

*Full Length Research Paper*

# Survey and realization of distiller's prototype to three horizontal compartments

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**This work consists of an experimental and theoretical survey of a distiller composed of three compartments of which the coolant fluid used is water. Distiller's type is conceived for an adequate separation of constituent of a water-ethanol mixture of which the temperature of boiling point are lower than the hot water. The theoretical survey is based on a model of heat transfers between the compartments and coolants fluid and based on liquid-vapor equilibrium at the distiller. The results show notably that one can bring back the temperature of the fluid to distill around the temperature of boiling point of the mixture. In this paper, one could study the importance of the temperature of the hot water that is a parameter fundamental of the system and the one of debit of the fluid coolant acceptable for the distiller's good working.**

**Key words:** Distiller, fluid coolant, boiling point temperature, numeric simulation.

## INTRODUCTION

The distillation is very used in the chemical industries. The small operators practice also the flash distillation with a lot of energy's losses in the distiller. This is how the development of new configurations for the optimization of the energy used made the object of many works. Hilde (2005) developed the multi-effect distillation applied to an industrial case study, (Bonsfills, 2004) conceived a Batch distillation and (Sami, 2001) studied experimentally the multicomponent distillation in packed columns. Vorayos has been demonstrated that several sequences of distillation coupled thermally contribute to the improvement of the thermal efficiency of the conventional sequences of distillation (Vorayos and al., 2006). In the flash distillation process, the temperature of distillation is often neighbor of the temperature of normal boiling point of water. Of this fact, it is necessary to conduct a rectification in continuous or discontinuous of the distillate to get a good separation of mixture (Lange, 1967; McCabe, 1925).

In this survey, we are going to try to improve the simple distillation while conceiving a distiller in three compartments based on the transfer of heat between these compartments and the coolant fluid in out-flow. The objective is to get the temperature of the water-ethanol mixture, calculated by Perry and Al (1987) superior to the temperature of normal boiling point of the mixture. A model is proposed to follow the evolution of the system according to the parameters as mass flow rates, hot water temperature and mixture concentration of ethanol so that one can determine the concentration of the product.

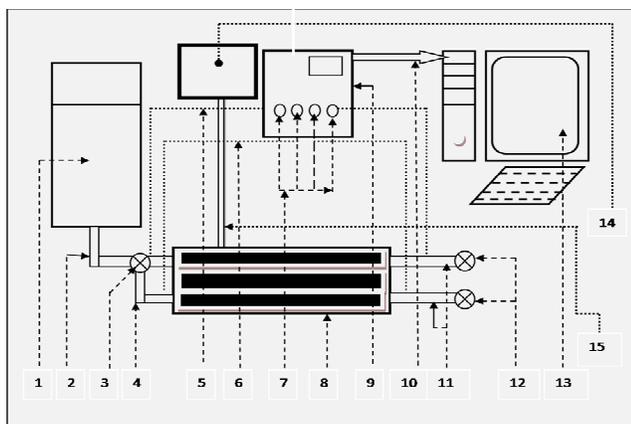
In this work, a theoretical survey adopting the semi-analytical method associated to an experimental survey of the distillation of the water-ethanol mixture permitting to control the mixture temperature is presented. First of all, one established a program permitting to calculate physico-chemicals properties of water while using the proposed data by Bailly (1971) and Chassériaux (1984). For the ethanol physico-chemicals properties one served some data (Vine and Al, 1989; Barrow, 1976; Karapetiantz M, 1978) and software named « Alco Dens Version 2.0. Ethanol alcohol properties, product by

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**Table 1.** Devices and materials.

1	Fluid coolant's tank.
2	Pipe joining the tank and the distiller: 15mm of inner and 21mm of outer diameter.
3	Valve of separation in the entry of the C1/C3 compartments.
4	Pipe in the entry of the C1 and C3 compartments.
5	Thermocouple in Copper-constantan that permits to measure the temperature of the coolant fluid F2 in the entry (C3 compartment).
6	Thermocouple in Copper-constantan that permits to measure the temperature of the coolant fluid F1 in the entry (C1 compartment).
7	Analogical entries of the power station.
8	Prototype of the distiller to three compartments C1, C2 et C3
9	Power station 21X Microllogger, CAMPBELL SCIENTIFIC, INC.
10	SC32A cable joining the 21X to the port RS232 of the computer.
11	Conducted in the exit of the coolant fluid of the C1 and C3 compartments.
12	Faucets permitting to control the debit of the coolant fluid F1 and F2.
13	Computer to stock and to treat the data of the power station 21X.
14	Cylindrical condenser to bundles of 6 pipes, 15mm of diameter, 10 rows horizontals (Krasnochtchekov and SoukomeI, 1985).
15	Conducted transporting the distiller's vapor toward the condenser

Alcohol-meter (Gay Lussac) was used for measuring the concentration of the ethanol.

**Figure 1.** Experimental set up.

Katmar Software (2007) » has been used. These properties permit to calculate all parameters of the mixture and heat transfer coefficients as indicated by Sieder-Tate and Hausen, Tan and Charters (Rakotondramiarana, 2004; Ramamonjisoa, 1993; Leontiev, 1985). Thereafter, the exit temperature of the coolant fluid and the mixture temperature are calculated to be able to deduct the heat received by this last. The distiller's efficiency will be given from the calculation of enthalpies of the coolant fluid to

the entry and to the exit of the system. Finally, a numeric resolution method (Bakhvalov, 1984) is used for the resolution of the differential equation. Vapor-liquid equilibrium equations are necessary to determine the vapor concentration to the exit of the condenser (gotten distillate).

## EXPERIMENTAL ANALYSIS

### Experimental device

The system of distillation is composed of (Figure 1 and Table 1): (1) a cylindrical tank ( $1 \text{ m}^3$ ) containing the coolant fluid, (2) a distiller including a horizontal compartment C2 ( $0,75 \times 0,40 \times 0,04 \text{ m}^3$ ) disposed between two channels C1 and C3. The partitions of the system are made in sheet metal TPN of a thickness, 2 mm.

### Principle of working

The coolant fluid previously boiled in the tank, maintained to a constant temperature; flow out by gravity toward the C1 and C3. It follows a transfer of heat between the fluid coolant and the fluid to distill. An increase of the temperature of the fluid to distill and an evaporation of a quantity of ethylic alcohol results from it if the contribution of heat is sufficient. The ethylic alcohol vapor condenses thereafter in the condenser.

The intensity of the heat transfer between coolants fluid and the mixture is; on the one hand, function of the mixture temperature and, on the other hand, of his mass flow rate. The distillate mass

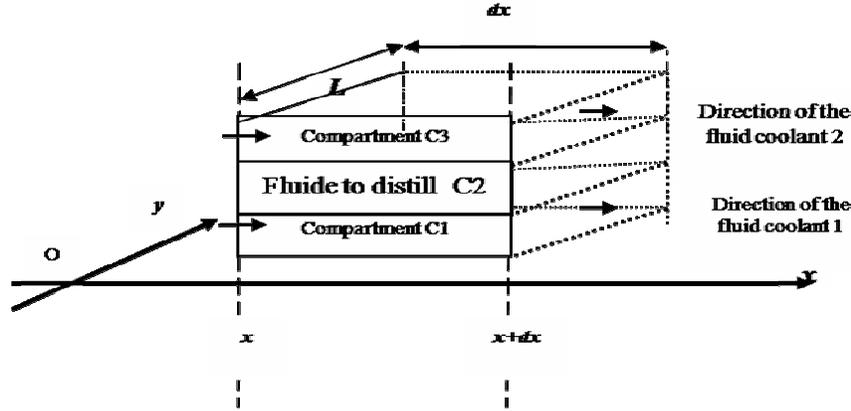


Figure 2. Diagram of the distiller's slice.

flow rate depends on the mixture temperature and on the difference between the air pressure and the one of vapor in the distiller. It is noted that a free space is required for an efficient vaporization of the ethanol.

