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

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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 η_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:

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

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

I_o, 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:

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

- 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	τ_{Tc} (s) meas c-Si PV cell	τ_{Tc} (s) theor c-Si PV cell	τ_{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:

$$\rho c V * dT_c(t)/dt = (1-\eta_c) * A_c * I_T \quad -2 * h * A_c * [T_c(t) - Ta] \qquad (4)$$

η_c is the PV cell conversion efficiency, which depends on T_c by:

$$\eta_c^{-1} d\eta_c / d\, T_c = -0.4\% / {}^{o}C \qquad (5)$$

- I_T, is the level of light illumination upon the cell, A_c, is the surface of the cell, a 5x5 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.

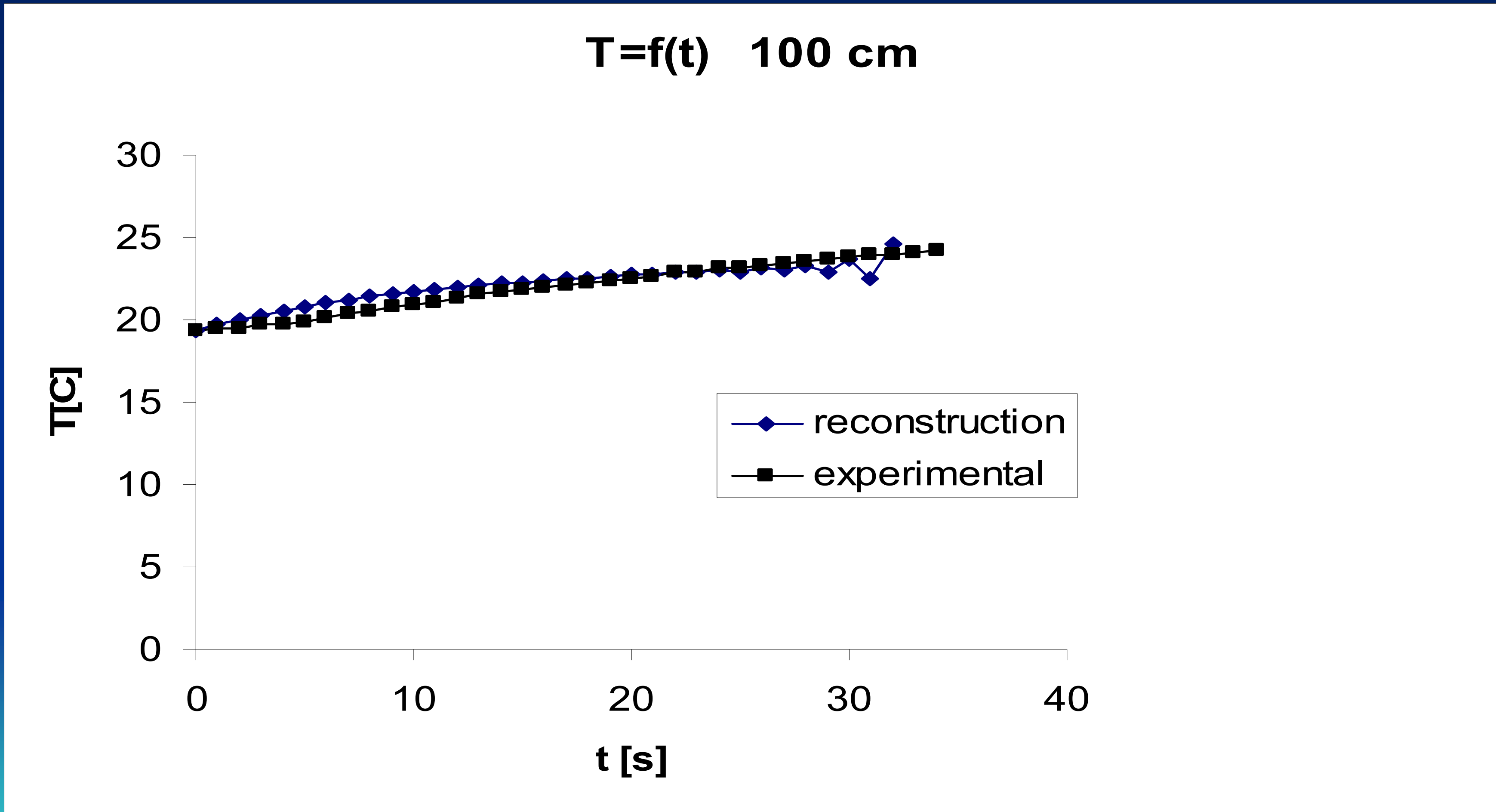
Results

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.

