



Solar cell temperature on Mars

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Abstract

The operating temperature of a solar cell determines its efficiency and performance. This temperature depends on the materials used to build the cell but also on the environmental variables surrounding it (i.e., radiation, ambient temperature, wind speed and humidity). Several equations have been proposed to calculate this temperature, depending on these variables. Also, for Earth conditions, simplified equations have been developed, but are not valid for other planets, as Mars, where the environmental conditions are extremely different. In this paper, we develop a simplified equation to calculate the temperature of a solar cell under Mars environmental conditions and discuss the effect that altitude and wind on Mars might have on the solar cell temperature. The correct determination of the operating temperature of the cell will help to optimize the design of the next solar cell powered rovers for the exploration of Mars.

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1. Introduction

The operating temperature of a solar cell is a key factor for its efficiency, and has implications on its performance and ability to produce electricity. Although the materials and design of fabrication has implications on the temperature of the cell, the environment surrounding it is a key factor for the determination of the temperature.

On Earth there are several physical processes affecting the temperature of the cell. On one side, the irradiance reaching the panel is converted to electrical energy, but also heats the cell. On the other hand, the wind refrigerates the

cell by convection, and the difference of temperature with the environment allows the cell to loss heat by radiation. Several methods and equations have been developed to determine with the highest accuracy the temperature of the cell taking into account these physical processes.

Under certain conditions (Ross, 1979), it is possible to simplify these equations and convert them in a linear equation as a function of the ambient temperature and the irradiance flux. Those conditions are not valid for all environments, for example for the planet Mars.

There are big differences between the environmental conditions on Earth and Mars that affect the temperature of a solar cell in Mars' surface. Mars atmosphere lacks of ultraviolet absorbers like ozone, and then extreme levels of UV radiation are reaching any solar cell located on its surface; and the low density of the atmosphere, composed mainly by CO₂, is not a good refrigerator, even with wind

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speeds similar to those on Earth. As a consequence of these conditions, there are very large diurnal variations of temperature in Mars, making necessary the development of a particular cell temperature equation for the Mars environment, where cooling by convection and radiation are taken into account.

Mars exploration rovers powered by solar radiation have been a success previously (i.e, Mars Pathfinder http://www.nasa.gov/mission_pages/mars-pathfinder/, and the twins Spirit and Opportunity http://www.nasa.gov/mission_pages/mer/index.html). The determination of an accurate operating cell temperature will optimize the efficiency of the performance of solar cells for future missions.

In this paper, we provide the equations to calculate the operating cell temperature taking into account the heating of the cell by solar radiation and its refrigeration by forced convection and radiation. In Section 2, we develop the general equation that should be used on Mars, considering all the physical processes that can be of importance on Mars. In Section 3, we present a linear simplification of the general equation dependent on air temperature, incident radiation and wind speed, and we prove its validity. In Section 4 we use the simplified linear expression to calculate the operating cell temperature on Mars based on air and ground temperature data provided by the Rover Environmental Monitoring Station (REMS) (Gómez-Elvira et al., 2012) on board the Curiosity rover currently on Mars (Grotzinger et al., 2012).

2. General equation for the temperature of the solar cell, T_c

Skoplaki et al. (2008) proposed a number of relations to determine the temperature of a Photovoltaic (PV) cell depending on the environment conditions. These relations are extensively used on Earth (Townsend, 1989), being the simplest of them a linear relation between the cell temperature (T_c) and the ambient temperature (T_a):

$$T_c = T_a + k\phi_s \quad (1)$$

where k is the Ross coefficient (Ross, 1979) and ϕ_s the direct solar radiation.

This equation that comes from a simplification of the general equation (Skoplaki et al., 2008):

$$T_c = \frac{T_a + \left(\frac{\phi_s}{\phi_{s,NOCT}}\right) \frac{U_{L,NOCT}}{U_L} (T_{c,NOCT} - T_{a,NOCT}) \left[1 - \frac{\eta_{ref}}{(\tau\alpha)} (1 + \beta_{ref} T_{ref})\right]}{1 - \frac{\beta_{ref}\eta_{ref}}{(\tau\alpha)} \left(\frac{G_T}{G_{NOCT}}\right) \frac{h_{w,NOCT}}{h_w} (T_{c,NOCT} - T_{a,NOCT})} \quad (2)$$

is not valid under Mars atmosphere conditions fundamentally because the atmosphere of Mars is extremely thin compared to the Earth's atmosphere, and the processes that could refrigerate the cell could be different. The ways in which a solar cell could loss heat are convection (forced, free or mixed) and radiation. On Earth, the forced convection is usually the only process taken into account, since it is several times more important than the other loss heat

processes, as explained in Skoplaki et al. (2008). However, the assumption that only forced convection refrigerates a solar cell on Mars is wrong, because the losses by radiation account for at least three quarters of the total heat lost, and therefore all the equations determined under that hypothesis are incorrect (Osczevski, 2013).

