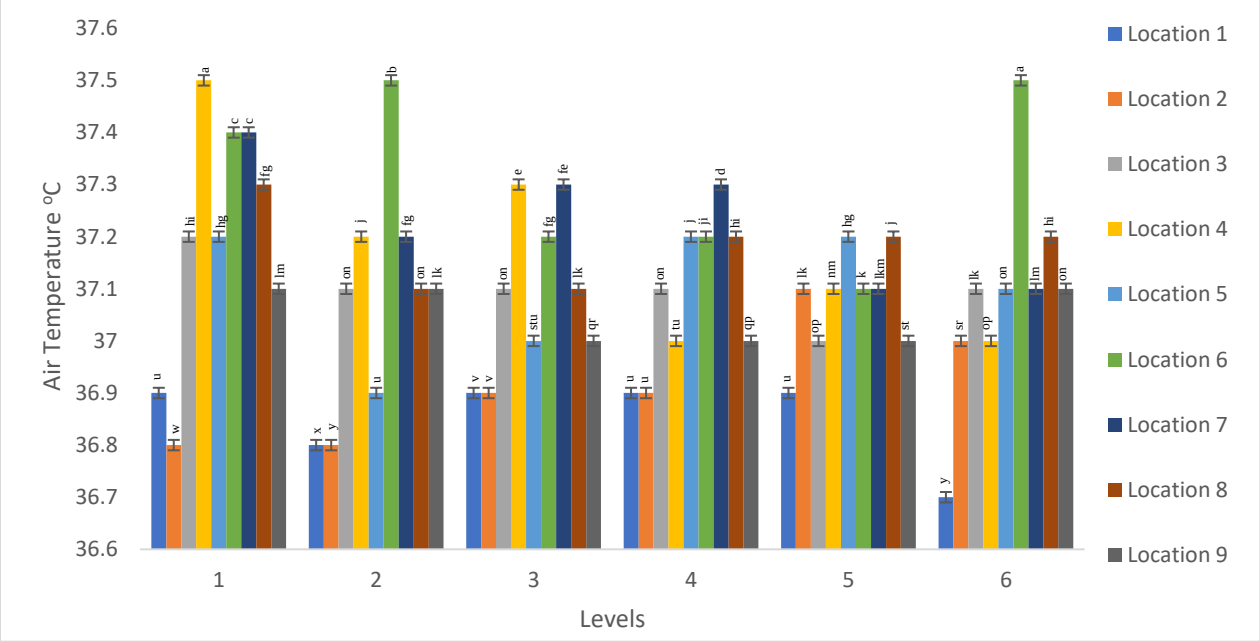


Figure 9. Spatial mapping of air temperature for each set of egg trays at each level during setter-phase incubation. The interior incubator wall perimeter and fan are included for reference. The white dashed line indicates the perimeter of each egg tray at each level.

Hatcher-phase Incubation

There was a location, level, and location × level interaction for air temperature ($P < 0.0001$). Least Squares means for each location by level combination are summarized in Fig. 10. The overall air temperature was 37.1 ºC. The minimum air temperature of 36.7 ºC occurred at location 1 on level 6. The maximum air temperature of 37.5 ºC occurred at levels 1, 2, and 6, and locations 4 and 6. The maximum range of air temperature across the incubators during HPI was 0.8 ºC. For each level 1 through 6, the maximum range of air temperature were 0.7 ºC, 0.7 ºC, 0.4 ºC, 0.4 ºC, 0.3 ºC, and 0.8 ºC, respectively. Fig. 11 illustrates the mean air temperature map across each of the six levels during hatcher-phase incubation. The dimensions of the incubator and fan location are included for reference. The white dashed line indicates the perimeter of each egg tray at each level. In general, air temperature is generally warmer near the back of the incubator near the fan and colder at the front of the incubator near the doors.



Means with different superscripts differ $P < 0.05$.

Figure 10. The statistical output of least square mean air temperature for the hatcher-phase (basket).

