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Research Article

THEORETICAL AND EXPERIMENTAL ESTIMATION METHODS OF THE AMBIENT TEMPERATURE BY THREE SEMI-EMPIRICAL MODELS ON THE SITE OF THE CITY OF OUAGADOUGOU

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ABSTRACT

Weather parameters such as ambient temperature fundamentally influence the cost effectiveness and performance of solar energy conversion systems. The optimization of solar energy converters depends on the ambient temperature model used. Our work consists in determining the theoretical model of the temperature which is close to the reality in the city of Ouagadougou. The study was conducted at the Laboratory of Environmental Physics and Chemistry of the Joseph KI-ZERBO University and lasted three months. We have chosen to simulate three semi-empirical models of ambient temperature. The different models are evaluated on a graphical and statistical basis, using statistical indicators such as the coefficient of determination R^2, the root mean square error (RMSE) and the mean absolute error percentage (MAPE). The equations for the different ambient temperature models were programmed with matlab software. The experimental curves were smoothed with the Excel software. A validation of the obtained results is established by comparing the theoretical values calculated by matlab of the three models of the ambient temperature with the experimental data obtained at the National Agency of Meteorology of Burkina Faso. Our research work proved that among the three models, the Capderou model presents the best estimate of the ambient temperature in the city of Ouagadougou. The reason for this research work is that measuring stations are rare in underdeveloped countries. Sometimes the use of numerical simulation of a theoretical model is more than necessary because it allows to compensate a little for the lack of experimental data on a physical phenomenon. This study will allow not only to estimate to a few degrees Celsius the ambient temperature by the Capderou theoretical model but also to predict in the long term the ambient temperature in the city of Ouagadougou.

Keywords: Ambient temperature, Capderou model, corrected Capderou model, Howell model, statistical indicators.

INTRODUCTION

Among the major problems that the world must solve, since the end of the last century, the one posed by climate change is gaining more and more ground. Indeed, according to the IPCC climate change assessment reports[1], the average air temperature has increased by 0.76°C over the last 100 years. According to these reports, the increase in average temperatures between 1980 and 2080 will range between 3 and 4°C over the entire African continent, which is 1.5 times more than at the global level[1]. In Burkina Faso, the Ministry of the Environment and Sustainable Development, in its National Action Program for Adaptation to Climate Variability and Change, has shown that ambient temperatures have a high spatiotemporal variability with a slight upward trend [2]. Work carried out for this purpose in Burkina Faso has shown that the ambient temperature is increasing with a difference of 1.05°C in Ouagadougou[3]. It is in this context that the following question arises: In a context of climate change, how to predict the evolution of ambient temperature? Several methods have been developed to describe the theoretical evolution of ambient temperature. They are generally based on empirical analyses. Prediction could be useful to obtain viable and accurate information on the future development of a physical phenomenon like ambient temperature. The stations for measuring meteorological data in Burkina Faso are limited. We will mention the National Agency of Meteorology of Burkina Faso(NAM-BF) with which we benefited from the data on the average ambient temperature of the year 2017. These experimental data were confronted with those of theoretical semi-empirical models of ambient temperature from numerous studies and research works in various kinds of meteorological and geographical conditions. The aim of this work is to make a comparative study between three semi-empirical models of ambient temperature estimation to determine the best estimation model.

COORDINATES AND SOLAR TIMES

1. THE DECLINATION

The declination δ (degrees) for any day of the year can be calculated approximately by the equation (1)[4]:

$$\delta = 23.45\sin\left(\frac{360}{365}(284+N)\right) \quad (1)$$

2.THE HOURLY ANGLE ω

The hourly angle, in points on the surface of the earth, is defined as the angle through which the earth would rotate around the meridian of the point directly under the sun. It is obtained by the true solar time[4].

$$\omega = 15(TSV-12) \quad (2)$$

The solar times are composed of the universal time, the local solar time, the true solar time.

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3. THE UNIVERSAL TIME

The universal time, TU, is determined by the time of passage of the sun at the meridian origin.

