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ANALYSIS AND COMPUTER SIMULATION OF A NATURAL CONVECTIVE SOLAR-HEATED ANIMAL BUILDING

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ABSTRACT

A model has been developed to predict the outlet air temperature and air flow rate from a solar collector based on the theory of thermal buoyancy. A high capacitance solar collector directly coupled to an animal building absorbs solar radiation, which heats up air and forces entry into the building by convection.

In order to test the validity of predictions of the model measured outlet air temperatures of the solar collector are compared to the predicted values and the results are presented. The predictions of outlet temperature and air flow rate agree reasonably well with experimental data, differences being of less than 1.5% significance.

Key words: Solar collector, thermal buoyancy, outlet air temperature, and Air flow rate

INTRODUCTION

Proper environmental conditioning of agricultural buildings require the supply of thermal energy at a specified temperature and relative humidity (Cooper et al, 1998). Currently, existing poultry brooding systems are powered by fossil fuels, electricity and other conventional energy sources. Studies have shown that these systems account for the high mortality rate, environmental hazards and fire outbreaks in most animal housing (Bhandari, et al 1994). Solar energy, which is pollutant free, abundant and widely available in Nigeria, seems to be a most attractive option.

An experimental and theoretical study of the outlet air temperature and air-flow rate of a solar collector were conducted in this work. The relationship between outlet air temperature T_o, air-flow rate V, and solar collector parameters were studied based on an approach derived from fluid mechanics.

The process of designing for environmental control in agricultural buildings has undergone significant evolution during the past decade. New information has become available for analyzing heat and fluid flow in buildings. Computers have become everyday tools in design (Albright, 1989). With computers, many potential designs can be investigated to determine effects of changes of pertinent design variable values. Repeated simulation can lead to better understanding of system behaviour, and result to designs having a significantly greater chance of success (Miguel et al, 1998).

Thermal environment within a livestock housing can be defined in terms of air temperature, relative humidity (RH), thermal radiation and air velocity; air temperature and relative humidity are commonly used criteria for ventilation control in animal housing (Awbi, 1991). The work reported here is part of a wider study whose objectives are as follows:

1. To predict the outlet air temperature of a solar collector;
2. To determine the outlet air velocity from solar collector going into an animal building and hence the air flow rate;

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Methodology

Analytical and experimental approaches were used. In the analytical approach, existing mathematical models were used to develop a computer program to predict air temperature and air flow rate, using static and dynamic models derived from theories of heat and mass transfer.

Consider a typical animal building as shown in Figure 1. If one begins at any point around the collector and traces pressure changes along the path labelled 1-4, the pressure changes should sum up to zero upon return to the starting point. If the path traverses the point 1, 2, 3, 4 and back to 1, some of the pressure differences will be due to fluid statics and some due to fluid dynamics.

The differences are:
1 to 2: $P_1 - P_2 = -\rho_o g\Delta h$ (a fluid statics differences)
2 to 3: $P_2 - P_3 = \rho_o V_2^2/2$ (a fluid dynamics differences)
3 to 4: $P_3 - P_4 = \rho_1 g\Delta h$ (a fluid statics differences)
4 to 1: $P_4 - P_1 = \rho_1 V_4^2/2$ (a fluid dynamics differences)

If the differences are summed up, the following equation is the result:

$$2g\Delta h(\rho_o - \rho_i) = \rho_o V_2^2 + \rho_i V_4^2 \qquad [1]$$

where: g is the acceleration due to gravity, m/s^2
Δh is the difference in elevation of the two vents, m;
ρ_o, ρ_i are the outlet and inlet air densities respectively kg/m^3;
V_4, V_2 are the outlet and inlet air velocities respectively, m/s;

With the assumption that ρ_o and ρ_i are known, equation [1] contains two unknowns: the two velocities.

