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## **ABSTRACT**

### **TOMATO PURÉE CONVECTIVE HEAT TRANSFER SIMULATION USING BOUSSINESQ APPROXIMATION**

**by  
Matteo Fabbri**

With the advance of new technologies, the food industries are requiring systems that allow to produce the desired products with faster rates at cheaper costs. In this case, the study was initiated with the purpose to better understand what happens inside a package containing tomato puree when this is heated above 343 K in a tunnel pasteurizer. If the fluid must reach the thermal and microbiological condition of “pasteurization”, the system must guarantee that the temperature (around 343° Kelvin) is kept for a certain time allowing to pasteurize even the cooler package’s fluid-particle. The faster the system can heat the bottle, the higher the productivity could be but, to guarantee the same heat treatment, it may be needed a longer tunnel, raising equipment costs and space allocation.

While looking at the thermal conditions of the package, it was decided to check the existence of any convective movement along the boundaries of the very viscous fluid. The research was conducted using the OpenFoam application, an open-source CFD simulation system based on Linux OS. The study started from simple cases in 2-dimensional geometry, and gradually were added more complex situations to the model (3D, non-newtonian conditions, rotation). The simulation showed the fluid flow behavior resulting in very poor convective movements along the fluid’s boundaries; temperature profiles were studied for both vertical, horizontal and rotating cylinders proving the latter as the most efficient condition for a pasteurization heat treatment.

**TOMATO PURÉE CONVECTIVE HEAT TRANSFER SIMULATION  
USING BOUSSINESQ APPROXIMATION**

**by  
Matteo Fabbri**

**A Thesis  
Submitted to the Faculty of  
New Jersey Institute of Technology  
in Partial Fulfillment of the Requirements for the Degree of  
Master of Science in Mechanical Engineering**

**Department of Mechanical and Industrial Engineering**

**May 2019**



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**APPROVAL PAGE**

**TOMATO PURÉE CONVECTIVE HEAT TRANSFER SIMULATION  
USING BOUSSINESQ APPROXIMATION**

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This dissertation is dedicated to my loving family. A special feeling of gratitude to my parents, Lorella and Giuseppe whose words of encouragement and push for tenacity ring in my ears. I also dedicate this dissertation to my girlfriend Francesca who never left my side and have been my cheerleader throughout the entire master program. Special thanks to my brother, Emanuele and all my grandparents and relatives for believing and supporting me in every occasion.

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## TABLE OF CONTENTS

<b>Chapter</b>	<b>Page</b>
1 INTRODUCTION.....	1
1.1 Tunnel Pasteurizer.....	1
1.2 Tomato Products.....	3
1.2.1 Industry Nutrition Facts Of Tomato.....	4
1.2.2 Tomato Rheology.....	5
1.2.3 Tomato Juice, Purée And Paste Production Lines.....	7
1.3 The OpenFOAM Software.....	8
1.3.1 BouyantBoussinesqPimpleFoam Solver.....	10
2 SIMULATION STEPS.....	12
2.1 Initial Modeling.....	12
2.1.1 Simulation Test.....	14
2.2 Tomato Purée Simulation.....	16
2.2.1 Vertical Tin Can.....	19
2.2.2 Horizontal Tin Can.....	21
2.2.3 Horizontal Tin Can Rotating.....	29
2.3 Viscosity Range Analysis.....	31
3 RESULTS.....	33
3.1 Tomato Juice.....	33
3.2 Tomato Sauce .....	34
3.3 Tomato Purée .....	35
3.4 Tomato Paste.....	36
3.5 Conclusion.....	37
3.5.1 Future Work.....	38
REFERENCES.....	39

## LIST OF TABLES

<b>Table</b>	<b>Page</b>
1.1 Tomato nutrition facts.....	<b>4</b>
1.2 Food products viscosity data chart.....	<b>6</b>
2.1 Rheological data of tomato juice and concentrates.....	<b>18</b>
2.2 Tomato product ranges and parameters.....	<b>32</b>

## LIST OF FIGURES

<b>Figure</b>	<b>Page</b>
1.1 Tunnel pasteurizer Side View .....	1
1.2 Scheme of tunnel pasteurizer with “heat recovery” .....	2
1.3 Triple effect, no recycle evaporator.....	8
2.1 Hypothesis assumed using BuoyantBoussinesqPimpleFoam Solver.	14
2.2 Benchmark Temperature, Velocity and Density profiles for Newtonian Fluid using BuoyantBoussinesqPimpleFoam Solver.....	15
2.3 Hexahedral mesh of a tin can obtained with Salome GUI software.....	19
2.4 Temperature, Velocity and Density profiles for Tomato Purée product with vertical setup.....	20
2.5 Temperature profile for Tomato Purée product with bottom heating.....	21
2.6 Front and Side Temperature profiles with horizontal setup.....	23
2.7 Velocity vector profiles with horizontal setup.....	24
2.8 Plot Over Line Configuration	24
2.9 Temperature plot in the z direction at 600 seconds for tomato purée horizontal setup.....	25
2.10 Temperature plot in the z direction for different tomato purée cases.....	27
2.11 Temperature plot in the z direction with pre-heating condition.....	28
2.12 Temperature profiles with both rotating and horizontal setup.....	29
2.13 Side velocity profile with both rotating and horizontal setup.....	30
2.14 Temperature plot in the z direction at 75 seconds.....	30
3.1 Time - Viscosity - Configuration performance chart Tomato Juice.....	33
3.2 Time Percentage Reduction - Viscosity - Configuration chart Tomato Juice..	33
3.3 Time - Viscosity - Configuration performance chart Tomato Sauce.....	34
3.4 Time Percentage Reduction - Viscosity - Configuration chart Tomato Sauce	34