We have to study the influence of the temperature to the entry of the coolant fluid and her mass flow rate on the temporal evolution of the mixture temperature. Coolants fluid temperature to the entry and to the exit of the C1 and C2, the one of the fluid to distill and of the ambient environment are measured by 4 thermocouples of T type. These thermocouples are connected to a power station of measures 21X Microllogers (Ramamonjisoa, 2000) and in a microcomputer Pentium IV equipped of the software MATLAB. Coolants fluid mass flow rates are determined with the measure during a time of a quantity of fluid recovered in a test-tube.

**Experimental protocol**

We fix coolants fluid F1 and F2 mass flow rates, the power station records the instantaneous values of the temperature of the fluid to distill. These same measures are done for a temperature of the coolant fluid and different mass flow rate of this fluid. The length of a set of measures is consisted between 30 and 100 min.

**THEORETICAL ANALYSIS**

**Mixture temperature model**

On this mathematical model, is considered to the instant *t* the distiller's slice *dx* in which flows out the coolant fluid in the (*Ox*) direction (Figures 2 and 3).

The following hypotheses are adopted:

- (1) The partitions of the system in contact with the outside are deprived of heat exchange.
- (2) The temperature of the strong surroundings is uniform in a normal plan to the out-flow.
- (3) The out-flow is one-dimensional and remain identical to himself all along the ducts, that means that it is laminar, transient or turbulent.
- (4) The thermal losses in the conducts of links are disregarded.
- (5) The losses of loads during the out-flow are disregarded.
- (6) The chemical reaction is absent during the distillation.

The total heat flux (*dq*) received by the fluid to distill during the instant *t* in a slice *dx* verifies the following equation:

$$dq = dq_1 + dq_2 \tag{1}$$

Where; *dq*<sub>1</sub>, *dq*<sub>2</sub>: heat flux given to the fluid to distill in the slice of length *dx* respectively by the fluid coolants 1 and 2 (Chassériaux, 1984).

$$-dq_1 = L \cdot dx \cdot h_{c1} \cdot (T_{p1}(x) - T_{mc1}(x)) = \frac{\lambda dS}{e} (T_{ip1}(x) - T_{p1}(x)) \tag{2}$$

$$-dq_2 = L \cdot dx \cdot h_{c2} \cdot (T_{p2}(x) - T_{mc2}(x)) = \frac{\lambda dS}{e} (T_{ip2}(x) - T_{p2}(x)) \tag{3}$$

$$dS = dx \cdot l \text{ (} l \text{: width of the distiller)}$$

Then again:

$$-dq_1 = D_1 \cdot c_{p1} \cdot dT_{mc1}(x) \tag{4a}$$

$$-dq_2 = D_2 \cdot c_{p2} \cdot dT_{mc2}(x) \tag{4b}$$

Where;

*dT*<sub>mc1</sub>(*x*): differential of the average temperature of the coolant fluid 1 crossing the slice.

*dT*<sub>p2</sub>(*x*): differential of the external face temperature of the lower partition of the compartment 2 in the slice.

*dT*<sub>mc2</sub>(*x*): differential of the average temperature of the coolant fluid 2 in the slice.

*dT*<sub>p1</sub>(*x*): differential of the temperature of the lower plate C1 compartment in the slice.

While combining the equations (2) and (4a), it comes:

$$D_1 \cdot c_{p1} \cdot dT_{mc1}(x) = L \cdot dx \cdot h_{c1} \cdot (T_{p1}(x) - T_{mc1}(x)) \tag{5}$$

$$\frac{dT_{mc1}(x)}{T_{mc1}(x) - T_{p1}(x)} = \frac{-L \cdot dx \cdot h_{c1}}{D_1 \cdot c_{p1}} \tag{6}$$

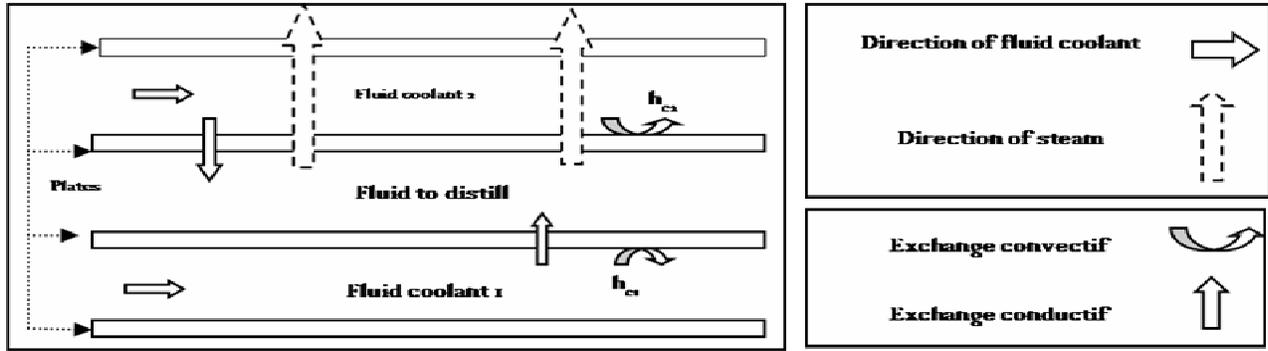


Figure 3. Descriptive diagram of the thermal exchanges within the distiller.

$$Ldxh_{c1} \cdot (T_{p1}(x) - T_{mc1}(x)) = \frac{\lambda S}{e} (T_{fp1}(x) - T_{pl}(x)) \quad (7)$$

The integration between 0 and x of the relation (6) conducted to the expression of the local temperature of the fluid coolant 1:

$$T_{mc1}(x) = T_{p1}(x) - (T_{mc1}(0) - T_{p1}(0)) \cdot \exp\left(\frac{-L \cdot x \cdot h_{c1}}{D_1 \cdot c_{p1}}\right) \quad (8)$$

with  $T_{mc1}(0) = T_{e1}$  et  $T_{p1}(0) = T_{p10}$

$T_{mc1}(0)$ : temperature of the coolant fluid 1 to the entry ( $x = 0$ ).  
 $T_{p1}(0)$ : temperature of the lower plate C2 compartment to the entry ( $x = 0$ ).

