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Experimental Study of a Solar Thermal Incubator Using a Phase-Change Material for Off-Grid Use

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Abstract

The aim of this study was to provide a simple, easy-to-use incubation system for small-scale rural poultry farmers far from the electricity grid. To this end, a naturally ventilated solar thermal incubator was built and experimentally tested. A U-shaped evacuated tube collector and a wooden crate holding 50 eggs were used to build the solar thermal incubator. Water was used as the heat transfer fluid, and an EPCM was integrated into the incubation chamber for operation at night or when the sun was hidden. The heat generated by the solar collector and stored in the heat transfer fluid is transported to the incubation chamber by thermosiphon to heat the chamber. Temperature and humidity probes powered by a solar panel were placed at various locations to monitor the thermo-hygrometric efficiency of the incubation system. The incubator, heated by natural convection, proved to function normally, and the incubation chamber was maintained throughout the incubation period within a temperature range of 35.53˚C to 39.53˚C and relative humidity averaging 49.4% to 68.5%. The experiment was carried out by introducing 30 eggs and the results of the experimental study showed that the incubator's efficiency was 87%. The performance tests gave a fertility rate of 93% and a hatching rate of 93%, *i.e.* 28 fertile eggs and 26 hatched eggs, respectively.

Keywords

Solar Incubator, Vacuum Tube Collector, Encapsulated PCM, Poultry Eggs

1. Introduction

Poultry farming in Côte d'Ivoire is an essential link in the livestock production system. A 2008 FAO report indicated that 70% of marketed poultry came from the family sector, in rural areas, and 80% of this production is carried out by women, who include it in their domestic activities and constitute an important source of income [1]. Despite this high contribution of the rural sector to poultry production and consumption, 39% of children suffer from stunted growth. Most of this production is incubated naturally by the mother hen. The natural process of producing meat and eggs from hens does not meet the protein needs of a rapidly growing population. To improve production and, above all, to empower women in rural areas, we need to move from natural incubation to artificial incubation, which is accessible to the vast majority of rural populations. Artificial incubation is the scientific process whereby poultry eggs are transformed into chicks in the absence of the mother hen, by providing an appropriate environment for the embryo to develop in the egg until it hatches [2]. The majority of artificial incubators used by large and medium-sized hatcheries on the national market operate with various types of energy: electricity, coal, paraffin, gas or generators (diesel or petrol) [3]. This complex operation consumes a lot of energy, especially non-renewable energies such as oil and gas. What's more, electric incubators remain inaccessible to small-scale poultry farmers in rural areas. Two hypotheses are put forward: the weakness of electrical networks in these areas and the high cost of energy inputs [4]. Innovations in the design of artificial incubators aimed at improving energy efficiency and the use of clean, renewable energies for the poultry industry could reduce energy consumption and the production costs of eggs and poultry meat [2]. The use of solar energy in poultry production has received particular attention from researchers in recent years. Several studies have been carried out on the design and construction of solar-powered incubators [5]. Dalangin and Ancheta (2018) [6] designed a solar incubator using solar panels as an energy source and a temperature controller. The incubator they developed proved effective, operating 24 hours a day throughout the incubation period. The hatching rate and chick vigor of the system were 73% and 71% respectively. The incubator developed was able to maintain the incubator temperature between 37˚C and 39˚C with the use of the temperature controller. Osanyinpeju *et al.* (2018) [7] developed a photovoltaic-powered incubator and achieved an efficiency (hatching) of the solar incubator developed for poultry eggs of 44%. Uzodinma *et al.* (2020) [5] conducted a study to evaluate the performance of a solar-powered hybrid poultry egg incubator equipped with a phase-change material energy storage system. This is a photovoltaic/thermal energy source. The study revealed that the average hatching percentage and incubation temperature after three replications were 62.3% and 37.6˚C respectively. Peprah *et al.* (2022) [8] have designed and built an intelligent GSM/IoT-based solar incubator that limits human contact during the incubation cycle. After several tests on their developed incubator, they achieved hatching rates between 97.14% and 95.24%. Muleta (2023) [2] studied and experimentally evaluated a solar incubator with integrated thermal energy storage. The prototype built consisted of a flat solar collector with integrated thermal storage and an incubation chamber with a capacity of 50 eggs, and achieved a percentage of fertile eggs and a hatching rate of 61.11% and 27.27% respectively.

