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Design and Construction of Forced-Air Heating systems for Poultry Brooding: A Comprehensive Review

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Abstract

Brooding is among the most sensitive stages in the poultry production cycle because neonatal chicks bear premature thermoregulatory body systems making them rely totally on external sources of heat for growth and development however, the inadequacy and the inconsistency of the heat supply remain a major challenge as such, the design and construction of forced-air heating systems is vital in the chick's production sector. The study is limited to the design and construction of these systems particularly for poultry brooding purpose and this information is crucial in the establishment of a precised forced-air heating system globally. This review discussed the fundamentals of heat generation and heat transfer in poultry brooding, different forced-air heating systems and their operational principles including construction procedures, material selection, the design approach for system's components and insulation. The study found that, Computational Fluid Dynamics has the possibility of optimization of duct geometry, analysis of air flow velocity and heat distribution. It equally found that the recommended brooding temperature during the first week ranges between 32°C – 36°C with gradual reduction of approximately 5°C every week. The study further identified the existing research gap such as experiments carried out under controlled laboratories without considering ambient environmental conditions, no evidence of affordably developed automated forced-air heating system suitable for small-scale farmers, no evidence of developed hybrid power system involving the common photovoltaic solar system and any other renewable energy system like biomass energy for poultry brooding with clearly stated future research directions. The study concluded that, performance of the system doesn't only rely on the heat source or mode of heat transfer but also on the proper design considerations, the fabrication workmanship while material selection and insulation remain indispensable.

Keywords: *Forced-air heating methods, design considerations, construction, insulation, material selection.*

1.0 Introduction

Poultry production has become one of the rapidly-growing sectors in agriculture globally and it's proving to be the hub where all human life revolves around by ensuring the availability of affordable, high-quality protein in the form of chicken and egg. The global demand for chicken and eggs has been accelerated by rapid population growth, urban development, increasing demand for income and attempt to alleviate malnutrition[1]. The short production cycle associated with poultry has prompted many people to embark on poultry farming coupled with a reasonable cost of production in comparison to other livestock practices and also the possibility to manage the stock at a minimized mortality rate. Currently, poultry farming has emerged as the highly employing sector, including the most contributor to the per capita income and boosting the national economy [2].

In spite of the rapid growth rate recorded in the poultry practices in the past few years, the adoption is highly dependent on the capacity to provide the indispensable requirements responsible for the birds to survive during the early stage of growth and development. The provision of these vital requirements is termed as brooding where naturally, the mother hen provides to ensure newly hatched chicks adapt to the environmental conditions especially self-regulation of body temperature, an indication that they already have fully developed thermoregulatory body system. The ability of the birds to self-regulate the body temperature is determined by the extend at which the feathers have grown, relatively high surface-area to body-mass ratio making them resilient in all forms of environmental conditions. Given the optimal thermal environment during the brooding process, a healthy growth, low mortality rate, strong immune system and the overall performance throughout the bird's life cycle is ensured [3].

The brooding period basically stretches for a period of roughly six weeks though depends on the breed, environmental condition and all other management practices put in place. During the period, newly hatched chicks require a well-controlled environmental temperature that gradually decreases as weeks elapses to strike the balance between the heat generated by the chicks and the supplemental heat. Commercial poultry management system recommends the brooding temperature in the first week to be maintained between 32°C – 36°C which should gradually reduce by approximately at most 5°C every week till the chicks fully develop their thermoregulatory body

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system. It's highly advisable to adhere to this guide in order to realize a good flock quality in terms of the disease resistivity, good body weight and size and ultimately, high production rate of eggs [4].

[5] stated that, the management of poultry brooding temperature is carried out concurrently with other parameters such as relative humidity, air velocity, brooding chamber ventilation, beddings and moisture content. The interactions between these parameters determines the thermal comfort of the chicks and how well the exchange of gases occur within the facility. A case in point is adequate ventilation facilitates the regulation of humidity to deters the microbial activities, maintains the litter's moisture content at the appropriate level, and reducing the concentration of harmful gases such as ammonia and carbon dioxide as such, the respiratory health issues are contained which improves on the overall flock performance. In contrast, inappropriate management of ventilation especially during cold conditions causes heat loses which results in high heat energy demand, increasing the cost of heat generation. Therefore, recording a higher percentage in the flock performance require careful monitoring and regulation of necessary brooding parameters to ensure the recommend levels are maintained.

Although paying attention to these environmental factors is paramount, temperature is singled out as the most difficult parameter to manage and it influences the survival rate of the stock the most, particularly in the first week of chick's life[6]. The quantity of heat basically determines the outcome of the flock and has been identified as the factor directly linked to the minimization of mortality rate when its supply is under control. Supply of heat at a low temperature compels individual bird to alter the metabolic energy towards generation of additional heat for the maintenance of body temperature when it would have been utilized in backing up tissue growth and strengthening the body immunity. This diversion of metabolic energy causes a reduction in feed conversion efficiency, stunted growth, slows down feather development, and amplifies the vulnerability to communicable diseases. Contrarywise, extreme heating results in to heat stress, dehydration, panting, slows down feed consumption, electrolyte imbalance, oxidative stress, and it's a setback to defense against infection, eventually lowering productivity and marking the onset of mortality [6]. Thus, ensuring a steady and homogeneous thermal environment stands out as the major requirement for the best poultry production result.

Earlier on, poultry farming practitioners have implemented a quite a number of heat generation technologies to attain the required brooding temperature. The ancient heat generation methods such as charcoal stoves, kerosene heaters, firewood furnaces, coal burners, and open-flame gas were being commonly used because of their simplicity and less initial investment capital for example [7] conducted an experiment to determine the genetic variability in indigenous chicken under intensive deep litter system in Uganda, East Africa where the eggs were hatched then chicks brooded using charcoal a method of heat generation. Despite the fact these heat generation approaches have run brooding system for a long period of time, they portray several drawbacks such as non-uniform temperature maintenance, generation of combustion gases, risk of fire hazards, environmental pollution, including the drudgery associated with maintaining the fuel quantity for a 24-hour production. These demerits are majorly realized when an attempt is made to practice large scale poultry operations with limited man power, [8] further explained.

The fast technological improvement in agricultural engineering has sprung the innovation of better-quality heating technologies with the capacity to bridge the bottle-neck related to traditional brooding systems. Recent poultry facilities continuously utilize automation systems in heat generation methods such as electric resistance heaters, indirect-fired furnaces, gas-fired heat exchangers, radiant heating systems, hydronic heating network, heat pumps, solar-assisted heaters, and forced hot-air generation units. These innovations have meaningfully enhanced temperature regulation processes, energy efficiency, control of other environmental parameters and ease of operation while lowering the intensity of labor requirement and the entire costs of production [9]. In Nigeria, [10] developed a micro-physical element monitoring device for Trombe wall solar energy poultry brooding chamber for real time measurement of brooding temperature, relative humidity and daily solar radiation using data logger. Nonetheless, considerable disparity is still being noticed in the aspect of thermal efficiency, energy demand, installation technicality, preventive maintenance requirements, and the cost of scaling up production and suitability in various geographical location.

Amongst these heating technologies, forced-air heating has drawn substantial consideration based on the fact that it does not offer localized heating rather a uniform heat distribution in the entire brooding chamber. For instance, radiant heaters primarily warm only a spot in the chamber or surfaces directly underneath the heat source but forced-air heating systems employ blowers or fans to distribute heated air homogeneously throughout the brooding perimeter. The movement of air due to the blower's suction force facilitates the expulsion of unwanted gases that had previously accumulated in the brooding environment including the minimization of cold spots and thermal stratification allowing chicks to spread uniformly. In addition, forced-air systems can be incorporated with an air filtration unit there by improving on the quality of air supplied in the brooding area.