**LIST OF FIGURES**  
**(Continued)**

<b>Figure</b>	<b>Page</b>
3.5 Time - Viscosity - Configuration performance chart Tomato Purée.....	35
3.6 Time Percentage Reduction - Viscosity - Configuration chart Tomato Purée	35
3.7 Time - Viscosity - Configuration performance chart Tomato Paste.....	36
3.8 Time Percentage Reduction - Viscosity - Configuration chart Tomato Paste.	36

## LIST OF SYMBOLS

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$\int$	Integration
$d()$	Derivative
$\nu_t$	Turbulent kinematic viscosity
$Pr_t$	Turbulent Prandtl number
$\bar{T}$	Mean temperature
$T_0$	Reference temperature
$\beta$	Coefficient of expansion
$\nu_{eff}$	Effective kinematic viscosity
$\tilde{p}$	Resolved kinematic pressure
$g_i$	Gravity acceleration vector
$\bar{u}$	Mean velocity vector
$\partial()$	Partial Differential
#	Number Sign
$\nu$	Kinematic viscosity
$\gamma$	Shear stress
K	Consistency index
n	Flow behavior index

# CHAPTER 1

## INTRODUCTION

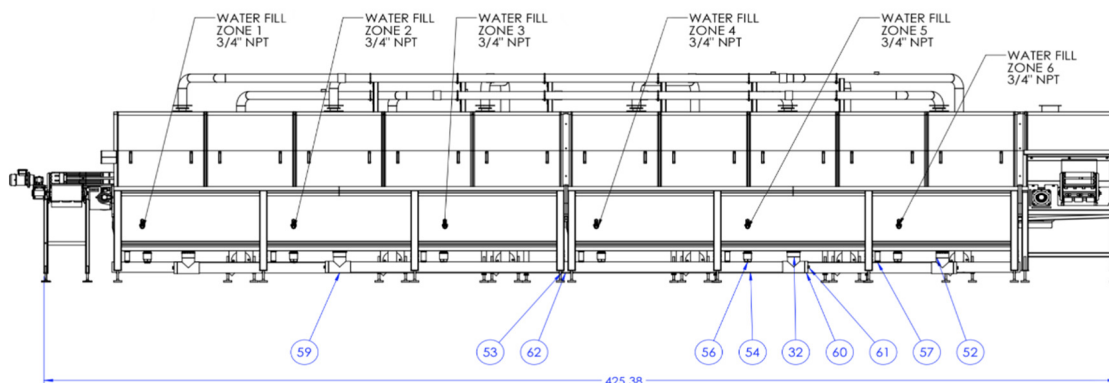
This thesis deals with the control and the modelling of the pasteurization process for tomato products, with different values of viscosity, in tunnel pasteurizers. These machines are integral part of production lines of many breweries and other producers of beverages all over the world. The pasteurizers quality control has a cardinal impact on the flavor and biological safety of their products and not least on the economy of the plant operation.

### 1.1 Tunnel Pasteurizer

The tunnel pasteurizer is mostly spread in the beverage industry, but it's widely used in canning industries too because of its reliability, practicality and exercise simplicity.

The machine consists in a long tunnel where the bottles, moving forward with a set velocity based on the thermic cycle to implement, are covered by liquid nozzles with different temperatures. Usually, the liquid used is water, with appropriate physical-chemical characteristics to which are added sterilizing agents and sequestering compounds.

[1]