The convective heat transfer at a surface is measured by the Nusselt (Nu) number, and its value depends on the type of convection (forced, free or mixed); and the type of convection which occurs under Mars atmosphere conditions is determined by relative values of the Reynolds (Re) and Grashof (Gr) dimensionless numbers. The Reynolds number is defined as the ratio of inertia to viscous forces:

$$Re = \frac{uL}{\nu} \quad (3)$$

and the Grashof number as the ratio of buoyancy to viscous forces:

$$Gr = \frac{g\beta(T_s - T_a)L^3}{\nu^2} \quad (4)$$

The ratio Gr/Re^2 will determine the type of convection (Kays et al., 2004).

Obviously for Mars, the environmental values determining Re and Gr are different than those for Earth: the Martian atmosphere is about 95% CO₂ (for our purposes we will assume that is 100% of CO₂), and typical values of density (ρ) and kinematic viscosity (ν) are (ρ) = 0.01308 kg/m³ and (ν) = 0.0010868 m²/s. For Earth these values are (ν) = 1.460 · 10⁻⁵ m²/s and (ρ) = 1.225 kg/m³. Typical Martian values for surface and air temperature (at 1.5 m) are $T_s = 240$ and $T_a = 220$, as can be deduced from REMS data (Gómez-Elvira et al., 2012), and therefore $\Delta T = 20$ K. Considering a solar panel with length of 0.5 m and taking into account that the gravitational constant for Mars is $g = 3.69$ m/s², we obtain the ratio

$$\frac{Gr}{Re^2} = \frac{g\beta(T_s - T_a)L}{u^2} = \frac{3.69 \cdot 1 \cdot 20 \cdot 0.5}{220 \cdot u^2} = \frac{0.168}{u^2} \quad (5)$$

Usual wind speeds in Mars range between $u = 5$ m/s and $u = 20$ m/s. For these values the ratio of Gr and Re numbers is always $\ll 1$, and therefore is possible to assume forced convection under Martian conditions (Incropera and DeWitt, 1996).

The Nusselt number is the dimensionless magnitude that characterizes the convective heat transfer at a surface. It depends on the type of convective heat transfer and also on the shape of the panel. For a flat plate, the expression for laminar flow is (Incropera and DeWitt, 1996):

$$Nu = \frac{h_w L}{k_m} = 0.664 Re^{1/2} Pr^{1/3} \quad (6)$$

where h_w is the wind convection heat transfer coefficient [W m⁻² K⁻¹] and k_m is the molecular thermal conductivity [W m⁻¹ K⁻¹]. Pr is the Prandtl number, defined as:

$$Pr = \frac{\mu C_p}{k_m} \quad (7)$$

where μ the dynamic viscosity of air, C_p the specific heat of air at constant pressure and k_m the molecular thermal conductivity. The relation between kinematic and dynamic viscosity is given by $\nu = \mu/\rho$.

Considering a thermal conductivity of $0.01465 \text{ W m}^{-1} \text{ K}^{-1}$ at 273 K and a specific heat of $850 \text{ m}^2 \text{ s}^{-2} \text{ K}^{-1}$ we can estimate the Pr number for Mars atmosphere as:

$$Pr = \frac{1.422 \cdot 10^{-5} \cdot 850}{1.465 \cdot 10^{-2}} \simeq 0.825 \quad (8)$$

For the sake of simplicity, we will consider the Prandtl number equal to 1 in this calculations, as it is assumed in General Circulation Models for Mars (Medvedev et al., 2006).

The relation between wind convection heat transfer coefficient and wind speed is therefore:

$$h_w = \frac{k_m}{L} \cdot 0.664 \cdot \left(\frac{uL}{\nu}\right)^{1/2} \quad (9)$$

Assuming that the atmosphere of Mars is nearly 100% of CO_2 this equation can be written as:

$$h_w = \frac{0.01465}{0.0010868^{1/2}} \cdot 0.664 \cdot \left(\frac{u}{L}\right)^{1/2} \quad (10)$$

$$h_w = 0.295 \cdot \left(\frac{u}{L}\right)^{1/2} \quad (11)$$

The radiation losses on Mars are very important and must be considered for the correct estimation of the temperature of the cell. Convection constitutes only one quarter of the heat transfer on Mars, and therefore radiation must be considered (Osczevski, 2013).

