MODELLING OF A POULTRY SHED.

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Abstract

Tegel Foods is New Zealand's leading producer and supplier of poultry products, providing an extensive range of quality poultry products to New Zealanders for over thirty years. Tegel is a fully-integrated poultry producer involved in breeding, hatching, feeding, growing, processing and marketing of chicken and turkey in New Zealand. The problem presented by Tegel was specifically to model the energy exchange between the chickens and their shed environment in order to better understand and control the shed climate and thereby maximize growth rate.

A model for the heat production and water respiration rate of a typical chicken was developed, based on physical principles. A thermodynamical model of the whole chicken+shed system included the temperature of the external air, the internal air, the chickens, the litter, the concrete floor and the underlying soil. It also included the relative humidity (RH) of the external and internal air and the water flows into and out of the shed.

Modelling of the shed environment's inputs and outputs will be particularly valuable for continuing assessment of three fundamental inputs of economic importance: feed nutrient density in terms of energy formulation, heating in terms of gas/power usage, and heat removal via extraction fans. Optimisation of liveweight gain and feed conversion potential are the end targets.

1. Introduction

Tegel Foods is New Zealand's leading producer and supplier of poultry products, and has been providing an extensive range of quality poultry products to New Zealanders for over thirty years. Tegel is part of the Heinz-Wattie group of companies, owned by multi-national food producer HJ Heinz Co. Tegel Foods began operations as a department

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of General Foods Corporation in 1966 and now employs approximately 1700 people at its sites throughout New Zealand.

Tegel Foods is a fully-integrated poultry producer involved in breeding, hatching, feeding, growing, processing and marketing of chicken and turkey in New Zealand. Its product range includes fresh, frozen and cooked whole chickens and fresh and frozen chicken portions. NRM New Zealand markets all feed and animal health products that are sold externally.

The problem presented by Tegel was specifically to model the energy exchange between the chickens and their shed environment in order to better understand and control the shed climate and thereby maximize growth rate.

A typical shed has chickens placed as day-old chicks at a stocking density of about 21 birds per square metre. They are reared on a concrete floor (about 15 cm thick), with a 5 cm layer of dry wood shavings spread as 'litter'. This litter remains with flock for the duration of the batch, 'composting' down to a friable litter material consistent with '50% sawdust mixed with 50% dry garden soil'. The sheds are of 'controlled environment' type, and the birds are grown within a specific temperature profile as they get older. The shed temperature control starts at 32°C at the day of placement, reducing down about 0.4° per day to 20°C by the time the birds reach final processing age (average 37 days). The chickens have unlimited access to feed and water, and grow to a specific growth profile with target weight-for-age expectations. Specific air exchange requirements are necessary to maintain a shed environment acceptable for animal welfare and performance parameters. Water generated into vapour/humidity, through evaporation, and CO_2 are the predominant waste products which must be removed.

The moisture content of the dry wood shavings prior to placing the chicks is close to 5%. By the end of the growing cycle the litter moisture is ideally no more than 20%. Water accumulation in the litter is insignificant compared to total water throughput during the run. The air exchange is determined by total biomass within the shed and therefore increases throughout the life of the flock. Failure to remove sufficient waste air leads to 'wet litter' which causes welfare problems as well as performance depression expressed by low feed intakes, low weight gains and poorer feed conversion.

As the birds grow, progressively generating their own body heat, the supplementary heat requirement in the shed decreases and the need to remove heat from the shed starts to overlap. This transition from a heating to a cooling mode is strongly influenced by the weather conditions outside the shed, combined with insulation values of the shed, weight for the age of the flock and target shed environment temperature.

These daily shed temperature targets are based on achieving the optimum 'comfort' of the birds at every stage. However as the biomass increases and the influence of heat build-up occurs at floor level, then cooling requirements become harder to formulate on a mathematical basis. Daily temperature monitoring normally measures 'ambient' air temperature 30cm above the birds' heads. This temperature is therefore not an accurate temperature requirement but an assumption based on visual flock behaviour. This temperature 'perceived' by the birds is a combination of ambient shed temperature, relative humidity, air flow, metabolic heat production and litter temperature.

