POLITECNICO DI MILANO

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A STUDY OF DIFFERENT MULTI EFFECT EVAPORATORS DESIGNED FOR THERMAL PROCESSING OF TOMATO PASTE: OPTIMIZATION AND QUALITY EVALUATION

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ABSTRACT

Thermal processing is an important method for food preservation, and since its invention, it has been a mainstay of the food industry.

The main purpose of this research is the development of a model for optimizing multiple effect counter current evaporator systems for tomato paste concentration, in which diluted food enters at 5 °Brix and must be processed to 30 °Brix for product sale.

The economic evaluation will include a quality parameter that influences final price, modifying the classical chemical engineering view that considers only cost minimization for the best arrangement of individuation. In this particular case, the sale price will be considered directly dependent by the final lycopene retention.

In addition, the final content of ascorbic acid and furosine as well as the color will be analyzed as part of the determination of quality.

The study will be concentrated on a 4 effect evaporator system that returns the best gains in the basic disposition.

Variations in the arrangement and in the operating conditions will be evaluated, and the following will be analyzed: the introduction of a pre-heating and pre-concentrating stage; the use of a larger evaporator; the utilization of evaporators with different areas; and changes in the fresh, hot steam pressure necessary for the treatment.

The best configuration for economic analysis and lycopene retention will be identified as the one without recycling, with an equal heat exchange area for each evaporator and with the highest fresh, hot steam pressure, offering a NPV (net present value) of 45600000 $.

1 - INTRODUCTION

Under the name “food industry” are included all factories that process products of the primary sector (principally farming, hunting and breeding) for providing consumer products.
Normally, it is possible to classify the food processing industry with a standard industrial classification (SIC) that recognizes 47 different processes; more generally, it is easier to divide it in 6 different branches; jams, dehydrated foods, frozen foods, juices, confectioneries and various seafood products.
Today, the total Italian sales of the alimentary sector amounts to 120 Mld€, while the rate of exportation is about 20 Mld€ (65% in the European Union (EU), especially Germany). The rate of importation is about 16 Mld€, which means it is the most important, even before the chemical and mechanical fields.
This sector has always been dominated by local companies and a homogeneous study of its development is quite difficult; only in the last few years has it been largely influenced by multinational corporations.
In the EU, the food industry is also the leader: it is first in the number of workers, and it has a turnover of 913 Mld€ and exportations of 54.7 Mld€.
Since its birth, the alimentary market has been in continuous development (except for some periods of crisis, as is the case today) to satisfy the demands for higher quantity and quality.
The field of quality, in particular, is in a constant state of evolution as it tries to stay in line with changing lifestyles and the demand for healthier food. For these reasons, food engineering in recent years has gained greater visibility.
One of the principal products of the food industry are tomatoes. They are the most important vegetables produced and processed in the world, with total sales of 300 Mil€ and a market volume of 136,000 tons.
Two-thirds of the world’s tomato production is processed, dried and concentrated for tomato paste, which is the most convenient form of conservation.
In this process, the tomato pulp is normally heated and dried in evaporators resulting in a partial removal of the water. This gives the product a longer life, improving a market that is highly seasonal because of the concentration of this vegetable’s production in the summer months.
It is estimated that 60 to 65% of the raw production worldwide is concentrated in California and Italy. Northern Italy in recent years has registered an increase in tomato paste consumption.

The Italian tomato paste market is influenced by a competition between all of the producers to provide better convenience. There is no clear company leader, and the four most important companies do not account for more than 30% of the sales.

The industrial standard for commercialization is the attainment of 30 ºBrix of the final pulp, which means that of 100 parts, 30 have to be solid.

While paste concentration is a constraint, the quality of the product is investigated by the final amount of several substances like ascorbic acid, furosine and lycopene (as well as many others) and by the color.

Furosine (2-furoylmethyl-lysine) is an amino acid generated by the undesired acid hydrolysis of an Amadori compound. It is a recognized indicator of heat damage, and its amount is a quality indicator for vegetables such as beans, potatoes, rice and tomato products.

Furosine is the product of the first step of the Maillard reaction, a complex system of reactions that gives high molecular products, starting from the reaction of a reducing sugar with an amino acid, secondary properties like changes in appearance (mainly color) and flavor, a reduction of natural content, possible toxicity, losses of antioxidant proprieties, and increased water activity.

Ascorbic acid is a water-soluble, anti-oxidant vitamin that has various functions in the human body, which cannot synthesize it and must obtain it by alimentary consumption.

A lack of ascorbic acid can generate hypercholesterolemia and an accumulation of cholesterol in certain tissues.

Color is another index for quality change analysis after thermal processing and for the determination of product conformity.

Lycopene is another essential substance that the human body is unable to synthesize and must get from food. Tomato products are the major source of Lycopene.

Increasing studies on its biological and physicochemical proprieties support its function of protection against heart disease and cancer. In particular, its role as a micronutrient with anti-oxidant proprieties has attracted attention.

Lycopene is the main carotenoid of tomatoes and is the pigment that gives the fruit its characteristic red color. It is an enzyme that could be degraded or lost after thermal treatment.

In fresh tomatoes, it is available only in the trans-configuration, but heating could activate reactions of oxidation and isomerization, giving it the high energy cis-configuration.

The bioavailability of lycopene could be improved after processing and after the destruction of the food matrix that makes it more accessible. However, the effects of heating on lycopene and on some proprieties of this substance are still poorly understood and will likely be investigated in the future.

Today, tomato paste is normally obtained with a system of 3-5 multi-evaporators under low pressure with a temperature that does not exceed 70 °C.

The choice of the number of effects used is derived by an economic evaluation of the whole process.

This evaluation depends on investment costs (linked with the number of devices), maintenance costs and operation costs. First, the sale price of the product is fixed, followed by the function of lycopene retention after concentration while introducing a variable influenced by final paste quality.

The goal of this work is to study of the economic convenience of different multi evaporator systems for tomato paste concentrations from 5 °Brix to 30 °Brix with the final content of Lycopene as the quality parameter of the process.

In addition, the retention of ascorbic acid, the formation of Furosine and the color of the final product will be analyzed, but without considering economic influence.

Starting from a normal counter current system, the effects of the introduction of a preconcentration stage of and of some changing operative variables on cost and on different quality parameters will be evaluated.

2 - LITERATURE REVIEW

2.1 - Evaporation

Unit operation in which a liquid solution is concentrated by removing part of the solvent after boiling is called evaporation.

Evaporation differs from dehydration because the final product is still in a liquid phase and from distillation because the vapor produced is not divided into fractions.

Other techniques are present in the food industry, like freeze concentration, reverse osmosis, membrane concentration and ultra filtration. However, evaporation is still the most economic and most used thanks to the technologies developed for energy recovery.

In most cases, and in the following studies, the solution to be concentrated is dilute food and the solvent removed is water in vapor form.

The removal of water from foods has two main purposes:

- Improve microbiological stability with the reduction of water activity, which is the predominant factor in most organic degradation processes;
- Reduce transportation, packaging, distribution and storage costs by minimizing volume and weight.

Vacuum evaporation is often used with the goal of reducing the temperature necessary for boiling because of the high heat sensitivity of food.

Because of the equilibrium between pressure and the boiling point, lower pressures allow boiling at reduced temperatures, thereby minimizing heat damage and food degradation.

2.2 - Evaporators

An evaporator is a device that concentrates a solution by removing part of its solvent (normally water) in the form of vapor.

Generally, all evaporators are comprised of the same components. In fact, they could be defined as heat exchangers in a large chamber with a chest for fluid introduction, which in most cases is condensing steam supplying latent heat.

If there is only the operation of evaporation, the device is called a single unit evaporator.

If the vapors produced are reused in a following chamber, it is possible to create new configurations called multiple effect evaporators (where the number of the effect is the number of the evaporators).

A low concentration fluid is heated until evaporation temperature and then loses water, giving a highly concentrated liquid, while high pressure steam changes phase, becoming saturated water. Dilute fluid is normally preheated and divided equally to the heat transfer surface of the device: a better distribution of the food is requested for efficient operation and minimal product degradation. The next stage is an efficient separator (to avoid wasting elaborated work) that could isolate concentrate from vapor, which can be reused in an eventual following device or could go to a final condenser for warming water with the objective of energy recovery.

Evaporator design is a key factor in the whole process because most of the financial investment depends on the heat exchanger. An improvement in the transfer surface could mean a strong decrease in costs. This is because food products normally have a high heat sensitivity and can also be damaged with relatively short residence times resulting from poor distribution.

Evaporator process performance depends on fluid characteristics: the removal of water increases viscosity, which reduces the heat transfer rate and increases the boiling point.

Thermal degradation can be minimized using vacuum evaporators, reducing temperature and residence time, and resulting in optimal quality products.

A summary of the requirements for efficient evaporation are:

- Suitable heat exchange: the heat exchange rate depends on the evaporator type, the thermo-physical characteristics of the products, the heat exchanging area and its fouling;
- Efficient liquid-vapor separation: this is a crucial for not wasting good technology;
- Recover of energy: the vapor produced is an energy source, and for a more economic process it should not be wasted;
- Product treatment: working with food means that the product could be highly heat sensitive and damaged during the process. Therefore, it is necessary to pay particular attention to the quality of the product and its possible contamination. The formation of foam could allow the product to escape through vapor outlets.

2.2.1 - Simple effect evaporation

A simple effect evaporator is the easiest to use and consists of only one unit of work.

In this device, the liquid receives energy directly from high-pressure steam fed from the chest that condenses and is put out as hot, saturated water. Product flows out in a concentrated state after the removal of water. The vapor produced has a lower pressure and lower energy than the initial steam, which is not reused and goes to a condenser.

This process presents minimal investment costs, but the operational costs are quite high, being linked with the elevated costs of high pressure steam.

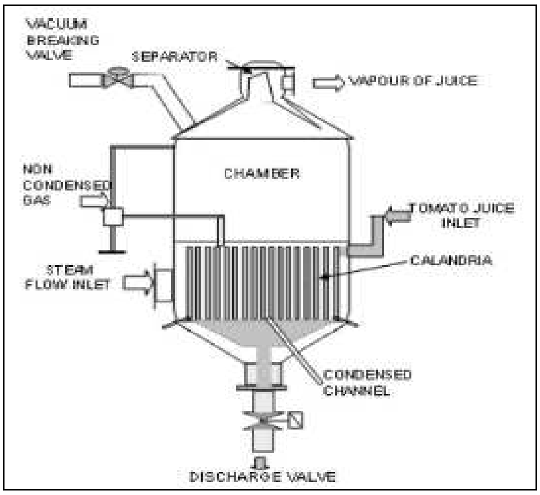


Figure 1: Simple effect evaporator

2.2.2 - Multiple effect evaporation

In a multiple effect configuration, several devices are combined in a sequence with the goal of using vapors from a previous stage as a service fluid in the following step, in which food enters partially concentrated without losing its associated energy.
The pressure of the following step is always lower, assuring the necessary driving force for the evaporation of the solution solvent.
The food industry normally uses a number of effects between three and seven. By adding more stages, it is possible to obtain lower operating costs but with higher investments costs. A final choice is made after an adequate economic evaluation of the whole process.

2.2.3 – Equi current systems

A multi effect process is called an equi current system, if the tomato paste and steam flow are in the same direction and are fed into the same device (which is the first and has the highest temperature).

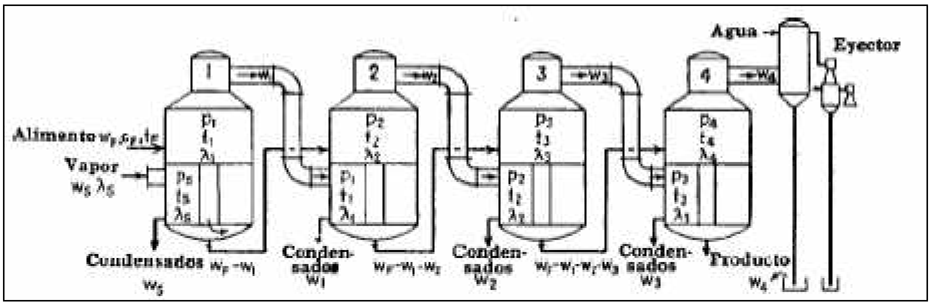


Figure 2: Equi current system of multiple effect evaporator (KERN.Q.D 1999)

2.2.4 – Counter current system

When steam enters the first evaporator and paste is fed in the last evaporation, two fluid flows in different directions create a counter current system.

This schema avoids processing concentrated fluid, which has the highest viscosity in the last stage than in the equi current configuration, which has lowest pressure and lowest temperature.

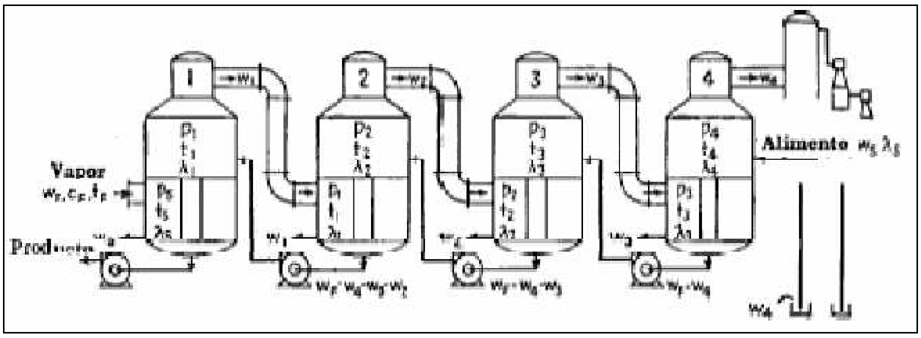


Figure 3: Counter current system of multiple effect evaporator.(KERN.Q.D 1999).

2.3 – Quality degradation

Degradation of the chemical products of organic compounds is a natural consequence of the thermal processing utilized for obtaining better food preservation.

The addition of thermal energy influences microbiological instability and quality attributes with the loss or denaturization of important nutritional compounds accompanied by changes in color, flavor and texture.

The control of evaporation by temperature and residence time analysis is a key factor in preventing these undesired reactions.

The best food conservation is assured with the lowest temperature and lowest residence time: for this reason it is important to utilize the best evaporator type that achieves the highest heat exchanging coefficient.

The vulnerability of some substances could depend on the material of the evaporator. In some cases, it is important to avoid metals that could give possible catalytic effects to undesired reactions (Perry, 1980).

In keeping with a universal request for higher quality, studies on the influence of thermal processing on nutritional content have improved in recent years.

The following work will analyze product quality by calculating the final content of furosine, ascorbic acid, lycopene, and by examining color modification.

A preview study developed a kinetic of reaction for all of these indexes.

The furosine content follows a pseudo 0.5 order kinetic model formation, in which the final concentration depends on temperature, residence time and initial concentration (Hidalgo, 2000).

The equation associated with this theory results in:

$$C_{out} - C_{in} = -k \cdot \tau \cdot C_{out}^{0.5}$$

The preview equation is typical of CSTR systems, which will be studied in this work.

While τ is the residence time, C_{out} is the final concentration of furosine, C_{in} is the initial concentration, and *k* is the kinetic constant of the reaction that changes the function of the temperature by an Arrhenius equation:

$$K = A \cdot \exp(-\frac{Ea}{R \cdot T})$$

where A is the pre-exponential factor and Ea is the activation energy of the furosine reaction in tomato.

Ascorbic acid follows a first order kinetic degradation (Giovanelli):

$$C_{out} - C_{in} = k \cdot \tau \cdot C_{out}$$

where the constant k is calculated, similarly to furosine, with the same typology of the Arrhenius equation.
Color follows a power law model in line with the following equation (Lavelli):

$$\Delta E = k \cdot t^{0.5}$$

2.4 – Economic evaluation

A multiple effect evaporation system is part of a typical industrial plant. The goal of these installations is to make the highest profit, so an economic evaluation of the whole system is necessary.
In this particular case, cost estimation allows for individuating the optimal number of effects and the best operating conditions before the construction of the plant.
In fact, these investments need a large amount of capital for installation, and it is essential to analyze several alternatives.
For chemical engineering, the best configuration is the one that minimizes total costs.
By the classical definition, “Plotting total costs of the process and number of effects, it is possible to individuate a minimum of the function that corresponds to optimal number of effects” (Kern,1999).
This analysis appears to be the right one, until we consider final price of the product fixed and independent.
Tomato concentration is an invasive thermal process, and different operating conditions can deeply influence the final quality of the products.
This means that with different process designs and different process conditions it is possible to obtain the same concentration with a distinct nutritive content.
When the final price is not independent, but a function of the retention of some important compounds, the classical definition is changed and the study of quality is introduced.