4.THE LOCAL SOLAR TIME

The longitude correction is the difference between the local solar time and the universal time, noted TSL. The longitude correction is given by the equation (3)[5]:

$$\mathrm{TSL} = \mathrm{TU} + \frac{\lambda}{15} \quad (3)$$

λ: the latitude of the location.

5. THE TRUE SOLAR TIME

It represents the angle formed by the meridian of the place, the vertical plane passing by the South and the meridian of the direction of the sun, the plane passing by the axis of the Earth and by the sun, it is noted TSV . It designates the local solar time corrected by the equation of time, universal astronomical data related to the eccentricity of the orbit of the earth around the sun[5]. It is obtained by the equation (4):

$$TSV = TSL + \Delta\mathrm{t} \quad (4)$$

6. SUNRISE, SUNSET AND DURATION OF THE DAY

The sun rises and sets when the solar altitude angle is zero. Thus the hourly angle at sunset ω_c is obtained for h=0° [6]:

$$\cos(\omega_c) = -\tan(L)\tan(\delta) \quad (5)$$

The sunset time is given by the equation (6) [4]:

$$T_C = 12 - \frac{\omega_c}{15} \quad (6)$$

The hour angle ω_c at sunset is opposite to the hour angle at sunrise, so $\omega_c = -\omega_l$.

Where The sunrise time is given by the equation (7) [4]:

$$T_L = 12 + \frac{\omega_l}{15} \quad (7)$$

The duration of the day is given by the equation (8) [4] :

$$\Delta t = 2\frac{\omega_c}{15} \quad (8)$$

A FEW SEMI-THEORETICAL MODELS OF AMBIENT TEMPERATURE

Several models exist to model the ambient temperature, we have chosen the following models:

1. CAPDEROU MODEL

In the Capderou model, the ambient temperature is determined using a sinusoidal function. It should be noted that the simulation is not carried out over a period of 24 hours, this equation is limited to the interval in which the sun arrives on the surface of the collector[7].

$$T_a(\mathrm{t}) = \left(\frac{T_{amax}+T_{amin}}{2}\right) + \left(\frac{T_{amax}-T_{amin}}{2}\right) sin\left[\frac{(t-8)\pi}{2}\right] \quad (9)$$

T_{amax} : the average daily maximum ambient temperature for the month considered.

T_{amin} : the average daily minimum ambient temperature for the month considered

t : local time.

2. CAPDEROU CORRECTED MODEL

The model presented by Capderou has been corrected by introducing a "thermal midday" where the ambient temperature reaches its maximum value of the day at solar midday with respect to nocturnal radiative exchanges, the ambient temperature takes its minimum value at sunrise and finally at sunset. Thus the ambient temperature can be modeled by the equation (9)[7] :

$$T_a(t) = \left(\frac{T_{amax}+T_{amin}}{2}\right) + \left(\frac{T_{amax}-T_{amin}}{2}\right) cos\left[\frac{2\pi\left(t-12-\frac{\Delta t}{8}\right)}{\Delta t}\right] \quad (10)$$

3. HOWELL MODEL

In 1982, J.R. Howell, R.B. Bannerot, G.C. Vliet modeled the ambient temperature by the following equation (10)[8]:

$$T_a(t) = \left(\frac{T_{amax}+T_{amin}}{2}\right) + \left(\frac{T_{amax}-T_{amin}}{2}\right) sin\left[\frac{\pi}{12}(TL - (TL_{0L}+\frac{3}{2})\right] \quad (11)$$

Where TL the legal time in hours.