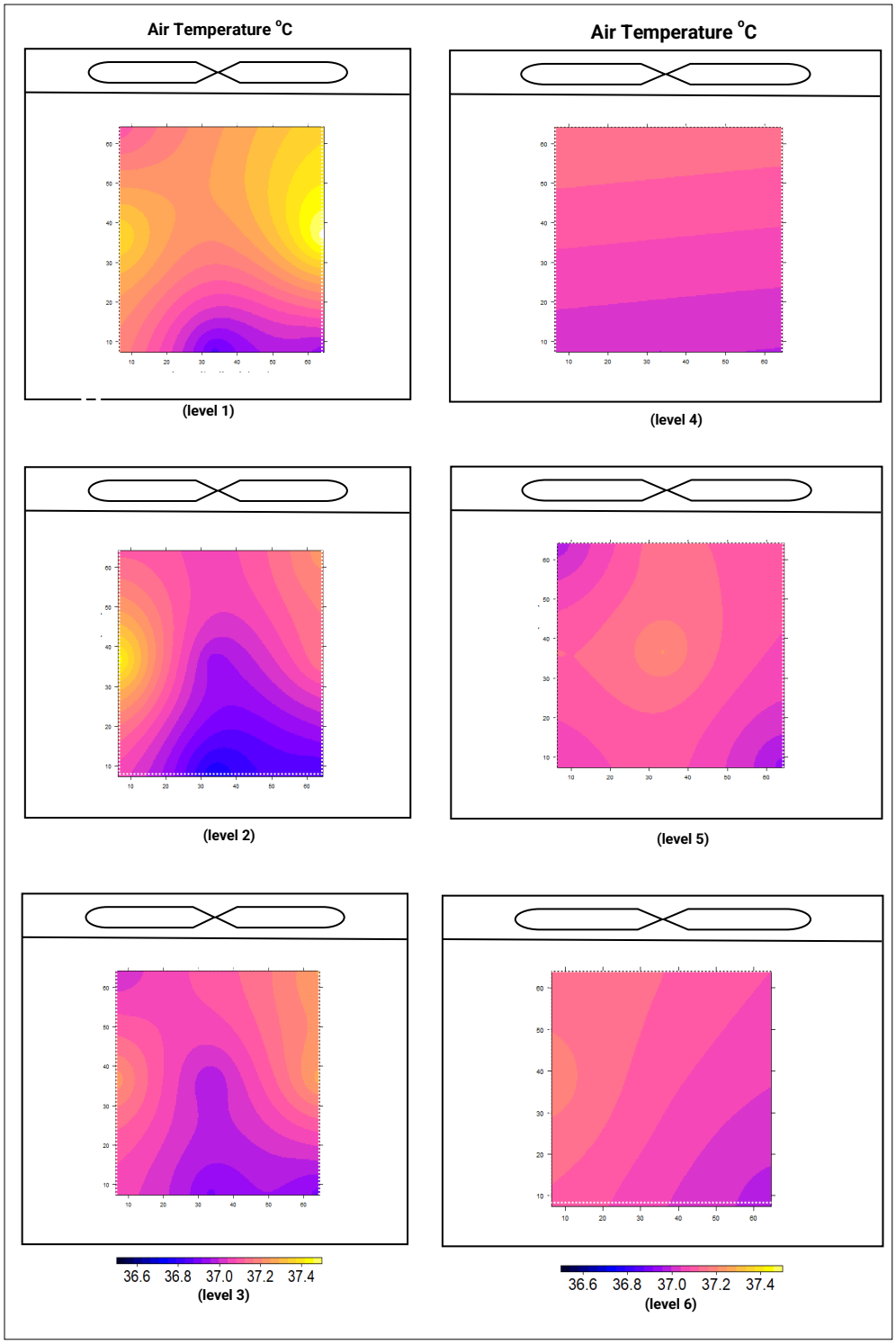


Figure 11. Spatial mapping of air temperature for each chick basket at each level during hatcher-phase incubation. The interior incubator wall perimeter and fan are included for reference. The white dashed line indicates the perimeter of each chick basket at each level.