The important variables which needed careful consideration by the MISG 'Chicken team' included:

- The temperature and relative humidity outside the shed.
- Supplementary heating into the shed.
- Energy and nutrient density of feed consumed by the chickens.
- Increase in biomass within the shed.
- Heat accumulation and 'storage' in the litter and floor under the chickens from biomass heat generation.
- Heat generated by composting effect of litter bed.
- Increase in insulating effect of birds on litter heat from increasing biomass.
- Effect of air flow on heat transfer.

2. Problem description

The MISG group found that Tegel's farmers raise their chickens in sheds of rough size 80 m long, 15 m wide and 3.5 m high. Between 25,000 and 40,000 one-day-old chickens are introduced to the shed where they are kept with unrestricted access to food and water for between 30 and 40 days, at which time they are between 2 and 3 kg in weight.

The shed's floor is concrete. On this is the litter, which is initially wood shavings which then gets mixed with chicken manure, a good deal of which is excreted water which must be removed by ventilation. The shed's ceiling and walls are well insulated. While the chicks are under about 2 weeks old the shed is heated to between 30 and 35°C, with minimal ventilation. After that time the chickens are weaned off the heat, and the shed may be intensively ventilated, depending on the interior and exterior climatic conditions.

A field trip to one of Tegel's sheds convinced us that the shed could be treated fairly accurately as a homogeneous structure; the air seemed to be well-mixed and the chickens and litter were spread evenly across the shed floor. Therefore the model of the situation consisted of stratified layers: at the bottom was the soil below the shed, then the concrete and then the litter; above that was the 'chicken layer', then the internal air, the shell of the shed, and finally the external air.

Our model of the situation included the temperature of the external air, the internal air, the chickens, the litter, the concrete floor and the underlying soil. It also included the relative humidity (RH) of the external air, the internal air and the moisture content of the litter.

The main input of heat into the system was through the metabolism of the chickens. Experimental data suggested that a sufficiently precise model for a chicken was that its heat and moisture output was proportional to the surface area of its lung. A typical 2 kg bird produces roughly 10 W of sensible heat, and respires 0.28 kg of water per day. For a shed of 30,000 birds, this is about 8 tonnes/day, or 0.1 kg/s.

The heat from the chicken passes into the air, but is also used to evaporate moisture from the litter. Much of this is usually vaporised because of the heat input from the chickens and the high water activity of the droppings, but occasionally, if the shed is inadequately ventilated, the water builds up and the litter becomes uncomfortably saturated.

Heat also passes through to the concrete and the underlying soil. Since the shed is virtually in thermal equilibrium at all times, a simple calculation revealed that roughly 1W per chicken is conducted through to the ground. Similarly, in climatic conditions typical of Auckland, roughly 1W per chicken is conducted through the shed's wall and roof. This leaves about 8 W per bird, or a total of about 240 kW of heat to be removed by ventilation.

The rate of food and water intake was also investigated using Tegel's data. We found that the chickens' intake was proportional to their surface area, assuming that they were spherical - remarkably, this latter assumption appears to be fairly good! A model for the heat production and water respiration rate of a typical chicken was developed, based on physical principles. Perusal of actual data on chicken weight vs feed and water intake led to some simple models for growth rate as a function of mass.

The problem naturally divided into two parts: (a) modelling the chicken in a fixed environment and (b) modelling the shed.

