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# COOLING OF SOLAR PV PANELS USING EVAPORATIVE COOLING

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## ABSTRACT

The efficiency of solar collection systems particularly the photovoltaic panels is generally low. This is due to several reasons including dust formation and thermal losses. For instance, the PV panels efficiency is affected by the increase of their surface temperature. This increase is associated with the absorbed solar radiation that is not converted into electricity causing a drop in the PV module efficiency.

Several cooling methods are available to reduce the cells temperature and their respective effectiveness has been investigated in several previous works. This study deals with PV panels cooling using evaporative cooling of water. A theoretical model based on the heat and mass transfer occurring in the vicinity of the bottom side of a solar PV panel has been developed. The model incorporates the heat and mass exchange occurring between a layer of water and ambient air as well as the heat transfer with the PV panel. The obtained results show the effect of some geometrical parameters as well as the air flow rate, temperature and humidity on the cooling process. It was found in particular that when the air inlet temperature decreases, the temperature of the PV panel decreases significantly.

## INTRODUCTION

Flat Photovoltaic panels produce electricity from global solar radiation. The efficiency of their electricity generation decreases as their temperature increases. This temperature rise is associated with the absorbed solar radiation that is not converted into electricity causing a drop in the PV module efficiency.

At the present level of technological development, the efficiency of solar photovoltaic systems is around 15%. Thus, solar PV panels with 10 $m^2$ area with an average daily radiation of 250 $W/m^2$ could produce only 375 W of electrical power.

The efficiency of such systems is based on the standard test temperature of 25 $^oC$. However, the practical situation of rise in temperature of the panels results in much reduction of the efficiency which could come down to as low as 8%. This would reduce the power production to lower values.

Cooling the panels using a suitable cooling method helps to partially tackle this problem. This would help to improve the power output per square meter area and reduce the overall cost. Many cooling techniques were proposed to cool the PV panels and enhance their electrical performance. This includes active and passive cooling with different cooling media.

Andreev et al. [1] reported that the photocurrent increases with the temperature at a rate of 0.1% $°C^{-1}$ due to the reduction of the energy gap of the solar cell and that the open-circuit voltage decreases at −2 mV $°C^{-1}$ between 20 and 100 °C due to a decrease of the energy gap and an increase of the saturation current. These two effects lead to a reduction in the maximum available power equal to 0.35% $°C^{-1}$. More recently, this influence has been estimated to vary between -0.3 and -0.5% $°C^{-1}$ [2].

Mattie et al [3] calculated the temperature of polycrystalline PV cells (the most common type) using a simple method of energy balance. The importance of solar cells operating temperature for the electrical performance of silicon based photovoltaic installations is discussed by Skoplaki et al

[4]. Royne et al. [5] reviewed the main techniques adopted to reduce the temperature of concentrating photovoltaic systems using active and passive cooling techniques. Del Cueto [6] studied the thermal performance of different PV module technologies.

The degradation of the PV efficiency with temperature is also a significant area of research and several formulas were introduced in the literature. The most known formula is:

$$\eta = \eta_r[1 - \beta(T_m - T_r) \quad (1)$$

where $\eta_r$ is a reference efficiency and β value is about 0.004 $K^{-1}$.

On the other side, the performance of the hybrid PV/T has been studied analytically, numerically and experimentally in several investigations [7-9]. Florschuetz [7] modified the Hottel–Willier [8] analytical model developed for solar flat plate collectors to be applied to PV/T collectors. Zondag et al. [9] studied numerically the dynamic and steady state PV/T performance. They developed a 3D dynamic model in addition to three steady state models (1D, 2D and 3D). An important conclusion was that the 1D steady state model can be used to predict accurately the performance of the PV/T collectors.

Sandberg and Moshfegh [10] developed expressions for optimizing the air gap behind roof mounted PV panels in order to minimize the temperature. Other methods include water flow over the front of the panels, heat pipe cooling and simultaneous hot air/water generation [11-15]. Phase change material (PCM) is able to absorb large amounts of energy as latent heat at the phase transition temperature. Pal and Joshi [16] proposed to use PCM as heat sinks for cooling of electronic components. The possibility of adding fins to enhance the heat transfer rates was explored. PCMs are characterized among others by their low thermal conductivity. Evaporative cooling was also used but in only in few studies [17-18].

