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DYNAMIC MODELLING AND SIMULATION WITH ECOSIMPRO OF AN EVAPORATOR STATION IN THE SUGAR INDUSTRY

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Abstract

This paper describes how a library of evaporation process units created in EcosimPro can be used to simulate the behaviour of any evaporation station and experiment with different working conditions.

For the tests, we have focused on an evaporator station used in the sugar industry comprised of five effects and eight evaporators. The first five are of the Robert type and the last two of the descending film type which allows us to build a model which is very similar to the real industrial facilities.

Key words: Simulation, EcosimPro, object-oriented, evaporator station, evaporator.

1 INTRODUCTION

Before concentrating on the development of the evaporation library in EcosimPro, it is necessary to explain some of the fundamental concepts of evaporation to be able to correctly understand the workings of a station. The objective of the operation is to concentrate a dissolved solid into a liquid.

The equipment in which the operation is carried out is called an evaporator. It consists of a shell where steam is condensed and a separation chamber in which the solution to be concentrated is boiled. As the solution loses solvent, the proportion of solute increases.

Evaporation can be carried out in one or several evaporators. When working with high flows and the cost of steam is high, a chain of evaporators is usually used. In this configuration the product to be concentrated passes from one evaporator to another in series, and the steam produced in the evaporation of one of them is used for heating the next evaporator. This is known as a

multiple effect system. The interest in this multiple effect system basically lies in the more efficient use of the steam. In these systems the term *first effect* is given to the evaporators which receive steam directly from the boilers, the term *second effect* to those which receive steam from the first effect, and so on. Likewise, the steam extracted from each effect is called *vapour*, so the vapour produced from the first effect is called *first effect vapour*.

With regard to the flow of each of the fluids, steam and solution to be concentrated, we have the following:

- The steam flows from the effect with most pressure to the effect of least pressure
- The solution to be concentrated can:
 - Flow in the same direction as the steam: direct flow
 - Flow in the direction opposite to that of the steam: countercurrent flow
 - Simultaneously feed several evaporators: parallel flow
 - Flow in no determined order: mixed flow

The direct flow feed system is the most common, largely because it is simpler to operate. With this system, it is the difference in pressure in each concentration chamber which makes the solution to be concentrated flow through the different evaporators. In some cases, therefore, it is necessary to make a vacuum in the last effect. The heat flux through the condensation chamber (shell) and the concentration chamber arises due to the temperature difference between the two.

With regard to the selection of an evaporator type, the trend is generally towards the one that has the highest heat transfer coefficient in the desired operating conditions. In this work we have used two –the Robert types and the descending film type– and so we will focus on describing the two.

The Robert type evaporator has a vertical cylindrical body and the tubes are anchored between two horizontal tubular plates. It has a large central downpipe with which a good solution flow can be obtained and this is a big advantage; however, its greatest disadvantage is the amount of space it occupies.

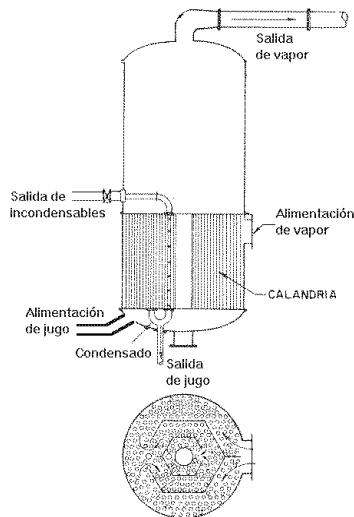


Figure 1: Robert type evaporator

In the descending film evaporators the liquid to be concentrated is pumped from a tank at the bottom and flows into the top of the evaporator, as does the vapour which is discharged from the equipment; the concentrate, meanwhile, is discharged from the bottom. So here we have an evaporator in which the substance to be treated flows in the form of a descending film along the internal walls of a tube bundle heated by steam. The main advantage of these evaporators is that they provide a thinner and faster film and therefore the heat transmission coefficient is quite high.