STATISTICS INDICATORS

Statistical indicators were used to determine the performance of these models. These statistical indicators are:

1. THE COEFFICIENT OF DETERMINATION R^2

The indicator R^2 varies between 0 and 1, a value of 1 or close to 1 indicates a perfect agreement between the measured and calculated value, on the other hand a value close to 0 indicates a total disagreement.

$$R^2 = 1 - \frac{\sum_{i=1}^{k}\left(I_{ghm}-I_{ghc}\right)^2}{\sum_{i=1}^{k}\left(I_{ghm}-I_{ghmm}\right)^2} \quad (12)$$

2. THE ROOT MEAN SQUARE ERROR (RMSE)

The RMSE is a measure of the variation of the calculated values, according to each model around the measured values. The smaller the value, the better the model.

$$\mathrm{RMSE} = \sqrt{\frac{1}{\mathrm{K}}\sum_{i=1}^{K}\left(I_{ghm}-I_{ghc}\right)^2} \quad (13)$$

3. THE MEAN ABSOLUTE PERCENTAGE ERROR (MAPE)

It is given by the following equation:

$$\mathrm{MAPE} = \frac{1}{\mathrm{K}}\sum_{\mathrm{i}=1}^{\mathrm{K}}\left(\left|\frac{\mathrm{I_{ghm}}-\mathrm{I_{ghc}}}{\mathrm{I_{ghm}}}\right|\right) \quad (14)$$

THEORETICAL AND EXPERIMENTAL RESULTS

1. THEORETICAL RESULTS

The following figures show the ambient temperature variations of the three theoretical models for four typical days in 2017.

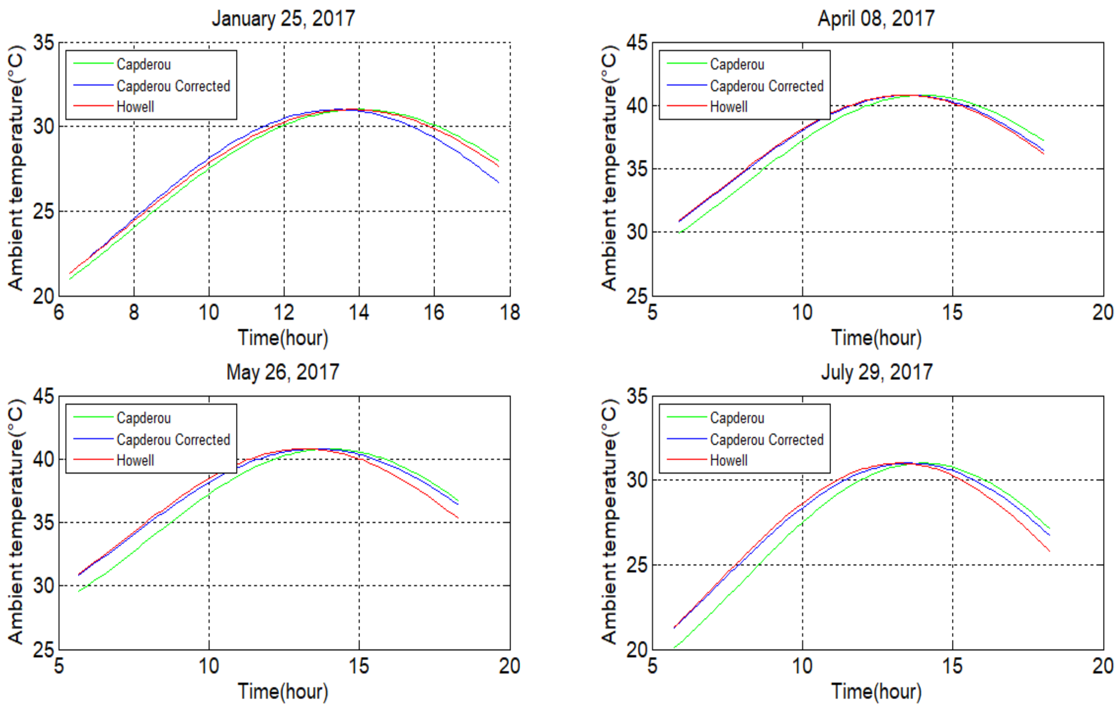

Fig.1. Ambient temperature variation curves of the three theoretical models for four typical days of the year 2017.

