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Full Length Research Paper

Numeric and experimental survey of a condenser to porous media of granite

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This article evaluates the numeric and experimental survey of a distiller's condenser for brackish water whose saltiness varies between 5 to 10 g/L. The condenser is a cylindrical tank, in which is vertically arranged and the pieces of granite constituent of porous media. The governing equations that describe the transfers are deduced from a thermal and mass global balance within the condenser. Finite difference explicit method is employed to solve the governing partial differential equations coupled to an iterative calculation. The influence of the equivalent diameter of the granite piece, the thickness and the initial temperature of the porous media, the inlet steam mass flow rate of the condenser on the condensate quantity, and the condensation efficiency were analyzed. The condensate quantity increases with the porous media thickness, the steam mass flow rate and the condensation efficiency decreases with the augmentation of the steam mass flow rate and is especially more elevated than the porous media initial temperature which was weak. The numeric and experimental results are in good qualitative and quantitative agreement.

Key words: Condenser, steam, granite, porous media, thickness, condensation.

INTRODUCTION

The progressive weariness of resources in water due to the development of the industrial activities, to the growth of the population, to the dismissals of domestic water, and of the unprocessed industrial water, influenced the development of desalination and distillation techniques (Khalifa and Habib, 2010; Christopher et al., 2009; Saravanan et al., 2009; Lang and Modla, 2008; Lang and Modla, 2006; Dhifaoui, 2005; Huicochea et al., 2004; Larbi et al., 1995; Yagi et al., 1961; Ergun, 1952; McCabe and Thiele, 1925). In the arid regions whose solar area is important, the solar distillation development can contribute to protect the environment and forests preservation (Khalifa and Habib, 2010; Zheng et al., 2009). However, the water production quantity is conditioned by the condenser type and the working mode, notably the cooling type of the partitions and the contact surface with the fluid in out-flow (Chun-Lu and Ling-Xiao, 2010; Domanski and Yashar, 2007). Also, the basis of condensers equipment in many industrial sectors as the petrochemistry, the agro-food etc, bring about the object of many theoretical and experimental works (Chun-Lu and Ling-Xiao, 2010; Sundararajan et al., 2009; Cuevas, 2009; Cropper and Ge, 2005; Leducq et al., 2003; Ma, 2003; Corberan and Melon, 1998; Leontiev, 1985; Krasnochtchekov and Soukomel, 1985; Chassériaux, 1984; Chung and Chang, 1984; Vos and Tames, 1975). Among the physical parameters susceptible to increase the condenser efficiency and therefore the condensate quantity, the contact surface of the condenser with the fluid in out-flow influences the heat, mass transfers and the condensation efficiency. Thus, the heat transfer during the condensation of film type on the partitions inserted into the porous media is improved for a deformed partition in relation to the one of a plane partition (Wang et al., 2006, 2005, 2003). The equations governing the transfers during the condensation of steam in a porous media are generally based on the Darcy and Darcy-Brickman models (Wang et al., 2006).

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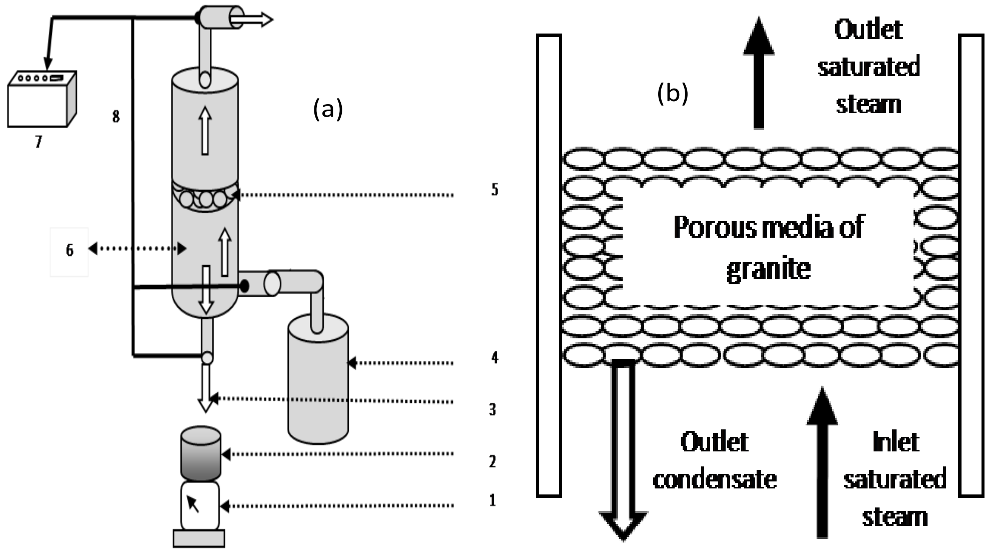

Figure 1. (a) Experimental set up, (b) Porous media diagram.

Table 1. Device and materials.

S/N	Materials used
1	Electronic balance
2	Container to recover condensate
3	Outlet condensate
4	Electric boiler (1500 W/220 V)
5	Porous media.
6	Condenser to porous media of granite ,
7	Power station 21X Microloger, CAMPBELL SCIENTIFIC, INC.
8	Thermocouple in Copper-constantan, type T.

On this fact, it appears that the condensation in the porous media of granite was not known until now, which is the subject of study.

The aims of this work consist of the numeric and experimental determination of better conditions of steam condensation in a porous media of granite. The governing equations that describe the transfers are deduced from the thermal and mass global balance inside the condenser. The heat transfer coefficients intervening in the thermal balance are calculated from the semi-empiric correlations (Krasnochtchekov and Soukomel, 1985; Yagi et al., 1961; Ergun, 1952), and the physical-chemistry properties of the fluid were calculated from the data of Bailly (1971), Chassériaux (1984), and from the software [Water and Steam Properties, by Katmar (2012). The influence of the equivalent diameter of the granite piece, the thickness and the initial temperature of the porous media, the inlet steam mass flow rate of the condenser on the condensate quantity and on the condensation efficiency will be analyzed.

EXPERIMENTAL ANALYSIS

Experimental device

The system of distillation is shown in Figure 1a and Table 1:

i) An electric boiler (1500 Watts/220 V) which constitute of a cylindrical tank (height: 25.4 cm, internal diameter: 28.2 mm and external diameter: 28.4 mm), equipped with an electric resistance and a potentiometer, to vary the temperature of 10 to 110°C. The brackish water of which the concentration of 5 to 10 g/L is carried to the boiling point was transformed into steam of water.
ii) A cylindrical tank (height: 33 cm, and internal and external diameters, respectively equal to 29.7 and 29.9 mm), whose partitions consist of TPN sheet metal. The superior and lower partitions present openings of diameter 15 mm by which the steam is produced and passed by the boiler and the porous media which consist of the granite pieces arranged there.
The temperatures and the condensate quantity measurement are assured by:

A) The type T thermocouples connected to a power station 21X Microloger, CAMPBELL SCIENTIFIC, INC (Ramamonjisoa, 2000). The temperatures were recorded in a microcomputer Pentium IV

equipped with the software MATLAB to be treated.
B) An electronic balance (KERN EW4200-2NM, maximal load 4200 g, minimal load 0.1 g, precision 0.01 g) to follow the evolution of the gotten condensate quantity.

Principle of working

Steam produced in the electric boiler is routed to the bottom part of the condenser to porous media of granite cooled by natural convection. This steam that flows out through the porous media, by forced convection from the bottom to the top condense to the contact of the granite pieces if steam temperature is equal to the temperature of dew.