Basically, the objectives of the review include the following;

- To understand the fundamental principles of heat generation and transfer applicable to poultry brooding.
- To understand the design approaches, construction, materials and insulation requirements of forced-air heating system components.

- To understand the possibility of automation in forced-air heating system for brooding.
- To discover the research gap and propose future research directions for developing efficient, affordable, reliable and sustainable forced-air heating systems for brooding.

2.0 Fundamentals of heat generation and transfer for poultry brooding

2.1 Principles of Heat Generation

Generation of heat encompasses changing the various forms of energy sources directly in to heat energy or indirectly into electrical energy. The heat energy is then transferred to a working fluid such as surrounding air or water to achieve a change in temperature before being channeled to do the intended work for example to provide heat for the chicks to maintain an optimal brooding temperature. Heat is an energy form that can be transferred due to the difference in temperature of the surrounding or the body. According to the Second Law of thermodynamics, heat generally flows from a region of higher concentration to the region of lower concentration with temperature as a quantification parameter until thermal equilibrium is attained [11].

In a statement made by [12] in engineering perspective, heat may evolve through several mechanisms depending on the energy source employed. These mechanisms include electrical resistance heating, burning of petroleum or carbon-based material, infrared radiation, geothermal heating, solar thermal energy, and heat pump technologies. Brooding systems are required to be supplied with sufficient quantity of heat continuously for maintaining the recommended thermal condition of the chicks for a particular period of time.

2.2 Sensible and Latent Heat

[12] mentioned that, transfer of heat within poultry house happens majorly in two ways; sensible heat and latent heat. A better grasp of these concepts informs the decision on the effective design of the brooding systems because both plays significant roles in the thermal and moisture conditions with the chick's environment. Sensible heat can be explained as thermal energy that causes a quantifiable change in the temperature of a substance while retaining its physical state. Sensible heat literally takes charge of changing the temperature of the ambient air, litter material, building space, and the birds themselves. The quantity of sensible heat requirement for raising the temperature of ambient air can be computed using expression (1).

$$Q_s = mC_p\Delta T \quad (1)$$

where, Q_s is the Sensible heat (J), m is the Mass of air (kg), C_p is the Specific heat capacity of air roughly 1,005 J kg^{-1} K^{-1} and ΔT is the Temperature difference (°C or K)

[13] explained that, in the interior of the brooding chambers, sensible heat emanates from quite a number of sources including supplemental heat, metabolic heat generated by birds, solar radiation penetrating through walls and roofs, and electrical appliances. On the first week of the brooding stage, the rate at which chicks generate heat through metabolism is relatively low, which requires supplemental heat in form of sensible heat. On the other hand, Latent heat may be discussed as the heat energy absorbed or given out during a phase change of substance at corresponding constant temperature. An example in relation to poultry production, latent heat production is primarily associated with the evaporation of water during bird's respiration process, the process of passing out droppings, litter material drying process and drinking water evaporation. The latent heat energy responsible for these processes can be quantified using expression (2) according to [12].

$$Q_L = m_w h_{fg} \quad (2)$$

where, Q_L is the Latent heat (J), m_w is the Mass of evaporated water (kg), h_{fg} is the Latent heat of vaporization (J kg^{-1}) of water at normal brooding temperatures and is approximately $2.45 \times 10^6\ Jkg^{-1}$.

In the bird's respiration process, moisture continues to be released in to the poultry brooding space. Moist litter equally take part in increasing the relative humidity. While evaporation drives away heat from surfaces through evaporative cooling phenomenon, excessive latent heat given out raises the level of relative humidity, facilitating microbial growth, ammonia release and accumulation, deteriorating litter quality spreading respiratory diseases if the ventilation in the brooding chamber is poor. The difference between sensible and latent heat varies with bird's development. On week one of the brooding, sensible heat surpasses latent heat due to the fact that chicks generate relatively little heat since they have under developed thermoregulatory body system. As the bird's development process progresses, metabolic heat generation and moisture production elevates, causing latent heat to contribute progressively a greater fraction of the overall heat requirement. Therefore, ventilation systems must be adequate for simultaneously allowing the removal of surplus moisture while preserving the right quantity of sensible heat for maintaining the required brooding temperature [13].

3.0 Forced-air heating systems

[14] described an air heating system as a thermodynamic system that converts primary energy into heat energy and transfer of heat energy to air occurs when air gets in contact with the heat emitting object prior to distribution

within an enclosed space. The objective is to generate heat, supply and maintain a desired indoor temperature by striking the balance between heat generation and heat losses. The heat losses fundamentally occur through conduction, convection, radiation, infiltration and ventilation process. The operation of a forced-air heating system entails four primary processes. Once heat evolves from the heat emitting surface, it's transferred to the surrounding flowing air. The heat transfer process involves conduction through the heater material, radiation between the heater surface and the surrounding air and or convection process between hot air and cold air. The forced-air heating system can be classified as direct fired air heater, indirect fired air heaters and electric hot air generators.

3.1 Direct-fired air heaters

[15] explained that direct-fired air heaters fall under the ancient and most widely adopted heating systems in agricultural sector because of the simplicity of construction, high heat generation capacity and heat production within a short period of time. This method of heat generation is by burning fuel directly in a combustion chamber that air stream passes and absorbs heat. There is no physical barrier placed between the combustion gases and the heated air. Therefore, the bi-products of combustion such as carbon dioxide, water vapor, carbon shoots if any and product of incomplete combustion e.g. carbon monoxide and nitrogen oxide mixes with the air stream and all are delivered in to the brooding space and because of this air quality issue, interest for the development of alternative heating technologies has increased. Direct-fired systems remain viable where ventilation is adequate to effectively reduce the concentration of by-products of combustion.

Besides, the sequence of operation of the direct-fired air heater involves supply of fuel into the burner through a fuel delivery system especially a horse pipe and a control valve if Liquid Petroleum Gas is the source of fuel. An ignition device is used to initiate combustion process. A blower forces ambient air longitudinally through the combustion chamber where heat is produced. Heat generated from combustion is transferred in to the moving air stream and because of the ability of air to absorb heat, its temperature raises. The heated air and the combustion products mixture is discharged into the brooding chamber. A thermostat or electronic controller regulates the volume of gas reaching the burner to maintain the temperature in the desired range. Because the heated air is not passed through a heat exchanger, thermal losses are minimal and this allows direct-fired heaters to attain combustion efficiency close to 100% measured in terms of the sensible heat delivered in to the space.

3.2 Indirect-fired air heaters

Indirect-fired air heating systems were later innovated to overcome the indoor air-quality challenges associated with direct-fired systems. Just like direct-fired heating system, combustion takes place within a confinement i.e. combustion chamber, and the bi-products of combustion are discharged outdoors through a flue exhaust pipe. The system comprises a suction fan, combustion chamber from where heat evolves, a metallic heat exchanger that transfers heat to the ambient air. This design largely improves indoor air quality and its adoption has continuously increased for use in livestock buildings where minimization of exposure to harmful gases determines the animal health [15].

The working principle of indirect heating system follows a chronological sequence where fuel burns inside a well-designed combustion chamber and high-temperature gas is allowed to pass through the heat exchanger. A blower sucks fresh air and forces it across the outer surface of the heat exchanger that has gained heat, as a result, the stream of air getting in contact with the wall of the heat exchanger absorbs heat. Only clean hot air enters the brooding chamber while combustion gases exit through the exhaust chimney. The fact that combustion gases do not mix with the heated air, the concentration of carbon monoxide and nitrogen oxides inside the production room are greatly minimized. For large scale brooding operation, indirect-fired heaters are highly preferred because good air quality is a priority, in spite of their high initial investment and operational cost [11].