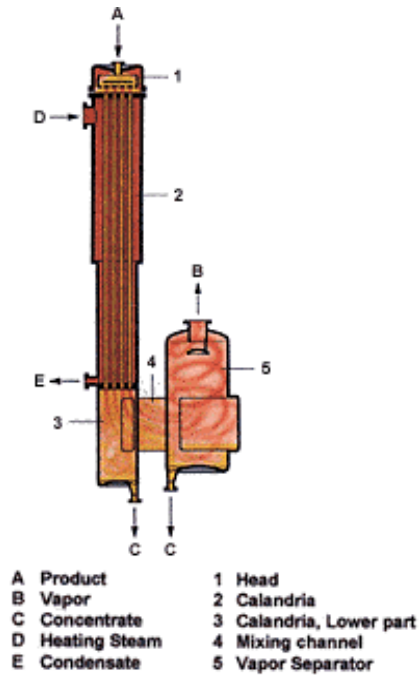


Figure 2. Descending film evaporator

2 EXAMPLE OF AN EVAPORATOR STATION IN THE SUGAR INDUSTRY

Figure 3 shows a schematic of a typical installation in a sugar factory.

The schematic shows an evaporator station comprised of five effects and eight evaporators. Each of the first five effects is composed of two Robert type evaporators with parallel flow, while the last two effects are comprised of two descending film evaporators. Furthermore, they also include the associated preheaters of the sweetened juice feed, expansion balls and a barometric condenser.

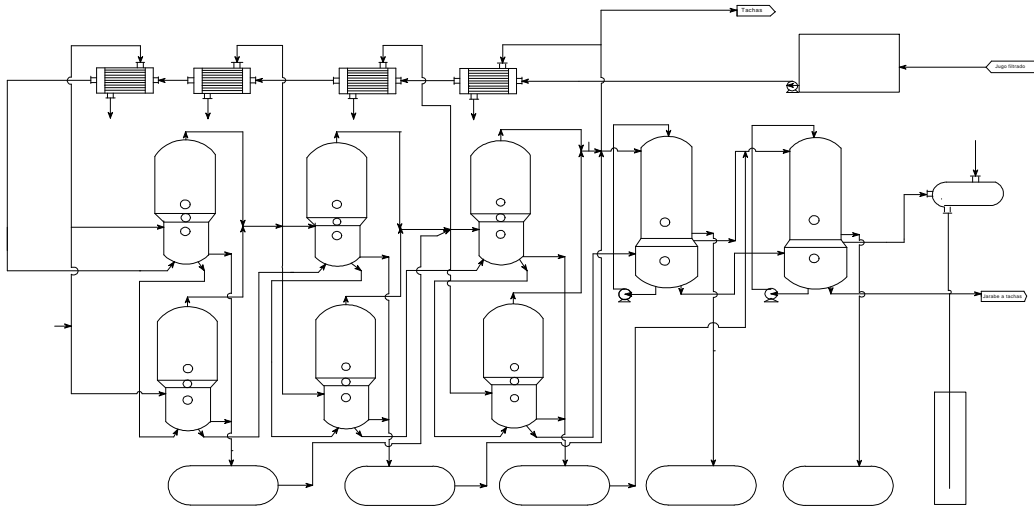


Figure 3. Schematic of an evaporator station

3 MATHEMATICAL MODEL OF AN EVAPORATOR

The model has been built on the basis of different hypotheses:

1. In the evaporator we have a perfect mix.
2. In the concentration chamber the steam and the solution to be concentrated are in equilibrium.
3. There is no accumulation of condensate in the calandria or the shell.
4. There is no accumulation of heat on the walls or in the tubes.
5. No consideration is given to the non-condensates from the steam condensation chamber.
6. No consideration is given to the heat losses to the exterior.

The following abbreviations are used:

W	mass flow of steam
W _c	mass flow of condensate
F	mass flow of feed
C	mass flow of concentrated juice (syrup)
E	vapour from the juice concentration chamber
c	fraction of solids in the juice

m	juice mass in the evaporator
m _v	steam mass in the evaporator
T	temperature
P	pressure
h	juice enthalpy
H	steam enthalpy
h _c	condensate enthalpy
q	flow of heat transferred from the condensation chamber to the juice concentration chamber
t	time

They are all expressed in SI units.