2.5 – General economic analysis: NPV

NPV (Net Present Value) is an index that can help individuate the best configuration of the studied process. The word Net suggests that both total costs and benefits will be included in this measure. To calculate NPV, it is first necessary to estimate the capital required for the installation of the plant, then the operating costs of the system and, finally, of the income from product sales. While the first parameter is immediate and fixed, the next are time dependent and may be actualized with an adequate interest rate for providing future variations.
If the NPV is negative, the investment is not justified because it doesn't give a profit, but a loss of capital. On the contrary, a positive NPV warrants earnings, and an increase of this index is synonymous with cost minimization.
The mathematical expression for NPV evaluation is the following:

$$NPV = -I + \sum_{J=1}^{n} \frac{\beta_j}{(1+i)^j} = -I + \sum_{J=1}^{n} \frac{Q_j \cdot (P_u - C_u)}{(1+i)^j}$$

Where:

- I is the total investment for the process
- B_j are the benefits in the j year
- Q_j is the annual production in the j year
- P_u is the unitary price in the j year
- C_u is the unitary cost in the j year
- i is the discount rate
- n is the number of periods for NPV evaluation.

The system design and process conditions directly influence investment costs, annual production and unitary costs, while the unitary price is influenced by how the product is sold.
If the quality influences the price, this parameter depends on the same factors; instead it becomes a fixed value.
Today, quality is increasing in importance, and it is not possible to hold the price of the product as independent. However, it is possible to justify this simplification for an initial microeconomic evaluation of the process.

The total investment depends on the number of effects.

2.6 – Multi effect evaporators

The following study of multi effect evaporators introduces the quality parameter of final lycopene retention. After initial considerations, starting from the NPV equation:

$$NPV = -I + \sum_{j=1}^{n} \frac{\beta_j}{(1+i)^j}$$

Where Bj are the annual benefits:

$$\beta_j = Q_j \left(P_u - C_u \right)$$

it is possible to evaluate the optimal effect number when considering that the final price of the product is a function of the lycopene retention and is not fixed. This means that the parameter is influenced by a number of effects and operating conditions.
Hence, it is possible to point out the dependence of all the parameters from the system's variables of connotation:

$$NPV = -I(N_e) + \sum_{j=1}^{n} \frac{Q_j \cdot (P_u(N_e, O) - C_u(N_e, O))}{(1+i)^j}$$

Because the purpose of the analysis is the individuation of the number of effects that maximize this function, it is necessary to derive the expression in the function of this variable.
If the second derivation of the function is lower than zero, it is possible to individuate the maximal point:

$$\frac{d(NPV)}{dN_e} = -\frac{d(I(N_e))}{dN_e} + \frac{d}{dN_e}\left(\sum_{j=1}^{n} \frac{Q_j \cdot (P_u(N_e,O) - C_u(N_e,O))}{(1+i)^j}\right)$$

In the following study, the discount rate and production do not depend on the number of effects, so it is possible to introduce the following simplification:

$$\left(\sum_{j=1}^{n} \frac{Q_j}{(1+i)^j}\right) = K$$

The NPV equation becomes:

$$\frac{d(NPV)}{dN_e} = -\frac{d(I(N_e))}{dN_e} + \frac{d(K(P_u(N_E,O) - C_u(N_e,O))}{dN_e}$$

This means that for the independence of k from the number of effects:

$$\frac{d(NPV)}{dN_e} = -\frac{d(I(N_e))}{dN_e} + K\frac{d(P_u(N_e,O)}{dN_e} - K\frac{d(C_u(N_e,O))}{dN_e}$$

This preview equation allows the individuation of the optimal number of effects in the function of product quality.

Normally, in a chemical engineering conception, the final amount of NPV is not linked with the quality parameter, which means that with the minimization of costs, it is possible to obtain maximization of NPV with the following equation:

$$\frac{d(NPV)}{dN_e} = -\frac{d(I(N_e))}{dN_e} - K\frac{d(C_u(N_e,O))}{dN_e}$$

Quality strongly impacts the price of food products, which means that for a better evaluation of the NPV parameter, it is necessary to introduce a study of quality parameters.

3. MATERIALS AND METHODS

3.1 - Problem description

The goal of the following study is to analyze the optimization of a multi effect evaporator with different configurations while introducing quality parameters.
Energy costs are relevant and often greatly influence the final value.
Hence, a non-linear mathematical model for solving the problem of optimization of a multi effect evaporator system will be analyzed. Here, a solution will depend on lycopene retention as a quality parameter and from the associated energy costs of the process. The final quality will be analyzed by examining the retention and behavior of important nutritive substances after thermal processing.
A system of 4 effect evaporators will be more deeply investigated; in fact, this option normally gives best results, and it is industrially used.

3.2 - Materials

Matlab 7.0.

3.3 - Method

A work plan was developed with the intention of solving the problem with the right parameters for this system and of a correct investigation of the requests.
It is possible to divide the work in the following points:

- individuation of the equations necessary for the study of a counter current multi evaporator system with the possibility of a pre-heating stage;
- solving the non-linear problems of the multi evaporator system, adding studies on different possible configurations;
- implementation of the method of resolution;
- economical evaluation and final quality analysis;
- cost analysis.

The software used for the solution of the non-linear problems was Matlab 7.0.

3.3.1 - Modeling

In this study, a classical and basic relationship for mass balance and enthalpy balance is used, with a particular correlation for tomato paste.

The final classical system configuration is the following:

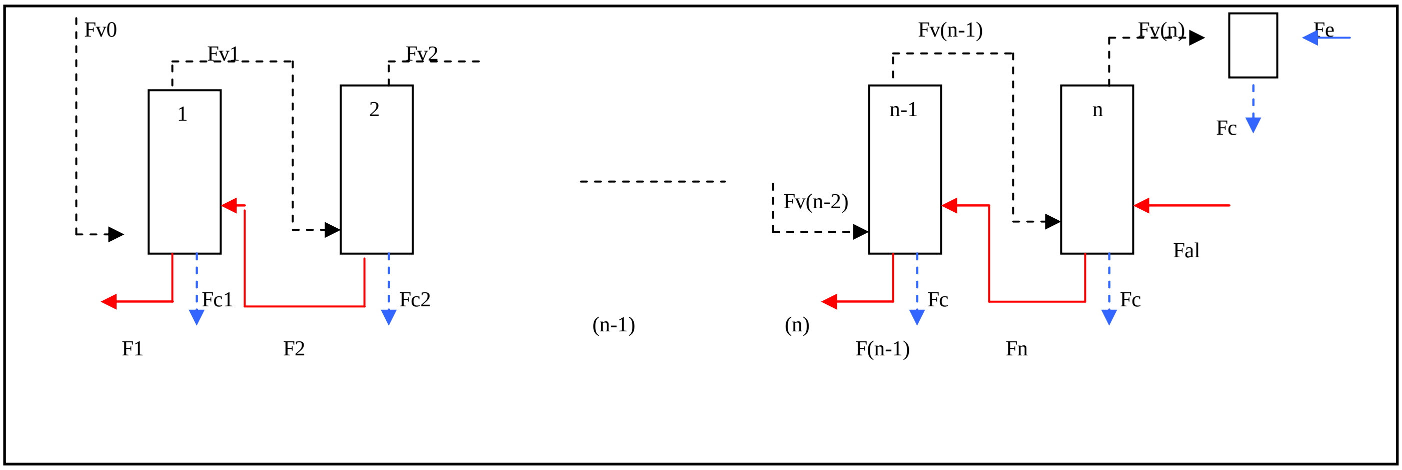


Figure 4: n-Multi-effects evaporator system in counter-current

where:

Hot steam

Condensed steam

Tomato paste

In particular, the most typical industrial configuration, with four effects, will be analyzed.

The relationship of mass balance and enthalpy balance for a generic i-evaporator for a multiple effect evaporator is shown:

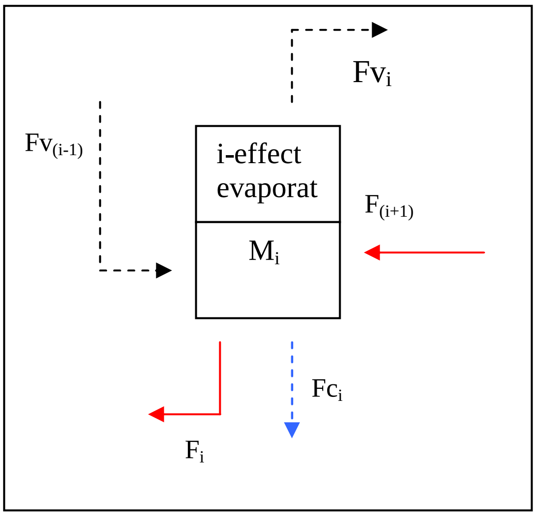


Figure 5: i-effect evaporator

The proper equations used for the final condenser are:

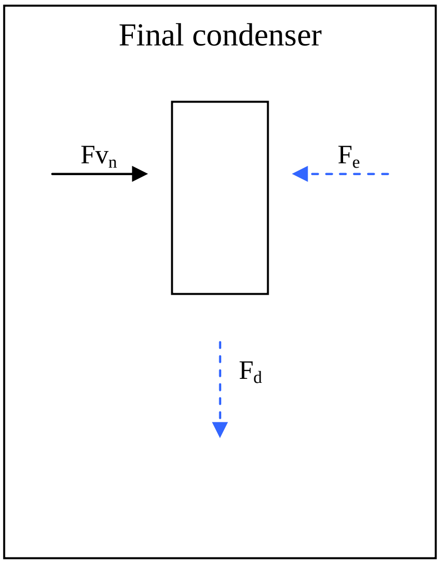


Figure 6: Final condenser of the process

3.3.2 - Mass and Energy Balances

Evaporator

The i-effect evaporator can be represented with the following balance equations:

Mass balance

$$\frac{d(M_i)}{dt} = F_{i+1} - Fv_i - F_i$$

The equation for a stationary system becomes:

$$0 = F_{i+1} - Fv_i - F_i$$

If i=n:

$$0 = F_{Al} - Fv_n - F_n$$

Energy balance

$$\frac{d(H_i M_i)}{dt} = F_{i+1} \cdot H_{i+1} + Fv_{i-1} \cdot Hv_{i-1} - F_i \cdot H_i - Fv_i \cdot Hv_i - Fc_i \cdot Hc_i - Q_p$$

Thanks to the hypothesis of the stationary stage, it is possible to eliminate the accumulation term, and the relationship becomes the following:

If i≠n:

$$0 = F_{i+1} \cdot H_{i+1} + Fv_{i-1} \cdot Hv_{i-1} - F_i \cdot H_i - Fv_i \cdot Hv_i - Fc_i \cdot Hc_i - Q_p$$

If i=n:

$$0 = F_{Al} \cdot H_{Al} + Fv_{n-1} \cdot Hv_{n-1} - F_n \cdot H_n - Fv_n \cdot Hv_n - Fc_n \cdot Hc_n - Q_p$$

In the following studies, possible losses of heat in the field will be ignored, meaning Q_p=0.
The normal counter current system will not be the only one studied in this work. Two different multi evaporator systems in particular will be studied, including a pre-concentrating stage.
In the first configuration with pre-concentrating, the hot steam generated in the last evaporator is completely recycled for the coldest stage of heating, while the steam produced in the penultimate stage is discharged in the condenser. This arrangement allows a pre-concentration that cannot be too high, so it will allow a total recycling of the steam generated in the last device.

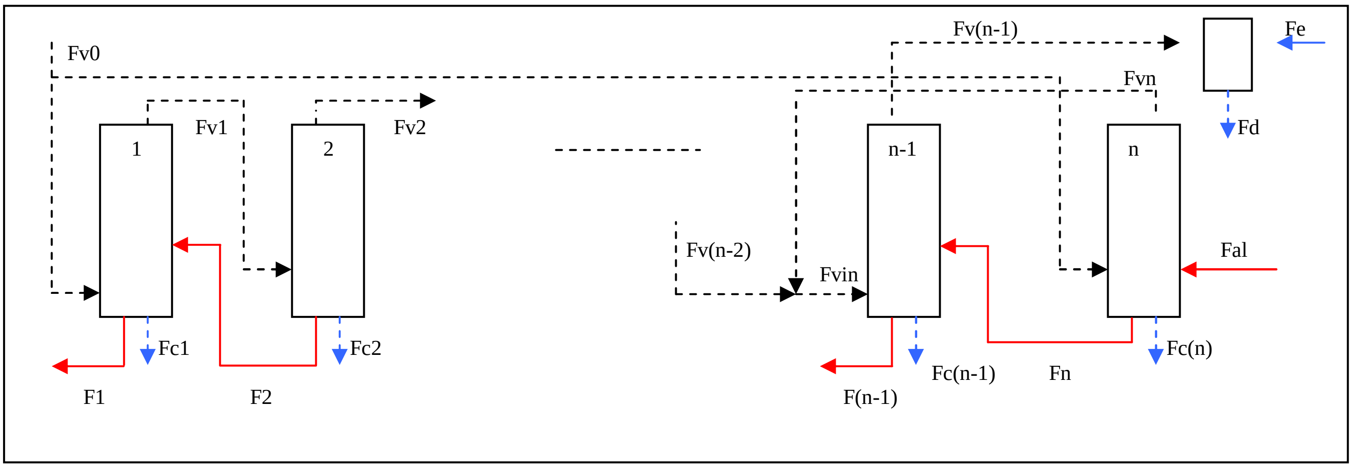
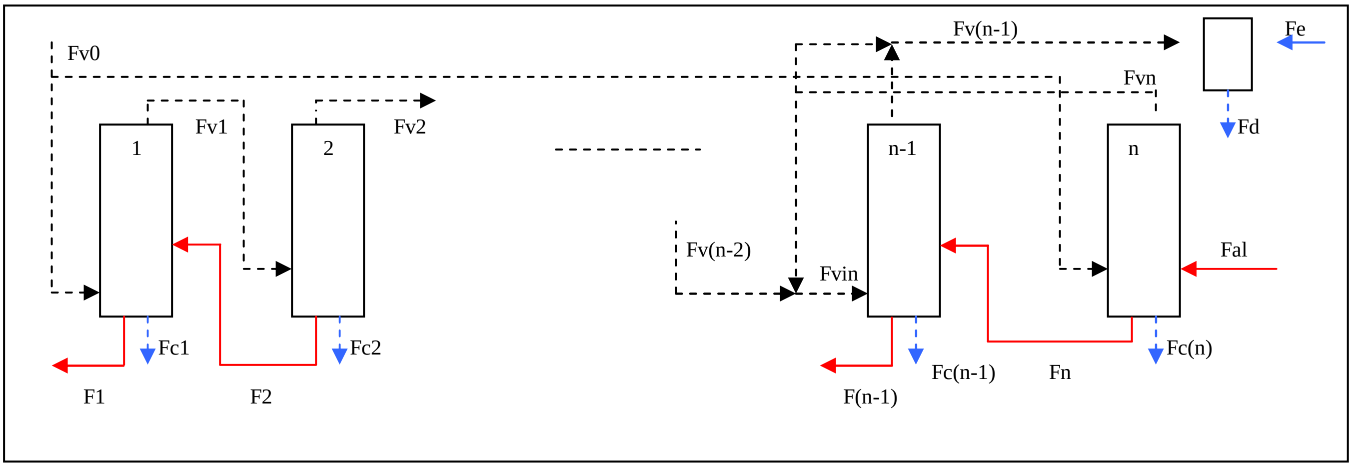


Figure 7: n-Multi effects evaporator system in counter current with pre-heating and total recycle

In the second configuration with pre concentrating, the hot steam generated in the last evaporator is partially recycled for the coldest stage of heating. The steam produced in excess in the pre-concentrating stage is mixed with the steam generated in the penultimate stage and is discharged in the condenser. This arrangement does not give any limit to pre-concentration (in this study tomato paste will be pre-concentrated until 15 °Brix in the first stage).



In both case, the mass and energy balance for an i-evaporator remains the same.

If i=n-1, the energy balance in the stationary hypothesis becomes:

$$0 = F_{i+1} \cdot H_{i+1} + Fv_{in} \cdot Hv_{in} - F_i \cdot H_i - Fv_i \cdot Hv_i - Fc_i \cdot Hc_i - Q_p$$

Where:

$$Fv_{in} = Fv_{i-1} + \alpha \cdot Fv_n$$

α is the fraction of the steam produced that is recycled, which is null in the first configuration with pre-concentration;

And:

$$Hv_{in} = \frac{Fv_{i-1} \cdot Hv_{i-1} + Fv_n \cdot \alpha \cdot Hv_n}{Fv_{in}}$$

If i=n, the energy balance becomes:

$$0 = F_{Al} \cdot H_{Al} + Fv_0 \cdot Hv_0 \cdot \lambda - F_i \cdot H_i - Fv_i \cdot Hv_i - Fc_i \cdot Hc_i - Q_p$$

While if i=1:

$$0 = F_2 \cdot H_2 + Fv_0 \cdot Hv_0 \cdot (1-\lambda) - F_1 \cdot H_1 - Fv_1 \cdot Hv_1 - Fc_1 \cdot Hc_1 - Q_p$$

Where λ corresponds to the split factor of fed steam necessary for the final stage of pre-heating.
In all cases, it is possible to neglect the contribution of Q_p.

Solid balance

The equation utilized for the solid balance is:

$$\frac{d(M_i X_i)}{dt} = F_{i+1} \cdot X_{i+1} - F_i \cdot X_i$$

At another time, under the hypothesis of the stationary state, the accumulation term is not relevant, and the equation becomes:
If i≠n:

$$0 = F_{i+1} \cdot X_{i+1} - F_i \cdot X_i$$

And if i=n:

$$0 = F_{Al} \cdot X_{Al} - F_n \cdot X_n$$

Condenser balance

For the condenser, the following relationships will be used:

Mass balance

$$Fv_n + Fe = Fd$$

Where Fv_n is the steam generated in the last evaporator, Fe is the cooling water and Fd is the water discharged by the device.

