MODELLING AND SIMULATION OF DIRECT STEAM INJECTION FOR TOMATO CONCENTRATE STERILIZATION

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ABSTRACT
Direct steam injection (DSI) is a sterilization technique which is often used for high viscosity fluid food when the preservation of the quality characteristics and energy efficiency are the priority.

In this work an apparatus for the sterilization of tomato concentrate has been analyzed by means of multidimensional CFD (Computational Fluid Dynamics) models, in order to optimize the quality and safety of the treated food.

A multidimensional two-phase model of steam injection inside a non-newtonian pseudoplastic fluid was adopted to evaluate the thermal history of the product and the steam consumption during the target process.

Subsequently CFD analysis has been extended to examine the effects of the different process parameters (sterilization temperature, steam flow rate, radial and axial temperature profiles, nozzle geometry) on the resulting product.

Result obtained are in agreement with available data acquired in industrial plant.

Keywords: Steam injection, non-Newtonian flow, CFD, Multiphase flow, Design optimization

1. INTRODUCTION
Fluid food products in the agri-food industry are commonly subjected to thermal treatments to ensure safety and improve quality. Process parameters need to be accurately selected and monitored in order to effectively sterilize the product while at the same time avoiding over-processing, which would negatively affect product quality (Abdul Ghani et al 2001). A compromise is therefore required between safety, taste preservation and energy efficiency.

Among the different thermal treatments available, continuous direct steam injection is widely used to quickly raise the temperature of a process media, either for pure heating or for sterilization of the product. The basic idea is to heat the liquid flow by injection of superheated steam from several nozzles, in order to reach homogeneous heating. The main benefit of the direct contact condensation process is the high heat transfer rates and the low product fouling compared with other methods such as heat exchangers. For these reasons, steam injection is used in various applications across in the food industry, such as the sterilization of milk, fruit juices and puree.

In this work, an apparatus for the sterilization of the tomato concentrate has been analyzed by means of multidimensional CFD (Computational Fluid Dynamics) models. CFD has been applied in recent years to model the sterilization problem in order to gain a better understanding of the process and optimize quality while at the same time guaranteeing the safety of the product (Debonis and Ruocco 2009; Marsh 2006).

While the overall energy balance for the process can be easily calculated from the process parameters (steam properties and product flow rate), a numerical model is required for the evaluation of temperature history and distribution Moreover, the available literature on direct steam injection is mostly limited to the case of steam injection in a stagnant liquid, typically water (Sagar 2006; Sachin 2010).

Modeling and simulation of fluid process allow: (a) the optimization of heat transfer in terms of energy efficiency, equipment design, product safety and quality retention; (b) better understanding of the heat transfer process, which helps to control the process and manage deviations, thus reducing production costs and improving quality and safety of the product (Norton 2006).

The rheological behavior of tomato concentrate is non-Newtonian. Due to the high viscosity of the product, enhanced heat transfer surface such as embossed or corrugated pipes are usually employed to ensure a good overall heat transfer coefficient; in this case CFD simulations may help to understand the effects of pipe shape on temperature distribution.

2. MODEL SET-UP

2.1. Geometrical model

A 3D CAD model of the exchanger was defined: the geometry consisted of a horizontal pipe with a series of equally-spaced radially injectors placed in the first half section (injection section). The second half section (mixing section) presents several hemispherical bosses, whose function is supposed to improve the mixing effect and the heat transfer coefficient and avoid flow stratification.

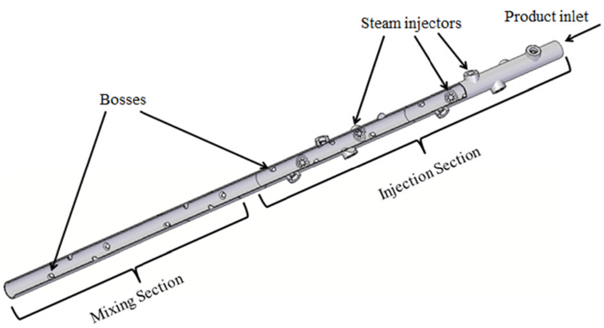

Figure 1: Pipe and injectors geometry

The inner diameter of the pipe is 51 mm; the total length of the exchanger is 2.1 m.