The substitution of the expression of  $T_{mc1}(x)$  in the equation (8) conduct to the expression of the temperature of the lower plate-C2 compartment

$$T_{fp1}(x) = T_{p1}(x) - \frac{h_{c1} \cdot e}{\lambda} (T_{mc1}(0) - T_{p1}(0)) \cdot \exp\left(\frac{-L \cdot x \cdot h_{c1}}{D_1 \cdot c_{p1}}\right) \quad (9)$$

While proceeding as previously, the relation (9) becomes:

$$T_{fp2}(x) = T_{p2}(x) - \frac{h_{c2} \cdot e}{\lambda} (T_{mc2}(0) - T_{p2}(0)) \cdot \exp\left(\frac{-L \cdot x \cdot h_{c2}}{D_2 \cdot c_{p2}}\right) \quad (10)$$

With  $T_{mc2}(0) = T_{e2}$  et  $T_{p2}(0) = T_{p20}$ .

$T_{mc2}(0)$ : temperature of coolant fluid 2 C3 ( $x = 0$ ) to the entry.  
 $T_{p2}(0)$ : temperature of the superior plate - C2 compartment to the entry ( $x = 0$ ).

The fluxes of heat transferred on the length (l) of the distiller by coolants fluid 1 and 2 to the fluid to distill verify the following expressions:

$$q_1 = -\int_0^l D_1 \cdot c_{p1} \cdot dT_{mc1}(x) \quad (11a)$$

$$q_2 = -\int_0^l D_2 \cdot c_{p2} \cdot dT_{mc2}(x) \quad (11b)$$

$$q_1 = D_1 \cdot c_{p1} \cdot (T_{mc1}(0) - T_{mc1}(l)) \quad (12a)$$

$$q_2 = D_2 \cdot c_{p2} \cdot (T_{mc2}(0) - T_{mc2}(l)) \quad (12b)$$

On the other hand,

$$-\int_0^l dq_1 = \int_0^l L \cdot h_{c1} \cdot (T_{p1}(x) - T_{mc1}(x)) dx \quad (13a)$$

$$-\int_0^l dq_2 = \int_0^l L \cdot h_{c2} \cdot (T_{p2}(x) - T_{mc2}(x)) dx \quad (13b)$$

The substitution in the expression (13a) of  $(T_{p1}(x) - T_{mc1}(x))$  by (10) and, in the expression (13b) of  $(T_{p2}(x) - T_{mc2}(x))$  by (11) conducted to the following relations (14a and b):

$$-\int_0^l dq_1 = -\int_0^l L \cdot h_{c1} \cdot (T_{mc1}(0) - T_{p1}(0)) \cdot \exp\left(\frac{-L \cdot x \cdot h_{c1}}{D_1 \cdot c_{p1}}\right) dx \quad (14a)$$

$$-\int_0^l dq_2 = -\int_0^l L \cdot h_{c2} \cdot (T_{mc2}(0) - T_{p2}(0)) \cdot \exp\left(\frac{-L \cdot x \cdot h_{c2}}{D_2 \cdot c_{p2}}\right) dx \quad (14b)$$

Either:

$$q_1 = D_1 \cdot c_{p1} \cdot (T_{mc1}(0) - T_{p1}(0)) \cdot (1 - \exp\left(\frac{-L \cdot l \cdot h_{c1}}{D_1 \cdot c_{p1}}\right)) \quad (15a)$$

$$q_2 = D_2 \cdot c_{p2} \cdot (T_{mc2}(0) - T_{p2}(0)) \cdot (1 - \exp\left(\frac{-L \cdot l \cdot h_{c2}}{D_2 \cdot c_{p2}}\right)) \quad (15b)$$

While combining the expressions 12a and b and 15a and b, one has the relation (16a and b):

$$T_{mc1}(l) = T_{mc1}(0) - (T_{mc1}(0) - T_{p1}(0)) \cdot (1 - \exp\left(\frac{-L \cdot l \cdot h_{c1}}{D_1 \cdot c_{p1}}\right)) \quad (16a)$$

$$T_{mc2}(l) = T_{mc2}(0) - (T_{mc2}(0) - T_{p2}(0)) \cdot (1 - \exp(\frac{-L \cdot l \cdot h_{c2}}{D_2 \cdot c_{p2}})) \quad (16b)$$

With  $T_{mc1}(l) = T_{s1}$  et  $T_{mc2}(l) = T_{s2}$

$T_{mc1}(l)$ : temperature of the coolant fluid 1 to the exit.  
 $T_{mc2}(l)$ : temperature of the coolant fluid 2 to the exit.

The heat flux  $q$  transmitted by coolants fluid 1 and 2 to the fluid to distill generates an increase of his average temperature that verifies the following equation (Duffie, 1977):

$$m_f \cdot C_{pf} \cdot \frac{dT_f}{dt} = q_1 + q_2 \quad (17)$$

where  $m_f$ : mass of the fluid in a fictional slice  $dx$ .  
 $C_{pf}$ : calorific capacity of the fluid to distill.  
 $T_f$ : average temperature of the fluid to distill.

$T_f(t) =$

$$T_f(t - \Delta t) + \Delta t \cdot \frac{(D_1 \cdot c_{p1} \cdot (T_{m1}(0) - T_{p1}(0)) \cdot (1 - \exp(\frac{-L \cdot l \cdot h_{c1}}{D_1 \cdot c_{p1}})) + D_2 \cdot c_{p2} \cdot (T_{m2}(0) - T_{p2}(0)) \cdot (1 - \exp(\frac{-L \cdot l \cdot h_{c2}}{D_2 \cdot c_{p2}})))}{m_f \cdot C_{pf}}$$

(18)

The quantity of steam produced in the distiller is calculated by:

$$\dot{m}_v = \frac{Q_{acc}}{L_{vm}} \quad (19)$$

With :

$Q_{acc}$ : the heat accumulated by the fluid.  
 $L_{vm}$ : the water-ethanol mixture latent heat of vaporization.

$$Q_{acc} = \sum_{t=t_0}^{t=t_1} (q_1 + q_2) \quad (20)$$

The distiller's thermal efficiency is calculated by the report of the heat really transferred to the maximal heat capable to be transferred (Chassériaux, 1984):

$$\sigma = \frac{q_{1m} + q_{2m}}{Q_{max}} \quad (21)$$

For the calculation of the maximal heat  $Q_{max}$ , the relation (12a and 12b) is used. While taking,

$T_{mc1}(l) = 0$  et  $T_{mc2}(l) = 0$  ;

$$q_{1m} = D_1 \cdot c_{p1} \cdot T_{mc1}(0); q_{2m} = D_2 \cdot c_{p2} \cdot T_{mc2}(0) \quad (22)$$

$$Q_{max} = q_{1m} + q_{2m} \quad (23)$$

### Heat transfer coefficients models: $h_{c1}$ , $h_{c2}$

A thermal exchange by forced convection presented between the face of the C2/C1 compartment and the coolant fluid 1 and 2; one calculates the Nusselt adimensionnal number (Rakotondramiarana, 2004):

Laminar:  $Re < 2100$ , Sieder-Tate and Hausen equations, If  $Gz < 100$ :

$$Nu = 3,66 + \frac{0,085 \cdot Gz}{1 + 0,047 \cdot Gz^{2/3}} \quad (24)$$

If  $Gz > 100$ :

$$Nu = 1,86 Gz^{1/3} + 0,87 \cdot (1 + 0,015 \cdot Gz^{1/3}) \quad (25)$$

Transitory:  $2100 < Re < 10000$ , Sieder-Tate and Hausen equations:

$$Nu = 0,116 \cdot (Re^{2/3} - 125) \cdot Pr^{1/3} \cdot \left[ 1 + \left( \frac{D_H}{L} \right)^{2/3} \right] \quad (26)$$

