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An insight into the heat and mass transfer mechanisms of eggshells hatching broiler chicks and its effects to the hatcher environment

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ABSTRACT

Thermodynamic study of incubated eggs is an important component in the optimisation of incubation processes. However, research on the interaction of heat and moisture transfer mechanisms in eggs is rather limited and does not focus on the hatching stage of incubation. During hatch, both the recently hatched chick and the broken eggshell add extra heat and moisture contents to the hatcher environment. In this study, we have proposed a novel way to estimate thermodynamically the amount of water evaporated from a broken eggshell during hatch. The hypothesis of this study considers that previously reported drops in eggshell temperature during hatching of chicks is the result remaining water content evaporating from the eggshell, released on the inner membrane by the recently hatched wet chick, just before hatch. To reproduce this process, water was sprayed on eggshells to mimic the water-fluid from the wet body of a chick. For each sample of eggshell, the shell geometry and weight, surface area and eggshell temperature were measured. Water evaporation losses and convection coefficient were calculated using a novel model approach considering the simultaneous heat and mass transfer profiles in an eggshell. The calculated average convective coefficient was $23.9 \pm 7.5\ \mathrm{W/m^2\ {}^\circ C}$, similar to previously reported coefficients in literature as a function of 0.5–1 m/s air speed range. Comparison between measured and calculated values for the water evaporation showed 68% probability accuracy, associated to the use of an experimentally derived single heat transfer coefficient. The results support our proposed modelling approach of heat and mass transfer mechanisms. Furthermore, by estimating the amount of evaporated water in an eggshell post-hatch, air humidity levels inside the hatcher can be optimised to ensure wet chicks dry properly while not dehydrating early hatching chicks.

1. Introduction

Understanding and modelling the thermodynamics behind egg incubation helps optimise the incubation process (Decuypere and Michels, 1992; Youssef et al., 2014) and chicken embryo development (French, 1997; Van Brecht et al., 2005b; Yalcin et al., 2009). Furthermore, embryonic thermal-responses may have long-term effects, influencing broilers' growth performance (Piestun et al., 2011; Yahav et al., 2004). During incubation, energy exchanges in the form of heat and moisture comprise the physical process of simultaneous heat and mass transfer between an egg and the surrounding micro-environment. In principle, for natural contact-incubation, this process is mediated by the parental-embryo physiology (Turner 1994a,b), whereas in artificial convective-incubation, this is thermodynamically driven.

The partition of heat exchanges includes both sensible and latent heat. The former relates to the metabolic heat generated by the growing embryo, which is dissipated to the air stream passing through the egg by forced convection. The latter, relates to the evaporation of egg-water content into a gas, which is rather difficult to be predicted and quantified (Van Brecht et al., 2005a,b). Conduction and thermal radiation are less effective and often negligible (French, 1997; Kashkin, 1961).

Energy changes and thermal balance within an avian egg are governed by embryonic heat production, which in turn affects

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eggshell temperature (Tong et al., 2013). Thermoregulation by the central nervous system controls the mechanisms of heat production, heat conservation and heat loss (Tzschentke, 2008). Embryonic heat production can be measured by monitoring the eggshell surface temperature (Frye et al., 2011; Lourens et al., 2011) or calculated from O_2 consumption measurements (Nichelmann et al., 1998). Evaporative heat losses are due to the loss of water vapour by diffusion through the eggshell pores from inside the egg (high concentration) to the incubator environment (low concentration), which decreases egg weight continuously during incubation (Ar and Rahn, 1980). In practice, egg weight loss is calculated by the difference between egg weight at setting ('d0'—day 0 of incubation) and day 18 (d18) of incubation when eggs are transferred from trays to baskets (Tona et al., 2001). Alternatively, egg weight loss can be monitored in the setter (d0–d18) by continuously weighing a tray with 150 eggs using an automated system (Dynamic Weight Loss System-DWLS™, Petersime N.V., Belgium). One way to measure incubation efficiency is to manually weigh sampled chicks from the hatcher (d18–d21) and calculate chick yield (relative chick body weight from initial egg weight) (Tona et al., 2001).

Furthermore, physiological mechanisms that regulate long-term effects on chickens, including thermoregulation, can be altered by changes in the energy and moisture exchange rates between egg and micro-environment (Moraes et al., 2004, 2003; Nichelmann, 2004; Tazawa et al., 2001; Yahav et al., 2004).

Despite the efforts on measuring (Sotherland et al., 1987; Turner, 1985; Van Brecht et al., 2005b) and modelling (Eren Ozcan et al., 2010; French, 1997; Meijerhof and Vanbeek, 1993) heat transfer in eggs, mainly involving variations of eggshell temperature (T_{egg}) and micro-environmental air temperature (T_{air}) (Youssef et al., 2014), research on the interaction of heat and moisture transfer mechanisms is rather limited and does not focus on the hatching process.