Experimental protocol

For an inlet mass flow rate of the water steam, we take every 5 min by using the power station in measuring the inlet and outlet temperatures of the water steam of the porous media, the condensate mass by an electronic balance, and its volume by using a test-tube, SIMAX (STABILL KAVALIER).

THEORETICAL ANALYSIS

Mathematical model

On this mathematical model, the condenser consists of a cylindrical reservoir in which the pieces of granite assimilated to spheres are placed (Figure 1b). The external face of the partition of the cylinder is the seat of the heat exchange by natural convection with the surrounding environment. The equations that govern the condensation are deduced from a global thermal and mass balance of the condenser.

Hypothesis

i) The pieces of granite are assimilated to spheres and the bed of granite to an unalterable porous media, homogeneous and isotrope.
ii) There is no chemical reaction between the bed of granite and the steam of water.
ii) The heat and mass transfers are one-dimensional.

Transfer equations

The heat and mass transfer balance in the condenser are shown in the following equations:

$$P_R = P_p + P_{cond} + P_{incond} \qquad (1)$$

with:

$$P_p = h_{convext}.S_{ext}.\left(T_{pm} - T_{air}\right) \qquad (2)$$

$$P_{cond} = m_{cond}\, Cp_{cond}(T_g - T_{air}) \qquad (3)$$

$$P_{incond} = (\dot{m}_{vap} - \dot{m}_{cond})Cp_{incond}(T_{vincond} - T_{air}) \qquad (4)$$

$$P_R = m_g\, Cp_g \frac{dT_g}{dt} = h_{cvv}.A_{S.}Sec.Dxst(T_v - T_g)$$ (Duffie and Beckman, 1977) (5a)

$$P_{acc} = \sum_{t=t_i}^{t_f} P_R(t) \qquad (5b)$$

$$\dot{m}_{cond} = \frac{h_{cvg.}F_T(T_{sat} - T_g)}{L_V} \qquad (6a)$$

The outlet water steam is calculated by:

$$m_{in\,cond} = m_{vap} - m_{cond} \qquad (6b)$$

The condenser efficiency is defined by:

$$\eta = \frac{m_{cond}}{\dot{m}_{vap}} \qquad (7)$$

The Equations 2, 5, and 6a intervene the convective heat transfer coefficient between the partition of the condenser and the ambient air ($h_{convext}$), the condensation heat transfer coefficient mean of the water steam to the contact of the porous media (h_{cvg}), and the convective heat transfer coefficient between the water steam and the porous media. These coefficients are deduced from the semi-empiric relations.

Therefore, the convective heat transfer coefficient in the porous media constitute of a row of *n* spheres superimposed, verify the following relation (Asbik et al., 2007).

$$h_n = 0{,}826\left[\frac{g.\rho_L.(\rho_L - \rho_V).L_V.\lambda_L{}^3}{\mu_L.(T_{sat} - T_g).n.D_g}\right]^{1/4} \qquad (8)$$

To take in consideration the influence of the film out-flow of the condensate of a sphere to the other, Equation 8 is corrected by the coefficient

$$\varepsilon = 1 + \frac{0{,}2.(n-1).C_{pL}.(T_{sat} - T_g)}{L_V} \qquad (9)$$

and,

$$h_{cvg} = \varepsilon.h_n \qquad (10a)$$

For a porous media constituted of *N* columns of *n* spheres, this equation becomes:

$$h_{cvg} = \frac{\varepsilon.h_n}{N} \qquad (10b)$$

Numerical methodology

Equation 1 is solved by the finite difference explicit method

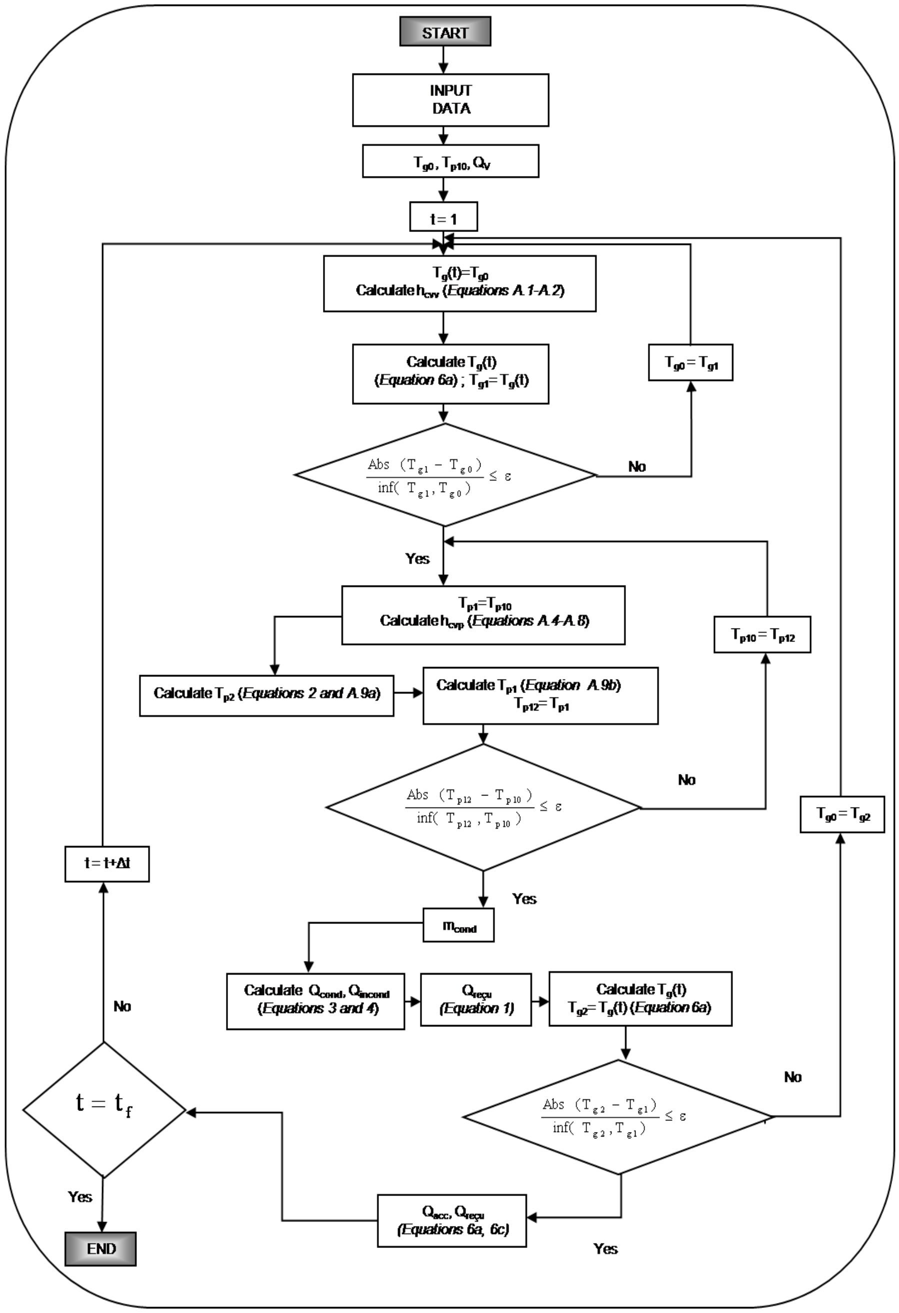

Figure 2. Calculation algorithm.