Energy balance

$$Fv_n \cdot Hv_n + Fe \cdot He = Fd \cdot Hd$$

In the arrangements with preheating and hot steam recycling, the steam fed to the condenser comes from both the penultimate and final stages, and the mass balance equation becomes:

$$Fv_{n-1} + (1-\alpha) \cdot Fv_n + Fe = Fd$$

While for energy balance:

$$Fv_{n-1} \cdot Hv_{n-1} + (1-\alpha) \cdot Fv_n \cdot Hv_n + Fe \cdot He = Fd \cdot Hd$$

Other relationship used in the work

Flow relationship

For every evaporator, it is assumed that all steam feeds out as saturated liquid, hence without any variations in temperature:

$$Fv_{i-1} = Fc_n$$

$$Tv_{i-1} = Tc_n$$

If there is recycling, the equations change for the last evaporator:

$$Fv_0 \cdot \lambda = Fc_n$$

$$Tv_0 = Tc_n$$

And for the penultimate:

$$Fv_{in} = Fc_{n-1}$$

$$Tv_{in} = Tc_{n-1}$$

Where Tv_{in} is the temperature of the steam fed in this stage and is calculated with the relationship after mixing.

Tomato paste properties

Tomato paste enthalpy

It is possible to estimate tomato paste enthalpy by the following relationship (Simpson, 2005):

$$H_i = (4.184 - 2.9337 \cdot X_i) \cdot T_i$$

Boiling point rise

Boiling point rise is an important thermodynamic property that cannot be ignored in multiple-stage evaporators. It is calculated experimentally and it is lower for diluted substances. In this study, then, it changes and becomes more relevant with the tomato concentration. It represents the temperature rise of the diluted solution over boiling point of water. Hence, the relationship is:

$$T_i - Tv_i = \Delta eb_i$$

The elevation of temperature, in particular, is calculated with the empiric correlation for tomato paste promoted by Tonelli (1990):

$$\Delta eb_i = 0.175 \cdot X_i^{(1.11)} \cdot \exp^{(3.86 \cdot Xi)} \cdot P_i^{0.2898}$$

Steam and condensed proprieties

This project utilized the hypothesis of having both saturated steam fed to the evaporator and saturated liquid discharged from the device.
The correlations utilized were obtained by an experimental study of Perry and Chilton and can return results with a very low error.

For 40°C<Tv<70°C:

$$Tv_i = 32.5515 \cdot P_i^{0.2898} - 17.7778$$

For 70°C<Tv<135°C:

$$Tv_i = 39.0514 \cdot P_i^{0.2382} - 17.7778$$

For 40°C<Tv<135°C:

$$Hv_i = 2509.2888 + 1.6747 \cdot Tv_i$$

For condensate:

$$Hc_i = 4.1868 \cdot Tc_i$$

Heat exchange equation

Heat exchange follows a relationship that depends on the global coefficient of heat exchanging U_i (Perry):

$$U_i \cdot A_i \cdot (Tv_{i-1} - T_i) = Fv_{i-1} \cdot (Hv_{i-1} - Hc_i)$$

Where A_i is the heat exchange area in the evaporator.

U_i estimation is influenced by the choice of evaporator type used in the process. In this study, it will be used the following empiric correlation, which allows the calculation of Ui for forced-circulation evaporators with a horizontal external steam chest in a function of the parameter T_i/X_i.

This estimation was developed with the software EVAPORATOR MODEL 2006 ENGL.

$$U_i = 3.6 \cdot \left(0.036 \cdot \left(\frac{T_i}{X_i} \right)^2 + 1.4063 \cdot \left(\frac{T_i}{X_i} \right) + 1335.3 \right)$$

4 – MODEL SOLVING

Model solving is possible after an analysis of the total number of liberty degrees of the whole process, calculation of the available equations and assignation of the necessary parameters for the saturation of the system, allowing problem resolution.
Analysis starts with the computation of the total number of liberty degrees of the basic multiple effects evaporator.

4.1 - Number of liberty degrees

Tomato paste

Variable		**Variable number**
Paste flow	F_i	n
Brix gradation	X_i	n
T of the paste	T_i	n
Enthalpy of the paste	H_i	n
Flow fed paste	F_{Al}	1
Brix gradation of fed paste	X_{Al}	1
T of fed paste	T_{Al}	1
Enthalpy of fed paste	H_{Al}	1
Total		**4n+4**

Figure 9: Number of variables linked with tomato paste

Steam

Variable		**Variable number**
Steam flow	Fv_i	n+1
Steam pressure	Pv_i	n+1
Steam temperature	Tv_i	n+1
Steam enthalpy	Hv_i	n+1
Total		**4n+4**

Figure 10: Number of variables linked with steam

Condensed

Variable		Variable number
Condensed flow	Fc_i	n
Condensed temperature	Tc_i	n
Condensed enthalpy	Hc_i	n
Total		**3n**

Figure 11: Number of variables linked with condensed

Evaporators

Variable		Variable number
Heat exchange area	A_i	n
Exchange global coefficient	U_i	n
Boiling point rise	Δeb_i	n
Total		**3n**

Figure 12: Number of variable linked with evaporators

Condenser

Variable		Variable number
Cooling water flow	Fe	1
Cooling water temperature	Te	1
Cooling water enthalpy	He	1
Discharged water flow	Fd	1
Discharged water temperature	Td	1
Discharged water enthalpy	Hd	1
Total		**6**

Figure 13: Number of variables linked with the condenser

Therefore, the final number of liberty degrees is **14n + 14**.

4.2 - Available equations

Equation	Equation number
Mass balance for each evaporator	n
Component balance for each evaporator	n
Energy balance for each evaporator	n
Condenser mass balance	1
Condenser energy balance	1
Flow relationships	n
Temperature relationships	n
Tomato paste enthalpy	n
Tomato paste fed enthalpy	1
Steam enthalpy	n+1
Condensed enthalpy	n
Cooling water enthalpy	1
Discharged water enthalpy	1
Liquid-vapor difference	n
Boiling rise up	n
Steam temperature	n+1
Heat exchange equations	N
Correlation for global coefficient heat exchange	N
Total	**13n+7**

Figure 14: Available equations for solving problem

Thanks to the preview analyses, it is possible to calculate the final liberty degrees that must be assigned for transforming the system in a solvable problem.

Variables	**14n+14**
Equations	**13n+7**
Liberty degrees	**n+7**

Figure 15: Final liberty degrees

It is necessary to introduce n+7 variables, where n is the evaporator number.

4.3 - Entrance data

The first step in defining the project is to discuss and assign the entrance data.
Normally, the whole condition of the tomato paste feed and of the product is announced. This is because the sale of tomato paste is only possible with the satisfaction of certain requests.

In addition, other data have to be introduced that are linked with the typology of the process. Normally, the values known are the steam pressure and the working pressure of the last evaporator, while the areas of all the evaporators are assumed to be equal. These assumptions are not compulsory and could be changed if the target is the study of the project under particular conditions like pre-heating or the regulation of temperature in an evaporator.

For the basic process, the defined variables are:

Variable	Symbol
Flow feed	F_{Al}
Tomato paste feed concentration	X_{Al}
Temperature of tomato paste feed	T_{Al}
Final product concentration	X_1
Steam pressure	P_{V0}
Cooling water temperature	Te
Temperature change between cooling water and discharged water in the condenser	dt
Operating pressure in the last evaporator	P_n
Equal heat exchange area in the evaporator	$A_1=A_2$; $A_2=A_3$ ….. $A_{n-1}=A_n$

Figure 16: Assigned variables for resolution of simple multi-effects system

4.4 - Solving the problem

The problem is non-linear and can be numerically solved with the help of software. In this case, it was utilized with Matlab 7.0.

It was necessary to optimize the system of 4N equations, where N is again the number of evaporators, and the equations set at zero are the mass balance, enthalpy balance, component balance and heat exchange of each evaporator.

Software can solve the problem after the introduction of adequate 4N first-tentative values of some parameters.

4.5 - Quality parameter retention

As discussed above, the quality parameter that influences the final value is lycopene retention, while other analyses will be done on other important nutrient substances without influencing sale price. These will be for making an evaluation on quality product after thermal processing.
The chemical degradation of lycopene follows a first order kinetic function of the temperature and the concentration of the component:

$$-\frac{dC}{dt} = k \cdot C$$

Where C is the enzyme concentration, t is the residential time and k is the velocity of the reaction, which can be estimated by an Arrenhius relationship linked with the device's temperature:

$$k = k_o \cdot \exp(-\frac{Ea}{R \cdot T})$$

Where Ea is the energy activation and K_0 is the frequency factor. These two parameters are directly linked to the sort of reaction analyzed.
Other studies (Goula, 2006) confirmed the first order kinetic for lycopene degradation, offering a different correlation for the estimation of the reaction velocity directly linked with processes of temperature and tomato paste concentration:

$$k = 0.121238 \cdot \exp(0.0188 \cdot X) \cdot \exp\left(-\frac{2317}{T}\right) \quad (\mathrm{min}^{-1})$$

$$\text{Para } \mathrm{X} \geq 55 \quad (\mathrm{R}^2 = 0.996)$$

$$k = 0.275271 \cdot \exp(-0.00241 \cdot X) \cdot \exp\left(-\frac{2207}{T}\right) \quad (\mathrm{min}^{-1})$$

$$\text{Para } \mathrm{X} \leq 55 \quad (\mathrm{R}^2 = 0.998)$$

In this study, tomato paste is fed at 5 °Brix and is put out at 30 °Brix. This means that only the first equation is necessary:

$$k = 0.275271 \cdot \exp\left(-0.00241 \cdot X\right) \cdot \exp\left(-\frac{2207}{T}\right) \quad \left[\text{min}^{-1}\right]$$
$$\text{para X} \leq 55 \qquad \left(\text{R}^2 = 0.998\right)$$

To directly calculate the lycopene retention in each stage, it is possible to develop following equation:

$$F_{i+1} \cdot X_{i+1} \cdot Y_{i+1} - F_i \cdot X_i \cdot Y_i + M_i \left(\frac{d\left(X_i Y_i\right)}{dt}\right) = \frac{d(M_i X_i Y_i)}{dt}$$

In which:

- F is the mass flow [Kg/h]
- X is the tomato paste concentration in Brix degrees
- Y is the lycopene concentration
- M is the hold-up in the evaporator [kg]
- t is time [h]

If the evaporator is assumed to be working in a stationary stage and is completely mixed, with a first order kinetic degradation, it is possible to arrive at the next equation:

$$F_{i+1} \cdot X_{i+1} \cdot Y_{i+1} - F_i \cdot X_i \cdot Y_i - M_i \cdot X_i \cdot k_i \cdot Y_i = 0$$

With this correlation, it is easier to find the lycopene content after processing in one stage:

$$Y_i = \frac{F_{i+1} \cdot X_{i+1} \cdot Y_{i+1}}{F_i \cdot X_i + M_i X_i k_i}$$

K_i is derivable by the previous equation, giving the final expression:

$$Y_i = \frac{F_{i+1} \cdot X_{i+1} \cdot Y_{i+1}}{F_i \cdot X_i + M_i \cdot X_i \cdot \left(0.275271 \cdot \exp\left(-0.00241 \cdot X_i\right) \cdot \exp\left(-\frac{2207}{T_i}\right)\right)}$$

This equation allows the study of the lycopene concentration in every stage, starting from the concentration in the precedent device under the hypothesis of the stationary state and after the estimation of mass inside the evaporator.

The calculus of lycopene retention introduces a freedom degree that is easily saturated by the new relationship developed.

4.6 - Operating conditions

4.6.1 - Condition in heat exchanger pipes

This process relies on the production of several tons of concentrated tomato paste starting from a diluted food. Therefore, it is particularly important to sort the design and efficiency of the evaporators and of the modality of heat exchange.

The heat exchange area is linked with the configuration of the pipes in the chest. For this study, pipes with a length of 10 [m] and an inner diameter of 2 [in] will be considered (Perry). The residential time is fixed at one minute (Handbook of food engineering practice, P. Minton).

The correlation used for density [Kg/m^3] estimation is the following (Tonelli 1987):

$$\rho = 1000 \cdot (0.47 \cdot X_i + 1)$$

This relationship is necessary for analyzing the amount of volumetric flow that has to be pumped and re-circulated. It is a density expression for concentrated apple juice and it is valid as a first approximation.

4.6.2 - Hold up

Hold up determination is an important step in this study because lycopene retention is directly correlated with this variable.

First, it is necessary to evaluate the volumetric fluid that every pipe in the heat exchanger contains:

$$V_t = (\frac{D_i}{2} \cdot 0.0254)^2 \cdot 3.14 \cdot L_t$$

Where:

Vt = Volume of the pipe [m^3]

Di = Inner diameter of the pipe [inc]

Lt = Pipe length [m]

The heat exchange area for a tube is the external area. It can be calculated as follows:

$$A_t = D_i \cdot 0.254 \cdot 3.14 \cdot L_t$$

Where A_t = Pipe external area [m^2].

A preview expression can help determine the number of pipes necessary to assure a correct heat exchange:

$$N_t = \frac{A_i}{A_t}$$

Where:

N_t = Number of pipes used in the chest;

A_i = Total exchange area in the device [m^2].

Thanks to the preceding expressions, it is now possible to individuate the total amount of tomato paste that occupies the whole volume of all the pipes:

$$V_{tt} = V_t \cdot N_t$$

V_{tt} = Total volume of all the pipes [m^3].

As a hypothesis, the holdup necessary for the correct operation of the evaporators must have a volume 2 [m^3] higher than the total inner volume of all the pipes. Hence,

$$H_i = V_{tt} + 2$$

Where H_i is the evaporator hold up [m^3].
With the preview equation, it is possible to correlate the alimentary flow and hold-up of the device.

4.6.3 - Residential time

The residential time of the product in the evaporator is an essential parameter for studying nutrient degradation (associated with the device's temperature). In fact, a higher residential time normally gives a higher decomposition and a lower retention, and part of this study will focus on the variation of this important quality component:

$$\tau_i = \frac{M_i}{F_i}$$

Where:

τ_i = Residential time [h].

Variables assigned

Name	Variable	Value
Diluted tomato paste feed	F_{Al} [Kg/h]	50000
Tomato paste temperature	T_{Al} [ºC]	98
Brix gradation tomato paste feed	X_{Al} [% p/p]	5
Lycopene concentration in tomato paste feed	Y_{Al} [Kg Lic/Kg SS]	0.01
Brix gradation of final product	X_1 [% p/p]	30
Steam pressure	Pv_0 [KPa]	143.4
Change of temperature in the condenser	$Tv_n - T_d$ [ºC]	2
Operating pressure of n-evaporator	P_n [KPa]	16.5

Figure 17: Process variables assigned

The preview variables allow the solution of the problem and are adequate for a medium-sized industrial device. The areas of each evaporator are considered equal in accordance with the theory of 'basic multiple effect evaporators.'

4.7 - Economic evaluation

The target of this project is an industrial critique of different arrangements of multi effect evaporators. This analysis necessarily includes an economic evaluation of the whole process for individuating the most convenient disposition and best operating conditions to assure the highest possible profits for the company that finances the project.
As previously stated, this calculation will not be independent from a quality parameter that influences the final price of the product.
This quality parameter coincides with lycopene retention after thermal processing for the particularly high anti-oxidant action in the human body. The final content of this enzyme is deeply influenced by the operating temperature in all of the evaporators and by the residential time in the devices.
The following section will list all of the standards that intervene in an industrial process for the production of a 30 °Brix concentrated tomato paste.

4.7.1 - Sale price

The sale price is the parameter that expresses the direct dependence of the economy of the process as a function of the final quality of the paste; hence, it will be larger with a higher lycopene concentration:

$$P_u = P_u^* \cdot L - C_{mp}$$

Where:

- P_u = Final price of the product
- P_u^* = Basic price of the product
- L = Lycopene retention
- C_{mp} = Raw material cost

The tomato paste price and the simple tomato cost have a trend that can easily vary year-by-year. In this case, 2009 Italian prices will be used:

$$P_u^* = 450 \qquad €/ton$$

$$C_{mp} = 79.5 \qquad €/ton$$

In any case, both of these values can be easily changed and actualized.

4.7.2 - Inversion

The system inversion corresponds to the installation cost of all the devices indispensable to the development of the process. It is the sum of the evaporator inversion, which is directly dependent on the number of devices used for developing the process and the cost of the barometric contact condenser:

$$I = I_e + I_c$$

I = Total inversion

I_e = Evaporator inversion

I_c = Condenser inversion

4.7.2.1 - Evaporator inversion

The inversion associated with the evaporators is directly dependent on the total number of devices used and on the heat exchange area of all of these.

The following figures shows the costs of different kinds of evaporators: those with horizontal pipes, with vertical pipes and with forced circulation.

The evaporator cost represents the most relevant voice for the whole inversion of the process.

