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# THIN-LAYER SOLAR-DRYING OF SHELLED CORN

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## ABSTRACT

This paper presents a set of simple empirical equations for solar drying of shelled corn . A forced convection thin-layer solar dryer was designed , constructed and tested on the roof of the Department of the Agricultural Engineering ; Al-Azhar University. The dryer bin was 0.2 m$^3$ (0.5 m x 0.5 m x 0.8 m) . Since it was difficult to have an analytical solution, finite difference method was used to solve the basic equation controlling moisture movement during the falling rate period of drying based on Newton's equation of heat transfer for predicting moisture content at any time of the drying process. Since the boundary conditions continuously changed during the drying process for the solar thin-layer drying , the moisture content at any time of drying process is highly affected by the equilibrium moisture content at the same period and the same boundary conditions i.e. (temperature and relative humidity). It was found that predicted and observed data were highly correlated with a correlation coefficient of 0.98 .

## INTRODUCTION

Shelled field corn is used primarily as livestock feed , but some of it is used by the milling or processing industries in corn starch , corn oil and other products . This corn can be severely damaged by mechanical drying if drying air temperature exceeds 65 °C. Its cell wall structure is changed by higher temperatures , making separation of gluten from the starch very difficult (ASHRE 1985) . They reported that the market grade of dry corn is affected more often by the amount of broken corn and foreign materials than other grading factors . They also added that the grade limits on damage to the corn from molds and other causes can lead also to self-perpetuation spoilage in stored grains that can cause it to be downgraded . Hall (1980) reported that the drying of grains in deep layer can be thought of as several thin layers in which the humidity and temperature of air entering and leaving each layer vary with time depending upon the stage of drying . He also added that this procedure is sometimes used for estimating the time of drying and amount of moisture removed . Tayel and Wahby (1989) dried shelled corn by natural convection solar type dryer . They stated that the system behavior was similar to conventional drying system. They also added that the moisture content , at any time,

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could be predicted from a mathematical form using equilibrium moisture content , and the drying rate was affected by the surface area and mass of product.

Huizhen ( 1984), studied thin-layer drying rates for yellow dent corn as affected by drying air temperature, air flow rate , initial moisture content , and relative humidity . He reported that initial moisture content influences drying rate . He also added that air flow rate and relative humidity had smaller effects. Puiggali and Tiguert, (1986), introduced a simple numerical model for drying corn , and they mentioned that this model can improve the understanding of the thermal and hydrodynamic behavior of a dryer working under natural conditions .Chittenden and Hustrulid (1966) reported that shelled corn is often dried by circulating heated air through layers one or more feet thick . They said that it is difficult to connect mathematically the observed rate of moisture loss of a thick bed of corn to the external drying rates of all the corn kernels in the bed .They presented also a method of using individual kernel rates of drying called "differential drying rate " ,to predict the overall rates .Sabbah et al. (1979) studied the accuracy of using the log model of drying for simulating solar and natural grain drying using experimental moisture results of nine drying tests . They reported that incorporating an air velocity effect into the model improved the accuracy significantly . They added that using either cumulative –or-moving- time averages of the actual drying air temperature and humidity as input conditions to the model results in valid moisture prediction . They also stated that scaning – time interval of 4-hours was proved sufficient without significant loss in accuracy. Steinfeld and Segal (1986) introduced a mathematical formulation of the physical process for solar drying of thin layer process based on conventional heat and mass transfer equations. They did not accounted for resistance to moisture flow . Therefore, it is expected, that the drying curve will not fit to the experimental results . Then they introduced a correction factor in order to validate the model .

Shove (1977) reported that energy consumption to dry agricultural crops often approaches and can exceeds the energy required to produce the crop . He added that since crop drying is high energy use operation , the cost of drying is directly related to energy availability and cost .

In Egypt , the amount of incident solar radiation per square meter ranges between 5 to 8 kW.h/day through duration of 3000 to 4000 hours per year (Hecal and Kamal ,1986) . Therefore, solar energy is a renewable major clean source of energy which is alternative to using fossil fuel .

