Quantification of the Heat Exchange of Chicken Eggs

A. Van Brecht,* H. Hens,† J.-L. Lemaire,* J. M. Aerts,* P. Degraeve,‡ and D. Berckmans*,[1]

*Department of Agro-engineering and -Economics, Catholic University of Leuven, Kasteelpark Arenberg 30, B-3001 Leuven, Belgium; †Departement Burgerlijke bouwkunde, Catholic University of Leuven, Kasteelpark Arenberg 51, B-3001 Leuven, Belgium; and ‡Petersime N.V., Centrumstraat 125, B-9870 Zulte (Olsene), Belgium

ABSTRACT In the incubation process of domestic avian eggs, the development of the embryo is mainly influenced by the physical microenvironment around the egg. Only small spatiotemporal deviations in the optimal incubator air temperature are allowed to optimize hatchability and hatchling quality. The temperature of the embryo depends on 3 factors: (1) the air temperature, (2) the exchange of heat between the egg and its microenvironment and (3) the time-variable heat production of the embryo. Theoretical estimates on the heat exchange between an egg and its physical microenvironment are approximated using equations that assume an approximate spherical shape for eggs. The objective of this research was to determine the heat transfer between the eggshell and its microenvironment and then compare this value to various theoretical estimates. By using experimental data, the overall and the convective heat transfer coefficients were determined as a function of heat production, air humidity, air speed, and air temperature. Heat transfer was not affected by air humidity but solely by air temperature, embryonic heat generation, and air speed and flow around eggs. Also, heat transfer in forced-air incubators occurs mainly by convective heat loss, which is dependent on the speed of airflow. A vertical airflow is more efficient than a horizontal airflow in transferring heat from the egg. We showed that describing an egg as a sphere underestimated convective heat transfer by 33% and was, therefore, too simplistic to accurately assess actual heat transfer from real eggs.

(*Key words*: convection coefficient, temperature, velocity, humidity, airflow pattern)

2005 Poultry Science 84:353–361

INTRODUCTION

In the incubation process of domestic avian eggs, development of an embryo is mainly influenced by the physical microenvironment around the egg (Meir and Ar, 1987; Swann and Brake, 1990a,b,c). The incubation temperature around the eggs is of vital importance for the development of the embryo, because it is essentially a poikilotherm until hatch (Decuypere and Michels, 1992). Small deviations from the optimal incubation temperature (37.5 to 37.8°C) will lead to changes in total incubation length because the metabolic rate of an embryo is directly related to its temperature prior to pipping (Whittow and Tazawa, 1991), and greater deviations will affect the percentage hatchability of eggs (Burton et al., 1989; Visschedijk, 1991; Decuypere and Michels, 1992). Therefore, deviations in the physical microenvironment around the egg will cause practical, organizational, or management problems because modern hatcheries have a double goal—maximizing the hatchability as well as synchronizing the time of hatch.

The temperature of the embryo depends on 3 factors: (1) the air temperature, (2) the exchange of heat between the egg and its microenvironment, and (3) the time-variable heat production of the embryo (French, 1997). Estimates on the heat exchange between an egg and its physical microenvironment show that it is strongly influenced by the air speed around the egg (Sotherland et al., 1987; Meijerhof and van Beek, 1993). But the trend toward larger capacity incubators (e.g., 115,200 eggs per incubator) results in spatiotemporal gradients in air temperature, air speed, and complex 3-dimensional airflow patterns (Van Brecht et al., 2003), resulting in gradients in direction and magnitude of the air flowing around the eggs, which will affect this heat transport.

The heat transport between an egg and its environment is modeled by approximating the complex 3-dimensional asymmetrical shape of an egg as a sphere (Sotherland et al., 1987; Meijerhof and van Beek, 1993). However, these theoretical approximations have not been validated.

It has been shown that the uniformity in air temperature in an incubator could be increased by controlling the 3-dimensional airflow pattern (Van Brecht et al., 2003). But to be able to control the temperature of an

---

Received for publication June 1, 2004.

Accepted for publication October 27, 2004.

[1] To whom correspondence should be addressed: daniel.berckmans@agr.kuleuven.ac.be.