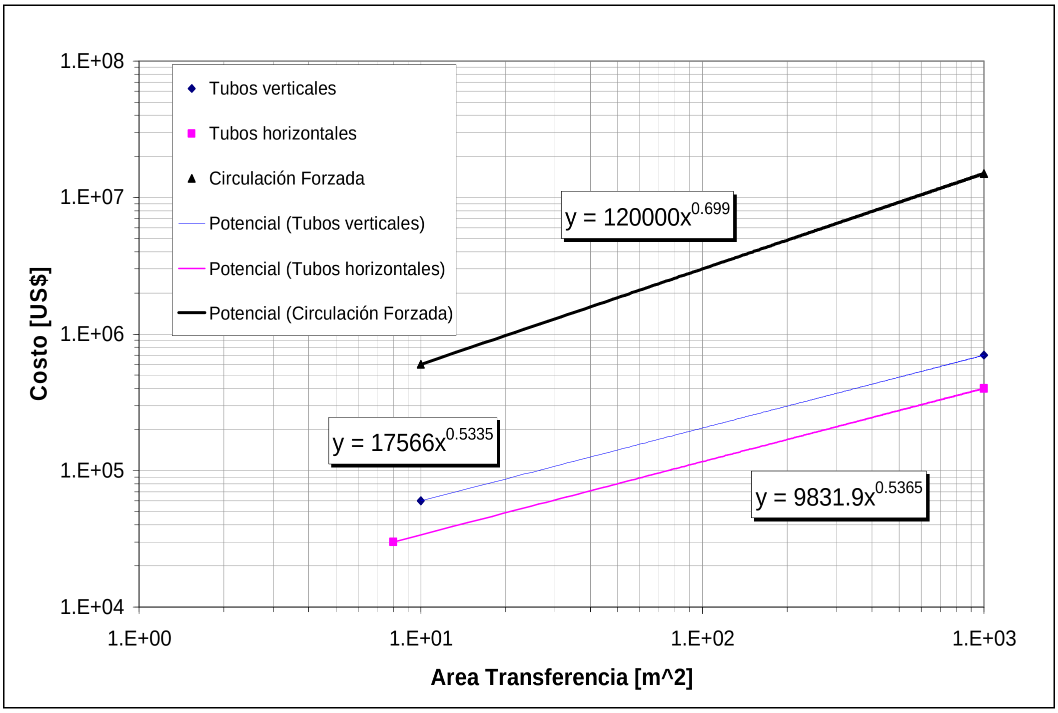


Figure 18: Evaporator costs as a function of the heat exchange area. Plant Design and Economics for chemical Engineers. Peters and Timerhause.

4.7.2.2 - Condenser inversion

The condenser inversion depends directly on the amount of water flow necessary for cooling the final steam.

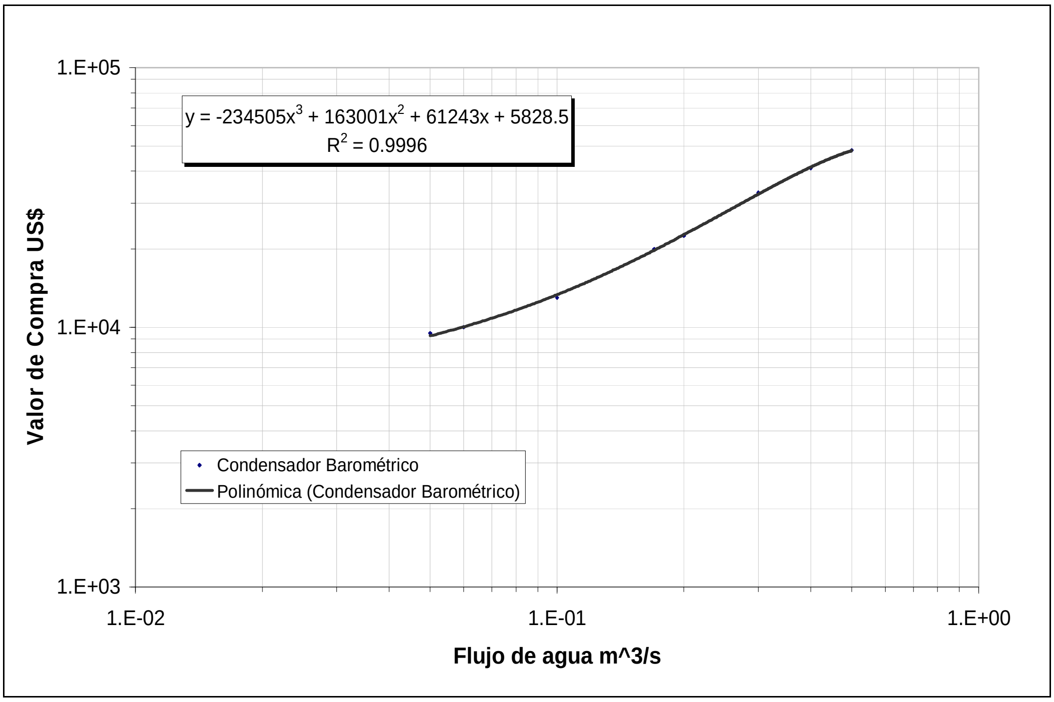


Figure 19: Condenser cost as function of cooling water flow.
Plant Design and Economics for Chemical Engineers. Peters and Timerhause.

The equation used to obtain the condenser cost is the following:

$$I_c = -234505 \cdot F_e^3 + 163001 \cdot F_e^2 + 61243 \cdot F_e + 5828.5$$

Where:

I_c = Condenser inversion

F_e = Water cooling flow [m^3/s].

4.7.3 - Operating Cost

In addition to the inversion costs necessary to install and start the process, a multiple effect evaporator system presents several operating costs for tomato paste thermal processing.
This computation will be done under the hypothesis of 2000 working hours for every year (Cost data analysis for the food industry. A.Z. Marouli, Z.B. Maroulis).
The operating costs can be subdivided as:

- Steam
  - Fresh steam
  - Vacuum steam
- Cooling water
- Electric energy

4.7.3.1 - Fresh steam

Fresh steam is fed into the first evaporator's steam chest in the basic configuration and is divided between the first and last devices in the pre-heating and recycling disposition.
Starting from the basic cost, it is possible to obtain an annual cost for fresh steam:

$$C_{vs} = \frac{F_{v0} \cdot h_a \cdot Q_{vs}}{1000}$$

Where:

C_{vs} = Annual cost of fresh steam [$]
F_{v0} = Fresh steam flow [Kg/h]
h_a = Working hour for year [h]
Q_{vs} = Basic fresh vapor cost [$/Kg]

4.7.3.2 - Vacuum steam

The following diagram shows the required steam for transforming the last evaporator in a under low pressure device.

As previously shown, the pressure of the last device is fixed at 16.5 [kPa] for a 55°C steam entering the barometric condenser.

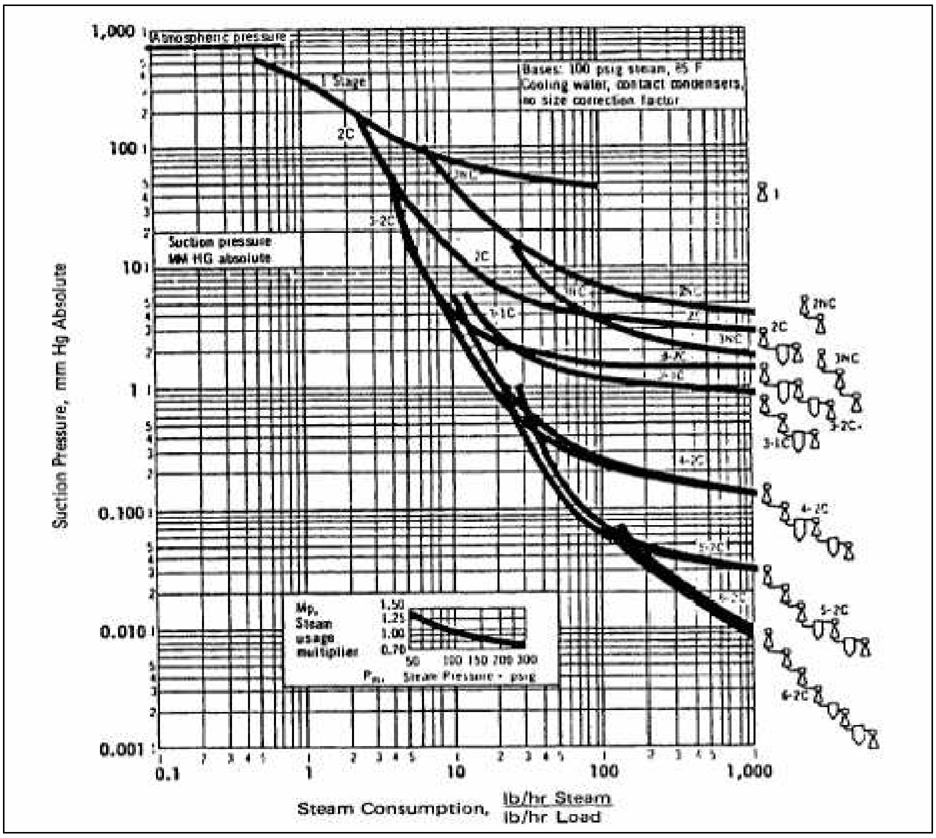


Figure 20: Steam necessary in function of vacuum pressure. Handbook of evaporation technology.

From this diagram, it is possible to obtain a value of 2 [lb fresh steam/ lb load steam]. Starting from a fresh steam of 150 psig, the final value is 2·0.8=1.6 [lb fresh steam/ lb load steam].

The final equation cost for low-pressure generation in the last device becomes:

$$C_{vv} = 1.6 \cdot F_{vn} \cdot h_a \cdot Q_{vv}$$

Where:

C_{vv} = Annual cost of vacuum vapor [$]

F_{vv} = Vacuum steam flow [Kg/h]

h_a = Annual working hours [h]

Q_{vs} = Vapor basic cost [$/Kg]

4.7.3.3 - Cooling water

The cooling water flow necessary for condensing the last evaporator's steam is derivable from the mass and enthalpy balance of the barometric condenser.

With the following equation, it is possible to get the total cost of the cooling water:

$$C_{AE} = F_e \cdot h_a \cdot Q_{AE}$$

Where:

C_{AE} = Total cooling water cost for year [$]

F_e = Cooling water flow [Kg/h]

H_a = Working hours for year [h]

Q_{ae} = Cooling water cost [$/Kg]

4.7.3.4 - Electric energy

The normal functioning of recirculation pumps in forced circulation evaporators requires a high electric energy consumption. The flow in the pump is the sum of the fluid that has to be recirculated and the fluid that comes out from the pump:

$$F_{VB} = F_{vr} + F_{vs}$$

Where:

F_{vb} = Volumetric flow of the pump [m^3/h]

F_{vr} = Volumetric recirculation flow [m^3/h]

F_{vs} = Outing volumetric flow [m^3/h]

The outing volumetric flow is derivable from the ratio of mass outing flow and density:

$$F_{vs} = \frac{F_i}{\rho_i}$$

Where:

F_{vs} = Outing volumetric flow [m^3/h]

F_i = Outing mass flow [Kg/h]

ρ_i = Density of the concentrated paste [Kg/m^3]

The recirculation volumetric flow is computable with the following relationship:

$$F_{vr} = \frac{V_{tt} \cdot 60}{t_{Rt}}$$

Where:

F_{vr} = Volumetric recirculation flow [m^3/h]

V_{tt} = Volume of total pipes [m^3]

t_{Rt} = Residential time in pipes [h]

From the volumetric flow of the pump, it is possible to get the power [KW] request starting from the capacity [m^3/h]:

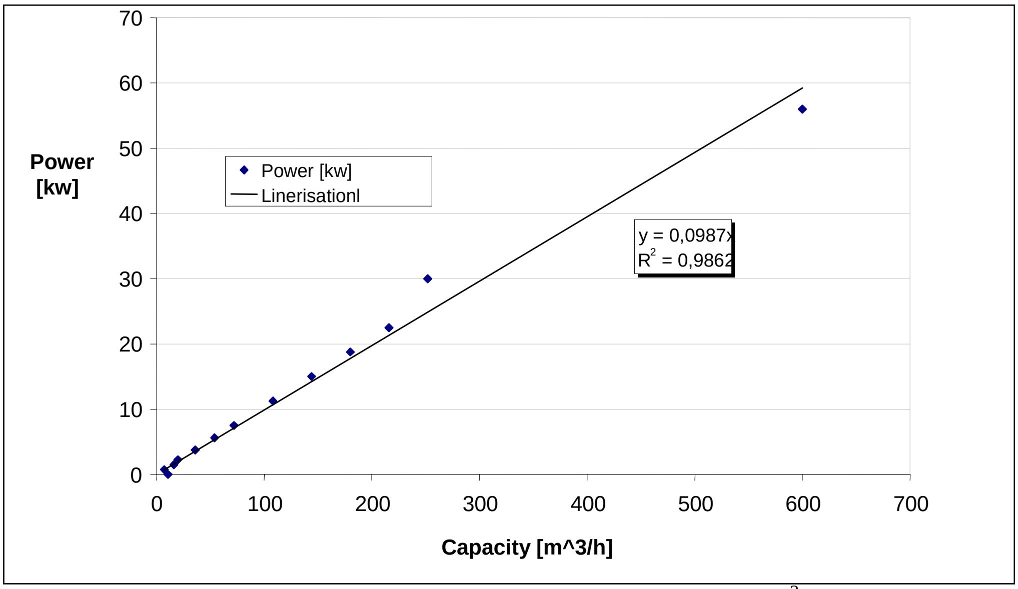


Figure 21: Power function [KW] versus capacity [m^3/h]

Hence, is possible to obtain the total electric energy cost by summing the cost of each device.

The electric energy cost for an evaporator is derivable from the preview diagram and the following relationship:

$$C_e = C_k \cdot 0.0987 \cdot \sum_{i=1}^{n} K_{Bi}$$

C_e = Annual electric energy cost

C_k = Energy cost

0.0987 = Relation between power request and cost

$\sum_{i=1}^{n} K_{Bi}$ = Sum of all of the capacity of the pumps in the entire system.

The sum of the electric energy, cooling water, fresh steam and vacuum steam costs gives the total operating cost:

$$C_O = C_{VV} + C_{VS} + C_E + C_{AE}$$

5 - RESULTS AND DISCUSSION

It is now possible to make a total critique of the counter current multi effect evaporator systems for tomato paste concentration concerning of the final content of lycopene, furosine, and ascorbic acid and of the color of the product.

In addition, thanks of all of the preview relationships, it is now possible to analyze the whole process with the NPV indicator, which allows the necessary economic comparison.

A basic multiple effect evaporator system has a number of devices that change from one to seven, all with the same heat exchange area.

5.1 - Residential time in the system

Quality parameters strictly depend on the residential times and the temperatures of every device. Higher temperature and higher residential times result in higher degradation of the product. Thus, by analyzing these two variables, it is possible to foresee the quality of the product.

Figure 22 shows the results of the basic multiple effects evaporator system.

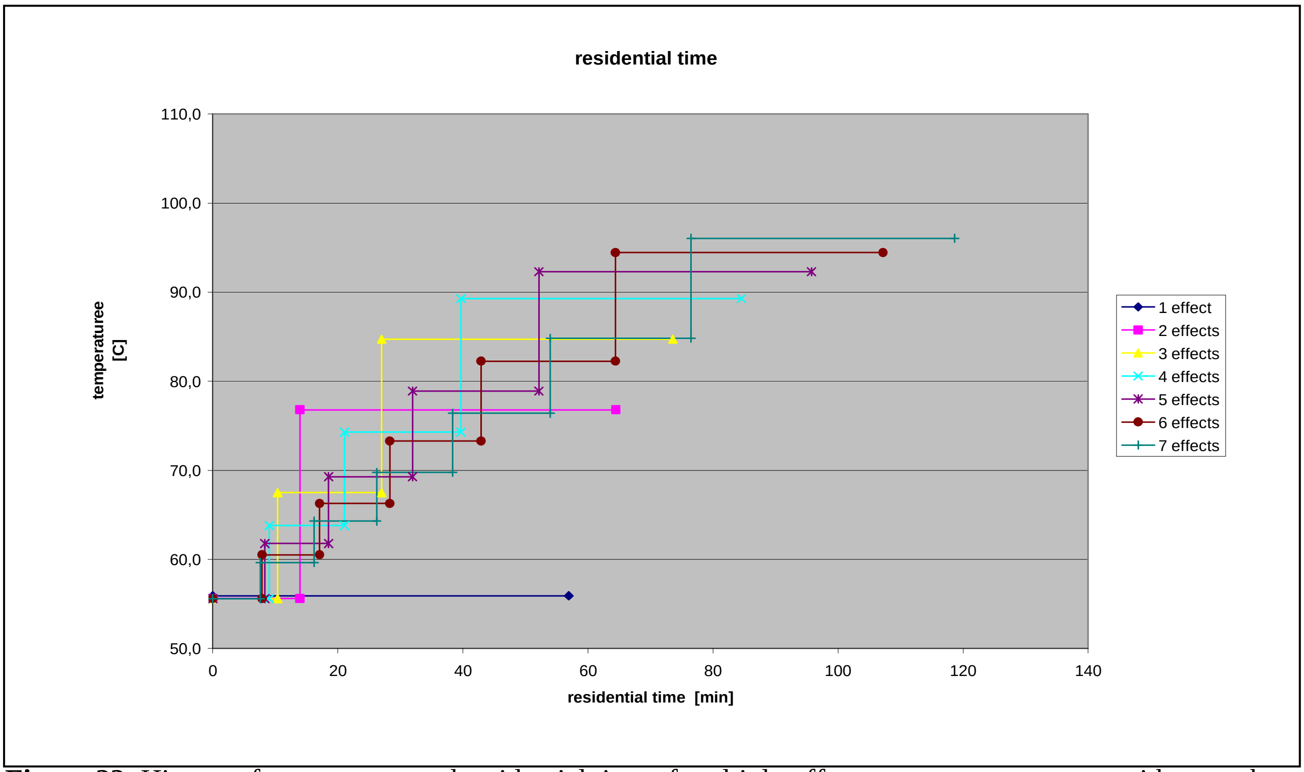


Figure 22: History of temperature and residential time of multiple-effects evaporator systems, with a number of device variables from 1 to 7

5.2 - Lycopene retention

As said before, lycopene retention is the most important quality parameter for tomato paste, deeply influencing the final product cost. Figure 23 shows the retention of this enzyme after thermal processing as a function of device number.