## MODEL DESCRIPTION

The physical model consists of a PV panel attached to an inclined duct. The dimensions of the duct is 3 cm height, 140 cm long and 67 cm width. On the lower side of the duct, water flows on a piece of cloth. Air is blown inside the duct via a fan in same direction of water flow (co-current configuration). A schematic diagram on the considered physical model is shown in figure 1. The lower part of the duct is adiabatic. The PV panel is subjected to a uniform solar radiation intensity and heat losses to the ambience. As the air flows over the wetted surface inside the duct, water evaporates and cools the air which in turn, absorbs the heat from the PV panel. As the heat is transferred to the air, the temperature of the PV panel decreases and electricity production enhances.

## MODELLING

A uni-dimensional steady state model of heat and mass transfer is used in this work. This model assumes a mass-less layer of saturated gas between the liquid and air. The temperatures of air, water, interface saturated layer and PV panel change in the flow direction (x axis).

Ambient air enters the channel at known conditions of temperature, humidity and mass flow rate ($T_{ai}$, $w_{ai}$ and $\dot{m}_a$). It exchanges heat and mass with the water layer as well as the solar PV bottom surface. The PV panel receives solar radiation G and exchanges heat also with ambience.

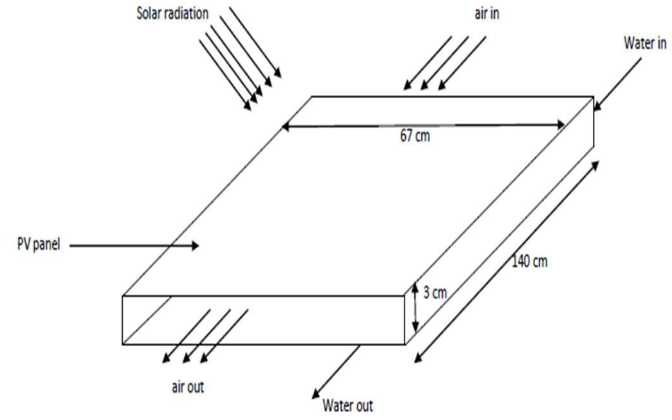

Figure 1 A schematic diagram for the PV panel with evaporative cooling

The present model is based on a previous model developed by Boulama et al. [19] for the heat and mass transfer between a wetted surface and a gas stream flowing in a duct. It assumes the existence of a very thin film of saturated air between the water and gas streams. The temperature and mass flow ratio for this mass-less layer depend on the axial position but are related by the appropriate saturation equation corresponding to the line for 100% relative humidity on the psychrometric chart. The solar radiation gained by the PV panel and the heat losses to its surrounding are included in the present model.

It is also assumed that, the air and water vapor are ideal gases and their specific heat capacities are independent of temperature. Energy balances on the PV panel, air and water layers as well as the water mass balance form the main governing equations of the model. They are expressed as follows:

$$U_a P(T_s - T_a) + \dot{m}_a \frac{dw}{dx} C_{p,v}(T_s - T_a) + SP$$
$$\dot{m}_a(C_{p,a} + wC_{p,v}) \frac{dT_a}{dx} \quad (2)$$

$$\mathrm{U_a P(T_a - T_s) + U_l P(T_l - T_s) = \dot{m}_a h_{fg} \frac{dw}{dx}} \quad (3)$$

$$\mathrm{U_l P(T_s - T_l) = \dot{m}_l C_{p,l} \frac{dT_l}{dx}} \quad (4)$$

$$\mathrm{SP = G_s(\tau\alpha)P - U_t P(T_{pv} - T_{amb})} \quad (5)$$

$$\mathrm{G_s(\tau\alpha)P = U_t P(T_{pv} - T_{ai}) + U_a P(T_{pv} - T_a)} \quad (6)$$

Equations 5 and 6 concern the solar energy, heat exchanges between the PV panel and air. P refers to the air-water interface length.

$U_t$ and $U_a$ are the overall heat transfer coefficients on the top and bottom of PV panel respectively.

The change in the water concentration in the flowing air is accounted by the following equation:

$$\dot{m}_a \frac{dW}{dx} = U_m P(ws - w) \tag{7}$$

where $w_s$ stands for the saturation humidity evaluated using the Engineering Equations Solver (EES) software [20].