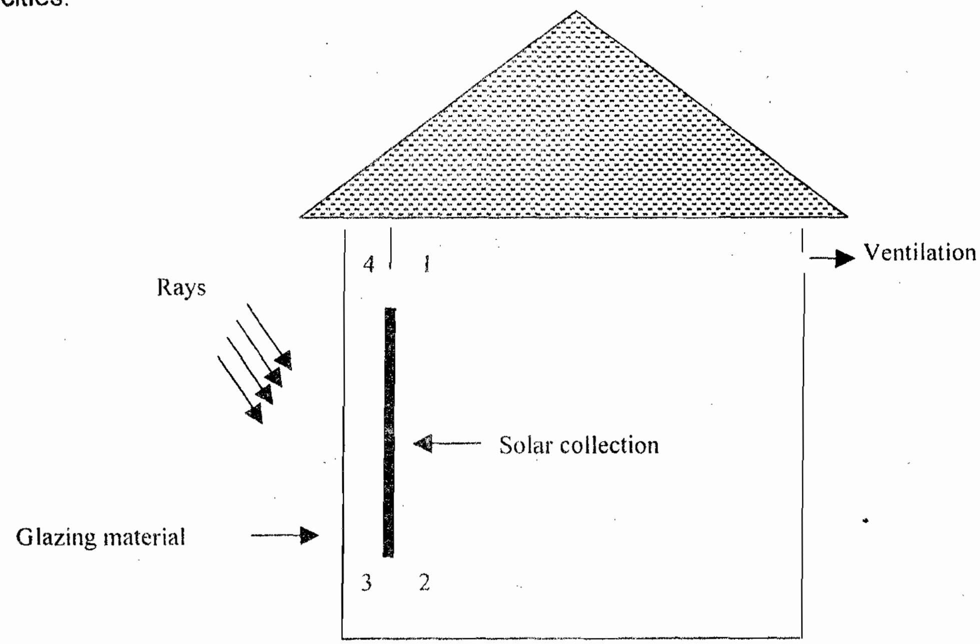


Figure 1: A typical Animal building with attached solar collector

However, the velocities can be related through the mass continuity relationship, thus:

$\rho_o C_{d2} A_2 V_2 = \rho_i C_{d4} A_4 V_4$ .... [2]

where: Cd_4, Cd_2 are the coeffients of discharge for outlet and inlet vents respectively, and A_4, A_2 are the outlet and inlet areas respectively, m^2. Coefficient of discharge is the ratio of vent diameter to the length of collector.

If the coefficients of discharge of the two openings are the same, equations [1] and [2] can be solved to yield one equation in one unknown (Louis, 1989):

$$V_3 = 1 \frac{2g\Delta h\,(1 - \rho_i / \rho_o)}{(\rho_i / \rho_o) + (\rho_i + \rho_o)^2 \, (C_{d4} A_4 / C_{d2} A_2)^2} 1 \frac{1}{2} \text{............} (3)$$

Again, if air is assumed to act as perfect gas, then:

$\rho_i/\rho_o = T_o/T_i$ ....[4]

where, T_i and T_o are respectively the indoor and outdoor air temperatures in (K) of the solar collector.

Using the perfect gas relationship, equation [3] can be restated in terms of temperature, a more useful form:

$$V_4 = 1 \frac{2g\Delta h\,(T_i - T_o)}{T_o + (T_o^2 / T_i)(C_{d4} A_4 / C_{d2} A_2)^2} 1 \frac{1}{2} \text{..............} (5)$$

This form is not useful for design as it might be that temperature difference is not known before.

However, if q_{pro}, sensible heat gain from the sun by the solar collector, is known then a simple

$$q_{so} = \left[(\Sigma\, UA + FP)\,(T_o - T_i) + C_p \rho_i C_{d4} A_4 V_4 (T_i - T_o)\right] \text{.........} (6)$$

sensible heat balance is:

where,

C_p	=	the specific heat of air, 1006 J/kg K.
AU	=	Area thermal conductance, W/m^2
FP	=	Perimeter heat loss factor, W/m

Equation [6] can be solved for T_i-T_o and substituted into equation [5] to obtain:

$$V_4 = 1 \frac{2g\Delta h q_{so}}{\left[T_o\left(1 + T_o / T_i\right)(C_{d2} A_4 / C_{d2} A_2)^2\right]\left[\Sigma\, UA + FP + C_p \rho_i C_{d4} A_4 V_4\right]} 1 \frac{1}{2} \text{......} (7)$$

and $q_{so} = [\alpha \times A_g \times I] - (T \times A_g + q_b]$

where,

q_{so}	=	Solar heat gain in the solar collector, W/m
α	=	the transmittance, W/m^2
Ag	=	the glazing area, m^2