In the case of an evaporator in the sugar industry which is used to concentrate a sweetened juice, the total mass, sucrose mass and energy balances in the juice concentration chamber are as follows:

$$\frac{dm}{dt} = F - E - C \quad [1]$$

$$\frac{d(m \cdot c)}{dt} = F \cdot c_F - C \cdot c \quad [2]$$

$$\frac{d(m \cdot h)}{dt} = F \cdot h_F - C \cdot h - E \cdot H + q \quad [3]$$

The juice enthalpy, h , is a function of the sugar content, c , and of the temperature, T .

$$h=1500 + (4122-1512c)T + (0.55+3.75c)T^2 \quad [4]$$

We can therefore write the follow expression:

$$\frac{dh}{dt} = \frac{\partial h}{\partial c} \frac{\partial c}{\partial t} + \frac{\partial h}{\partial T} \frac{\partial T}{\partial t}$$

and, working with these equations, they can be expressed more appropriately as:

$$\frac{dc}{dt} = \frac{F \cdot (c_F - c) + E \cdot c}{m} \quad [5]$$

$$\frac{dT}{dt} = \frac{F \cdot \left((h_F - h) - \frac{\partial h}{\partial c} (c_F - c) \right) - E \cdot \left(H - h - \frac{\partial h}{\partial c} c \right) + q}{m \frac{\partial h}{\partial T}} \quad [6]$$

In this way, the mass, Brix and temperature of the juice are state variables of the model. The steam enthalpy is a known function of the pressure and the temperature:

$$H = 2.5 \cdot 10^6 + 1813 \cdot T_{sat} + 0.471 \cdot T_{sat}^2 - 0.011 \cdot T_{sat}^3 + 2090 \cdot (T - T_{sat}) \quad [7]$$

$$\text{where } T_{sat} = 2147 / (10.76 - \log(P)) - 273.2$$

and the pressure, p , is fixed by the ratio of equilibrium:

$$T = T_{sat} + a_1 + a_2 \cdot T_{sat} + a_3 \cdot T_{sat}^2 \quad [8]$$

where:

$$a_1 = -0.2 + \exp(-1.5254 + 2.2962c + 2.163c^2) \quad [9]$$

$$a_2 = 0.01(-0.15 \exp(-3.202 + 6.6743c - 1.161c^2)) \quad [10]$$

$$a_3 = 1e^{-4} \exp(-1.4278 - 2.4382c + 6.047c^2) \quad [11]$$

So now, to obtain the evolution of m , c and T in time, we only need additional equations for the heat and mass flows. Since q depends on the transmission of heat from the condensation chamber, the mass and energy balances of this chamber are expressed as follows:

$$\frac{dm_v}{dt} = W - W_c \quad [12]$$

$$\frac{d(m_v H)}{dt} = W \cdot H - W_c \cdot h_c - q \quad [13]$$

The constants of time associated with these balances are very low in relation with those of the concentration chamber. It was therefore possible to assume a steady state in the condensation chamber and express the following:

$$W \cdot (H - h_c) = q \quad [14]$$

Here, H is a function of P_1 and T_1 , and

$$h_c(T) = 1500 + 1122T + 0.55 T^2 \quad [15]$$

Therefore, beginning with the initial values of the state variable and for certain external conditions, all the flows can be determined and, therefore, by integrating the differential equation we obtain new values for T , c and m .

In the event that we have multiple effects, the flow of steam from each evaporator is calculated taking into account that it is equal to the flow of steam which condenses in the next evaporator.

4 EVAPORATION LIBRARY

Based on the models presented, a series of components and ports has been developed which forms the evaporation library. The fundamental components are the evaporators and their chambers, as well as the preheaters, balls, etc. In the same way, juice and steam ports are identified. In all these a series of functions is used with which different physical properties are calculated, whether they belong to the steam or to the solution to be concentrated.

With all the ports created, the system automatically introduces all the related equations with the way in which the connections are made. This means, basically, equality of pressure and addition of the mass flows (taking into account their inlet or outlet direction) in all the connection points.