The theoretical results show that the theoretical curves have the same pattern. The maximum is reached between 13:00 and 14:00 at 32°C for the days of January 25 and July 29, 2017 and 41°C for the days of April 08 and May 29, 2017 corresponding to hot periods in Burkina Faso. The theoretical results also show that the difference between the curves is not as high. Some days like January 25, 2017 they tend to coincide.

2.COMPARISON OF THEORETICAL RESULTS WITH EXPERIMENTAL RESULTS

In this part, the experimental curves have been smoothed and replaced by trend curves whose coefficients of determination R^2 are very close to 1. Superimposing the theoretical curves with the trend curves, we obtain the following figures:

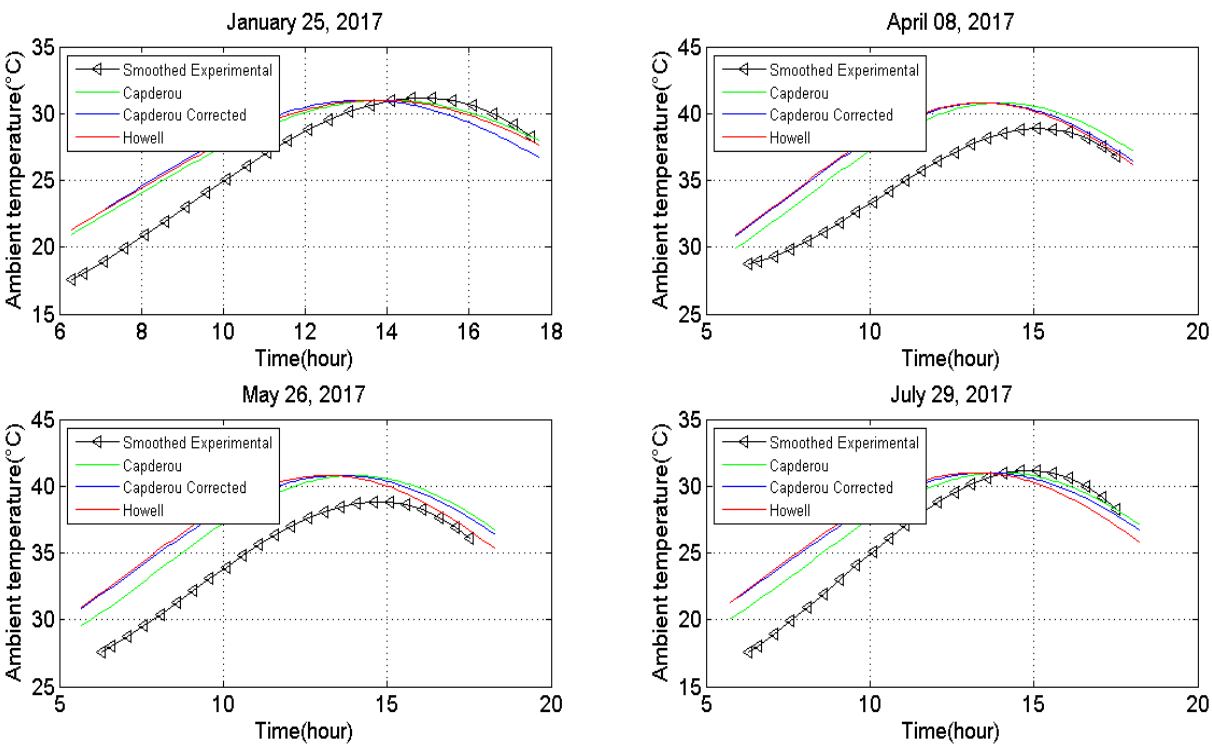

Fig.2. theoretical and experimental curves of ambient temperature variation for four typical days of the year 2017.

