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Solar Thermal Treatment: Case Study for Cashew Juice Pasteurization

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Abstract: Energy and food are very intertwined and important in human life. Cashew juice is a very abundant product in southern Senegal. Unfortunately, due to lack of processing and conservation, this product cannot last 24 hours without being fermented. The aim of this study is to study the heat treatment processes of agri-food products, particularly the pasteurization of cashew fruit juices. Pasteurization often uses heat from fossil fuels. In this heat treatment process of cashew juice, we are interested in the energy source. Thus thermal solar energy is used in this heat treatment. A solar thermal collector with an area of 17.9 m^2 and a hot water storage tank with a capacity of 0.1 m^3 are used. With the pasteurization model used, the juice circulates in a copper coil immersed in hot water coming from the solar thermal field or the hot water storage tank. A numerical simulation program has been developed on Ansys Fluent 2020 R1 to study the evolution of the temperature of the juice from the inlet to the outlet of the coil. The results obtained give outlet temperatures varying from 70 to 80°C depending on the speed of circulation of the juice. We can also achieve outlet temperatures of 100°C. This means that our system can operate in sterilizer mode.

Keywords: Pasteurization, Solar Thermal Collectors, Storage Tank, Thermal Treatment

1. Introduction

To increase the shelf life of food, new preservatives method such as smoking or adding salt were used to protect meat and fish from putrefaction. Despite a long tradition of efforts to prevent spoilage of food, it was not until the 19th century, with the work of Nicolas Appert (1809), that a new method of preservation was developed: sterilization of food in sealed bottles. Emerging alternative technologies are being adopted in addition to traditional thermal processing, thus the term pasteurization has been broadened. The requisite scientific parameters for designing a thermal pasteurization process have become more important and need to be clear [1]. The word pasteurization was originally named after the French scientist Louis Pasteur, who invented the process of heating liquids (wine and beer) at a relatively mild temperature (about 55°C) for a short time to prevent spoilage [2-4].

It was not until the early 1920s that a modeling coupling the kinetics of thermal destruction of bacterial spores and heat transfers, will allow the first simulations and the first optimizations of thermal treatments. Today, the canning industry has constantly sought to diversify and develop its products. However, the development of this food preservation process is faced with a limit which is the very basis of its existence: thermal treatment. Thermal sterilization, pasteurization, and blanching techniques have been extensively used in the food industry to control bacteria, fungi, and other microorganisms as well as undesirable enzymes in foods [5-7].

Sterilization is the destruction of all the microorganisms in a product, while pasteurization makes it possible to destroy all of the non sporulated pathogenic germs as well as most of the common germs. The pasteurization is therefore a less severe thermal treatment than sterilization. Two recently published reviews have provided insights into designing pasteurization processes using two particular pathogens in foods as references, namely, non-proteolytic Clostridium botulinum spores and Salmonella [1].

This thermal treatment responsible for the total elimination of microorganisms nevertheless causes a lot of damage to the quality of the product itself. The destruction of microorganisms by heat is often done at the expense of the nutritional and organoleptic qualities of the food.

The vitamins and the proteins are not very stable at high temperatures. Cooked flavors and changes in texture may also appear. These effects of thermal treatment make canned food less and less attractive to the consumer, to the benefit of fresh products despite their reduced consumption in limited time. The current desire of preserver is to strive towards a reduction in pasteurization scales to improve the final quality of their products, while maintaining the microbiological safety. This optimization of the pasteurization scales amounts to determining the minimum thermal treatment to be applied to the product in order to achieve the desired microbial reduction rate.

The source of energy used for thermal treatment in food industry are most often sources of fossil fuels. In our country, the agro-food production areas are not often accessible to the electricity network due to their remote area, also they cannot support the high costs of the kilowatt hour. Likewise, the environmental challenges prompt us to explore renewable energy sources in order to reduce greenhouse gas emissions. Fortunately, the agro-food areas are often very sunny around all the year with a good rainfall. They therefore have a good resource of thermal solar energy and biomass. Therefore, we must think to substitute the use of fossil energy in the thermal treatments of agro-food products by renewable energies.

This study focuses on the thermal treatment of cashew juice in the southern regions of Senegal.