The main objective of the present study is to develop a solution to the basic equation controlling moisture movement during the falling rate period of drying based on Newton's equation of heat transfer for predicting moisture content at any time of the drying process. The model accounts for variable boundary conditions prevailed in solar drying i.e. (temperature and relative humidity) and also internal resistance to moisture flow within the corn kernels .

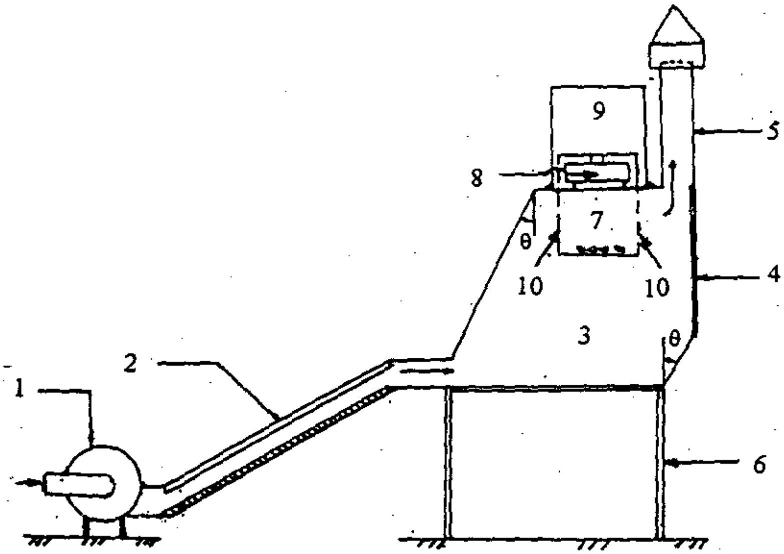
## MATERIALS AND METHODS

### 1. Solar -dryer construction

The dryer was constructed on the roof of the Agr. Eng. Dept. , Al-Azhar Uni. It was 0.2 $m^3$ (0.5 m x 0.5 m x 0.8 m) , made of plywood of 0.8 cm thick connected to a flat plate collector . The solar collector was 1.125 $m^2$ area (1.5 m x 0.75m). The absorber plate was made of light-gauge steel sheet of 0.7 mm thick . Frame of a wooden structure of (10 x 5) $cm^2$ cross sectional area . The bottom of the collector was insulated by a plywood of 0.8 cm thick. All air passages were made of steel sheets and insulated by 5 cm glasswool . The absorber plate of the collector was painted with a black paint. The collectors passages was 7.5 cm deep and also equipped with 2.5 cm air gap between the transparent glass cover and the absorber plate( stagnant air barrier) for reducing heat losses through the cover . The collector was oriented to the south and has a 4-bar mechanism to obtain the optimal inclination angle during the experiment . El-Rafey and El-Sherbiny (1988), reported the optimum tilt angles , insolation data base for estimating system performance in Egypt. Fig.(1) shows experimental solar drying setup.

### 2. Weighing setup

Two steel frames were used for constructing the balance assembly that used for weighing the corn specimen . Steel wire net was fixed to one of the previous frames and used as a shelf . The other frame was supported to the balance to transfer specimen weight by means of four smooth wires of a similar length through four holes in the dryer ceiling . Shelled corn specimen was continuously weighed during elapsed time of drying . Four hours time step was used for predicting moisture content through the drying process as reported by Sabbah et al (1979).Air handling unit was stopped at the period of specimen weighing . Specimen weight was an average of three respective instantaneous readings.




1-Air handling unit.
2-Solar collector .
3-Dryer bin .
4-Dryer door .
5-Chimney .
6-Supporting steel frame carrying the dryer bin .
7-Shelled corn shelf .
8-Balance display .
9-Balance box with a transparent door.
10-Four smooth wires for carrying the specimen shelf , by which it is supported to the balance .
11- θ = 30 ° .

