

IWTPV`10

Czech Technical University

25-26 March 2010

**Transient and steady state simulation studies and experiments for the performance of c-Si and pc-Si PV cells in high illumination levels**

S. Kaplanis<sup>1</sup> E. Kaplani<sup>2</sup>

1. Mech. Engineering dep., TEI Patra, Greece, [kaplanis@teipat.gr](mailto:kaplanis@teipat.gr)

2. Mech. Engineering dep., TEI Patra, Greece, [elina.kaplani@gmail.com](mailto:elina.kaplani@gmail.com)



A set of experiments was carried out to study the  $V_{oc}$ ,  $i_{sc}$  and the PV cell temperature time profile  $T_c(t)$  of a c-Si and a pc-Si cells.

The analysis of the transient performance for  $V_{oc}$ ,  $i_{sc}$  and the cell temperature  $T_c(t)$ , vs time at different illumination levels was tried.

A prediction model for the PV cell temperature,  $T_c$ , is developed and the results are compared with measured values. The same is tried for the prediction of  $V_{oc}$ .

The predicted  $V_{oc}$  values by this model are compared to measured ones.

## •INTRODUCTION

The PV cell performance under real field conditions has been extensively studied, even under high Concentration values,  $C$ .

In fact, it was understood that increasing the  $C$  values the Peak power,  $P_m$ , increased with  $C$ .

On the other hand, the PV cell temperature has a negative effect on both  $\eta_c$  and  $P_m$


A further analysis showed that, due to the PV cell series resistance,  $r_s$ , the Joule effect within the cell  $P_j = i^2 * r_s$ , rapidly increases with  $C$ .

Consequently,  $P_m$ , which initially increases with  $C$ , reaches a high value at a certain  $C$ , dependent mainly on  $r_s$  and then starts decreasing as  $C$  further increases.

The rest of the solar radiation absorbed into the cell and not converted into power, appears as heat with an increased temperature,  $T_c$ , on both sides of the cell.

Thus, there is developed on both of its sides a temperature profile,  $T_c(t;C)$ .

The  $T_c(t;C)$  profile undergoes a transient behaviour along with  $V_{oc}$  and  $i_{sc}$  following the changes of the solar irradiation on the PV cell, till the cell reaches thermal and subsequently electric steady state conditions.



Theoretical analysis and experimental investigation have shown that the temperature profile has an effect on  $V_{oc}$  and  $i_{sc}$ , too.

The effect on  $V_{oc}$  and  $i_{sc}$ , as to be highlighted in this paper, depends on the temperature level reached, i.e. on the  $C$  value.

The interpretation of the PV cell performance under such solar radiation conditions is tried.

Experiments were carried out, both at conditions of air free flow and air forced flow, in order to cool the PV cell.



## Theoretical Analysis

General expressions for the short circuit,  $i_{sc}$ , may take the form:

$$i_{sc}(C) = C * i_{ph}(C_{ref}) - I_0 * \left[ \exp\left(\frac{i_{sc}(C) * r_s}{k * T_c / q}\right) - 1 \right] - \frac{i_{sc}(C) * r_s}{R_{sh}} \quad (1)$$

$$i_{sc}(C) = C * i_{ph}(C_{ref}) - I_0 * \left[ \exp\left(\frac{i_{sc}(C) * r_s}{k * T_c / q}\right) - 1 \right] - I_r * \left[ \exp\left(\frac{i_{sc}(C) * r_s}{2 * k * T_c / q}\right) - 1 \right] - \frac{i_{sc}(C) * r_s}{R_{sh}} \quad (2)$$

$I_0$ , although it does not depend directly on C or on the level of solar radiation on the PV cell, does depend on  $T_c$  by 15.4%/K

$I_r$ , is the saturation current due to the electron- hole recombination effect, which obviously increases with C.

- Therefore, it is expected that  $i_{sc}$  just upon illumination does not follow exactly a step function but it takes a time profile due to the  $T_c(t;C)$  profile developed.
- On the other hand,  $T_c(t;C)$  depends on  $C$  and on the geometrical and physical conditions and structure of the PV cell.
- $r_s$ , is the series resistance of the PV cell, which generally depends on  $T_c$
- $R_{sh}$ , is the shunt resistance which will not be considered in our case, as it takes a high value and thus the last term in eq (1) & (2) is negligible at the operating voltage of the cell.



- Eq(1) foresees that according to the value the brackets take along the time,  $t$ ,  $i_{sc}$  may either increase, till it levels out at a saturation value when steady state conditions have reached, or may take a complex shape, while during the transient conditions.
- This might be explained theoretically and will be shown experimentally. The above difference in the  $i_{sc}(t;C)$  shape depends on parameters related to the cell electric characteristic quantities which will be discussed deeper.



- A corresponding expression may hold for  $V_{oc}(C)$ , which for  $C = 1$  takes the form:

$$V_{oc}(C) = V_{oc}(C_{ref}) + m_c * \frac{k * T_c}{q} * \ln C \quad (3)$$

$$+ \frac{dV_{oc}}{dT_c} [T_c(C) - T_c(C_{ref})]$$

- There is a similar behaviour of the  $V_{oc}(t;C)$ , with the one for  $i_{sc}(t;C)$  and  $T_c(t; C)$ .