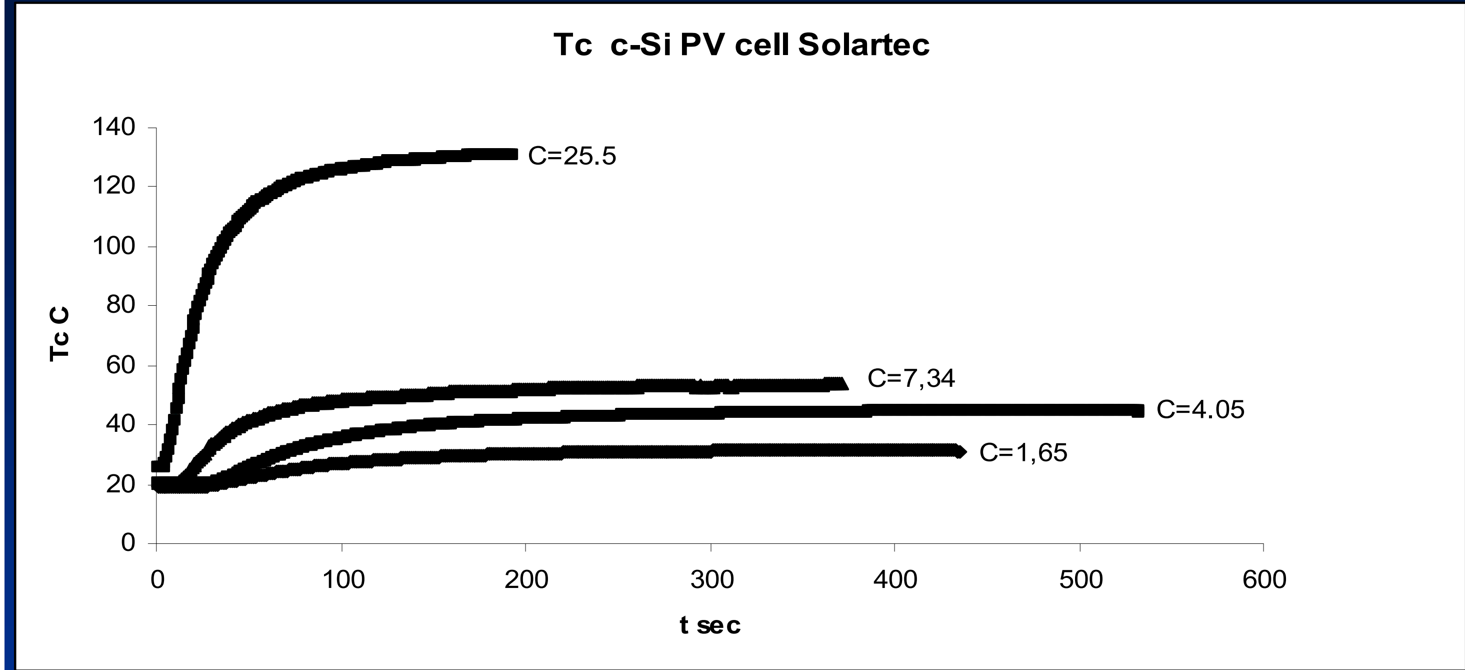
Fig 1 PV cell temperature $T_c(t)$ as measured and reconstructed. The comparison is shown for illumination of 0.2 Sun on the cell.



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/τ) 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.