2.2. Rheological Model

Tomato concentrate has a pseudoplastic non-newtonian flow behavior that follows the power-law model (Rozzi 2007):

$$\mu = K\dot{\gamma}^{n-1}, \qquad (1)$$

where μ is the dynamic viscosity, K the viscosity consistency, $\dot{\gamma}$ the shear strain rate and n the flow index.

Flow of pseudoplastic fluids is characterized by the generalized Reynolds number

$$Re' = \frac{\rho W^{2-n} D^n}{K' 8^{n-1}} \qquad (2)$$

where

$$K' = K\left(\frac{3n+1}{4n}\right)^n. \qquad (3)$$

Note that Re' is a generalization of the Reynolds number. Re' tends to Re when n is close to 1.

An exponential dependence on temperature was assumed for K, while for n a linear dependence on temperature reciprocal has been adopted, according to Trifirò (2001), as follows:

$$K = K_0 \cdot \frac{K_T \cdot 1000/T}{1000} \qquad (4)$$

$$n = n_0 + n_T \cdot 1000/T, \qquad (5)$$

where n_0 and n_T are parameters depending on the product, while k_0 and n_0 are the viscosity consistency and the flow index at the reference temperature.

The values used for the rheological parameter are reported in Table 1; they have been obtained from typical Hot-break tomato concentrate.

Table 1: Rheological constant of Hot-Break concentrate

K_0	0.3314
K_T	7.8814
n_0	1.114
n_T	-0.3152

In Figure 2 the variation of the rheological parameters with temperature is reported; Equation (1) describes a significant decrease of dynamic viscosity with temperature.

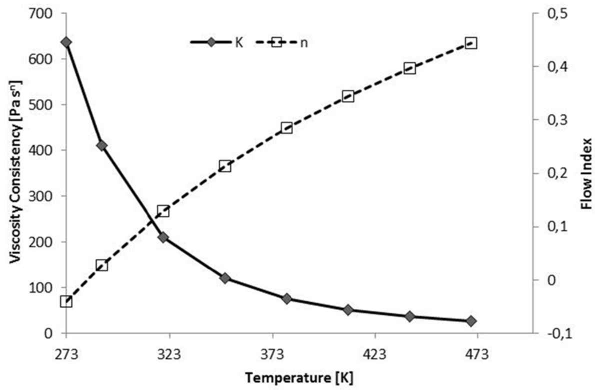

Figure 2: Temperature variation of rheological parameter for tomato concentrate

Rheological and physical properties of water steam are assumed from tabulated values depending on temperature and pressure.

2.3. Numerical model

An Eulerian-Eulerian homogeneous two-phase model was used to describe the flow of tomato concentrate and steam entering the exchanger. Tomato concentrate has been modeled as a continuous phase, while saturated water vapor was modeled as a dispersed phase. In the Eulerian multiphase model the continuous fluid forms a continuous connected region, while the dispersed fluid is present in discrete regions which can be not connected.

The Eulerian-Eulerian model was chosen as each phase is treated separately and it is applicable for wide range of volume fractions (Frank 2007). The phases can move at different velocities, but the model assumes local equilibrium over short spatial length scales, resulting in a strong coupling between phases. A particle model was chosen to describe the interaction between the two phases; the dispersed phase droplets are assumed to be spherical. All phases are assumed incompressible, accordingly with low kinetic energy; physical properties of all phases are assumed to be temperature dependent.

The flow of tomato concentrate, due to its high viscosity, is laminar; generalized Reynolds number *Re'* is always lower than 20.

The phases are not generally in thermal equilibrium, due to temperature differences across phase boundaries, therefore heat is transferred across phase interfaces via interphase transfer terms (Brennen, 2005). Heat transfer across a phase boundary is described in terms of a heat transfer coefficient. Only heat transfer between phases is taken into account, walls are assumed adiabatic. Two resistance heat transfer model was used to describe combined heat and mass transfer due to steam condensation. Ranz-Marshall correlation was used to evaluate the heat transfer coefficient of the continuous phase (Pechenko 2010); Nusselt number is evaluated through the following equation:

$$Nu = 2 + 0.6Re^{0.5}\, Pr^{0.3} \tag{6}$$

Inter-phase mass transfer has been tracked by using the thermal-phase change model. Latent heat is not directly specified, but is obtained indirectly as the difference between the enthalpies of the two phases.