Most solar incubators in the literature are designs based on glazed flat-plate solar collectors, and the PCMs used are integrated with the solar collectors. The entire heating system runs from the collector to the incubation chamber, usually using forced air; and if water is the heating fluid, then a pump is used. The design of our system is distinguished by three essential elements: the evacuated solar collector, the thermosiphon principle and, finally, the natural convection in the incubation chamber. The evacuated collector has a better thermal efficiency (50˚C to 200˚C) than the glazed flat-plate collector [9]; the evacuated collector follows the sun passively with an incident angle practically equal to 90˚. They capture both direct and diffuse incident rays [10], enabling incubation temperatures to be reached in low-sunlight conditions; moreover, as each glass tube is self-contained, one may break, but this will not interrupt the operation of the entire system, unlike flat-plate glass collectors. The thermosyphon principle offers many advantages for incubation in isolated locations: simple and low-cost, no power supply, no controller or pump, several collectors can be connected in parallel to increase the hot water supply, and easy to build and use, no fuel costs [11]. Finally, the use of natural convection instead of forced convection for heating the incubation chamber, will allow a homogeneous temperature distribution around the eggs; hence an improvement in the hatching rate and efficiency of the solar incubator designed. Furthermore, the integration of two storage modes (sensitive and latent), placed inside the incubation chamber, makes this incubation system more robust, compact and simple to maintain and move. By using a metal-encapsulated PCM, heat is retained inside the chamber over a long period.

This study project aims to support and monitor government programs for rural development, promotion of women, promotion of energy efficiency, use of alternative energy sources and innovation in local development processes. This study also shows enormous potential for adoption and adaptation, not only for local poultry production but also for the poultry industry.

2. Materials and Methods

The design of a solar-powered artificial incubator in an isolated site requires the integration of a unit for capturing and transforming solar energy into useful energy. This energy is then transmitted to the incubation chamber to raise the temperature of the air surrounding the eggs to be incubated. In order for the system to operate continuously and without interruption, it is necessary to integrate a storage element for this useful energy.

2.1. Prototype Description

The design, manufacture and testing of the solar thermal incubator were carried out at the Polytechnic Graduate School in Yamoussoukro (capital of Côte d'Ivoire), at coordinates 6.90˚N/5.35˚W and at an altitude of 196 m. The proposed solar incubator consists of two main components: a U-shaped evacuated-tube solar collector connected to a water tank, and an incubation chamber. The incubation chamber is a wooden box measuring 50 × 50 × 70 cm^3 and covered with polystyrene insulation. Two drawers are mounted in the upper part of the incubation chamber, each holding 50 eggs. A helical copper heat exchanger (coil), 4 m long, is fitted to the bottom of the box and connected to the solar collector's u-pipe. Its role is to supply the necessary heat to the incubation chamber, by natural convection, to heat the eggs. The heat exchanger is a polished copper pipe with an internal diameter of 6 mm and an external diameter of 8 mm. An opening has been made above the incubation chamber to serve as an air vent. Between the egg drawers and the heat exchanger, a 40 × 40 × 15 cm^3 box is inserted to store encapsulated phase-change material (EPCM). The EPCM receives heat from the heat exchanger by natural convection during the day. This EPCM is designed to maintain a temperature of around 38˚C during the freezing cycle (solid state) and 58˚C during the melting cycle (liquid state). The incubation solar system and EPCM are shown in Figure 1 and Figure 2.