This product, rich in nutrients is abundant in the region between the months of April and June. Despite this abundance, the product cannot last 24 hours without being fermented. It then becomes alcoholic drink. Our customs and religion prohibit us to use this alcoholic drink.

So, for the conservation of the product for a few days or even weeks, we have think for a heat treatment with solar thermal energy as a heat source. During thermal processes, such as pasteurization, sterilization, or freezing, the dissociation equilibrium of water and buffer solutions varies with pressure and temperature [8-10]. This change of the pKa-value (decadic logarithm of acid dissociation constant Ka) may play an important role in different pH-sensitive reactions, but its behavior has rarely been investigated [8, 11]. But the effects of thermal treatment on the chemical and physical composition of the product will not be studied. Thus, we are interested on the source of thermal energy production. Solar thermal systems are used to produce hot water by the absorption of solar irradiation. The performance of solar thermal systems is most commonly described using solar fraction [12]. We are going to use a solar thermal field for the production of hot water necessary for the pasteurization of the product.

2. Materiel and Methods

2.1. Cashew Apple

Cashew plantations are numerous in the southern regions of Senegal. The cashew apple is the main raw material used in the production of cashew juice. These must be ripe, healthy and integrated. Several types of cashew apples, distinct according to the color ranging from yellow to red exist. But for processing, it is recommended to use apples of the same skin color.

Figure 1. *Cashew apple.*

2.2. Thermal Solar Collector Field and Hot Water

The greatest quantity of processed fruit is preserved by heat treatment. The pasteurization of food requires the use of hot water in order to limit the temperature difference with the product. As a result, the thermal shock is reduced, therefore the quality is improved and the fouling is limited, which increases the operating times. The hot water is often produced through a hot water installation using steam, gas, superheated water or electricity. In this study, the hot water required for pasteurization is produced by solar thermal collectors. One of the most well-known and common applications of solar energy is the solar water heater (SWH) system, due to its viability and economics advantages. The solar water heating system has two main components, namely storage tanks and solar collectors [13]. The solar radiation can be useful for our life to the heating building, heated water in order to produce steam and used it in any way such as in industrial and domestic [14]. Solar irradiance is transformed inside of a collector into useful thermal energy, and this process results in an increased temperature of the inside flow [15]. The obtained thermal energy can be stored and utilized for hot water provision, space heating/cooling/drying, industrial energy demand, and applications demanding moderate temperature energy delivery less than 100°C [16-17]. The average monthly energy efficiencies of the solar collector in July and August were 45.3% and 32.9%, respectively, while the average monthly exergy efficiencies reached 2.62% and 2.15%, respectively [18]. By means of pump, the hot water circulates to the pasteurizer. Similarly, another pump circulates the product to be pasteurized to the pasteurizer. The pasteurizer is done using a heat exchanger. The heat exchanger is a device that can continuously heat or cool a product. Between the two fluids there is a heating surface which can be a tube or a plate. The difference of temperature between the two fluids causes a thermal current through the heating surface. The heat transfer process requires to bring two substances with different temperatures side by side, so that one heats or cools the other. The pump flow rates are adjustable for low flow rates. The outlet of the pasteurized product is fitted with a tap which allows the product to be kept for a long time in the pasteurizer, as shown in Figure 2.