Direct and indirect heating system is governed by the combustion equation (3) where oxygen is required to mix with the fuel volatiles stored within the fuel molecules as chemical energy as such, the chemical energy is converted into heat energy.

$$Fuel + Oxygen \rightarrow Carbon\ dioxide + Water + Heat \tag{3}$$

Even though combustion heaters release fairly high heat quantity at a relatively lower fuel costs, they emit high volume of harmful gases which require adequate ventilation to prevent excessive accumulation otherwise the poor indoor air quality adversely affect bird's health. On another note, too much ventilation increases the heat demand in the brooding chamber which in turn increases the production cost. The quantity of heat produced through combustion process is estimated using expression (4).

$$Q = m_f \times CV \tag{4}$$

where, m_f is the Fuel consumption rate and CV is the Calorific value of fuel [16].

3.3 Electric hot-air generators

Electrical resistance heating has recorded a reasonable rate of adoption because of its ease of operation, cleanliness, and suitability of control system integration. Electric air heating systems involves the conversion of electrical energy into heat energy through the principle of electrical resistance heating and the heat transfer mechanism in to the moving ambient air occurs through radiation. Unlike combustion-based heating systems, electric air heaters do not require combustion of any sort of fuel, making them characteristically cleaner and noiseless. In fact, no proportion of combustion products forms part of the hot air discharged into the brooding environment. This system is not only applicable in brooding operations but also to enclosed spaces where indoor air quality is paramount such as hatcheries, pharmaceutical industries, laboratories, hospitals, food-processing plants, and environmental test chambers [17].

According to [18], in the electrical heater system, current flows through a high-resistant electric cable such as nichrome wire. The resistivity of the electrical cable impedes the flow of current as a result, heat is generated and this is termed as Joule heating, which is mathematically expressed as shown in equation (5).

$$Q = I^2Rt \tag{5}$$

where, Q is the Heat generated (J), I is the Electric current (A), R is the resistance to flow of current (Ω), t is the heating time (s)

According to [19] , the working principle of an electric hot-air follows the three chronological processes which are, conversion of electrical energy into heat energy using a resistant heating element, absorption of heat by the fluid (air) that gets in contact with the hot surface or that passes closer to the hot surface through radiation heat transfer mechanism, distribution of heated air all over the brooding enclosure. A blower aids the flow of air across the heating element and continuous distribution into the brooding chamber. In summary, the overall process involves the electrical energy conversion, heat transfer and heat distribution.

3.3.1 Design of electric heating element

[18] demonstrated that, by knowing the voltage and electrical energy input of the power source, the design of the heating element is required to determine its diameter and length. The heating wire of various types can be employed for example nichrome, circular in cross section. The determination of the parameters i.e. Diameter and length of the heating element is performed using expression (6).

$$\frac{d}{l^2} = \frac{4\rho H}{V^2} \tag{6}$$

where, *d* is diameter of the wire*, l* is the length of the wire*,* ρ is the specific resistance (Ω-m) and V is the coil's input voltage. Since the mode of heat transfer from heating wire surface to the flowing fluid is radiation, the component H is the heat dissipated per unit area and can be computed by the mathematical model (7).

According to [18], $H = 5.72\times 10^4 ke\left[\left(\frac{T_1}{1000}\right)^4 - \left(\frac{T_2}{1000}\right)^4\right]$ (7)

where, T_1 is the maximum absolute operating temperature of nickel-chromium alloy, T_2 is the maximum absolute temperature at which the heating element is supposed to be maintained, *e* is the emissivity, and *k* is the radiant efficiency.

Electric air heating systems can easily be integrated with electronic controllers such as solid-state relays for on and off switching, digital temperature sensors, and affordable microcontrollers. This has elevated the rate of adoption of electric air heating systems in the current precision livestock practices. This integration enables effective temperature regulation, intermittent heating schedules, remote monitoring with IoT technology which is aimed at reducing the drudgery associated with conventional brooding activities and ensuring efficient energy utilization hence lowering production costs [20].

4.0 Construction of forced-air heating systems for poultry brooding

[21] elaborated that construction entails various activities which are much more than simply assembling component parts. Marking, cutting, welding of selected materials, electrical system installation are key elements of construction. Every selected material must be capable of withstanding repetitive heating cycles without developing mechanical lines of weakness or corrosion. The heating chamber must safely retain the designed quantity of heat with negligible heat loss to the environment while permitting efficient heat transfer to flowing air. Current carrying conductors must be properly insulated to prevent risk of associated with short circuit e.g. blowing of electrical components, fire hazards while the installation of the electronic control systems must be properly accomplished to accurately monitor and regulate environmental conditions in the brooding chamber.

4.1 Fabrication Process

Fabrication generally involves the measurement, marking, cutting and joining the metal component of the construction by welding, a common metal joining technique based on the engineering drawings. During measurements, allowances are considered to cater for bends, seams, and flanges. Cutting involves sheet metal portioning in to required sizes using guillotine shears, plasma cutters, angle grinders, Computer Numerical Control laser cutters. Accurate cutting minimizes misalignment of parts during assembly and material wastage. Forming where the cut metal sheets are folded with the help of a press brake or manual folding machine to come up with the required profile is another element of fabrication [22]. A summary of common fabrication defects is presented on table 1.

A metal plate is rolled using a slip roller to form a circular duct or a hollow section. Joining the sections are performed with the help of lock seams, rivets, spot welding, Metal Inert Gas welding and or flanged connections with bolts. The heated air passage's joints should be sealed with heat-resistant materials like sealants or gaskets to prevent or stop air leakages. After the completion of fabrication process, the components should undergo surface finishing in order to improve on the physical appearance. This involves grinding weld beads, removing burrs, restructuring indentations, sandblasting or wire brushing, applying high temperature primer, degreasing, applying heat-resistant paint. Surface finishing prevents corrosion by rust hence prolonged service life, especially in humid environments for instance poultry keeping environment where ammonia that accelerates metal deterioration is generated [22].

Table 1: Common fabrication defects and preventive measures

Defect	**Possible Cause**	**Recommended Solution**
Air leakage	Incomplete welding	Continuous seam welding and leak testing
Chamber distortion	Excessive welding heat	Balanced welding sequence and controlled heat input
Corrosion	Inadequate surface protection	Apply high-temperature anti-corrosion coatings
Poor airflow distribution	Improper chamber geometry	Incorporate diffusers and optimize internal layout
Excessive heat loss	Insufficient insulation	Increase insulation thickness and seal gaps
Heating element contact with metal	Improper mounting	Use ceramic insulators and maintain adequate clearances

Source: Kalpakjian and Schmid (2020); Callister and Rethwisch (2020)

4.2 Insulation

In an explanation made by [23] , heat losses from ducts or heat chamber reduces the quantity of heat that is supposed to reach the intended end point in a system hence lowering the operating efficiency of the system therefore, insulation is greatly important. Insulation is equally important where heat duct or heat chamber is exposed to the workers or can easily be reached by workers. The insulation materials such as glass wool, mineral wool, rock wool, ceramic fiber blankets possess high thermal resistant property that allows for efficient heat retention. The thickness of Insulation to be installed depends on the quantity of heat to be generated but it commonly ranges between 25 to 50 mm. Heat losses can also occurs due to air leakages which as well decreases system efficiency by limiting the volume of hot air required in system.

