This is not a peer-reviewed article.
Pp. 482-489 in Livestock Environment VI: Proceedings of the
6th International Symposium (21-23 May 2001, Louisville, Kentucky, USA) eds. Richard R. Stowell, Ray Bucklin and Robert W. Bottcher. Pub date May 21, 2001. ASAE Publication Number 701P0201.

Prediction of Black Globe Humidity Index in Poultry Buildings

T. Yanagi, Jr. [1], G. S. Damasceno [2], V. H. Teixeira [3], H. Xin [4]

ABSTRACT

A computer model was developed to predict the black globe humidity index (BGHI) to simulate different resultant conditions in designing poultry buildings. The simulated BGHI values were compared to experimental measurements, obtained in a poultry facility at Viçosa, MG, Brazil, giving a mean deviation of 1.31 %. The model was then used to predict BGHI values as affected by roof slopes of 25°, 30°, and 35°, and column heights of 3.0 and 3.5 m. The results showed that BGHI can be reduced by 0.12 units per 5° increase in roof slope, or 0.10 units per 0.5 m increase in column height. The maximum reduction of BGHI, 0.33 units, was obtained when comparing the extreme conditions of 25° roof slope and 3.0 m height vs. 35° slope and 3.5 m height.

KEYWORDS: Poultry environment, Roofs, Thermal comfort.

INTRODUCTION

Poultry production is playing an increasingly important role in the global agricultural economy. This development is mainly due to improved genetic breeding, nutrition, sanitation, and poultry housing. Paralleling to the faster growth of poultry are negative factors such as lung, heart and leg problems. However, these problems could be reduced with proper design and control of the environmental conditions to better meet the needs of poultry.

To delineate the thermal environment for the animals and to project potential outcome of the environmental modification, many mathematical models have been developed. Most of them are used to predict the temperature, relative humidity, airflow and thermal comfort index for livestock buildings. Oliveira (1980) developed a model to estimate the black-globe humidity index (BGHI) using data referent to edification (dimensions and thermal conductivity of the buildings materials) and climate (temperature, relative humidity, wind velocity, atmospheric pressure, and solar radiation). In this model, the incident overall solar radiation on the surface of the roof was estimated by the overall solar radiation measured by instruments and corrected to the surface of the roof. This model was tested for a poultry building in the county of Viçosa, Brazil by Teixeira (1983) who verified that the model could also be used to predict BGHI for hot climatic conditions. Alves (1981) proposed a model to estimate the global solar radiation in surfaces of different inclinations and azimuths. The model expresses the global solar radiation as a function of direct and diffuse radiation components, from the surface inclination angle, incidence angle of direct solar rays, surface albedo and the zenithal angle of the sun. The results were presented in the form of abaci and tables. Although the model by Oliveira (1980) is of great importance to estimating BGHI, the requirement of direct solar radiation data as an input presents a limitation to the model. Therefore, inclusion of a routine to predict the direct solar radiation would make it more suitable to simulate, in a computer the effects of various structural conditions on the internal environment of poultry buildings.

[1] Assistant Professor, MS, Dept. of Exact Science, Federal University of Lavras, Lavras, MG, Brazil. PhD Student at Federal University of Viçosa / Iowa State University, yanagi@iastate.edu.
[2] Professor, PhD, Dept. of Agricultural Engineering, Federal University of Viçosa, Viçosa, MG, Brazil.
[3] Associate Professor, DS, Dept. of Engineering, Federal University of Lavras, Lavras, MG, Brazil.
[4] Associate Professor, Agricultural and Biosystems Engineering Dept., Iowa State University, Ames, IA.

Bond et al. (1954) stated that 26.4 % of thermal radiation incident on an animal inside a shelter was due to the roof. Baêta (1995, 1998) cited that column height and slope of the roof could affect the environmental conditions inside a building. Thus, the objectives of the present work were: (1) to develop a computational model to predict BGHI which includes a routine to predict the solar radiation, and (2) to analyze the effect of column height and roof slope of a typical poultry building on its BGHI.