All curves have the same shape and take low values during sunrise and sunset. They reach their maximums around 14 hours. We can also notice that, the results obtained show that before 14h the theoretical curves overestimate the experimental curve. Indeed, the experimental curve is below all the theoretical curves before 14 hours. After 14 hours, it is only the days of January 25 and July 29, 2017 where we realize that the experimental curve is above the theoretical curves. The results indicate the presence of a gap between the theoretical and experimental curves. This gap is large before 14:00 and small from this time. It emerges that the three theoretical models overestimate the ambient temperature before 14 hours and from this hour they underestimate the experimental curves or are cofounded with these nevertheless, the curve of the Capderou model is closer to the experimental curve.

DISCUSSIONS

All the curves have the same shape as the experimental curve. They increase in the morning and reach their maximum between 13h30 and 14h and decrease thereafter. All the theoretical curves generally overestimate the ambient temperature before 2pm and after this time they underestimate the ambient temperature. The Howell model curve is above all the curves before 14h after this hour it is below except for the one of January 25 where the corrected model curve is above. All the curves meet and reach their maximums together at the same time. We note that the curve that is closer to reality seems to be the curve of the Capderou model. The difference between the experimental curve and that of the Capderou model is illustrated by the following figures:

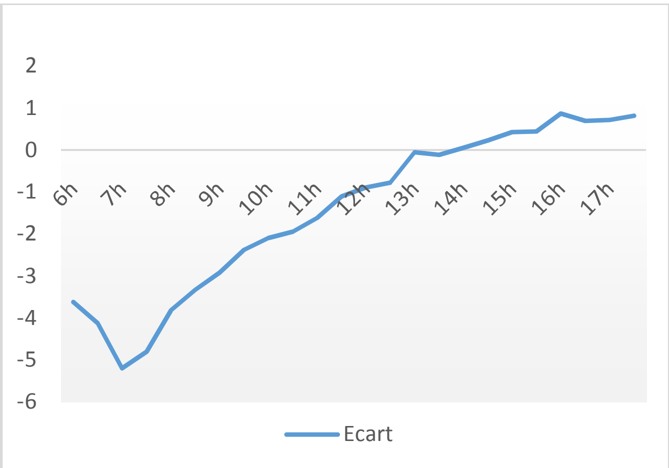

Fig.3. Evolution of the differences between the experimental curve and the curve of the theoretical model of Capderou for the day of January 25, 2017

Considering the day of January 25 between 6:00 and 13:00 the experimental curve is below the theoretical one of the Capderou model and the difference is -3 at 6:00 and -5 at 7:00. This difference will decrease with time and will be cancelled between 1 and 1:30 pm. At this level, the two curves merge and take the same maximum value. From 13h30 onwards, the experimental curve is above the Capderou curve. The difference in temperature between the two curves will not exceed 1°C.

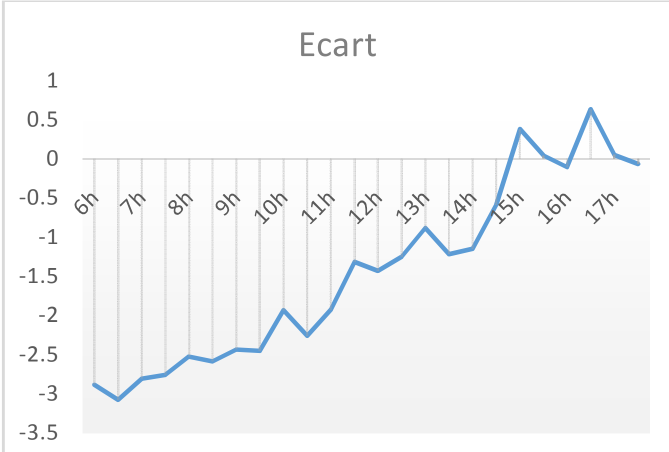

Fig.4. Evolution of the deviations between the experimental curve and the curve of the theoretical model of Capderou for the day of May 26, 2017

In the same way for the day of May 26 between 6h and 14h30 the theoretical curve of the Capderou model overhangs the experimental one, the difference between the two curves is reached -3 at 6h. This difference becomes increasingly weak and is cancelled at 14h45. This level is the point of intersection of the two curves where they take the same maximum value. From 14h45 it is the experimental curve which overhangs that of Capderou. The difference between the two curves will not exceed 1°C.