Humidity

Setter-Phase Incubation

Level was different (P<0.0001) for VPD during SPI. The minimum VPD of 2.00 kPa occurred at level 6, while the maximum VPD of 2.05 kPa occurred at level 2. The difference between minimum and maximum VPD (0.05 kPa) translates to a difference of 0.97% in relative humidity. This would be smaller than the accuracy of our humidity meter at ±5%

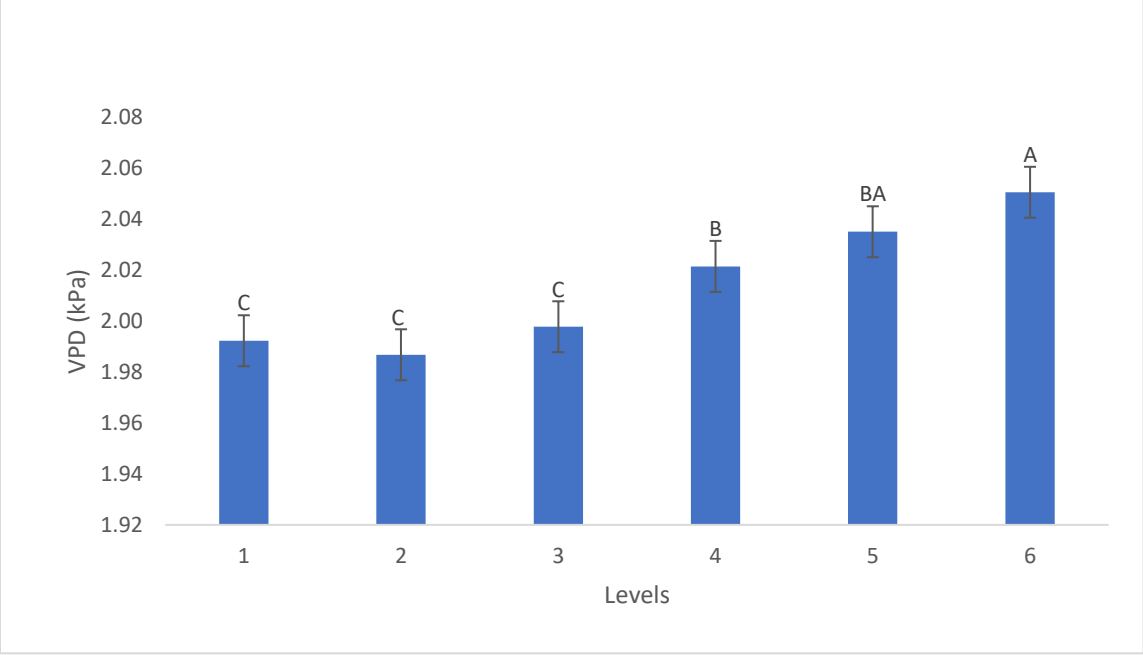


Figure 12. Mean vapor pressure deficit (VPD) at the top surface of egg trays for each of six levels during setter-phase incubation.

Hatcher-phase Incubation

Level was different (P<0.0001) for VPD during HPI. The minimum VPD of 1.99 kPa occurred at level 2, while the maximum VPD of 2.05 kPa occurred at level 6. The difference between minimum and maximum VPD (0.05 kPa) translates to a difference of 0.78% in relative humidity. Again, this would be smaller than the accuracy of our humidity meter at ±5%