GOVERNING EQUATIONS

BGHI is based on the combined effects of dry bulb temperature, air humidity, radiant energy, and air speed. Tinôco (1988) verified that BGHI greater than 75.0 could cause heat stress to broiler chickens. The BGHI can be calculated by the following equation (Buffington et. al., 1981):

$$BGHI = T_{bg} + T_{dp} - 330.08 \tag{1}$$

The black globe temperature can be determined by the mean radiant temperature (T_m) equation, obtained through the heat balance on the surface of the globe, where the heat gained or lost by radiation on the globe must be equal to the heat gained or lost by convection. Therefore, Esmay (1986) proposed the following equation to calculate T_m:

$$T_m = 100 \cdot \left[2.51 \cdot \sqrt{v} \cdot \left(T_{bg} - T_{air} \right) + \left(\frac{T_{bg}}{100} \right)^4 \right]^{1/4} \tag{2}$$

The radiant temperature of the environment can be defined as a function of the Stefan-Boltzmann law that after rearranging can be expressed as follows:

$$T_m = \left(\frac{RHL}{\sigma} \right)^{1/4} \tag{3}$$

As stated by Kelly et al. (1954), the RHL expresses the flux of incident radiation on the black globe from the different portions of the surroundings (lower roof surface, cold sky, horizon, shaded and unshaded floor). It depends, therefore, on the materials used and on the construction geometry, being calculated by the following equation:

$$RHL = \sigma \cdot \sum_{i=1}^{n} T_i^4 \cdot F_i \tag{4}$$

Around the black globe, five well-defined regions are present and are shown in Figure 1. The temperature in each of the sections, described above, can be estimated according to different models. Oliveira (1980) suggested that the temperatures of shaded floor (T_{sg}), unshaded floor (T_{ug}), and horizon (T_{hor}) be estimated by:

$$T_{sg} = T_{air} \tag{5}$$

$$T_{ug} = T_{air} + 6 \tag{6}$$

$$T_{hor} = T_{air} + 5 \quad (7)$$

For the cold sky temperature (T_{sky}) Duffie and Beckman (1974) recommended the following relations proposed by Swinbank:

$$T_{sky} = T_{air} - 6 \quad (8)$$

$$T_{sky} = 0.0552 \cdot T_{air}^{1.5} \quad (9)$$

Mackey and Wright (1944) presented an equation to determine the absolute temperature of the interior surface of the roof (T_{is}).

$$T_{is} = T_{air} + \frac{0.606 \cdot \left(\frac{b \cdot I_g}{f_c} \right)}{0.856 + \frac{L}{K}} \quad (10)$$

According to Paltridge and Platt (1976) the global solar radiation on the roof (I_g), under clear sky conditions, can be determined by the following equation:

$$I_g = I_0 \cdot \cos\theta + I_d \cdot \cos^2\left(\frac{i}{2}\right) + \alpha \cdot (I_0 \cdot \cos Z + I_d) \cdot \left[1 - \cos^2\left(\frac{i}{2}\right)\right] \quad (11)$$

The above expression requires knowing the various parameters that depend on the virtual motion of the sun around the earth. The direct solar radiation on a surface normal to the solar rays (I_0) can be obtained by the expression recommended by Brooks (1959):

$$I_0 = S \cdot (\overline{D}/D)^2 \cdot \tau \quad (12)$$

The atmospheric transmittance can be determined by:

$$\tau = \exp\left[-0.089 \cdot (p \cdot m/1013)^{0.75} - 0.174 \cdot (W \cdot m/20)^{0.60} - 0.083 \cdot (d \cdot m)^{0.90}\right] \quad (13)$$

The optical mass of the air varies with the zenithal angle of the sun (Z), varying from 1, when the sun is at the zenith, to 35, when the sun rises or sets (Vianello and Alves, 1991). The amount of water in the atmosphere that is able to precipitate (W) is calculated as a function of the water vapor pressure (p_w).

The flux of diffusive solar radiation (I_d) that reaches the roof of the building ($W.m^{-2}$) varies with the zenithal angle of the sun, corresponding to approximately 15 % of the total solar radiation reaching the surface. Under clear sky days conditions, it is estimated by the following equation:

$$I_d = 11.631 \cdot \{0.43 + 8.25 \cdot [1 - 0.0111 \cdot exp(0.05 \cdot Z)]\} \quad (14)$$