PORT vapor

```
EQUAL REAL P RANGE 0,Inf "Presión(bar)"
REAL T RANGE -273,Inf "Temperatura (°C)"
SUM REAL W RANGE 0,Inf "Flujo másico de vapor (kg/s)"
SUM REAL f_energ "Flujo de energía (KW)"
CONTINUOUS
T=temperatura_sat(P)
f_energ=W*entalp_vap(P)
END PORT
```

```

PORT jugo
SUM REAL W RANGE 0,Inf "Flujo másico (kg/s)"
REAL c RANGE 0,1 "Fracción de sólidos
(% 1 en peso)"
REAL T RANGE -273,Inf "Temperatura (°C)"
SUM REAL f_energ "Flujo de entalpía (KW)"
REAL F "Flujo volumétrico (m3/s)"

```

```

CONTINUOUS
f_energ=W*h_jugo(T,c)

```

```

W=F*den_jugo(T,c)

```

```

END PORT

```

Among the constants defined we have the purity of the solution to be concentrated, because this value remains constant throughout the complete evaporation stage.

```

CONST REAL pureza=0.93

```

With respect to the components, the following have been developed:

- Condensation chamber
- Concentration chamber (Robert)
- Concentration chamber (descending film)
- Evaporator
- Flow mixer
- Flow disperser
- Heat exchangers
- Barometric condenser
- Proportional controller
- PI controller

The following studies the most significant in more detail.

4.1 CONDENSATION CHAMBER COMPONENT

This component is common to all types of evaporators. It basically consists of a chamber into which steam flows, is condensed and causes a latent heat transfer, and from which the same flow, now condensed, is discharged.

This component therefore contains the equations that refer to the balance of mass and energy of the chamber. These equations are represented in steady state for the reasons indicated in the development of the mathematical model.

```

COMPONENT camara_cond

```

```

PORTS

```

```

IN vapor v_in
OUT agua f_out
OUT termico q_out

```

```

CONTINUOUS

```

```

v_in.W=f_out.W
v_in.f_energ-f_out.f_energ=q_out.q
f_out.P=v_in.P
q_out.T=f_out.T

```

```

END COMPONENT

```

4.2 CONCENTRATION CHAMBER COMPONENT

The concentration chamber of an evaporator is modelled according to the type of model in question, because each evaporator has different characteristics which make them particularly advantageous in determined applications. In particular, the available surface for heat transmission varies from some types to others.

The Robert evaporator is a sugar industry evaporator par excellence, although as we mentioned earlier, it is being substituted by the descending film evaporators.

The equations used in this component have already been described and, as in the previous case, they basically correspond to the mass and energy balances and equilibrium equations related with that chamber.

```

COMPONENT camara_conc

```

```

PORTS

```

```

IN termico q_in
IN jugo f_in
OUT jugo f_out
OUT vapor v_out

```

```

DATA

```

```

REAL Nt=5000 "número de tubos"
REAL di=0.03 "diámetro interior de
los tubos (m)"

```

```

DECLS

```

```

REAL c -- fracción de sólidos en el
jugo (%Brix/100)
REAL m -- masa de jugo (kg)
REAL T -- temperatura (°C)
REAL Pjugo --Presión jugo (bar)
REAL dhc -- derivada de entalpía
respecto a concentración
REAL dhT -- derivada de la entalpía
respecto a la temperatura

```

```

REAL volumen
REAL nivel
REAL Sup -- Superficie disponible

```

para la circulación de jugo

```

REAL SP_L    -- consigna de nivel
CONTINUOUS
dhc=(-1522*T+3.75*T**2)/1000
dhT=(4122-1522*c+1.1*T+7.5*T*c)/1000
m'=f_in.W-f_out.W-v_out.W
c'=(f_in.W*(f_in.c-c)+v_out.W*c)/m
T'=(f_in.W*(h_jugo(f_in.T,f_in.c)-
  h_jugo(T,c))-dhc*(f_in.c-c)\
-v_out.W*(entalp_vap(v_out.P)-
  h_jugo(T,c)-dhc*c)+q_in.q)/(m*dhT)
v_out.P=presion(T,c)
q_in.T=T
f_out.T=T
f_out.c=c
Pjugo=v_out.P+den_jugo(T,c)*9.8*nivel)/
  10**5
volumen=m/den_jugo(T,c) --volumen de jugo
Sup=PI*di**2*Nt/4
nivel=(volumen-4.5)/Sup
END COMPONENT

```

4.3 EVAPORATOR

Once the components of the condensation and concentration chambers have been defined, it is easy to define an evaporator by composition.