(Bakhvalov, 1984), and the Newton method. An iterative calculation is necessary because the heat and mass transfer coefficients are function of the partitions and porous media temperatures that are unknowns (Figure 2)

RESULTS AND DISCUSSION

The calculations have been done for an inlet water steam temperature of the condenser in the porous media which is equal to 95.6°C, for three equivalents diameters of granite piece (7, 3, and 2 cm) and for an initial temperature of the porous media which is equal to 20°C. The granite properties used in this survey are reported in Table 2 (Toulokiany, 1970).

One analyzes the influence of the porous media thickness and the debit of water steam on the quantities of heat used during the condensation, the porous media temperature, and the condensation efficiency.

Table 2. Physicochemical properties of the granite (Toulokiany, 1970).

Granite temperature (°C)	Density ($kg.m^{-3}$)	Mass heat ($kJ.kg^{-1}.K^{-1}$)	Thermal conductivity ($W\ m^{-1}\ K^{-1}$)	Thermal diffusivity ($m^2.s^{-1}$)
20-100	2600	0.86	2.5	1.10

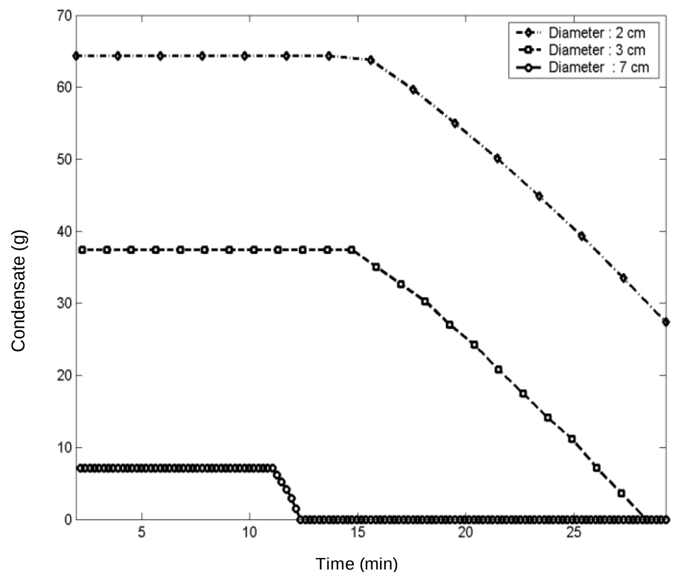

Figure 3. Condensate quantity as a function of the time. $\dot{m}_{vap}$ = 0.5554 $g.s^{-1}$; m_g = 23 kg.

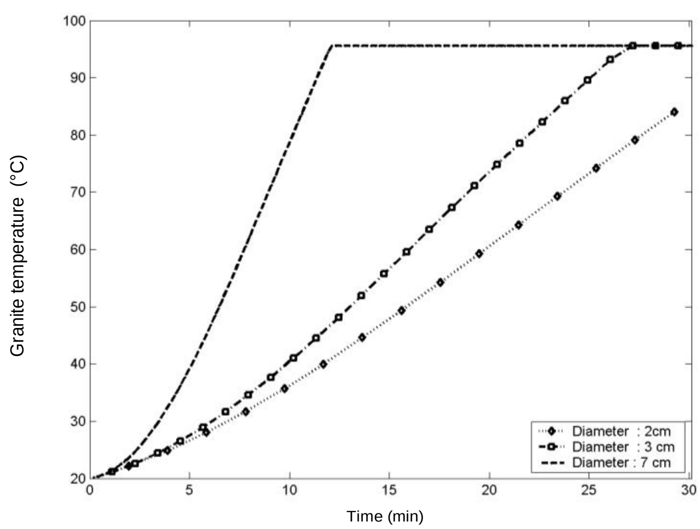

Figure 4. Porous media temperature as a function of the time. $\dot{m}_{vap}$ = 0.5554 $g.s^{-1}$; m_g = 23 kg.

Equivalent diameter of the granite pieces influence

Figures 3 and 4 illustrate the influence of the equivalent diameter of the granite pieces on the evolution of the quantity of the condensate and the temperature of the porous media according to the time. The average

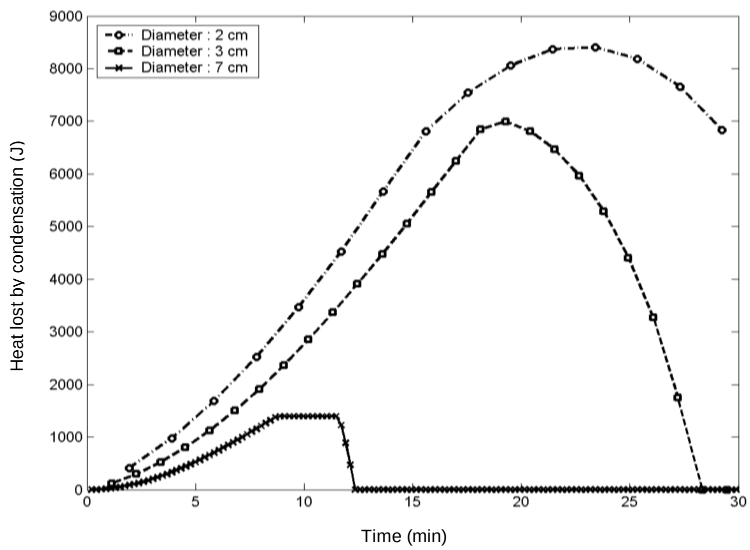

Figure 5. Heat lost by condensation according to the time. m_{vap} = 0.5554 g.s^{-1} ; m_g = 23 kg.

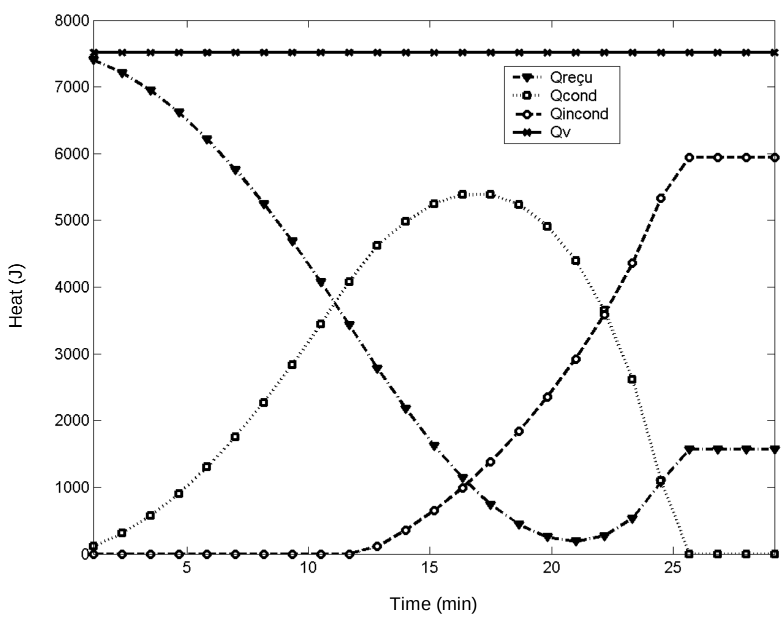

Figure 6. Heats as a function of the time. L= 21cm, m_{vap} = 0.5554 g.s^{-1} .

temperature of the porous media increases quickly during the process of condensation to reach the temperature of the saturated steam after 12 min at the beginning of the operation, for a porous media which constitute of granite pieces of equivalent diameter equal to 7 cm (Figure 4*)*. For lower values of diameter less than 7 cm, the growth of the temperature according to the time is monotonous and the temperature of saturation is reached after condensation duration more elevated than the equivalent diameter which is small. These results join those concerning the evolution of the quantity of condensate that decreases strongly for a porous media constituting of pieces of granite of diameter of 7cm and of less fast manner for the other diameters kept in this survey.It is the same way for the condensation heat (Figure 5) and for the heat received by the porous media (Figure 6). These results are due to the growth of the convective transfers between the steam and the porous media once the

Table 3. Calculated condenser efficiency.