The major leakage points include flanged joints, access panels, sensor positions. The prevention of leakage can be achieved by applying heat-resistant silicone sealants for example shellac, using compressible gasket papers, uniform torque bolt tightening, regular joints inspection during operation. Adhering to this construction measures improve the system's performance efficiency at a reduced rate of energy consumption. The process of thermal insulation requires that insulators be placed all-round the heat chamber. It's very vital to adhere to the procedures of insulation for instance, ceramic fiber blankets are supposed to be wrapped around the chamber followed by the outer protective casing. An air gap between the insulation and outer protective housing may further minimize heat loss through conduction [24].

4.2.1 Designs of the insulation

[25] stated that, determining the thickness of insulation involves the consideration of the surface area heat chamber and that surface area of the insulation. By making L the length of the heating chamber and that of the insulation, the surface area of the heat chamber, A_1 and the surface area of the heat chamber when insulated, A_3.

The steady rate of heat loss from the air is expressed as; $Q = \frac{T_i - T_o}{R_T}$ where, T_i is the final temperature of the air, T_o is the initial temperature of the air and R_T is the total thermal resistances given by;

R_i+$R_{chamber}$+$R_{insulation}$+R_0, where R_i is the convection resistance at the chamber's interface $(\frac{1}{h_i A_1})$, $R_{chamber}$ is the thermal resistance of the chamber material $(\frac{t_c}{k_c})$, $R_{insulation}$ is the thermal resistance of the insulation material $(\frac{t_{in}}{k_{in}})$ and R_0 is the convection resistance at the insulation's interface $(\frac{1}{h_o A_3})$ therefore, Q = $\frac{T_i - T_o}{(\frac{1}{h_i A_1})+(\frac{t_c}{k_c})+(\frac{t_{in}}{k_{in}})+(\frac{1}{h_o A_3})}$ where,

h_i is the heat transfer coefficient inside the heat chamber.

t_c *and* k_c is the thickness and the thermal conductivity of the heat chamber's material respectively.

t_{in} *and* k_{in} are the thickness and the thermal conductivity of the insulation material respectively.

h_o is the heat transfer coefficient outside the heat chamber.

Also, the rate of heat loss can be expressed as, Q = $\frac{T_3 - T_o}{R_o}$, T_3 being the temperature at the outside surface of the insulation as such, the rate of heat loss expressions is equated and solved to arrive at t_{in} i.e.

$$\frac{T_3 - T_o}{\frac{1}{h_o A_3}} = \frac{T_i - T_o}{(\frac{1}{h_i A_1})+(\frac{t_c}{k_c})+(\frac{t_{in}}{k_{in}})+(\frac{1}{h_o A_3})} \quad (8)$$

4.3 Electrical Wiring

The heating element may support different magnitude of current up to 10 A and above depending on its power requirement but have the capacity to draw such a huge magnitude of current, the cross-sectional area of the element is essential therefore, appropriate conductor sizing is necessary for example [26] recommended that, 80 W should be supported with a conductor of 1.5 mm² cross sectional area, 150 W to be connected to 2.5 mm² wire while 300 W to 4 mm² wire and if these instructions are violated, cables can be at risk of blowing. Furthermore, heat-resistant silicone-insulated cables are recommended for use inside the heating chamber since they are heat resistant materials, meanwhile PVC-insulated cables are acceptable outside hot zones because it melts at high temperatures.

4.4 Materials Selection

Material selection is one of the most crucial factors to be considered during the construction of an air heating system. Poor material selection often results in to rapid corrosion, heat loss, structural deformation, electrical hazards, and increase in maintenance costs. When carrying out material selection, [23] mentioned that it should base on a number of properties such as mechanical strength, thermal properties, corrosion resistance, manufacturability, availability, and cost. The surface temperatures of air heating element basically range from 35°C to over 500°C however, the air temperature to be conveyed to chicks is supposed to be maintained between 32°C and 36°C in the first week of the brooding process. The fact that different components require materials of different engineering properties, the material to be used for a particular component should possess those properties that makes it suite the intended purpose for instance, mild steel is basically fit for the fabrication of heat chamber due to its high mechanical strength, good weldability, excellent machinability, low cost and ubiquitous with a thermal conductivity of roughly 50 W/m·K and this is the reason it permits moderate heat transfer as it maintains sufficient structural integrity to achieve the design purpose.

However, mild steel deteriorates quickly in ammonia generated environment because in poultry brooding, ammonia released as a result of litter decomposition, increases the humid condition of the chamber. Thus, protective coatings such as high-temperature resistant and moisture proof paint or powder coating should be applied. Application should be on points such as heat chamber casing, structural frame, support brackets, mounting plates. In a situation where corrosion is to be avoided without preventive measures, stainless steel material is supposed to be used. Stainless steel grades which include AISI 304, AISI 316 provide outstanding resistance against moisture, ammonia, oxidation, high temperatures. Stainless steel enables the system the work for a long period of time without corroding although it's a somewhat costly material. It is therefore recommended for the Interior layer of the heat chamber, outside surfaces that gets exposed to moisture or air. This is a testament of it being both heat and rust resistant because it can be placed on multiple positions and still serve the required purpose [21]

Aluminum is another alternative material that can be used in the construction of air heating systems. It offers numerous advantages lightweight that makes it easily lifted, exceptional thermal conductivity of approximately 205 W/m·K, possesses best corrosion resistance property, provide ease of molding to any required shape. The truth of the matter is that, aluminum transfers heat easily which makes it best fit heat exchanger fins construction, protective covers, heat sinks, sensor mounting brackets. However, aluminum loses mechanical strength at temperatures above 200°C as such, it should not be used as an inner material directly around the heating coils [23].

4.5 Heat chamber construction

The heat chamber serves as the pillar of a forced-air heating system, which is an enclosure where electrical energy is converted into heat energy and transferred to the moving air stream. Its design which entails the heating area sizing, material selection and construction in general has a direct influence on heat generation efficiency, air temperature increment, air pressure loss, structural durability, and operational safety. In poultry brooding practices, the heat chamber must be capable of delivering, continuously a clean and uniformly heated air at a right temperature to prevent heat or cold stress from affecting the chicks. Heat chambers prevent the interaction between the heating element and the external environment. This configuration reduces the rate of heat loss, minimizes accidental electric shock or burn as a result of accidental contact with the energized heater components [27]

Furthermore, the ability of the heat chamber to withstand repeated heating and cooling cycles without significant thermal expansion, deformation, or mechanical fatigue is the evidence of its structural durability. After a successful completion of the heat chamber construction, performance test should be carried out to check if it meets the following engineering requirements; provision sufficient residence time for air to absorb heat, promotion of uniform airflow velocity across the heating element, minimization of pressure losses, reduction of conductive and radiative heat losses, provision of access for convenient maintenance and replacement of heating elements, compatibility with heat and electrical insulation for user safety, accommodation of sensors and control devices.

4.5.1 Design Considerations for Heating Chamber

The effective performance of an air heating system depends particularly on the geometric and thermal design of the heating chamber. Before the commencement of the construction, several design parameters must be catered for. In determining the chamber dimensions, the end point heat consumption requirement should be known. The total quantity of heat required depends on the number of chicks, the temperature at which the brooding chamber is supposed to be maintained, ventilation rate and infiltration. The heat requirement can be estimated using expression (9).

$$Q = \mathrm{UA\Delta T} \tag{9}$$

where Q is the Heat transfer rate (W), U is the overall heat transfer coefficient of the heat chamber material, A is the surface area of the brooding chamber and ΔT is the difference between inside temperature and the outside temperature of the brooding chamber. This equation ensures that the heating requirement is properly computed to meet the thermal demand of the brooding chamber [28].