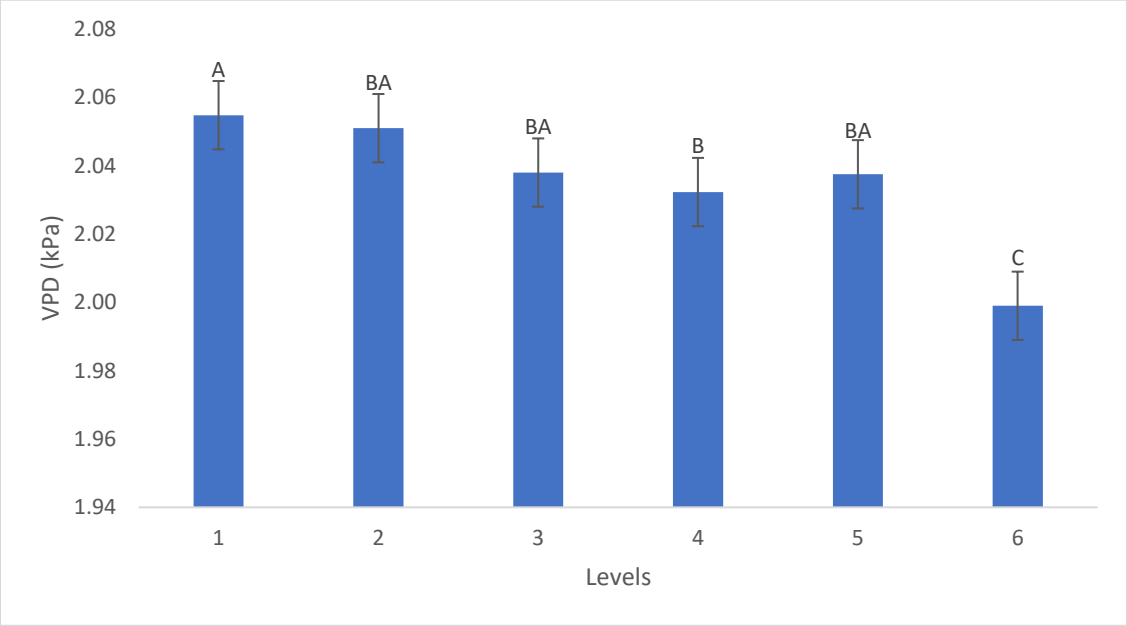
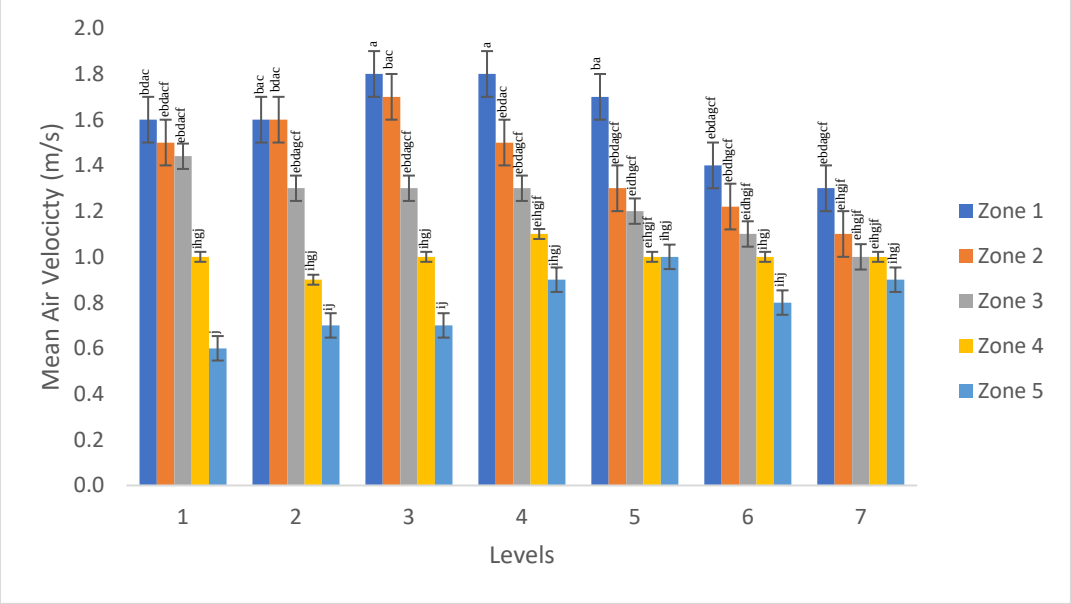


Figure 13. Mean vapor pressure deficit (VPD) at the top surface of chick baskets for each of six levels during hatcher-phase incubation.

Air Velocity

Setter-Phase Incubation

There was a location ($P < 0.0001$), level ($P < 0.0001$), and location by level interaction ($P < 0.0039$) for air velocity. Least Squares means for each location by level combination are summarized in Fig. 14. The minimum air velocity of 0.6 m per s occurred at zone 5 on level 1. The maximum air velocity of 1.8 m per s occurred at zone 1 on levels 3 and 4. Fig. 15 illustrates the mean air velocity map across each of the seven levels (six above the egg trays and one at bottom of the incubator) during setter-phase incubation. The dimensions of the incubator and fan location are included for reference. The white dashed line indicates the perimeter of each egg tray at each level. In general, air velocity is higher near the back of the incubator near the fan and lower between the egg trays and at the front of the incubator near the doors. However, the air velocity is within the recommended range of 0.25 to 3.00 m per s (Lourens, 2001; Kaltofen, 2007).



Means with different superscripts differ $P < 0.05$.

Figure 14. Least square means of air velocity by zone and location of egg tray.