The value of $U_m$ is the mass transfer coefficient in [kg/m$^2$ s] and is obtained from the heat transfer coefficient and Lewis number according to the following equation:

$$Le = U_a/U_m(C_{p,a} + WC_{p,v}) \tag{8}$$

The above set of equations was solved using EES [20]. The developed model was validated using a specific case with no mass transfer and previous results of reference [19]. The validation case with no mass transfer represents a parallel heat exchanger with the following conditions: $T_{li}$ =15 °C, $T_{ai}$=30 °C $W_i$=0.02, $\dot{m}_a = \dot{m}_{li}$= 0.1 kg/s and uniform heat flux q = 100W/m$^2$ is supplied to the lower duct (the wetted side). In this case, the term $SP$ in equ. (2) is zero. Equ. (3) is modified also when adding the contribution of the external heat flux q. Therefore, equations (2-4) become under the above conditions:

$$U_a P(T_s - T_a) = \dot{m}_a (C_{p,a} + wC_{p,v}) \frac{dT_a}{dx} \tag{9}$$

$$U_a P(T_a - T_s) + U_l P(T_l - T_s) = 0 \tag{10}$$

$$U_l P(T_s - T_l) + qP = \dot{m}_l C_{p,l} \frac{dT_l}{dx} \tag{11}$$

Equations (9-11) was solved analytically. Fig. 2 shows the variation in the air and water temperatures with respect to the dimensionless coordinate X, where X= P x $U_a/(\dot{m}_a C_{p,a})$. The dots in Fig. 2 represent the exact solution obtained from equations 9-11 and the lines represent the numerical solution of the general model under the above specific conditions. A very good agreement can be observed.

The validity of the present numerical model has also been checked by comparing the results obtained using this model with those of the previous model of [19].

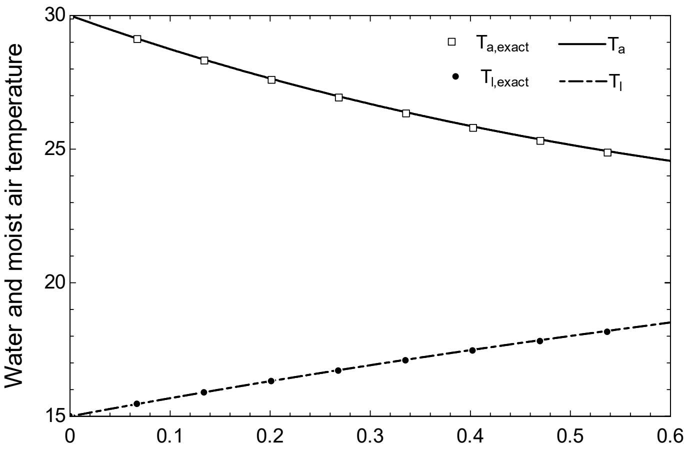

Fig. 2. Validation of the proposed model for parallel-flow heat exchanger

## RESULTS AND DISCUSSION

The proposed model has been used to simulate the temperature distributions of the air, water in the duct and PV panel bottom surface under various conditions of solar radiation, air mass flow rate and inlet air and water temperatures. The following parameters were fixed as: Le=0.9; $(\tau\alpha)$ = 0.8; $U_t$ =10 Wm$^{-2}$ K$^{-1}$, $U_l$ =51 Wm$^{-2}$ K-$^1$, $U_a$=8 Wm$^{-2}$ K$^{-1}$.

### Effect of Solar Radiation

Fig. 3 shows the variation of the air and water temperatures with flow direction at different solar radiation intensities. One can first observe that the water temperature is almost constant even with high radiation values due to its large specific heat capacity.

However, air temperature changes mainly at the exit of the duct. With solar radiation, air temperature increases as it flows inside the duct due to heat exchange from the PV panel. The slope of the air temperature curve increases as solar radiation intensity increases. However, when the solar radiation is zero, the air temperature decreases since the required heat for water evaporation is absorbed from air.

Fig. 4 shows the variation of PV panel temperature for different solar radiation intensity values. It is seen that the PV surface temperature is almost constant along the x direction. It increases however as the solar radiation intensity G rises. High temperatures approaching 90 °C can be reached when G approaches 900 W/m$^2$.