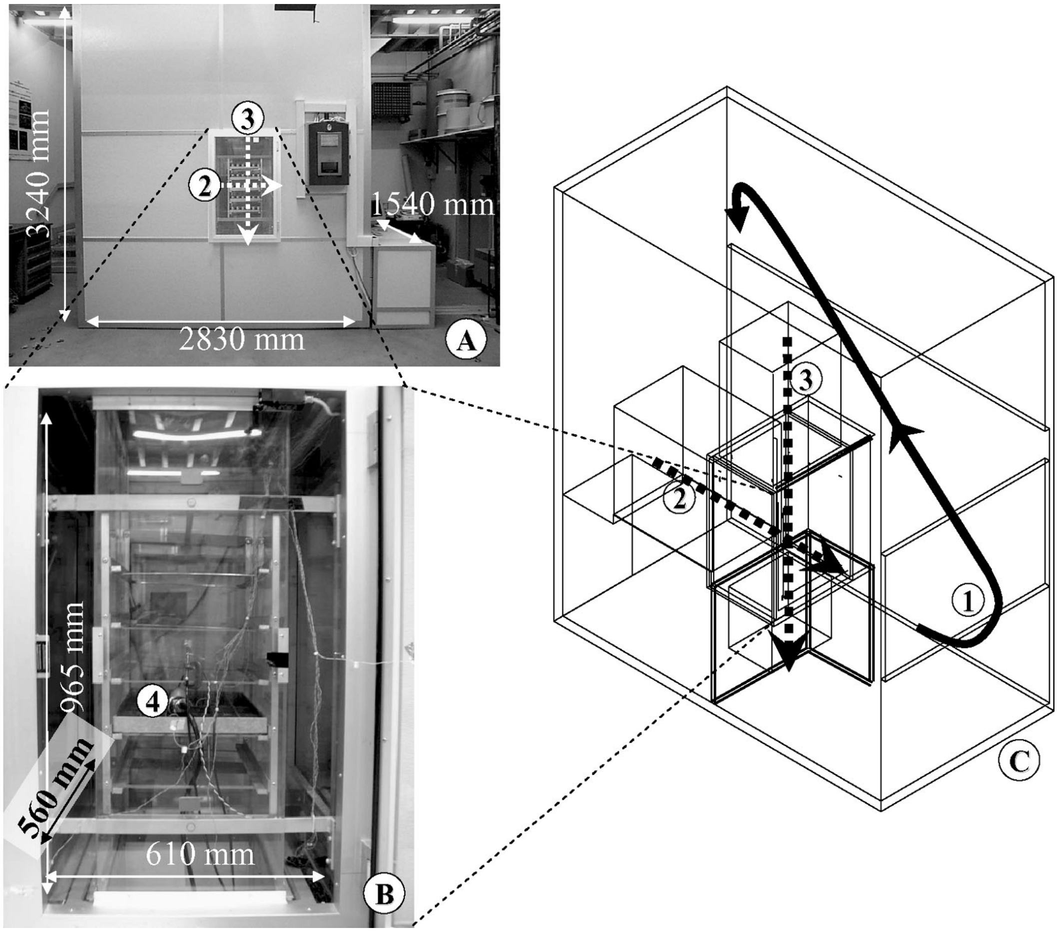

FIGURE 1. Incubator installation: (A) front view, (B) detail of egg trays, and (C) schematic 3-dimensional drawing. (1) Airflow through axial ventilator, (2) air inlet horizontal flow, (3) air inlet vertical flow, and (4) egg trays and turning mechanism.

embryo more uniformly, it is important to gain understanding as to which parameters primarily affect heat transport between the embryo and its microenvironment under practical conditions.

The objective of this research was to quantify the effect of air temperature, air humidity, air speed, and airflow direction by measurements on the heat exchange between the eggshell and its microenvironment.

MATERIALS AND METHODS

Test Installation

To be able to quantify the heat exchange between the eggshell and its microenvironment, a laboratory incubator test installation measuring 2,830 × 3,240 × 1,540 mm was built, which is a small section of an industrial incubator and can incubate 300 chicken eggs (Figure 1). Five egg trays can be placed in this incubator, with 60 eggs per tray (485 × 295 mm) (number 4 in Figure 1B). The ratio of air to egg volume in this incubator (0.12% of the total incubator volume is occupied by eggs) is much larger than in commercial incubators. The larger air-to-egg volume ratio made horizontal and vertical airflows over the eggs possible and increased the uniformity of

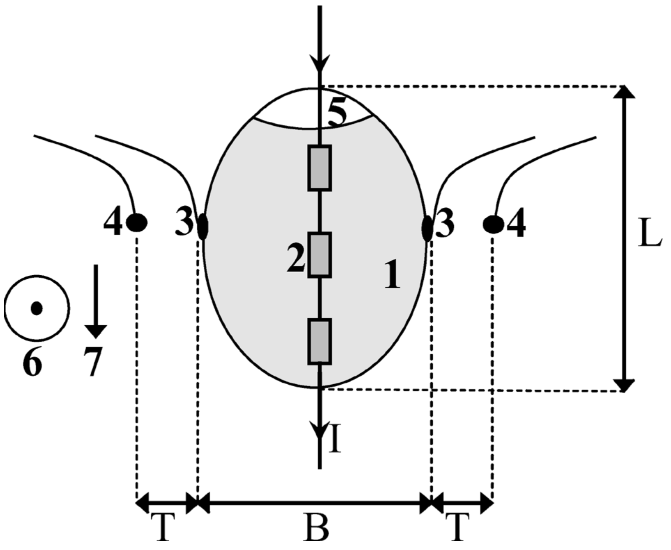

FIGURE 2. The instrumented egg with breadth (B) and length (L). T = distance between the air thermocouple and the eggshell at the equator of the egg. (1) Water, (2) resistors, (3) thermocouples attached to eggshell, (4) thermocouples measuring air temperature, (5) air chamber, (6) direction of horizontal airflow, and (7) direction of vertical airflow.

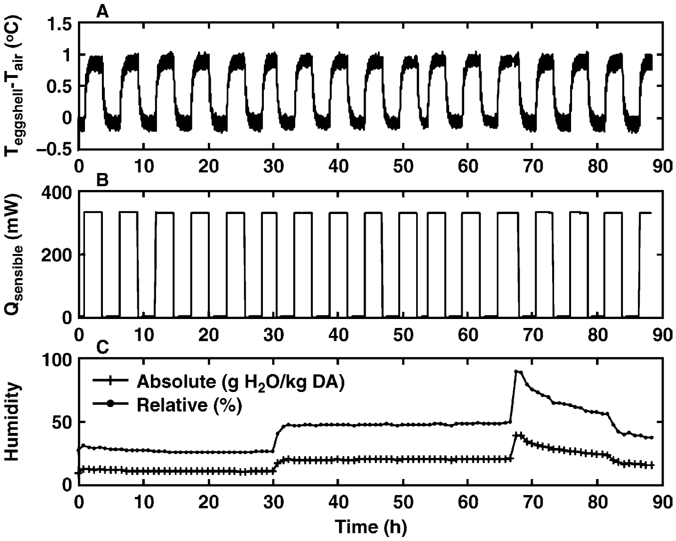

FIGURE 3. (A) Difference between eggshell and microenvironmental air temperatures between 0 and 88 h under variable heat production and horizontal airflow as well as constant air temperature and air speed. (B) Sensible heat production. (C) Absolute and relative air humidity of horizontal airflow. DA = dry air.

air entering the inlet section (2 or 3 in Figure 1) and flowing toward the eggs.