The radiation heat transfer coefficient can be written as (Eckstein, 1990):

$$h_{rad} = \epsilon \sigma (T_c^2 + T_a^2)(T_c - T_a) \quad (12)$$

i.e., it is dependent on the temperature of the body itself, the temperature of the cell (T_c) in our case.

We need to take into account that the temperature of the cell will be intrinsically coupled to the temperature of the platform (in the case of a cell in a rover or lander) or the surface if it is lying directly on the ground. In those cases, the temperature must be determined considering heat conduction instead of convection, and it will be mainly determined by the temperature of the hosting body.

Therefore, an iteration process will be needed in order to calculate it. The convergence is reached after five iterations and a good assumption for the starting seed could be $T_c = T_a + 20 \text{ K}$. In Figs. 1 and 2 we show the temperatures of the air and the cell.

Hence, the overall loss coefficient, U_L , is the sum of the wind and radiation coefficients (Eckstein, 1990), i.e., $U_L = h_w + h_{rad}$:

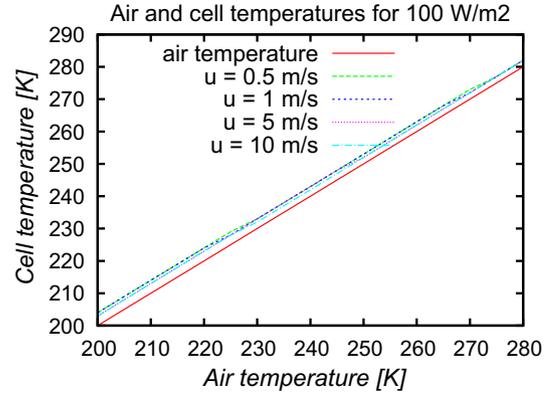


Fig. 1. Air and cell temperatures for solar flux of 100 W/m^2 .

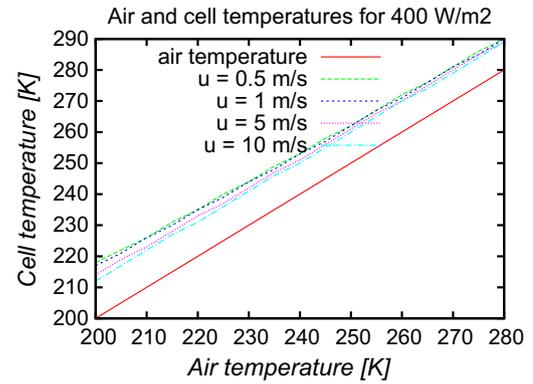


Fig. 2. Air and cell temperatures for solar flux of 400 W/m^2 .

$$U_L = 0.295 \cdot \left(\frac{u}{L}\right)^{1/2} + \epsilon \sigma (T_c^2 + T_a^2)(T_c + T_a) \quad (13)$$

In order to provide an useful approximation of the cell temperature, we must consider the radiation reaching the surface, ϕ_s . On Earth, the mean irradiance is $S_0 = 1380 \text{ W m}^{-2}$ at the top of the atmosphere. The irradiance on Mars TOA (ϕ_{Mars}) can be computed by simple geometrical scaling as:

$$\phi_{Mars} = S_0 \cdot \frac{R_0^2}{R_{Mars}^2} \cdot \cos(\theta) \quad (14)$$

where θ depends on latitude and L_s . At a latitude of 23°S during the summer time, where the maximum is accomplished, for an average distance of Mars of 1.524 AU , we obtain

$$\phi_{Mars} = 1380 \cdot \frac{1}{1.524^2} \simeq 600 \text{ W m}^{-2} \quad (15)$$

at the top of the atmosphere. Considering an opacity index of $\gamma = 0.3$ (Lemmon, 2014), the reference value for the irradiance on the surface could be $\phi_s = 444.5 \text{ W m}^{-2}$ (more than 3 times smaller than on Earth). Note that the opacity value depends on the atmospheric dust load, that change along the day and seasons in Mars (see Table 1).