- The PV cell temperature profile,  $T_c(t; C)$  may be obtained theoretically by applying the heat balance equation on the PV cell.
- A theoretical analysis based on Heat Transfer principles, determines that  $T_c(t;C)$ , when the cell is steadily illuminated, starts increasing with a time constant,  $T_{Tc}$ .
- Theoretically derived values of  $T_{Tc}$ , measured  $T_{Tc}$  values and measured  $V_{oc}$  are given in Table 1

**Table 1.**

**Time constants of  $V_{oc}(t;C)$  and  $T_c(t;C)$  as determined both experimentally and theoretically for various C values, for c-Si )**

C	$\tau_{Tc}$ (s) meas c-Si PV cell	$\tau_{Tc}$ (s) theor c-Si PV cell	$\tau_{Voc}$ (s) meas c-Si PV cell
1.65	37.1	36.8	36.0
4.05	34.3	34.4	32.2
7.34	36.6	31.8	37.5
20.52	27.4	26.9	28.1
25.5	25.3	24.0	24.3

To predict  $T_c(t;C)$ , a simple energy balance equation for the illuminated PV cell which takes the form:

$$\rho c V \frac{dT_c(t)}{dt} = (1 - \eta_c) A_c I_T - 2 h A_c [T_c(t) - T_a]$$

(4)

$\eta_c$  is the PV cell conversion efficiency, which depends on  $T_c$  by:

$$\eta_c^{-1} \frac{d\eta_c}{dT_c} = -0.4\% / ^\circ\text{C}$$

(5)

- $I_T$ , is the level of light illumination upon the cell,  $A_c$ , is the surface of the cell, a  $5 \times 5 \text{ cm}^2$  SOLARTEC c-Si,
- While, 2 in the third term stands for the two sides, front and back, of the cell from which heat is taken off by air convection.
- $h$ , the overall heat transfer coefficient, is dependent from  $T_c$  (t;C) and is determined for any  $T_c$  value, using appropriate formulae.




## Results

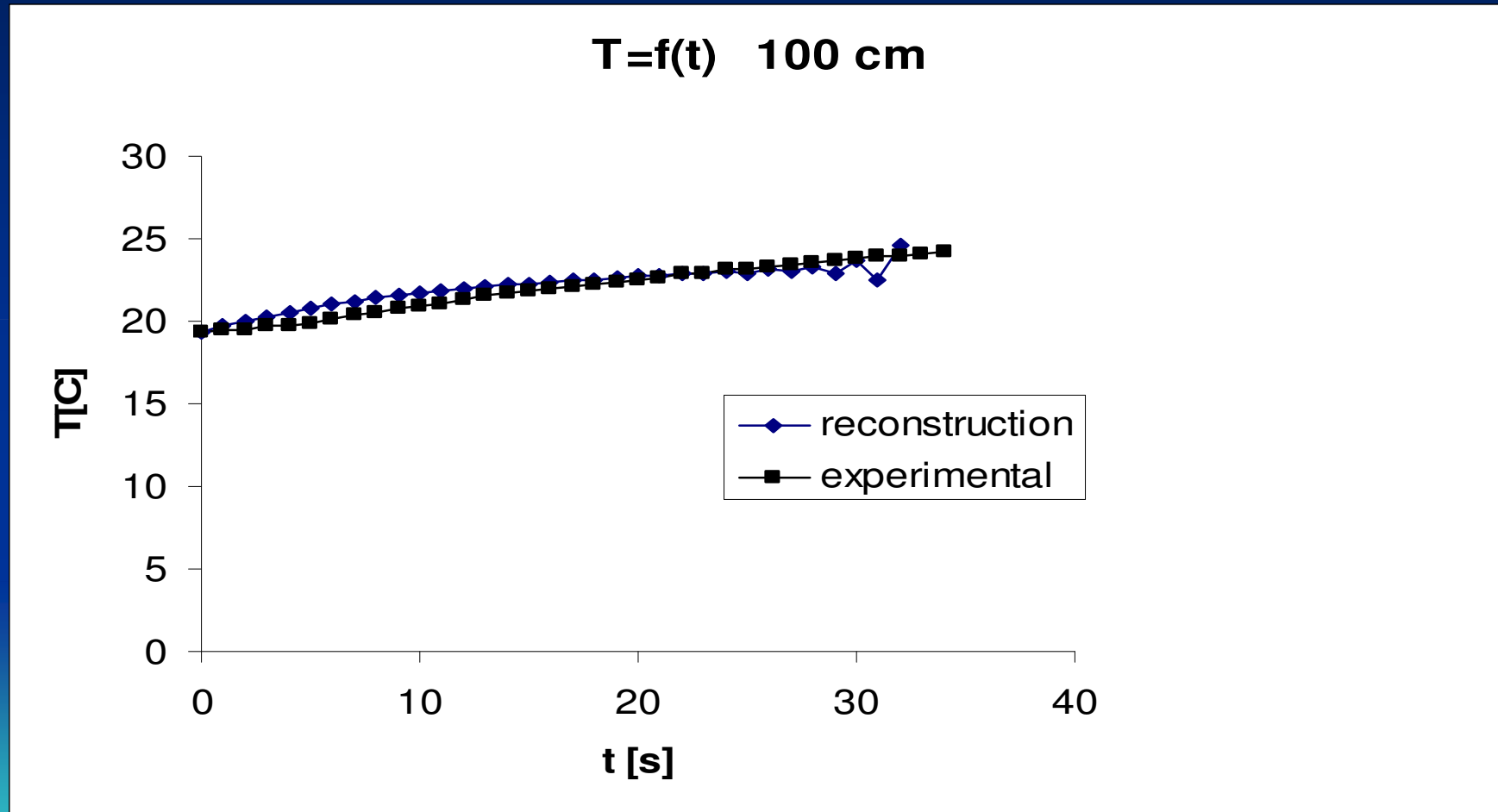
Results of measured and predicted  $T_c(t)$  values are provided in Fig 1.