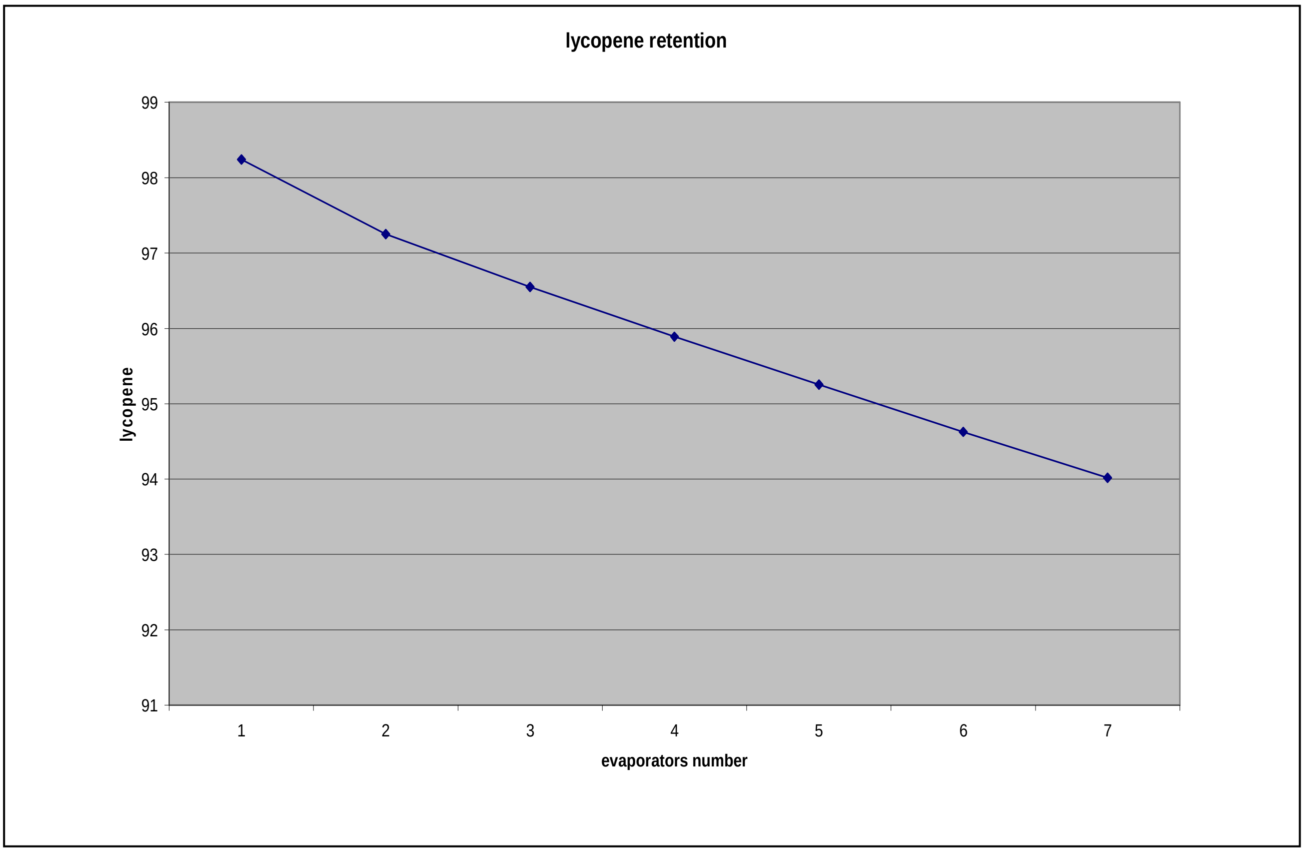


Figure 23: Lycopene retention as a function of the number of effects

It is easy to note that the degradation of lycopene increases linearly with the number of effects. This is consistent with figure 22, which shows higher residential times and higher temperatures with the elevation of the device number.

Hence, the raising of the number of elevators deteriorates the final product quality.

5.3 - Furosine content

For a better investigation of the final quality of the product, the final furosine content will be analyzed.

Higher furosine content is an index of heat damage, as it is an indicator of the activity of the Maillard reaction, which causes sugar degradation with a high molecular product formation. Furosine is an amino acid that follows a pseudo 0.5 kinetic order degradation.

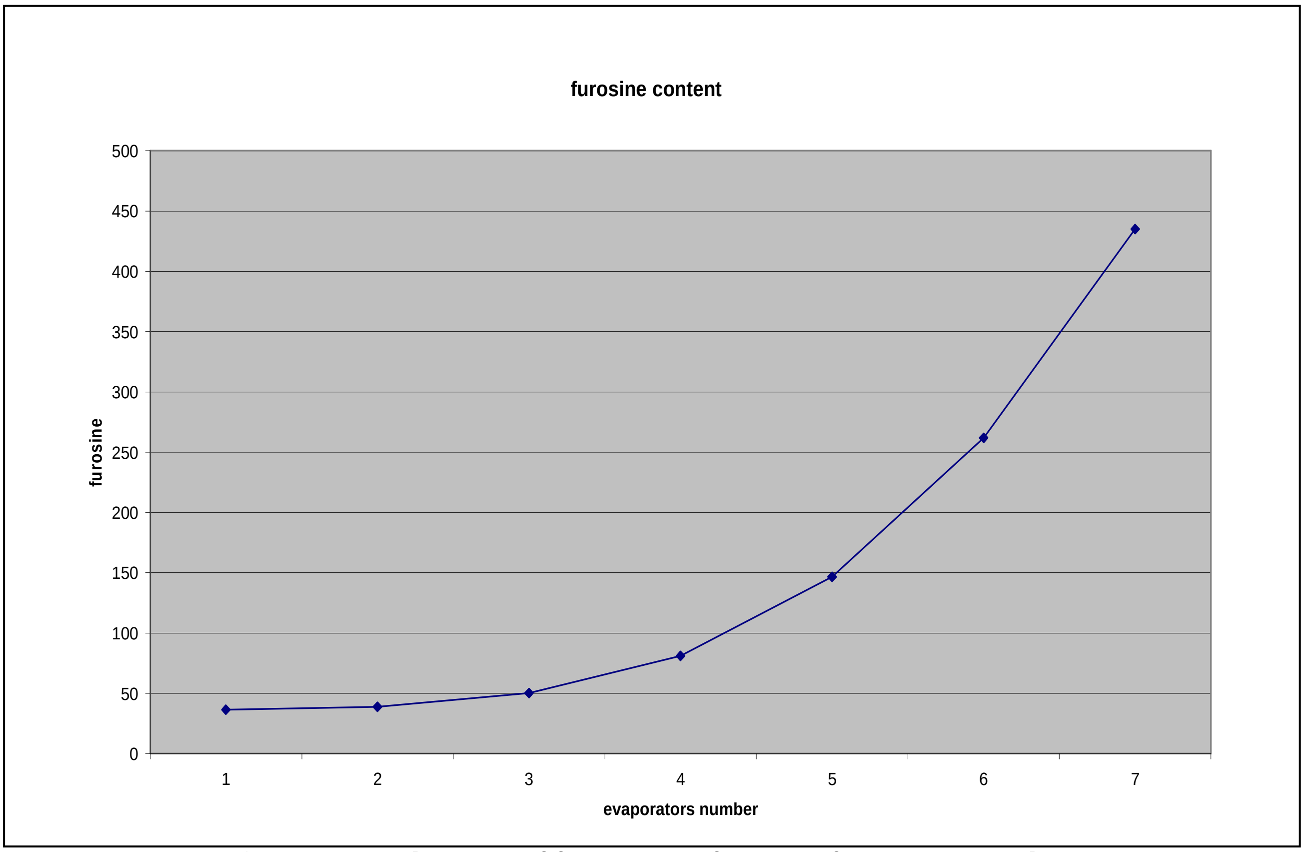


Figure 24: Final content of furosine as a function of evaporator number

In the diagram, the furosine content, starting at 36.5 mg/100 g, increases in an exponentially. In particular, using more than four evaporators results in a strong elevation, while systems with a number of devices up to three do not show a relevant formation of this amino acid. With seven elevators, the final furosine content is more than ten times the starting content, a value that suggests a high degradation of the processed tomato paste.

5.4 – Ascorbic acid content

Another possible quality index is ascorbic acid retention. Ascorbic acid is a vitamin with high anti-oxidant properties. It hinders the onset of several diseases in human body and is an index of the nutritional content of tomato paste. This compound follows a first order kinetic degradation.

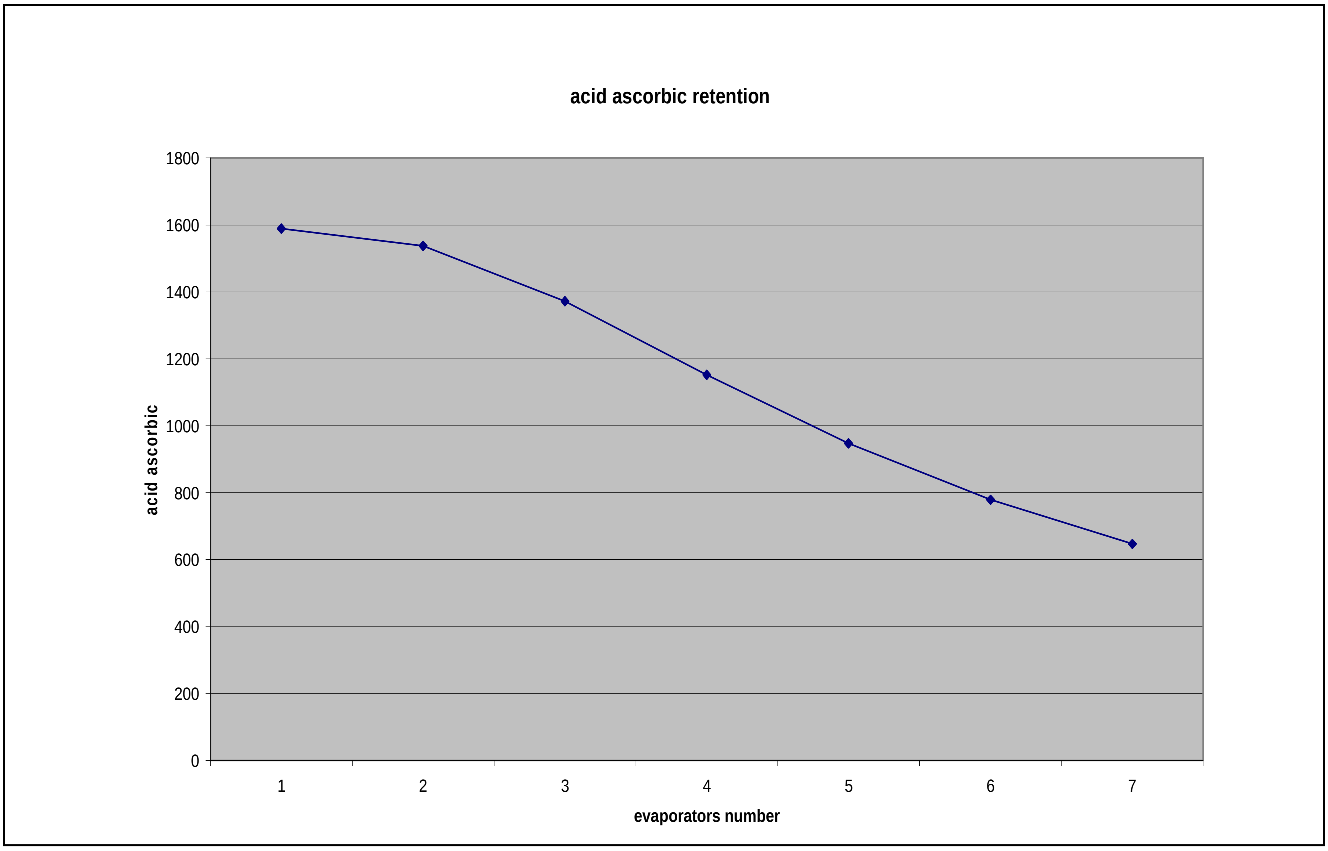


Figure 25: ascorbic acid retention as a function of evaporator number

Starting from a value of 1,590 mg/kg, the ascorbic retention decreases quite linearly with the number of effects; systems of one or two devices show a very low degradation.
With six or seven devices, half of the total content of this vitamin is lost.

5.5 - Color

Color is an index of quality for tomato paste that is an indicator of ripeness and, generally, of the deterioration of the product. Color degradation can, in fact, be a sign of an advanced stage of the Maillard reaction.

Color is also an immediate parameter for a first-analysis of the consumer, as it is a sign of freshness, maturity and storage time. A potential costumer is sure to buy the tomato paste with the most agreeable color.

In this analysis, the tomato paste's final color will be compared with an initial tonality that has a symbolic value of zero. A higher amount of color is a symbol of higher degradation.

Color follows a power law relationship independent of the concentration of the paste, but dependent on the temperature and residential time.

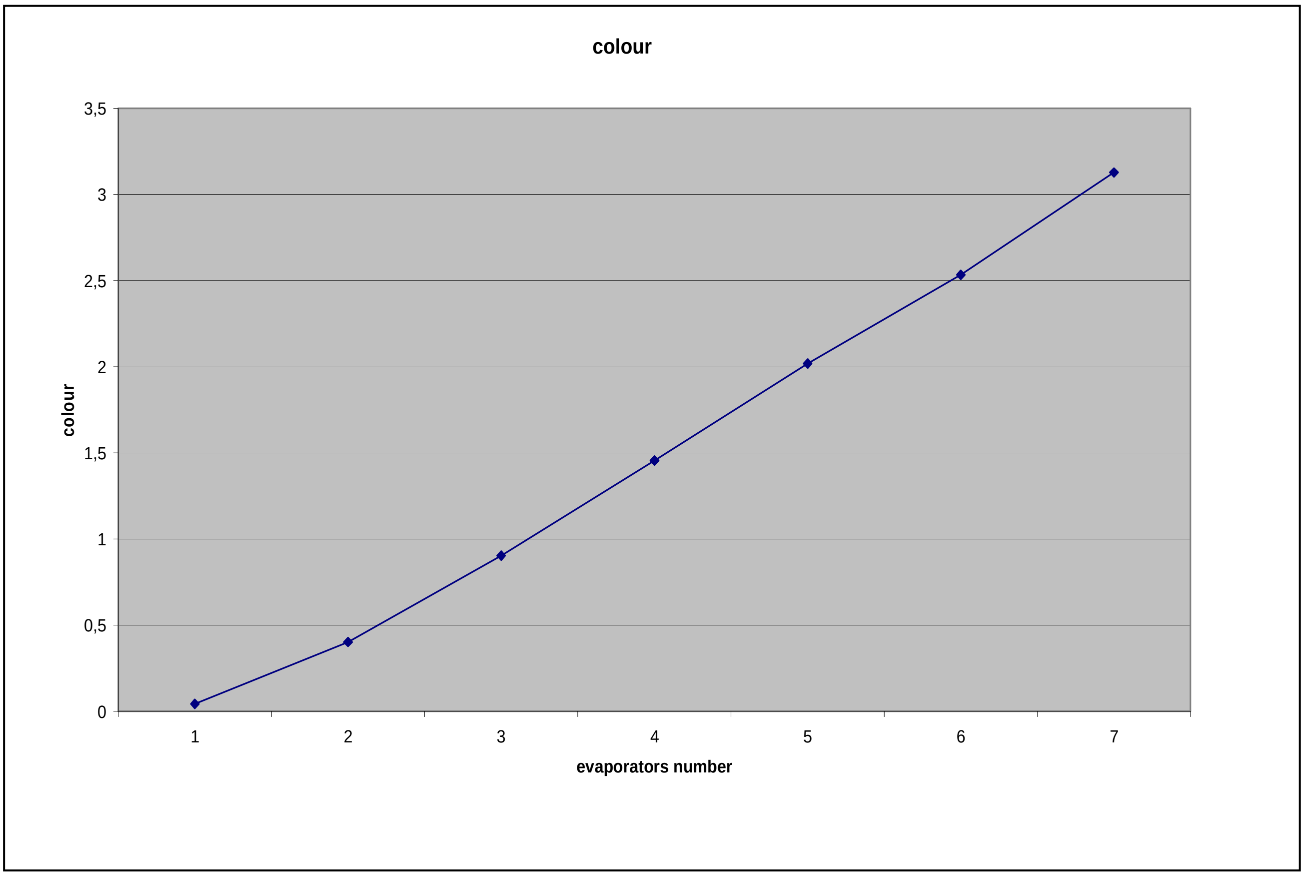


Figure 26: Tomato paste color study as a function of evaporator number

Figure 26 shows that an increase in evaporator number gives a linear degradation. This is in accordance with Figure 22, which suggests a higher residential time for a higher number of devices.