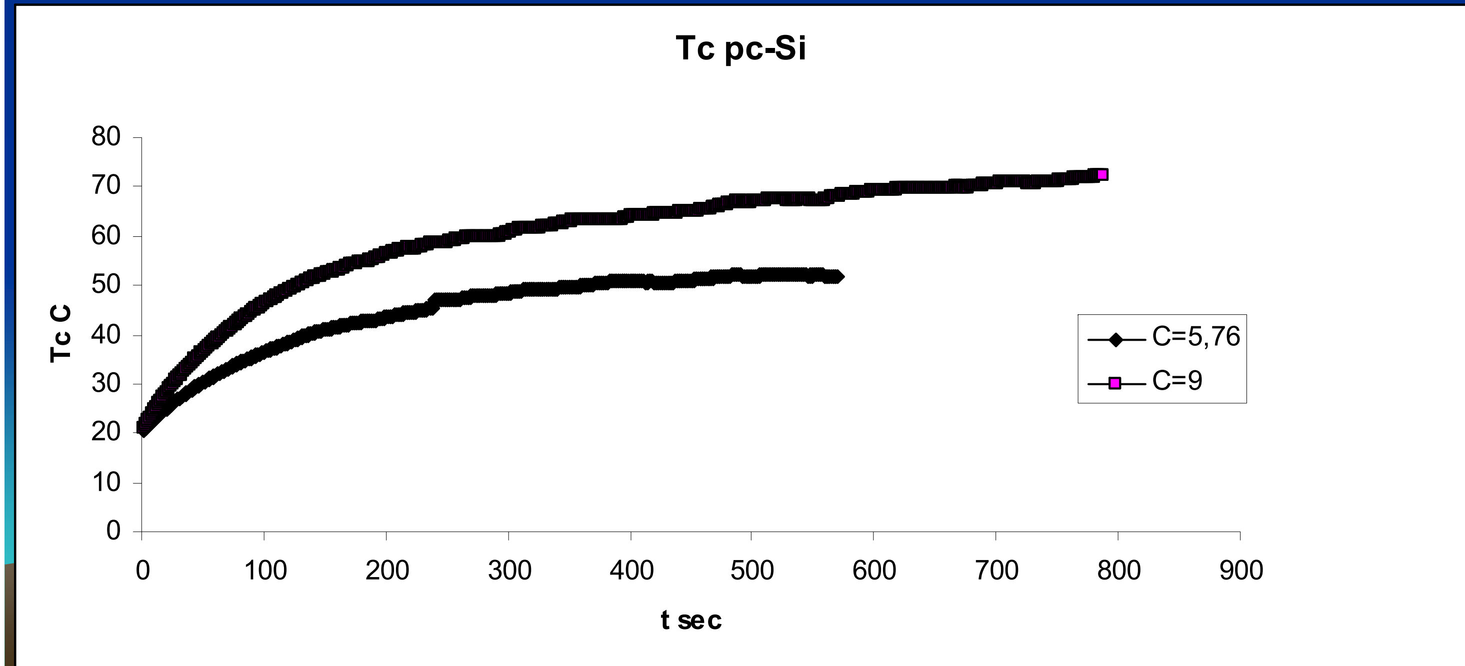


Fig 2 a,b

$T_c(t)$ 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.