MATERIALS AND METHODS

A computational model was developed in FORTRAN language using equations 1 to 14 to estimate the BGHI in poultry buildings. To validate the model, experimental data obtained by Teixeira (1983) at the Dom Bosco farm, located in the county of Viçosa, MG, from September 15 to October 25 of 1982, was used. The location is at the latitude of 20°45’45” South and longitude of 42°52’04” West, with an altitude of 657 meters. The climate of the region is characterized as hot climate, rainy temperate, dry in winter and wet in summer. The poultry building had the following dimensions: 8.5 m in width by 89.0 m in length and 2.3 m in column height. The structural characteristics are as follows: gable roof with French-type ceramic shingles, a slope of 26.5° with regard to the horizontal plane, 1.0 m overhang; walls were built with solid bricks to the height of 0.30 m and the remaining in wire netting with a mesh of 5.0 cm. The floor was built with solid bricks covered with cement. The stocking density averaged 13 birds per m^2 and floor area covered with corncob litter. Measurements of dry bulb and wet bulb temperatures, relative humidity, black globe temperature, and overall solar radiation were taken daily at 8:00, 10:00, 12:00, 14:00 and 16:00 hr during the 49 days of growth period.

To obtain the estimated BGHI values, the model described earlier was used. The values used in the calculations included the roof-surface absorptivity of 0.85, the convective heat transfer coefficient of 22.6 $W.m^{-2}.K^{-1}$, shape factors of 0.040 for the unshaded floor, 0.460 for the shaded floor, 0.087 for the horizon, 0.009 for the cold sky, and 0.404 for the roof. The temperature for the cold sky was calculated by averaging the values obtained from equations 8 and 9. A comparison between the calculated BGHI values and those obtained experimentally by Teixeira (1980) was made based on the root mean square deviation for each of the sampling times. The effect of column height and roof slope on BGHI was analyzed using the data obtained at 12:00 hr. Three roof slopes (25, 30 and 35°) and two column heights (3.0 and 3.5 m) were evaluated.

The geometrical characteristics of the building are illustrated in Figure 2. It had a length (C) of 125.0 m; width of 12.0 m (2 L1), lower-end height (H2) of 2.3 m or 2.8 m corresponding to the heights (H) of 3.0 m or 3.5 m, respectively. Height of the center of the black globe thermometer to the floor was 0.30 m and the distance from the center of the black globe thermometer to bottom cord of the wooden truss was 2.0 m. The shape factors used in the simulations are presented in Table 1. The meteorological data used were averages over the month collected by the meteorological station at the Federal University of Viçosa, Viçosa, MG, Brazil, during 1998, as shown in Table 2.

RESULTS AND DISCUSSION

The BGHI values were observed and predicted with the model from the 10^{th} to the 49^{th} day of the growing period for the times of 8:00, 10:00, 12:00, 14:00 and 16:00 hr. The BGHI profile at 14:00 hr is shown in Figure 3. The data corresponding to the first ten days were discarded due to the influence of heater operation in the center of the building on the black globe temperature measurements. For the considered period it can be verified that estimated BGHI values agreed very well with those observed for all the times. Root mean square deviation found was 0.99, 0.99, 1.37, 0.99, 1.25 for the 8:00, 10:00, 12:00, 14:00 and 16:00 hr, respectively. The lowest coefficient of determination found was 0.88 for the 12:00 hr and the highest was 0.94 for the 14:00 and 16:00 hr. For 8:00 and 12:00 hr the values were 0.91 and 0.93, respectively. The overall mean deviation was 1.31%. Generally, during the period from 8:00 to 12:00 hr the BGHI was below 75.0, providing thermal comfort to the chickens (Tinôco, 1988). At 14:00 (Figure 3) and 16:00 hr, the BGHI values were higher than 75.0, causing certain thermal stress to the birds.

The program was used to obtain the monthly average BGHI for a typical poultry building (12 x 125 m) that is naturally ventilated with a ceramic shingles roof at 25, 30 or 35° slope and column height of 3.0 or 3.5 m. The results are summarized in Figure 4, where the highest and lowest values of BGHI are presented for 1-year period. It can be seen that increasing the roof slope by 5° and maintaining the same column height, the mean BGHI value inside the building is reduced by

0.12 units. For the same slope of the roof and an increase of 0.5 m of column height, the BGHI was reduced by approximately 0.1 unit. When comparing the BGHI in a building with a roof slope of 25° and a column height of 3.0 m with the one having a slope of 35° and a column height of 3.5 m, a reduction of 0.33 units was noted for the latter.