USE MATH

USE PROCESS

COMPONENT un_evapR

PORTS

IN jugo	jugo_in
IN vapor	vapor_in
OUT vapor	vapour_out
OUT agua	cond_out
OUT jugo	jugo_out

DATA

```

REAL Ntubos=5000 "Número de tubos"
REAL dint =0.033 "diámetro interior tubos(m)"
REAL esp=0.002 "espesor de los tubos(m)"
REAL Long=3.5 "longitud de los tubos(m)"
REAL Usup =2

```

DECLS

REAL salto

TOPOLOGY

```

camara_cond    c1
camara_conc    c2
Pared          p1

```

```

CONNECT c1.v_in TO vapor_in
CONNECT c1.f_out TO cond_out
CONNECT c2.f_in TO jugo_in
CONNECT c2.f_out TO jugo_out
CONNECT c2.v_out TO vapour_out
CONNECT c1.q_out TO p1.pared_in
CONNECT p1.pared_out TO c2.q_in

```

CONTINUOUS

salto = cond_out.T - jugo_out.T

END COMPONENT

4.4 PREHEATER COMPONENT

The evaporator feed is preheated in a row of heat exchangers in series. These are heat exchangers that are comprised of a shell and tubes. Through these tubes flows the solution which is to be heated to the desired temperature (the temperature of the concentration chamber of the first evaporator) and through the chamber flows the steam (normally small vapour currents) which condenses.

Once the flows, temperatures, pressures... are known the flow of transferred heat can be calculated, because the heat given off by steam condensation is equal to the heat taken by the sweetened juice and, in turn, it is the heat which is transferred through the heat exchanger tube wall. That is:

$$q = m_v \cdot I = m_j \cdot C_{pj} \cdot \Delta T = U \cdot S \cdot \Delta T_{in} \quad [16]$$

where m_v , is the mass flow of steam that condenses, λ the latent condensation heat, m_j , the mass flow of sweetened juice, C_{pj} , the specific heat of the juice, ΔT the difference in temperature between juice output and input, U the overall heat transmission coefficient, S the heat exchanger surface and ΔT_{ln} , the difference in temperature (logarithmic average between the extremes of the evaporator temperature profile).

As the flow of transferred heat and the temperature difference are known, assuming an overall heat transmission coefficient from the previous equation, the value of the surface S can be obtained.

Some standard heat exchanger tube dimensions are selected, ie, inside diameter, thickness and length. With these values we can calculate the surface of each tube and, therefore, the number of tubes.

$$S_{tubo} = p \cdot d_o \cdot L \quad [17]$$

$$N_{tubos} = \frac{S}{S_{tubo}} \quad [18]$$

Once all the heat exchanger dimensions have been calculated, the assumed overall heat transmission coefficient is verified (equation 19). To do this, we have to calculate the individual heat transmission coefficients on the tube side, h_i , and on the shell side, h_o , with the use of empirical equations.

$$\frac{1}{U} = \frac{1}{h_o} + \frac{d_o}{d_i \cdot h_i} + \frac{d_o \cdot \ln\left(\frac{d_o}{d_i}\right)}{2 \cdot K_w} + \frac{1}{h_{od}} + \frac{d_o}{d_i \cdot h_{id}} \quad [19]$$

where K_w is the thermal conductivity of the tube material h_{od} and h_{id} the coefficients that take into account the effect of dirt on the transmission of heat for the shell and tube sides, respectively.

Individual heat transmission coefficient on the outside of the tubes

Complete condensation takes place in the shell. The overall heat transmission coefficient in the case of condensation on the outside of horizontal tubes is calculated for one tube only and it is corrected with a factor related to the

number of tubes in a horizontal row, expressed as follows:

$$h_o = 0.95 \cdot K_L \cdot \left[\frac{(r_L - r_V) \cdot r_L \cdot g}{m_L \cdot \Gamma_V} \right]^{1/3} \cdot N_r^{-1/6} \quad [20]$$

where:

K_L , thermal conductivity of the liquid, W/m²°C

ρ_L , density of the liquid, kg/m³

ρ_V , density of the stem, kg/m³

μ_L , viscosity of the condensate, kg/m s

Γ_V , flow of condensate per perimeter unit of tube, that is, W_c / (N_t L)

N_r , average number of tubes per vertical row

Individual heat transmission coefficient on the inside of the tubes

Sweetened juice flows on the inside of the tubes, where it is heated by means of convection. In this case, the heat transmission coefficient is calculated with equation 21.

$$hi = 0.023 \cdot \left(\frac{k_L}{di} \right) \cdot Re_L^{0.8} \cdot Pr_L^{0.33} \quad [21]$$

where:

k_L , thermal conductivity of the liquid, W/m²°C

d_i , inside diameter of the tube, m

Re , Reynolds number, adimensional=($d \cdot u \cdot \rho / \mu$)

Pr , Prandtl number, adimensional=($C_p \cdot \mu / k_L$)

Based on the foregoing, we can model the preheater as a component comprised of another three components:

1. the shell where steam condensation takes place with the consequent emission of heat,
2. the tube walls through which heat is transmitted, and
3. the inside of the tubes through which the solution to be heated flows.