4.5.2 Design of the heat generation chamber

The heat generation chamber is an enclosure within which heat from the heating element is transferred. The heat generation chamber can be of a rectangular cross section with the heating element enclosed inside for the efficient heat transfer in to the flowing air. [29] mentioned that expression (10) is used in the computation of the heat chamber size.

$$Q = h\,A\,\theta_m \tag{10}$$

where, Q is the total heat requirement, A is the cross-sectional area of the heat chamber, *h* is the heat transfer coefficient of the heating element, θ_m is the Logarithmic Mean Temperature Difference (LMTD) between the heat chamber surface and the air stream. LMTD is applied because the temperature of air goes on changing along the length of the heat chamber.

$\theta_m = \left\{\frac{\theta_1-\theta_2}{\ln\frac{\theta_1}{\theta_2}}\right\}$ but $\theta_1 = (T_3 - T_1)$ and $\theta_2 = (T_2 - T_1)$ where T_3, T_2 and T_1 is the temperature at which the heating element is to be maintained, the temperature of the heated air and the temperature of the ambient air respectively.

4.6 Heating Element Mounting Provisions

[30] emphasized the prevention of the heating element from getting in contact with the heat chamber by creation of a mounting support. When mounting, the following factors should be considered; provision of adequate spacing between adjacent coils, sufficient clearance from heat chamber surfaces, easy removal during maintenance, provision of room for thermal expansion, secure attachment to insulation ceramic. Inappropriate mounting of the element can result in coil sagging, electrical short circuits, and premature heater failure. Access point for purpose of repairs and maintenance should be incorporated into the chamber design. A well-positioned access panels allows easy access of the heating element during replacement, sensor inspection, cleaning accumulated dust, electrical wiring inspection, ceramic insulator replacement. Heat-resistant silicone gaskets are normally placed around access covers and fitted firmly to prevent air leakage.

4.7 Chamber Shape

Different chamber geometries are being used depending on the preferred design. Rectangular chambers are commonly used because of their ease of fabrication, less sheet metal requirement, availability of adequate mounting surfaces and a good working space for maintenance. They can be down-sized or upscaled for the suitability of use by farmers ranging from small to larger-scale. Cylindrical chambers however offer uniform pressure distribution, reduced area of stress concentration, uniform airflow velocity due to smooth walls although rolling equipment are highly necessary and the fabrication processes is more complex compared to rectangular shape chambers. Square shape is another geometry that offer simplicity in the fabrication process although airflow and pressure tend to be non-uniform because of the sharp corners [22]

In addition, the geometry of the heat chamber should allow 80% of the flow volume to absorb a greater percentage of the heat quantity by directly getting in contact with the surface area of the heating element while avoiding excessive redundant chamber zone that could increase the chances of much air stream passing unheated. The clearance between the chamber walls and the heating element should be good enough to prevent localized overheating of the chamber walls to guard against accidental burns and heat loses. A recommended minimum clearance is normally 40–60 mm. Other constructions integrate a tempered glass window that allows frequent inspection of the heating element during operation without dismantling any part of the chamber. Borosilicate glass is preferred because of its high heat-resistant property which enables it to withstands temperatures beyond 500°C.

4.8 Duct design and fabrication

Air ducts are enclosed passways intended to permit a smooth flow of heated air from the heating chamber to the brooding environment. In forced-air mode of heat transfer, the duct network is the distribution channels that allows conveyance of conditioned air at a minimized rate of heat loss and pressure drop. The design and fabrication of ducts are thus vital in achieving a transfer of heated air at a designed flow rate which in turn improves the ventilation efficiency, and optimization of the overall thermal distribution of heat in the brooding system. Heated air ducts are subjected to conditions of high humidity, airborne dust, feathers, ammonia, and prolonged period of thermal exposure. These operating conditions require ducts that are mechanically robust, corrosion-resistant, thermally insulated, and easy access for cleaning, repairs and maintenance. Appropriately fabricated ducts also minimize the overall energy consumption by lessening the resistance to airflow and leakages [31].

In addition to heated air conveyance, duct system performs other essential functions within the brooding system. The water and feed supply network in automated brooding system is constructed using ducts while maintaining the required feed and water discharge rate. The design of duct system is to ensures that chicks all over the brooding area receive nearly equal quantity of the requirement i.e. heat, water, feeds. A perfect sizing of ducts guarantees the blower operation within the design range where heat chamber receives satisfactory air volume for effective convective heat transfer. When an upstream air filtration system is integrated in to the duct system, cleaner air supply, reduced respiratory stress and disease risk in poultry is realized.

4.8.1 Design considerations for ducts

A number of engineering factors must be taken into consideration during duct design. The duct size should be in a position to contain the required airflow capacity without causing turbulence or pressure losses. The designs depend on number of chicks, brooding area, heater capacity, ventilation requirements, blower characteristics, airflow velocity and the materials to be used. [19] stated that, the volumetric airflow rate can be estimated by mathematical formular (11).

$$Q = AV \tag{11}$$

where, Q is the Volumetric airflow rate (m^3/s), A is the Cross-sectional area of the duct (m^2), V is the Air velocity (m/s).

For a constant airflow rate, the duct area is inversely proportional to the air velocity implying that increasing duct area reduces air velocity, while decreasing duct area increases velocity and pressure losses. Ducts must be firmly held to prevent sagging, or mechanical failures due to its own weight. Support structures that can be used are steel brackets, hangers, ceiling suspension rods, wall-mounted supports. The spacings between the structures must be appropriately deigned to avoid excessive deflection as it accommodates thermal expansion. At the end of the duct fabrication inspections should be carried out against dimensional inaccuracy, rough internal surfaces, improper alignment, unsecured joints, presence of sharp edges, incorrect flange dimensions and inadequate corrosion protection. Pressurized water or smoke tests may be performed to identify leakages before commissioning. At the end of the duct system, diffusers or outlet nozzles that increases the surface area of heated air distribution within the brooding area is fitted. Effective diffuser design should prevent draft formation and distributes heated air uniformly within the entire brooding area to prevent hot spots or cold spots. Perforated diffusers or multi-slot outlets are normally installed to accomplish these tasks [31].

4.9 Blower selection and installation in forced-air heating systems

Another essential component of the forced-air heating system is the blower because it facilitates the flow of air which in turn transfer thermal energy from the heating chamber to the brooding environment. The blower enables the development of air pressure differential sufficient to move air against the resistance of intake filter, heating element, the bends and sudden expansion or constriction of the duct network, and air outlet or dispenser's orientation, so as to deliver the required heat quantity in to the chick's environment.

[17] mentioned that, the efficiency of heat delivery in to the brooding space doesn't only depend on the effectiveness of the heating element in generation of heat but also on the ability of the blower to convey air at a designed flow rate with sufficient pressure. An undersized blower may fail to achieve the discharge of the required heated air volume causing a heat deficiency within the brooding space hence potential underheating of the chicks may happen and again, an oversized blower may convey ambient air at a velocity that doesn't give air enough time to absorb heat, resulting in to insufficient heat being transferred to the brooding chamber therefore, selecting a blower capable of delivering the required airflow rate at the calculated static pressure guarantees an effective operation of the air system. Proper blower selection thus involves consideration of volumetric flow rate and the pressure losses. The total pressure losses are the summation of the individual pressure loss that occur at the air filters, heating element, duct bends, diffusers or dispensers. Pressure losses can be minimized by ensuring a smooth airflow along the airflow path which in turn improves heat transfer efficiency. The airflow path should avoid dead zones, air recirculation pockets, high turbulence, sudden expansions, sharp constriction.