The governing equations are the unsteady Navier-Stokes equations in their conservation form. For a multicomponent fluid, scalar transport equations are solved with respect to velocity, pressure, temperature and other quantities of the fluid. An additional equation must be solved to determine how the components of the fluids are transported within the fluid. Each component has its own equation for mass conservation:

$$\frac{\partial \alpha_i \rho_i}{\partial t} + \nabla \cdot \left(\alpha_i \rho_i \boldsymbol{U_{ij}}\right) = \Gamma_i, \tag{7}$$

which is solved for each phase i; U_{ij} is the mass-averaged velocity of fluid component i:

$$U_{ij} = \frac{1}{\rho_m} \sum \left(\rho_i U_{ij}\right) \tag{8}$$

and

$$\rho_m = \sum (\alpha_i \rho_i), \tag{9}$$

where α_i is the volume fraction of phase i. The term Γi in Equation (7) represent the mass source per unit volume into phase i due to interphase mass transfer.

The following general form is used to model interphase drag force acting on phase i due to phase j:

$$M_i = c_{ij}\left(\boldsymbol{U_j} - \boldsymbol{U}_i\right), \tag{10}$$

where c_{ij} is the drag coefficient. For the particle model (spherical particle), the drag coefficient can be obtained in terms of dimensionless drag coefficient C_D as follows:

$$c_{ij} = \frac{C_D}{8} A_{ij} \rho_i \left|\boldsymbol{U_j} - \boldsymbol{U}_i\right|. \tag{11}$$

Energy equation is also modified adding the contribution S_E due to steam condensation inside the continuous phase, depending on Γi in Eq. (7)

$$S_E = \Gamma_i \Delta h \tag{12}$$

2.4. Initial and boundary conditions

Temperature and flow rate have been set for tomato concentrate at the exchanger inlet. A constant temperature of 75°C was set for tomato concentrate at the inlet of all simulations.

During normal operation the exchanger is under a constant head of 5 bar. The absolute level of pressure at the exchanger outlet was assumed to be 5 bar. Steam pressure and temperature have been fixed at the injectors inlet accordingly to normal operation settings of the exchanger. All walls are assumed adiabatic, with imposed no slip condition.

2.5. Simulation Details

An unstructured tetrahedral grid of $1.3\text{x}10^6$ nodes was employed; meshes were created with ICEM CFD Software. Grid density has been increased near walls and at injector-pipe junctions. To improve stability and reduce the overall number of elements the hexa-core option was activated.

The commercial code Ansys CFX© was employed for all simulations. A coupled solver was used to solve governing equations. A high resolution discretization scheme was used for the continuity, energy and momentum equations, while the upwind discretization scheme was employed for the volume fraction equations. Tolerance was set for all variables at $1\text{x}10^{-3}$.

3. RESULTS AND DISCUSSION

3.1. Injector detail simulations

A first set of simulations were carried out to estimate the flow characteristic of the injectors using a simplified computational domain. As shown in Figure 3, the computational domain consist of a 200 mm pipe section with a single radial injector. The junction between the main pipe and the injector is obtained with six radial slots, through which steam enters in the exchanger.

Different simulations were carried out with imposed tomato flow rates ranging from 1500 l/h to 20000 l/h; all simulations were performed with vapor mass flow from 0.002 kg/s to 0.04 kg/s.

Vapor penetration inside tomato concentrate is heavily dependent on both tomato and vapor flow rate (Figures 4 and 5).