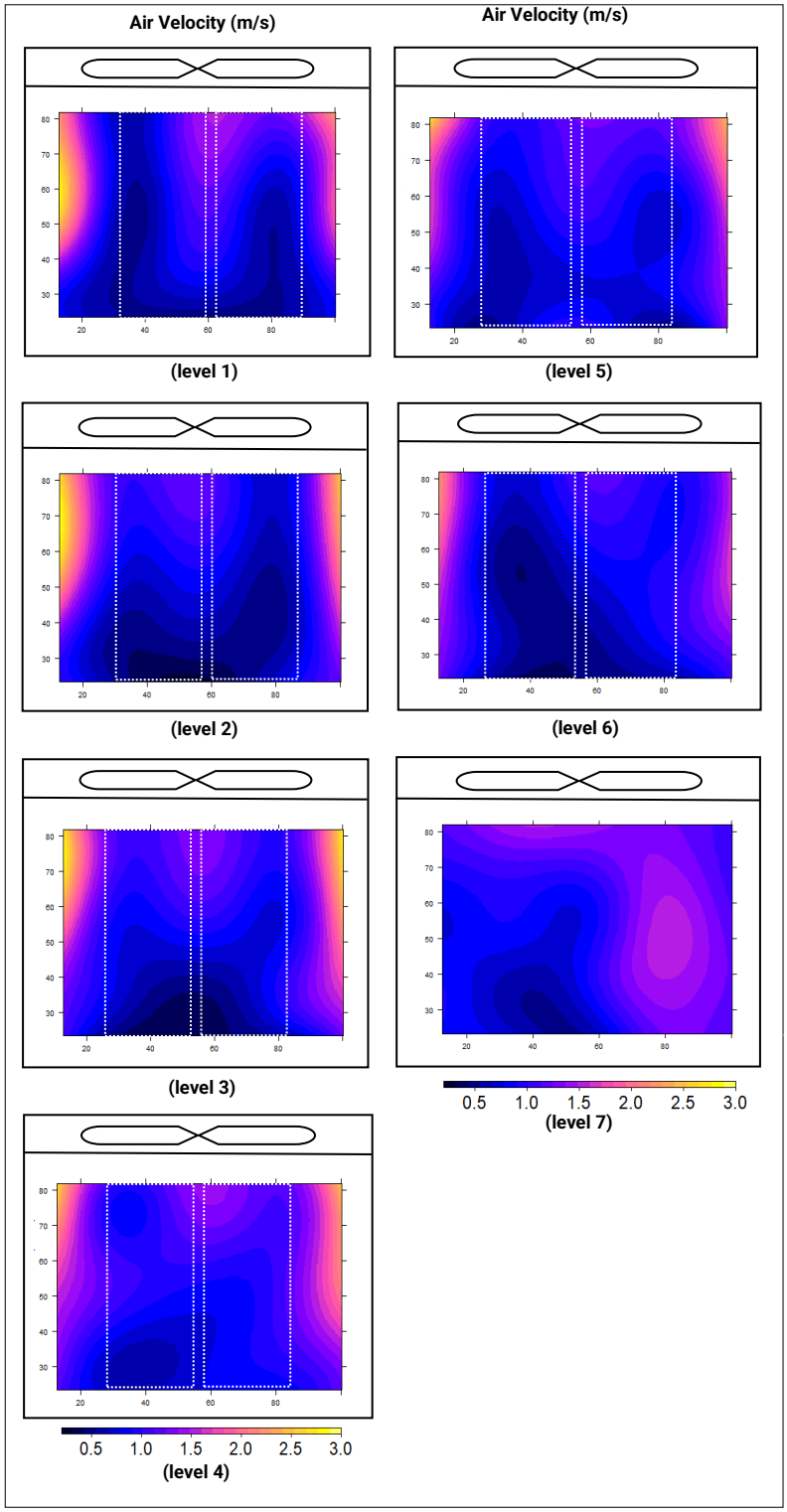
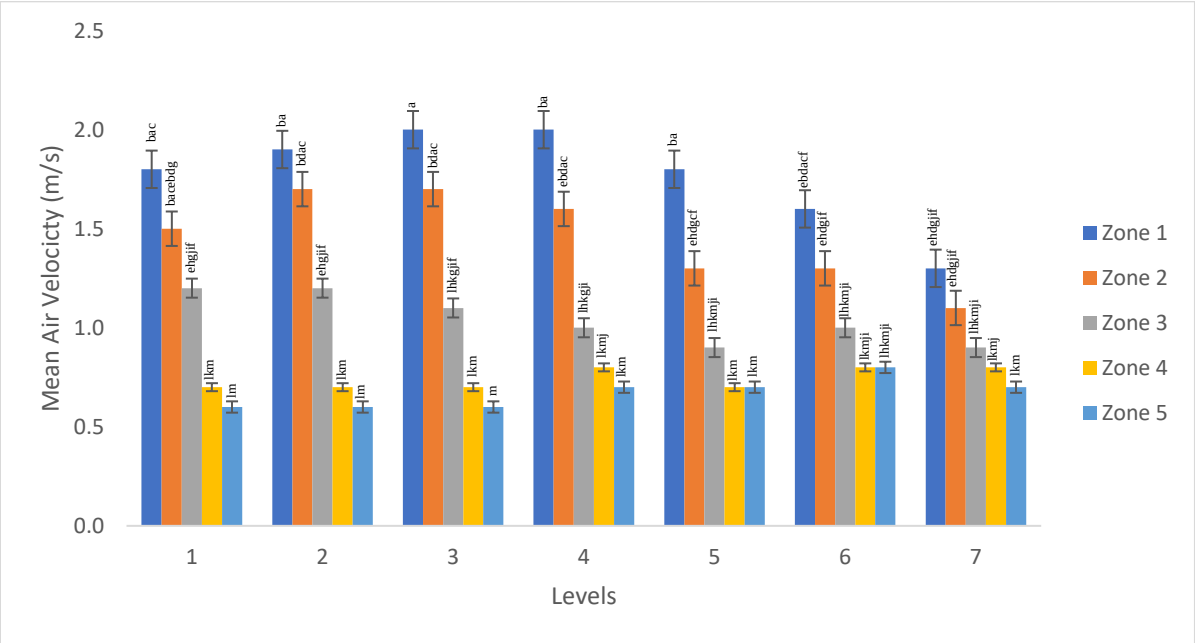