I	=	the solar intensity, W/m^2
T	=	the reflectance, W/m^2
q_b	=	the heat stored in the intrinsic thermal mass inside the connector, W/m

Equation [7] completes the sequence of expressions needed to determine the airflow rate in a solar collector due to thermal buoyancy. However, equation [7] cannot be evaluated directly. It is

Table 1 The inlet and outlet air temperatures of a solar collector for days of observation
DAY 1 15/05/99

DAY 2 17/05/99

Time of the day	Inlet Air Temperature T_i (°C)	Outlet Air Temperature T_o (°C)
09:00	28.5	37.2
09:30	29.0	37.6
10:00	30.1	38.9
10:30	30.9	39.9
11:00	31.2	39.9
11:30	36.2	44.4
12:00	37.3	45.8
12:30	39.2	48.1
13:00	38.4	46.8
13:30	36.2	45.0
14:00	36.5	45.1
14:30	37.6	46.3
15:00	35.7	45.0
15:30	36.3	45.1
16:00	36.2	45.0
16:30	35.1	44.0
17:00	34.2	42.8
17:30	33.0	42.1
18:00	32.9	42.0

Time of the day	Inlet Air Temperature T_i (°C)	Outlet Air Temperature T_o (°C)
09:00	28.0	37.0
09:30	29.1	37.9
10:00	29.9	38.6
10:30	30.7	39.5
11:00	31.0	39.7
11:30	31.1	39.4
12:00	34.5	42.5
12:30	36.7	45.6
13:00	38.1	47.1
13:30	38.0	47.0
14:00	37.0	45.6
14:30	35.0	44.0
15:00	37.0	46.0
15:30	37.8	46.5
16:00	35.7	44.8
16:30	36.0	44.4
17:00	34.0	43.0
17:30	32.5	40.8
18:00	32.0	40.4

DAY 3 20/05/99

Time of the day	Inlet Air Temperature T_i (°C)	Outlet Air Temperature T_o (°C)
09:00	28.5	36.9
09:30	30.1	39.0
10:00	31.9	40.6
10:30	32.5	40.9
11:00	34.0	42.9
11:30	34.7	43.8
12:00	35.0	44.0
12:30	34.0	43.1
13:00	33.0	41.9
13:30	33.9	42.8
14:00	33.6	42.1
14:30	32.3	41.0
15:00	31.4	40.2
15:30	31.2	39.6
16:00	30.5	39.4
16:30	30.9	39.5
17:00	30.4	39.0
17:30	30.1	39.0
18:00	29.4	38.2

DAY 4 22/05/99

Time of the day	Inlet Air Temperature T_i (°C)	Outlet Air Temperature T_o (°C)
09:00	29.4	38.2
09:30	31.7	40.3
10:00	32.1	40.8
10:30	32.8	41.7
11:00	33.5	42.3
11:30	33.0	42.0
12:00	33.7	42.6
12:30	35.0	43.9
13:00	33.3	42.4
13:30	34.5	43.6
14:00	35.1	44.0
14:30	34.6	43.5
15:00	34.8	43.8
15:30	34.8	43.6
16:00	32.3	41.4
16:30	32.0	41.0
17:00	31.5	40.5
17:30	30.2	39.4
18:00	29.5	38.5