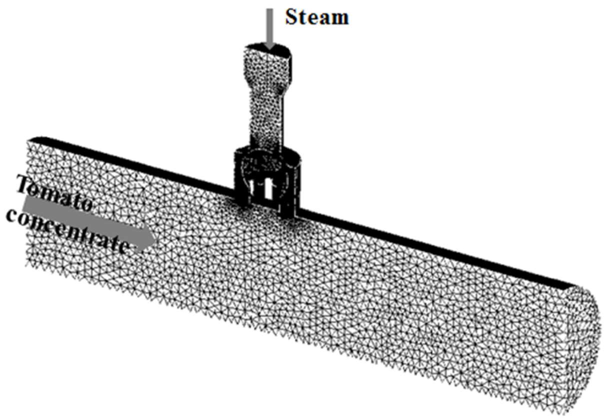

Figure 3: Simulation grid around injector

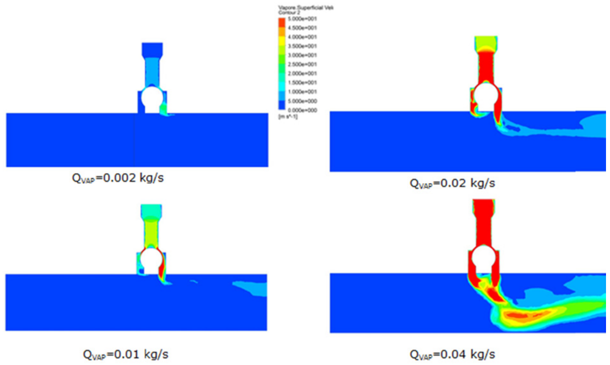

Figure 4: Dispersed phase (steam) superficial velocity contours at different steam flow rates (tomato flow rate 1500 l/h)

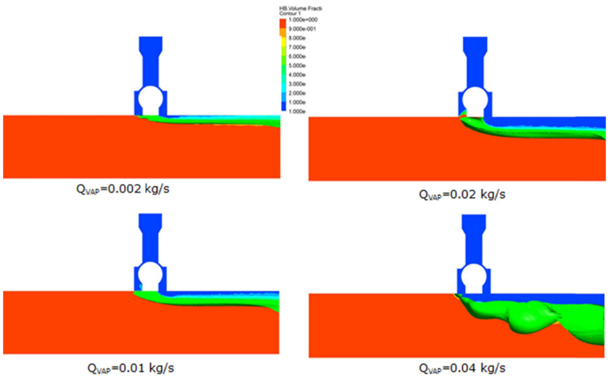

Figure 5: Tomato volume fraction contours and iso-surface (volume fraction = 0.5, green) at different steam flow rate (tomato flow rate 20000 l/h)

Steam penetration inside tomato concentrate is extremely low for high product flow rates. A well distributed radial pattern of injector is critical to avoid over-processing of fluid near the walls.

Simulations allowed to compute the flow characteristic of the injector depending on tomato flow rate, as shown on figure 6 influence on flow characteristic of tomato flow rate is relevant only for high values of steam mass flow rates, typically over 0.02 kg/s.

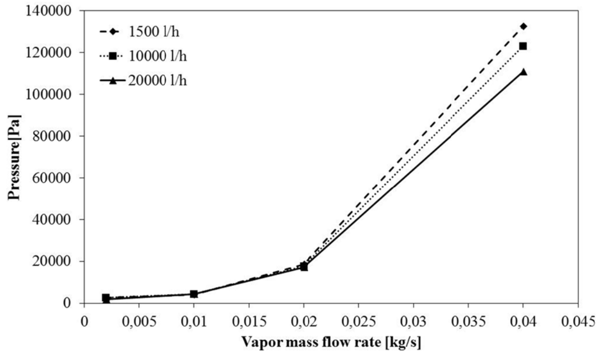

Figure 6: Injector flow characteristic (pressure vs mass flow rate) at different product flow rate

Knowledge of the injector characteristic allows the control of the amount of steam injected inside the exchanger during the sterilization process.

3.2. Injection simulations

Simulations of the complete geometry were carried out to investigate the effects of steam flow rate on the temperature history of product. Constant steam mass flow rates at the injector inlet were imposed. Since not all the injectors are active during the sterilization, the effects of different number of active injectors were investigated. Figure 7 shows the simulation results of different active injectors working with same steam mass flow rate of 0.02 kg/s. Inlet temperature of tomato and steam are respectively 75°C and 158°C. Steam temperature is referred to saturated conditions at average exchanger absolute pressure (5 bar). Tomato concentrate volumetric flow rate at inlet is fixed for all the simulations at 15000 liters per hour.