An air conditioning unit provides heat, cooling, and moisture used by a control unit to keep the air temperature and the humidity at the desired set points. The test installation is equipped with an electrical heating system of 4 heating coils of each 600 W. To cool, water flows through a cooling tube of 5.05 m and a diameter of 1.50 cm. The water enters the cooling tube at approximately 10.5°C, flows at 0.55 m^3/h, and flows out at a temperature of about 11.8°C. This process yields a cooling capacity of about 800 W.

A humidifier consists of cylinders with plastic discs that slowly rotate in a water pan and provides a smooth, constant humidification as needed. A fan circulates the conditioned air around the eggs before being returned to the air conditioning unit; a variable recirculation airflow (from 0 to 4,000 m^3/h with an accuracy of ±40 m^3/h), was achieved with this process, resulting in air speeds ranging from 0.22 to 3.10 m/s.[2]

Heat Exchange of an Egg

The heat exchange of an egg with its microenvironment is dependent on the physical environmental conditions. Metabolic reactions of the growing embryo produce sensible heat $Q_{sensible}$ (W). On the other hand, water is evaporated from the embryo and diffused through the eggshell pores. The evaporation of water removes latent heat Q_{latent} (W) from the embryo. The latent heat production of the egg is the result of the evaporation of water:

$$Q_{latent} = \dot{m}_{water} \times \varepsilon \qquad [1]$$

where $\dot{m}_{water}$ is the rate of water loss (kg_{water}/s); ε is the latent heat of evaporation of water (2,500.4 kJ/kg_{water}]. The net amount of heat Q (W) lost or retained by the embryo is

$$Q = Q_{sensible} + Q_{latent} \qquad [2]$$

The latent heat production of an embryo depends on the amount of water evaporated, which is determined by the water vapor eggshell conductance and the partial pressure difference over the eggshell (Visschedijk, 1991), because the respiratory gas exchange does not result in total mass changes (Drent, 1975). Moreover, the latent heat production is directly proportional to the amount of water lost, which can be measured by changes in weight.

The sensible heat exchange of an egg with its environment is more complex and may occur by 1 or more of the 3 basic heat mechanisms of heat transfer: conduction, convection, or radiation. Heat exchange though conduction is important in natural incubation, in which an incubating bird makes contact with the egg by its brood patch. However, in commercial incubation, heat transfer through conduction is negligible because the contact area of the egg with the egg tray is very small. Heat transfer through convection involves the heat exchange between the eggshell and the surrounding air. Unlike natural incubation in which mainly free convection occurs when the hen leaves the nest, in commercial incubators mainly forced convection occurs because the air speed in these incubators is high (Van Brecht et al., 2003). Radiation differs from heat transfer by conduction and convection in that no physical medium is needed for its propagation. It is less important in commercial

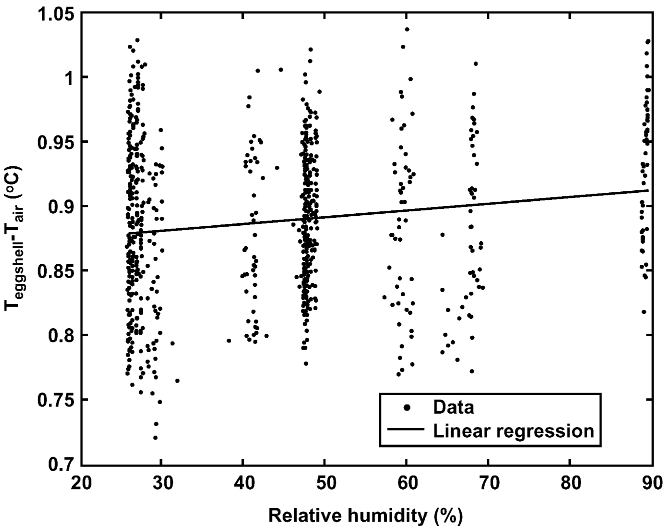

FIGURE 4. The temperature difference between the eggshell and the air as a function of the relative air humidity.

---

[2] TSI 8455-225, 2% accuracy of reading, TSI Inc., Shoreview, MN (www.tsi.com).

TABLE 1. Overview of the experiments

Experiment	Heat production	Air temperature	Air humidity	Air speed	Air flow direction
1	0 constant value	Constant	Variable	Constant	Horizontal
2	0 constant value	Constant	Constant	Variable	Horizontal
3	0 constant value	Constant	Constant	Variable	Vertical

incubators because most eggs are surrounded by other eggs with the same surface temperature (Kashkin, 1961). However, for eggs located at the edges, radiation could be important when these eggs are facing the heating or cooling coils or the colder walls of the incubator. Heat transport through radiation must be considered in natural incubation when a hen leaves her nest and in eggs that are located at periphery of a commercial incubator facing a heat exchanger or a wall.

The total amount of sensible heat exchange is the sum of the heat dissipated by radiation ($Q_{radiation}$; [W]), convection ($Q_{convection}$; [W]), and conduction ($Q_{conduction}$; [W]):

$$Q_{sensible} = Q_{radiation} + Q_{convection} + Q_{conduction} \qquad [3]$$

Instrumented Egg

To be able to measure the sensible heat exchange of an egg with its microenvironment, an instrumented egg was manufactured. The albumen and yolk of an egg with length 66.4 mm and maximum breadth 44.5 mm were removed by drilling 2 holes of 3 mm diameter at the top and the bottom of the egg. To be able to simulate the sensible heat production of the egg, 3 electrically isolated resistors connected in series were placed in the center of the egg (Figure 2). After resistors were inserted in the egg, the holes were closed with glue.[3] The total resistance of the resistors was 129.4 Ω. By applying current over this series of resistors, an amount of power is dissipated, which can be calculated by measuring the current through the series:

$$Q_{sensible} = R \times I^2 \qquad [4]$$

where R is the resistance (Ω), and I is the current through the resistors (A).

