Development of a solar heat assisted egg incubation system

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Abstract. This study is an attempt to provide the poultry industry with an appropriate technology suited for small to medium scale production. The main strategies implemented to enhance energy efficiency were solar assisted heating of the incubation space and intermittent operation of the ventilation device. The study revealed that 72.6% of electrical energy was conserved by using the proposed system. If the prototype was used for balut production, payback period for initial investment is just 10.5 month and annual income would be 3.3 times compared with the income from a conventional system. Response surface methodology was used to characterise the incubation system using a Box and Behnken Design. Response variables were electrical energy consumption and evaporation of water in the incubator. Parameters used in the modelling work were incubator temperature setting, tank water temperature and ventilation port opening. Mathematical models that were generated by the statistical software, Design Expert®, had a good fit and was found to be 94% and 98% accurate for predicting electrical energy consumption and evaporation of water, respectively. Numerical optimisation revealed the ideal region of operation for system for incubating duck eggs was at 0% ventilation port opening, incubator temperature setting of 37.5-38°C and tank water temperature of 47.5-60°C. The solar heat collector assisted egg incubation system promotes energy efficiency, utilizes a renewable energy resource, and can also be considered an environmentally sound technology. This study presents tremendous potential for adoption not just for balut production but also for the entire poultry industry.

1. Introduction

Agriculture, hunting, forestry, and fishing accounts for about 10% of the Philippines’ GDP. It was estimated that the poultry sector accounted for the 17.41% of the total agricultural output. It was also estimated that there were about 197 million chickens and ducks in the poultry industry [1, 2, 3]. Throughout the Philippine archipelago, there are communities that are deeply involved in the poultry industry.

Majority of the chickens and ducks in the poultry industry are in the small to medium scale poultry production. Most of the birds in this inventory are incubated artificially. Artificial incubation is the process of providing a suitable environment for the development of the embryo in the egg until it hatches. This is a complex and energy intensive operation, and a major contributor to production cost. A wide variety of designs and incubation systems that are utilized for the incubation of poultry...
eggs. Some of the artificial egg incubators are imported, while others are made locally. In addition, these incubators vary in size, shape, features and capacity. Innovations in artificial incubator design to improve energy efficiency and the utilisation of clean and renewable energy for the poultry industry would help reduce energy consumption and lower production costs. This would lead to a more competitive stand for our small to medium scale poultry enterprise in the local and global market [4,5].

In order to support and follow the programs of the government for development in the countryside, promotion of energy efficiency, utilisation of alternative sources of energy, and process innovation for the local industry, as well as to pave the way for system adoption with industries requiring incubation or even slow dehydration, this study, ‘The development of SINAG: a solar heat assisted egg incubation system’, was conducted [6]. The prototype was dubbed SINAG, an acronym for Solar INcubation for AGricultural applications, which in Filipino means sun’s ray; implying its utilisation of solar energy.

2. Conceptual Framework
A unique feature of the system was its ability to harness solar energy to aid in the incubation process. It utilised solar thermal energy absorbed by a flat plate solar heat collector to augment the heat that was needed during incubation. Figure 1 depicts the ideal heat provision scheme for the system.

Water would be heated by a solar heat collector. Hot water would be less dense and eventually move upward, accumulating in an insulated water tank which also serves as the hot water storage tank. Whenever heat would be needed in the incubation space, the hot water from the tank would be actively conveyed to the incubator and release heat by means of a heat exchanger. After losing some heat, water would be reheated in the solar heat collector. The process then proceeds in a cycle. In times of minimal solar radiation or when heat gain for the incubation space was not possible, the auxiliary heating system incorporated in the incubator would provide the necessary heat needed by the eggs.

3. Objectives

3.1. General objective
The general objective of the study was to establish the optimum operating conditions of the designed SINAG prototype.

3.2. Specific objectives
Specifically, the study aimed to: (1) Conduct modelling experiments and study the effects of operating parameters on the mode with the least electrical energy consumption. Parameters included were: temperature setting inside the incubator, tank water temperature, and ventilation port opening. (2) Develop empirical equations or regression models that would relate the different parameters with the electrical energy consumption and evaporation of water in the incubator prototype using response
surface methodology; and (3) Determine the optimum areas of operation which would minimise electrical energy consumption.

4. Materials and Method
The development of SINAG was anchored on the principle of energy efficiency and the utilization of solar energy to aid in the incubation of poultry eggs. The overall design was suited to be appropriate for small to medium scale production and designed particularly for incubation of duck eggs for balut production. Balut is a delicacy in the Philippines and some other Asian countries like Vietnam, Laos Cambodia and China. These are partially incubated duck or chicken eggs and boiled for about 20-30 minutes.

4.1. Design of SINAG: a solar heat assisted egg incubation system
The prototype (Figure 2) was different from other egg incubators in a number of ways. Foremost was that it was designed to be suitable for small to medium scale poultry production. Large scale incubator capacity is about 10,000 to 100,000 eggs. The prototype had a designed full load capacity of 4000 eggs.