Based on the specific example presented for the roof sloop, the chickens will likely experience thermal stress between January and April. During this period, the shade provided by the facility and natural ventilantion would not be sufficient to provide thermal comfort to the birds. Thus, mecanical ventilation and evaporive cooling system, such as fogging or misting system, may be used to improve the thermal environment. It should be pointed out that the analyses for roof sloop effect in this study were made using the one-year monthly average climatic conditions and it only provided a trend of the BGHI profile during the whole year. Greater values of BGHI could be encountered within the months when maximum values of the climatic variables occurred or rather than BGHI values computed at other locations of the facility besides the center. Although there was not a great reduction in BGHI when the column height and roof slope were increased, these modifications can be implemented due to low demand of resources.

CONCLUSIONS

The effects of roof slope and column height on black-globe humidity index (BGHI) of poultry buildings were simulated with a computer model and compared with field observations. The following conclusions were drawn.

(a) The BGHI values estimated with the model agreed well with the experimentally measured values. The overall mean deviation between the predicted and measured values was 1.31%.
(b) For a given column height, a 5° increase in roof slope yielded 0.12 unit reduction in BGHI. For a given roof slope, a 0.5 m increase in column height yielded 0.10 unit reduction in BGHI.
(c) BGHI was reduced by 0.33 units when changing the roof slope and column height from 25° and 3.0 m to 35° and 3.5 m, respectively.

ACKNOWLEDGMENTS

The authors wish to extend their gratitude to the CAPES Foundation of Brazil for providing the financial support to this research.

REFERENCES

1. Alves, A.R. 1981. Irradiância solar global em superfícies de diferentes inclinações e azimutes, para Viçosa, MG. Thesis, Universidade Federal de Viçosa: MG. Diss. 92p.

2. Baêta, F.C. 1995. Planejamento de instalações avícolas considerando as variações de temperatura: frangos de corte. In: Simpósio Internacional Sobre Ambiência e Instalação na Avicultura Industrial, 123-129, Campinas, SP: FACTA.

3. Baêta, F.C. 1998. Acondicionamento térmico natural de galpões avícolas. In: III Simpósio Goiano de Avicultura, 29-34, Campinas, SP: FACTA.

4. Bond, T.E., C.F. Kelly, and N.R. Ittner. 1954. Radiation studies of painted shade material. *Agricultural Engineering*, 35(6):389-392.

5. Brooks, F.A. 1959. *An introduction to physical microclimatology*. Davis, CA.: University of California.

6. Buffington, D.E., A. Collazo-Arocho, G.H. Canton, D. Pitt, W. W. Thatcher, and R.J. Collier. 1981. Black Globe-Humidity Index (BGHI) as comfort equation for dairy cows. *Transactions of the ASAE* 24(3):711-714.

7. Duffie, J.A., and Beckman, W.A. 1974. *Solar energy-thermal processes.* New York, NY: Jons Wiley & Sons.

8. Esmay, M. L. 1986. *Principles of animal environment.* Westport, CT: AVI.

9. Kelly, C.F., T.E. Bond, and N.R. Ittner. 1954. Thermal design of livestock shades**.** *California Agriculture* 8(8):3-4.

10. Mackey, C.O. and L.T. Wright. 1944. Periodic heat flow-homogeneous walls or roofs. *Transactions of the ASH&VE* 50(1255):293-312

11. Oliveira, J.L. 1980. *Hot Weather Livestock Housing Analysis*. Thesis, Michigan State University: East Lansing, MI. Diss. 120p.

12. Teixeira, V.H. 1983. Estudo dos índices de conforto em duas instalações de frango de corte para as regiões de Viçosa e Visconde do Rio Branco, MG. Thesis, Universidade Federal de Viçosa: Viçosa, MG. Diss. UFV, 1983, 62p.

13. Tinôco, I.F.F. 1988. Resfriamento adiabático (evaporativo) na produção de frangos de corte. Thesis, Universidade Federal de Viçosa: Viçosa, MG. Diss. UFV, 1988, 92p.

14. Paltridge, G.W., and C.M.R. 1976. Platt. *Radiative processes in meteorology and climatology*. Amsterdam: Elsevier Scientific.