We observe a very good prediction at small levels of  $C$  which deteriorates at high  $C$  values.

That implies a correction to be introduced in the formulae to determine  $h$ , in order to take into account the changes in the air flow Pattern, as  $T_c$  increases.




**Fig 1** PV cell temperature  $T_c(t)$  as measured and reconstructed. The comparison is shown for illumination of 0.2 Sun on the cell.



The  $T_c(t; C)$  profile for various  $C$  values for the c-Si and pc-Si cells is shown in fig 2.

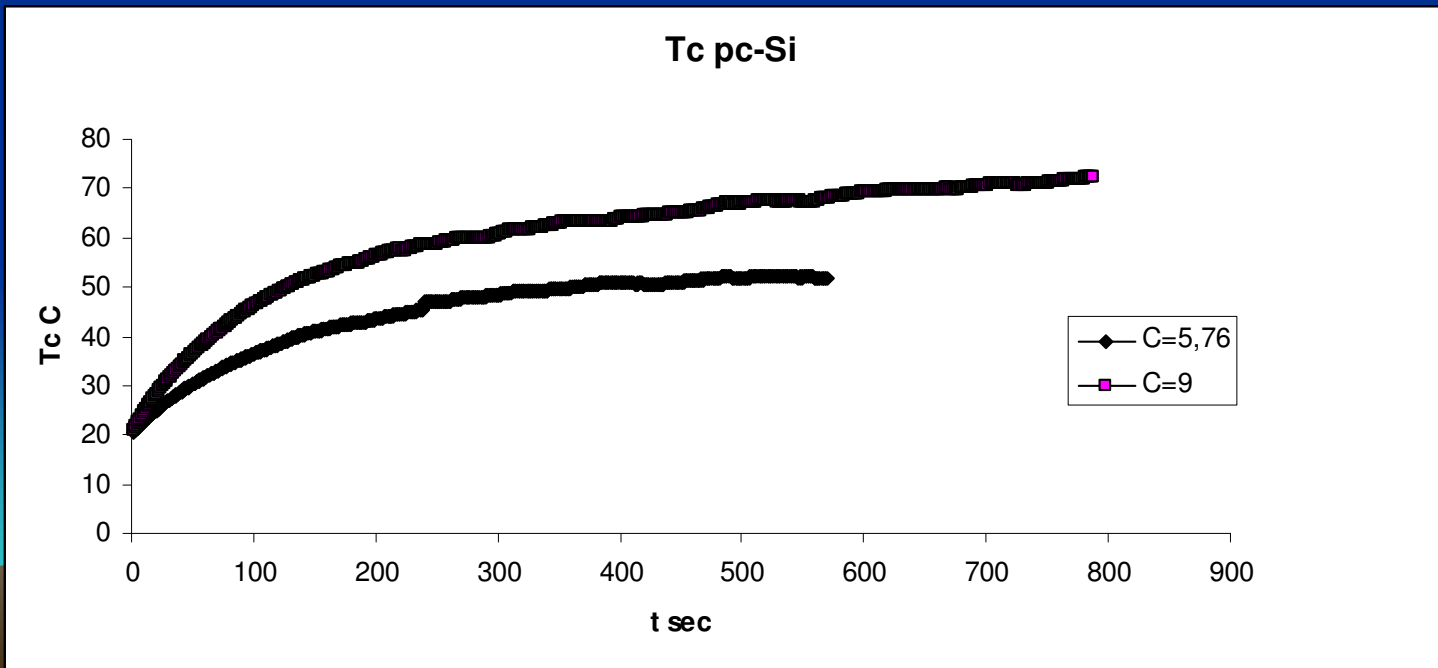
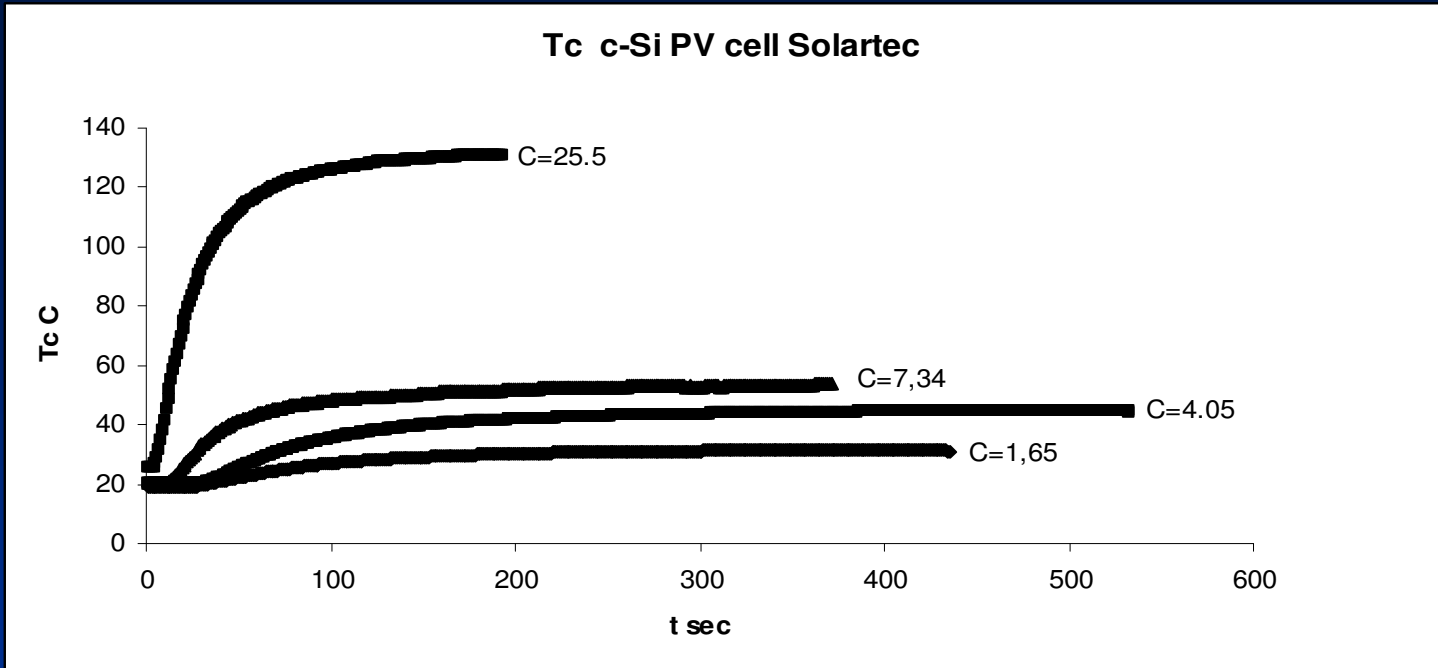
Fitting a function of the type  $1 - \exp(-t/\tau)$  to the measured  $T_c(t)$  values, for the c-Si and pc-Si cells, there were obtained very good results with correlation coefficient = 0.998.