Equivalent diameter (cm)	1	1.5	2	2.5	3	7
Efficiency (%)	59.59	75.32	85.35	91.78	76.28	38.69

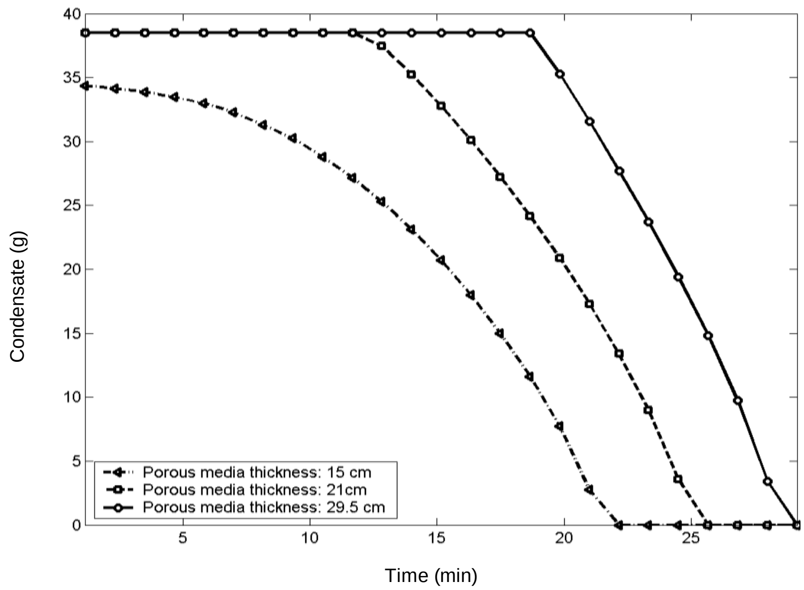

Figure 7. Condensate quantity according to three values of the porous media thickness. $\dot{m}_{vap}$ = 0.5554 g.s^{-1}, D_g = 3 cm.

equivalent diameter decreases. Then, the condensation efficiency decreases as the equivalent diameter of the granite pieces increases (Table 3).Thus, the condenser efficiency reaches the maximal value of 91.78% for an equivalent diameter of the granite pieces which is equal to 2.5 cm (Table 3). The thermal efficiency of the condenser decreases during the time because the condensation of steam is conditioned by the porous media temperature (Figure 4).

Porous media thickness influence

The condensation efficiency is important, for the reasons mentioned previously, which is more elevated than the porous media thickness (Figure 7) because the exchange surface between the porous media and the steam is particularly important as the quantity of granite pieces is important. This result must be correlated with the growth of the losses of loads through the porous media (not considered in this survey). Also, the porous media thickness must not be superior to an optimal value.

The duration so that the temperature of the porous media is equal to the one of the saturated steam is especially weak as the thickness of porous media is small (Figure 8). This result is explained by the fact that for the same steam debit to the entry of the porous media, the quantity of heat abandoned by the steam during the condensation in the porous media provokes the growth of the temperature which is important as the quantity of material is weak; this means that the thickness of the porous media is small.

The condensation heat quantity increases during the time as far as reaching a maximal value about 16 min of the beginning of the condensation, which corresponds to the maximal quantity of the gotten condensate and to the optimal temperature of the porous media (Figure 6). From this instant, the condensation heat quantity decreases with the quantity of heat received by the granite because its temperature increases during the time as far as reaching the temperature of saturation. For optimal condensation efficiency, we recommend to keep a thickness of the granite bed of 29.5 cm for an equivalent diameter of 2 cm and a debit of steam to the entry of the granite porous media of 0.5554 gs-1. Figure 9 presents the evolution of the quantity of the condensate and the temperature of the granite. The condensate quantity is maximal, some seconds after the beginning of the condensation. The steam is condensed entirely in the porous media of granite. Then, the condensate quantity

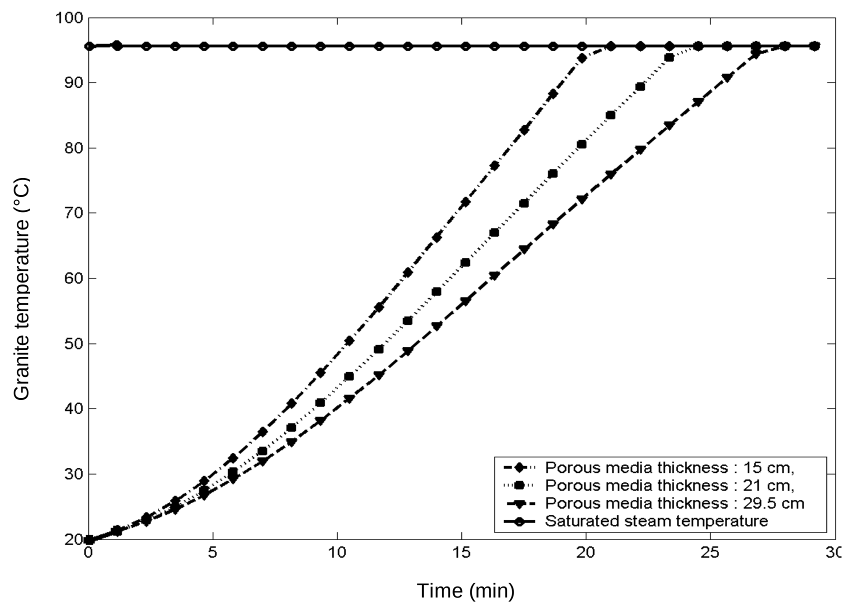

Figure 8. Porous media temperature as function of a distillation according to the porous media thickness. $\dot{m}_{vap}$ = 0.5554 g.s^{-1}, D_g = 3 cm.

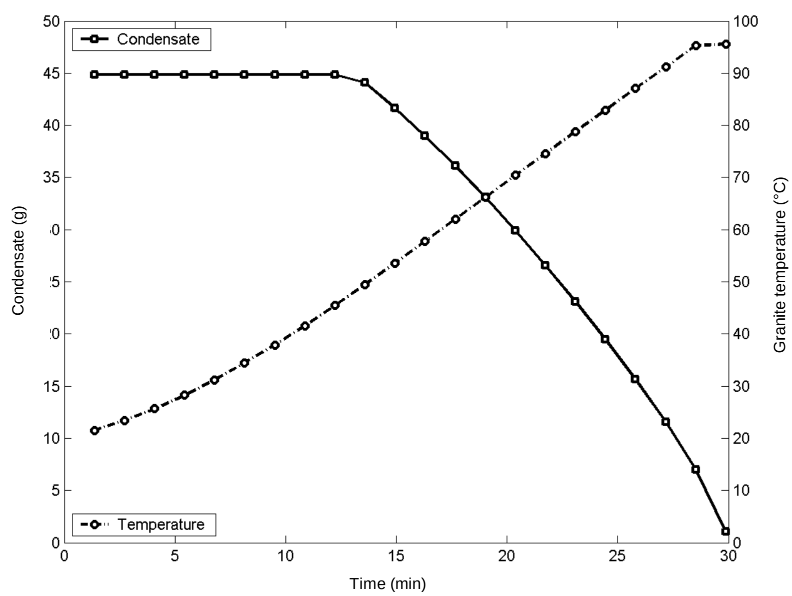

Figure 9. Condensate quantity and porous media temperature as a unction of the time. m_{vap} = 0.5554 g.s^{-1}, D_g = 3 cm.

decreases and the temperature of the granite increases and the temperature of saturation of the steam was reached.

