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CFD Analysis of a Tube-in-tube Heat Exchanger to Pre-heat Olive Pastes

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The pre-heating of the paste could reduce the malaxation time and enhance the temperature control during this process. In this study a 3D CFD analysis of a tube-in-tube heat exchanger was carried out to predict its behaviour when the rheology of the olive paste varies. The "What if Analysis" tool of Flow Simulation allowed to perform multiple analyses to analyse the temperature and pressure drop inside the exchanger. Numerical model is confirmed to be a useful tool to identify the main factors affecting the optimization of the heat exchanger.

1. Introduction

Heat exchangers are used in many food processes for applications such as heating and cooling as reported in (Balaji et al., 2020; Jafari et al., 2017; Strpić et al., 2020). Regarding the industry extra virgin olive oil (EVOO) there is the need to pre-heating the olive pastes before the malaxation phase. The olive paste is generally heated to 24–27 °C for about 30–45 min, and the heat transfer is obtained by means of hot water that flows in the external jacket of the malaxer (Ayr et al., 2015; Bianchi et al., 2020; Tamborrino et al., 2010). However, heating the olive paste with the malaxer machine has many drawbacks, as reported in (Leone et al., 2014), such as: time and temperature profiles depending on the filling levels of the malaxer; non uniformity of time and temperature profile due to the fouling effect of the paste that remain attached to the walls; long operating times (two-thirds of the total time required of the process).
In food industry sector there is an increasingly need to save energy (Catalano et al., 2020; Perone et al., 2017), and regarding the EVOO extraction process, new technologies have been proposed to solve the negative aspects related to malaxation. These technologies could be summarized as: microwave-assisted systems, low-frequency ultrasound, high-frequency ultrasound, and pulsed electric fields (Leone et al., 2014, 2017; Romaniello et al., 2019; Servili et al., 2019; Tamborrino et al., 2020). In recent years in the attempt to reduce the malaxation time the use of heat exchanger (HE) was proposed. A first attempt was carried out by (Amirante et al., 2006), which founded that HE has a positive effect on the malaxation and on the increment of olive oil extraction yield and quality. Esposto et al. (2013) and Veneziani et al. (2015) studied the use of tube-in-tube heat exchanger to assess its influence on the malaxation time, olive oil extraction yield, and the quality of the olive oil. They confirm the possibility of using a heat exchanger to rapidly increase the olive paste temperature and reduce malaxation time. Another research showed a reduction in the malaxation time of 10 min and an improvement in phenolic and volatile compounds (Leone et al., 2016). While the oil extraction yield is statistically equal to the traditional process yield when the heat exchanger was employed. HE is also studied in cooling treatment of the olive paste resulting in a significant increase in phenols (Veneziani et al., 2017). An innovative mixing-coil heat exchanger was studied in (Leone et al., 2018), which showed a reduction of about 50 % of malaxation time. HE was also analysed in combination with other technologies (Tamborrino et al., 2019), with a consequent reduction in the conditioning time. Since the olive pastes have a high variability of inlet conditions, affecting the HE behaviour, a mathematical modelling could represent a powerful aid to predict the performance

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of the heat exchanger. The CFD analysis is essential to optimize the design of this component without realizing expensive prototypes and experimental tests. In this research a three-dimensional CFD analysis was performed to predict the heat transfer behaviour and pressure drop in a tube-in-tube heat exchanger, when the rheology of the inlet paste varies according to typical operative conditions.

2. Materials and methods

2.1 Tube-in tube heat exchanger physical model and mesh generation

In this study the CFD analysis was performed by SolidWorks Flow Simulation software, which reliability is confirmed in others researches, also in more severe flow conditions (Abbasian Arani & Moradi, 2019; Ambekar et al., 2016; Mokkapati & Lin, 2014). The heat exchanger consists of an inner tube and external jacket. In the inner tube flows the olive paste, to be heated before its entering in the subsequent malaxation phase of the extraction process. Hot water is used as service fluid, which flows counter-current in the external tube (the jacket) and supplies the heat to rise the temperature of the paste before its exit from the exchanger. The heat exchanger is generally installed near the malaxers, thus a long supply pipe to connect it to the crusher is needed. In the present study it was considered a pipe of about 10 m with two 90° elbows (Figure 1). The inner tube is made of stainless steel AISI 316 with an inner diameter of 88.9 mm, while the jacket is realized in stainless steel AISI 304 has an inner diameter of 101.6 mm. The single module has a length of 1.6 m and could be connected in series with other modules via two 90° elbows (r/R equals to 1.75) of the same diameter of the inner tube, and two vertical tube of ½ " for the service fluid. This kind of heat exchanger is studied in (Leone et al., 2016), focusing more on its influence on malaxing times and qualitative aspects of the final product (EVOO). The mills equipped with such a device are few and therefore it is useful to perform CFD simulations to evaluate its applicability in the EVOO extraction process. The heat exchanger equipped with the supply pipe was modelled with SolidWorks CAD (2016). Figure 1 shows the model created and used for the CFD simulation.