Water in	Liquid consumed	183 tonnes
	Liquid in food	10.5 tonnes
	Manufactured via respiration	negligible
Water out	Evaporated from manure	67.1 tonnes
	Respired	64.0 tonnes
	Retained in chicken biomass	54.8 tonnes
	Retained in manure	7.6 tonnes

Table 1. Water gained and lost in a chicken shed during one chicken life-cycle

Day	chicken mass (g)	feed consumed per day (g)	water consumed per day (g)
0	40	9.5	14
7	200	38	64
14	500	73	119
21	1000	114	186
28	1600	157	259
35	2300	200	314

Table 2. Chicken mass, feed consumed per day and water consumed per day per chicken - typical data provided by NRM/Tegel.

3. Models of the chicken

3.1. A water audit

NRM/Tegel provided the following data for a typical shed over the time of a batch of chickens: initial mass of wood shavings (litter); typical moisture content of faeces; total mass of food and water consumed; moisture content of food; final mass of chickens taken from the shed; and, the final mass and moisture content of litter.

Table 1 shows a water audit based on this data. Evidently, most of the water deposited in the litter must be evaporated, which is important since occasionally the shed environment prevents this and the litter becomes water-logged. NRM/Tegel attempt to prevent this.

3.2. Food and water consumed by a chicken

NRM/Tegel provided typical food and water consumption for a shed every week. This translates to the data shown in table 2.

Graphical display of this set of data reveals a relationship that is closely linear on a log-log plot; this leads to the interesting feature that

$$\text{feed consumed per day} \propto (\text{mass})^{n_{feed}}$$

$$\text{water consumed per day} \propto (\text{mass})^{n_{water}}$$

$$n_{feed} = 0.74 \text{ and } n_{water} = 0.76 \tag{1}$$

The exponents are and the fit is shown in Figure 1.

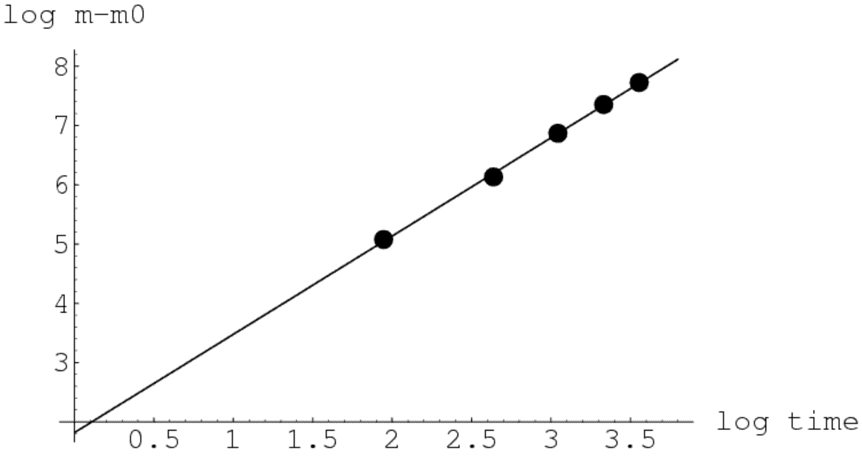

Figure 1. Log-log plots of the feed (black) and water (grey) intake as a function of the chicken's mass are well-fitted by straight lines with slope given by the exponents in Equation equation (1).

Interestingly, these exponents are close to 2/3, which implies that

$$\begin{aligned} \text{feed consumed per day} \propto (\text{mass})^{2/3} &\propto \text{area of spherical bird} \\ \text{water consumed per day} \propto (\text{mass})^{2/3} &\propto \text{area of spherical bird} \end{aligned} \tag{2}$$

Growing a chicken is therefore very similar to an accretion process, but with a small extra amount of food required (parameterised by the difference 0.74 - 2/3) to provide the energy to drive the process.

Finally, the data indicates that the mass of a chicken grows as a power of time:

$$\text{mass} - \text{mass}_0 \propto \ \text{time}^{n_{time}} \text{ with } n_{time} = 1.66 \tag{3}$$

This is shown in Figure 2.