Inlet saturated steam mass flow rate influence

The quantity of the condensate is especially elevated as the water steam mass flow rate is important because the heat and mass coefficients that govern the transfers between the out-flow of steam and the porous media are function of the speed of out-flow of this steam (Figure 10). It results that the temperature of the granite increases with the debit of water steam (Figure 11).

The quantity of heat lost by the steam passing through the porous media is weak as the steam mass flow rate is

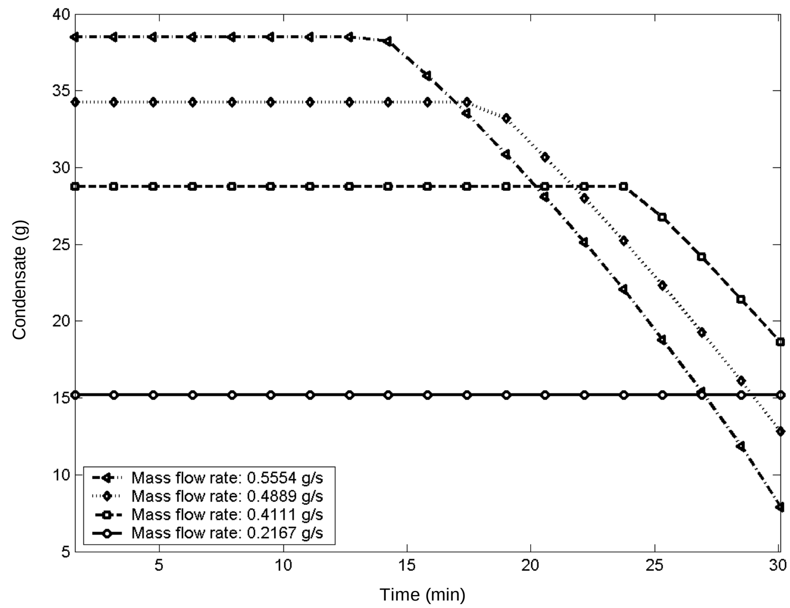

Figure 10. Condensate quantity as a function of the time according to theinlet saturated steam mass flow rate. L=30 cm, m_g = 23 kg, D_g = 2 cm.

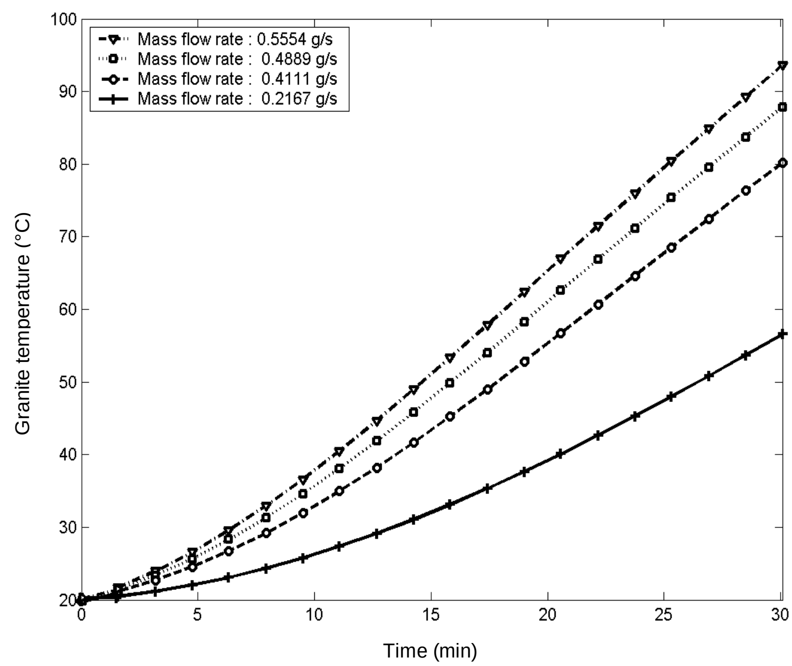

Figure 11. Porous media temperature as a function of the time. Inlet saturated steam mass flow rate influence. L=30cm, m_g = 23 kg, D_g = 2 cm.

small. Hence for weak debits of steam, the condensation is total because the quantity of heat lost by the non-condensing saturated water steam is hopeless (Figure 12).

As we mentioned previously, the evolution during the time of the quantity of heat decreases to reach the same value after 15 min of condensation marking the end of the condensation process, the heat transfer between the steam, and the porous media by sensible mode. It is followed by the reduction of the quantity of condensate

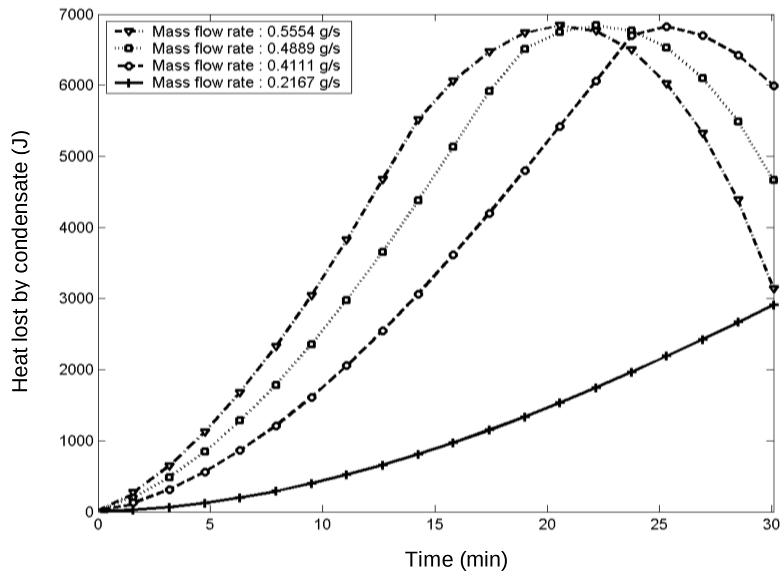

Figure 12. Steam condensation heat as function of the time. Inlet saturated steam mass flow rate influence. L=30cm, m_g = 23 kg, D_g = 2 cm

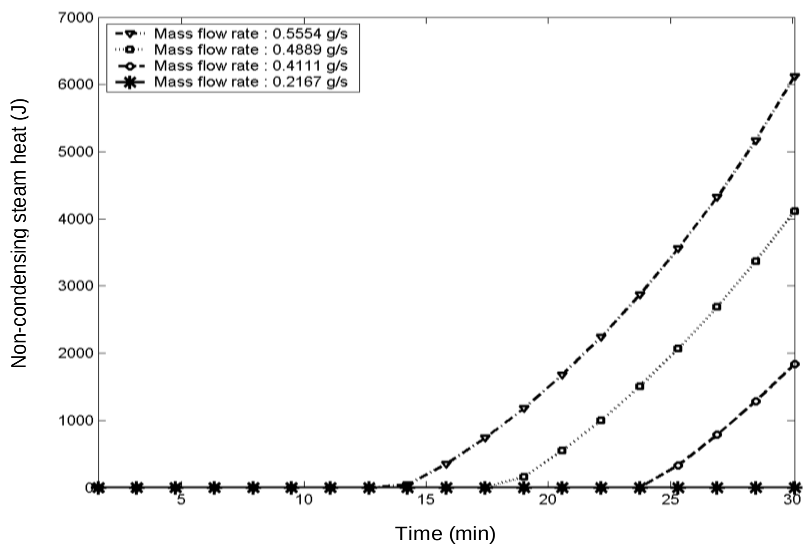

Figure 13. Non-condensing steam heat. Inlet saturated steam mass flow rate influence. L=30 cm, m_g = 23 kg, D_g = 2 cm.

and the quantity of heat carried away by the non-condensing steam (Figure 13).