Turbulent:  $Re > 10000$ , Tan and Charters equations:

If

$$\frac{L}{D_H} < 60 \quad Nu = 0,018 \cdot Re^{0,8} \cdot Pr^{0,4} \cdot \left[ 1 + \frac{D_H}{L} \cdot \left( 14,3 \cdot \log \frac{D_H}{L} - 7,9 \right) \right] \quad (27)$$

$$\text{If } \frac{L}{D_H} > 60 \quad Nu = 0,018 \cdot Re^{0,8} \cdot Pr^{0,4} \cdot \left[ 1 + 17,5 \cdot \frac{D_H}{L} \right] \quad (28)$$

Vapor-liquid equilibrium: Water-ethanol mixture

Perry and Al (1987) established the following equations:

$$y = -947613^8 + 45032^7 - 901175^6 + 98803^5 - 64097^4 + 25985^3 - 645050^2 + 971706 \quad (29)$$

Where;

$y$  = concentration in ethanol to vapor phase (if condensed) (ml ml<sup>-1</sup>)  
 and  $x$  = concentration in ethanol to liquid phase (ml. ml<sup>-1</sup>).

Temperature of boiling point of the mixture:

$$T_{ebm} = 60,526x^4 - 163,16x^3 + 163,96x^2 - 83,438x + 100 \quad (30)$$

## RESULTS AND DISCUSSION

### Simulation results

#### Effect of the coolant fluid temperature

Data used during the experiences are served to nourish the simulation. The survey is limited to coolant fluid

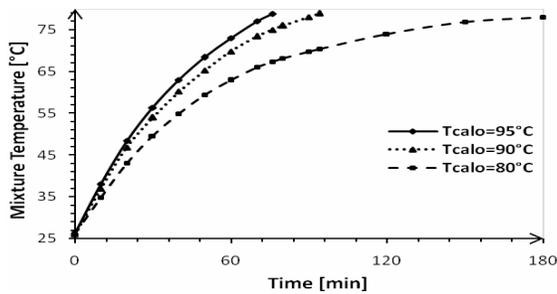


Figure 4a. Effect of the coolant fluid temperature on the ethanol-water mixture temperature,  $D_1 = D_2 = 24 \text{ ml.s}^{-1}$

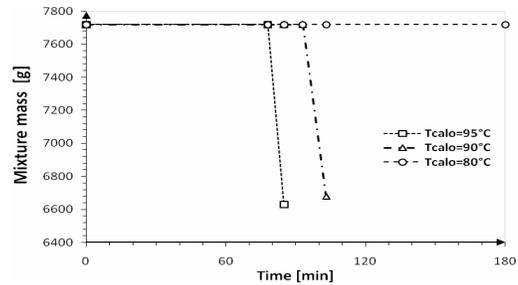


Figure 5b. Effect of the coolant fluid temperature on the evolution of the mixture mass,  $D_1 = 24 \text{ ml.s}^{-1}$   $D_2 = 6.67$

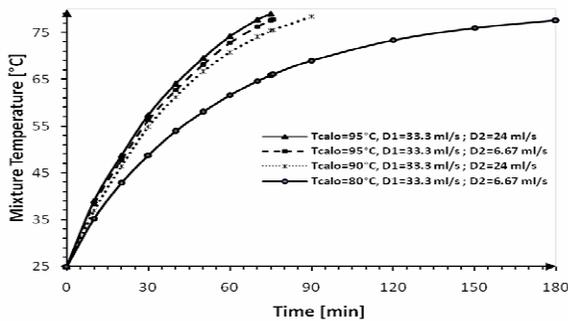


Figure 4b. Effect of the coolant fluid temperature on the ethanol-water mixture temperature  $D_1$  and  $D_2$  different.

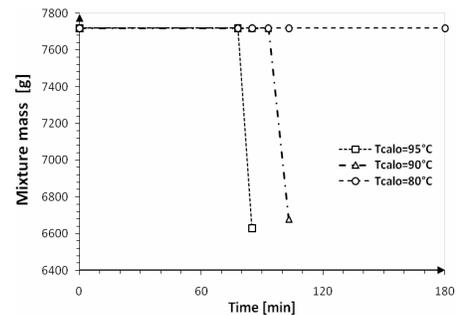


Figure 5b. Effect of the coolant fluid temperature on the evolution of the mixture mass,  $D_1 = 24 \text{ ml.s}^{-1}$   $D_2 = 6.67 \text{ ml.s}^{-1}$ .

temperatures between 80 and 96°C and for mass flow rate between 2.9 and 100  $\text{ml.s}^{-1}$ . The concentration of the mixture is 25% v/v. The initial temperature of the fluid to distill is 25°C. Temperatures of the fluid coolant being in the C1 compartments and C3 are supposed equal.

**Evolution of the ethanol-water mixture temperature:**

The temperature of the ethanol-water mixture is an increasing function of the coolant fluid temperature. The Figures 4a, of which the mass flow rates  $D_1$  and  $D_2$  are equal to  $24 \text{ ml.s}^{-1}$  and 4b, whose mass flow rates are different, represent the evolution of the temperature of liquid mixture to different values of the temperature of the coolant fluid ( $T_{\text{calo}}$ ) respectively 80, 90 and 95°C. The duration of the operation decreases if the temperature of the coolant fluid increases.

When  $D_1$  and  $D_2$  are the same value  $24 \text{ ml.s}^{-1}$  (Figure 4a), for a temperature of the coolant fluid is 95°C, the temperature of the mixture is 78°C to the 70th min of the operation. When one continues the operation to a longer length, the temperature of boiling point of the mixture will be reached, 87°C (Perry, 1987). On the other hand, for a temperature lower to 95°C the time of the operation is extensively bigger and the temperature of boiling point of the mixture is not gotten, the evaporation does not exist. This fact is the consequence of the insufficiency of the

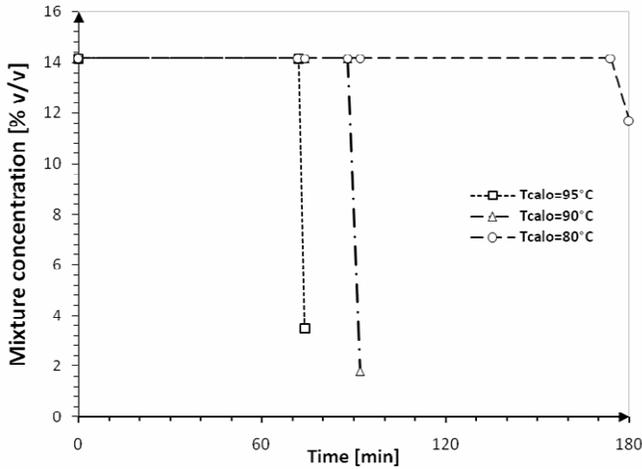
thermal exchange between the fluid to distill and the coolant fluid the mixture is not gotten, the evaporation does not exist.

