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CFD Simulation for the Pasteurization of Fruit Puree with Pieces

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Thermal pasteurization is a technique widely utilized in the industry to reduce the microbial content of foods and increase their shelf life. The food pasteurization is commonly carried out in continuous process where the food undergoes to a rapid heating and a subsequent cooling with high heat transfer coefficients in order to reduce the degradation of main constituents like proteins and vitamins, and keeping almost unchanged the food organoleptic properties. Continuous pasteurization processes are commonly used to treat creams, tomato sauce, fruit juice, as well as products with solid particles or pieces like soups or baby foods. In such cases, the presence of dispersed large particles in the fluid can causes issues in the correct process setup. Indeed, the process setup must assure the pasteurization condition in the overall product food, included the centre of the particles. Here the heat penetrates by conduction and usually it becomes the actual limiting step of the process. In this work we estimate the pasteurization condition for a pilot scale pasteurization process for the thermal treatment of pear puree with pieces by the use of the Computational Fluid Dynamic approach. The results show that the heat penetration resistance into the solid particle reduces of about 32% the microbial abatement in the particle centre; however the P_{85} value results always higher than the minimum required for the food pasteurization.

1. Introduction

A continuously pasteurization plant generally include one or more heat exchangers to warm the product up to the pasteurization temperature; the temperature is than kept constant in a holding unit and, finally, the food is cooled in other heat exchangers before being packaged in aseptic condition. A continuous pasteurization plant allows the independent assessment of two main process parameters: the pasteurization temperature and the residence time in the holding unit. The temperature and the flow rate of the service fluids, as well as the exchanger typology, must be chosen to ensure high heating/cooling rates, as discussed for conventional units (e.g. Agarwal et al., 2014; Rozzi et al., 2007) or for new system designs (e.g.D'Addio et al., 2012; D'Addio et al., 2013).
The fluid residence time in the holding unit depends on the needs of process productivity, while the pasteurization temperature is calculated from the thermal death time model (Lewis and Heppell 2000). Therefore it is essential to verify that the overall product enters in the holding unit at the pasteurization temperature. This issue can be easily verified on field measuring the product temperature at the holding inlet. However, this check may be not sufficient if the processed fluid contains solid particles. The pertinent literature generally addresses this issue through the evaluation of the residence time distribution of solid suspensions in the holding tube (Chakrabandhu and Singh 2006; Palmieri et al., 1992; Mabit et al., 2008; Cas; Castelain et al., 1997), and consequently the pasteurization temperature is calculated on the base of the fastest particle (Ramaswamy et al., 1995). However, this approach is not sufficient to validate the pasteurization process if the suspended solid are large particles of food for which the internal temperature can be very different respect to the fluid. This leads to a significant limitation in the process optimization and control.

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In this work, we estimated the pasteurization conditions by means of a computational fluid dynamic approach. The plant modelled is a pilot scale system based on helical heat exchangers. The plant is used by the Heinz Italy to tests new baby foods formulations. The plant was designed to treat fruit puree without particles. For such foods, a specific process setup were developed by the company and consists in setting the temperatures and flow rates of the service fluids to warm the product up the pasteurization temperature. The pasteurization temperature, calculated by means of the thermal death time model applied on the holding unit, corresponds to 94°C; however, for safety conditions, this temperature is set to 98°C. The aim of this work is verify if the same plant set up used to treat pear puree is able to guarantee the pasteurization condition if the fluid contains solid pieces of different sizes. To this end, the estimation of the pasteurization condition is carried out by means of the commercial software Ansys Fluent®. The methodology adopted provides a first step of CFD simulations to evaluate the thermo-fluid dynamic of the overall pasteurization plant with reference only to the fluid phase, taking into account all the complexity of the exchanger geometry and of the non-Newtonian fluid behaviour. In a second step, the worst pasteurization condition are assumed as reference for 3D CFD simulations to study the heat penetration in the solid food particles.

2. Materials and methods

2.1 Plant description

The system modelled is a pilot scale plant located at the Heinz Italia S.p.A. in Latina, Italy. The fluid is formulated and pumped in the pasteurization section at a constant flow rate. The pasteurization section consisted of four helical units. The first two were heat exchangers to warm the fluid up to the pasteurization temperature, the third was the holding unit and the last was used to cool the product in order to preserve the fluid organoleptic properties.
The first two exchangers used a countercurrent flow of hot pressurized water to warm the product, while the service fluid of the cooler was water at room temperature. The holding unit was positioned in a cylindrical container partially insulated. The pilot plant was instrumented with one fluid flow meter and seven temperature probes to measure the product and auxiliary fluids temperatures. The sensor location is shown in Figure 1, while the main dimension of the exchangers are reported in Table 1.