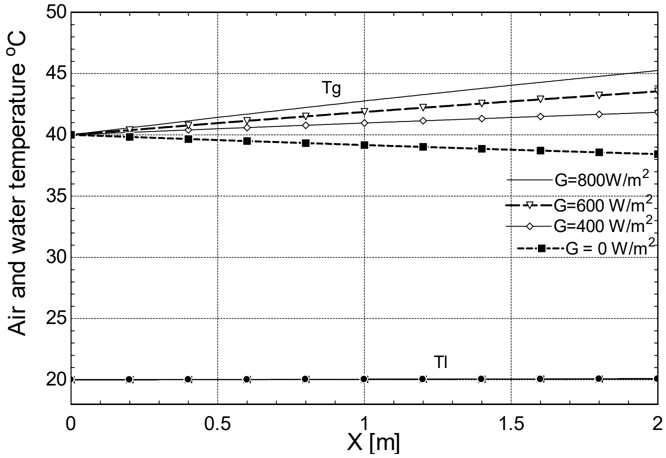

Figure 3 Effect of solar radiation on air and water temperatures along the duct ($\dot{m}_a$=0.048 $kg/s$, $\dot{m}_{li}$= 0.1 kg/s, $T_{li}$ = 20 °C and $T_{ai}$ = 40 °C.)

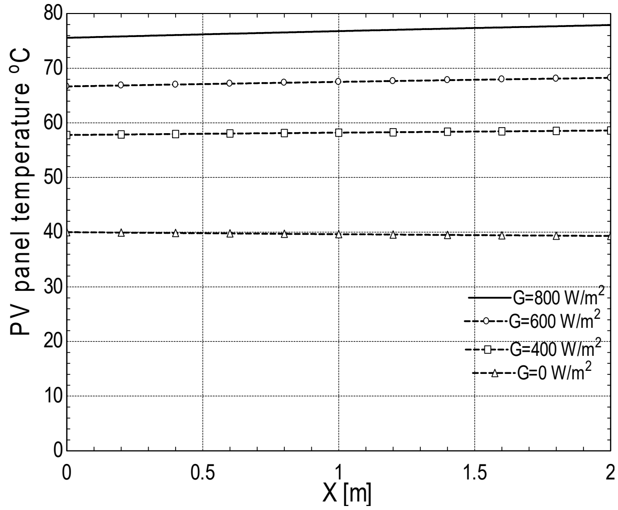

Figure 4 Effect of solar radiation on PV panel temperature ($\dot{m}_a$=0.048 $kg/s$, $\dot{m}_{li}$= 0.1 kg/s, $T_{li}$ = 20 °C and $T_{ai}$ = 40 °C.)

### Effect of Inlet Air and Water Temperatures

Fig.5 shows the effect of the inlet water temperature on the temperature of PV panel and air in the duct. Three water temperatures ($T_{li}$=20,30,40 °C ) are considered. Fig. 5 shows two almost parallel curves in which the change in both air and PV panel temperatures is very small. Therefore, the effect of inlet water temperature can be considered as weak and can be ignored.

Similarly, the effect of inlet air temperature on PV temperature is shown in figure 6. As the inlet air temperature increases the PV temperature increases significantly although it keeps the same behavior. It was also found that the temperature of water is not affected by the change of air temperature.

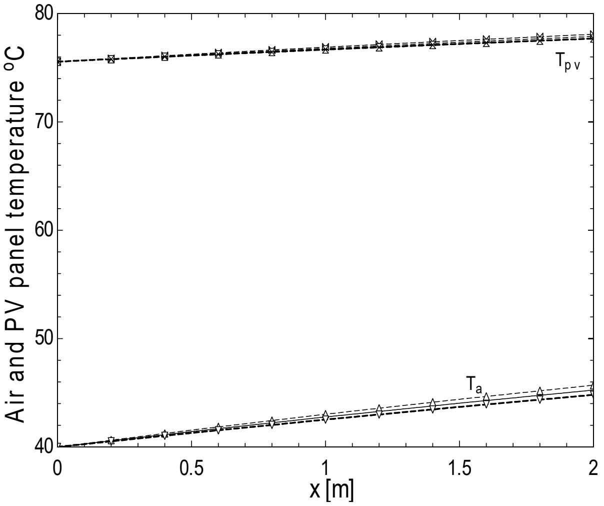

Figure 5 Effect of inlet water temperature on the PV panel and air temperatures (at G=800 W/m², $\dot{m}_a$=0.048 $kg/s$, $\dot{m}_l$=0.1 $kg/s$ and $T_{li}$=20,30,40 °C)