15. Vianello, R.L. and A.R. 1991. Alves. *Meteorologia básica e aplicações.* Viçosa, MG: UFV/Imprensa Universitária.

SYMBOLS AND ABBREVIATIONS

σ	Stefan-Boltzmann constant (5,67 x 10^{-8} $W.m^{-2}.K^{-4}$)
θ	Incidence angle of the direct solar rays, that is, angle between the referred rays and normal to the inclined surface (radians)
τ	Atmospheric transmittance (decimal)
b	Surface absorptivity of the roof to solar radiation (decimal)
BGHI	Black Globe Humidity Index
d	Dust parameter (dimensionless)
D	Instant distance between the earth and the sun
$\overline{D}$	Mean distance between the earth and the sun
f_c	Heat transfer coefficient by convection ($W.m^{-2}.K^{-1}$)
F_i	Shape factor of each surrounding session of the globe (dimensionless)
i	Surface inclination angle (radians)
I_0	Direct solar radiation on a surface normal to the solar rays ($W.m^{-2}$)
I_d	Diffuse solar radiation on a horizontal surface ($W.m^{-2}$)
I_g	Global solar radiation incident on the roof of the building ($W.m^{-2}$)

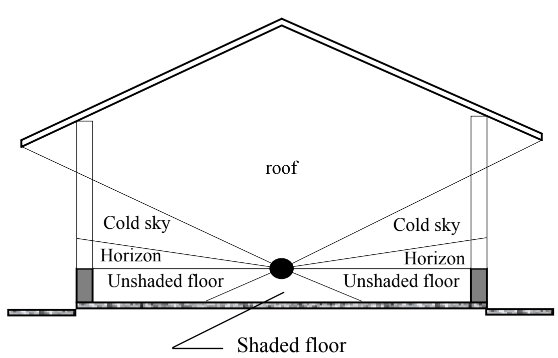
K	Thermal conductivity of the roof material ($W.m^{-1}.K^{-1}$)
L	Thickness of the roof material (m)
m	Absolute optic mass of the air, varying from 1 (sun culminating on the local zenith) to 35 (rising and setting of the sun)
n	Number of surrounding sessions of the globe
p	Atmospheric pressure (mbar)
RHL	Radiant heat load ($W.m^{-2}$)
S	Solar constant (1353 $W.m^{-2}$)
T_{air}	Air temperature (K)
T_{bg}	Black globe temperature (K)
T_{dp}	Dew point temperature (K)
T_{hor}	Horizon temperature (K)
T_{is}	Interior surface temperature of the roof (K)
T_{sg}	Shaded floor temperature (K)
T_{sky}	Cold sky temperature (K)
T_{ug}	Unshaded floor temperature (K)
T_i	Temperature of each surrounding session of the globe (K)
T_m	Mean radiant temperature (K)
v	Wind speed ($m.s^{-1}$)
W	Amount of water that can precipitate in the atmosphere in the zenithal direction (mm)
Z	Zenithal angle of the sun (radians)

Table 1. Overhang dimensions and shape factors of the various sections of the black-globe-thermometer surroundings for the roof with various inclinations.

	roof slope					
I	**25°**		**30°**		**35°**	
H	3.00	3.50	3.00	3.50	3.00	3.50
B	1.50	1.50	1.21	1.21	1.00	1.00
	Shape factor		**Shape factor**		**Shape factor**	
Shaded floor	0.464	0.464	0.464	0.464	0.464	0.464
Unshaded floor	0.036	0.036	0.036	0.036	0.036	0.036
Lower roof surface	0.408	0.392	0.404	0.388	0.397	0.384
Horizon	0.087	0.087	0.087	0.087	0.087	0.087
Cool sky	0.005	0.021	0.009	0.025	0.016	0.029

Table 2. Monthly average of air temperature (°C), atmospheric pressure (mbar), relative humidity (%) and wind speed ($m.s^{-1}$) data.

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
T_{air}	25.0	25.2	24.6	23.3	19.4	17.2	17.7	20.2	21.5	20.9	21.5	23.6
P_{atm}	935.14	935.67	935.95	936.51	938.85	941.43	940.7	939.07	938.33	937.22	934.46	933.79
RH	78.6	78.3	81.3	80.7	81.6	82.1	78.8	82.2	73.2	83.8	84.7	82.5
V_{wind}	1.50	1.85	1.26	1.35	1.08	0.65	1.15	1.22	1.81	1.65	1.36	1.81



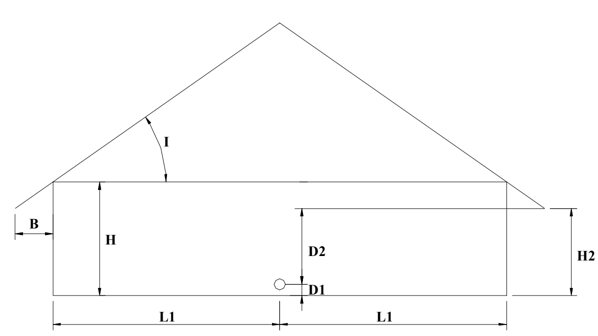


Figure 1. Building section related to the black globe.