To simulate the embryo and transport the heat produced by the resistors, the instrumented egg was filled with water, leaving a small air space at the top of the egg. The inner shell of the instrumented egg was treated with a plastic film[4] to reduce the water vapor conductance.

This instrumented egg was placed in the center of an egg tray, which was positioned in the middle of the incubator. Four very small (1 mm diameter) and accurate thermocouples[5] were used to measure the air and the eggshell temperature. Air thermocouples (4 in Figure 2) were mounted 1 cm (T = 1 cm) away from the eggshell thermocouples that were attached in the middle of the eggshell by a small piece of aluminum tape (0.3 × 0.3 cm). A dew point meter[6] was used to accurately measure the air humidity. The sensors (6 in Figure 2) were positioned such that they were always in the airflow (7 in Figure 2). Recordings from the thermocouples, humidity sensor, and current through the resistors were taken every 30 s.

Eggshell Area

All heat exchange occurs through the eggshell surface, making it necessary to determine the surface area of the eggshell ($A_{eggshell}$; m^2), which was calculated from measurements of its length (L; m) and breadth (B; m) (Figure 2) using equation [5] provided by (Narushin, 2001).

$$A_{eggshell} = 3.142 \times \left(\frac{L}{1{,}000}\right)^2 \times n^{-0.532} \qquad [5]$$

in which

$$n = 1.057 \left(\frac{L}{B}\right)^{2.372} \qquad [6]$$

The characteristic dimension (D; m) of an egg is spherical with diameter D that has an identical surface area to an egg (equation [7]). The characteristic dimension is used in the literature to calculate the convective heat transfer coefficient (Meijerhof and van Beek, 1993).

$$D = \sqrt{\frac{A_{eggshell}}{\pi}} \qquad [7]$$

Radiative Heat Transport

When a large number of eggs are closely packed in insulated incubators, each egg is surrounded by other eggs, all of which have more or less the same surface temperature (Kashkin, 1961). Under these circumstances, radiation heat emission as a fraction of the total heat emission is minimal, and the total sensible heat will be exchanged mainly by convection.

TABLE 2. Physical properties of the instrumented egg

Breadth	Length	Total surface area	Characteristic dimension
4.45 cm	6.64 cm	81.17 cm^2	5.08 cm

---

[3] Cyano acrylate lime, Henkel KGaA, Düsseldorf, Germany.

[4] Plastic 70 film, Kontact chemie GmbH, Rastalt Germany.

[5] Thermocouple Type T, accuracy <±0.1% of reading, Comark (www.comarkltd.com).

[6] Michell Instruments Benelux, accuracy ±0.5% relative humidity, Michell Instruments (www.michell-instruments.nl).

TABLE 3. Summary of microenvironmental conditions in experiment 1

$T_{eggshell} - T_{air}$ at 0 mW	Maximal heat production	Average air temperature	Air humidity	Air speed
0.0046 ± 0.0057 °C	328.14 ± 0.02 mW	37.35 ± 0.16°C	16–39 g H_2O/kg dry air 26–88%	3.10 ± 0.0011 m/s

Because the aim of this research was to study the factors affecting heat transport between the eggshell and the surrounding air in forced-convection incubators, the effect of heat emission by radiation was considered to be of minor importance. To eliminate the effect of radiant heat emission in the test installation, the walls surrounding the egg were covered with anodized aluminum foil, which has an emissivity of only 0.05. As in commercial incubators, almost all radiant energy emitted by an egg is reflected back to the egg, yielding no net energy loss through radiation.

Experiments

Three types of experiments were conducted to quantify the heat exchange between an egg and its environment (Table 1). In all experiments, the air temperature was kept constant, sensible heat production was set on and off for a fixed time, and the temperature difference between the eggshell and air was measured. In the first experiment the effect of air humidity on the heat exchange was studied. The absolute and relative humidities inside the incubator were changed by adding moisture to the air in the incubator and then ventilating with dry air, resulting in a wide range of air humidities. In the second experiment the air velocity of the horizontal airflow over the egg was varied. The third experiment was the same as the second, but the airflow was vertical.

Statistical Analysis

The method of least squares was used to estimate the parameters in the regression equations. All confidence intervals and statistics were based on a normal distribution with a significance level of 0.05.

RESULTS AND DISCUSSION

Instrumented Egg

The physical properties of the instrumented egg are given in Table 2. The breadth B and length L of the egg were measured with a micrometer with an accuracy of 0.1 mm.[7] The total surface area of the egg was calculated with equation [5], from which the hydraulic diameter was calculated using equation [7]. In all the analyses, averages were taken of the air temperature measurements and of the eggshell temperature measurements.

The water vapor conductance of the egg after the treatment with plastic film was 2.32 mg of $H_2O/(\text{day} \times \text{torr})$. The latent heat production resulting from this water loss was calculated using equation [1] and yielded 1.65 mW. Because the energy dissipated through the resistors was about 300 mW, almost all the heat produced by the resistors was lost to the environment as sensible heat.

Experiment 1

In the first experiment, we investigated whether the overall heat transport of the instrumented egg was a function of absolute humidity, relative humidity, or both. In Figure 3, the temperature difference between the eggshell and its microenvironment as a function of the heat production, the absolute air humidity, and the relative air humidity is shown. The air temperature and air velocity were kept constant (Table 3). Heat production of the instrumented egg was alternated between being turned on for 3 h and off for 3 h. The temperature difference reached steady state after approximately 1 h. When there was no heat production, the temperature difference between the eggshell and the air temperature was approximately zero (Table 3). From Figure 3 it can be concluded that the increases in absolute and relative humidities at approximately 67 h did not appear to affect the temperature difference between the eggshell and surrounding air.