5.6 - Economic evaluation

All of the preview studies show that an increase of stages causes a higher degradation of the product. This means that the tomato paste concentrated in a single evaporator has a better content of lycopene, acid ascorbic, and furosine and a better color.
The content of each quality factor changes with the increasing number of devices as function of its own kinetic law.
In reality, the only restriction for processed tomato paste is that the final concentration cannot be lower than 30 °Brix.
In just the last few years, in response to higher demands for better food quality, the industrial sale price changed with the introduction of dependence on lycopene retention.
This means that it is a necessary economic evaluation for the different multi-effect evaporator systems.
The following figure shows the NPV results for the basic system [US$]:

Effect number	**NPV without quality factor**	**NPV with quality factor**
1	5.834 E+07	1.84 E+07
2	3.72 E+07	3.86 E+07
3	3.216 E+07	4.303 E+07
4	3.12 E+07	4.337 E+07
5	3.192 E+07	4.204 E+07
6	3.347 E+07	3.989 E+07
7	3.559 E+07	3.719 E+07

Figure 27: NPV values for different evaporator numbers

A NPV without the quality factor coincides with an investigation of total installation costs; hence, it must be minimized. A NPV with a quality factor dependent on lycopene retention must be maximized for better convenience.
In both cases, a 4 effect multi evaporator system gives better values.

5.7 - Study of different typologies of 4 effect evaporator systems

The most convenient system is the 4 effect evaporator, which returns highest NPV and highest gains for the investment.
Single evaporators give best product in terms of lycopene retention, but they return the lowest NPV.
For these reasons, normal configurations in the industrial world have a number of devices that can change from 3 to 5.
Analysis will be now concentrated on systems with four effects. This will allow for further elevation of NPV values, the analysis of different dispositions and if changing operating conditions would be convenient for this application.

Possible configurations

Some variations to the system will now be evaluated to search for an improvement in the final value of NPV and of quality parameters.
The different configurations are:

- normal counter current process with same heat exchange area for all evaporators;
- normal counter current process with different heat exchange area for each evaporator;
- normal counter current process with a larger first evaporator;
- counter current process of evaporators with equal area with a pre-heating and pre-concentrating stage and total recycling of the hot steam generated in the last device;
- counter current process of evaporators with equal area with a pre-heating and pre-concentrating stage and partial recycling of the hot steam generated in the last device

The last two arrangements are the most different, with the target of investigating if the introduction of a pre-heating and pre-concentrating step could be advantageous.
The following figures will show the results of the whole process for these different configurations.

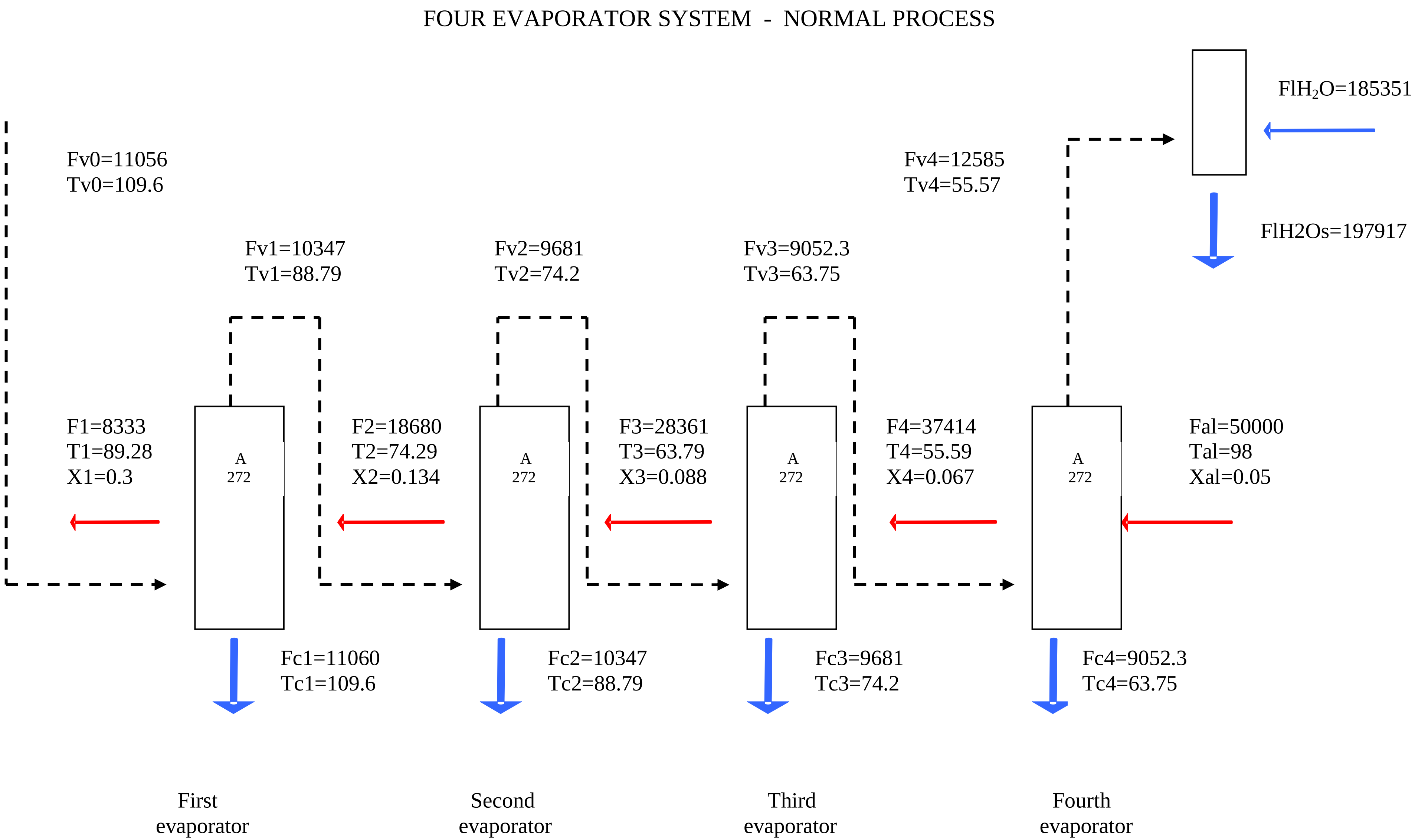


Figure 28 : normal counter current process with same heat exchange area for all evaporators

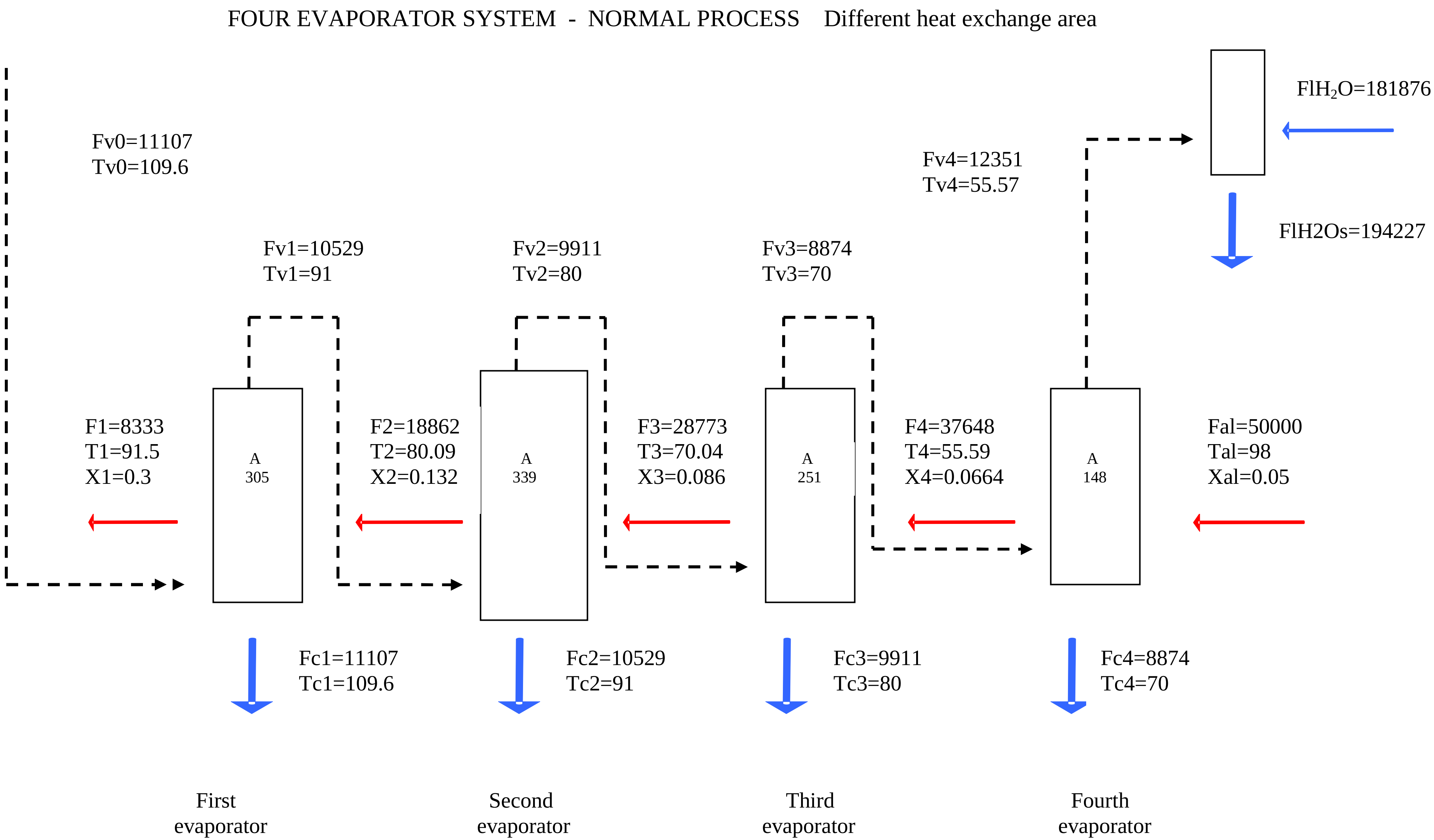


Figure 29: normal counter current process with a larger last evaporator

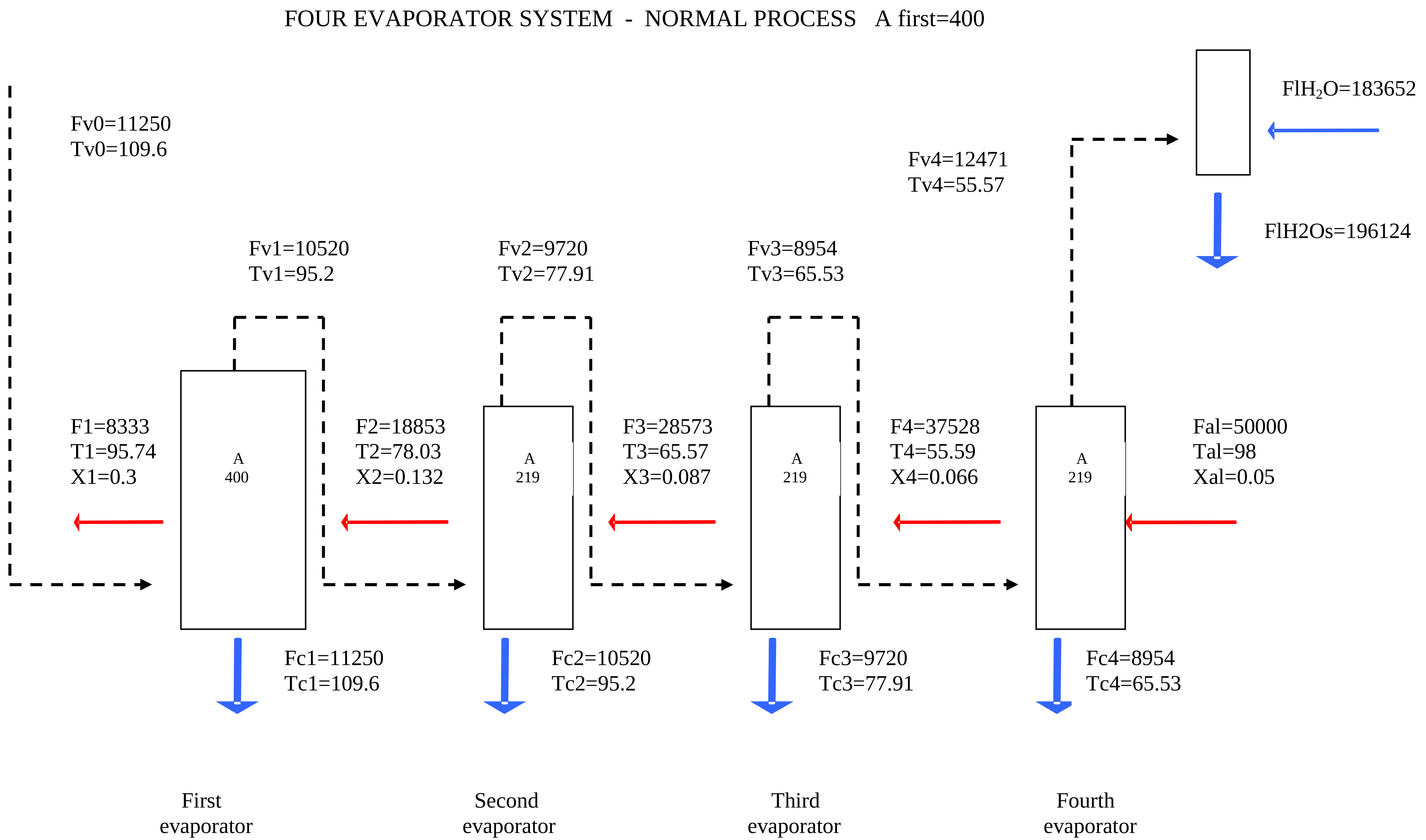


Figure 30: normal counter current process with a larger first evaporator

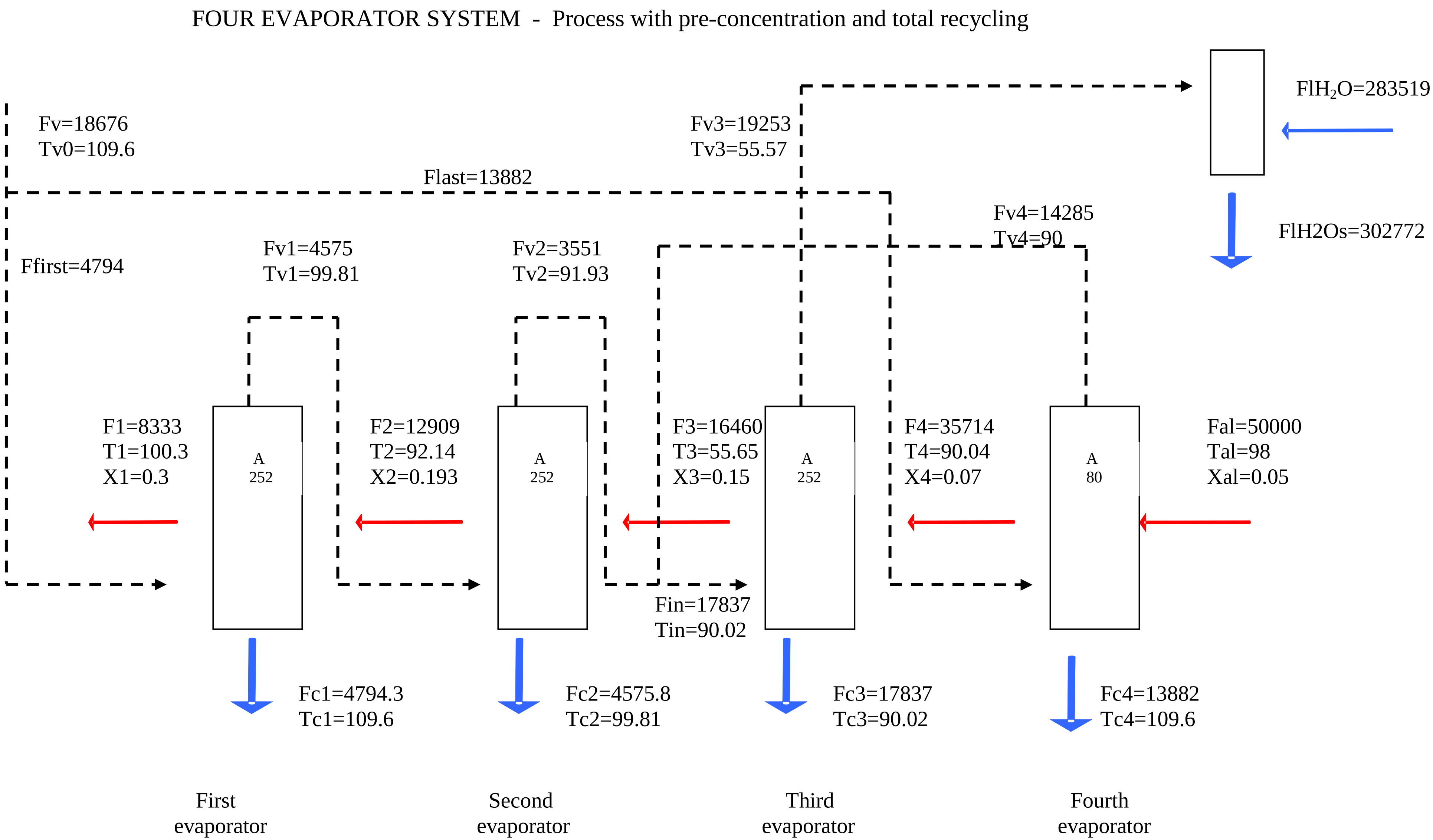


Figure 31: counter current process of evaporators with pre-concentrated stage and total recycling