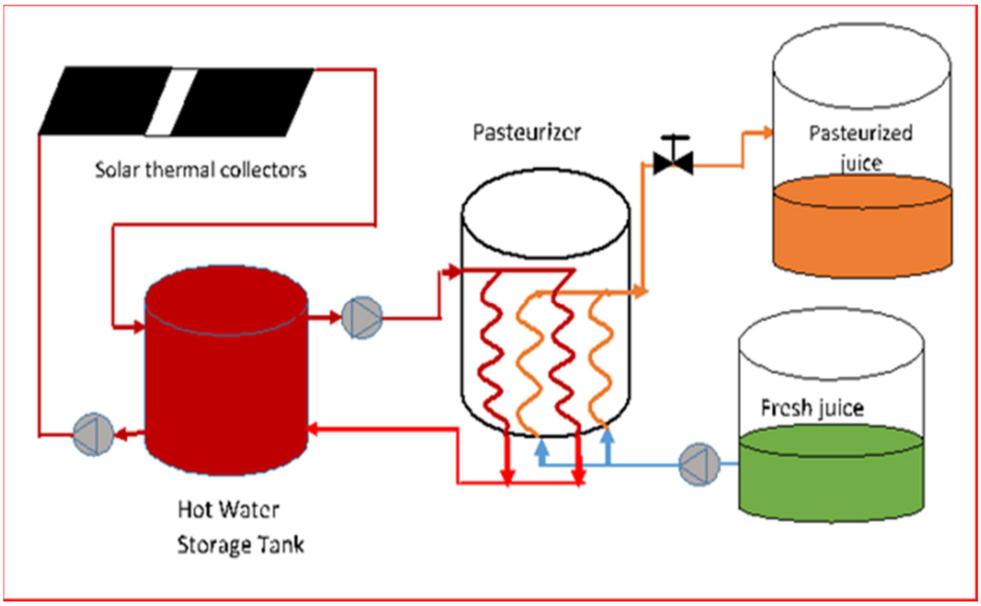

Figure 2. *Schematic diagram of the device.*

The necessary quantity of heat for the pasteurization of the fresh product is given by the equation (1):

$$Q_{pas} = V_{prod} Cp_{prod} \left(T_{hotprod} - T_{colprod}\right) \quad (1)$$

With;

V_{prod}: volume of the product to be pasteurized in m^3;

Cp_{prod}: specific heat of the product kWh/m³K;

$T_{hotprod}$ and $T_{colprod}$ are respectively the hot and the cold temperature of the product;

The knowing of this heat allows us to design a system of hot water production with a solar thermal collector field that provides the source of thermal energy. The heat stored in hot water needed for heat treatment of the product is given by the equation (2):

$$Q_{he} = V_e Cp_e (T_{out} - T_{in}) \quad (2)$$

With:

V_e: volume of water in m^3;

Cp_e: specific heat of water kWh/m³K;

T_{out} and T_{in} are respectively the outlet hot water temperature of the solar thermal collector and the inlet water temperature of the solar thermal collector.

The equality of the equations (1) and (2) makes it possible to calculate the need for hot water V_{HWN} for pasteurization. The size of the hot water storage tank is given by equation (3):

$$V_{st} = V_{HWN} \times 1.2 \quad (3)$$

The daily energy requirement for the hot water need Q_{HWN} to ensure the pasteurization of the product is given by the following equation:

$$Q_{ECS} = V_{HWN} Cp_e (T_{out} - T_{in}) \quad (4)$$

The principal element in solar thermal system is the evacuated tubes solar panels that collect the maximum possible of solar irradiation. The thermal power provided by the solar system, Q_{col}, is calculated by (5) [19-22]:

$$Q_{col} = I_r \eta_{col} \eta_{sys} I_r \quad (5)$$

solar irradiation in kWh/ m². day;

η_{col} and η_{sys} are respectively the efficiency of the solar thermal collector and that of the system.

The area of the thermal solar collector field is given by equation (6) [19, 23]:

$$A_{col} = \frac{Q_{ECS}}{Q_{col}} \quad (6)$$

2.3. Sizing of Pasteurizers

Four case studies were conducted under the same operating conditions (flow rate, temperature, volume, juice flow section), namely:

Two coaxial cylinders with the juice circulates inside and the hot water outside and vice versa;

Cylinder and coil whose juice circulates inside the coil and hot water outside and vice versa.

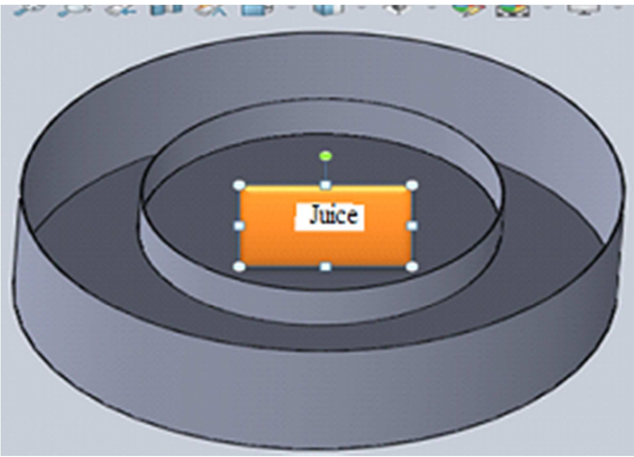

Figure 3. Pasteurizer with 2 coaxial cylinders in which the juice circulates in the internal cylinder and the hot water in the external cylinder.