**Fig. (1) :** Experimental solar drying setup.

## 3. Measuring instrumentation

- Thermocouples :Temperatures were measured using chromel- alumel thermocouples, made in U.S.A of model 8528-40 . Ten channel switch for the same thermocouples were also used.
- Solar intensity :The solar intensity was measured using a black and white Pyranometer constructed and calibrated by Ghanem (1989) . The apparatus was recalibrated at the Solar Energy Department " National Research Center , El-Doky Square " before being used in (1996) . The output of the apparatus is in millivolts using a digital multi-meter , manufactured in Japan, model no. 2000 , of sensitivity 0.1 mV .
- Air velocity : The air velocity was measured using a standard pitot tube and inclined manometer as recommended by Tuve and Domholdt (1966) .
- Samples were weighed using Sartorious electrical balance, made in Japan of accuracy 0.0001 g .

- Oven method was used for initial moisture content determination according to ASAE (1994), i.e. corn was dried for 72 h to 103 °C .

4. **Purposed drying model**

The moisture content at any time ( $M_t$ ) dry basis, decimal , was computed from the weight of sample at any time ( $W_t$ ), gram , and initial weight ($W_o$) , gram and initial moisture content $M_o$, dry basis , decimal , using the following relationship :

$$M_t = \{(W_t / W_o)(1 + M_o) - 1\} \qquad (1)$$

The average drying rate over a time interval ( $t_i$ ) to ( $t_{i+1}$ ) was computed as follows :

$$dM/dt = (M_{i+1} - M_i) / (t_{i+1} - t_i) \qquad (2)$$

The average moisture content and average temperatures were calculated as follows :

$$(M_{av})_i = (M_i + M_{i+1}) / 2 \qquad (3)$$

$$(T_{av})_i = (T_i + T_{i+1}) / 2 \qquad (4)$$

The ambient relative humidity was computed using equations (5) , (6) and (7) as follows:

$$RH = [ P_w / P_s] \qquad (5)$$

The saturated vapor pressure , $P_s$ , at dry bulb temperature , ( $T_d$ ) , in absolute scale is given by Chambell (1977) , as follows :

$$P_s = \exp [( 52.576 - 6790.5) / (T_d - 5.028) \ln (T_d)] \qquad (6)$$

The vapor pressure , ( $P_w$ ) at wet bulb temperature , ( $T_w$ ) , in absolute scale is also given by :

$$P_w = P_s - \gamma (T_d - T_w) \qquad (7)$$

Where : $\gamma = 0.063$ and , $P_s$ , is calculated using ($T_w$ ) instead of ($T_d$ ) in equation ( 6) . The humidity of air was calculated from the following relationship:

$$H = 0.622 P_w / (P - P_w) \qquad (8)$$

For any time interval the ambient air outside was assumed to be heated to average air temperature inside the dryer without any change in absolute humidity during that interval . The equilibrium moisture content for the average temperature and average relative humidity over the time interval was computed from the Henderson's empirical equation for shelled corn (Henderson et al; 1976) :

$$1 - RH_{eq} = e^{-CT (M_{eq})^n} \qquad (9)$$

Where :

$RH_{eq}$ : equilibrium relative humidity (ratio ) .

$M_{eq}$ : equilibrium moisture content , (decimal ) dry basis .

T : temperature °R .

Values of equilibrium constants ( C, n ) are C = $1.1 \times 10^{-5}$ and n = 1.9 respectively .

Thin layer drying refers to the drying of grain which is entirely exposed to the air moving through the product . The air flow rate used in the drying process was $4 m^3/m^2$ s . The equation representing moisture movement during the falling rate period is based on Newton's equation of heat transfer of solids (Hall ,1980). Since the ambient conditions are changed from hour to hour , the initial conditions and equilibrium moisture content are also changed from hour to hour . So , it is difficult to have an analytical solution and therefore, the drying equation in the present work was solved using finite difference method . The drying equation in finite difference form can be expressed as :

$$M_{t+1} = M_{eq} + (M_t - M_{eq}) \, e^{-(k \Delta t)} \qquad (10)$$

For calculating equation (10) preliminary tests were conducted for the determination of the drying coefficient ( k = 0.1285) . For each time step Henderson's equation was solved to predict equilibrium moisture content of the shelled corn at variable ambient conditions .The equilibrium moisture content was used for solving equation (10) to predict the moisture content at any time. Excel 97, was used for calculating moisture contents and for the solution of Newton's equation simultaneously with Henderson's equation .