![Figure 2. The SINAG prototype.](image)

4.2. Model development
The modelling experiment was based on the Box-Behnken Designs. These designs do not have simple design generators, and have complex compounding of interaction. However, the designs are economical and therefore particularly useful when it is expensive to perform the necessary experimental runs. For three factors with three levels factorial Box and Behnken Design (BBD), a total of fifteen (15) experimental runs are required, with three (3) centre point runs to allow for a more uniform estimate of the prediction variance over the entire design space [7].

Tank water temperature setting for the design of experiment was set at 40°C and 60°C. During the preliminary experiments, water temperature inside the water tank can reach as high as 70°C. This occurred when the skies are clear and solar insolation was more than 800W/m². Nonetheless, the temperature range that was used was the observed usual operational temperature range that was reached in the water tank.

Primarily, ventilation ports in incubators were manipulated for controlling humidity and temperature inside the incubator. Most incubators with ventilation ports, depending on the situation, were just opened up to 50% of the opening. This was to minimise escape of hot, moist air inside the incubator. On the other hand, most egg incubators that have no provision for mechanical turning of eggs do not have ventilation ports. This was the reason for selecting 0% and 50% as high and low levels for ventilation port opening.
5. Results and Discussion

5.1. Modelling for optimisation

The SINAG system is a complex system. It is very dynamic and there are factors that would likely affect the system that are difficult, if not impossible to control. Some of these factors are from environmental conditions (e.g., ambient temperature and humidity, wind speed, solar radiation), egg respiration and egg heat evolution.

The design of experiment for the system, aimed to establish a mathematical model that would predict electrical energy consumption and water evaporation for its operation within a prescribed set of operational conditions. The models were used in finding the optimum setting for operation for the prototype.

5.2. Response surface methodology experiment results

Results of the Box and Behnken design of experiments can be found in Table 1.

| Box and Behnken Run Number | A Incubator Temperature Setting, (°C) | B Storage Tank Water Temperature, (°C) | C Ventilation Port Opening, (%) | R1 Electrical Energy Consumption, (kW-hr) | R2 Evaporation of Water Inside the Incubator, (mL) |
|----------------------------|---------------------------------------|----------------------------------------|---------------------------------|-------------------------------------------|-----------------------------------------------|
| 1                          | 37.5                                  | 40                                     | 25                              | 1.882                                     | 112                                           |
| 2                          | 37.5                                  | 60                                     | 25                              | 1.280                                     | 119                                           |
| 3                          | 39.7                                  | 40                                     | 25                              | 5.331                                     | 130                                           |
| 4                          | 39.7                                  | 60                                     | 25                              | 2.064                                     | 134                                           |
| 5                          | 37.5                                  | 50                                     | 0                               | 0.993                                     | 108                                           |
| 6                          | 37.5                                  | 50                                     | 50                              | 1.901                                     | 119                                           |
| 7                          | 39.7                                  | 50                                     | 0                               | 1.816                                     | 128                                           |
| 8                          | 39.7                                  | 50                                     | 50                              | 5.422                                     | 140                                           |
| 9                          | 38.6                                  | 40                                     | 0                               | 3.923                                     | 115                                           |
| 10                         | 38.6                                  | 40                                     | 50                              | 2.140                                     | 131                                           |
| 11                         | 38.6                                  | 60                                     | 0                               | 1.411                                     | 119                                           |
| 12                         | 38.6                                  | 60                                     | 50                              | 1.014                                     | 134                                           |
| 13                         | 38.6                                  | 50                                     | 25                              | 1.800                                     | 125                                           |
| 14                         | 38.6                                  | 50                                     | 25                              | 1.956                                     | 125                                           |
| 15                         | 38.6                                  | 50                                     | 25                              | 2.116                                     | 126                                           |

Using stepwise regression, the ANOVA results revealed that the variability in the electrical energy consumption (R1) and evaporation of water inside the incubator (R2) was adequately accounted by the factors or independent variables used in the study. Factors used were temperature setting of the incubator (A), water temperature in the hot water tank (B), and ventilation port opening (C). Adequacy statement was based on the high R-squared, adjusted R-squared, and predicted R-squared values which ranged from 0.9568 to 0.9989. This also implies that no other significant or major factors had been overlooked in the selection of the design parameters.

5.3. Mathematical model for electrical energy consumption

A reduced cubic model was the mathematical model that best characterised R1, equation (1). This meant that interactions between factors were present and that the relationships were non-linear. The Model F-value of 251.36 for R1 implied that the model was significant and that there was only 0.01% chance that a "Model F-Value" that large could occur due to noise.
5.4. Final equation in terms of coded factors for R1
Electrical Energy Consumption =
+ 2.05 + 1.07A - 0.94B - 0.54 C - 0.67AB + 0.67AC + 0.35BC + 0.53A² + 1.67A²C

(1)

5.5. Mathematical model for evaporation of water
The mathematical model for evaporation of water was performed in order to see if a relationship could be established with the model of electrical energy consumption and to augment information for the moisture balance for the system.