Due to high temperature difference and a low value of steam flow rate, the steam is completely condensed before reaching the exchanger outlet. Figure 8 shows a contour representation of tomato volume fraction on an axial cut plane. A complete condensation which occurs near the end of the injection section of the exchanger, can assure a gradual temperature rise and the mixing section reduces temperature difference when the product exit the exchanger.

In the industrial practice it is extremely difficult and expensive to measure and adjust the steam flow rate. Steam flow rate is usually set indirectly by adjusting the pressure in the manifold before the injectors. Due to high pressure losses within the pipe, constant steam pressure at the injectors inlet normally produce different steam flow rate in the exchanger.

Injection with constant pressure at the injector inlets was simulated to investigate the effect of steam flow rate on the temperature distribution at the product outlet. Constant pressure boundary condition was applied to eight equally- spaced injectors along the exchanger; the remaining four injectors were modeled using a wall condition. The values imposed are referred to exchanger outlet absolute pressure.

Figure 9 shows the tomato volume fraction at different steam relative pressure at the injectors. In all the simulations the pressure imposed at the injector inlet of the first injectors is lower than tomato pressure inside the exchanger; an automatic wall condition is set by the solver; due to high pressure difference on the last injectors, steam flow rates are extremely high and non-condensed steam exits through the exchanger outlet.