2.3.1. Dimensionless Parameters and the External Convection Coefficient He

For the calculation of the external convection coefficient (he), we will consider a natural convection in the juice tank where the movement of the fluid is generated by the Archimedes forces due to the variations of the density with the temperature. We will calculate here the dimensionless Grashof and prandtl numbers, then the Rayleigh number. We will also determine the Nusselt number by applying the corresponding correlation.

Grashof number

The Grashof number characterizes the flow in natural convection. It is defined by:

$$G_r = \frac{G\beta\rho_f^2 d_{ij}^8 \Delta T}{\mu_f^2} \quad (7)$$

The temperature variation between the juice and the outer wall of the hot water tank will be taken as 1°C given that the exchanger (the outer surface of the hot water tank) is completely immersed in the juice.

$$\mathrm{Gr} < 10^9$$

We have a laminar flow.

Prandtl number

It is the ratio between the diffusivity of momentum (kinematic viscosity) and that of heat (thermal diffusivity). It compares the speed of thermal phenomena and hydrodynamic phenomena in a fluid. It is defined by:

$$P_{rf} = \frac{C_{pf}\mu_f}{\lambda_f} \quad (8)$$

Rayleigh number

It is a dimensionless number used in fluid mechanics and characterizing the type of heat transfer within a fluid through a critical value (1700). If the number is lower than this value, the heat transfer takes place by a simple conduction and in the opposite case there is a natural or forced convection. It is defined by:

Nusselt number

It is a dimensionless number used to characterize the type of heat transfer between a fluid and a wall by relating convection to conduction. The following formula corresponds to the case of a laminar regime, $\mathrm{Gr} < 10^9$.

$$N_{uf} = 0.508 \frac{P_{rf}^{\frac{1}{2}}}{(0.95+P_{rf})^{\frac{1}{4}}} G_r^{\frac{1}{4}} \quad (9)$$

External factor he

$$h_e = \frac{\lambda_c N_{uc}}{d_{ej}} \quad (10)$$

2.3.2. The Dimensionless Parameters and the Internal Convection Coefficient Hi

In this section, the hot water is forced to circulate in the internal tank while the juice is still circulating in the external tank.

Reynolds number

It is a dimensionless number characterizing the type of flow, in particular its regime (laminar, transient, turbulent).

$$R_{ec} = \frac{\rho_c v_c d_{ej}}{\mu_c} \quad (11)$$

Prandtl number

$$P_{rc} = \frac{C_{pc}\mu_c}{\lambda_c} \quad (12)$$

Nusselt number

$$N_{uc} = 0.023 \times R_e^{0.8} \times P_{rc}^{0.3} \quad (13)$$

2.3.3. Calculation of the Global Thermal Exchange Coefficient

$$\frac{1}{U} = \frac{1}{h_e} + \frac{d_{ej}}{2\lambda} ln\left(\frac{d_{ej}}{d_{ij}}\right) + \frac{d_{ej}}{d_{ij}} \cdot \frac{1}{h_i} \quad (14)$$

This same approach was followed in the case where the juice circulates outside the cylinder but in the case where there is a coil immersed in hot water.

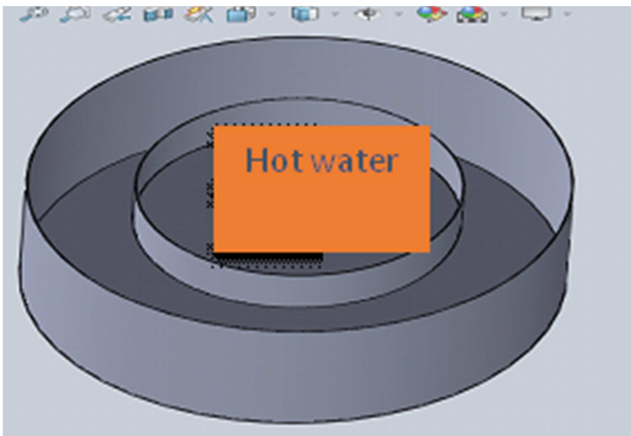

Figure 4. Pasteurizer with 2 coaxial cylinders in which the juice circulates in the outer cylinder and the hot water in the inner cylinder.