For different mass flow rates, to same temperature of fluid coolant,  $T_{\text{calo}} = 95^\circ\text{C}$ , more the average of  $D_1$  and  $D_2$  is large, the ethanol-water mixture temperature increases more quickly (Figure 4b).

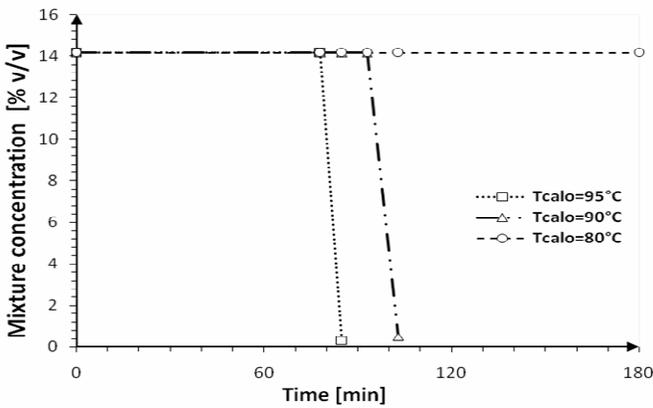
**Evolution of the mass of the ethanol-water mixture (fluid to distill):**

We examined coolants fluid having a same mass flow rate, Figure 5a and a different mass flow rate, Figure 5b. The reduction of the quantity of the fluid to distill is proportional to the quantity of vapor produced (distillate). Figures 5a and b show that if the temperature of the coolant fluid or the quantity of heat accumulated are sufficient, the temperature of boiling point of the ethanol is reached more quickly. The distillate begins to leave, followed by a dimunition of the quantity of fluid to distill as shown in Figures 5a and b. On the other hand, for very weak average mass flow rate, Figure 5b,  $T_{\text{calo}} = 80^\circ\text{C}$ , this temperature does not have an influence on the working of our boiler (distiller).

**Evolution of the mixture concentration:** Figures 6a and b show the evolution of the quantity of ethanol contained in the distiller. When the temperature of the



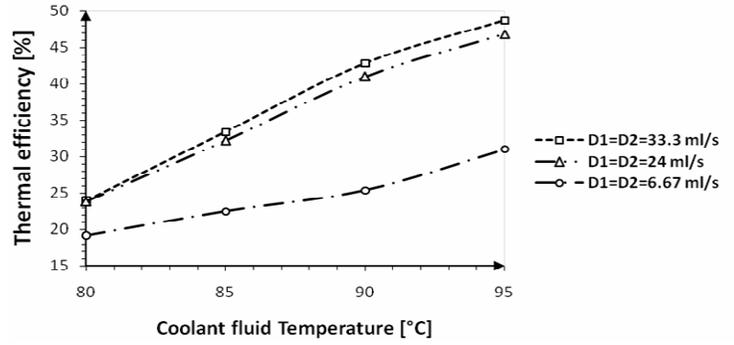
**Figure 6a.** Effect of the coolant fluid temperature on the mixture concentration of ethanol in the distiller,  $D_1 = D_2=24\text{ml}\cdot\text{s}^{-1}$ .



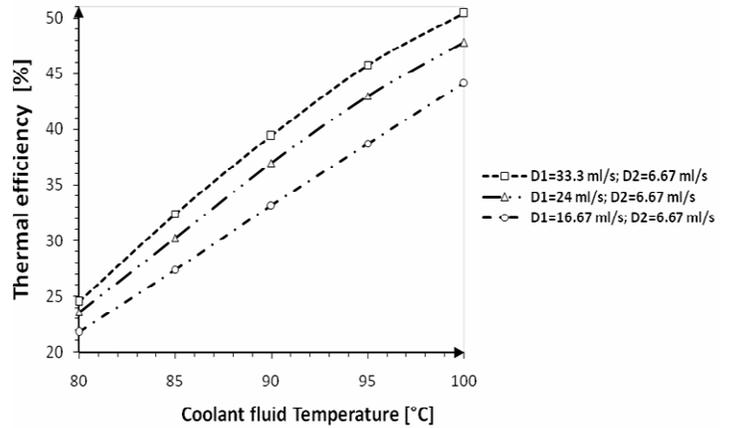
**Figure 6b.** Effect of the coolant fluid temperature on the mixture concentration of ethanol in the distiller,  $D_1 =24\text{ml}\cdot\text{s}^{-1}$ ,  $D_2 = 6.67\text{ml}\cdot\text{s}^{-1}$ .

coolant fluid increases, the distillation duration decreases, as well as the ethanol quantity produced. The reduction of the quantity of ethanol is explained by the followed fact, the temperature of the fluid to distill is nearly constant during a determined length, here and the profile of the graph is not vertical. It shows that the stabilization of the temperature of the fluid to distill around the temperature of boiling point of the mixture is possible.

**Thermal efficiency of the distiller:** The distiller is more efficient when one increases the temperature of the fluid coolant. when the fluid coolant mass flow rate is very weak, the efficiency remains weak even though her temperature is maximal. Figures 7a and 7b attest this



**Figure 7a.** Thermal efficiency of the distiller according to the coolant fluid temperature.  $D_1 = D_2$ .



**Figure 7b.** Thermal efficiency of the distiller according to the coolant fluid temperature.  $D_1$  and  $D_2$  different.

result. Besides, according to the analysis of Tables 2a and b, more the distiller is efficient, to reasonable average fluid coolant mass flow rate, more the quantity of ethanol produced is important.

After Perry and Al (1987), for a concentration 25% v/v of aqueous ethanol, the equivalent boiling point temperature is 87°C. This reference allows us to summarize results of our simulation in Tables 2a and b.

In the case of the Table 2a, when the temperature of the coolant fluid is smaller than the temperature of boiling point of the mixture, the operation duration is relatively important and the quantity of the distillate produced is weaker or do not exist. More the mixture temperature approaches the normal boiling point temperature of water, 100°C; our distiller (boiler) is more efficient. The operation duration decreases according to the chosen temperature and the ethanol produces flow rate increase.

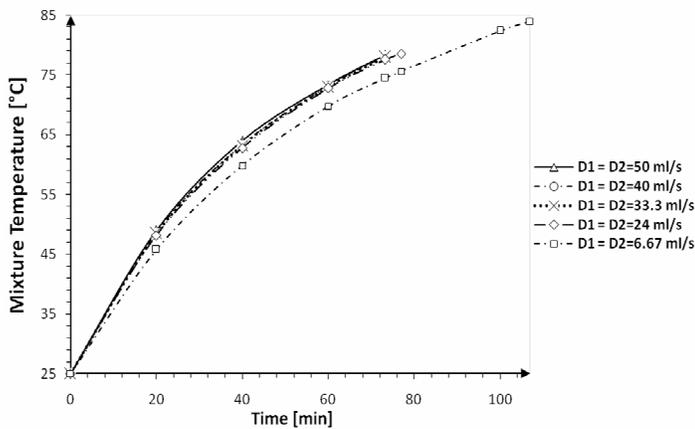
Table 2b is presented, one notices that the distiller becomes less efficient. Besides, we note that the energy