A reduced cubic model was the mathematical model that best characterised R2, equation (2). This meant that interactions between factors were present and that the relationships were non-linear. The Model F-value of 362.73 for R2 implied that the model was significant and that there was only 0.01% chance that a "Model F-Value" that large could occur due to noise.

5.6. Final equation in terms of coded factors for R2
Evaporation = +125.15 +10.25A +1.75B +7.75C -0.75 AB +0.25 AC -1.27A² -0.27B² + 1.00A²B - 2.00A²C -2.00AB²

(2)

5.7. Adequacy and validation of the models
"Adequate Precision" measures the signal to noise ratio. For most experiments, a ratio greater than 4 is desirable. However, for R1 and R2, the ratio was 40.313 and 67.366, respectively. These indicated that both models have adequate signals and that the models could be used to navigate the design space.

5.8. Optimal operational settings
In determining the optimal operational settings, there is a need to establish the goal, limits and weight of importance for the factors considered. Optimal settings meant identifying areas of operation that minimized electrical energy consumption for the system. Occurrence of highest electrical energy consumption was when the incubator temperature is set at 39.7°C, with tank water temperature at 50°C and ventilation port opening of 50%. Also, least electrical energy consumption was observed at 0-25% ventilation port opening. Using range constraints of 37.5-38.6°C for incubator temperature setting, 0-25% ventilation port opening, and 40-60°C of tank water temperature, numerical optimisation was conducted using a computer software. Thirty-six solutions were generated. As can be seen in Figure 3, ideal region of operation at 0% ventilation port opening, incubator temperature setting of 37.5-38°C and tank water temperature of 47.5-60°C.

![Figure 3. Optimum operational region minimising electrical energy consumption](image)

5.9. Environmental benefits from using SINAG
Aside from the economic benefits that could be realized in using the developed system, the electrical energy conserved due to lower electrical energy consumption equivalent to 761.8 W, also translates to avoided carbon dioxide emissions. It was estimated that for the Philippines, grid emission factor is
about 0.592 tons of CO$_2$/MW-hr [8]. Hence, at the same time that SINAG has recovered the added investment for its solar components, that is 10.46 months, it has also foregone the release of about 3.396 tons of CO$_2$ to the atmosphere. Now, with a clean energy production system, this could attract more consumers and investors for the business especially at this point in time that people are more aware of conserving resources and are becoming more educated about the effects of climate change.

6. Conclusions
The study was about the development of a solar assisted egg incubation system. It is an attempt to develop an appropriate technology for the poultry industry. A SINAG prototype was designed and fabricated. The overall design was geared towards developing a more energy efficient system that is appropriate for small to medium scale poultry production.

Response surface methodology was used to model the system. Modelling experiment done was based on the Box–Behnken Design with three factors with three levels. The experiment was done to model the effects of the parameters (temperature setting inside the incubator, the tank water temperature of the solar heat collector, and the ventilation port opening) on the response variables (electrical energy consumption and evaporation of water). Design Expert® software was used for the statistical analysis, modelling work, and optimization for the system. The model that fitted best for both responses were in the form of reduced cubic models. This means that interactions between factors are present and that the relationships were non-linear. The mathematical models generated was validated under controlled condition and was found to be 94% and 98% accurate for predicting electrical energy consumption and evaporation of water, respectively.

Numerical optimisation was conducted for the system. The range constraints for the factors were set at 37.5-38.6°C for incubator temperature setting, 0-25% ventilation port opening, and 40-60°C of tank water temperature. It was established that the ideal region of operation for incubating duck eggs was at 0% ventilation port opening, incubator temperature setting of 37.5-38°C and tank water temperature of 47.5-60°C. The temperature range is the ideal setting for incubating duck eggs in the Philippines.

In conclusion, the study revealed that a great deal of electrical energy could be saved from operating an artificial incubator using the system. This study presents tremendous potential for adoption not only for balut production but also for the entire poultry industry. The system promotes energy efficiency and utilizes a renewable energy resource. Its adoption translates to a reduction in production costs, thus improving profit. The SINAG system can also be considered an environmentally sound technology and should now be promoted for sustained development in our countryside.

7. Recommendations
With regards to the SINAG prototype, the following improvements could still be done to make it more energy efficient:
- Further research on material selection to optimise thermal insulation while minimising total cost for the unit.
- There are times when the system would have gained and stored enough solar heat in the hot water tank to sufficiently provide the needed heat for incubation.
- The study of making a low cost, intelligent control system would maximise its potential is probably another step in its development.
- Evacuated tube solar heat collectors are more expensive than flat plate solar heat collectors. However, the claimed higher operational temperature range and better thermal efficiency of evacuated tube solar heat collectors may, in the long run, be a more cost-effective option.
- The study proves that considerable energy could be conserved with the SINAG system, it is recommended that piloting and commercialization be actively pursued.

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