A steady state has been considered for the preheaters, in order to reduce the number of equations and simplify the calculations. In addition, a constant thermal gradient has been assumed on the tube side (equivalent to the minimum thermal gradient), which gives us the most unfavourable situation.

USE MATH

```

USE PROCESS

PORT termico_camb
    EQUAL REAL Tent
    EQUAL REAL Tsal
    SUM REAL q
END PORT

COMPONENT camara_liq

PORTS
    IN jugo f_in
    IN termico_camb q_in
    OUT jugo f_out

CONTINUOUS
    f_in.W=f_out.W
    q_in.Tent=f_in.T
    q_in.Tsal=f_out.T
    q_in.q=f_out.W*4.21*(f_out.T-f_in.T)
END COMPONENT

COMPONENT camara_conden

PORTS
    IN vapor v_in
    OUT agua f_out
    OUT termico_camb q_out

CONTINUOUS
    v_in.W=f_out.W
    v_in.f_energ-f_out.f_energ=q_out.q

    f_out.P=v_in.P
    q_out.Tent=q_out.Tsal
    q_out.Tent=f_out.T
END COMPONENT

COMPONENT pared_camb

PORTS
    IN termico_camb pared_in
    OUT termico_camb pared_out

CONTINUOUS
    pared_in.q = pared_out.q
END COMPONENT

COMPONENT precalentador

PORTS
    IN jugo jugo_in
    OUT jugo jugo_out
    IN vapor v_in
    OUT agua cond_out

DATA
    REAL temp=8 "salto térmico del jugo en
    el precalentador(°C)"
    
```

```

TOPOLOGY
    camara_liq cjugo
    camara_conden cvapor
    pared_camb pared

CONNECT jugo_in TO cjugo.f_in
CONNECT jugo_out TO cjugo.f_out
CONNECT v_in TO cvapor.v_in
CONNECT cond_out TO cvapor.f_out
CONNECT cvapor.q_out TO pared.pared_in
CONNECT pared.pared_out TO jugo.q_in

CONTINUOUS
    cjugo.f_in.c=cjugo.f_out.c
    cvapor.f_out.T=cjugo.f_in.T +temp
END COMPONENT
    
```

4.5 BAROMETRIC CONDENSER

The steam from the last effect of an evaporate is usually extracted by means of a condenser. The most commonly used type is the countercurrent barometric condenser. This is direct contact equipment in which steam is condensed as it ascends through a fine mist of cooling water. These condensers are not expensive and prove to be economical as far as water consumption is concerned.

The barometric condenser is so called because of the way the condensate is removed. It descends through a vertical pipe, known as a barometric head, which is long enough so that the pressure at the bottom is slightly higher than atmospheric pressure. The condensate is vented to a tank which is open to the atmosphere. The condenser must therefore be installed high enough so that the water can be discharged by gravity from the condenser vacuum.

The ratio of water consumption versus the flow of condensed steam can be determined by means of the following equation:

$$\frac{\text{Flujo de agua}}{\text{Flujo de vapor}} = \frac{H_v - h_2}{h_2 - h_1} \quad [22]$$

where H_v is the enthalpy of the steam, and h_1 and h_2 is the enthalpy of the water that enters and leaves the condenser.

```

USE PROCESS

COMPONENT cond_bar

PORTS
    IN vapor v_in
    IN agua f_in
    
```

```

OUT  agua  f_out
DATA
REAL Cp=4.184 "calor específico (KJ/kg
°C)"
DECLS
REAL sp_P
CONTINUOUS
f_out.W=f_in.W+v_in.W
f_out.P=v_in.P
f_in.W=v_in.W*(entalp_vap(v_in.P)-
h_liq(f_out.T))/(h_liq(f_out.T)-Cp*f_in.T)

END COMPONENT