Figure 5. *Diagram of the operating principle in case of cylinder and a coil whose juice circulates inside the coil and hot water outside.*

Hypotheses

1) Heat transfer takes place without a change of state.
2) The exchanger is of the single-phase type.
3) For the sizing of the exchanger, we put ourselves in the conditions of atmospheric pressure and we will neglect the heat losses in the exchanger.

The steps for sizing are given in figure 6:

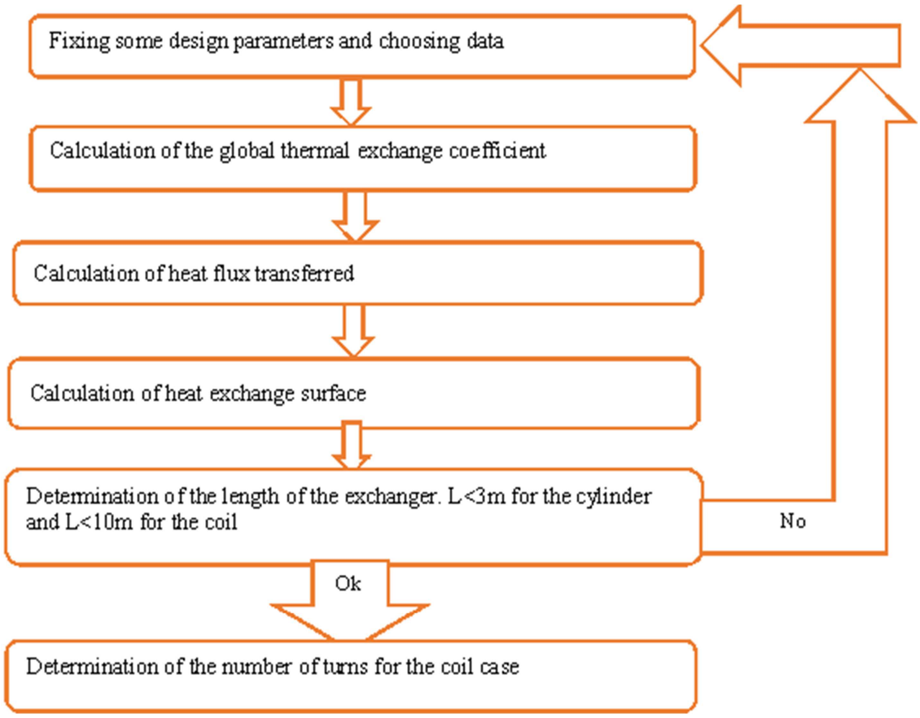

Figure 6. *Different stages of sizing.*

3. Results and Discussions

Using the dimensionless numbers of Grashof, Prandlt, Rayleigh and Nusselt, we obtained in table 1 the values of the four studies case.

For the same heat flux to be exchanged, the same volume of heat fluid transfer and the same efficiency of the exchangers, we have a greater overall exchange coefficient in the case where the juice circulates in the coil. We also note that this exchange coefficient is greater when the heat exchange takes place from the outside to the inside.

These calculated coefficients respect the magnitude order of the global coefficients of the fluids according to their viscosities for the case where the juice circulates in the coil. For the other cases, they are lower than the interval of magnitude presented. This is probably due to the fact that the amount of heat is greater when the heat transfer is from the outside to the inside.

Indeed, the external surface being larger, the volume of external hot water is greater, hence the increase in the overall exchange coefficient. Table 2 gives the order of magnitude of the global exchange coefficient.

Table 1. *Comparative study of the sizing of the four heat exchange surfaces.*

designations	units	Coaxial cylinders		Cylinder containing a coil	
		Juice circulating in the internal cylinder	**Juice circulating in the outer cylinder**	**Juice flowing through the coil**	**Juice circulating in the tank containing the coil**
Heat flux exchanged	W	7524			
Passage section	m^2	0,0005	0,0005	0,00008	0,00008
Juice flow speed	m/s	0,4	0,4	0,347	0,347
Global exchange coefficient	W/m^2K	45,55	44,13	909,090	172,56
Surface of exchanger	m^2	2,35	2,43	0,82	4,360
Exchanger length	m	2,47	2,56	11,86	63,08
Number of turns				20	50
Efficiency of the exchange surface	%	79,85			