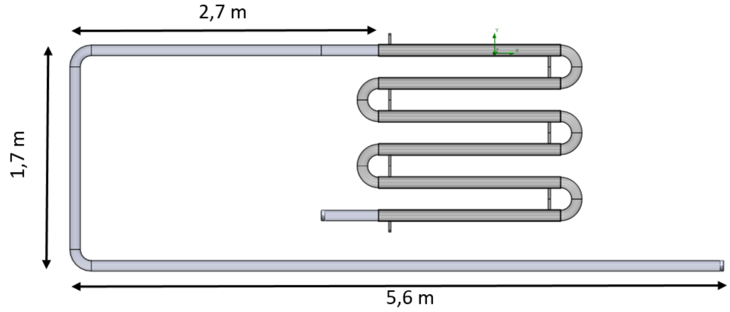


Figure 1: 3D model of the heat exchanger equipped with the supply pipe.

2.2 Governing equation and boundary conditions

Flow Simulation is capable to predict both laminar and turbulent flows and uses the Favre-averaged Navier-Stokes equations in their general form to solve the problem. The system of equations is employed to describe both laminar and turbulent flows, and transition from a laminar to turbulent state and/or vice versa is also possible (Solidworks, 2014). To solve this system, transport equations for the turbulent kinetic energy and its dissipation rate are used (k-ε model). The general Navier-Stokes equations in the Cartesian coordinate system implemented in the software can be written as follows:

$$\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u_i)}{\partial t} = 0 \tag{1}$$

$$\frac{\partial (\rho u_i)}{\partial t} + \frac{\partial (\rho u_i u_j)}{\partial x_j} + \frac{\partial p}{\partial x_i} = \frac{\partial (\tau_{ij} + \tau_{ij}^R)}{\partial x_j} + S_i \tag{2}$$

$$\frac{\partial \rho H}{\partial t} + \frac{\partial \rho u_i H}{\partial x_i} = \frac{\partial (u_j(\tau_{ij} + \tau_{ij}^R) + q_i)}{\partial x_i} + \frac{\partial p}{\partial t} - \tau_{ij}^R \frac{\partial u_i}{\partial x_j} + \rho\varepsilon + S_i u_i + Q_H \tag{3}$$

where u is the fluid velocity, ρ its density, S the mass-distributed external force per unit, H is the total enthalpy, Q_H is the heat source or sink per unit volume, τ_{ij} is the viscous shear stress tensor, τ_{ij}^R the Reynolds-stress tensor, and q_i is the diffusive heat flux. The subscripts denote summation over the three coordinate directions. The Reynolds stresses, which includes the turbulent viscosity μ_t, appear in these equations. Obviously, parameters k and μ_t are zero for purely laminar flows, as in the case of the olive paste flows, while are considered for the water flow in the jacket. Also, the time-derivative terms were not considered since the simulation was performed in steady state conditions. In this study, the fluid flowing in the inner tube is the olive paste, which is a non-Newtonian fluid, and its rheological behavior could be well described by the power-law model (Boncinelli et al., 2013). Thus, the viscous shear stress in equations (2) and (3) becomes:

$$\tau_{ij} = \mu(\dot{\gamma})\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) \quad (4)$$

with the apparent viscosity expressed by the power-law model:

$$\mu(\dot{\gamma}) = K(\dot{\gamma})^{n-1} \quad (5)$$

where $\dot{\gamma}$ is the share strain rate, K is the consistency index, and n is the flow behavior index.
Although the olive paste flow is laminar (the calculated generalized Reynolds number is very low), the water in the thin jacket must be evaluated. In this case, to solve the turbulence model two additional transport equations are used by the software to describe the turbulent kinetic energy and dissipation (Solidworks, 2014).
To evaluate the boundary layer effects near the walls, the tool implements a model based on the so-called Modified Wall Functions approach. This model can characterize both laminar and turbulent flows near the walls, and is also able to describe transitions from laminar to turbulent flow and vice versa. The modified wall function of the software (Two-Scale Wall Functions) uses a Van Driest's profile instead of a logarithmic profile. Which method to use is determined by the software according to the size of the mesh cell near the wall (more or less than the boundary layer thickness).Regarding the heat transfer in fluids, it is described by the energy conservation equation (3), while the heat conductivity in solid requires the following equation:

$$\frac{\partial(\rho e)}{\partial t} = \frac{\partial}{\partial x_i}\left(\lambda_i \frac{\partial T}{\partial x_i}\right) + Q_H \quad (6)$$

where $e = cT$ is the specific internal energy, c the specific heat, and λ_i are the eigenvalues of the thermal conductivity tensor (which is diagonal for an isotropic medium as in this case).
The problem was completely defined by introducing the following boundary conditions:

- the inlet of the olive paste was set with a mass flow rate of 3000 kg/h and a temperature of 15 °C;
- the inlet of the water was set with a total pressure of 2.40 bar (pressure supplied by the cavity pump) and a temperature of 40 °C;
- the outlet of olive paste was set as pressure opening at environment pressure (1.01 bar) and temperature defined in initial conditions;
- Solid walls as were set with the no slip condition;
- External walls were considered adiabatic.

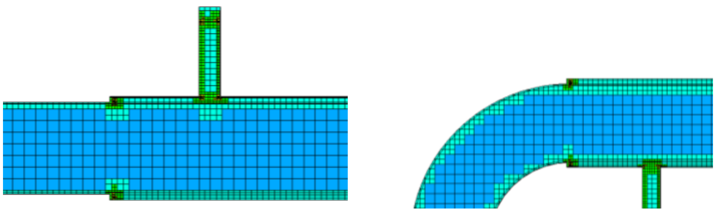
In particular, the output temperature of the olive paste and the total pressure at the inlet of the supply pipe were set as main goals and used as finishing conditions in the simulation.

2.3 Mesh generation

Flow Simulation is able to recognize automatically the model and generate a rectangular mesh in the computational domain distinguishing the fluid and soli domains. A preliminary mesh independent study was carried out and it was decided to generate the mesh with a number of cells as defined in Table 1, since this allowed a good accuracy and a saving of the computational time. Figure 2 shows the generated mesh near the inlet of the olive paste and in an elbow.

Table 1: Number of mesh cells

Description	No. Cells
Total	1,610,056
Fluid	589,399
Solid	1,020,657



a) b)

Figure 2: Mesh particular views - a) the entry; b) in a elbow.

2.4 "What If Analysis" scenarios

The physical parameters considered for the olive paste were chosen according to (Leone et al., 2014): ρ =1100 [kg/m^3]; Cp =3310 [J/kgK]; λ = 0.46 [W/mK]. While that of the water are well-known and already present in the software library. A parametric study with the "What If Analysis" tool inside Flow Simulation tool allowed varying the rheology of olive paste in order to analyse its influence in terms of both heat transfer and pressure. The evaluation of thermal and hydrodynamic conditions in the heat exchanger are of crucial importance to estimate its applicability in a new sector. The scenarios tested are illustrated in Table 2, where the consistency index and flow behaviour index were varied. The values were chosen by authors by analysing (Boncinelli et al., 2013; Leone et al., 2017, 2018).

Table 2: Scenarios and goals of the parametric study

Scenario	A	B	C	D	E	F
K [Pa s^n]	160	160	180	180	220	220
n [-]	0.30	0.35	0.20	0.35	0.10	0.25

3. Results and discussions

Figure 3 shows the pressure at the inlet of the supply pipe P_{IN} and pressure drop of the heat exchanger ΔP_{HE}. The maximum values were obviously obtained by increasing the consistency index. However, the lower pressure at the inlet, and therefore the lower pressure drop, are observed in scenario E with values of 4.24 bar and 3.08 bar respectively. Conversely, the higher pressure at the inlet, and therefore the higher pressure drop, are observed in scenario D with values of 5.77 bar and 4.61 bar respectively, with a total increase of about 36 %. This fact pointed out another important consideration. In fact, scenarios E had the higher consistency index (220 Pa s^n). This means that the flow behaviour index plays an important role, as expected since the apparent dynamic viscosity of a shear-thinning non-Newtonian fluid follow the power low with a negative exponent. Thus, a higher exponent produces lower dynamic viscosity when the shear rate is below 1 s^{-1}. This justify why pressure values of scenario E were also lower than that of scenario A. As an example, Figure 4a and b show the shear rate and dynamic viscosity inside the heat exchanger in scenario D, respectively. It easy to note that the shear rate decreases through the middle of the tube, where drops below 1 s-^{1}, since the velocity variations decrease. This produces an increase of the dynamic viscosity which reach about 300 Pa s. The pressure values generated by the introduction of the HE could affect the working of the pumps already installed in the mills, and forcing their replacement.