## RESULTS AND DISCUSSIONS

The purposed drying model accounts for changing boundary conditions during the drying time . It is considered that for any time interval , the average air temperature inside the dryer changes without any change in absolute humidity during that interval. The equilibrium moisture content for the average relative humidity and temperature was computed according to Henderson's empirical equation for shelled corn . Fig.(1) shows variation of the ambient ,inlet air temperature , relative humidities and solar intensity during the drying process . It is clear that the solar intensity increases to the maximum value around the solar noon . Also , air temperature has the same trend , and as the solar intensity increases, ambient air and drying air temperature increases. Relative humidity of the ambient air and also drying air decreased towards the solar noon, and then they increased to the maximum value at night.

As mentioned above average values of these variables were used as input data to the purposed drying model. Table (1) shows the observed moisture content (dry basis, decimal) at any time of the drying process. It also, shows the predicted moisture contents (dry basis, decimal) of the corn as calculated by the finite difference method. Fig.(3) shows also the trend line of predicted moisture content (wet basis, decimal) as determined by the finite difference method compared to observed moisture content. It is clear that the model was also sensitive to drying process or aeration process during night (night cooling). Fig.(4), shows also the relationship between predicted and observed moisture contents of shelled corn (wet basis, decimal) during the drying process. It is clear that values of predicted moisture content are highly correlated to observed data and regression coefficient was 0.98. This means that the equilibrium moisture content appears to be the most important variable controlling the drying rate.

## SUMMARY AND CONCLUSION

A forced convection thin-layer solar dryer was designed, constructed and tested on the roof of the Department of the Agricultural Engineering Al-Azhar University. The dryer bin was 0.2 $m^3$ (0.5 m x 0.5 m x 0.8 m). Since it was difficult to have an analytical solution, finite difference method was used to solve the basic equation controlling moisture movement during the falling rate period of drying based on Newton's equation of heat transfer for predicting moisture content at any time of the drying process.

From the present work we can concluded that:

1. In changing boundary conditions of drying for the solar thin-layer drying process we can predict the moisture content of corn or any cereal grains. The moisture content at any time of drying process is highly affected by the equilibrium moisture content at the same period and the same boundary conditions i.e. (temperature and relative humidity).