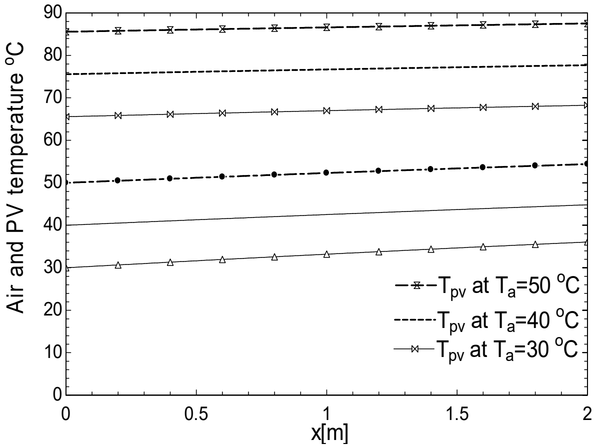

Figure 6 Effect of air inlet temperature on the temperature of PV panel (at G=800 W/m², $\dot{m}_a$=0.048 $kg/s$, $\dot{m}_l$=0.1 $kg/s$ and $T_{li}$=20 °C)

The impact of the evaporative cooling method used in this study can be shown in Fig. 7 where one can see a decrease in the PV panel temperature of about 6°C. Off course, this reduction in PV surface temperature is not too high. It can be higher and the cooling process can be more effective.

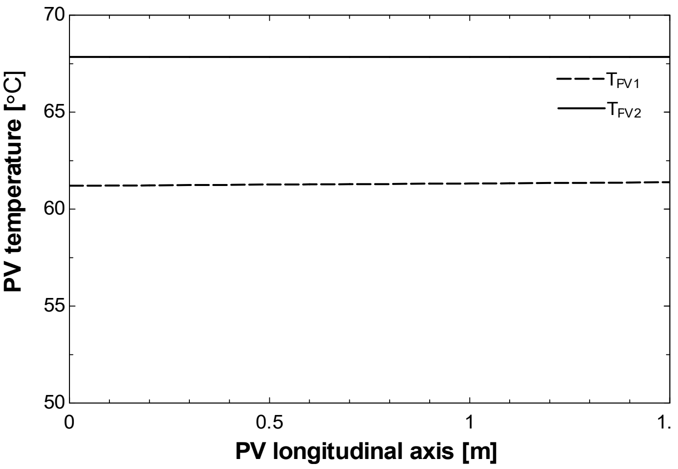

Figure 7 PV panel temperature with and without cooling for solar radiation intensity of G=900 W/m$^2$

## CONCLUSION

This paper presented a theoretical model that incorporates the heat and mass exchange occurring between a layer of water and ambient air as well as the heat transfer with the PV panel. The model based on mass and energy balances was used to investigate the effect of solar radiation intensity, inlet water and air temperatures on the PV panel temperature. It was shown that as solar radiation increases, the air temperature increases significantly while when there is no solar radiation, air temperature decreases. Change in water temperature is very small. Inlet air temperature has an important influence on the temperature of the PV panel. A reduction in PV panel temperature of about 6 °C has been obtained when cooling is used.

Deeper analysis on the evaporative cooling effectiveness including theoretical and experimental studies is being conducted.

## NOMENCLATURES

$C_p$: the specific heat capacity at constant pressure [kJ/kg K]
$dx$: elemental section in the length axis [m]
$dw$: change in water concentration of air
$G_s$: global solar radiation falling on PV panel surface[W/m$^2$]
$h_{fg}$: evaporation enthalpy [kJ/kg]
$Le$: Lewis number (Le = Ug/Um(Cp;A + WCp;v))
$\dot{m}$: mass flow rate [kg/s]
P: wetted length [m]
$U$ :coefficient of heat transfer [W /m$^2$ K]
$w$ : water concentration in air
$S$ : net solar energy falling on the PV module [W/m$^2$]
T: temperature [K]
x: Axial coordinate [m]

**Greek letters**

$\alpha$: absorptivity
β: PV temperature coefficient [1/K]
η: Efficiency
$\tau$: transmisivity

**Subscripts**

a : air
ev: evaporation
$l$: liquid
s: saturated layer
v: vapor
m:  PV module/panel
amb: ambient
i: inlet condition
r: reference condition

## REFERENCES

[1] V.M. Andreev, V.A. Grilikhes and V.D. Rumyantsev, Photovoltaic conversion of concentrated sunlight, Wiley, London (1967) [ISBN: 0471967653].