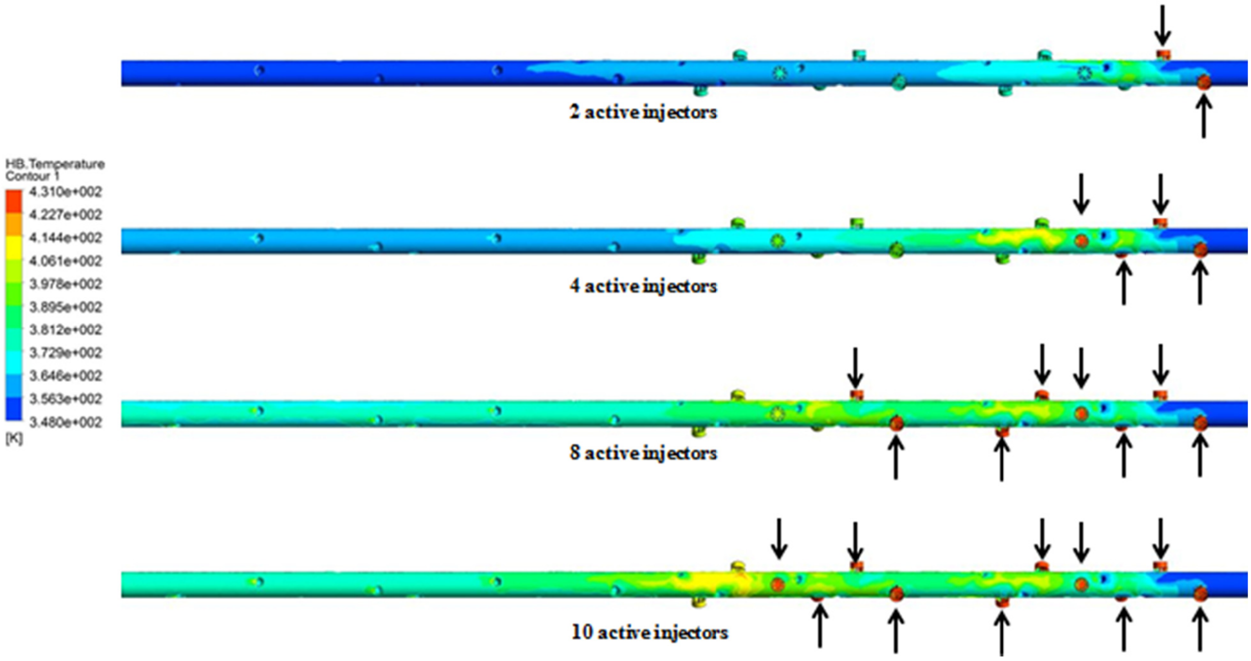

Figure 7: Tomato Temperature contours with 2, 4, 8, 10 active injectors

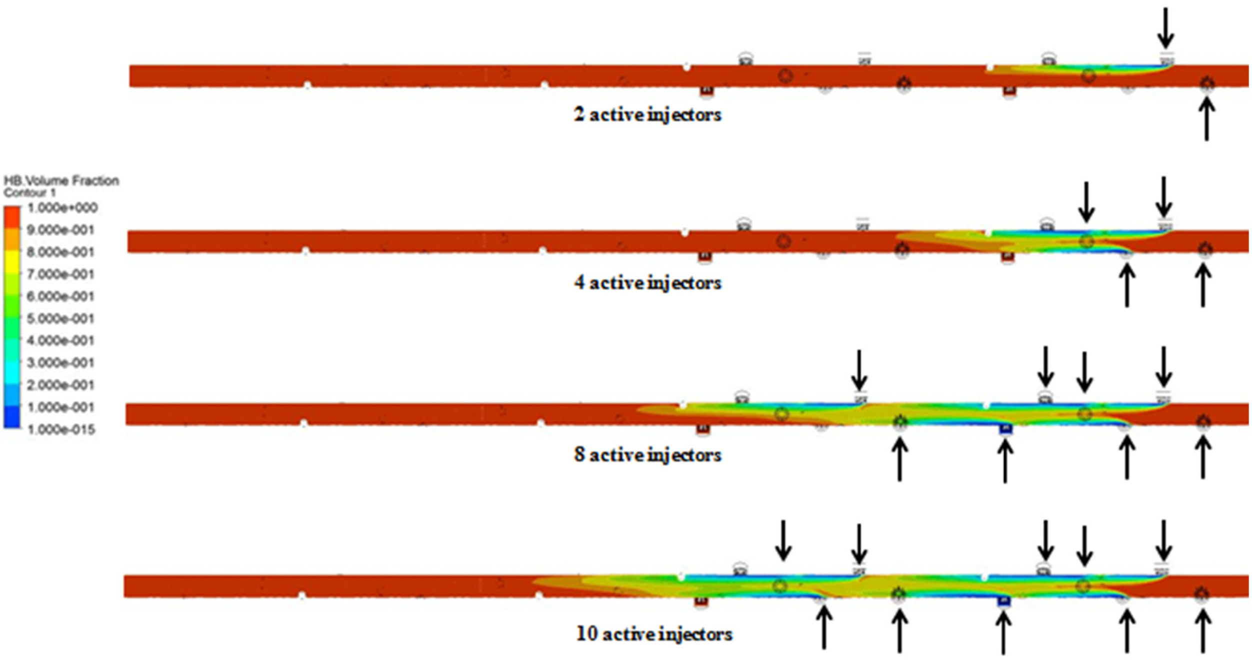

Figure 8: Tomato volume fraction contours with 2, 4, 8, 10 active injectors

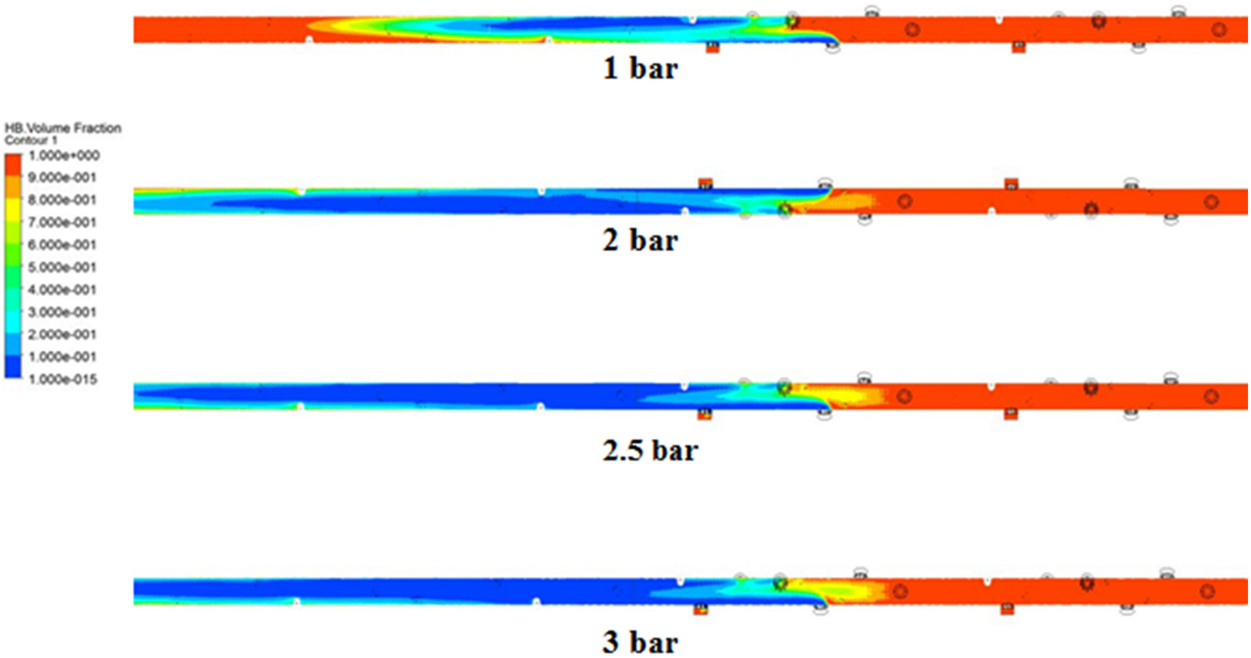

Figure 9: Tomato volume fraction contours with pressure value set to 1, 2, 2.5, 3 bar on injectors inlet

The mass flow rate averaged temperature of tomato on the exchanger outlet, with maximum and minimum temperature on the same section have been computed. Figure 10 shows the temperature values for each simulation with different injection pressure.

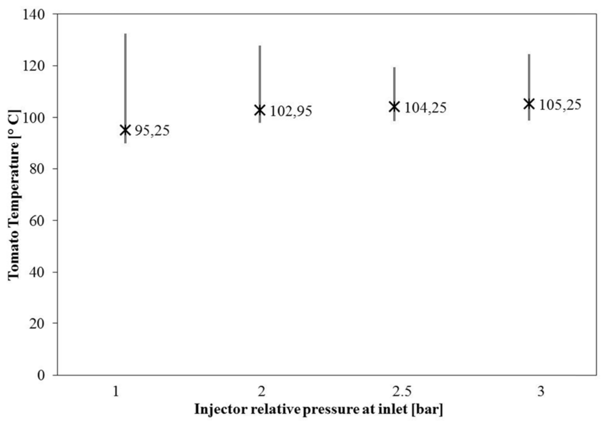

Figure 10: Mass flow rate averaged temperature (tomato) on the exchanger outlet. Lines show maximum and minimum values on the same section.