**Table 2a.** Summing up of the simulation results,  $D_1 = D_2 = 24 \text{ ml.s}^{-1}$ .

Coolant fluid temperature, $T_{\text{calo}}$ (°C)	80	90	95
Ethanol flow rate ( $\text{g.s}^{-1}$ )	0	0.09492	0.1414
distillate flow rate ( $\text{g.s}^{-1}$ )	0	0.1356	0.2022
distillation duration (min)	226	180	120
Thermal efficiency of the distiller, $\sigma$ (%)	-	40.93	46.67

**Table 2b.** Summing up of the simulation results,  $D_1 = 24 \text{ ml.s}^{-1}$ ;  $D_2 = 6.67 \text{ ml.s}^{-1}$ .

Coolant fluid temperature, $T_{\text{calo}}$ (°C)	80	90	95
Ethanol flow rate ( $\text{g.s}^{-1}$ )	0	0.0215	0.0857
distillate flow rate ( $\text{g.s}^{-1}$ )	0	0.0713	0.1224
distillation duration (min)	240	180	130
Thermal efficiency of the distiller, $\sigma$ (%)	-	37.64	43.38

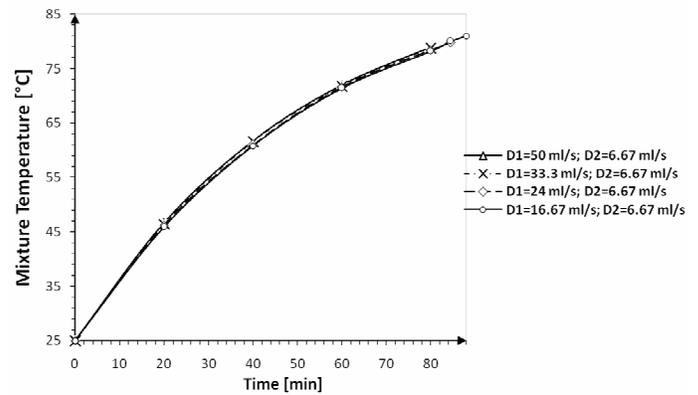


**Figure 8a.** Effect of the coolant fluid mass flow rate on the mixture temperature,  $T_{\text{calo}} = 95^\circ\text{C}$ .  $D_1 = D_2$ .

consumed by the fluid to distill correspondent to the conditions specified in Table 2a is superior to the one of the Table 2b. We can conclude that the operation is more efficient in the conditions of the Table 2a. It succeeds therefore, to a better result in the case where the C1 and C2 compartments are characterized by the same mass flow rate.

**Effect of the coolant fluid mass flow rate on the evolution of the mixture temperature and the distiller's thermal efficiency**

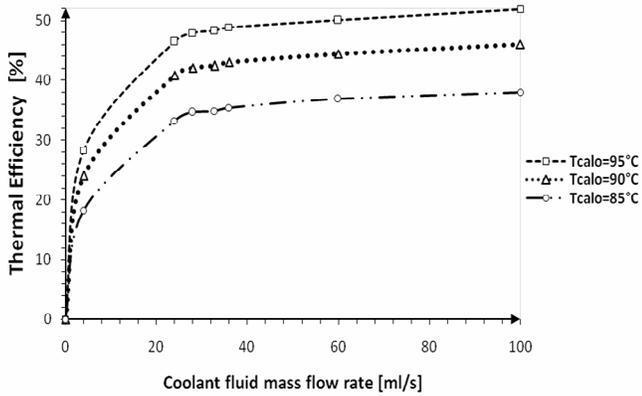
**Evolution of the ethanol-water mixture temperature:**  
The influence of the coolant fluid mass flow rate on the



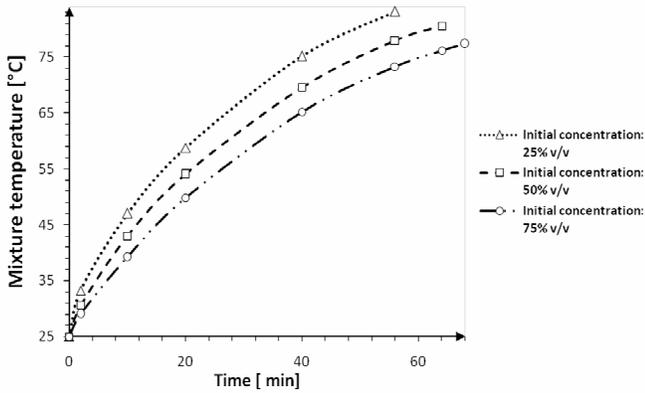
**Figure 8b.** Effect of the coolant fluid mass flow rate on the mixture temperature.  $T_{\text{calo}} = 95^\circ\text{C}$ .  $D_1$  and  $D_2$  different.

temperature of the mixture is not very meaningful safe for very weak mass flow rate (Figures 8a and 8b)  $6.67 \text{ ml.s}^{-1}$  on average for  $D_1$  and  $D_2$ . We also note that the operation duration is influenced directly by the mass flow rate, which means that the mass flow rate of the coolant fluid is inversely proportional to the operation duration. For a fluid coolant mass flow rate superior to  $10.67 \text{ ml.s}^{-1}$  and a gap between the fluid F1 mass flow rate and the one of the fluid coolant F2 relatively small, the augmentation of the temperature of the fluid to distill is relatively important, for the same reason as the operation time. This condition is equivalent to take the average value of two coolants fluid mass flow rate and it must be superior to  $10.67 \text{ ml.s}^{-1}$ . The result gotten for  $D_1 = D_2$  is better than the one operated to different mass flow rate.

**Thermal efficiency of the distiller:** Figure 9 shows the



**Figure 9.** Thermal efficiency of the distiller according to the coolant fluid mass flow rate,  $D_1 = D_2$ .



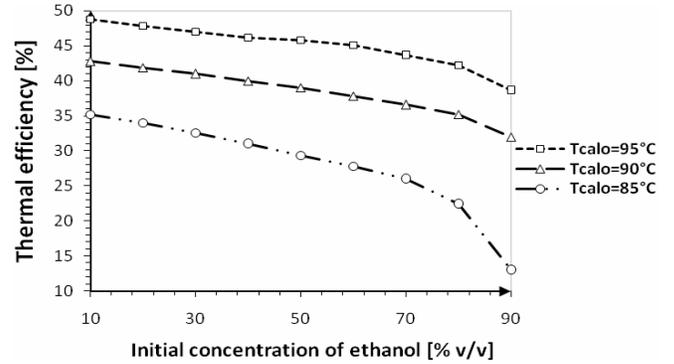
**Figure 10a.** Effect of the initial concentration of ethanol in the distiller on the mixture temperature.  $D_1 = D_2 = 33.34 \text{ ml.s}^{-1}$ ;  $T_{\text{calo}} = 95^\circ\text{C}$ .

evolution of the distiller's thermal efficiency according to the mass flow rate, to different values of the temperature of the coolant fluid. One notes that the profile of the graph is nearly constant from a certain value of the coolant fluid mass flow rate. This result shows that the values of the coolant fluid mass flow rate included between 20 and 55  $\text{ml.s}^{-1}$  are sufficient to make operate the system.

**Effect of the initial concentration of ethanol in the distiller**

**Evolution of the ethanol-water mixture temperature:** Figure 10a is presented; let's take a coolant fluid mass flow rate equals to  $33.34 \text{ ml.s}^{-1}$  and a temperature of the fluid coolant  $T_{\text{calo}} = 95^\circ\text{C}$  for the numeric simulation.