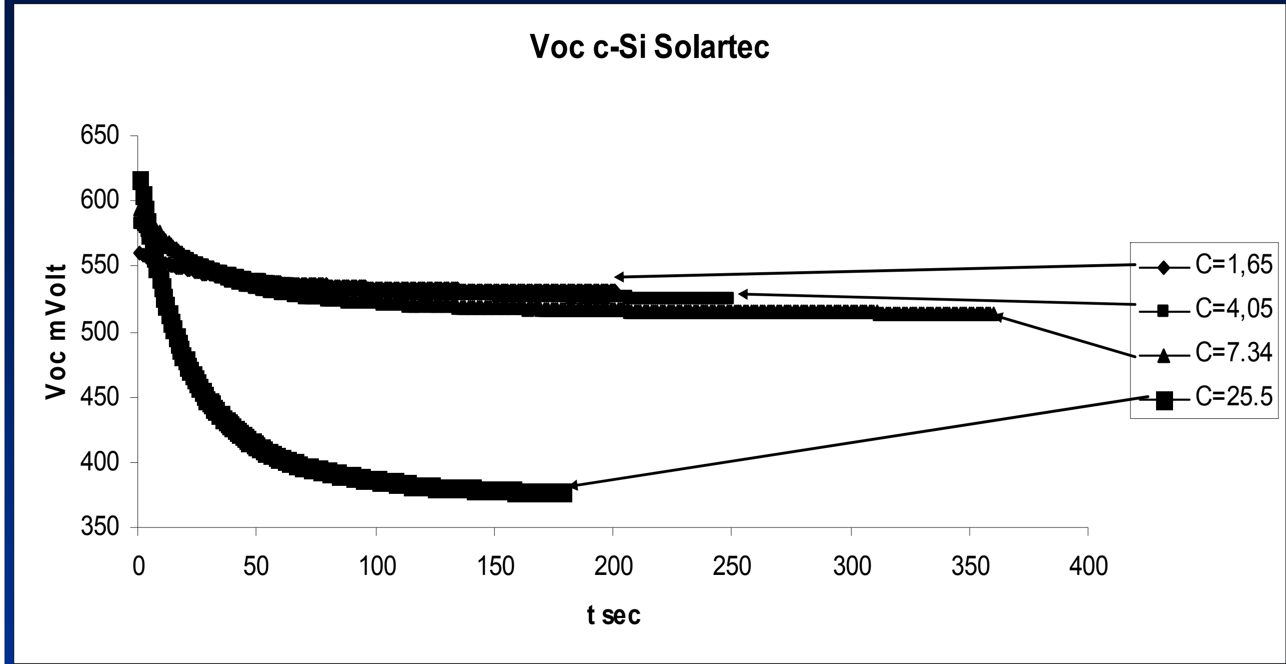
Table 2. Voc predicted and measured values for c-Si at concentration levels.

The experimental analysis of the i-V measurements, at transient conditions, gives that the Voc 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 τ_{Voc} 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.



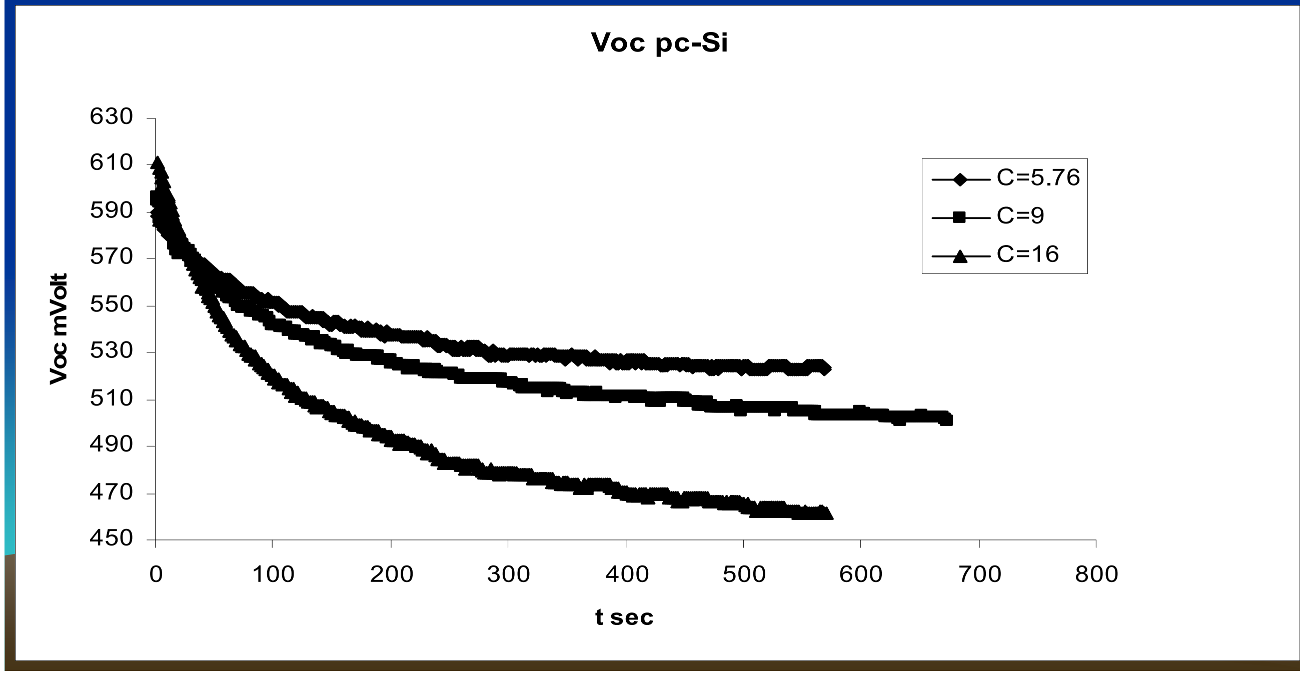


Fig 3a,b V_{oc} values at transient conditions experimentally obtained for c-Si cell (Solartec) and pc-Si cell (Velleman)

- 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.