Figure 15. Spatial mapping of air velocity for each level during hatcher-phase incubation with egg trays. The interior incubator wall perimeter and fan are included for reference. The white dashed line indicates the perimeter of each egg tray at each level.

Hatcher-phase Incubation

There was a location ($P < 0.0001$), level ($P < 0.0001$), and location by level interaction ($P < 0.0001$) for air velocity. Least Squares means for each location by level combination is summarized in Fig. 16. The minimum air velocity of 0.6 m per s occurred at zone 5 on levels 1, 2, and 3. The maximum air velocity of 1.8 m per s occurred at zone 1 on levels 3 and 4. Fig. 17 illustrates the mean air velocity map across each of the seven levels (six above the egg trays and one at bottom of the incubator) during hatcher-phase incubation. The dimensions of the incubator and fan location are included for reference. The white dashed line indicates the perimeter of each egg tray at each level. Again, air velocity is higher near the back of the incubator near the fan and lower between the egg trays and at the front of the incubator near the doors. There is no difference between setter-phase incubation and hatcher-phase incubation levels unless for low air velocity at locations 2 and 3. However, they are within the recommended range of 0.25 m per s and 3.00 m per s (Lourens, 2001, and Kaltofen, 2007).



Means with different superscripts differ $P < 0.05$.

Figure 16. Least square means of air velocity by zone and location of egg basket.