FOUR-EVAPORATOR SYSTEM - Process with pre-concentration and partial recycling

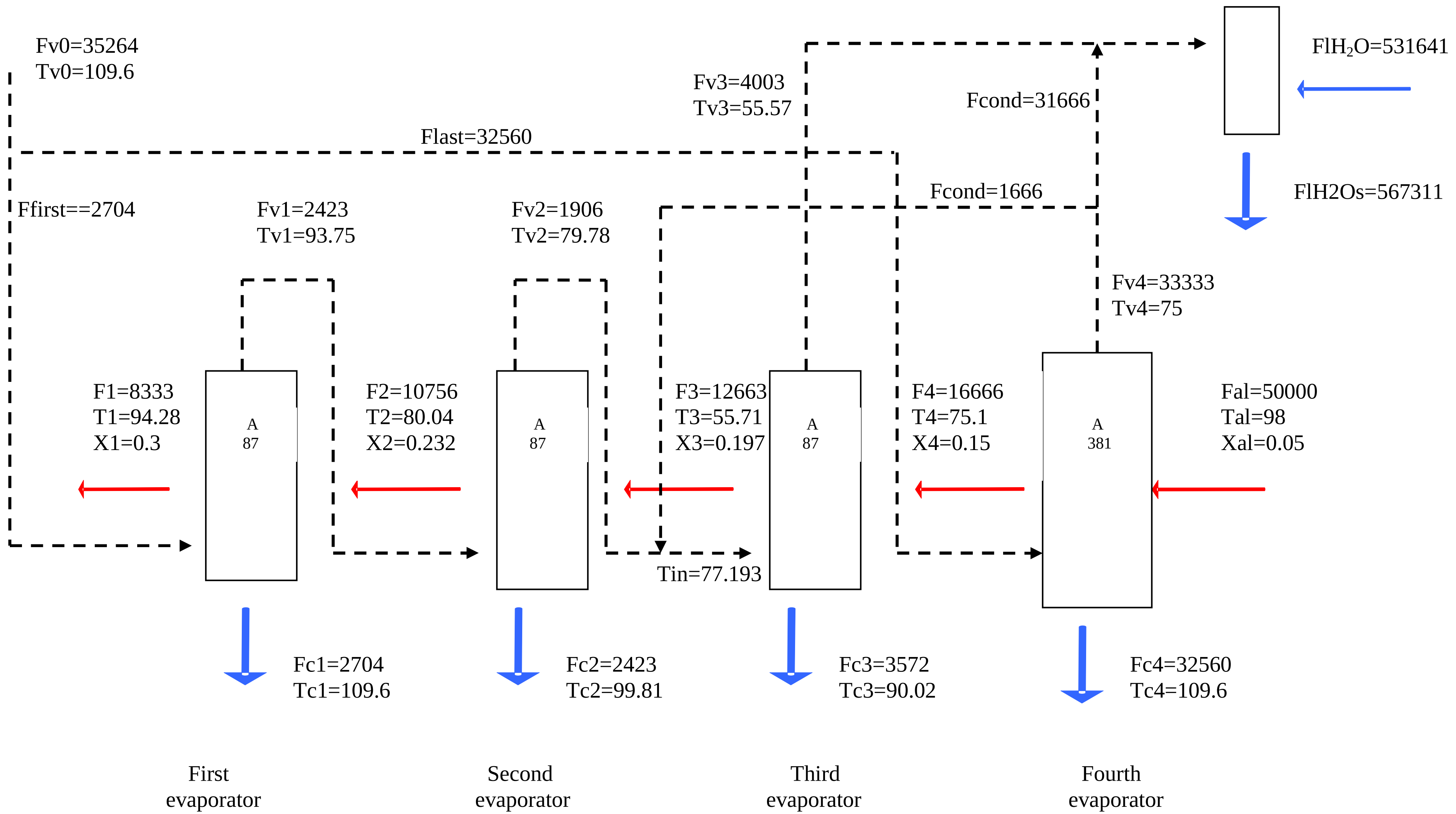


Figure 32: counter current process of evaporators with pre-concentrated stage and partial recycling

Quality analysis and economic evaluation

	NPV without quality factor	NPV with quality factor	Lycopene retention
normal counter current process with same heat exchange area for all evaporators	3.12 E+07	4.337 E+07	95.85
normal counter current process with different heat exchange area for each evaporator	3.04 E+07	4.37 E+07	95.44
normal counter current process with a larger first evaporator	3.075 E+07	4.29 E+07	94.96
Counter current process of evaporators with pre-concentrated stage and total recycling	3.73 E+07	3.6 E+07	94.06
Counter current process of evaporators with pre-concentrated stage and partial recycling	3.34 E+07	4.098 E+07	95.78

Figure 33: analysis of different configurations

Figure 33 shows the economic and quality results between all the typologies analyzed.

The NPV value is improved if each evaporator shows a different area. In particular, this option minimizes total costs, but it does not present the highest lycopene retention between all of the 4 effect evaporator modalities.

The best quality product is offered by the basic configuration with equal area evaporators.

The introduction of a pre-heating and pre-concentration stage with total recycling does not result in any improvement under a different point of view. The final lycopene retention is the lowest one, and it is linked with the high temperature of the process showed in the first and second evaporators. Also, the investment costs for this variation are the most relevant.

Arrangements with a pre-concentrating stage and partial recycling have good lycopene retention. However, the total costs are quite high because of the large amount of water needed for hot steam condensation.

6 – CHANGE IN PROCESSING CONDITIONS

In previous studies, the utilization of fresh hot steam pressure has always been assigned at 143.4 kPa, which corresponds to a temperature of 109.6°C.

The effects of changing this parameter, paying particular attention to NPV parameter variations and the final quality of the products, will now be observed.

Fresh, hot steam costs rise proportionally with temperature. By starting from a value of 0.0262 $/Kg for medium pressure fresh steam (122 kPa), high pressure steam costs can be estimated by adding the price of the fuel necessary for heating with the right efficiency.

6.1 - Lycopene

Figure 34 shows lycopene retention as a function of fresh, hot steam for the five typologies evaluated.

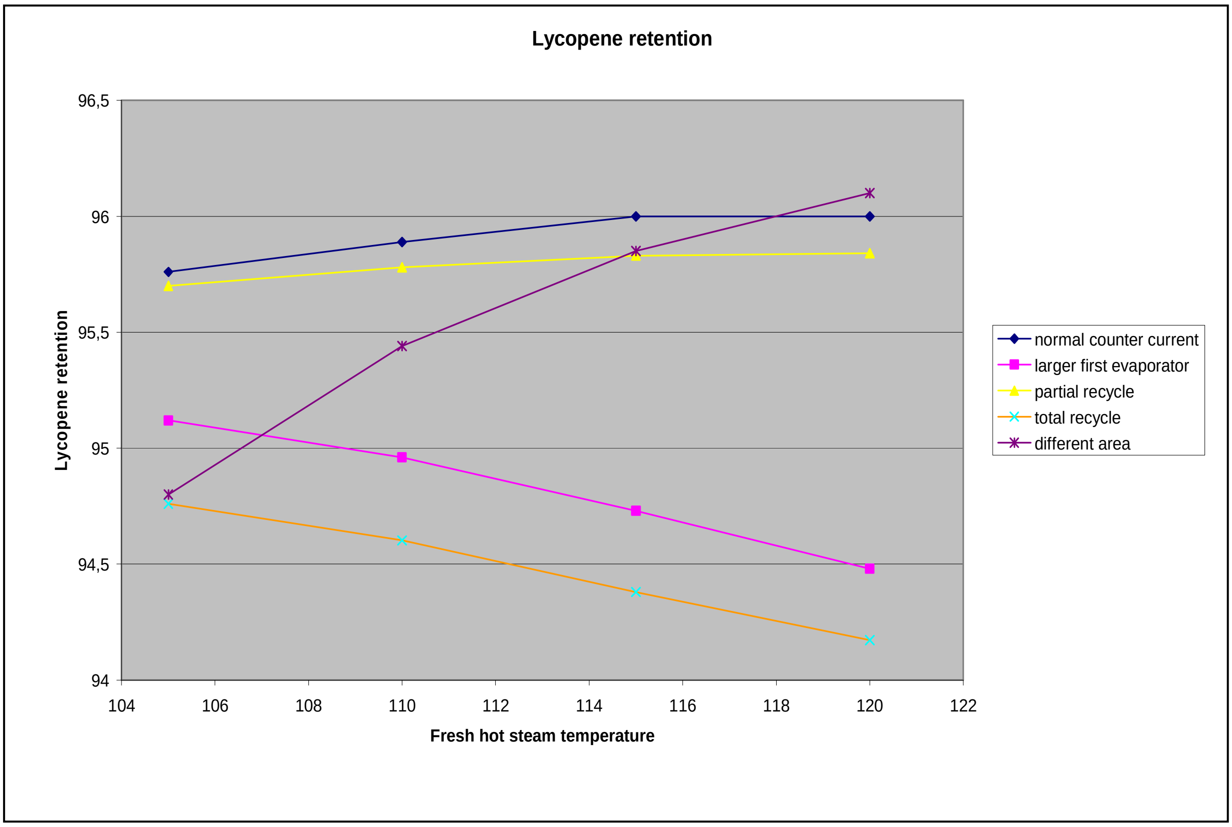


Figure 34: Lycopene retention as a function of different fresh, hot steam temperatures for different configurations

This figure shows a different behavior for all of the arrangements studied.

Basic counter current processes with evaporators of the same area or different area and configuration with pre-heating and pre-concentrating stage with a partial recycling of the steam generated in the last device shows an improvement in the final content of lycopene with higher fresh, hot steam pressures.

The option with different areas for each device is the most sensitive with change, and it offers the best retention if the fresh steam temperature is 120 °C, thanks to the strong reduction of residential time in the process.

The configurations with a larger first evaporator and with a stage of pre-concentration and total recycling show the lowest retention rates. These dispositions also show a different dependence on fresh steam temperature variations: the final content of lycopene decreases with higher fresh steam.

6.2 - Furosine

Figure 35 analyzes furosine formation as a function of fresh, hot steam for the 5 typologies evaluated.

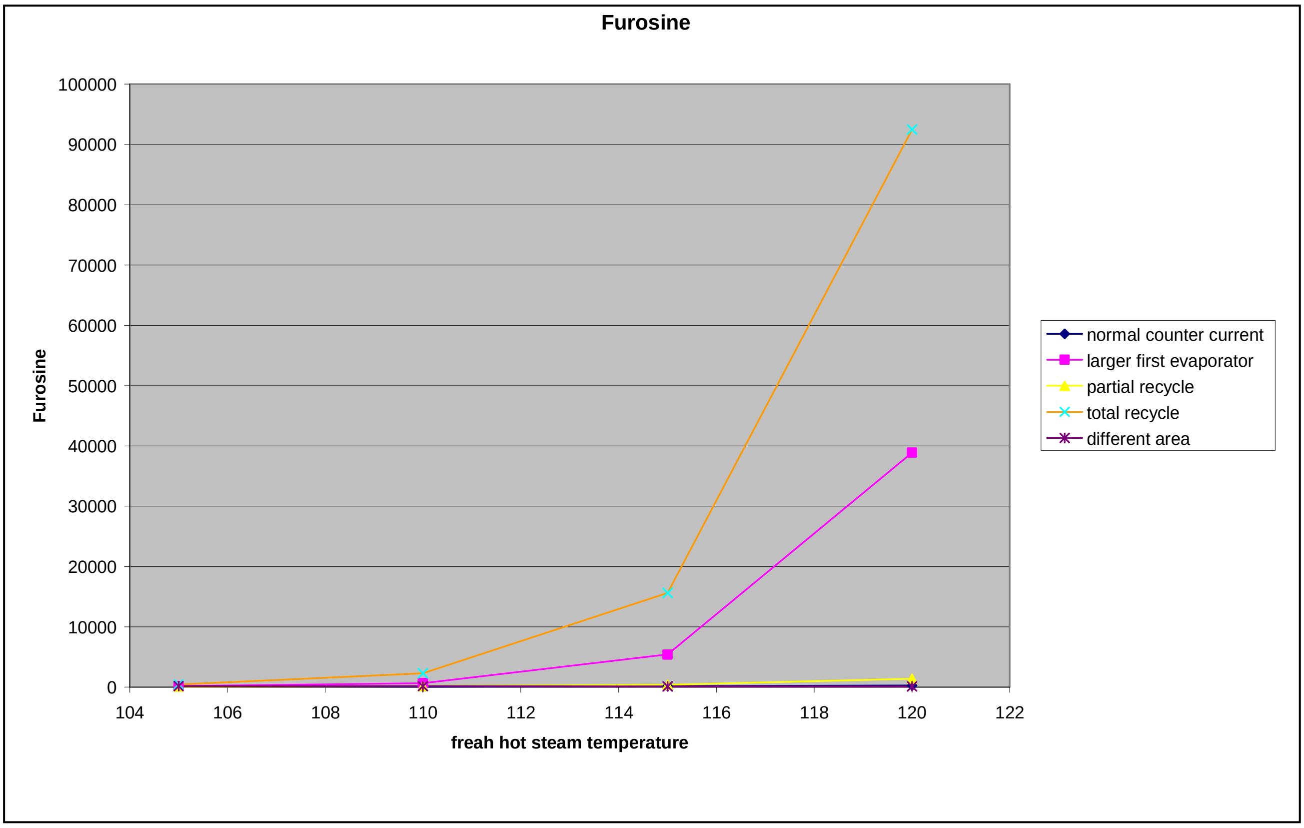


Figure 35: Furosine formation as a function of different fresh, hot steam temperatures for different configurations

The furosine content has a strong dependence on the fresh, hot steam temperature.

Best configurations for this quality parameter are the normal counter current with same area of evaporators, the normal counter current with different areas of evaporators and the arrangement with a pre-concentrating stage that offers lowest formation of this amino acid and, consequently, minimizes the Maillard reaction.

The option with a larger first evaporation generates a strong progress in this compound. The kinetic constant of this reaction results in the global elevation of the temperature of the devices, offering an exponential dependence.

The disposition with pre-heating and pre-concentrating causes the strongest growth in furosine content, probably because of the degradation of the processed food.

6.3 - Ascorbic acid

Figure 36 analyzes ascorbic acid degradation as a function of fresh, hot steam for the 5 typologies evaluated.