Table 2. *Order of magnitude of the global exchange coefficient.*

Hot fluid	Cold fluid	Us (W/m²K)
gas	gas	10-50
gas	viscous liquid	20-50
gas	low viscosity liquid	20-80
viscous liquid	gas	20-40
low viscosity liquid	gas	20-80
viscous liquid	viscous liquid	100-200
viscous liquid	low viscosity liquid	100-300
low viscosity liquid	low viscosity liquid	700-1800
Condensing vapor	viscous liquid	200-400
Condensing vapor	low viscosity liquid	1000-2000
low viscosity liquid	boiling liquid	700-1500

Table 2 shows the order of magnitude of the global coefficients of the fluids according to their viscosities. With regard to the heat exchange between low viscosity liquid - low viscosity liquid, the overall heat exchange coefficient varies between 700 W/m^2.K and 1800 W/m^2.K. This corresponds well to our case study.

Our choice of pasteurizer will therefore focus on the fourth case for our further study.

Figure 7: obtained by the solidworks software is a perfect illustration.

Generally, the Computational fluid dynamic (CFD) tool was related to solving the problems for non-linear partial differential equations that were described as the behaviors and phenomena of the fluid dynamics ([24]. In this part we studied the phenomenon of heat transfer taking place through our coil by doing the numerical simulation using the ANSYS FLUENT software.

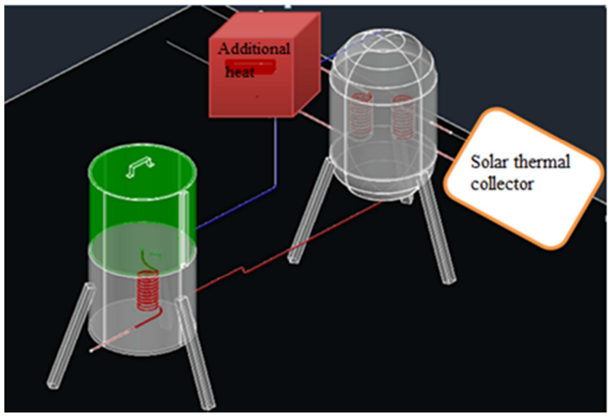

Figure 7. *Diagram of the pasteurizer system.*

ANSYS FLUENT is a software that solves and simulates fluid mechanics and heat transfer problems using the finite volume method using CFD (Computational Fluid Dynamics) codes. These CDF codes are structured around numerical algorithms that allow users to introduce the input parameters of the problem in order to examine the results.

In general, the mode of operation of these codes goes through three essential stages: pre-processing, resolution and finally post-processing focused on the visualization of the results as shown in figure 8.

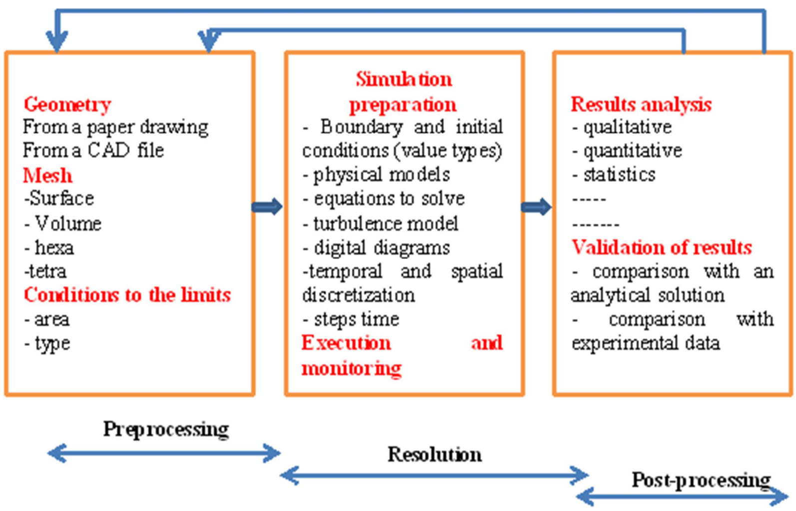

Figure 8. *Steps of the numerical simulation.*

Mesh generation (2D or 3D) is a very important phase in a CFD analysis, given its influence on the calculated solution. A good quality of mesh is essential to obtain a precise, robust and meaningful calculation result. The quality of the mesh has a serious impact on the convergence, the precision of the solution and especially on the computation time. A good mesh should also be smooth enough.