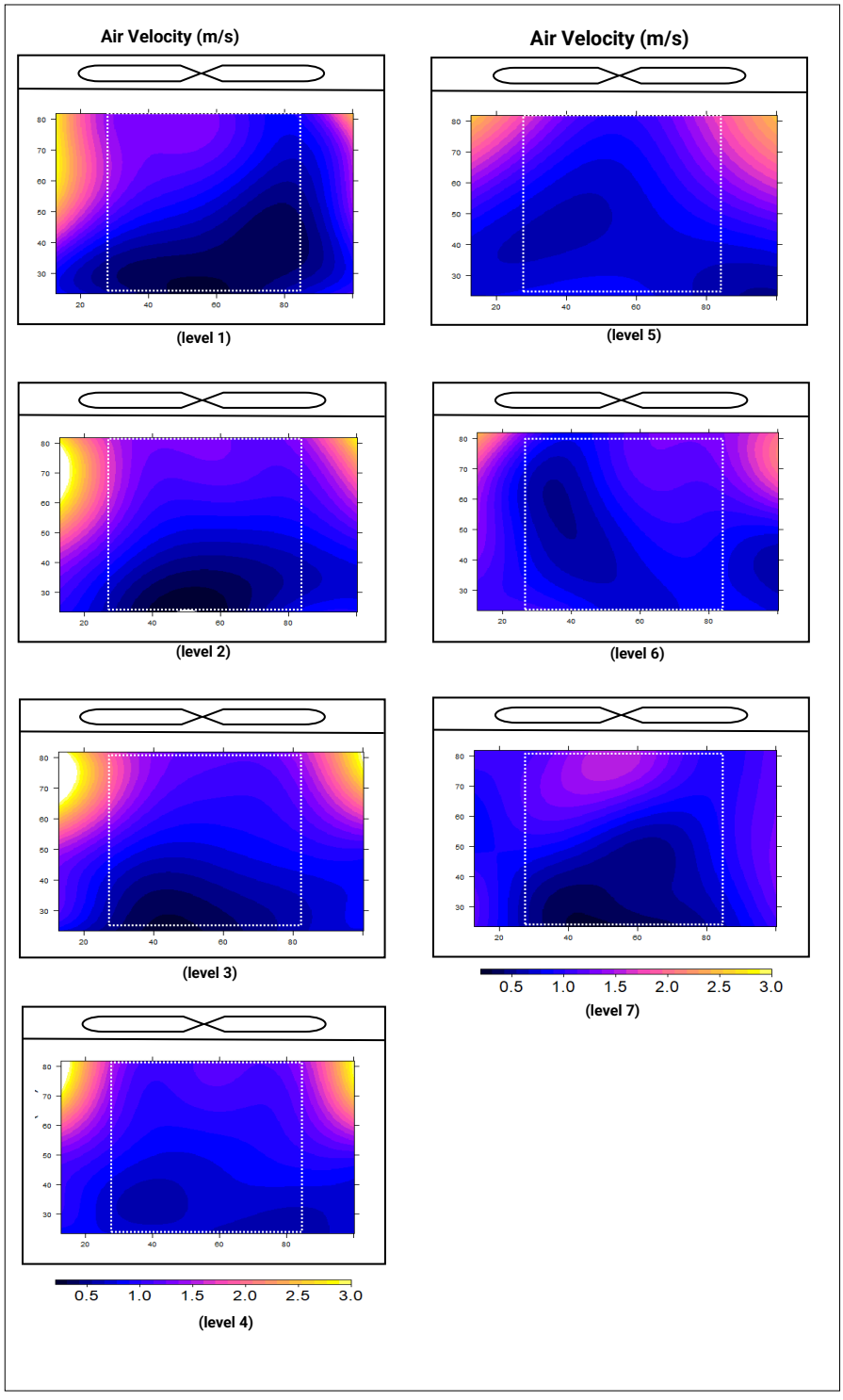


Figure 17. Spatial mapping of air velocity for each level during hatcher-phase incubation with chick baskets. The interior incubator wall perimeter and fan are included for reference. The white dashed line indicates the perimeter of each chick basket at each level.

Conclusions

This study evaluated the thermal parameters of air temperature, humidity, and air velocity within a Natureform single-stage incubator. Air temperature had an interaction between location and level within the incubator, with a maximum air temperature difference of 0.9 °C. In general, air temperature was warmest near the back of the incubator towards the heating bars, with an approximately 0.6 °C drop toward the front of the incubator within each level. Vapor pressure deficit was different for level; however, the difference in relative humidity was only approximately 1.8% different. Air velocity had an interaction between location and level within the incubator, with a maximum difference of 1.4 m per s. In general, air velocity was highest at the back of the incubator near the fans and around the outside of the trays and baskets. Air velocity was lowest between the egg trays and through the chick baskets due to obstructions from baskets and trays. However, all air velocities were above the minimum required level. This study characterized air velocity patterns in a Natureform single-stage incubator and provides a methodology to measure air temperature and relative humidity variation during research studies involving live embryos. Three-dimensional printed eggs fitted with iButtons can be used to capture air temperature and relative humidity near the egg surface.

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