In addition, Installation requires expertise in mounting configuration, vibration control, electrical integration, and future maintenance. Properly installed blower system minimizes vibration and ensures safe and reliable operation thus the common installation procedures involve mounting the blower on a rigid steel frame, aligning the blower's outlet accurately with the duct, using flexible connectors between the blower and duct to accommodate vibration, securing all mounting bolts with lock washers or thread-locking compounds, providing sufficient clearance for maintenance and inspection. Misalignment can lead to increased vibration, premature bearing wear, and airflow losses.

[17] further stated that, routine maintenance is crucial because a blower is required to operate continuously in order to maintain the heat requirement of the brooding area otherwise the birds can suffer cold stress which is risky during the first week of life since week-old chicks are highly heat demanding. Routine maintenance of the system requires cleaning dust and feather accumulation, inspecting joints for leakage, repairing damaged insulation, checking supports for corrosion or loosening, removing obstructions that restrict airflow. Regular maintenance helps maintain heating efficiency and ensures consistent environmental conditions throughout the brooding period.

4.9.1 Blower Selection Criteria

[32] listed the key considerations when selecting the blower as airflow rate in cubic feet per minute, static pressure requirements, heating chamber resistance, duct length and configuration, power requirement in horse power, operating noise, durability, ease of repairs and maintenance, availability of spare parts and compatibility with electronic controls. Among the factors to be considered when selecting the blower, a factor for instance power requirement involves a few steps of mathematical computation which demands parameters such as mass flow rate, specific heat capacity of air and the targeted temperature changes. The factor of power is vital because the heat quantity to be delivered in to the brooding chamber depends on the volume of airflow where by, if the blower's power requirement is not met, hot air flow volume may be inadequate.

In reference to [33] Work done by heater = Work done by air. Work done by air (W) = Mass flow rate of air ($\dot{m}$) × Specific heat capacity of air (C_p)× Temperature difference (ΔT).

$$W = \dot{m} \times C_p \times \Delta T$$

$$\dot{m} = \frac{W}{C_p \times \Delta T} \tag{12}$$

Discharge = Mass flow rate ($\dot{m}$) × Specific volume of air

$$\text{Fan horse power} = \frac{\text{Discharge}}{6320 \times \text{Fan efficiency}} \tag{13}$$

5.0 Performance metrics

The three categories of forced-air heating technologies can therefore be differentiated according to the condition that dominates the production system. Where low investment capital is one of the primary requirements, direct-fired forced-air heating system preferably is the best option, provided that ventilation and combustion safety are adequately ensured. Where high heating capacity must be combined with improved indoor air quality, indirect-fired heating becomes the best fit, due to the high stocking density meanwhile where hot air with good air quality, precise hot air temperature and automation of weekly temperature setpoints are the targets, electric forced-air heating becomes the most appropriate option, provided a reliable and economically affordable electricity is

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available[34];[19] . The parameters for comparison of the three forced-air heating system are pointed out on table 2.

Table 2: Comparison among the three forced-air heating systems

Heating systems	Thermal/ energy efficiency	Cost	Indoor air quality	Suitability for different scale
Direct-fired	Minimal heat losses because combustion gases transfer heat directly to the flowing air therefore, efficiency is high	Low, no much components required	Poor since combustion products mixes with air	Small to large scale, particularly where low capital cost is important
Indirect-fired	High, but lower than direct-fired because of heat loses at the heat-exchanger	High due to bulkiness in terms of components involved	Good to excellent; combustion gases flow within a heat exchanger but sometimes heat exchanger housing can accumulate dusts	Medium to commercial production
Electric resistance	Very high because electrical energy is converted directly into heat energy	Low to moderate for small systems but potentially high for large-capacity systems	Excellent because no combustion gases are introduced	Small to large scale, brooding facilities

Source: Hope (2014); Sutrisno and S. Sri (2020); Watlow (2025)

As illustrated on table 2, the parameters can be analyzed and discussed to provide a better understanding of the relevance of the parameters to the categories of forced-air heating systems considered in this study. The discussion required pairing the parameters although other parameters can be expanded to thoroughly examine which category of the heating system is appropriate for a particular parameter. This helps informs the decision when planning to adopt a forced-air heating system for poultry brooding.

5.1 Capital Cost versus Operating Cost

Direct-fired heaters generally have low initial cost because the construction is simple and the component parts are few. The components parts comprise; the air blower, the combustion chamber and the indispensable brooding chamber. [36] discussed that the cost of acquiring these components depend on the location of the market although the difference shouldn't double the minimum price at a different location provided it's within the same country. Overtime, the labor required to operate the system, fuel to be used for combustion which are the variable cost ends up increasing the operating cost beyond the initial investment cost.

Indirect-fired systems basically require more components. This explains why the initial cost becomes higher. The heat exchanger which is a complex technology alone is costly when combine with installation cost. Furthermore, some of the useful heat losses occur along the walls of the heat exchanger and exhaust gas flows along with some quantity of heat as well. In this case, not all the heat energy contained within the hot gas is transferred to the forced-air as such, more gas has to be burnt in order to ensure higher temperature on the heat exchanger surface area. This translates to a higher operational cost. In summary, indirect fired forced-air heater may not achieve the same heat transfer efficiency as it happens with direct-fired system[35].

Electric forced-air heating systems somewhat require high initial capital for commercial operation compared to small scale operation because the electrical system components become costly with the amount of current it's supposed to handle. Commercial operation requires heavy current in order to operate at a higher efficiency in terms heat transfer in to the forced-ar. In addition, for reliability of production since brooding operation is a 24-hour production process, non-stop, the grid system at times goes off therefore, a hybrid system is preferable for electric forced-air heating which makes it even more expensive in terms of initial cost[32]. In contrast, operational cost is low since the only major task remains payment of electricity tariffs and labor otherwise when photovoltaic power system is the integration, tariffs become omitted from the operational cost.

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5.2 Air Quality versus Thermal Efficiency

The air quality associated with direct forced-air heating system is generally poor since the air is passed directly into the hot burning fuel and also since no any air filtration system is always incorporated. The product of combustion of the fuel such as carbon dioxide, nitrogen oxides are unwanted constituents of the hot air to be supplied in to the brooding chamber. Most interestingly, the thermal efficiency is high because the overall quantity of heat generated by the gas is transferred to the forced-air as it passes directly in to the hot gas. In a situation where the insulation along the duct network is properly installed, the heat losses may be neglected completely[37].

Indirect fired system minimized the extend of forced-air contamination through the incorporation of a heat exchanger which prevents the direct mixing of the hot gas and the forced-air. The hot gas transfers its sensible heat through the walls of the heat exchanger and the forced-air passing absorbs the sensible heat as it gets in contact with the hot heat exchanger's walls. This modification improves the air quality delivered in to the brooding chamber however, if the heat exchanger is not well maintained, the dust particles that clogs the fins can get transferred in to the forced-air. The thermal efficiency is low compared to direct-fired system because not all the quantity of heat generated by the hot gas is transferred in to forced-air, a percentage of the heat remains within the hot gas and also the heat losses occur within the walls of the heat exchanger because it retains some of the heat from the hot gas [35].

Electric heating systems eliminates the aspect of this forced-air contamination far beyond how indirect-fired system does. The extend of clogging within the heating element is very minimal since it does not have fins or dust pockets as part of the resistance heating element. Besides, the resistance heating element is contained within a casing which prevents its interaction with the environment therefore, the air quality is very good. The thermal efficiency is equally high because the entire heat generated by the heating element is transferred to the forced-air without any form of heat loss. This is true because the forced-air passes and contacts the hot element directly without any barrier, besides, the heat chamber accumulates the radiant heat from the heating element whereby the forced-air first gets preheated before getting in contact with the hot element[20]. This mechanism enhances the thermal efficiency of the electric forced-air significantly.