Temperature differences on outlet sections are extremely high; maximum values over 125°C can result in degradation of the taste of the product. Average temperature around 105°C on the exchanger outlet is the typical set point for sterilization processes.

As shown in Figure 10, for injection pressure higher than 2 bar the average temperature remains constant at around 105°C.

Considering same operation parameters of the exchanger, values obtained with CFD simulations of average outlet temperature are in agreement with available data acquired in industrial plant.

A last set of simulation has been performed to analyze different pressure distributions on the injectors. For confidential reasons the pressure distributions on the injectors are not reported. .

The simulation results 1 are shown in Figures 11 and 12. Despite high global steam flow rate, complete condensation is reached before the exchanger outlet.

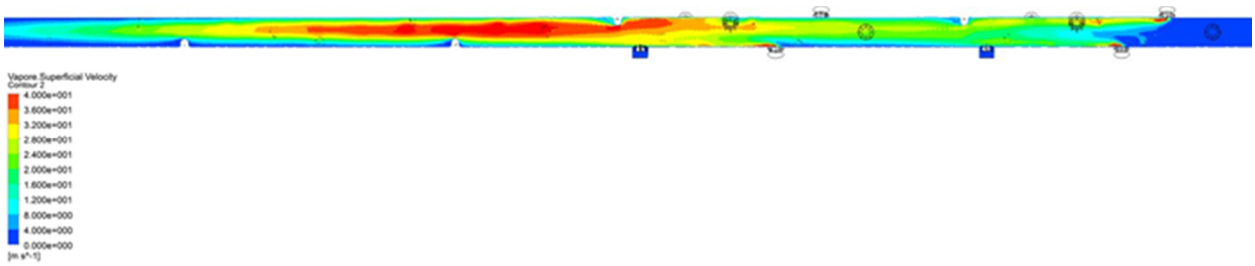

Figure 11: Steam superficial velocity contour, axial plane .