It shows the evolution of the ethanol-water mixture



**Figure 10b.** Thermal efficiency of the distiller according to the initial concentration of ethanol.  $D_1 = D_2 = 33.34 \text{ ml.s}^{-1}$ .

temperature to different values of the initial concentration of ethanol; more this concentration increases, the temperature of boiling point of the mixture is reached more quickly, marked by the ethanol latent heat of vaporization in relation to water. It drags to a reduction of the distillation length. We can conclude that the exchange of heat within the system is more efficient when the quantity of ethanol in the mixture increases, because the calorific capacity of the mixture is near to the calorific capacity of the ethanol that is the most volatile constituent, the distillation takes place quickly.

**Effect of the initial concentration of ethanol on the distiller's thermal efficiency:** More the concentration of ethanol contained in the distiller is weak, the distiller's energizing need increases. It is for this reason that we can affirm that the distiller's thermal efficiency decreases if the quantity of ethanol increases, Figure 10b.

**Influence of the initial temperature of the mixture**

Figure 11 shows the evolution of the mixture temperature to different values of the initial temperature of the fluid to distill. It is obvious that if the initial temperature of mixture increases, the distillation takes place. The concentration in ethanol decreases more quickly. Consequently, the preheating of the fluid to distill is necessary to accelerate the distillation process.

**Results validation**

It summarizes in Table 3 the adopted values during the experiments. These values are also used in the numeric simulations. In manner of validation, one compares the simulated results with those gotten experimentally. Vapor is considered condensed entirely in the condenser.

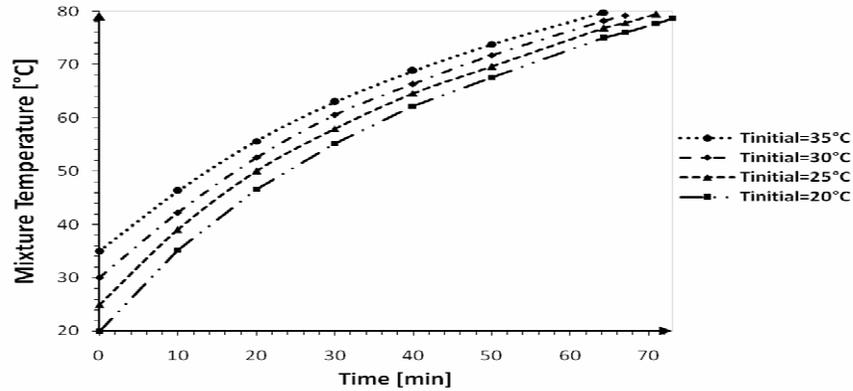


Figure 11. Effect of the initial temperature of the mixture.  $D_1 = D_2 = 33.34$  ml/s.

Table 3. Experimental used values.

Experimental	Coolant Fluids F1, F2			Mixture water-ethanol	
	$D_1$ (ml.s <sup>-1</sup> )	$D_2$ (ml.s <sup>-1</sup> )	$T_{calo}$ (°C)	T-initial	
Sample A1	30	55	80.67	56	Concentration 28.57% v/v in ethanol
Sample A2	4.583	2.916	92.30	25	Concentration 24.29% v/v in ethanol
Sample A3	18.34	31.67	94.91	57.64	Concentration 24.29% v/v in ethanol
Sample A4	12.17	31.84	94.47	20	Concentration 16.70% v/v in ethanol

Table 4. Comparison between the simulated and measured results.

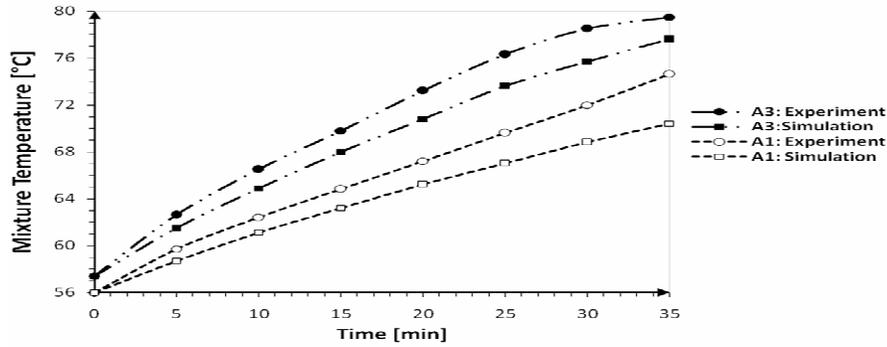
Operation		Sample A1	Sample A2	Sample A3	Sample A4
Model	Distillation duration (min)	127	240	43	83
	Distillate mass (g)	-	1252	880	976
	distillate flow rate (g.s <sup>-1</sup> )	-	0.087	0.341	0.196
	Mixture boiling point temperature (°C)	86.14	87.28	87.28	89.92
	Distillate concentration in ethanol (% v/v), Average	-	70,49	70,49	64,30
Experiment	Distillate mass (g)	0	1020	760	850
	distillate flow rate (g.s <sup>-1</sup> )	0	0.075	0.294	0.170
	Mixture boiling point temperature (°C)	86.14	87.28	87.28	89.92
	Distillate concentration in ethanol (% v/v), Average	-	50.8	63.5	55.3

The gotten results depend on the concentration of the ethanol in the mixture. One verifies that if the temperature of the coolant fluid is smaller than the temperature of the mixture, the evaporation does not exist (Table 4, sample A1). On the other hand, for a sufficient temperature of the mixture, the mass flow rate of the coolant fluid influences the gotten results. We compare the results descended of the simulated model ( $x_1$ ) with those gotten by

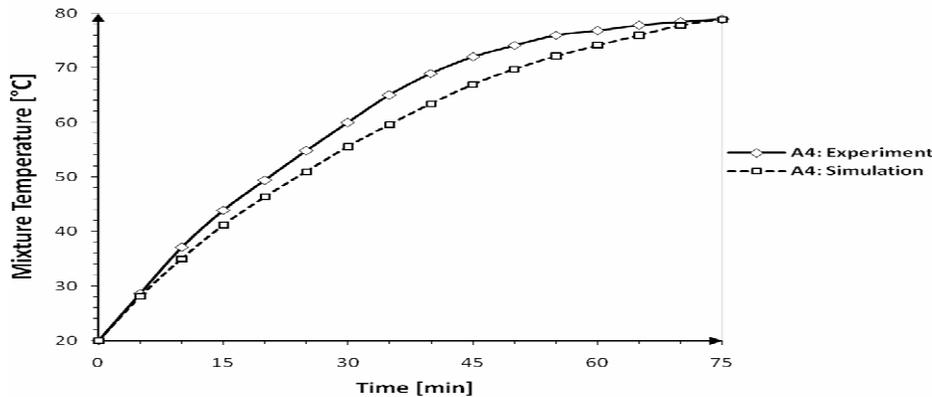
experiments ( $x_2$ ). A mathematical interrelationship between the simulated and measured results is written:

- Sample A2: distillate mass flow rate:  $x_2 = 0.862 \cdot x_1$
- Sample A3: distillate mass flow rate:  $x_2 = 0.862 \cdot x_1$
- Sample A4: distillate mass flow rate:  $x_2 = 0.867 \cdot x_1$

We find an acceptable difference between the simulated



**Figure 12a.** Comparison between the simulated and measured results (A1 and A3) of mixture temperature. Effect of the coolants fluid temperature.