VALIDATION DU MODELE

The tables above present the results of the statistical calculations obtained by comparing the theoretical results obtained by three models (Howell, Capderou and corrected) and the experimental data from National Agency of Meteorology of Burkina Faso(NAM-BF).The tables below have highlighted the statistical properties of each ambient temperature model. By analyzing the coefficients of determination R^2 of each model, we find that those of the Capderou model have higher values than the other theoretical models. The Capderou model has significantly higher coefficients of determination than the other models. Moreover, by comparing the average of the coefficients of determination of the three models, the Capderou model is largely superior. Indeed, for Capderou, we have 0.8196 against 0.5440 for the Howell model and 0.4809 for the corrected model. If the coefficient of determination R^2 is close to 1, it indicates a perfect agreement between the measured value. The analysis of the coefficients of determination R^2 of three theoretical models compared to the experimental model allows us to conclude that the Capderou model among the three models is close to the reality. Based on the sum of RMSE of each theoretical model, it appears that the Capderou model has the smallest sum of RMSE. Indeed, we have Capderou (14.6224), corrected Capderou (15.8774) and Howell (16.0359), but if we compare the RMSE, the best estimator is of course the one with the lowest RMSE. By analyzing the statistical properties of the theoretical models of the ambient temperature from the point of view of the percentage of the mean absolute error (MAPE), it appears that the sum of the MAPE values of the Capderou model is lower among the three (03) others, that is to say 0.1481 (14.81%), the Howell model 0.2862(28.62%) and the corrected model 0.2893 (28.93%). The more the percentage of the mean absolute error tends towards zero, the better the estimate. Based on the statistical properties (R^2, RMSE and MAPE) of the three (03) models, we can conclude that the Capderou model seems to be closer to reality. The comparison of the values estimated by the different models with the measured values shows in general that the three models give an overestimation of the calculated values. However, among the three models proposed for the Ouagadougou site, we note that the Capderou model presents the best estimate of the ambient temperature by providing the highest coefficients of determination and the lowest MSE, RMSE and MAPE in comparison with the three (03) models (Capderou, Howell and Capderou corrected).

Table 1: The results of the statistical calculation for the Howell model

DATE	R^2	RMSE	MAPE
25/01/2017	0,60397192	5,18710112	0,09582567
08/04/2017	0,57382144	3,90225265	0,06774283
26/05/2017	0,57831901	4,05530184	0,07014051
29/07/2017	0,42011145	2,89126389	0,05253798

Table 2: The results of the statistical calculation for the Capderou model.

DATE	R^2	RMSE	MAPE
25/01/2017	0,80397192	5,15038645	0,03518417
08/04/2017	0,87382144	3,76966876	0,04784092
26/05/2017	0,78052702	3,91150689	0,03744469
29/07/2017	0,82011145	2,79092269	0,02767624

Table 3: The results of the statistical calculation for the Capderou corrected model

DATE	R^2	RMSE	MAPE
25/01/2017	0,60397192	5,16798359	0,10579514
08/04/2017	0,57382144	3,89278308	0,06425506
26/05/2017	0,22605275	3,9098668	0,0916564
29/07/2017	0,52011145	2,90679024	0,027616

CONCLUSION

In this paper, we have proposed to estimate the ambient temperature by three semi-empirical models: the Capderou model, the Howell model and the Capderou corrected model. After having reviewed the literature on the subject, we programmed the three models using the matlab language. The instantaneous values of the ambient temperature were estimated by these three models. As for the experimental instantaneous values, they were obtained at the National Agency of Meteorology of Burkina (NAM-BF). A statistical analysis was performed using the coefficient of determination of the root mean square error (RMSE) and the percentage of the mean absolute error (MAPE). It was found that among the three proposed models, the best results on ambient temperature were obtained by the Capderou model at the Ouagadougou site.

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