In Figure 4, the temperature difference between the eggshell and its microenvironment is shown as a function of the relative air humidity. Because the air temperature was kept constant during the experiment, the absolute humidity was directly related to the relative humidity. A significance of regression test (Montgomory and Runger, 1994) was performed to test whether a linear relationship between the absolute and relative air humidity and temperature difference between the eggshell and its microenvironment was significant (Table 4). We concluded at a 5% significance level that absolute or the relative air humidity did not explain the variation in the temperature difference. The best

TABLE 4. Significance of regression between the regressor variable and the temperature difference between the eggshell and the air

Regressor variable	R^2	n	$t_{critical}$	$t_{\alpha/2,n-2}$	P-value
Absolute humidity	0.0218	816	4.259	1.645	1.15×10^{-5}
Relative humidity	0.0225	816	4.332	1.645	8.31×10^{-6}

---

[7] Mitutoyo (www.mitutoyo.com).

TABLE 5. Summary of microenvironmental conditions in experiment 2

$T_{eggshell} - T_{air}$ at 0 mW	Maximal heat production	Average air temperature	Air humidity	Air speed
0.0020 ± 0.0018°C	285.60 ± 0.10 mW	37.36 ± 0.035°C	49.3 ± 2.9%	0.22–2.52 m/s

TABLE 6. Summary of microenvironmental conditions in experiment 3

$T_{eggshell} - T_{air}$ at 0 mW	Maximal heat production	Average air temperature	Air humidity	Air speed
0.0015 ± 0.0021°C	288.68 ± 0.25 mW	37.03 ± 0.15°C	53.4 ± 2.0%	0.25–2.05 m/s

estimator of the temperature difference for any air humidity level was the mean temperature difference.

The data show that the heat transfer was unaffected by the humidity level of the air. This finding might be surprising, given that the thermal conductivity of liquid water is appreciably higher than that of dry air. However, the moist fraction of air does not consist of liquid water but of water vapor, which has a thermal conductivity of 0.017 W/(m × K) at 37.8°C (Kaye and Laby, 1973). Theoretical simulations have shown that the heat transfer coefficient depends largely on the thermal conductivity of air from 0.03 to 0.08 W/(m × K) (Meijerhof and van Beek, 1993). The minimum and maximum temperatures that are likely to occur in commercial incubators are 36.70 and 39.58°C, respectively, (Van Brecht et al., 2003); thus, the thermal conductivity may range only from 0.0269 to 0.0271 W/(m × K). Because the total mass of water vapor in moist air is a low percentage, the thermal conductivity of moist air is nearly the same as that of dry air, which explains why the humidity level of moist air does not have a significant effect on the heat transfer coefficient.

Experiment 2

The temperature difference between the eggshell and its microenvironment as a function of the heat production and air speed of horizontal airflow is shown in Figure 5. It is clear that the temperature difference varies due to the variations of the air speed of the horizontal airflow over the egg. Air speeds between 0 and 1 m/s during maximum heat production appear to result in greater temperature differences than the air speeds greater than 2.5 m/s. The result of heat exchange of the eggshell with its microenvironment is, in this case, through convection only.

The air temperature and air humidity were kept constant, and when the sensible heat production of the instrumented egg was off, the temperature difference between the eggshell and the air temperature was approximately zero (Table 5). The air speed was gradually increased from 0.22 to 2.52 m/s while the heat production of the egg was kept on. Toward the end of each air speed level, the data of the last hour were selected to explore the temperature difference between the air and the eggshell as a function of the air speed (Figure 6).

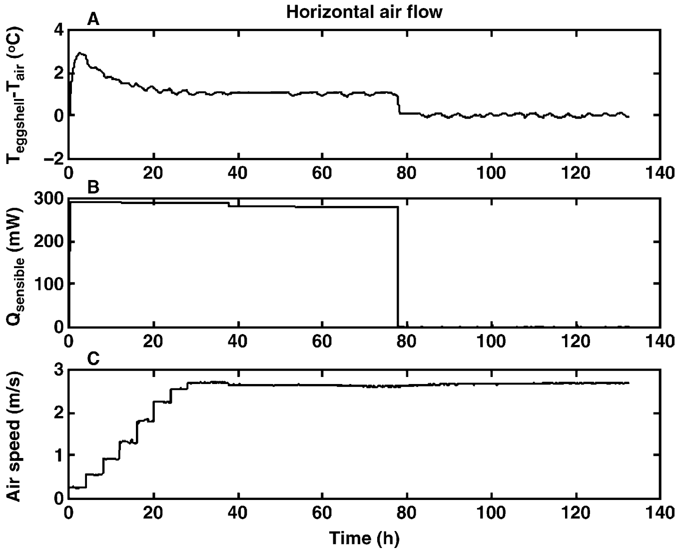

FIGURE 5. (A) Difference between eggshell and microenvironmental air temperatures between 0 and 132 h under variable heat production and horizontal airflow as well as constant air temperature and humidity. (B) Sensible heat production. (C) Air speed of horizontal airflow.

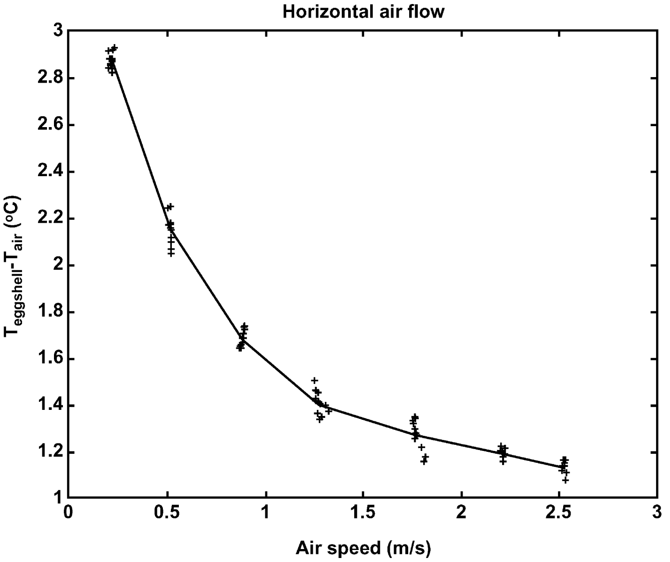

FIGURE 6. The temperature difference between the air and the eggshell as a function of the air speed of a horizontal airflow at 285.6 mW of sensible heat production.