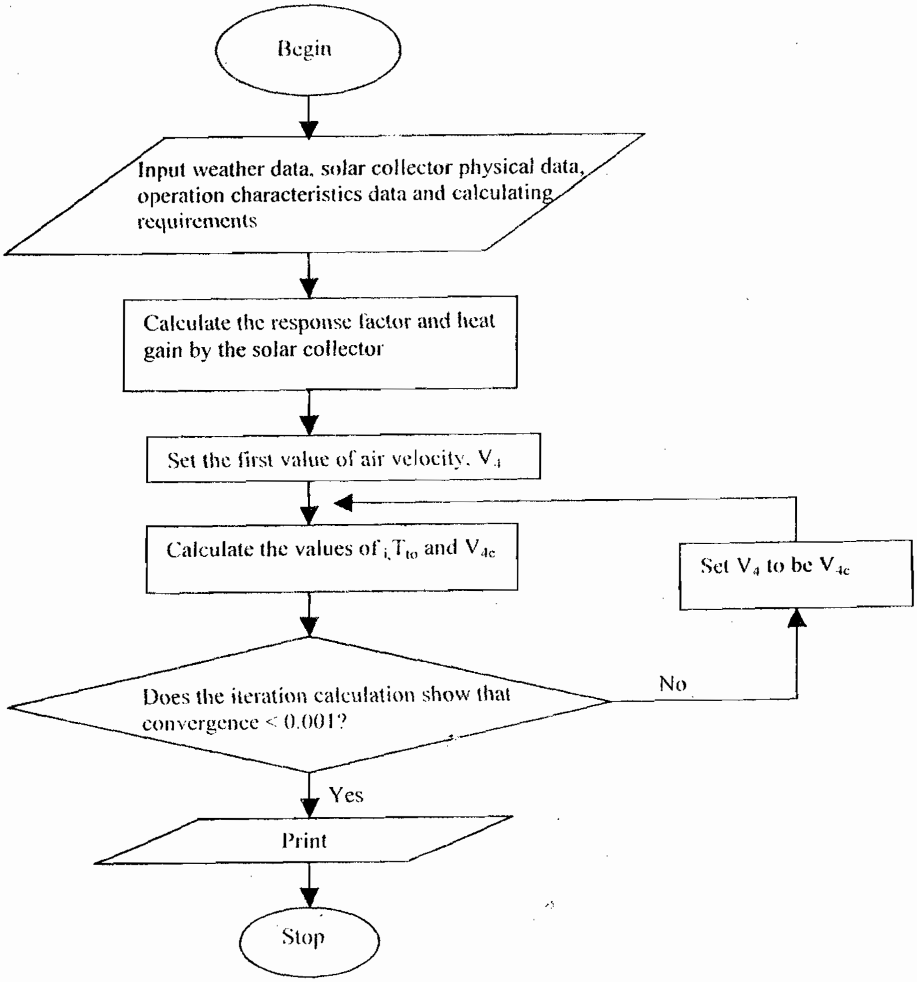


Fig.2 A flow chart of the program

RESULTS AND DISCUSSIONS

Table 2 and Figure 3 compare measured values of outlet air temperature from the solar collector for four days with the predicted values of outlet air temperature.

Statistical analysis indicates that the measured values of outlet air temperature are closely correlated (r = 0.92) with the corresponding predicted outlet air temperature within 5 percent of significance.

Implicitly, the air velocity (Vc) and hence the airflow rate (which are functions of air temperature) correlate equally closely.

Table 2a: Measured and predicted temperatures on 15/05/99

Time of the day	Inlet Air Temperature T_i (°C)	Outlet Air Temperature T_o (°C)	Outlet Air Temperature T_o (°C) predicted
09:00	28.5	37.2	37.8
09:30	29.0	37.6	38.3
10:00	30.1	38.9	39.4
10:30	30.9	39.9	40.2
11:00	31.2	39.9	40.5
11:30	36.2	44.4	45.5
12:00	37.3	45.8	46.7
12:30	39.2	48.1	48.6
13:00	38.4	46.8	47.8
13:30	36.2	45.0	45.5
14:00	36.5	45.1	45.8
14:30	37.6	46.3	46.9
15:00	35.7	45.0	45.0
15:30	36.3	45.1	45.6
16:00	36.2	45.0	45.5
16:30	35.1	44.0	44.4
17:00	34.2	42.8	43.5
17:30	33.0	42.1	42.6
18:00	32.9	42.0	42.2