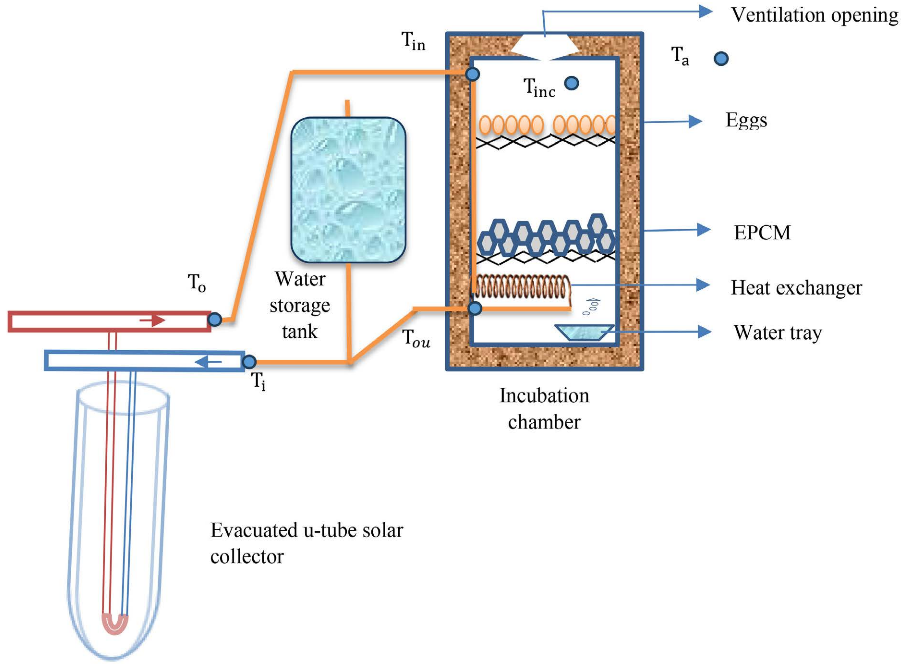

Figure 1. Schematic diagram of a thermosiphon egg incubator.

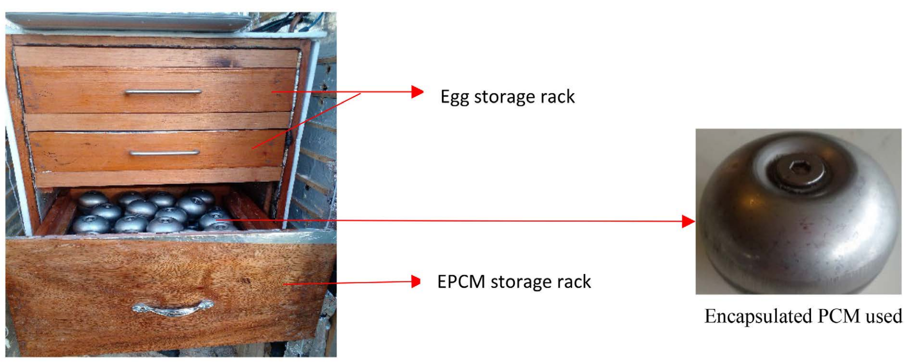

Figure 2. A view of the incubation chamber with PCM.

The solar collector is made up of 10 borosilicate evacuated glass tubes, each 150 cm long. It is modelled on an evacuated tube solar water heater with a U-shaped copper pipe inside, and the assembly is connected to two water collectors, one for the cold fluid coming from the water tank and the second collecting the fluid heated by the evacuated glass tubes. A great deal of research has been carried out into different thermosyphon collector technologies, both experimentally and analytically [12]. Today, flat-plate and evacuated-tube collectors are the most widely used technologies. However, glass vacuum tubes offer better thermal insulation and higher performance than flat-plate collectors [11]. What's more, given the absorber's cylindrical shape, evacuated glass tubes passively track the sun throughout the day, with an incident angle of almost 90˚. They capture both direct and diffuse incident rays [13]. A set of temperature and humidity probes (DHT11 and DS18B20) are placed at various points in the solar incubator to monitor environmental parameters in real time. The sensors are connected to an Arduino microcontroller, which transmits the values every 15 seconds to a computer. **Figure 3** and **Figure 4** show an overview of the proposed solar thermal incubator.

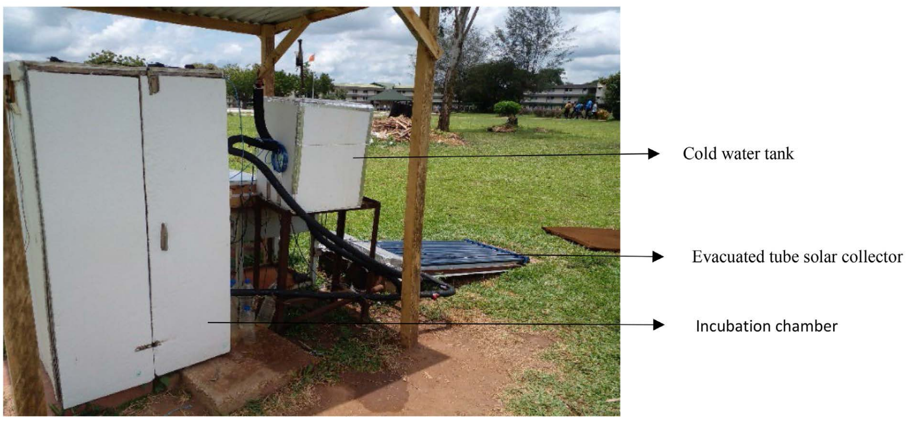

Figure 3. overview of solar thermal incubator designed.