The temperature of juice varies according to its flow speed and the speed of circulation of the hot water. Figures 10 and 11 are a perfect illustration.

Figure 9. *Mesh.*

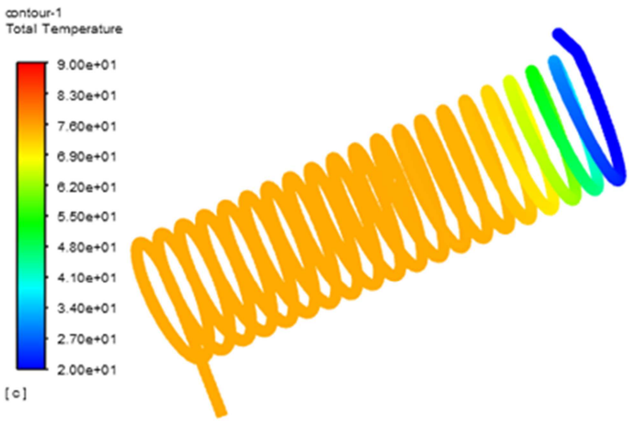

Figure 10. *Variation of juice temperature for a speed of the juice V = 0.347 m/s.*

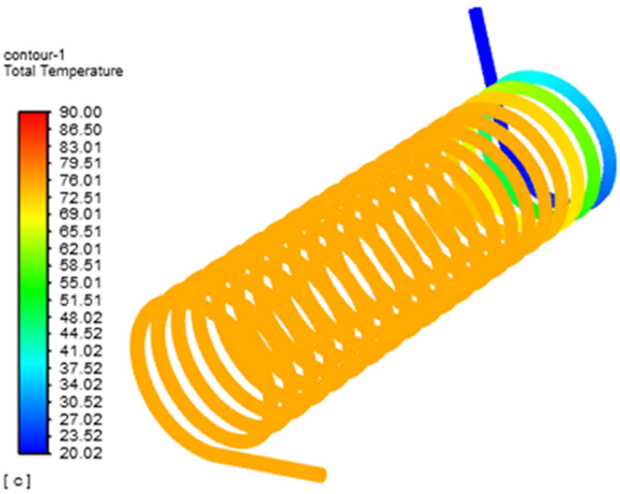

Figure 11. *Variation of juice temperature for a speed of the juice V= 0.1m/s.*

Figures 10 and 11 showed that the juice outlet temperature is Ts= 76°C for a juice speed vj= 0.347 m/s and Ts= 80°C for a juice speed vj= 0.1 m /s. We also note that the juice reaches these first heat peaks (in blue) as soon as it enters the coil when the hot water circulation speed is increased. The outlet temperature of the juice increases considerably when the speed of circulation of the juice is reduced. Indeed, the faster of hot water circulation and the more the flow of the juice is delayed, the more the juice gains heat in a short time.

4. Conclusion

We presented the sizing of our solar pasteurizer and studied the phenomenon of heat exchanges taking place within the system. The CDF codes allowed us to introduce the input parameters of the problem in order to examine the results. The results obtained show that the outlet temperature of the juice can reach the sterilization temperature (above 100°C) when the circulation speed of the juice is reduced and that of the heat transfer fluid is increased. This shows that our pasteurizer can also work as a sterilizer. In this study, we noted that the coil used as a heat exchanger seems to be the ideal compromise for the operation of our pasteurizer.

Abbreviations

Symbols	Designations	units
Cp	Heat mass	[J/kg K]
Cp_e	specific heat of water	[kWh /m³K]
I_r	solar irradiation	[W/m^2.day]
Gr	Grashof number	[-]
Pr	Prandtl number	[-]
h	Heat transfer coefficient	[W/m^2.K]
U	Overall thermal exchange coefficient	[W/m²·K]
d	External diameter of the juice tank	[m]
T	Temperature	[K]
μ_f	Dynamic viscosity of water	[kg/m.s]
β_f	expandability	[°C^{-1}]
λ_f	Water thermal conductivity	[W/m.K]
V	Fluid flow velocity	[m/s]
Ve	Volume of water	[m²]

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