5.3 Suitability for small-scale versus commercial poultry farmers.

Production scale significantly dictates the suitability of each heating system. Small-scale poultry practitioners basically operate under limitations in terms insufficient capital, restricted access to technical extension services and the interest for simple and easy to maintain equipment. Based on these limitations, direct-fired heating system can be a choice because it's relatively simple to set up, quick heat generation, heat transfer and affordable. However, its adoption still stretches from small to large-scale depending on the farmers capacity because the system is scalable[38].

Electric heating system is equally very suitable for small-scale production in a situation where a single energy source is utilized but because most of the small-scale operators are located in the remote areas where there is no access to electricity, solar photovoltaic energy which is a common energy system can be an alternative energy source though it's somewhat high in its initial capital when it comes to brooding activity. Medium-large scale farmers can utilize electric forced-air heating system with minimal challenges since most of them are located around grid connected areas and are generally able to afford in case of powering with a combination of hydroelectricity and photovoltaic system. The major reason being suitable for all levels of farmers still remains scalability[38];[39].

Indirect-fired systems are basically suitable for medium-large-scale brooding practitioners because the higher initial cost arising from the volume of the components involved but also the cost of acquiring the entire components makes small scale farmer hardly breakeven in the operation. Commercial producers are in a better position to maintain burners, heat exchangers, exhaust systems which may be a problem to small scale farmers. Most importantly, the improved indoor air quality offered by indirect-fired heating becomes a valuable aspect to larger stocking density practiced by commercial operation because the volume of unwanted gases generated by large stock density is quite much therefore, maintaining a healthy indoor environment in terms of air quality is a paramount for replacing a greater percentage of unwanted gases. Based on this reason, indoor air quality is one of the major production requirements for commercial production[35];[28].

6.0 Computational Fluid Dynamics (CFD) application in forced-air heating systems for poultry brooding

[40] highlighted that Computational Fluid Dynamics has proven to be a very powerful tool for the design, analysis, and optimization of air heating systems. Distinct from conventional design approach that rely solely on empirical equations and experimental testing, CFD give engineers the enablement to predict airflow characteristics, heat transfer mechanism at that instance, heat distribution, pressure loss occurrence, and ventilation performance within the brooding facilities prior to fabrication. Therefore, CFD lowers development costs, minimizes design errors, and improves thermal comfort of chicks by letting designers analyze the general operating conditions of

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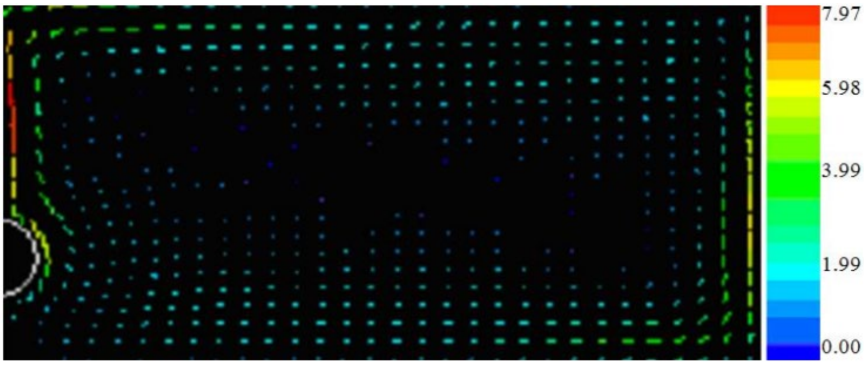
the system with the aid of a computer-based simulation. Several CFD softwares have been developed which includes; ANSYS Fluent, OpenFOAM, COMSOL Multiphysics, and STAR-CCM+ and have rapidly gained popularity. Engineers currently are able to examine how heat element orientation, blower capacity, duct configuration, insulation materials, and ventilators impact the thermal condition inside the brooding chamber ahead of the physical prototype construction.

6.1 Airflow Simulation

One of the direct applications of CFD is the prediction of airflow pattern using CFD softwares. The simulation helps observe how heated air travels from the heat source along the ducts and how it circulates within the chick's environment. The observation assists in determining whether to adjust either the dispenser's orientation or increase the perforation including the length to make sure the entire brooding room is receiving uniform volume of heated air. Poor design and positioning of the dispenser often produce localized cold spots that forces chicks to huddle in an attempt to utilize the hot spots [41].

In addition to air flow volume, air flow velocity analysis presents another core value of CFD utilization. Velocity contour maps illustrate the variation in air velocity across the entire system's network. Maintaining a suitable airstream velocity is paramount because very high velocity intensifies draft within chicks while too low air flow speed makes it impossible for heat to accumulate causing heat stress, moisture accumulation hence a rise in relative humidity, increase in ammonia concentration. CFD in this case displays velocity contour maps with different colors representing airflow speed variation at various points within the brooding chamber. The major illustrations produced by the contours are; horizontal velocity distribution, vertical airflow profile, duct exit velocity, floor-level velocity, recirculation zones. CDF therefore informs the designer's decision on the operation to be optimized e.g. fan speed, duct diameter, dispenser design so as to uniformize the velocity pattern without draft formation throughout the brooding chamber [42]. [37] employed CFD to simulate the air flow velocity in the poultry house and the air distribution within the poultry brooding chamber, achieved using an air blower was somewhat even as seen in figure 1. The air velocity as per the simulation was found to be within the range of 0.6m/s – 0.8m/s and this range was maintained within the poultry brooding chamber. The heating of air was achieved by blowing air through a firewood furnace. This demonstrates the direct-fired forced-air heating system.

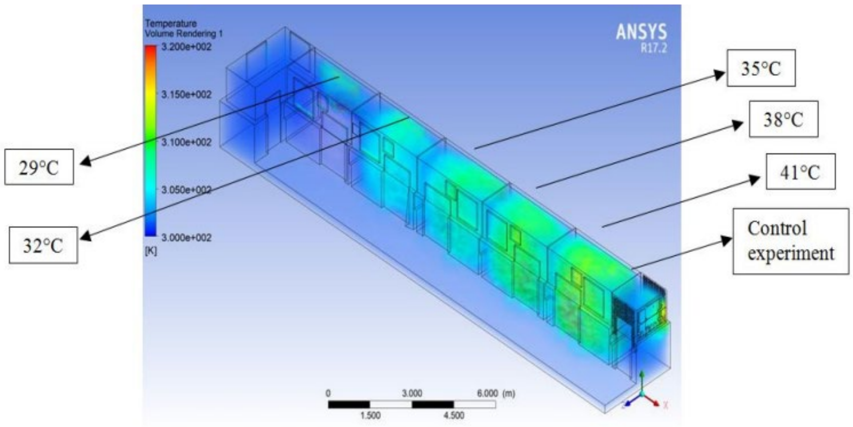


Source: Coradi *et al.* (2016)

Figure 1: Hot air velocity distribution pattern within the brooding chamber

6.2 Heat distribution

Firstly, the circulation of air all through the brooding environment ensure proper heat distribution however, the performance of the heat generation system determines whether the air is circulated at either low or high temperature. Temperature fluctuations of as small as 2–3°C within the brooding environment can result in to decreased rate of feed intake, impaired growth, and high rate of mortality. Preferably, the temperature variation across the brooding zone should remain negligible to prevent thermal discomfort and non-uniformity in flock performance. CFD software therefore generates temperature contours that brings a clear understanding on the extent of thermal gradients whereby, hot spots, cold regions, thermal stratification can be easily identified. An effective heat generation system should maintain air temperatures within roughly ±1°C of the target set value across the chick zone. Large temperature gradients is an indication of ineffective blower performance, inadequate insulation including issues with the heating system. Temperature contour plots are therefore useful in a sense that, they differentiate regions of varying temperatures by displaying color corresponding to the temperatures at that point. Engineers can therefore understand that, areas requiring design modifications exist and action has to be taken before the actual system's construction [43]. [44] applied AYSNS-CFX software package from CFD to analyze the heat distribution within the poultry brooding chamber and the CFD profile show sections of the chamber varying in temperatures such as 41^{o} C, 38^{o} C, 35^{o} C, 32^{o} C and 29^{o}C. The temperature profile in the building decreases along the left side as seen on the simulation figure 2 except for the control experiment where the temperature profile is determined by the ambient condition of the environment. Heating element powered by photovoltaic system was used to heat the flowing air which demonstrated the electric air heating system.