Figure 4. Designed evacuated tube solar collector view.

2.2. Methodology

To measure the incubator's ability to incubate and hatch poultry eggs, performance tests were carried out: physical performance tests and a biological performance test. One of the key parameters in the system's design is its ability to harness solar energy to facilitate the incubation process. Solar energy received by the evacuated tube solar collector is absorbed by the fluid and then transmitted to the incubation chamber to increase the heat required during incubation. Figure 5 shows the solar incubator's heat flow circuit and the control of measurable parameters at each stage.

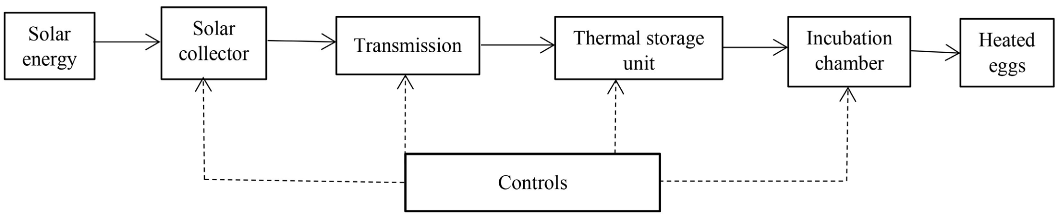

Figure 5. Diagram of heat supply to the incubation system.

The evaluation of physical parameters involved monitoring measured microclimatic elements such as temperature, relative humidity and sunshine [14] inside and outside the incubator (without egg load and without any associated active auxiliary heating system) to determine whether the system was suitable for incubating poultry eggs. The experiment was carried out between November and July, a period during which sudden weather changes are observed at the test site. These weather changes can be due to nebulae, sudden rainfall, dry and hot winds, and have an impact on the performance of any solar system. During the test days, the average hourly solar power received by the collector varied between 428 W/m^2 and 949 W/m^2.

The bioassay was used to determine the efficiency, hatching and fertility rates of poultry eggs using [7]:

$$\text{Efficiency}=\frac{\text{NEH}}{\text{TNEI}} \tag{1}$$

$$\text{Fertility rate}=\frac{\text{NFE}}{\text{TNEI}} \tag{2}$$

$$\text{Hatching rate}=\frac{\text{NC}}{\text{NFE}} \tag{3}$$

For this purpose, the incubation chamber (Figure 6) was loaded with 30 eggs from so-called hybrid hens obtained locally from a breeder-producer, and the whole system was monitored until the eggs hatched. Eggs were turned three times a day at regular 6-hour intervals (6:00 am; 12:00 noon; 6:00 pm). Egg turning was done manually and stopped at day 18.

3. Results and Discussion

Figure 7 illustrates the evolution of radiation and incubation chamber temperature for three test days when the system was operated at no load (*i.e.* without eggs in the incubation chamber). For the three days observed, sunny, cloudy and rainy, incubation chamber temperatures ranged from 35˚C to 44˚C. As can be seen, maximum temperature deviations outside the tolerance range of values required for naturally ventilated incubators were noted on all three test days; the highest deviation was 5˚C for the sunny day, 2.6˚C for the cloudy day. These deviations, are due to increases in ambient temperature at times when solar radiation is considerably high, as shown in Figure 7.

Figure 6. Eggs in the incubation chamber.