For our estimation, we will use the Nominal Operating Cell Temperature (NOCT) and reference values cited in

Skoplaki et al. (2008), summarized in Table 2, that allow to compare the results for Mars and Earth.

For a wind speed of 10 m/s, the second part of the denominator becomes $0.002530 \ll 1$, and can be neglected. In the numerator, the second part reads:

$$\left(\frac{\phi_s}{\phi_{s,NOCT}}\right) \frac{U_{L,NOCT}}{U_L} (T_{c,NOCT} - T_{a,NOCT}) \left[1 - \frac{\eta_{ref}}{\tau\alpha} (1 + \beta_{ref} T_{ref})\right] \quad (16)$$

For a wind speed of 10 m/s, the value is 3.27 K, and for 20 m/s is 2.31 K. This part of the equation cannot be neglected and even less knowing the very important variations of irradiance and wind speed on Mars.

Eq. (2) can be simplified as:

$$T_c = T_a + \left(\frac{\phi_s}{\phi_{s,NOCT}}\right) \frac{U_{L,NOCT}}{U_L} (T_{c,NOCT} - T_{a,NOCT}) \left[1 - \frac{\eta_{ref}}{\tau\alpha} (1 + \beta_{ref} T_{ref})\right]$$

$$T_c = T_a + \left(\frac{\phi_s}{\phi_{s,NOCT}}\right) \frac{U_{L,NOCT}}{0.295 \cdot \left(\frac{u}{L}\right)^{1/2} + \epsilon\sigma(T_s^2 + T_a^2)(T_s + T_a)} (T_{c,NOCT} - T_{a,NOCT}) \left[1 - \frac{\eta_{ref}}{\tau\alpha} (1 + \beta_{ref} T_{ref})\right] \quad (17)$$

3. Simplified linear equation for T_c

Assuming a square cell 1 m side, Eq. (17) can be simplified in order to compute the temperature of a solar cell as a function of ambient temperature, solar flux and wind velocity. After Eq. (17) we can generate a dataset for the different values of the variables, which can be easily fitted into a multivariable linear expression. The dataset is summarized in Tables 3–7, where the temperature of the cell is computed for different values of the variables in the typical ranges of variation on Mars. The solar irradiance varies typically between 0 and 400 W/m² as calculated before, considering a dust opacity of 0.3. Expected wind speed variations are in the range of 0–20 m/s, being 20 m/s dust devil conditions, and REMS measurements provide ambient temperatures in the range of 200–290 K (Gómez-Elvira et al., 2014).

The most accurate linear expression that fit those variables in the mentioned ranges is:

$$T_c = 1.00116 \cdot T_a + 0.0313174 \cdot \phi_s - 0.108832 \cdot u \quad (18)$$

Table 8 shows a comparison between the results obtained with Eqs. (17) and (18), showing that the difference between the exact equation and the approximation is negligible and therefore Eq. (18) can be used with confidence.

Key factors determining the cell temperature are the ambient temperature, the irradiance over the cell and the wind speed. In Mars, the typical values of wind speed are between 1 and 20 m/s, and therefore the contribution of the wind speed refrigerating the solar cell is about –2.2 K. On the other hand, the irradiance reaching the panel once it passes through the atmosphere is about 444.5 W/m² at noon, and therefore its contribution to the

Table 1
List of symbols and constants.

ϕ_s	Radiation flux (W m ⁻²)
A_{cell}	Cell area (m ²)
T_a	Air/ambient temperature (K)
T_c	Temperature of the cell (K)
k	Ross coefficient
NOCT	Nominal Operating Cell Temperature
U_L	Overall loss coefficient
$U_{L,NOCT}$	Overall loss coefficient at NOCT conditions
h_w	Wind convection heat transfer coeff. (W m ² K ⁻¹)
$h_{w,NOCT}$	h_w at NOCT
h_{rad}	Radiative heat transfer coeff. (W m ² K ⁻¹)
$h_{rad,NOCT}$	h_{rad} at NOCT
ϵ	Emissivity
$T_{c,NOCT}$	Temperature of the cell at NOCT
$T_{a,NOCT}$	Temperature of the air at NOCT
η_{ref}	Reference cell electric efficiency
T_{ref}	Reference cell temperature
τ	Transmittance of glazing
α	Solar absorptance of PV layer
u	Free-stream velocity of air (m s ⁻¹)
L	Characteristic length (m)
ν	Kinematic viscosity (m ² s ⁻¹)
k_m	Molecular thermal conductivity (W m ⁻¹ K ⁻¹)
ν	Kinematic viscosity of air (m ² s ⁻¹)
g	Gravitational constant (m s ⁻²)
ρ	Density (kg m ⁻³)
μ	Dynamic viscosity (N s m ⁻²)
C_p	Specific heat (J kg ⁻¹ K ⁻¹)
β	$1/T_a$ = coefficient of thermal expansion (K ⁻¹)
β_{ref}	$1/T_{ref}$ = coefficient of thermal expansion (K ⁻¹)
T_s	Surface temperature (K)
Gr	Grashof number
Re	Reynolds number
Pr	Prandtl number
Nu	Nusselt number
γ	Opacity index
θ	Solar zenith angle
$\phi_{s,NOCT}$	Radiation flux at NOCT
R_0	Earth's radius
R_{Mars}	Mars' radius