Figure 2 – Cross-sectional view illustrating the geometrical characteristics of the building.

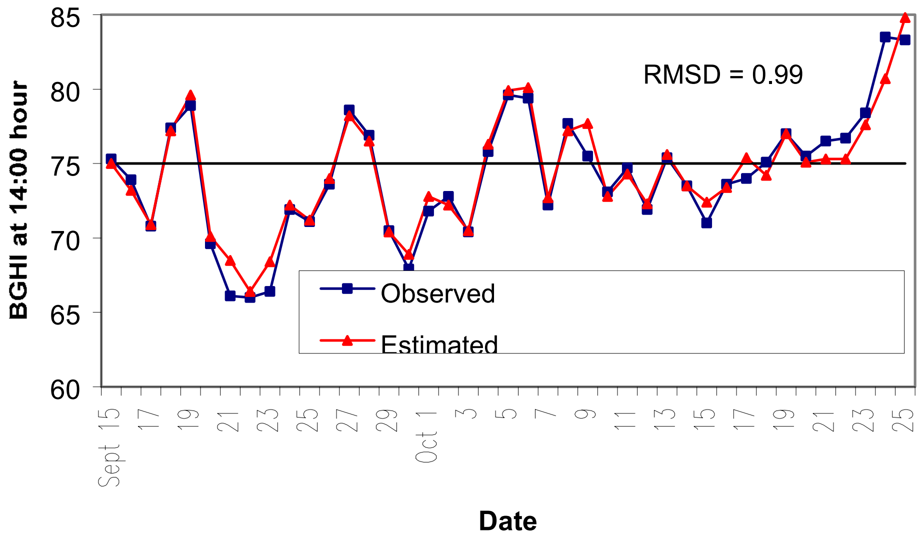


Figure 3. GHI mensured and predicted by the model, during 40 days, from 09/15/82 to 10/25/82, at 14:00 hours.

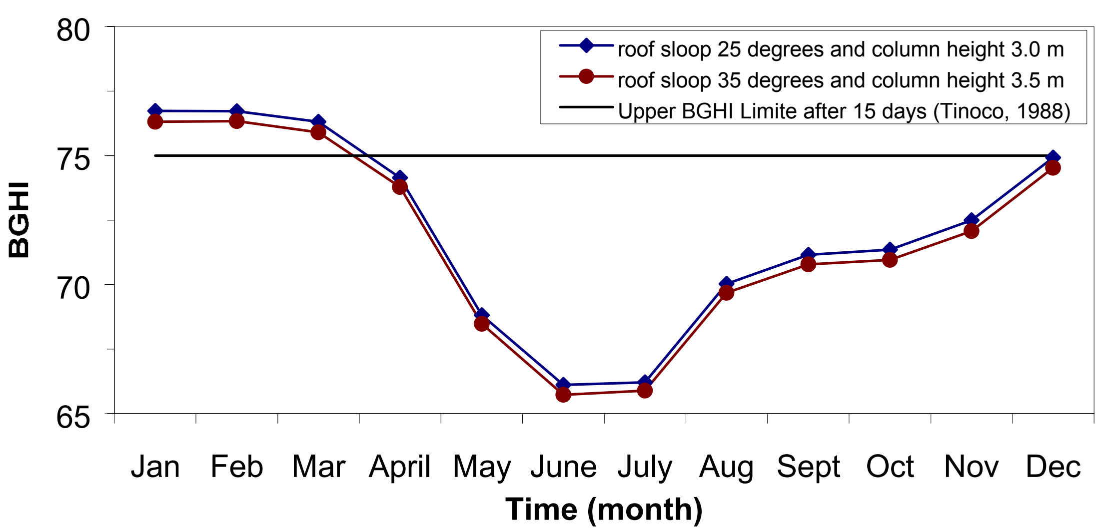


Figure 4. BGHI simulated by the model for roof slope of 25° and 35°, and column height of 3.0 and 3.5 m, respectively.