$T_{TC}$  values experimentally determined lie very close to the theoretically estimated ones, obtained by applying the heat transfer formulae, see Table 1 for comparison.





**Fig 2 a,b**  
 $T_c(t)$   
temperature  
profile vs  
time for  
various  
illumination  
levels for c-  
Si and pc-Si  
cells



Similarly, the  $V_{oc}(t;C)$  profile is given in fig 3. The experimentally obtained  $V_{oc}(t;C)$  values are shown in comparison with the predicted values for various  $C$ , see Table 2.

**Table 2.** Voc predicted and measured values for c-Si at concentration levels.



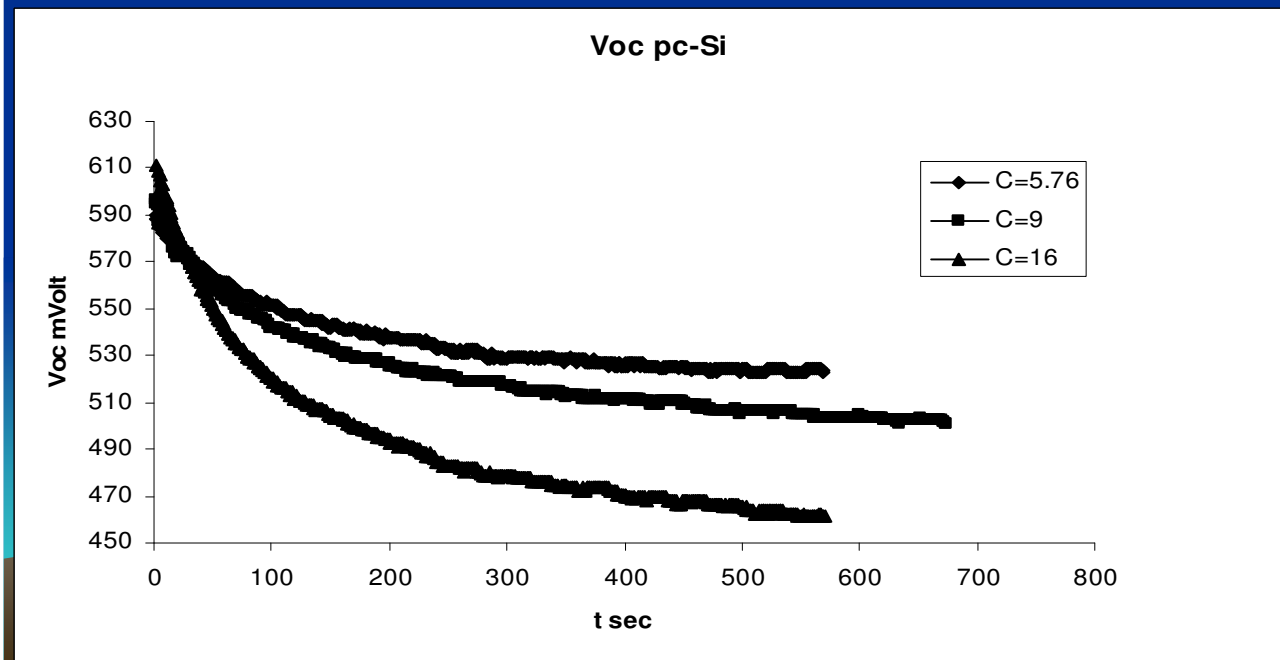
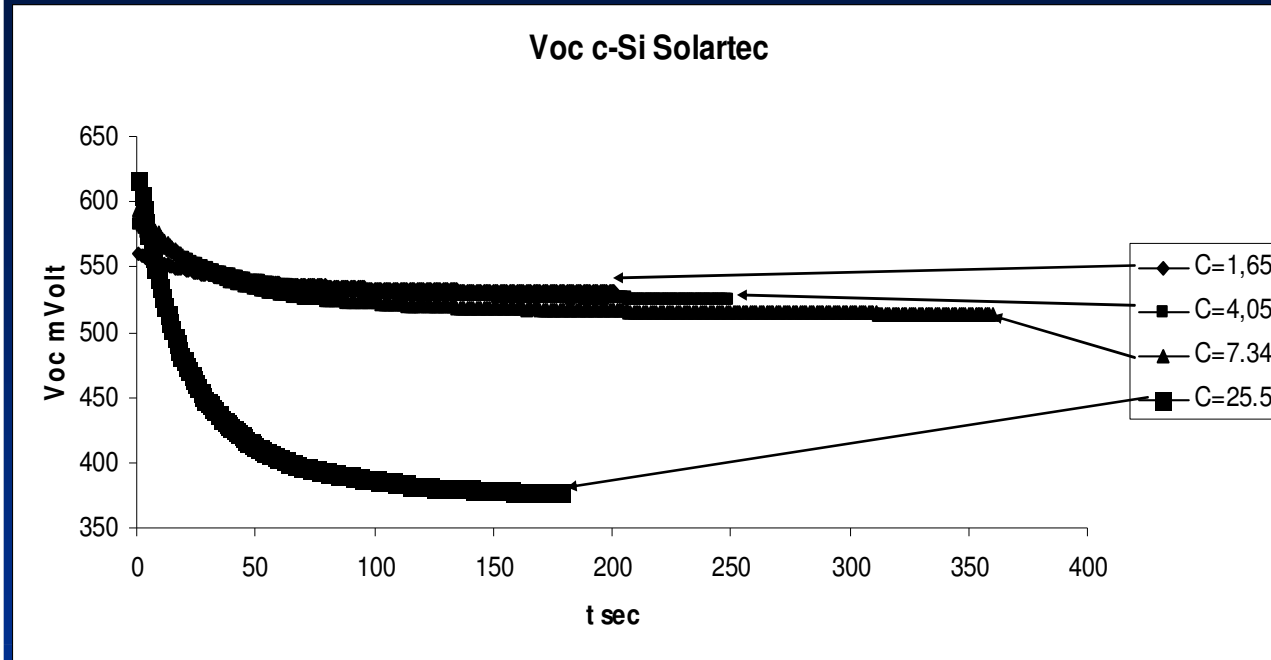
The experimental analysis of the  $i$ - $V$  measurements, at transient conditions, gives that the  $V_{oc}$  time constant is equal to the one of the  $T_c(t;C)$ , as the corresponding figures in Table 1 show.

This is understood when we study the derivative  $dV_{oc}/dt$  obtained from eq (3).



- Following the same analysis for  $V_{oc}(t)$ , as done for  $T_c(t)$ , we reach to the conclusion that  $T_{V_{oc}}$  values theoretically obtained, based on eq (3), lie very close to the experimentally determined ones.
- The analysis for both  $T_c(t;C)$  and  $V_{oc}(t;C)$  underlines that the simulation model developed provides the real performance of the PV cell both at transient and steady state conditions with good success.





**Fig 3a,b**  $V_{oc}$  values at transient conditions experimentally obtained for c-Si cell (Solartec) and pc-Si cell (Velleman)

- The experimental  $V_{oc}(t;C)$  profiles, for small C values, lie very close to the ones obtained by the theoretical model.

The prediction deteriorates for high C values.

- There should be introduced a corrected form for m.

- The deviation between measured and predicted values for  $C=25$  is about 6%, which in fact is small,

- while for lower C, this difference gets smaller.

- These results give the merit of this prediction model.


The study of the  $i$ - $V$  curve at transient conditions, gave the the  $i_{sc}$  Profile.