Source: Tehinse *et al.* (2020)

Figure 2: Temperature distribution inside the poultry brooding chamber in three dimensions

6.3 Optimization of Duct Geometry

According to [42] , pressure losses and airflow resistance are strongly dependent on the duct geometry whereby if not managed can affect the heat delivery efficiency. With the help of CFD, evaluation of different duct geometry before fabrication can be carried out. Design variables normally evaluated for optimization comprise duct diameter, duct length, outlet size and spacing, diffuser shape, bend radius, branching configuration, perforation diameter. The objectives of optimization is to permit sufficient air airflow at a minimized turbulence, reduction in pressure losses, lower fan power consumption, minimization of noise generation for instance, increasing bent radii or incorporation of streamlined diffusers can lower turbulence intensity and pressure losses whereas optimization of outlet spacing increases the surface area of hot air distribution which is an evidence of a wider area of heat distribution across the brooding environment. The optimization is performed through the systematic adjustment of the variables until a better performance is observed.

7.0 Research gaps and future direction in air heating systems

In the past few years, considerable efforts have been put in the development of air heating systems for brooding poultry. Advancements in forced-air heating technology showed incorporation of automated electronic temperature regulation as well as automated control of other environmental factors such as humidity, ammonia, carbon dioxide have gratefully contributed to the provision of optimum condition chick growth. Furthermore, computational modeling, precision livestock farming, Internet of Things based monitoring, and renewable energy technologies are the advancement in forced-air method of heat generation for poultry brooding. Nonetheless, despite these technological developments, numerous limitations that restrict the widespread adoption of forced-air heating systems, especially in developing countries where poultry production is majorly practiced by small and medium scale farmers continue to persist [45].

Current research on forced-air heating system has focused mostly on experimental studies that are carried out under controlled laboratory conditions, with limited evidence of efficient operation in environments associated with fluctuating ambient temperatures and different atmospheric conditions for instance large scale poultry production and also a challenge of thermal stratification continues to persist. Besides, there are no information on the reliability, durability, sustainability and cost-effectiveness under real farming conditions. Therefore, future study should consider conducting field tests to ascertain the performance efficiency of this heat generation method to be confident about its sustainability and economic viability and also addressing the challenge of thermal stratification.

Development of inexpensive automated air heating systems appropriate for small-scale poultry brooding farmers is one of the challenges that is proving to be a hard nut to crack. The current environmental control technology has always integrated programmable logic controllers, industrial sensors, variable-frequency drives, and proprietary software that significantly increase installation and maintenance costs. These systems are economically manageable by large-scale poultry enterprises and knocking out many farmers who fall under small and middle scale production categories [46]. Future research should therefore focus on developing low-cost automated system capable of being adopted by majority of production scales groups while operating efficiently with very few conditions that can hinder its adoption. Such systems should be designed for ease of installation, maintenance, operation and affordability to cater for the financial limitations of small-scale poultry farming practitioners particularly brooding farmers.

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Energy system forms the biggest percentage of the operating cost in poultry brooding, particularly where electricity is the power source. Even though solar photovoltaic systems, solar thermal collectors, geothermal heat pumps and biomass heaters have been considered, they are independently utilized as power sources. Limited studies have been conducted on the development of hybrid system arising from the integration between photovoltaic powered forced-air heating systems as a reliable renewable energy system and any other cost-effective energy source like biomass which is reasonably cheaper for poultry brooding. Existing photovoltaic powered brooding system is constrained by exorbitant initial investment capital. Future research should investigate the feasibility of hybrid renewable energy configurations particularly solar energy with battery storage and biomass to ensure reliable thermal performance under fluctuating climatic conditions.

Solar radiation produces adequate heat energy during daytime, whereas poultry brooding always require continuous heating both day and night. Current research has majorly concentrated on electrochemical battery storage for generation of electricity which is used to produce heat at night hours however, batteries drastically increase system cost and require intermittent replacement. In the other hand, efforts have been dedicated to develop thermal energy storage technologies capable of storing excess heat energy at periods of peak heat production but no good result has yielded. Therefore, potential research directions should be towards development of phase change materials, sensible heat storage systems. A combination of heat storage technologies and photovoltaic battery technology can substantially improve overall production efficiency of air heating systems with reduced power demand from battery as such, economic viability of renewable-powered brooding facilities will definitely be enhanced.

8.0 Conclusion

Artificial brooding remains one of the key components in the poultry production value chain ensuring progress in terms of mass production because the favorable conditions provided during the brooding periods impacts positively on chick survival, growth performance, feed conversion efficiency and immune development. As poultry production practices continue to strengthen, the demand for heating technologies capable of availing accurate, dependable, energy efficient, and environmentally friendly is increasing. This paper has comprehensively studied the designs and construction of forced-air heating system for poultry brooding covering the fundamentals of heat generation and transfer and the engineering principles governing the design and construction of the system.

Forced-air heating system of brooding offers many advantages over conventional brooding methods of heat generation such as improvement in the uniformity of heat distribution, improvement in the displacement of unwanted gases through continuous airflow, better interaction with ventilation systems, and the compatibility with automated environmental control technologies. The overall performance of this system does not only rely on the heat source but also on the correct design and fabrication of major components such as heat chamber, heating element, blower, network of ducts, insulation, electrical system's connections, and control unit including appropriate material selection, airflow management, thermal insulation. Nonetheless, the study identifies some of the existing research gaps especially on areas such as experimental studies that are carried out under controlled laboratory conditions, development of low-cost automated heating systems, renewable energy integration and energy storage technologies with suggested future research direction.

The involvement of digital sensing tools, microcontroller systems, Computational Fluid Dynamics, Internet of Things platforms has resulted in to a transition from manually operated environmental control systems to intelligent precision livestock farming technologies particularly in poultry brooding. This transition enables the real time monitoring of environmental conditions, adaptive heater control, predictive maintenance, optimized airflow control while instantaneously improving bird's welfare and the overall production efficiency. Nonetheless, the study identifies some of the existing research gaps especially on areas such as experimental studies that are carried out under controlled laboratory conditions, development of low-cost automated heating systems, renewable energy integration and energy storage technologies with suggested future research direction.

Generally, the summary of the findings that arose from this study indicates that future poultry brooding systems should consider piloting forced-air heating technologies to ascertain its potential in efficient heat generation, uniform oxygen distribution, efficient renewable energy utilization at a lower rate of energy consumption, automated temperature control, better chick welfare, lower mortality rate, and increase in poultry production profitability. The review has significant contributions to knowledge based on the fact that it provides valuable technical references for researchers, engineers, equipment manufacturers, and poultry farming practitioners to utilize so as to inform their decisions in order to arrive at the next-generation of air heating systems for precision poultry brooding.

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