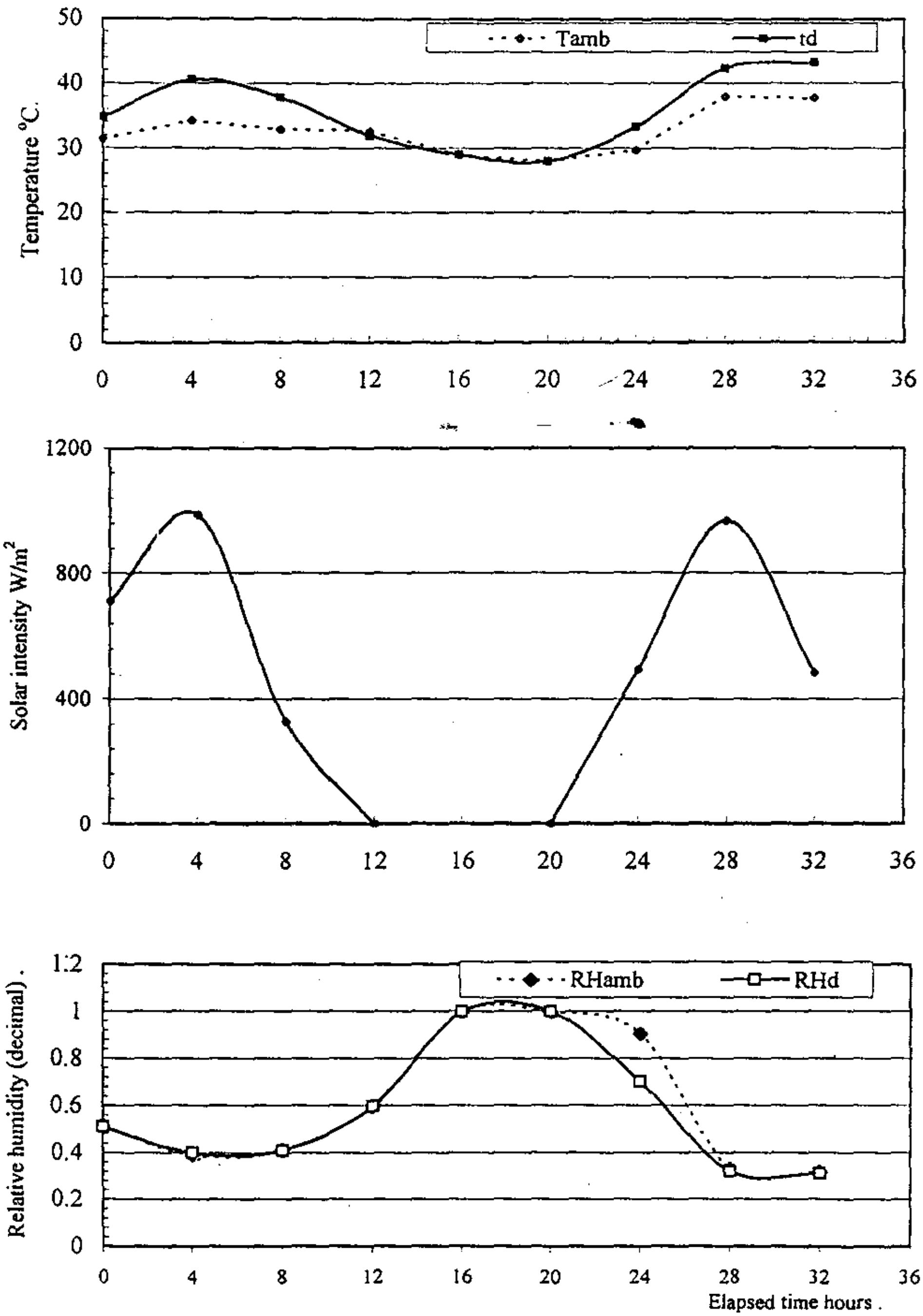



Fig.(2)Ambient,inlet air temperatures , relative humidities and solar intensity during the drying process.

**Table (1):** Observed moisture content and predicted moisture content (dry basis)of shelled corn as calculated by finite difference method

| Local time | 9A.M | 13Noon | 17 P.M | 21P.M | 1A.M | 5A.M | 9 A.M | 13 Noon | 17 P.M |
|---|---|---|---|---|---|---|---|---|---|
| Observedmoisture content | 1.95 | 1.45 | 0.72 | 0.48 | 0.46 | 0.47 | 0.39 | 0.26 | 0.17 |
| Predicted moisture content | 1.95 | 1.24 | 0.79 | 0.45 | 0.46 | 0.41 | 0.31 | 0.24 | 0.18 |

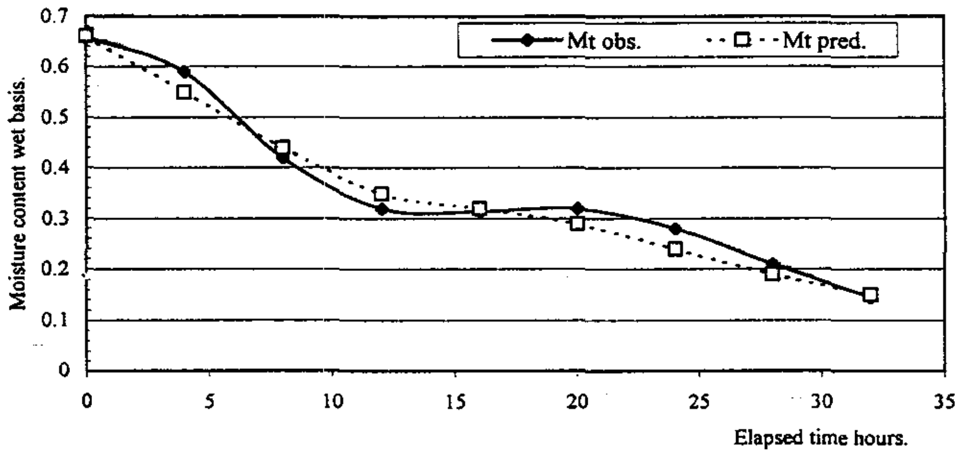



**Fig.(3):** Observed and predicted moisture content of shelled corn as calculated by finite difference equation and as affected by elapsed time.