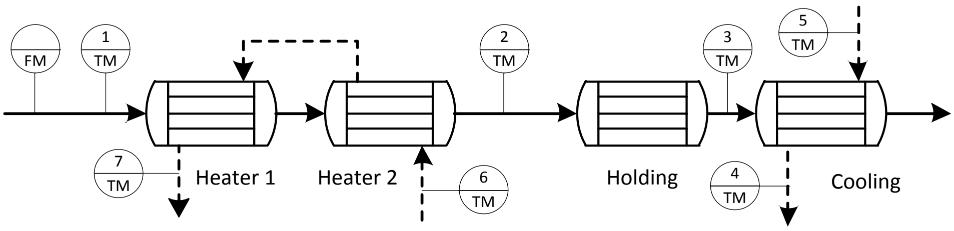

Figure 1: Layout of the pilot scale plant simulated. FM=flow measure, TM=temperature measure

Table 1: Dimensions of the helical heat exchangers

	Heater 1	Heater 2	Holding	Cooler
Tube diameter [mm]	45	45	45	57.5
Coil diameter [mm]	640	640	640	842
Total length [m]	90	90	40	90
Total exchange surface [m2]	12.78	12.72	5.65	16.34

2.2 Fluid and solid particles properties

The fluid used in this work mimicked a pear based puree. In order to provide a suitable description of the fluid, a pear based puree was characterized to assess its thermal and fluid dynamic properties. The density of the fluid was 1,045kg/m^3, while the heat capacity, measured with a differential scanning calorimeter, varied from 3.76 to 3.80 kJ kg^{-1} K^{-1} in the range 50-100°C. The thermal conductivity was measured with the unsteady Fitch's method reported by Donsì et al. (1996) and varied from 0.60 to 0.64 W m^{-1} K^{-1} in the range 50-100°C.
The fluid viscosity η was measured with a stress-controlled rheometer with a plate-plate geometry at four temperature levels in the shear rate range γ=1-500 s^{-1}. The fluid showed a shear-thinning behaviour and

the viscosity can be described by a power law constitutive equation. The flow behaviour index n and the flow consistency index K are shown in Table 2.

Table 2: Regression constant for the power law viscosity

T [°C]	n [-]	K [Pa s^n]
30	0.32	10.800
50	0.327	8.369
70	0.333	6.561
90	0.340	5.200

It was assumed that solid pear particles had the density of 993 kg m^{-3} and thermal conductivity 0.543 W m^{-1} K^{-1} according to Liang et al. (1999). These properties were assumed constant with temperature according to Ahmed and Rahman (2008). The heat capacity was estimated on the basis of the pear composition and assumed equal to 3,873 J kg^{-1} K^{-1} (Rao et al. 2010).

2.3 CFD simulations

CFD simulation were carried out with the software Ansys Fluent® 14, while the geometries and the meshes were designed with Gambit 2.1. A sensitivity analysis on the mesh number was performed to define the optimal number of cells. The two heaters, identical in size, resulted in 9,431,910 quadrilateral elements, the holding unit was discretized with 3,317,072 cells, and the cooler with 12,385,344 cells. All the meshes had an equiangle skewness lower than 0.28.

The simulations were performed with the laminar viscous model. The second-order scheme was used for convective flux discretization and for pressure field integration.

The heating and cooling exchangers' walls were treated as constant boundary temperature according with the service fluid temperatures. For the holding unit, a natural heat transfer coefficient between the wall and the ambient air was set as boundary condition. A value of 10 W·m^{-2}·K^{-1} as natural heat transfer coefficient was estimated (Perry and Green, 1950), while the free stream temperature was experimentally measured and fixed at 75°C.

The inlet temperature for the first heating exchanger corresponded to the experimentally measured value; the inlet velocity profile was instead imposed as a non-Newtonian parabolic profile (Bird et al., 2007). For the other units, the inlet temperatures and velocity profiles were imposed as the outlet condition from the previously unit.