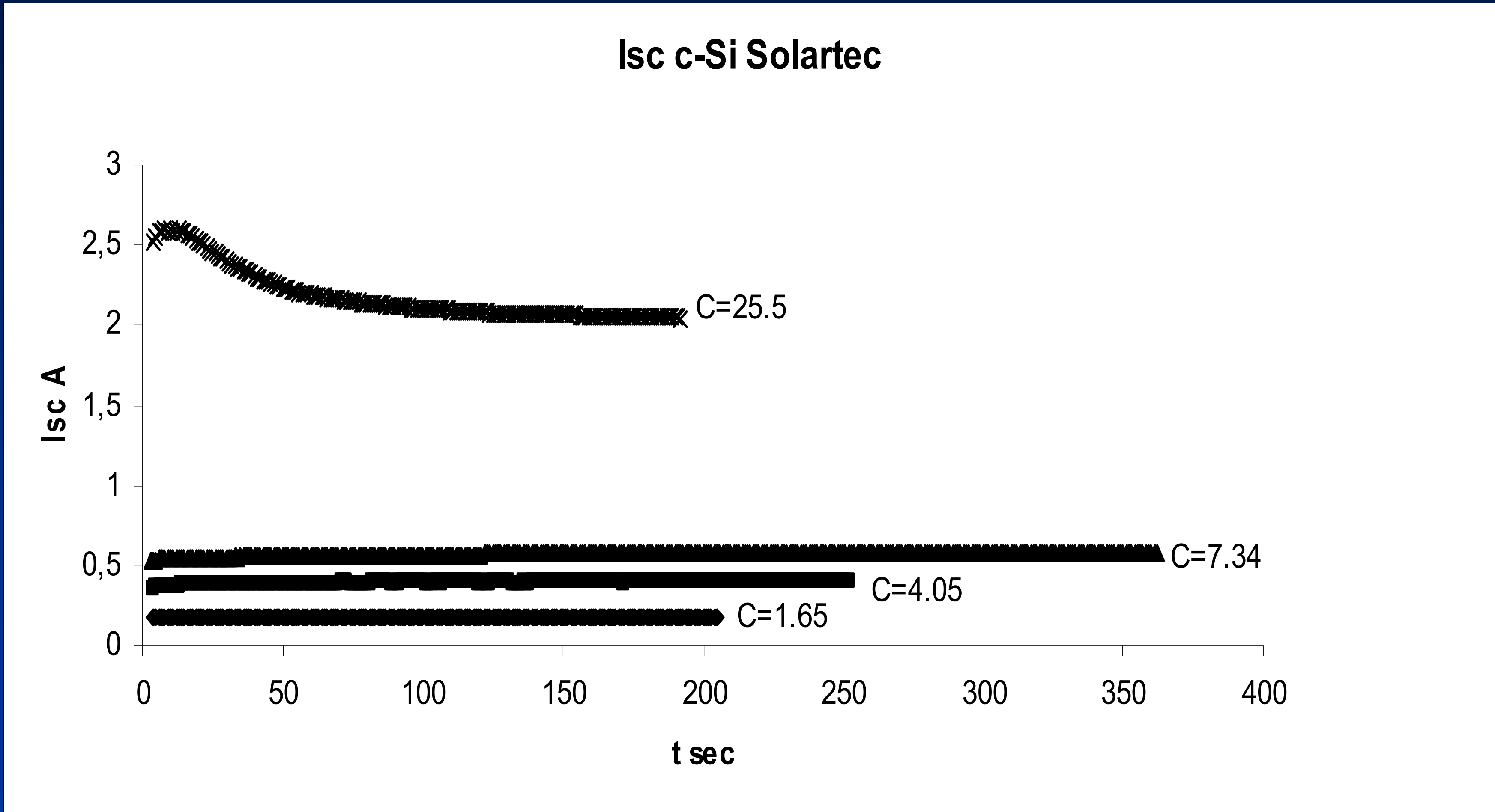


Fig 4 i_{sc} , short current profile vs time for various C values

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