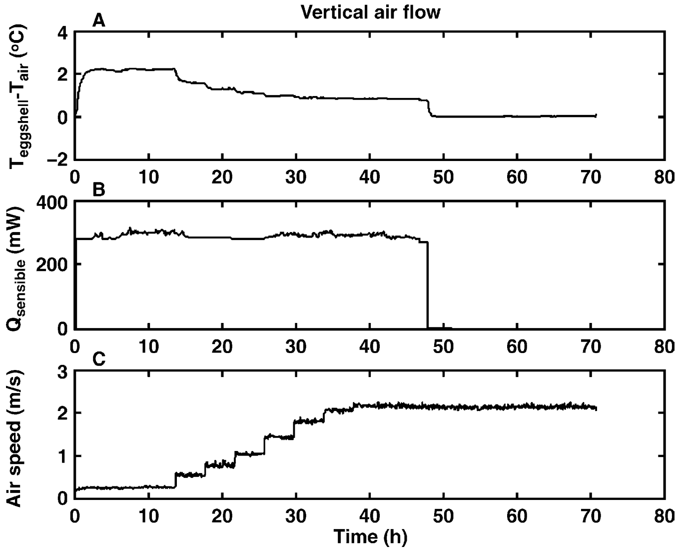

FIGURE 7. (A) Difference between eggshell and microenvironmental air temperatures between 0 and 71 h under variable heat production and horizontal airflow as well as constant air temperature and humidity. (B) Sensible heat production. (C) Air speed of vertical airflow.

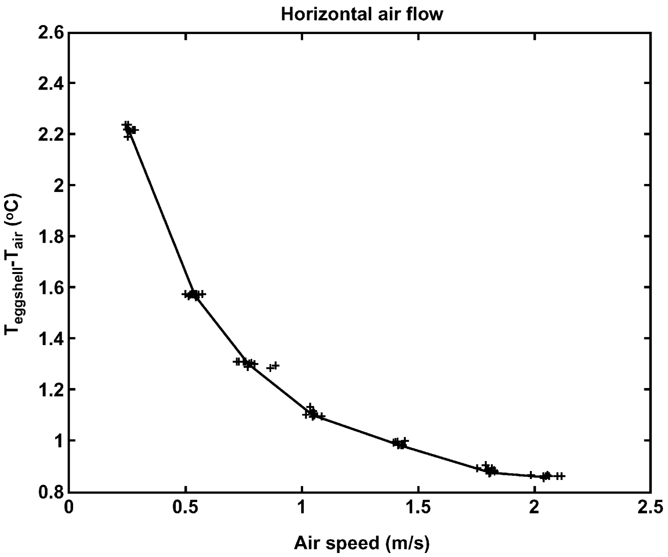

FIGURE 8. The temperature difference between the air and the eggshell as a function of the air speed of a vertical airflow at 288.7 mW of sensible heat production.

Figures 5 and 6 illustrate that the level of heat production, air speed, and temperature of the surrounding air have an effect on the temperature of the eggshell, which the embryo feels.

Experiment 3

The temperature difference between the eggshell and its microenvironment as a function of the heat production and air speed of a vertical airflow is shown in Figure 7. The air temperature and air humidity were kept constant, and when the sensible heat production of the instrumented egg was off, the temperature difference between the eggshell and the air temperature was approximately zero (Table 6). Figure 7 shows that increasing air speeds between 15 and 35 h during maximum heat production resulted in decreasing temperature differences.

Similarly as in experiment 2, the temperature difference between the air and the eggshell as a function of the air speed was calculated. Comparison of Figures 6 and 8 shows that the temperature of the eggshell was not only the result of the level of heat production, air speed, and temperature of the surrounding air but was also due to the way the air flowed around the egg.

To explore the effect of the way the air flows around the egg more in detail, the convective heat transfer coefficients for horizontal (experiment 2) and vertical airflows (experiment 3) were calculated from the mean air and mean eggshell temperature measurements. Because in experiments 2 and 3 almost all radiant energy emitted by the egg was reflected back to the egg, all sensible heat production of the egg was lost to its environment by convective heat transfer. The heat exchange of an egg by convection with the surrounding air could be expressed with the following equation:

$$Q_{sensible} = Q_{convection} = h \times A_{eggshell} \times (T_{eggshell} - T_{air}) \quad [8]$$

where h is the convection heat transfer coefficient [W/($m^2 \times K$)], $A_{eggshell}$ is the surface area of the eggshell (m^2), $T_{eggshell}$ is the mean surface temperature of the egg (°C), T_{air} is the reference air temperature of the egg (°C; determined from the mean of the 2 air temperature measurements). The mean surface temperature of the egg is determined from the mean of the 2 eggshell temperature measurements at the equator of the egg but might differ if large gradients are present in the temperature distribution of the eggshell. The value of the convection coeffi-

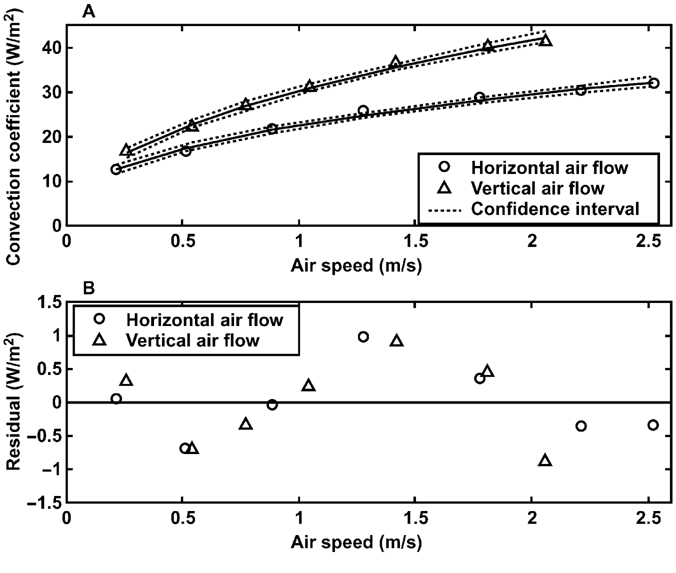

FIGURE 9. (A) Convective heat transfer coefficient measurements, fits of equations [12] and [13] and the 95% confidence intervals as a function of the air speed and airflow direction. (B) The residuals of equations [12] and [13] as a function of the air speed and airflow direction.