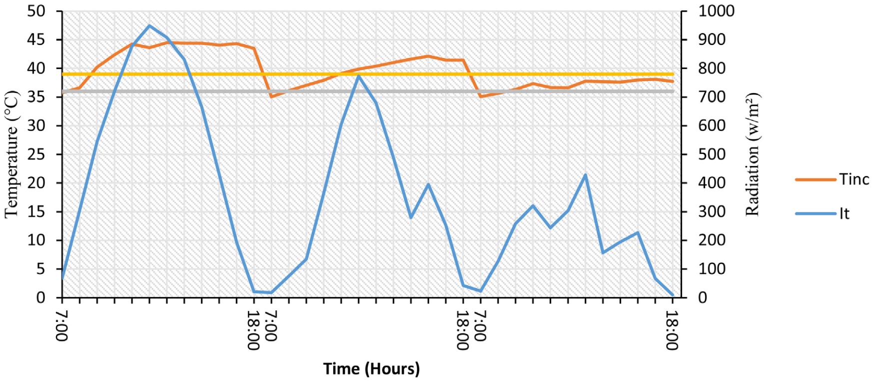

Figure 7. Comparison of incubation chamber temperature variation and hourly solar radiation collected as a function of time for the three selected test days.

If these variations outside the temperature tolerance range of the chamber last longer than 15 minutes, they can affect the hatching rate and therefore the efficiency of the incubator. The lowest maximum temperature was recorded on a rainy day and was 37.77˚C in the incubation chamber. To moderate the flow of warm air during periods of high temperature and supplement the heated air during periods of low temperature, heat diffusers were designed to be placed above the heat source to filter or block this heat flow. Figure 8 shows the thermal diffuser used to moderate the heat in the incubation chamber.

Figure 9 shows the evolution of ambient temperature, incubation chamber temperature and irradiation during the 21-day biological incubation test. It can be seen that the system was able to maintain the inside temperature of the incubation chamber between 36˚C and 39˚C throughout the incubation period. The average minimum temperature was 35.53˚C, recorded during the egg-turning hours at the start of the day. The maximum value was 39.53˚C on the 6th day of incubation, due to increased solar flux. The following curves show the evolution of environmental parameters over the 21 days of incubation.

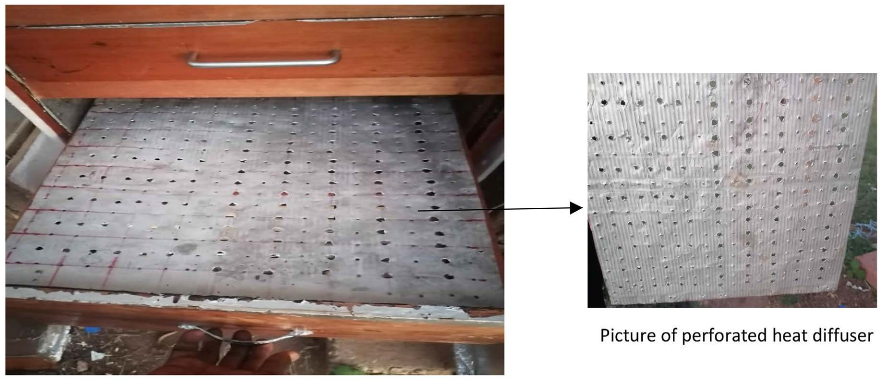

Figure 8. Perforated heat diffuser on EPCM box.

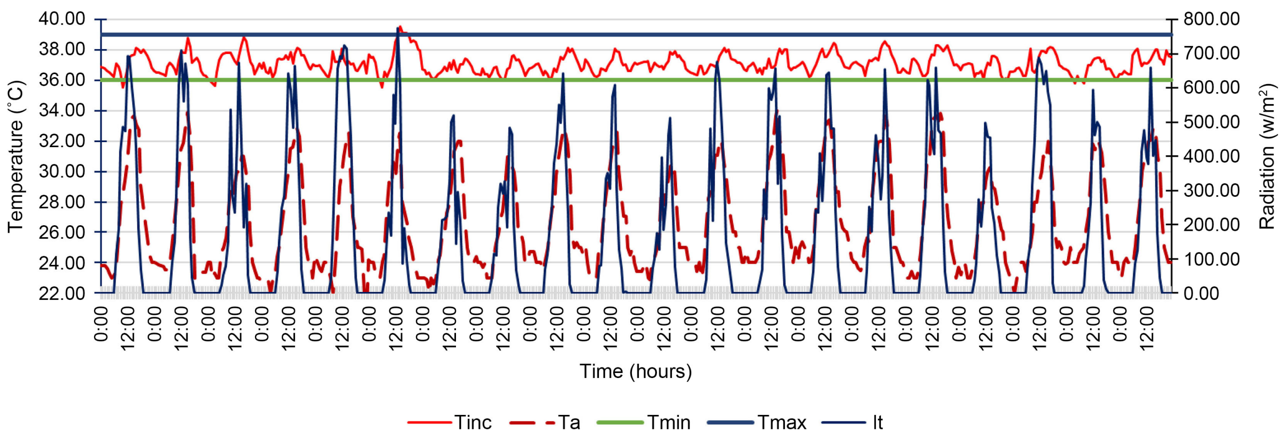

Figure 9. Variations in ambient temperature, incubation chamber temperature and solar radiation over the 21-days incubation period.