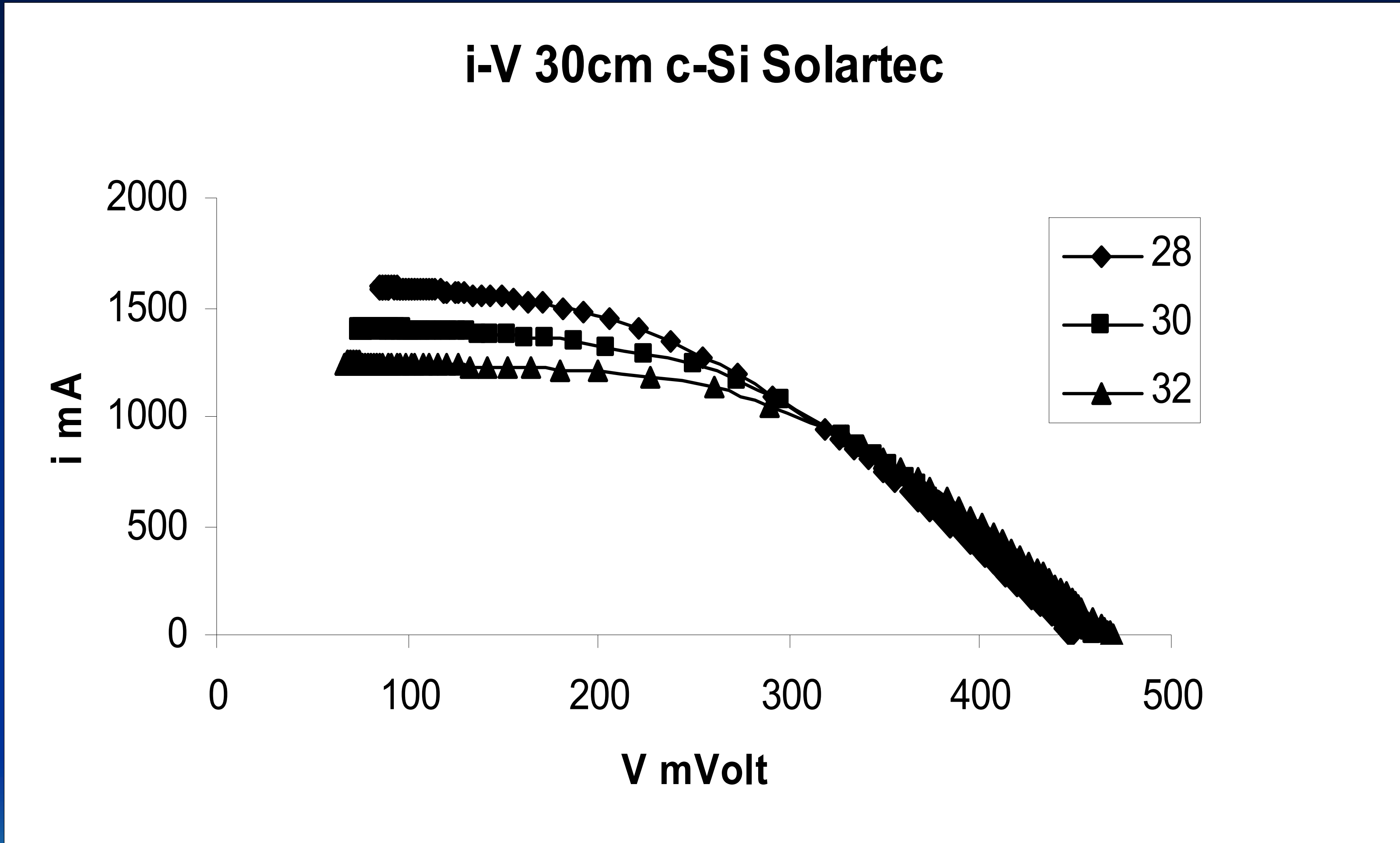


Fig 5 i-V for c-Si Solartec PV cell at distance of 28, 30, 32 cm from the light source, without ventilation