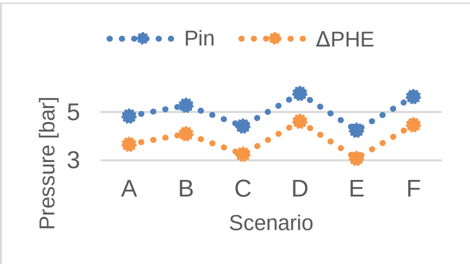
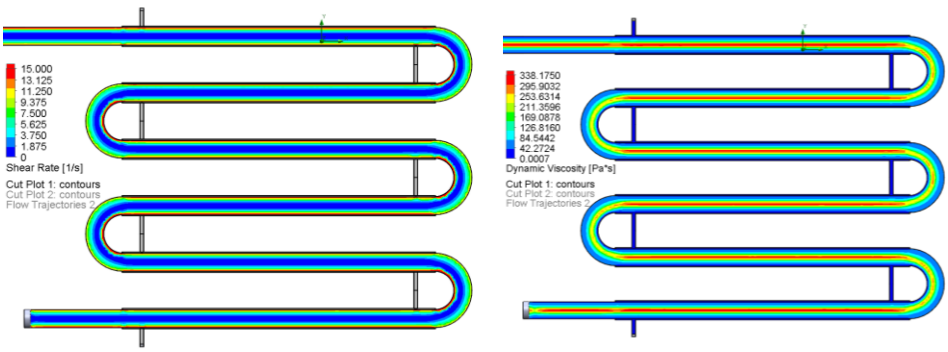
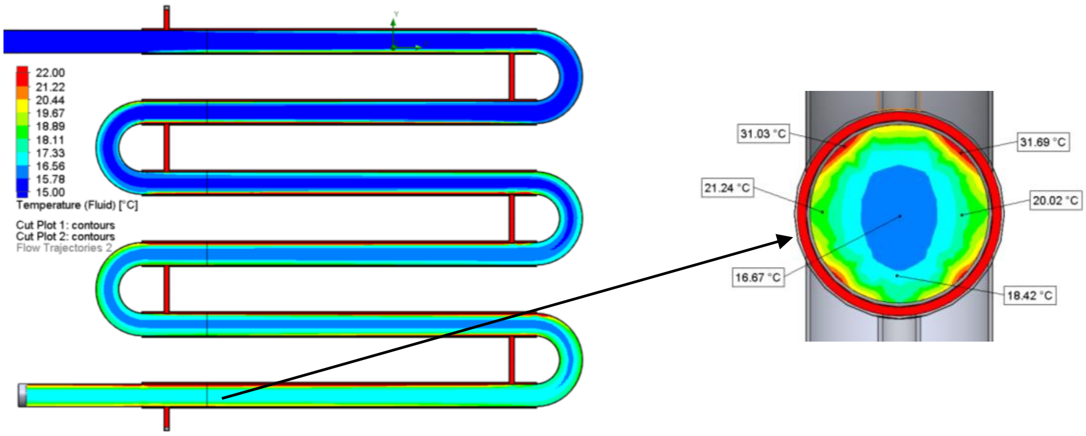


Figure 3: Pressure at the inlet of the pipe and pressure drop in different scenarios.



a) b)

Figure 4: Scenario D – a) shear rate; b) dynamic viscosity.



a) b)

Figure 5: Temperature contours in scenario D – a) longitudinal section; b) cross section at the outlet.

Figure 5a show temperature contours in a longitudinal section made in the middle of the heat exchanger under scenario D, while Figure 5b shows the temperature contours in a cross section near the exit from the heat exchanger, in the same scenario. It is worth to note that, in each scenarios the average output temperature was about 18.8 °C, with an average water output temperature of 37.3 °C (with a mass flow rate of 0.88 kg/s). However, as shown in Figure 5b there was an evident non-uniformity of temperature distributions. In additions, some regions near the wall reached very high temperature values, that could negatively affect the integrity of the product. Moreover, this fact could promote the fouling effect near the wall of the inner tube.
By considering, the thermal and hydrodynamic behaviour of this kind of exchanger, it could be argued that a inner device is necessary, to both improve heat transfer and flowing of the product.

4. Conclusions

Tube-in-tube heat exchanger could positively affect the malaxation phase, especially in terms of malaxation time. In this research the CFD simulation allowed to predict temperature distribution and pressure such an exchanger by varying the rheological conditions of the inlet olive paste, which is a high viscous fluid. The analysis of temperature distribution shows the non- uniformity and risk and the risk of cooking near the wall, compromising the quality of the final product. As regards the flow regime, due to its high viscosity, it is a typical plug flow, which produces high pressure drops. This fact could negatively affect the work of the pump, forcing its replacement. The authors suggest the introduction of properly designed device to improve the heat in the product and facilitating the transport of the fluid.

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