**Figure 12b.** Comparison between the simulated and measured results (A4) of mixture temperature. Effect of the initial temperature of the mixture.

and measured results, 15%.

Concerning the distillate concentration, another mathematical interrelationship is deduced:

Sample A2: concentration % v/v of ethanol:  $x_2 = 0.720$ .  $x_1$

Sample A3: concentration % v/v of ethanol:  $x_2 = 0.900$ .  $x_1$

Sample A4: concentration % v/v of ethanol:  $x_2 = 0.860$ .  $x_1$

The comparison of results show that the sample A3 (Table 3) constitutes the best validation. It permits to verify the performance of the model on the previous numerical simulated results, as: the influence of the temperature (Figure 12a) and mass flow rate (Figure 12c) of the coolant fluid, the importance of the mixture preheating (Figure 12b) and the impact of the mixture concentration of ethanol on the concentration of the distillate (Table 3).

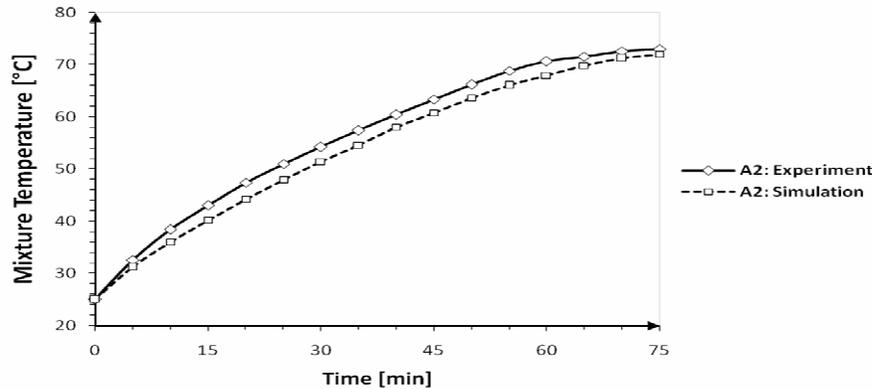
To conclude, the distiller's good working is dependent on the thermal exchange between the fluid to distill and coolants fluid from temperatures and mass flow rates that

are the first parameters influencing to the behaviour of the system.

## Conclusion

A distiller to three compartments for a water-ethanol mixture has been conceived. The developed model is based on the heat transfer and on the vapor-liquid equilibrium. Conditions of the distiller's working have been determined by the simulation of the model and have been validated by experiences: coolants fluid: mass flow rate: between 20 and 100 ml.s<sup>-1</sup>, temperature: 95°C to the minimum. The optimal mixture concentration is 25% v/v of ethanol and the product average concentration is 70% v/v of ethanol. Also, the preheating process influence the operation duration.

Theoretical and experimental results comparison drives to a satisfactory agreement. The difference does not exceed 15%.



**Figure 12c.** Comparison between the simulated and measured results (A2) of mixture temperature. Effect of mass flow rate of the coolant fluid.

## APPENDIX

### Nomenclature

$c_f$ , Specific heat of the fluid to distill ( $J.kg^{-1}.K^{-1}$ );  $c_{p1}$ , specific heat of the coolant fluid F1 ( $J.kg^{-1}.K^{-1}$ );  $c_{p2}$ , specific heat of the coolant fluid F2 ( $J.kg^{-1}.K^{-1}$ );  $d$ , distance between two successive partitions (m);  $D_1$ , coolant fluid F1 mass flow rate ( $kg.s^{-1}$ );  $D_2$ , Coolant fluid F2 mass flow rate ( $kg.s^{-1}$ );  $D_H$ , duct diameter (m);  $e$ , Thickness of the plate (m);  $h_{c1}$ , Thermal exchange coefficient between the partition of the C2 and the coolant fluid F1 ( $W.m^{-1}.K^{-1}$ );  $h_{c2}$ , Thermal exchange coefficient between the partition of the C2 and the coolant fluid F2 ( $W.m^{-1}.K^{-1}$ );  $l$ , Length of the distiller (m);  $L$ , Width of the distiller (m);  $m_f$ , mass of the fluid to distill (kg);  $m_v$ , distillate flow rate (kg/s);  $p$ , wet perimeter (m);  $Q$ , heat received by the fluid to distill by the coolant fluid F1 and F2 (J);  $Q_1$ , heat received by the fluid to distill by the coolant fluid F1 of C1 (J);  $Q_2$ , Heat received by the fluid to distill by the coolant fluid F2 of C3 (J);  $S$ , Surface of exchange ( $m^2$ );  $T_{calo}$ , temperature of coolants fluid F1 and F2 to the entry of the system ( $^{\circ}C$ );  $T_{e1}$ , temperature of the coolant fluid F1 to the entry ( $^{\circ}C$ );  $T_{e2}$ , temperature of entry of the coolant fluid F1 of C3 ( $^{\circ}C$ );  $T_{fp1}$ , temperature of the lower plate of C2, side to fluid distill ( $^{\circ}C$ );  $T_{fp2}$ , Temperature of the superior plate of C2, side to fluid distill ( $^{\circ}C$ );  $T_{initial}$ , initial temperature of the coolant fluid ( $^{\circ}C$ );  $T_m$ , Average temperature of coolants fluid F1 and F2 to the entry of the system ( $^{\circ}C$ );  $T_{mc1}$ , average temperature of the coolant fluid F1 ( $^{\circ}C$ );  $T_{mc2}$ , average temperature of the coolant fluid F2 ( $^{\circ}C$ );  $T_{p1}$ , Temperature of the lower plate of C2, side to F1 ( $^{\circ}C$ );  $T_{p10}$ , Initial temperature of the lower plate of C2 to the entry, side to F1 ( $^{\circ}C$ );  $T_{p2}$ , temperature of the superior plate of C2, side to F2 ( $^{\circ}C$ );  $T_{p20}$ , Initial temperature of the superior plate of C2 to the entry, side to F2 ( $^{\circ}C$ );  $T_{s1}$ , temperature of the

coolant fluid F1 to the exit ( $^{\circ}C$ );  $T_{s2}$ , temperature of the coolant fluid F2 to the exit ( $^{\circ}C$ );  $V$ , Out-flow velocity of the coolant fluid ( $m.s^{-1}$ );  $x$ , Liquid phase concentration ( $ml.ml^{-1}$ );  $y$ , vapor phase concentration (if condensed) ( $ml.ml^{-1}$ );  $\lambda$ , thermal conductivity of the plate ( $W.m^{-1}.K^{-1}$ );  $\nu$ , water kinematic viscosity ( $m^2.s^{-1}$ ).

### Adimensionnal number

$Nu$ , Nusselt Adimensionnal number;  $Re$ , Reynold

Adimensionnal number:  $Re = \frac{V.D_H}{\nu}$ ;  $Pr$ , Prandtl

Adimensionnal number;  $Gz$ , Graetz Adimensionnal number :  $Gz = Re . Pr . \frac{D_H}{L}$ .

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