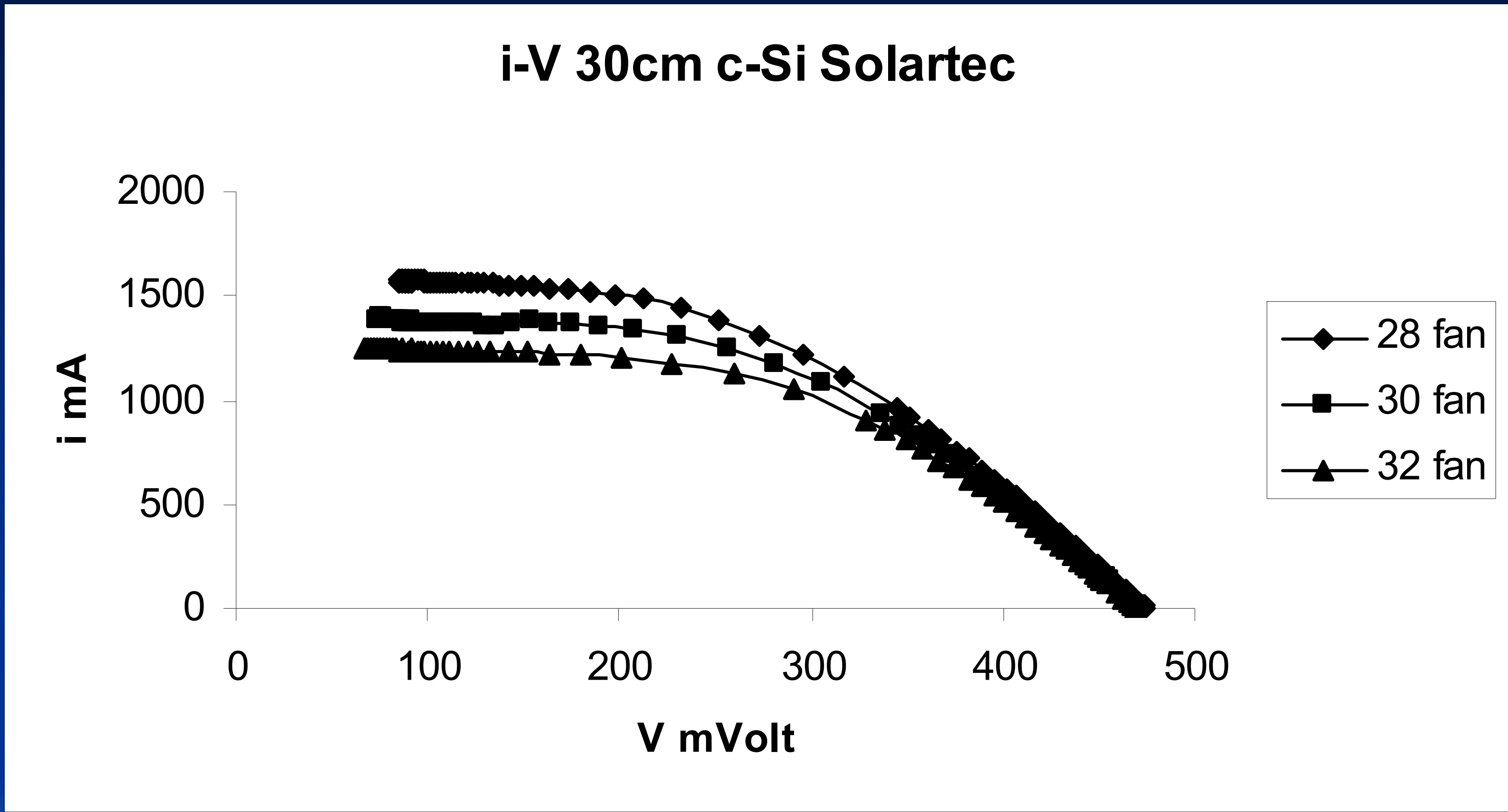


Fig 6 i-V for c-Si Solartec PV cell at distance of 28, 30, 32 cm from the light source, with ventilation

•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.

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