Table 2b: Measured and predicted temperatures on 17/05/99

Time of the day	Inlet Air Temperature T_i (°C)	Outlet Air Temperature T_o (°C)	Outlet Air Temperature T_o (°C) predicted
09:00	28.0	37.0	37.3
09:30	29.1	37.9	38.4
10:00	29.9	38.6	39.2
10:30	30.7	39.5	40.0
11:00	31.0	39.7	40.3
11:30	31.1	39.4	40.4
12:00	34.5	42.5	43.8
12:30	36.7	45.6	46.0
13:00	38.1	47.1	47.5
13:30	38.0	47.0	47.4
14:00	37.0	45.6	46.3
14:30	35.0	44.0	44.3
15:00	37.0	46.0	46.4
15:30	37.8	46.5	47.2
16:00	35.7	44.6	[illegible]
16:30	36.0	44.4	45.3
17:00	34.0	43.0	43.3
17:30	32.5	40.8	41.8
18:00	32.0	40.4	41.3

Table 2c: Measured and predicted temperatures on 20/05/99

Time of the day	Inlet Air Temperature T_i (°C)	Outlet Air Temperature T_o (°C) measured	Outlet Air Temperature T_o (°C) predicted
09:00	28.5	36.9	37.8
09:30	30.1	39.0	39.4
10:00	31.9	40.6	41.2
10:30	32.5	40.9	41.8
11:00	34.0	42.9	43.3
11:30	34.7	43.8	44.0
12:00	35.0	44.0	44.3
12:30	34.0	43.1	43.3
13:00	33.0	41.9	42.3
13:30	33.9	42.8	43.2
14:00	33.6	42.1	42.9
14:30	32.3	41.0	41.6
15:00	31.4	40.2	40.7
15:30	31.2	39.6	40.5
16:00	30.5	39.4	39.8
16:30	30.9	39.5	40.2
17:00	30.4	39.0	39.7
17:30	30.1	39.0	39.4
18:00	29.4	38.2	38.7

Table 2d: Measured and predicted temperatures on 22/05/99

Time of the day	Inlet Air Temperature T_i (°C)	Outlet Air Temperature T_o (°C) measured	Outlet Air Temperature T_o (°C) predicted
09:00	29.4	38.2	38.7
09:30	31.7	40.3	41.0
10:00	32.1	40.8	41.4
10:30	32.8	41.7	42.1
11:00	33.5	42.3	42.8
11:30	33.0	42.0	42.3
12:00	33.7	42.6	43.0
12:30	35.0	43.9	44.3
13:00	33.3	42.4	42.6
13:30	34.5	43.6	43.8
14:00	35.1	44.0	44.4
14:30	34.6	43.5	43.9
15:00	34.8	43.8	44.1
15:30	34.8	43.6	44.1
16:00	32.3	41.4	41.6
16:30	32.0	41.0	41.3
17:00	31.5	40.5	40.8
17:30	30.2	39.4	39.5
18:00	29.5	38.5	38.8

implicit as indoor air temperature is not known independently (Louis, 1989). An iterative solution is possible as follows:

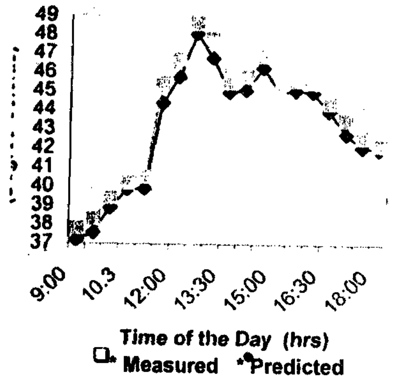
1. Begin with an initial estimate of V_4.
2. Solve for ρ_i using a rearrangement of equations [1] and [2] in the form of a quadratic equation as follows:

$$\rho_i^2[(C_{d4}A_4/C_{d2}/A_2)^2 (V_4^2/\rho_o)] + \rho_i(V_4^2+2g\Delta h) - 2g\Delta h\rho_o = 0 \quad [8]$$

   This is possible because when a value of V_4 is available, all terms in the equation except ρ_i are known.
3. Use the perfect gas relationship to estimate the value of T_o (the temperature of air entering the housing from solar collector):

$$T_o = (\rho_o T_i/\rho i) \quad [9]$$

4. Substitute the estimated value of ρ_i and T_o into equation [7] to obtain a new estimate of V_4.
5. Return to step 1 and continue to iterate until a stable solution of V_4 is obtained, i.e convergence occurs.



ig. 3a : A graph of measured and predicted outlet air temperature (°C) against time of the day (Hours) for the day 15/05/99.