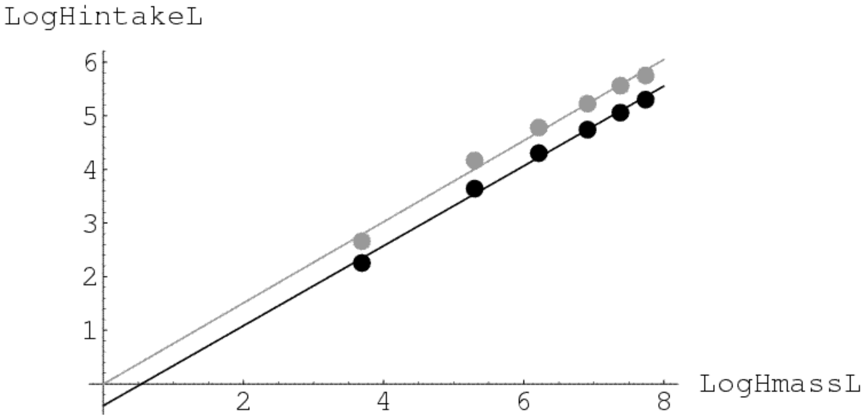

Figure 2. . Log-log plots of the chicken mass as a function of time. The straight line is given by Equation (3).

3.3. Heat produced by an chicken of arbitrary size in a thermal bath

Unlike humans, chickens don't sweat substantially. Rather, they predominantly cool themselves through their lungs, mainly via evaporation. They also cool via sensible heat loss from their comb, wattles and the rest of the body. At high temperatures chickens pant which results in an increased metabolic rate and a much-increased evaporative cooling.

At low temperatures the chicken's metabolic rate increases in order to maintain a core temperature of about 41°C. A small amount of data suggests that relative humidity is unimportant.

The model assumes that the rate of heat transfer from the chicken Q_{cool}, is proportional to the area of the chicken's lung:

$$\frac{Q_{cool}}{Area\ of\ lung} \quad = \quad E + \kappa(41 - T) + P(T - T_N)\theta(T - T_N) \qquad (4)$$

Here E parameterises the evaporative cooling, while $\kappa(41 - T)$ is the rate of conductive heat transfer assuming the chicken's core temperature is 41°C (T is measured in degrees Celsius). The third term, which is only non-zero for $T > T_N$ parameterises the effect of panting. This term is ignored since Tegel never deliberately heat-stresses the chickens.

The model also assumes the following relations

$$\frac{Area\ of\ lung}{mass\ of\ chicken} \propto \frac{chicken\ surface\ area}{chicken\ volume} \propto \frac{1}{radius\ of\ spherical\ chicken} \equiv \frac{1}{R} \qquad (5)$$

It is not absurd to treat the chicken as a sphere (also see further below) - without feathers they are roughly spherical, and reasonable agreement with experiment is achieved.

In steady-state, Q_{cool} must be equal to the total metabolic heat Q_{met} produced by the chicken. Calibration against data given in **?** for 2 kg chickens gives the final result

$$\frac{Q_{met}}{mass} = \frac{1}{R}[10 + 0.9(41 - T)] \qquad (6)$$

where Q is measured in Watts, the mass is measured in kg, R in cm, and T in C. Since chickens are of a similar density to water, $R \approx 6.2(\text{mass})^{1/3}$.

Figure 3 shows the calibration set and a comparison with experimental results from Misson [4] on day-old chicks. Further data is given by Hoffman **?**, according to Aerts et al. **?**, who measured the coefficient of T to be

$$-0.35\text{Wkg}^{-1}(°C)^{-1}$$

for broiler chickens weighing about 150 g. Equation (6) predicts this coefficient should be

$$-0.27\text{Wkg}^{-1}(°C)^{-1}.$$

The final comparison with experiment comes from a measure of CO_2 produced by day-old chicks. Assume that the metabolic heat comes from burning glucose in the reaction

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + 673 \text{ kcal/mole.}$$

Equation (6) then predicts that at 20 C the rate of CO2 production should be about 40 ml/min/kg-of-chicken for chicks weighing 35 g. This can be compared with the value of 36 ml/min/kg-of-chicken measured by Misson [4]. It may be important to note that the experimental errors in all these experiments were large, and that most experiments are at least a decade old.