By monitoring temperature changes in the chamber every 15 seconds, we were able to avoid prolonged peaks in chamber temperature during daytime periods by closing the EPCM box, thus stabilizing the temperature around the recommended values.

Figure 10 shows the variation in average relative humidity in the incubation chamber over the 21 days of incubation. An average value of 60.20% was maintained throughout the test period, within the recommended range of 45% to 90% [15]. The maximum mean value was recorded on day 6 at 68.5%, and the minimum of 49.44% was reached on day 16.

After day 18, the relative humidity curve continued to rise. This heralded the start of hatching. Eggs began to hatch on the evening of day 19, and by day 20 all chicks had hatched. This confirms the peak in relative humidity from day 18.

Maximum hatching days for eggs incubated in the developed incubator are 20 days. The results obtained from the two performance tests (physical and biological performance) showed that, out of 30 eggs deposited in the incubation chamber, the percentage of fertility was 93% for 28 fertile eggs. Of the 28 fertile eggs, 26 hatched, giving a hatching rate of 93%. The efficiency of the solar incubator is estimated at almost 87%. Figure 11 and Figure 12 show the results of the experiments.

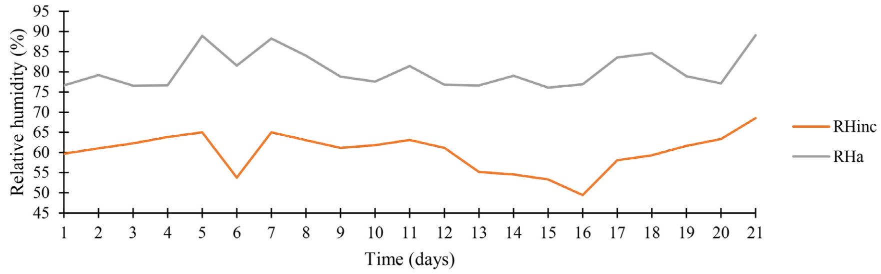

Figure 10. Variation in relative humidity of ambient air and incubation chamber during 21 days of egg incubation.

Figure 11. Chicks hatched on 20th day of incubation.

Figure 12. A view of the chicks 2 days after hatching.

4. Conclusion

The aim of this study was to design, build and test a solar-powered poultry egg incubator using a phase-change material for its application in isolated sites. The proposed incubator was equipped with an evacuated tube solar thermal collector and an incubation chamber with integrated heat storage. The incubation test gave average incubation chamber temperature and humidity values of 35.53˚C to 39.53˚C, and 49% to 68%, respectively. The results of the experimental tests, incubator efficiency and hatching rate, 87% and 93% respectively, lead to the conclusion that the system constructed can be used in rural areas for incubating poultry eggs. The results obtained show that the incubator designed fulfilled its egg incubation function, and the hatching and fertility rates are equal to, or even higher than, some of the research carried out in recent years, as stated in the introduction. Nevertheless, further research is needed to make the incubator more efficient and easier to use. To this end, the following points need to be addressed: automate egg turning and humidification by adding a 12V-powered motor.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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Nomenclature

PCM	Phase Change Material	RHa	Ambient Relative Humidity (%)
EPCM	Encapsulated Phase Change Material	It	Total Radiation (Wh/m^2)
FAO	Food and Agriculture Organisation	Ta	Ambient Temperature (˚C)
NEH	Eggs Hatchaed Number	Ti	Inlet Temperature (˚C)
NFE	Fertiles Eggs Number	To	Outlet Temperature (˚C)
NC	Chicks Number	Tinc	Incubation Chamber Temperature (˚C)
TNEI	Total Eggs Incubated Number	Tin	Exchanger Inlet Temperature (˚C)
RHinc	Incubation Chamber Relative Humidity (%)	Tou	Exchanger Outlet Temperature (˚C)