```

5. EXAMPLE OF APPLICATION

As an example the process shown in Figure 3 has been simulated, joining the library components necessary and adding the essential control elements; specifically, juice level regulators in each evaporator and syrup flow regulators at the outlet. Different experiments were subsequently carried out, of which some of the results are given below:

A. Live steam pressure rise

The live steam pressure has risen from 3 to 3.3 bar (Figure 4) approximately at the instant of time 2500 and, as a consequence, there has been a rise in the pressure (Figure 5) and temperature of the concentration chamber (Figure 6). From these figures we can see the temporary evolution of these magnitudes in the different evaporators, according to the legends in the figures. Likewise, we can see an increase in live steam flow (Figure 7), in this case in the first two evaporators because they are in parallel, and an increase in the feed juice (Figure 8). We can also see a decrease in the flow of syrup extracted (Figure 9) and therefore there are no significant changes in the syrup concentration (Figure 10).

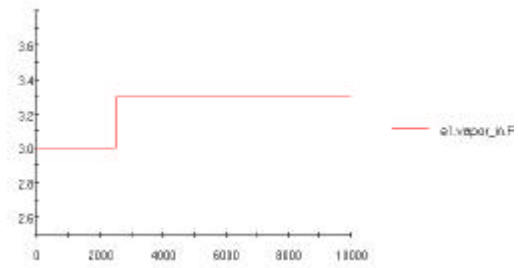


Figure 4. Rise in live steam pressure

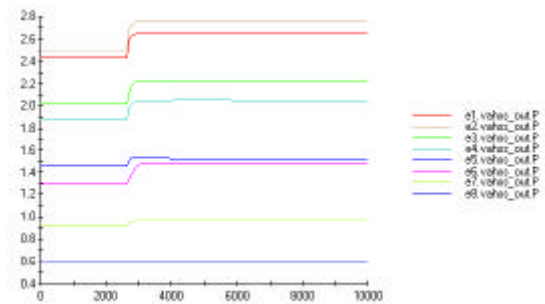


Figure 5. Vapour pressure

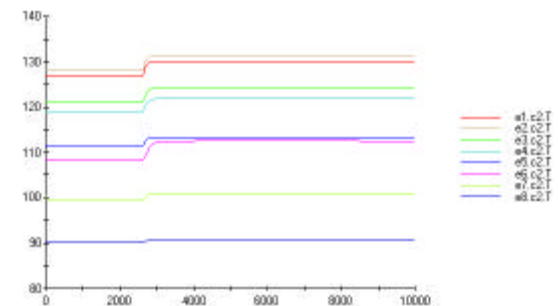


Figure 6. Concentration chamber temperature

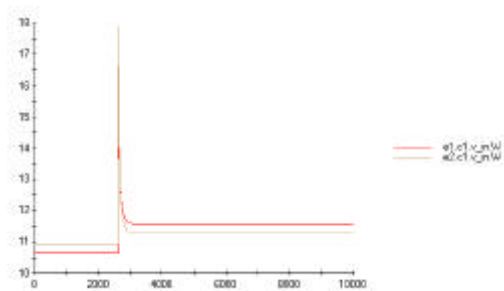


Figure 7. Live steam flow

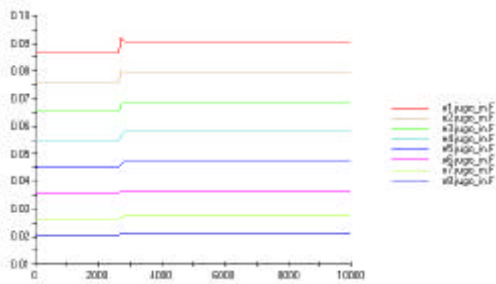


Figure 8. Feed juice flow

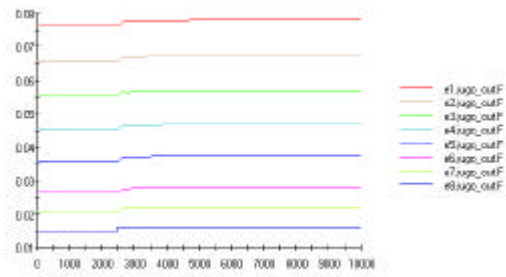


Figure 11. Flow of syrup at the outlet of the evaporators

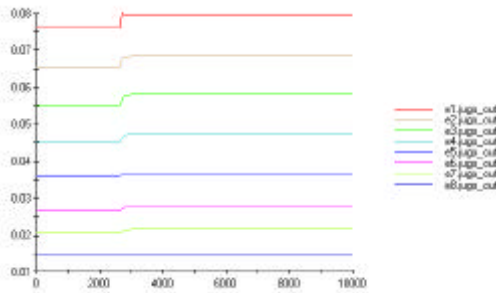


Figure 9. Extracted syrup flow

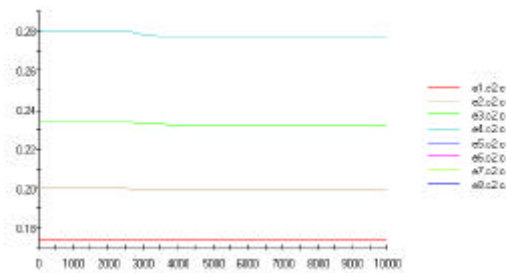