Porous media initial temperature influence

The quantity of heat abandoned by the steam through the porous media is elevated especially as the initial temperature of the granite bed which is weak. Indeed, for such values of temperature, the quantity of heat brought by the steam is used to heat the porous bed until the temperature of the steam is saturated. Consequently, this heat quantity decreases with the growth of the initial temperature of the porous media. It results to a quantity of condensate weaker than the one gotten for more elevated initial temperatures (Figures 14, 15, and 16). For the initial temperatures value near to the steam condensation temperature value, the quantity of heat given up by the steam in the porous media of granite is lower to the one corresponding to the different initial

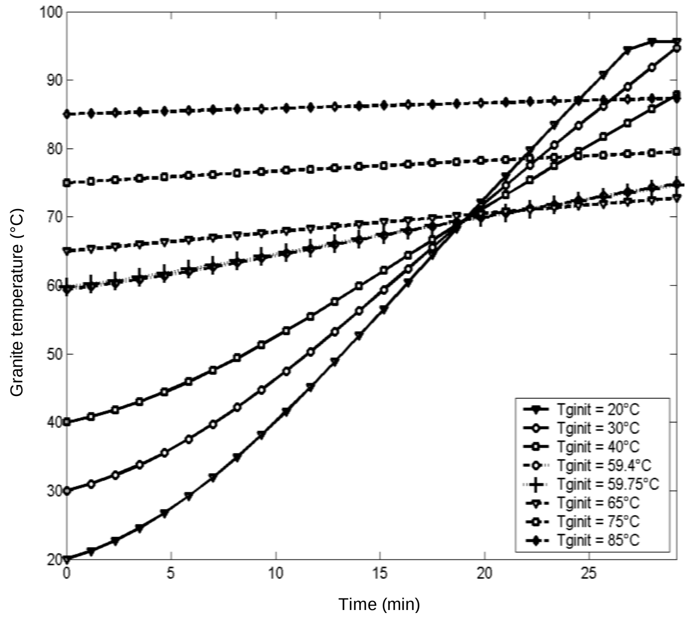

Figure 14. Porous media temperature as a function of the time. Porous media initial temperature influence. $\dot{m}_{vap}$ = 0.5554 g.s^{-1}, D_g = 3 cm, L = 30 cm.

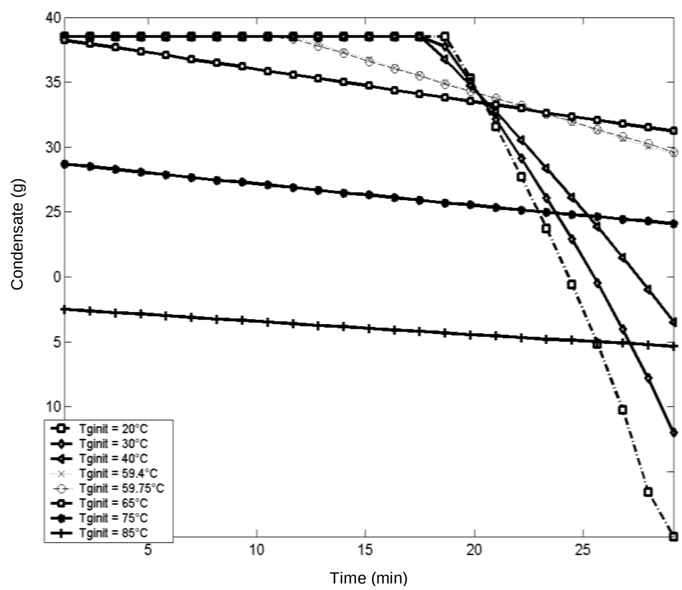

Figure 15. Condensate quantity as a function of the time according to the porous media initial temperature. $\dot{m}_{vap}$ = 0.5554 g.s^{-1}, D_g = 3 cm, L = 30 cm.

temperatures because the necessary heat quantity to heat the porous media is especially weak as the initial temperature is near to the temperature of condensation (Figure 15).

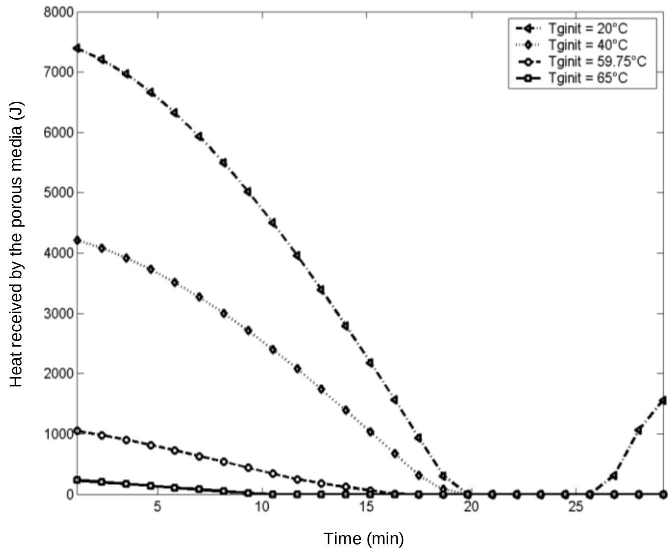

Figure 16. Heat received by the porous media as function of the time. Porous media initial temperature influence. m_{vap} = 0.5554 g.s^{-1}, D_g = 3 cm, L = 30 cm,

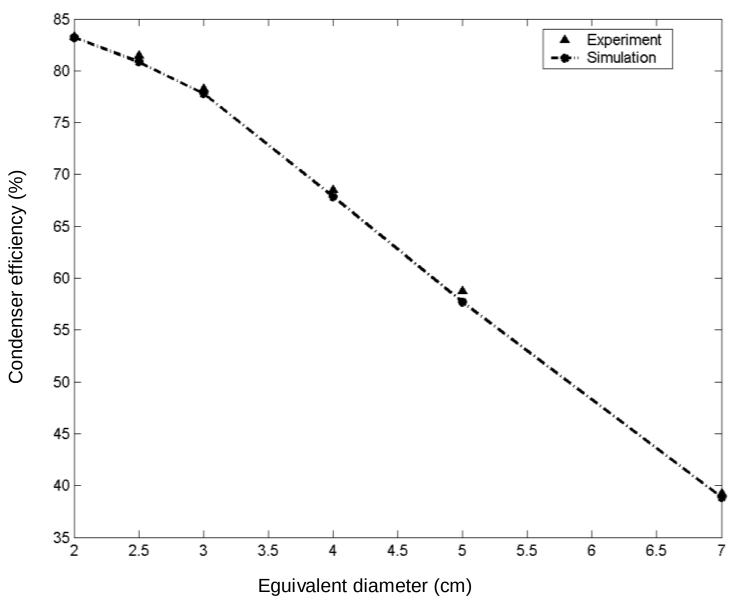

Figure 17. Condenser efficiency as a function of the equivalent diameter of the granite piece. m_{vap} = 0.5554 g.s^{-1}, L = 30 cm**.**