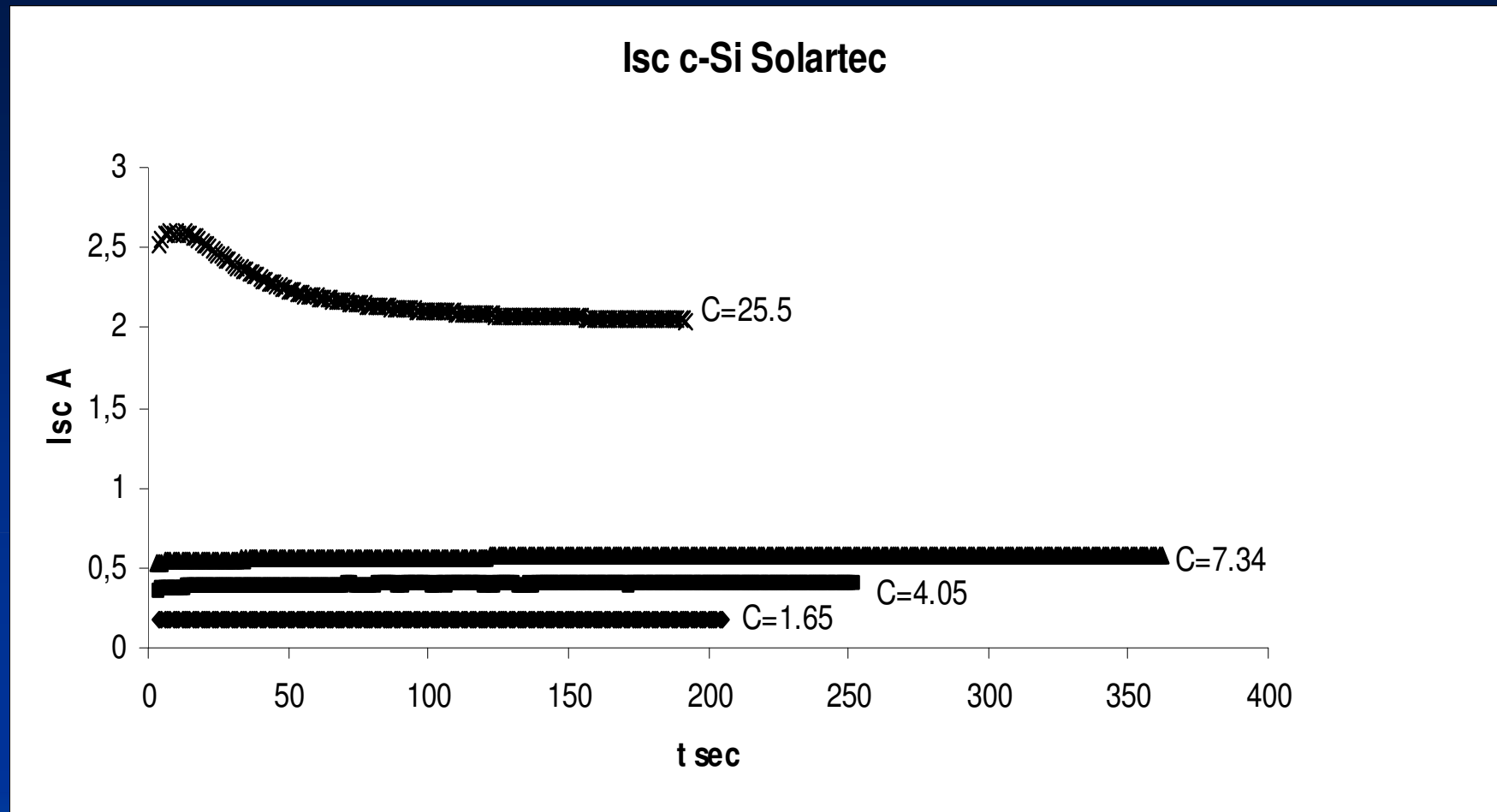
The  $i_{sc}$  profile, as in fig.4 shows an increase vs  $t$  or  $T_c$  for small to medium  $C$  values, as it is expected from the theory.

However, at high  $C$  values, there appears a peak in  $i_{sc}$  which is the turning point, at a time  $t_p$ , shortly after illumination gets started.

Thereafter, as  $T_c(t;C)$  increases, the  $i_{sc}$  starts decreasing. This  $i_{sc}(t;C)$  profile behaviour may be interpreted using the 1 or 2 diode electric equivalent circuit model.

This further analysis may disclose that the argument of the exponential terms in eq(1) & eq(2) may change its rate of change for different  $C$  values.





**Fig 4**  $i_{sc}$ , short current profile vs time for various  $C$  values



The combination of this behaviour for both  $V_{oc}(t; C)$  and  $i_{sc}(t; C)$  vs  $T_c$  and  $C$  affects the  $P_m$  profile, which at certain  $C$  value, gets a peak value and then starts decreasing.

- The recovery of the  $P_m$  was tried through an air ventilator which forced air parallel to the PV cell sides.



- The ventilation rate was such as to reduce the  $T_c$  value of the PV cell, when under illumination with Concentration ratio  $C$ , and reset it at the  $T_c$  value it had when the cell was illuminated at  $C_{ref}$  conditions.

That is, to zero the last term of eq (2) and reset the exponentials of the terms of eq (1) to  $C_{ref}$  conditions.

- However, the electron-hole recombination effect to the  $i$ - $V$  could not be recovered with the simple ventilation process. This effect increases with  $C$  as experimentally verified, too.