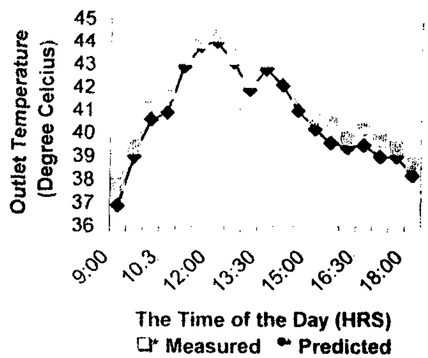


Fig. 3c: A graph of measured and predicted outlet air temperature (°C) against time of the day (Hours) for the day 20/05/99.

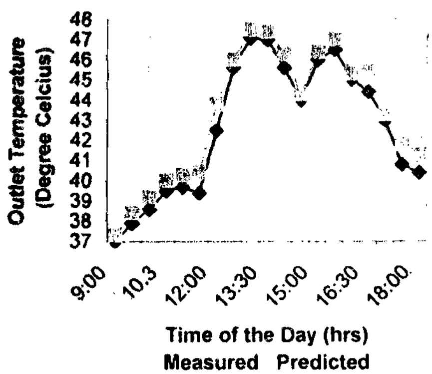


Fig. 3b: A graph of measured and predicted outlet air temperature (°C) against time of the day (Hours) for the day 17/05/99.

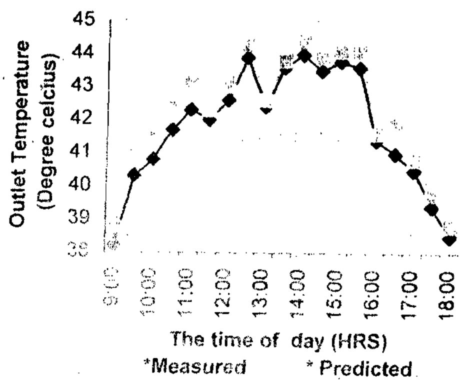


Fig. 3d: A graph of measured and predicted outlet air temperature (°C) against time of the day (Hours) for the day 22/05/99.

6. Rate of air flow is evaluated using the relation:

$$V = C_d\, A\, V \quad [10]$$

A computer program to perform the above described iterative solution was developed in this work. The logic flow chart of the program is shown in Figure 2.

EXPERIMENTAL STUDY

An existing solar collector was identified at the National Centre for Energy Research and Development, University of Nigeria, Nsukka, and used for experimental work in this study.

Inlet and outlet air temperatures of the collector were measured using a Rotronic digital thermometer/humidity sensor model CH 8040. The readings were in degrees centigrade (^oC) with an accuracy of $\pm$ 0.05^oC. Four experimental tests were carried out on 15th, 17th, 20th and 22nd May, 1999.

The tests were conducted on one of the plain absorber plate collectors with inlet and outlet areas of 0.195m^2 each, and elevation difference between the inlet and outlet vents being 2.4m. Seventeen readings corresponding to eight and half hours of sunshine were obtained between 8:30am and 17:30hrs (local time) at 30 minutes interval.

Table 1 presents the measured data.

VALIDATION AND APPLICATION OF THE COMPUTER PROGRAM.

Experimental results for the four days were compared with the predicted results. Table 2 and Figure 3 show comparison of the measured and the estimated values of outlet air temperature. It is observed that they are in very good accord.

CONCLUSIONS

Within the limits of predictive and experimental errors, and with the assumption that there was no wind effect, and the only driving force is thermal buoyancy, the following conclusions can be reached based on the results of this study:

(1) The computer program is a useful tool for predicting outlet air temperature and airflow rate from a solar collector.

(2) The program will be useful in evaluating outlet air flow rate from a solar collector, which is required in designing for environmental control in animal housing.

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