Results validation

The condenser efficiency decreases with the increase of the equivalent diameter because of the same thickness of the granite bed, the exchange surface between steam and the porous media decreases with the increase of the equivalent diameter of the granite pieces (Figures 17 and 18). This efficiency is natural, for the reasons mentioned

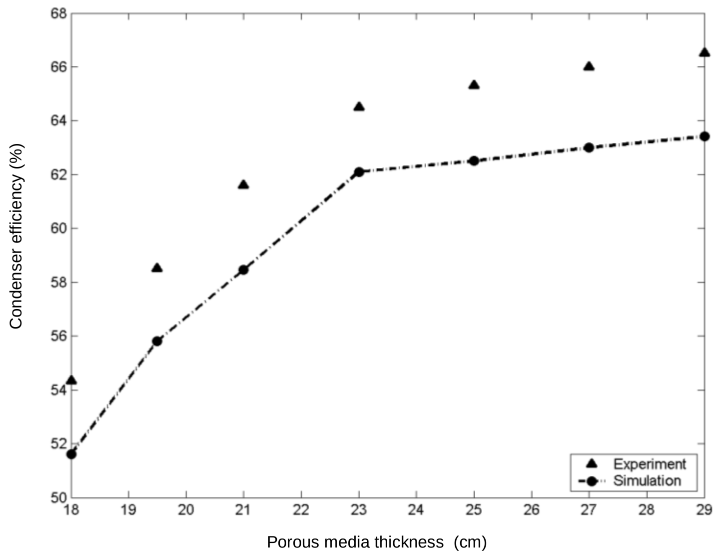

Figure 18. Condenser efficiency as a function of the thickness of the granite bed. $\dot{m}_{vap}$ = 0.5554 g.s^{-1}, D_g = 2cm.

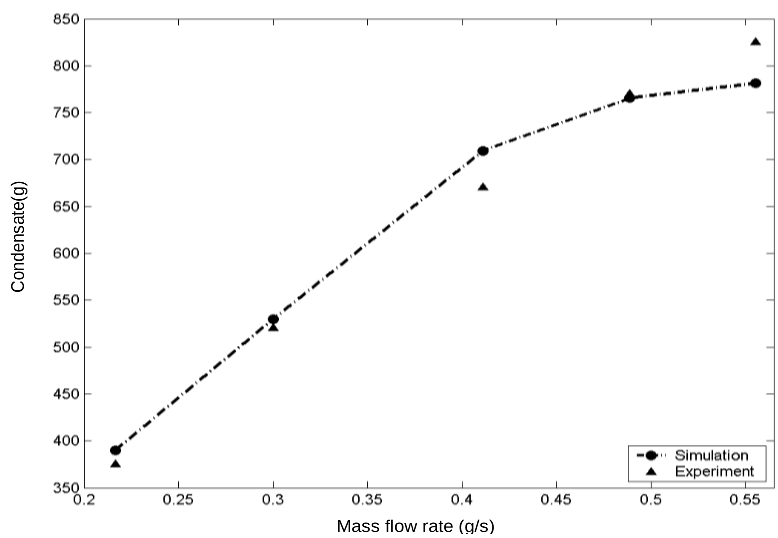

Figure 19. Condensate quantity as a function of the inlet saturated steam ass flow rate. D_g = 2cm, L = 30 cm.

previously, especially when elevated than the thickness of the granite bed which is important. This result must be correlated with the growth of the losses of loads through the porous media of granite (not considered in this survey). Also, the thickness of the granite porous media must not be superior to an optimal value.

The thermal efficiency of the condenser decreases during the time, because the condensation of the steam is conditioned by the temperature of the granite porous media that increases during the time. The condensate quantity is an increasing function of the inlet saturated steam mass flow rate (Figure 19). The condenser efficiency is mainly elevated as the steam mass flow rate is weak (Figure 20).

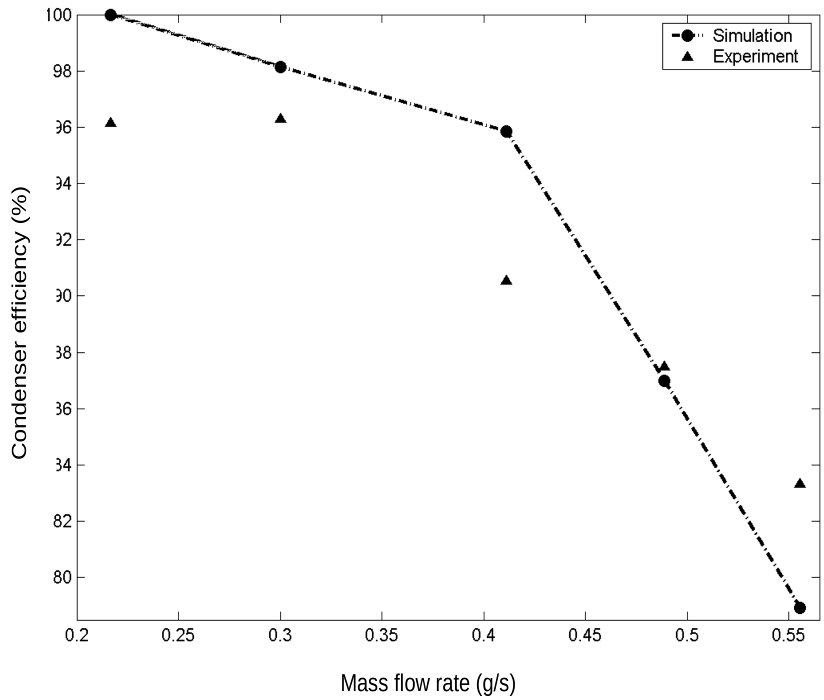

Figure 20. Condenser efficiency as a function of the inlet saturated steam mass flow rate. D_g = 2cm, L = 30 cm.

In general, the relative difference between the theoretical and the experimental results of the condenser efficiency is of 12.46%.

Conclusion

A numeric and experimental survey of a distiller's condenser for brackish water are presented. The theoretical model is based on the equations of transfer, established from a thermal and mass balance within the condenser. The resolution of the transfer equations by the finite difference explicit method is employed to solve the governing partial differential equations coupled to an iterative calculation, and the Newton Method allowed us to determine the values of the mass flow rate of the steam (0.2167 to 0.5554 $ml.s^{-1}$), the equivalent diameter of the granite piece (2 to 2.5 cm), and the optimal thickness of the granite porous media (30 cm) for which the condensation of the water steam is total. The results are in good qualitative and quantitative agreement with the gotten experimental results on a pilot unit of distillation including a condenser in porous media of granite. The relative difference between the theoretical and the experimental results of the condenser efficiency is of 12.46%.