Finally, Equation (6) appears to agree with all available experimental data to within experimental accuracy.

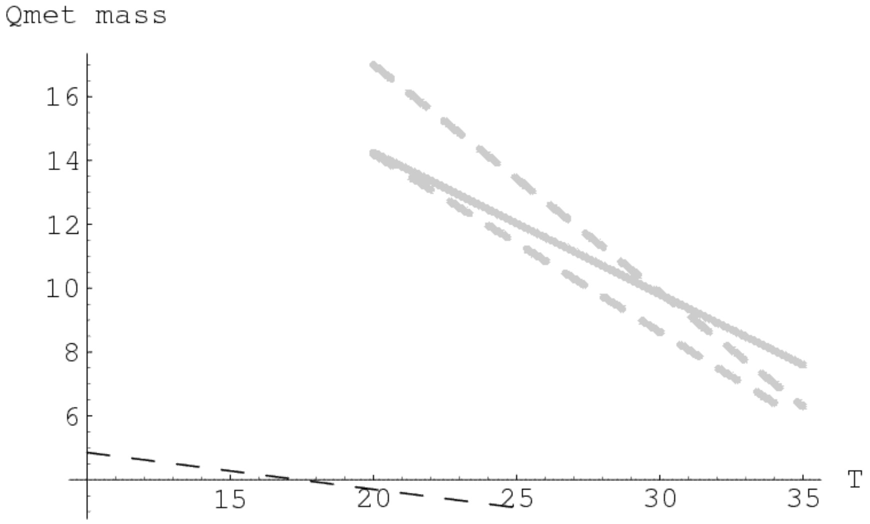

Figure 3. The heat produced per kg of chicken as a function of external temperature (T). The data used in the calibration resulting in Equation (6) is shown as a dashed black line in the lower-left corner of the graph. The upper grey dashed lines are data from day-old (35 gramme) chicks: the steeper of these is for 80% RH, while the other is for 20% RH [4, Figs 1 and 2]. The solid grey line is the prediction of Equation (6).

4. Heat flows in the shed

With 25,000 chickens spread over the floor of a shed which is 80 m long and 15 m wide, some concern about how to treat the chickens with respect to their rle in the model as heat and mass generators led the group to estimate the fraction of floor covered by the flock. A chicken weighing 1 kg, whose mass density is close to that of water (1000 kg m^{-3}), has a volume of 0.001 m^3. Since little of the body mass is in the legs or head, the remainder was modelled as either a sphere (when standing) or a hemisphere (when sitting). Using the standard formulae for the volumes of these shapes, the radii were calculated to be 0.020 and 0.078 m respectively. The projected areas onto the floor were then found to be 0.012 and 0.019 m^2 respectively. Using a population density of 21 birds m^{-2}, the average fraction of the total floor area occupied by the birds was calculated to be 25% when standing and 40% when sitting, so there was plenty of free space for chickens to move around.

As mentioned above, a field trip to one of Tegel's sheds convinced us that the shed could be treated fairly accurately as a structure which is horizontally homogeneous; the air seemed to be well-mixed and the chickens and litter were spread fairly evenly across the shed floor. Therefore the model of the situation was conceived of as a system of horizontal layers: at the bottom was the soil below the shed, then the concrete and then the litter; above that was the "chicken layer', then the internal air, the shell of the shed, and finally the external air (see Figure 4). Heat and water flows between the layers were then estimated.