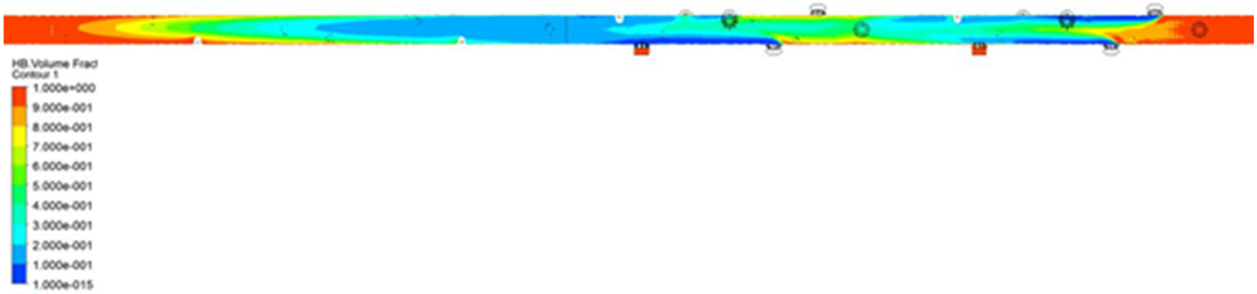

Figure 12: Tomato concentrate volume fraction contour, axial plane

Figure 13 shows that the temperature difference for three different pressure patterns imposed on the injector inlets is always lower than 5°C.

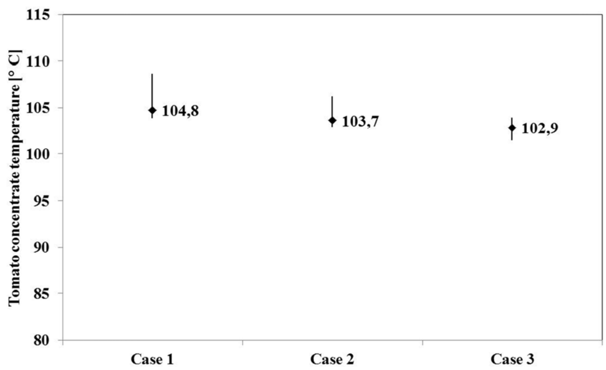

Figure 13: Mass flow rate averaged temperature (tomato) on the exchanger outlet. Lines show maximum and minimum values on the same section.

Compared to Figure 10, the decrease in the temperature difference on the exchanger outlet section is more than 4 times lower. Therefore a suitable pressure distributions on the injectors could reduce the temperature difference at a maximum value of 5°C.

As previously remarked, avoiding high temperature values ensures better product quality and avoids degradation of food taste. Decreasing steam pressure values on injectors inlet allowed to reach average product temperature on exchanger outlet comparable to constant pressure simulation; as result the sterilization is achieved with more uniform temperature at outlet.

4. CONCLUSIONS

In this work an apparatus for the sterilization of tomato concentrate was analyzed by means of multidimensional CFD models, in order to optimize quality and safety of the treated food.

A flow domain was created from the exchanger geometry and a flow model was built by using the ANSYS CFX® commercial code. A multiphase approach was adopted and a rheological model of tomato concentrate was created.

First simulations were carried out to investigate the flow characteristics of steam injectors. The knowledge of the injector characteristic allows to precisely control the amount of steam injected inside the exchanger during sterilization process.

In the second part of the work, simulations of the complete geometry were carried out to investigate the effects of steam flow rate on the temperature history of product. Different boundary conditions at the injector inlets were used to investigate the effects of the different process parameters. High differences in the temperature of the product at the exchanger outlet were found with constant pressure applied to the injector inlets.

Better results were reached by applying a suitable pressure distributions on the injector inlets: starting from temperature differences higher than 25°C on the outlet section of the exchanger, the simulation allowed to identify better injection settings and temperature differences lower than 5°C were obtained.

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