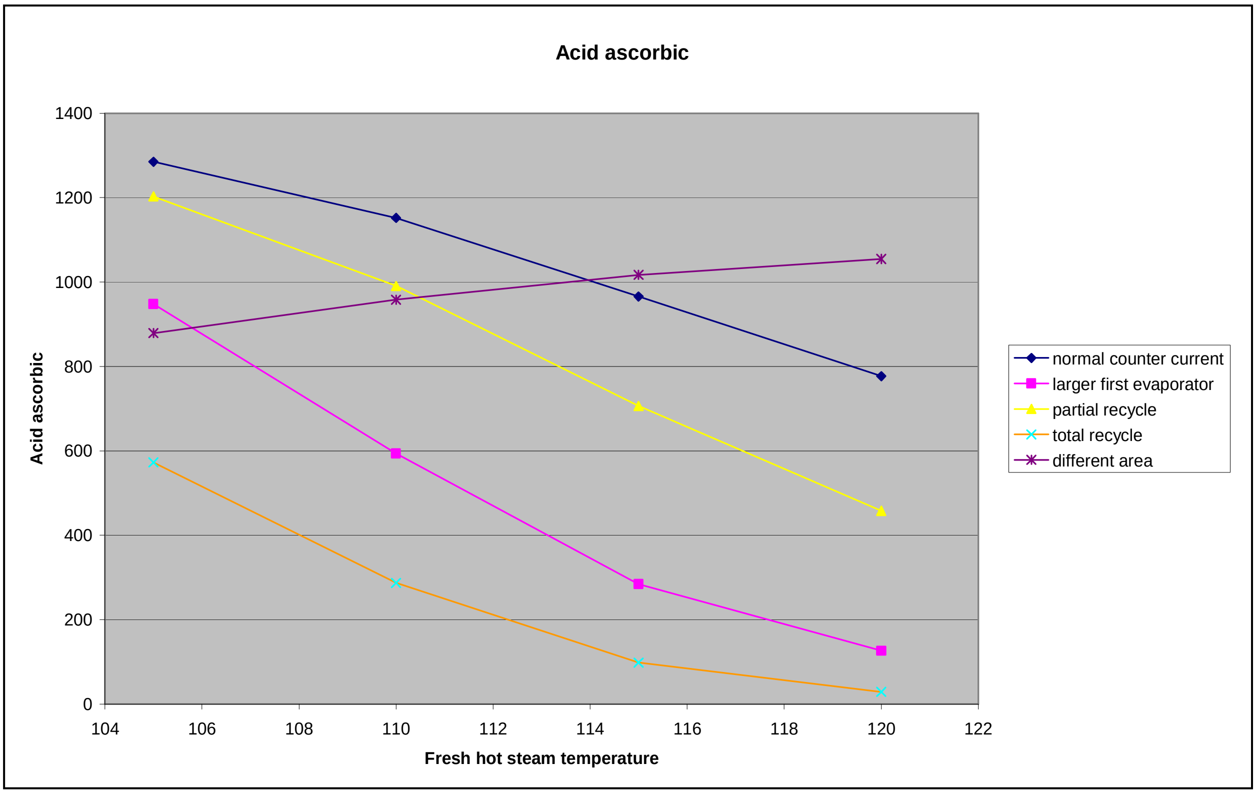


Figure 36: Ascorbic acid degradation as a function of different fresh, hot steam temperature for different configurations

Generally, ascorbic acid degradation grows proportionally with steam pressure for all systems, except for the configuration with different areas for each device, which shows an improvement in the final retention that is directly proportional to the fresh steam pressure. Also, the reasons for this different behavior are linked with the global reduction of the residence time.

Configurations with a larger first evaporator and a stage of pre-concentrating and total recycling destroy almost all of the vitamin C content if the fresh, hot steam temperature is 120 °C. This is also the case in the system with partial recycling. In the normal counter current with evaporators of the same area, the losses are about the half of the initial value.

6.4 - Color

Figure 37 analyzes color as a function of fresh, hot steam for the 5 typologies evaluated.

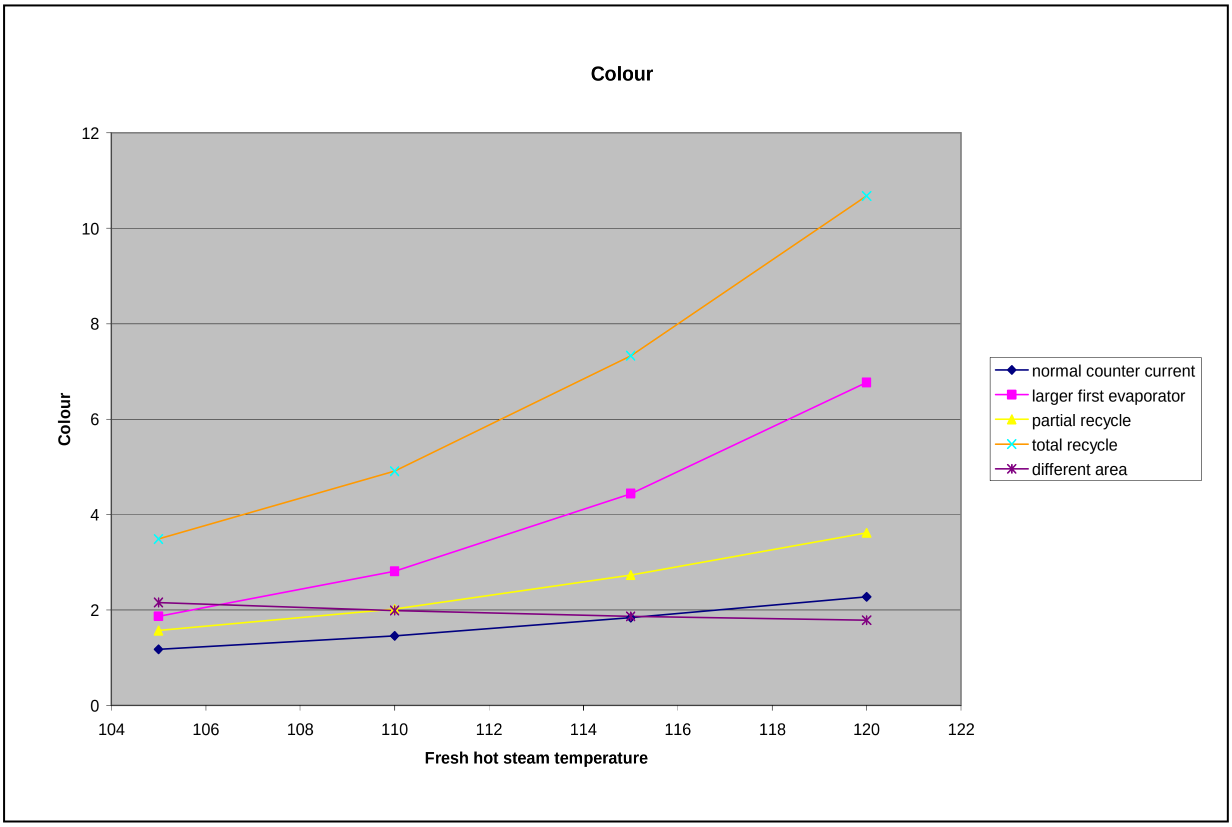


Figure 37: Color degradation as a function of different fresh, hot steam temperatures for different configurations

Configurations with different evaporator areas show a different dependence, and they present the best color with a higher fresh, hot steam temperature. All of the other arrangements produce a tomato paste with a worse color.

The introduction of a larger first evaporator and a stage of pre-heating and pre-concentrating with total recycling produces a paste with the strongest change in color by having a higher residential time and higher temperature in the devices.

6.5 - NPV analysis

Process analysis cannot be independent, as the necessary economic evaluation does not depend on all of the quality parameters, but only on lycopene retention.

The choice of the configuration that will be adopted will be tightly linked with NPV in all of the possible systems.

Figure 38 shows a NPV investigation without quality parameter. This coincides with the comparison of pure costs and must be minimized.

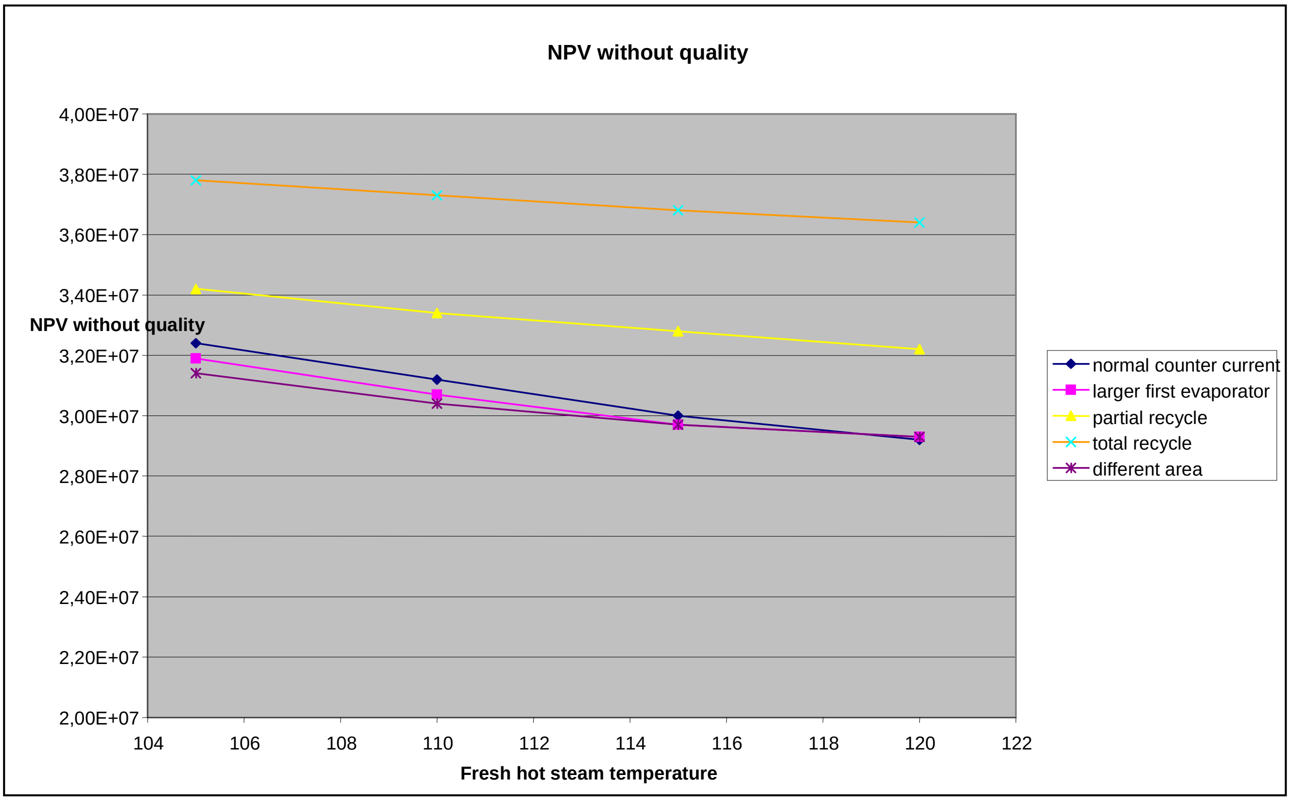


Figure 38: NPV without quality as a function of fresh steam temperatures for different configurations

Figure 39 presents NPV with quality analysis. This function of content shows the dependence of the final lycopene retention and has to be maximized.

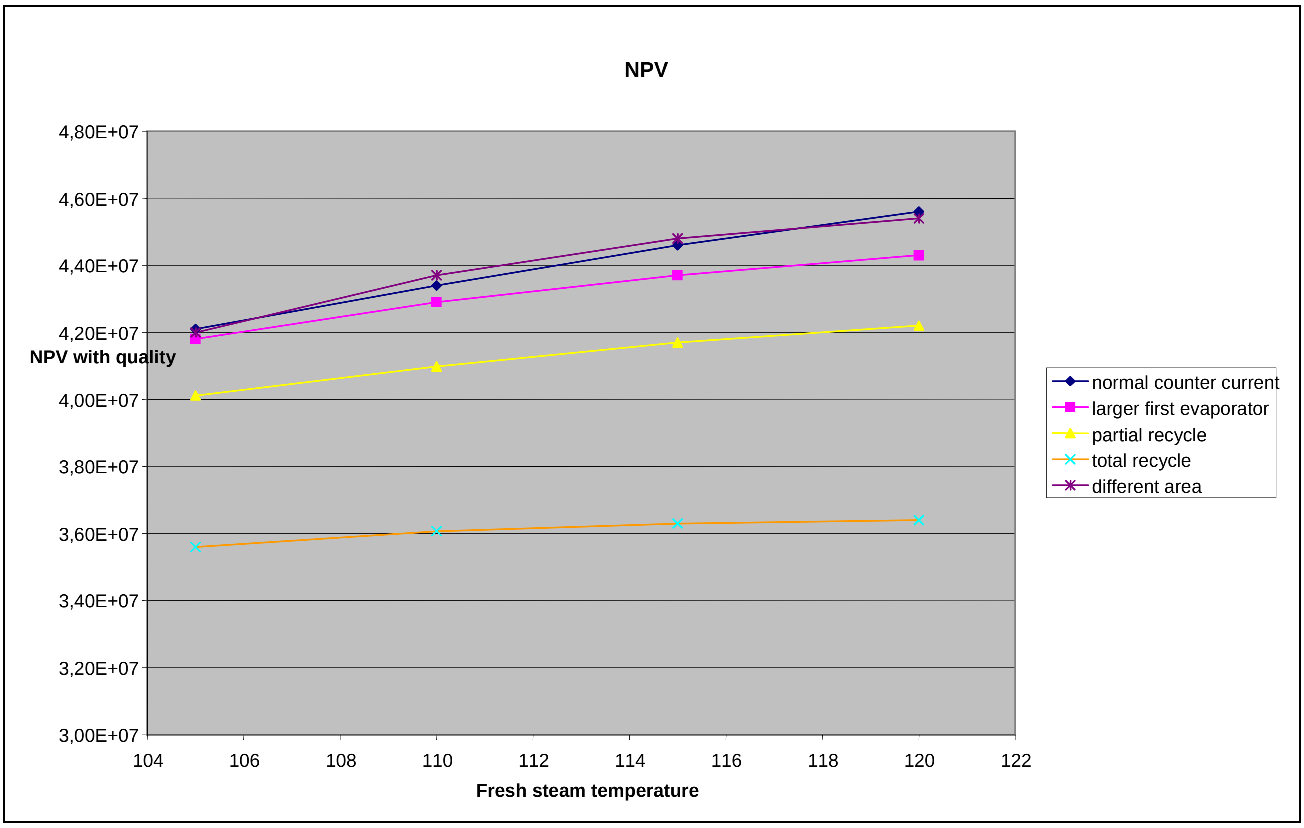


Figure 39: NPV with quality study as a function of fresh steam temperature for different configurations

The elevation of fresh, hot steam pressure improves the final gain with a growth that is linearly proportional.

Configurations with different evaporator areas minimize global costs and return the best NPV. These are followed by the normal counter current system with evaporators of the same area and by the disposition with a larger last evaporator.

If the fresh steam temperature is 120 °C, the normal counter current process with equal area becomes the one that returns the best value.

The introduction of pre-heating and pre-concentrating stages penalizes investments and returns the lowest NPV.

7 – CONCLUSIONS

- A model was developed for solving the problem of tomato paste concentration for multiple effect counter current evaporators under the hypothesis of the stationary stage.

The target of this study was the individuation of operating conditions for tomato processing for a number of evaporators that change from one to seven.

Resolution of the model was made possible with the help of Matlab 7.0 software.

- A study of several quality parameters was introduced, particularly the final content of lycopene, furosine, and acid ascorbic and color.

It was found that the lycopene content falls off linearly with the number of effects. Ascorbic acid shows the same behavior, while the presence of furosine grows with the number of effects exponentially.

Color worsened with the increasing of number of effects.

- A double economic evaluation (NPV) was done on the whole process for the individuation of the number of effects that return the best gain.

The first economic analysis considered investment and operating costs, while the second test added final lycopene content as a factor.

- Both of these studies individuated the 4 effect arrangement as the best option for the process.

- Attention was given to modifications of the 4 effect normal counter current system by changing the area of all the devices, introducing a larger evaporator in the process, and examining pre-heating and pre-concentrating with the goal of the individuating the best possible NPV.

- The disposition with different areas for each evaporator was the one that maximized lycopene retention as a consequence of the minimization of residencial time.

The best NPV is offered by the arrangement with evaporators of equal area.

- The influence of fresh, hot steam pressure variations were analyzed.

The elevation of pressure, and consequently of temperature, of the fresh hot steam improves the NPV of all these configurations, while the dependence of all the quality factors vary.

- Lycopene retention improved with higher fresh, hot steam pressure for the normal counter current processes with evaporators of the same area, for the normal counter current process with evaporators of different area and for the process with a pre-concentrating stage and partial recycling. The configuration with a larger first evaporator or stage of pre-concentration and total recycling offered a worse final content with the fresh, hot steam pressure growth.

The best retention was offered by the arrangement with devices of different heat exchange areas and a hot, fresh steam temperature of 120 °C.

- Other studies on several quality factors showed a worsening of the quality of the tomato paste processed for all configurations as a function of increasing fresh, hot steam pressure, except the one with different heat exchange areas for every evaporators. This option, linked with a general reduction in residence time, offers an improvement of the product with increasing steam pressure.

8 – FUTURE WORKS

The goal of this thesis was the individuation of the process configuration for tomato paste concentrating that allows the highest gains and highest convenience of investment.

The development of the NPV model evaluation focused solely on the final content of lycopene as a quality parameter of the final product. Following this consideration, the sale price of this product was function of only the retention of this enzyme.

In accordance with the general request of highest quality foods, subsequent works could develop a model in which final prices will depend more strongly on the final nutritive content of tomato paste. This will also introduce a dependence of the NPV index on the retention of acid ascorbic, the content of furosine, and color and other eventual quality factors while reinforcing the dependence on lycopene.

Particular attention could be paid to the process with a stage of pre-concentration and partial recycling of the steam generated in the last device. In fact, this configuration returns good lycopene retention and high operating costs, linked to the large amount of hot steam that has to be discharged in the condenser.

If it were possible to recycle the hot steam generated in the pre-concentrating stage, this configuration would become the best one.

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