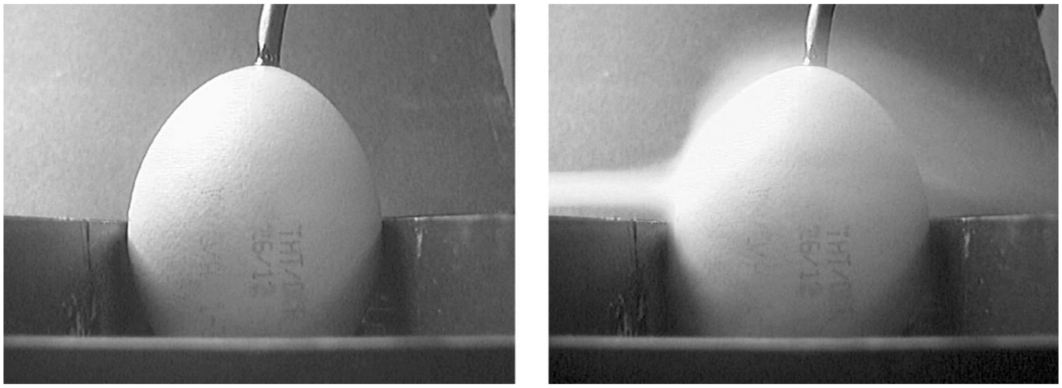

FIGURE 10. Airflow visualization around the instrumented egg for a horizontal airflow at 2 m/s.

cient depends on the choice of the reference temperature. The convection coefficient is not a physical quantity because it is specific to each measurement situation.

In the literature, theoretical equations are used for calculating convective heat transfer coefficient (Kashkin, 1961; Meijerhof and van Beek, 1993). Kashkin (Kashkin, 1961) used equation [9] for calculating the heat emission of an egg by convection. In this equation, the convective heat transfer coefficient [h; W/(m^2 × °C)] is a function of the air speed (V; m/s) around the egg.

$$h = 0.336 \times 4.184 \times (1.46 + \sqrt{V \times 100}) \qquad [9]$$

Meijerhof and van Beek (Meijerhof and van Beek, 1993) simulated the convective heat transfer coefficient of an egg by approximating the egg as a sphere. The convective heat transfer coefficient [h; W/(m^2 × °C)] is then a function of the air speed (V; m/s) around the sphere, the characteristic dimension of the sphere (D; m), and physical properties of air: thermal diffusivity (a_{air}; m^2/s), thermal conductivity [λ_{air}; W/(m × K)], and kinematic viscosity (ν; m^2/s).

$$Nu = 2 + 1.3 \times Pr^{0.15} + 0.66 \times \sqrt{Re} \times Pr^{0.33} \qquad [10]$$

where the dimensionless numbers used in equation [10] are defined as

$$Nu = \frac{h \times 2 \times R}{\lambda_{air}}$$

$$Pr = \frac{\nu}{a_{air}} \qquad [11]$$

$$Re = \frac{2 \times R \times V}{\nu}$$

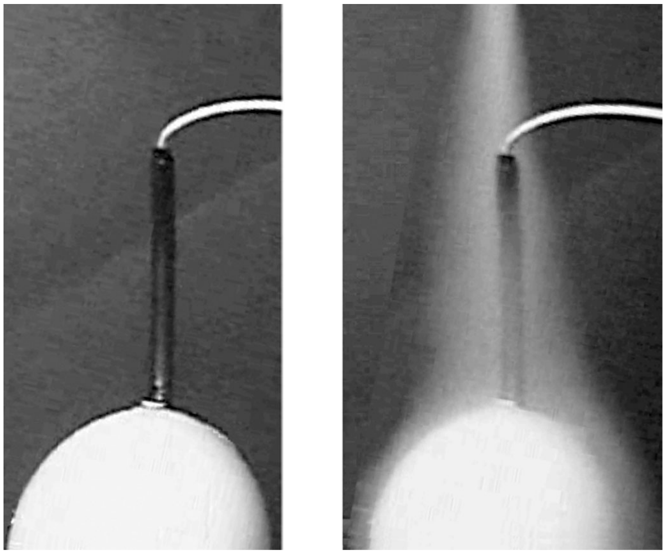

FIGURE 11. Airflow visualization around the instrumented egg for a vertical airflow at 2 m/s.

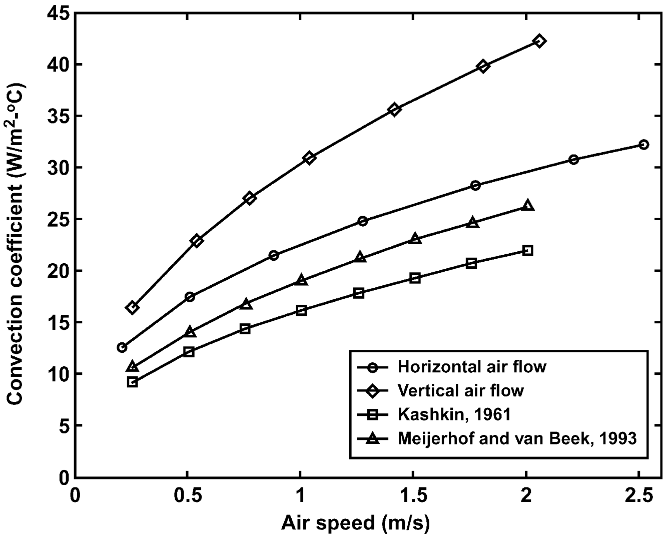

FIGURE 12. The convective heat transfer coefficient as a function of the air speed.