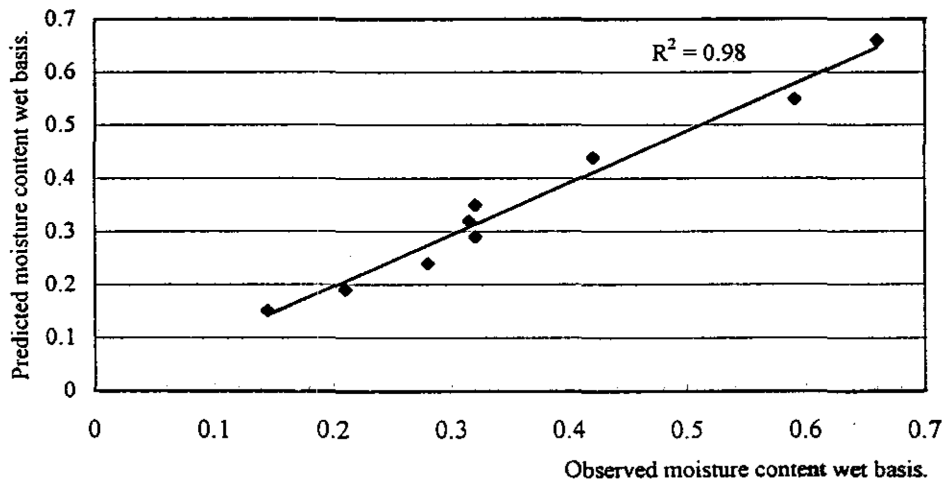



**Fig.(4):**Observed and predicted moisture content of shelled corn as calculated by finite difference equation .

2. Finite difference method is helpful for predicting moisture content during solar thin layer drying by solving Newton's equation simultaneously with Henderson's equation for equilibrium moisture content as a function of relative humidity and temperature .
3. The model was evaluated using Excel 97 , it was sensitive for predicting moisture content during drying process at night time (night cooling process ) .
4. It was found that predicted and observed data were highly correlated with a coefficient ( $R^2 = 0.98$ ) .

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## تجفيف الطبقة الرقيقة بالطاقة الشمسية للذرة المقشورة

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تم تصميم مجفف طبقة رقيقة يعمل بالطاقة الشمسية والحمل الجبرى وبحجم ٢,٠ م$^3$ وقد استخدم هذا المجفف فى تجفيف الذرة المقشورة . وحيث أنة من الصعب الحصول علـى حـل دقيق لعملية التجفيف، لذا فقد تم استخدام معادلة نيوتن للتبريد والتسخين والمستخدمة فى تجفيـف الطبقة الرقيقة وحلها بطريقة الفروق المتناهية (Finite difference method ) . ويمكننا مما سبق إستخلاص الآتى :

١. فى ظروف التجفيف غير المستقرة يمكن إستنتاج المحتـوى الرطوبـى للـذرة او أى محصول حبوب آخر بطريقة الفروق المتناهية . وقد تبين أن المحتوى الرطوبى التعادلى هـو العامل الأكثر فى الأهمية فى عمليات التجفيف، وبخاصة فى ظروف تغير الرطوبة النسـبية و درجات الحرارة .

٢. طريقة الفروق المتناهية هى وسيلة هامة للتنبؤ بالمحتوى الرطوبى بإسـتخدام معادلـة نيوتن وحلها تزامنيا مع معادلة هندرسون للمحتوى الرطوبى التعـادلى كدالـة فىالرطوبـة النسبية ودرجات الحرارة .

٣. وقد كان نموذج الحل ذا حساسية للتنبؤ بالمحتوى الرطوبى أثناء ساعات سطوع الشمس ، وأيضاً أثناء ساعات الليل أى أثناء عمليات التهوية بالهواء البارد ( Night cooling ) .

٤. كانت النتائج المتحصل عليها بطريقة الفروق المتناهية ذات إرتبـاط وثيـق بالنتـائج التجريبية بمعامل ( $R^2$ =0.98) .

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