Moreover, hatch is the most prominent physical change in the incubation process. During hatch, both the recently hatched chick and the broken eggshell add extra heat and moisture to the hatcher environment. A chicken embryo, to successfully develop and hatch, generates water by oxidizing yolk lipids (Ar and Rahn, 1980). As a result, a recently hatched chick with wet body surface (McArthur and Ousey, 1994) releases a certain amount of water-fluid on the inner eggshell membrane just before hatch. However, the underlying thermal-mechanisms of such water evaporation during hatching remains to be investigated (Ohi et al., 2010).

Chicks hatch in commercial incubators that house thousands of eggs at a time (capacities ranging from 19,200 to 115,200 eggs). The spread of hatch among individuals defines the hatch window (the hatching time span usually between 10% and 90% of chicks) and the hatching evolution is commonly monitored in practice by roughly monitoring the evolution of air humidity inside the hatcher.

The hatch window can be as long as 48 h (Willemsen et al., 2010), which causes variation in the holding time that individual chicks experience inside the hatcher before the entire batch is removed at 'take-off' (when the hatcher doors open and all chicks are removed together). As the spread of hatch window increases, the time to first access to feed and water also increases, affecting the welfare of young chicks and their post-hatch performance (Bergoug et al., 2013b; Careghi et al., 2005; Gonzales et al., 2003).

A peak in air humidity in the hatcher indicates that the majority of chicks have hatched and thus the take-off time is determined for the upcoming hours. In this regard, the evaporated water from a recently hatched wet chick is well studied for the purpose of heat loss calculations and its effects on the body surface temperature (McArthur and Ousey, 1994). However, little attention has been paid to the evaporated water from the broken eggshell during hatching.

Taken together, the purpose of this study was to extend the thermal-related study of Romanini et al. (2013) who precisely determined the hatch time of individual chicks through the detection of outstanding drops in T_{egg} measurements. In particular, this study further investigates eggshell thermodynamic relations between water evaporation and T_{egg} during hatching. Moreover, this work puts forth a simultaneous heat and mass transfer model to predict the amount of water-fluid left by the recently hatched chick on the inner eggshell membrane and thus evaporated. As a result, hatching evolution can be more precisely monitored and the control of air humidity in the hatcher environment can be optimised to ensure wet chicks dry properly while not dehydrating early hatching chicks.

2. Materials and methods

2.1. Incubator

A custom-built lab scale incubator model GVH 2000 (Petersime N.V., Zulte, Belgium) measuring $2.83 \times 3.24 \times 1.54\ m^3$, with capacity for 300 eggs, was used for this experiment. The installation details and the 3D schematic drawing is described in Van Brecht et al. (2005b). The incubator's air conditioning unit maintained the levels of air temperature at 37–38 °C and 65–70% of air relative humidity to reproduce usual thermally-challenge hatching conditions (Barbosa et al., 2013; Bruzual et al., 2000a,b; Yahav et al., 2004).

2.2. Eggshell temperature measurements

Eggshells naturally broken in roughly two parts after hatch were collected from a commercial incubation of Ross308 breeder eggs with 36 weeks of flock age. A total of 19 dried eggshells was randomly selected and placed inside the custom-built incubator for the current study.

The eggshells were individually weighed, numbered, and randomly placed in the incubator basket. Mechanical ventilation provided airflow around the eggshells. An air velocity transducer TSI model 8455 (TSI Inc., Shoreview, USA) with a measurement range from 0.25 to 50 m/s and output voltage of 0–5 V was used to manually check the air velocity range at eggshell level set to approximately 0.5–0.6 m/s.

Calibrated type T thermocouples of 1 mm diameter with ± 0.5 °C precision within the range of -40 °C to 125 °C were attached on each broken eggshell, at a distance of 5 mm from the shell equator using blue tack to measure T_{egg}. In addition, a type T thermocouple with same characteristics was placed 10 mm away from the measured T_{egg} to monitor T_{air} (Fig. 1).

The thermocouples were connected to a DaqPRO™ 5300 8-channel data acquisition and logging system (Fourier Technologies Ltd., Chatswood, Australia) to record temperature in real time. The Windows® based software DaqLAB™ was used to trigger the thermocouple data recording using a sampling frequency of one measurement per second.

2.3. Eggshell weight loss measurements

Water evaporation was assumed to cause the eggshell weight loss. Water was sprayed 4–5 times on the inner side of each broken eggshell to mimic the effect of water left by the recently hatched wet chick in a real incubation.

The hand holding sprayer bottle of mineral water was kept inside the incubator to reach a temperature equilibrium with the T_{air} around the eggshells, ensuring the water evaporation as the sole matter heat transfer mechanism. A glass precision