Table 2
NOCT reference values.

u_{NOCT}	1 m/s
$T_{a,NOCT}$	20 °C
$G_{T,NOCT}$	800 W
$T_{c,NOCT}$	47 °C
η_{ref}	0.12
β_{ref}	0.004 °C ⁻¹
T_{ref}	25 °C
$\tau\alpha$	0.9

Table 3
Cell temperatures as a function of ϕ_s and u ($T_a = 200$ K).

	0.5 m/s	1 m/s	5 m/s	10 m/s
100 W/m ²	204,9083	204,6548	203,8172	203,3611
200 W/m ²	209,528	209,0618	207,4953	206,6265
300 W/m ²	213,8946	213,2484	211,0441	209,8012
400 W/m ²	218,0371	217,2375	214,4726	212,8898

Table 4
Cell temperatures as a function of ϕ_s and u ($T_a = 220$ K).

	0.5 m/s	1 m/s	5 m/s	10 m/s
100 W/m ²	224,1930	224,0205	223,4237	223,0795
200 W/m ²	228,1851	227,8632	226,7361	226,0775
300 W/m ²	231,9967	231,5446	229,9445	228,9983
400 W/m ²	235,6455	235,0792	233,0556	231,8456

Table 5
Cell temperatures as a function of ϕ_s and u ($T_a = 240$ K).

	0.5 m/s	1 m/s	5 m/s	10 m/s
100 W/m ²	243,6343	243,5142	243,0828	242,8223
200 W/m ²	247,1252	246,8983	246,0770	245,5763
300 W/m ²	250,4851	250,1629	248,9879	248,2653
400 W/m ²	253,7245	253,3169	251,8203	250,8925

Table 6
Cell temperatures as a function of ϕ_s and u ($T_a = 260$ K).

	0.5 m/s	1 m/s	5 m/s	10 m/s
100 W/m ²	263,1937	263,1080	262,7911	262,5926
200 W/m ²	266,2825	266,1190	265,5116	265,1284
300 W/m ²	269,2738	269,0398	268,1652	267,6098
400 W/m ²	272,1745	271,8761	270,7554	270,0395

Table 7
Cell temperatures as a function of ϕ_s and u ($T_a = 280$ K).

	0.5 m/s	1 m/s	5 m/s	10 m/s
100 W/m ²	282,8423	282,7798	282,5431	282,3904
200 W/m ²	285,6058	285,4857	285,0294	284,7334
300 W/m ²	288,2954	288,1221	287,4616	287,0311
400 W/m ²	290,9154	290,6930	289,8423	289,2854

Table 8
Exact and predicted temperatures.

T_a	ϕ_s	u	Exact T_c	Predicted T_c	Difference (%)
215	130	1	220.37	219.21	0.52
240	140	3.5	244.45	244.28	0.07
280	200	1.5	285.40	286.42	0.35
215	390	11	226.62	226.26	0.15

cell temperature is about 12.7 K. However, wind on Mars must be taken into account because it changes significantly along the martian day.

4. T_c daily variations on Mars

In this section we evaluate the daily variations of the temperature of a solar cell temperature on Mars. For that we use measurements from the Rover Environmental Monitoring Station (REMS) on the Curiosity rover that is operating in Mars since August 2012 (Gómez-Elvira et al., 2012).