The methodology used to study the heat penetration in the particles consisted in four main steps:

1. The CFD simulations were preliminary carried out for all helical heat exchangers, therefore, the temperatures and the velocities were known in all the point of the computational domain.
2. For each unit, the pathlines were tracked from the inlet section to monitor the temperature along the exchanger. The pathlines represented the trajectory of neutrally buoyant particles in equilibrium with the fluid motion. In this work, the pathlines was approximate to the trajectory of food particles. We assumed that the pathline temperature profiles correspond to the particle wall temperature. For each pathline temperature profile, the thermal death time model was computed with the evaluation of the P_{85} value (Lewis and Heppell, 2000) by means of Eq(1).

   $$P_{85} = \int_0^{\tau} 10^{\frac{T-85°C}{Z}} \cdot dt \quad (1)$$

   By this elaboration, the worst pathline was identified as that one which corresponded to the lowest value of P_{85}.
3. Once that the worst path was individuated for all units, the corresponding temperature profiles were used to study the heat penetration in the solid particles by an unsteady CFD simulation. The temperature profiles of the four worst thermal path in the four simulated units, were applied as unsteady temperature boundary condition on the solid particle to study the heat penetration.
4. The particle centre temperature was monitored during the particle motion through the pasteurization plant. The P_{85} value was calculated with reference to the particle center temperature by the Eq (1).

3. Results

Table 3 shows the experimental process temperature (TM), and fluid flow (FM) at the steady state condition. The fluid entered at 55.97 °C in the first exchanger and reached the temperature of 98.15 °C at the entrance of the holding unit. In this unit, the heat dissipation produced only a decrease of 0.3 °C of the mean fluid temperature. The hot water, for product heating, entered in countercurrently in the second exchanger at 99.28 °C and exited from the first unit at 97.37 °C, while the cold water increased its temperature from 29.65 to 31.5 °C passing through the cooling unit.

Table 3: Process variable measured. For the location of the probes refers to Figure 1.

	Value
TM1	55.97 °C
TM2	98.15 °C
TM3	97.85 °C
TM4	31.50 °C
TM5	29.65 °C
TM6	99.28 °C
TM7	97.37 °C
FM	3,701.7 kg/h

The simulated cross sectional average values of fluid temperatures along the pasteurization plant are shown in Figure 2. The simulated temperature increased monotonically in the first two heaters from 55.97 °C to 97.02 °C, while the temperature slightly decreased to 96.68 °C in the holding, and finally felt down to 54.10 °C in the cooler unit. In Figure 2, experimental values of temperature are reported for comparison. Numerical data are consistent with experimental one, with a maximum error of 1.2 %; thus confirming the correctness of the numerical simulations for the fluid phase.

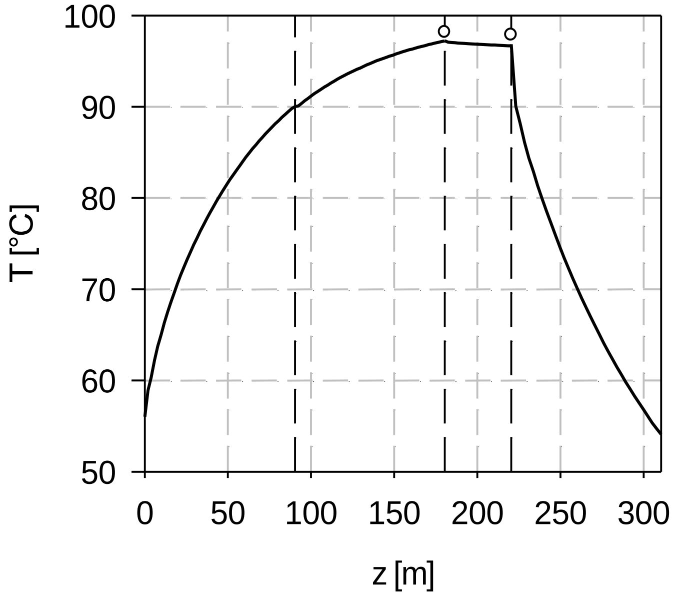

Figure 2: Simulated (continuous line) and experimental temperature (points) in function of the overall plant length. The vertical dashed lines represent the transition between two units

The results of CFD simulations for food particles are displayed in Figure 3. The black continuous line corresponds to the temperatures of the worst pathlines evaluated in the four units. These temperatures are assumed equal to the particle surface temperature. The black dashed line represent the theoretical P_{85} values computed with the Eq(1) based on the particle surface temperature. The grey continuous line represents the particle centre temperature as result of the CFD simulations on the solid 3D particle, while the grey dashed line is the corresponding P_{85} value in the particle centre.

The results are plotted as a function of the cumulative particle residence time in the plant.