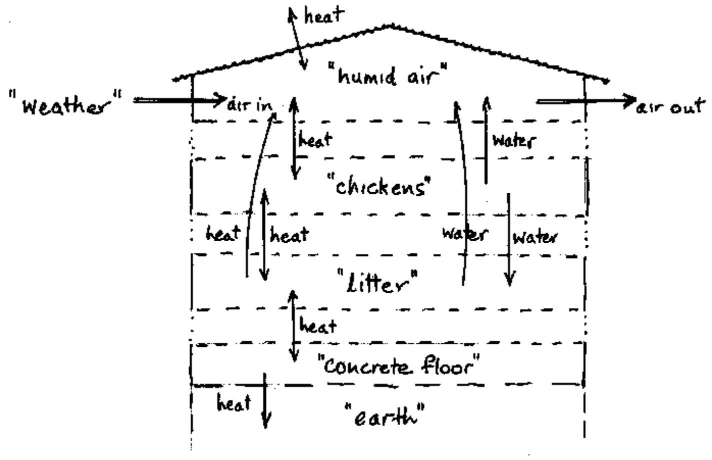

Figure 4. A schematic diagram illustrating the conceptual model of a chicken shed as a system of horizontal layers, with heat and water flows across the layer interfaces.

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The group made a sample calculation based on an air speed of 1 m/s provided by the ventilation fans. The science of psychrometry (or hygrometry) was invoked, where calculations are based on the thermodynamics of moist or humid air flows, which are gas-water mixtures. While air itself is a mixture of gases, its properties are well-documented. The thermodynamic properties of the air and water depend on two thermodynamic variables; in this case, the mixture temperature and the partial pressures of the constituents (air and steam) were used.

A trial calculation was made using an inflow of ambient (outside) air at conditions of T = 20°C and 60% relative humidity (RH), and a shed throughflow airspeed of 1 m^{-s}. The humidity (sometimes called the humidity ratio) is defined by

$$\omega = \frac{\text{mass of water}}{\text{mass of dry air}}$$

while ϕ, the relative humidity (RH) is given by

$$\phi = \frac{P_g}{P_{sat}} = \frac{\text{partial pressure of steam}}{\text{saturation pressureofwater at the same T}}$$

From steam tables, for T = 20°C, the saturation pressure of water is $p_{sat} = 0.024$ bars (1 bar $= 10^5$ Pa) and then $p_s = \phi p_{sat} = (0.60)(0.024) = 0.014$ bars. Then the humidity is calculated by appealing to the ideal gas law; since the partial pressure of the steam is small, this is appropriate.

$$\omega = \frac{18}{29}\frac{0.014}{1.013 - 0.014} = 0.0088$$

where the standard total atmospheric pressure is 1.013 bars, and the molecular weights of steam and air are 18 and 29 respectively.

If the expelled air is assumed to be at 20°C with a RH of 70%, a similar calculation gives ω for the air exiting from the shed. A width of 17 m and a height of 3 m gives a shed cross-sectional area of about 50 m^2. An air speed of 1 m s-1 gives a volume flow rate of 50 $\mathrm{m}^3\mathrm{s}^{-1}$. At inlet, the air density is approximately 1.2 kg m^{-3}. This provided a water uptake between inlet and exit of 0.1 kg/s and a heat gain of 235 kW, which matched the sample data closely (see above). This was very encouraging, as it showed that a simulation of the thermodynamics and psychrometry of the shed environment produced feasible results.

5. Conclusions and recommendations

The simple physical chicken models developed from the supplied data showed relationships which could be explained using standard physical principles. The chickens' food and water intake were closely proportional to their body surface area. Their mass (or weight) appears to be nearly quadratic with age. A model for respiration and heat production from a typical chicken was used to provide water mass and energy inputs into an overall model of the complete shed+chickens system.

A trial calculation of air, water and energy flow processes into and out of the shed revealed a very good match to a set of sample data. While psychrometric parameters are not described by simple formulae, it should be possible to automate the calculation process so that the models developed here can be used for design purposes.

The industry representatives indicated that the models developed by the team confirmed Tegel's thoughts about important parameters, and reassured them that the modelling process used had taken pains to ensure that everything was accounted for.

Acknowledgements

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