[2] S. Krauter, R.G. Araujo, S. Schroer, R. Hanitsch, M.J. Salhi, C. Triebel and R. Lemoine, Combined photovoltaic and solar thermal systems for facade integration and building insulation, Solar Energy 1999 67 (4–6), pp. 239–248.

[3] M. Mattei, G. Notton , C. Cristofari, M. Muselli and P. Poggi, Calculation of the polycrystalline PV module temperature using a simple method of energy balance Renewable Energy Volume 31, Issue 4, April 2006, pp. 553-567.

[4] E. Skoplaki, J.A. Palyvos, Operating temperature of photovoltaic modules: A survey of pertinent correlations, Renewable Energy 34 (2009) pp.23–29.

[5] Anja Royne, Christopher J. Dey, David R. Mills, Cooling of photovoltaic cells under concentrated illumination: a critical review Solar Energy Materials & Solar Cells 86 (2005) 451–483.

[6]J. A. Del Cueto, Comparison of energy production and performance from flat-plate photovoltaic module technologies deployed at fixed tilt," Technical report, NREL/CP-520-31444, 2002.

[7] L. W. Florschuetz, "Extension of the Hottel-Whillier model to the analysis of combined photovoltaic/thermal flat plate collectors," Solar Energy, vol. 22, no. 4, pp. 361–366, 1979.

[8] H. C. Hottel and A. Whillier, "Evaluation of flat-plate solar collector performance," in Transactions of the Conference on Use of Solar Energy, vol. 2, pp. 74–78, University of Arizona Press, 1958.

[9] H. A. Zondag, D.W. de Vries,W. G. J. van Helden, R. J. C. van Zolingen, and A. A. van Steenhoven, "The yield of different combined PV-thermal collector designs," Solar Energy, vol. 74, no. 3, pp. 253–269, 2003.

[10] M. Sandberg and B. Moshfegh, "Buoyancy-induced air flow in photovoltaic facades effect of geometry of the air gap and location of solar cell modules," Building and Environment, vol. 37, no. 3, pp. 211–218, 2002.

[11] S. Krauter, Increased electrical yield via water flow over the front of photovoltaic panels, Solar Energy Materials & Solar Cells 82 (2004) 131–137.

[12] T. T. Chow, W. He, and J. Ji, "Hybrid photovoltaic thermosyphon water heating system for residential application," Solar Energy, vol. 80, no. 3, pp. 298–306, 2006.

[13] W. He, T. T. Chow, J. Ji, J. Lu, G. Pei, and L. S. Chan, "Hybrid photovoltaic and thermal solar-collector designed for natural circulation of water," Applied Energy, vol. 83, no. 3, pp. 199–210, 2006.

[14] G. Pei, H. Fu, H. Zhu, and J. Ji, "Performance study and parametric analysis of a novel heat pipe PV/T system," Energy, vol. 37, no. 1, pp. 384–395, 2012.

[15] *Du* D., *Darkwa* J., Kokogiannakis G., (2013), *Thermal management systems* for Photooltaics (PV) *installations*: A critical review, Solar Energy 97, 238-254.

[16] D. Pal and Y. K. Joshi "Melting in a side heated tall enclosure by a uniformly dissipating heat source," International Journal of Heat and Mass Transfer, vol. 44, pp. 375-387, 2001.

[17] H. Alami, "Effects of evaporative cooling on efficiency of photovoltaic modules," Energy Conversion and Management , vol. 77, pp. 668-679, 2014.

[18]V. Suresh, S. Naviynkumar and V. Kirubakaran, "Improved power output of PV system by low cost evaporative cooling technology," in G2013 International Conference on Green Computing, Communication and Conservation of Energy (ICGCE), 2013

[19] K. Boulama, N. Galanis, J. Orfi, Heat and mass transfer between gas and liquid streams in direct contact, International Journal of Heat and Mass Transfer, 47 (2004) 3669–3681.

[20] www.fchart.com