Figs 5 and 6 show these results.

The difference between  $i$ - $V$  curves for the same  $C$  value, taken with and without ventilation, shows that the recovery using air ventilation is effective for small  $C$  values, while the impact is very obvious at high  $C$  values



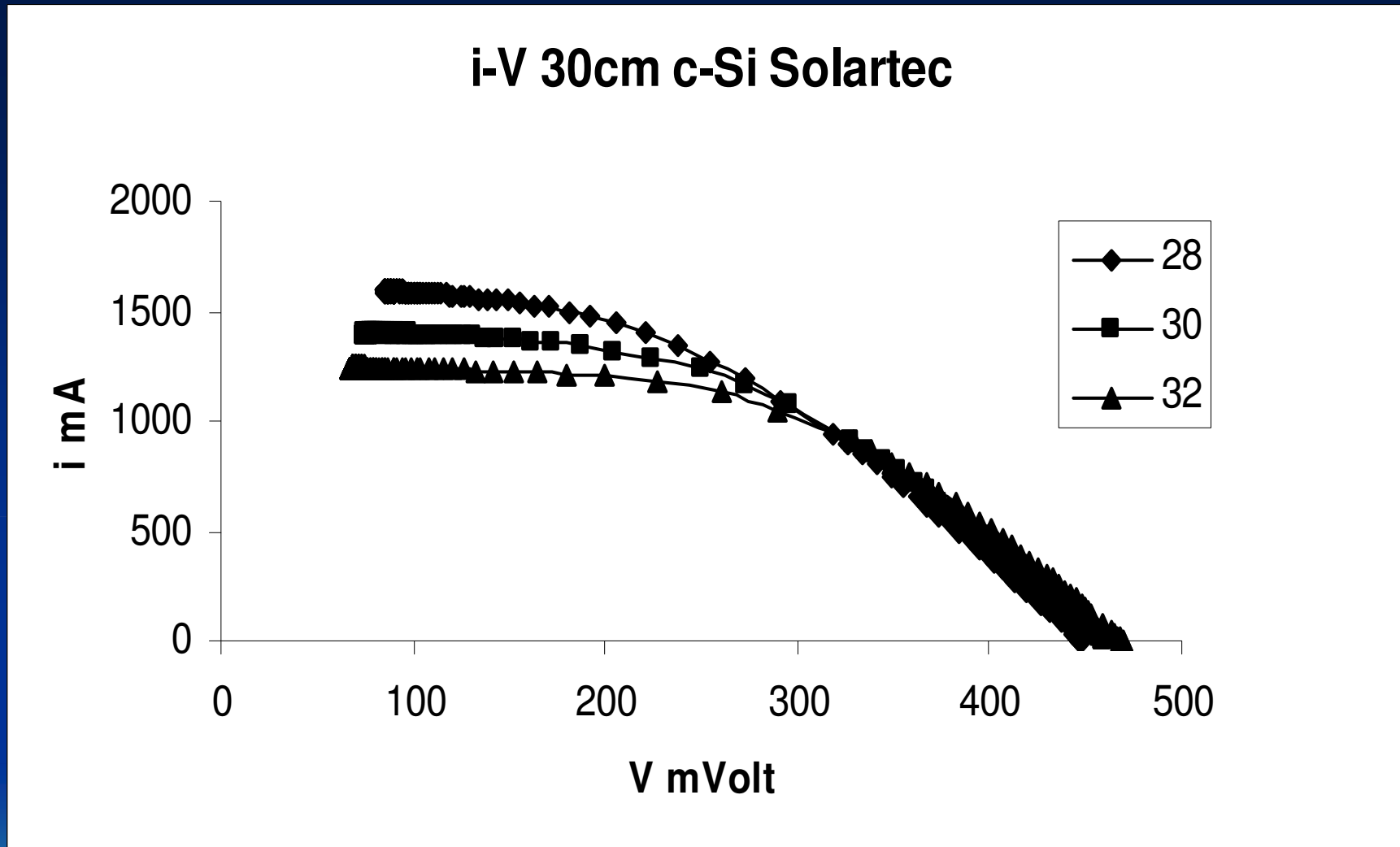
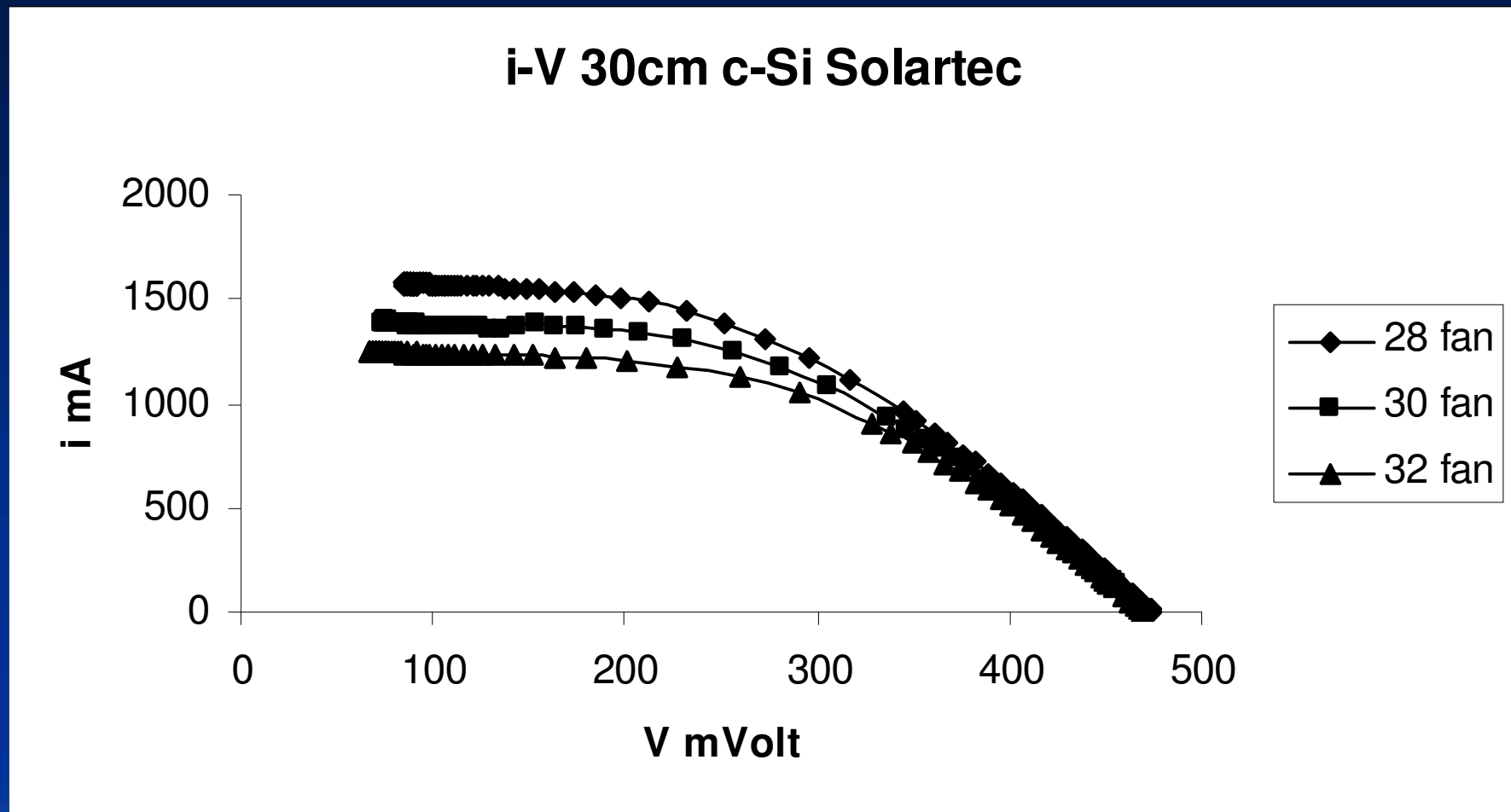