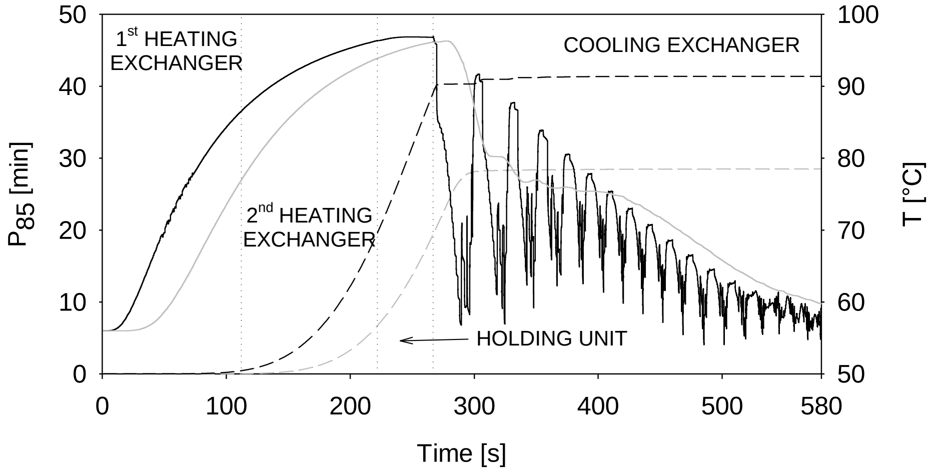

Figure 3: P_{85} (dashed lines) and temperature (continuous lines) values referred to the particle wall (black lines) and centre (grey lines) as a function of particle residence time

In the range 0-267 s, the particle surface temperature in Figure 3 shows a monotonic trend similar of those in Figure 2, however the worst pathline in the first exchanger correspond to a path that travel along the centre of the exchanger section because the particle wall temperature do not increase in the first 10 meters of the exchanger. The maximum particle surface temperature registered at the inlet of the holding tube is 96.83 °C, and is therefore lower than the mean fluid temperature in the same point. Subsequently the temperature decreases with strong fluctuations up to 57 °C. Yamamoto et al. (2002) and Hayamizu et al. (2008) suggested that the fluctuation can be ascribed to the Dean cells that consist in a double vortex circulation on the section of the helical tub. Therefore, the worst pathline in the cooling unit corresponds to a pathline that moves in a vortex that bring it between the colder exchanger wall and hotter fluid bulk.
With reference to the temperatures computed in the solid particle centre, the profiles tend to follow the wall temperature but, due to the time required to penetrate into the solid bulk, the particle centre temperature results damped and free of fluctuations. Moreover the maximum centre temperature resulted lower than the maximum particle surface temperature equal to 96.06 °C.
The P_{85} values for both particle surface and centre show that the first heating unit do not have effect on the abatement of the microbiological content due to the low temperatures. The P_{85} value increases in the second unit and continue up to the end of the holding unit. In the cooling exchanger the P_{85} do not change anymore due to a drastic temperature drop. The P_{85} values for the particle centre and its surface are qualitatively similar, but, however, the microbial abatement in the particle centre results lower.
Finally, the results show that particles boundary undergoes to a pasteurization treatment corresponding to P_{85}=41 min, while the particle centre is pasteurized to 28 min. This value corresponds to the minimum lethality.

4. Conclusions

In this work, the pasteurization conditions for the thermal treatment of pear pure with large solid particles is estimated by means of a CFD approach. The methodology adopted is based on the assumption that effects of the solid particles on the liquid fluid dynamic are negligible. However, in the case of a real macroscopic dispersion, this can be considered as a conservative assumption since the solid particles in the fluid are able to mix the fluid, increasing the heat transfer coefficient. As a consequence, the fluid, and the food particles will warm up faster and the microbial content will result lower respect to the simulated scenario.
The results show that the particle size represents a fundamental parameter in the pasteurization process. Indeed, the resistance to the heat penetration in the particle determines lower microbiological abatement resulting in a final value of P_{85} that is about 32 % lower than the abatement computed from the particle surface.
In spite of this, the minimum P_{85} value results higher than the minimum acceptable value of 5min. Consequently, the pasteurization condition is theoretically verified for the thermal treatment of pear puree with particles if the pasteurization plant is exerted under the operating conditions reported in Table 3.

Therefore, the simplified methodology can provide a first evaluation of the pasteurization conditions of industrial plants and can reduce the necessary but complicated experimental verification of the food shelf life.

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