Figure 12. Concentration of syrup at the outlet of the first and second effects

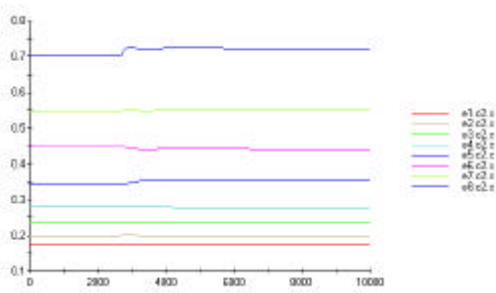


Figure 10. Juice concentration

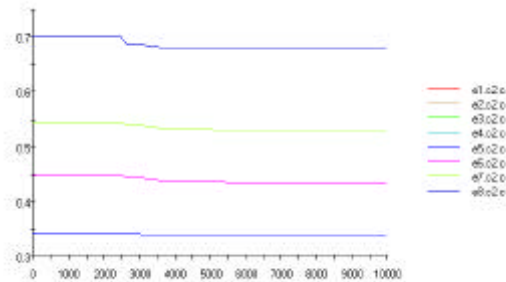


Figure 13. Concentration of syrup at the outlet of the remaining evaporators

B. Rise in flow of extracted syrup

Exactly as though we had only one evaporator, as the discharge flow of final syrup increases (Figure 11) the less amount of time the juice remains in the evaporator and, therefore, the syrup concentrations at the outlet decrease (Figures 12 and 13). Because of this, to maintain the level of juice in the tubes the feed flow must be increased (Figure 14). With the addition of more juice, the concentration continues to decrease and it is therefore necessary to increase the flow of steam (Figure 15).

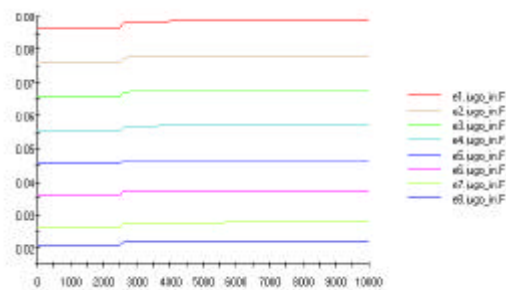


Figure 14. Flow of feed juice

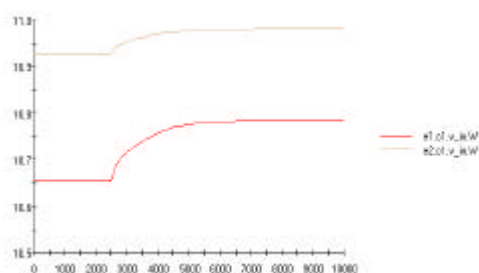


Figure 15. Flow of live steam

6 CONCLUSIONS

Throughout this work, one of the main advantages of EcosimPro has been put to good use: the modularity. This means that once we have the dynamic model of an evaporator and its correct operation has been checked, it forms a component which can be connected to other components, whether they are the same or not. In this way we can “build” any evaporator station, no matter how many evaporators it has or their arrangement (in series, in parallel, etc), using a minimum number of components.

The above results show great similarity with the real behaviour of evaporator stations. This means we have an evaporation library in EcosimPro which can be used as a reliable tool for the simulation of different operating conditions.

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