The experimentally determined convective heat transfer coefficient as a function of the air speed and airflow direction is shown in Figure 9. The convective heat transfer coefficient for horizontal and vertical airflows could be described by equations [12] and [13] with coefficients of determination 0.989 and 0.997. The 95% confidence intervals for equations [12] and [13] are shown in Figure 9.

$$h_{horizontal} = 22.55 \times V^{0.387} \qquad [12]$$

$$h_{vertical} = 30.28 \times V^{0.460} \qquad [13]$$

At 0.26 m/s and 2.0 m/s, the convective heat emission for vertical airflow was, respectively, 3.1 W/(m^2 × °C) and 12.2 W/(m^2 × °C) higher than for horizontal airflow.

Horizontal and vertical airflows around the instrumented egg are diagrammed in Figures 10 and 11, respectively. The horizontal airflow impinges on the left side of the eggshell and is then forced upward and downward. Most of the heat transfer will occur at this impinging area, where the air jet has a high velocity, raising the temperature of the air. The air in the wake behind the egg will remove less heat from the heat-producing egg because this air is already warmer and has a lower velocity.

A vertical airflow is much more efficient in transferring heat from or to the egg because the air is spread over the total surface area of the eggshell and speed is not dramatically reduced.

Although the convection coefficient is specific to each measurement situation (positions of temperature and air velocity sensors), in Figure 12 the experimental convective heat transfer coefficient and the convective heat transfer coefficient obtained from literature were compared as a function of air speeds that were measured in commercial incubators (Van Brecht et al., 2003). Equations that approximate the shape of an egg as a sphere underestimate the average measured convective heat transfer coefficient by 39% (Kashkin, 1961) and 29% (Meijerhof and van Beek, 1993) at a velocity of 0.5 m/s and by 38% (Kashkin, 1961) and 27% (Meijerhof and van Beek, 1993) at a velocity of 2.0 m/s, or on average by 33%.

The overall and convective heat transfer coefficients were determined with experimental data as a function of heat production, air humidity, air speed, and air temperature. Heat transfer was not affected by air humidity but by air temperature, embryonic heat generation, and air speed and flow around eggs. Also, heat transfer in forced-air incubators occurs mainly by convective heat loss, which is dependent on the speed of airflow. A vertical airflow is more efficient than a horizontal airflow in transferring heat from an egg. It was shown that describing an egg as a sphere underestimated convective heat transfer by 33% and was, therefore, too simplistic to accurately assess actual heat transfer from real eggs.

ACKNOWLEDGMENTS

The authors kindly thank IWT (Flemish Institute for encouragement of the scientific-technological research in industry) and Petersime (Zulte, Belgium, www.petersime.com) for their contributions to this research.

REFERENCES

Burton, F. G., J. M. Stevenson, and S. G. Tullett. 1989. The relationship between eggshell porosity and air space gas tensions measured before and during the parafetal period and their effects on the hatching process in the domestic-fowl. Respir. Physiol. 77:89–99.

Decuypere, E., and H. Michels. 1992. Incubation temperature as a management tool: A review. Worlds Poult. Sci. J. 48:28–38.

Drent, R. H. 1975. Incubation. Pages 333–420 in Avian Biology. D. S. Farner and J. R. King, ed. Academic Press, New York.

French, N. A. 1997. Modeling incubation temperature: The effects of incubator design, embryonic development, and egg size. Poult. Sci. 76:124–133.

Kashkin, V. 1961. Heat exchange of bird eggs during incubation. Biophysica 6:97–107.

Kaye, G. W. C., and T. H. Laby. 1973. Tables of Physical and Chemical Constants And Some Mathematical Functions. Longman, London

Meijerhof, R., and G. van Beek. 1993. Mathematical modeling of temperature and moisture loss of hatching eggs. J. Theor. Biol. 165:27–41.

Meir, M., and A. Ar. 1987. Improving turkey poult quality by correcting incubator humidity to match eggshell conductance. Br. Poult. Sci. 28:337–342.

Montgomory, D. C., and G. C. Runger. 1994. Applied Statistics and Probability for Engineers. John Wiley, Inc., New York.

Narushin, V. G. 2001. Shape geometry of the avian egg. J. Agric. Eng. Res. 79:441–448.

Sotherland, P. R., J. R. Spotila, and C. V. Paganelli. 1987. Avian eggs: Barriers to the exchange of heat and mass. J. Exp. Zool. 1(Suppl. 1):81–86.

Swann, G. S., and J. Brake. 1990a. Effect of dry-bulb temperature, relative humidity, and eggshell conductance during the first three days of incubation on egg weight loss and chick weight. Poult. Sci. 69:535–544.

Swann, G. S., and J. Brake. 1990b. Effect of dry-bulb temperature, relative humidity, and eggshell conductance during days seventeen to twenty-one of incubation on egg weight loss and chick weight. Poult. Sci. 69:545–553.

Swann, G. S., and J. Brake. 1990c. Effect of incubation dry-bulb and wet-bulb temperatures on time of hatch and chick weight at hatch. Poult. Sci. 69:887–897.

Van Brecht, A., J.-M. Aerts, P. Degraeve, and D. Berckmans. 2003. Quantification and control of the spatio-temporal gradients of air speed and air temperature in an incubator. Poult. Sci. 82:1677–1687.

Visschedijk, A. H. J. 1991. Physics and physiology of incubation—1. Br. Poult. Sci. 32:3–20.

Whittow, G. C., and H. Tazawa. 1991. The early development of thermoregulation in birds. Physiol. Zool. 64:1371–1390.