Fig 5 i-V for c-Si Solartec PV cell at distance of 28, 30, 32 cm from the light source, without ventilation



**Fig 6** i-V for c-Si Solartec PV cell at distance of 28, 30, 32 cm from the light source, with ventilation

## •Conclusions

The results of a research project to investigate the behaviour of fundamental PV cell quantities such as the  $i_{sc}$ ,  $V_{oc}$ ,  $T_c$  and  $P_m$  at various Concentration ratios,  $C$  were given.

The studies of the  $i_{sc}$ ,  $V_{oc}$  and  $T_c$  transient curves, experimentally obtained were compared with theoretically predicted values and a very good approach was achieved, which confirmed the theoretical model developed.

It became evident that there is an important domain of the PV cell performance to investigate through transient characteristics induced by step function, as the illumination on the PV cell, is.

In particular, the time constants of the transient phenomena are quite high, as they exceed 10-30 secs. These changes in the  $i_{sc}$  and  $V_{oc}$  imply changes in the i-V curve and its  $P_m$  coordinates,  $(i_m, V_m)$ .



- It was found that the  $i_{sc}(C)$  and  $V_{oc}(C)$  change considerably with time as  $T_c$  and  $C$  take higher values.
- The effect of  $T_c$  on the  $P_m$  decrease may be partially recovered by ventilation of the cell or with a heat exchanger coupled to its back surface.
- There was also studied the behaviour of the PV cell electric parameters along with  $T_c$  and  $C$ , based on the Heat Balance equation. The prediction of  $T_c(t)$  and  $V_{oc}(t)$  are very good for low to medium  $C$ , but as  $C$  increases predicted values deviate, but not significantly.
- Further investigation continues and additional full analysis will be presented.





- **Acknowledgement**

- The authors express their appreciation to the support given by the EPEAEK Programme of the Hellenic Ministry of Education and especially by the Archimedes I Programme, as well as by the EC FP6 project CRISTAL.
- The authors acknowledge the contribution of Mr. D. Xristoforidis, N. Pappas, S. Loumpos, Ap. Mavroudis and 4 Czech research students for joining the  $h_c$  determination tasks and the i-V measurements, during the Summer University in Patra, Greece.

## References

4<sup>th</sup> International Conference on Sustainable Energy & Environmental Protection (SEEP) 2010 Conference Proceedings, Politecnico di Bari Italy