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NOMENCLATURE

Latin letters: $\mathbf{A_S}$, Contact surface rate (m^{-1}); $\mathbf{C_p}$, calorific capacity ($J.kg^{-1}.K^{-1}$); $\mathbf{D_g}$, equivalent diameter of a granite sphere (m); **Dxst,** diameter of the porous media (m); $\mathbf{F_S}$, sphere surface (m^2); $\mathbf{F_T}$, exchange surface between the water steam and the porous media (m^2); **g,** gravitational acceleration ($m\ s^{-2}$); $\mathbf{G_z}$, Graetz number; $\mathbf{h_{convext}}$, convective heat transfer coefficient between the condenser and the ambient air ($W.m^{-2}.K^{-1}$): $\mathbf{h_{cv}}$, convective heat transfer coefficient between the water steam and the partition of the porous media ($W.m^{-2}.K^{-1}$); **L,** porous media thickness (m); $\mathbf{L_v}$, latent heat of vaporization of the water steam ($kJ.kg^{-1}$); $\dot{m}_{cond}$, condensate mass flow rate ($kg.s^{-1}$); $\mathbf{m_g}$, mass of the porous bed (kg), $\dot{m}_{incond}$, outlet non-condensing steam mass flow rate ($kg.s^{-1}$), $\dot{m}_{vap}$, inlet saturated steam mass flow rate ($kg.s^{-1}$); **n,** granite piece number; **N,** column number into the porous media; **Nu,** Nusselt number; **Poro**, Porosity; $\mathbf{P_R}$**,** power received by the porous media (Average value) (W); $\mathbf{P_V}$**,** inlet water steam power (W); $\mathbf{P_{cond}}$**,** average power lost by condensation of the condensate towards the outside (W); $\mathbf{P_{incond}}$**,** Average outlet non-condensing steam power (W); $\mathbf{P_p}$**,** average power lost through the external partition of the condenser (W); $\mathbf{P_{acc}}$**,** average power stocked in the porous media (W); **Re,** Reynolds number; **sec,** section of the media (m^2); $\mathbf{S_{ext}}$**,** external surface of the condenser (m^2); $\mathbf{S_{int}}$**,** internal surface of the condenser (m^2); $\mathbf{S_P}$**,** exchange surface between steam and the condenser (m^2); $\mathbf{T_{air}}$**,** ambient air temperatur (K); $\mathbf{T_g}$**,** granite temperature to the instant *t* (K); $\mathbf{T_{ginit}}$**,** granite initial temperature (K); $\mathbf{T_{p1}}$, internal partition temperature of the condenser (K); $\mathbf{T_{p2}}$, external partition temperature of the condenser (K); $\mathbf{T_{pm}}$**,** average temperature of the external partition of the condenser (K), $\mathbf{T_{sat}}$**,** saturated steam temperature (K); $\mathbf{T_v}$**,** inlet water steam temperature (K); $\mathbf{T_{incond}}$**,** outlet non-condensing steam temperature (K); $\mathbf{U_L}$**,** global coefficient of heat transfer ($W.m^{-2}.K^{-1}$); **W,** wind speed ($m.s^{-1}$).

Greek letters: Δ**t,** Time (s); $\mathbf{\mu_L}$**,** condensate dynamic viscosity ($kg.\ m^{-1}.s^{-1}$); $\mathbf{\mu_V}$**,** water steam dynamic viscosity (($kg\ m^{-1}\ s^{-1}$); **ε,** correction coefficient; **η,** condenser efficiency (%); **λ,** thermal conductivity of the partition of the condenser ($W\ m^{-1}\ K^{-1}$); $\mathbf{\lambda_L}$**,** condensate thermal conductivity ($W\ m^{-1}\ K^{-1}$); $\mathbf{\lambda_V}$**,** water steam thermal conductivity, ($W\ m^{-1}\ K^{-1}$); $\mathbf{\rho_L}$**,** condensate density ($kg.m^{-3}$); $\mathbf{\rho_V}$**,** water steam density ($kg.m^{-3}$).

Subscripts: Cond, Condensate; **g,** granite; **incond,** non-condensing steam; **v,** vapour, water steam or water vapour; **p,** partition of the condenser; **sat,** saturated steam.

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APPENDIX

A). Convective heat transfer coefficient between the water steam and the partition of the porous media: h_{cvv} (Rakotovao, 1983; Donadieu, 1961)

$$hcvv = \frac{\lambda . Nu}{Dp} \quad (A.1)$$

With

Pour $\mathrm{Re} < 600.\frac{\mathrm{poro}}{1-\mathrm{poro}}^{3}$

$$\mathrm{Nu} = 2{,}62.10^{-4}.\left[\frac{1-\mathrm{poro}}{\mathrm{poro}^3}\right]^{1{,}6}.\mathrm{Re}^{1{,}6} \quad (A.2)$$

Pour $\mathrm{Re} \geq 600.\frac{\mathrm{poro}}{1-\mathrm{poro}}^{3}$

$$\mathrm{Nu} = 6{,}6.10^{-2}.\left[\frac{1-\mathrm{poro}}{\mathrm{poro}^3}\right]^{0{,}75}.\mathrm{Re}^{0{,}75} \quad (A.3)$$

A2) Convective heat transfer coefficient inside the condenser: h_{cvp}

Laminar regime: Re < 2100, Sieder-Tate and Hausen correlation (Rakotondramiarana, 2004).

For Gz < 100

$$\mathrm{Nu} = 3{,}66 + \frac{0{,}085\mathrm{Gz}}{1+0{,}047\mathrm{Gz}^{2/3}} \quad (A.4)$$

For Gz > 100

$$\mathrm{Nu} = 1{,}86\mathrm{Gz}^{1/3} + 0{,}87.(1+0{,}015\mathrm{Gz}^{1/3}) \quad (A.5)$$

Transient regime: 2100 < Re < 10000, Sieder-Tate and Hausen correlation

$$\mathrm{Nu} = 0{,}116(\mathrm{Re}^{2/3} - 125).\mathrm{Pr}^{1/3}.\left(1+\left(\frac{\mathrm{D_H}}{\mathrm{L}}\right)^{2/3}\right) \quad (A.6)$$

Turbulent regime: Re >10000, Tan and Charters correlation (Rakotondramiarana, 2004)

$$Si\ \frac{\mathrm{L}}{\mathrm{D_H}} < 60 \quad Nu = 0{,}018.\mathrm{Re}^{0{,}8}.\mathrm{Pr}^{0{,}4}.\left[1+\frac{D_H}{L}.\left(14{,}3.\log\frac{D_H}{L} - 7{,}9\right)\right] \quad (A.7)$$

$$Si\ \frac{\mathrm{L}}{\mathrm{D_H}} > 60 \quad Nu = 0{,}018.\mathrm{Re}^{0{,}8}.\mathrm{Pr}^{0{,}4}.\left[1+17{,}5.\frac{D_H}{L}\right] \quad (A.8)$$

A3. Heat loss global coefficient: U_L

The heat flux exchanged by the system with the outside environment is determined by:

$$q_p = \frac{2\pi.\lambda.L}{Log(\frac{r_2}{r_1})}.(T_{p1} - T_{p2}) = h_{convext}.S_{ext}.(T_{p2} - T_{air}) = h_{cvp}.S_{int}.(T_v - T_{pl}) \quad (A.9)$$

From here:

$$\frac{1}{\mathrm{U_L.S_{ext}}} = \frac{1}{\mathrm{h_{cvp}.S_{int}}} + \frac{\mathrm{Log}\left[\frac{\mathrm{r_2}}{\mathrm{r_1}}\right]}{2\pi.\lambda.\mathrm{L}} + \frac{1}{\mathrm{h_{convext}.S_{ext}}} \quad (A.10)$$

A4. Thermal exchange coefficient between the condenser and the ambient air: $h_{convext}$

We keep a relation translating a mixed convection, used by Alidina (1991). It ensures the experimental results gotten by Kittas (1980) for a tunnel greenhouse:

$$\mathrm{h_{convext}} = \frac{\rho.\mathrm{Cp(T_{air})}}{1045}.\left[1{,}14.(\mathrm{T_{pm}} - \mathrm{T_{air}})^{0{,}5} + 6{,}97.\mathrm{W}^{1{,}6}\right]^{0{,}5} \quad (A.11)$$

$\rho.\mathrm{Cp(T_{air})}$: Calorific capacity of air to constant pressure [$J.m^{-3}.K^{-1}$].