Two different types of solar cells have powered rovers in Mars: those lying on the ground (i.e., Mars Pathfinder),

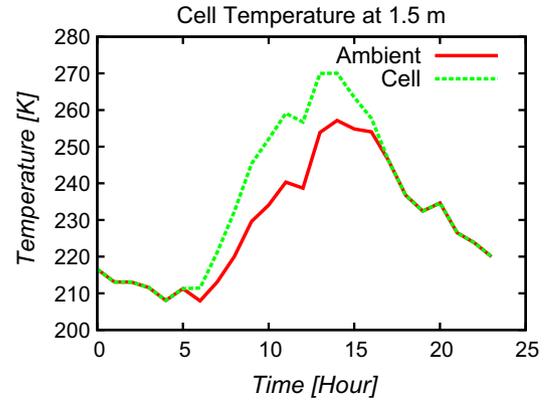


Fig. 3. Ambient and cell temperature on Mars at Gale coordinates using REMS data.

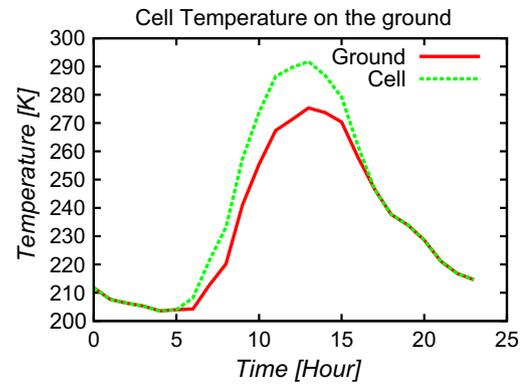


Fig. 4. Ground and cell temperature on Mars at Gale coordinates using REMS data.

and those at some distance above the surface (i.e., Spirit and Opportunity). On Earth, the difference between the temperatures on the ground and, for Example 1.5 m altitude are negligible, but that difference on Mars is remarkably important (about 20 K at noon in Equatorial regions). It is therefore important to distinguish between these situations. In order to do that, we will use the 1.5 m temperature measured by REMS with the Air Temperature Sensor (ATS) (Gómez-Elvira et al., 2012; Gómez-Elvira et al., 2014) for the Spirit-like panels and the ground temperature provided by the Ground Temperature Sensor (GTS) for those panels lying on the ground like the Mars Pathfinder ones.

Additionally, the difference in wind velocities in altitude is very important. The order of magnitude at the ground is about 0.5 m/s, which means that the wind term in Eq. (18) can be neglected, but at 1.5 m the order of magnitude is 7–10 m/s, making an effect in the temperature, and should be used. Unfortunately, the wind speed sensor on REMS was damaged during the landing, and there is no real data available at this point. To estimate the wind speed and solve the lack of data, we have used the values between 0.5- and 20-m/s as suggested by Mars mesoscale models.

In Figs. 3 and 4 we show the ambient temperature measured by REMS at solar longitude (Ls) 270 and the calculated temperature of an hypothetical solar cell standing on Mars. We have used the Gale Crater coordinates (4°36S 137°12E) to estimate the irradiance reaching the panel.

5. Conclusions

On Earth the simplest equation for the temperature of a cell depends on the ambient temperature and the incident solar radiation:

$$T_c = T_a + k\phi_s \quad (19)$$

The main uncertainty in this equation is the value of the Ross coefficient, k , with values between 0.021 and 0.054 (Nordmann and Clavadetscher, 2003).

Here we show that a similar linear expression can be found for Mars environment, depending on ambient temperature, incident solar radiation, and wind speed:

$$T_c = 1.00116 \cdot T_a + 0.0313174 \cdot \phi_s - 0.108832 \cdot u \quad (20)$$

The operating temperature of a solar cell is an important factor determining the efficiency and performance of the solar radiation conversion. The general equation to determine the temperature of the solar cell depends on the different ways of refrigeration that might affect the panel, which is related with the environment. Usually, on Earth, only forced convection is considered, and simply linear expressions have been proposed to determine the effective temperature of the panel. However, on Mars, the radiation losses are extremely important because of the characteristics of the extreme environment, and the equations developed for Earth conditions are not valid.

Wind on Mars is very important and it might have strong variations within a day. We provide a way to quantify the value of the refrigeration by wind convection over the solar cell, which may change the solar cell temperature up to 2.5°.

Considering convection and radiation losses, an iteration process has been carried out until convergence to determine the operating temperature of a solar cell on Mars. The results have been fitted to a linear expression depending on ambient temperature, solar irradiance and wind speed. We reach an equation similar to the usually used on Earth with an additional term accounting for the loss of heat by convection, which is proportional to the wind speed.

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