**Figure 1.1** Tunnel Pasteurizer Side View.

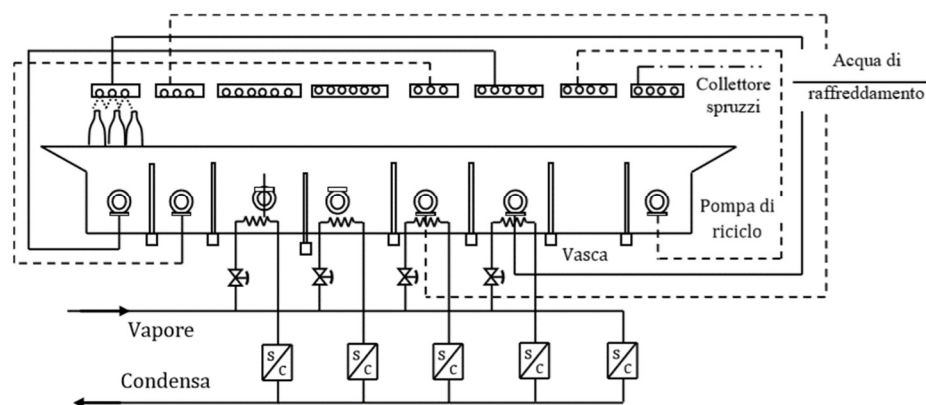
Source: Sourceline Machinery (2018). *Compact tunnel pasteurizer*. Retrieved January 10, 2019, from <https://sourcelinemachinery.com/listings/compact-tunnel-pasteurizer/>

Bottles or tin cans, moving at a fixed velocity on a moving carpet, follow a thermic cycle caused by the medium coming from the series of sprayers located on the top, plumped by suction centrifugal pumps placed in the collection tanks underneath.

Usually there are 4 sections:

1. Pre-heating section
2. Intermediate heating section (pre-pasteurization)
3. Pasteurization section
4. Cooling section

The last cooling tank is powered by running water with the last sprayers series. If the running water is not available with enough amount, it's better to recycle water from the last tank filtering it with particular care and lowering the temperature in cooling towers.



**Figure 1.2** Scheme of tunnel pasteurizer with “heat recovery.”

Source: Ingegneria delle macchine e degli impianti dell’industria alimentare (2017). *Il trattamento termico post confezionamento*. Retrieved December 2018, from [http://elly.dia.unipr.it/2017/pluginfile.php/18247/mod\\_resource/content/1/12\\_trattamento%20post%20conf.pdf](http://elly.dia.unipr.it/2017/pluginfile.php/18247/mod_resource/content/1/12_trattamento%20post%20conf.pdf)

These machines thermic cycle can be defined with the term “heat recovery”: the cool running water, stored in the last tank, is filtered and, through a pump, it powers the second to last tank. The water from the first cooling tank powers the second pre-heating tank, while the second cooling tank goes to the first pre-heating tank and so on. Both the

pasteurizing and pre-pasteurizing water are constantly recycled. The main objective of the pre-pasteurization is to provide enough thermic jump so that the bottle could reach the pasteurization temperature from the beginning of the pasteurization section.

The thermic jump between the pre-heating, pre-pasteurizing and pasteurizing sections depends on the dimensions, the bottle volume as well as the type of process it must be realized. In the cooling sections the thermic jump shouldn't exceed 12°C.

## **1.2 Tomato Products**

The tomato, from the species *S. lycopersicum*, was originated in South America. The tomato plant lives in tropical ambient with a broad selection: the main distinction is between the table variety and the industry type.

By an agronomic point of view, the main characteristics required are:

1. High performance production
2. Pathogens resistance
3. High consistence and coloration uniformity
4. Easy removal
5. Blanching, cracking and overripen resistance
6. High content of dry substances, sugars and natural antioxidants

### 1.2.1 Industry Nutrition Facts of Tomato

- Sugars: mostly glucose and fructose (40-60% of the dry residuum)
- Insoluble substances: mainly polysaccharides such as pectin, cellulose and lignin

In the industrial derivates, pectins are responsible for viscosity and consistence. All the present amino-acid are judged as indispensable for the human diet.

**Table 1.1** Tomato Nutrition Facts

<b>Tomato Nutrition Facts</b>	
Serving Size 1 small whole (2-2/5" diameter) (91 g)	
Per Serving	% Daily Value*
<b>Calories 16</b>	
Calories from Fat 2	
Total Fat 0.2g	0%
Saturated Fat 0g	0%
Polyunsaturated Fat 0.1g	
Monounsaturated Fat 0g	
Cholesterol 0mg	0%
Sodium 4mg	0%
Potassium 215.67mg	6%
Carbohydrates 3.5g	1%
Dietary Fiber 1.1g	4%
Sugars 2.4g	
Protein 0.8g	
Vitamin A 15% · Vitamin C 21%	
Calcium 1% · Iron 1%	
<i>*Based on a <a href="#">2,000 calorie diet</a></i>	

Source: Veriwellfit (2019). Tomato Nutrition Facts, Calories, Carbs, and Health Benefits of Tomato. Retrieved January 11, 2019, from <https://www.verywellfit.com/tomatoes-nutrition-facts-calories-and-health-benefits-4119981>

Tomatoes are very sensible to cold temperatures, they cannot resist below 0°C, to germinate at least 10° to 12°C are required while the optimum stands between 18°-26° degrees Celsius. The best soils are the deep and draining ones, with a good amount of organic substances and a pH between 5,5 and 7,9. [4]

### 1.2.2 Tomato Rheology

The relationship between shear stress and shear rate of large number of liquids can be represented as:

$$\tau = \tau_0 + K \left( -\frac{dv}{dz} \right)^n \quad (1.1)$$

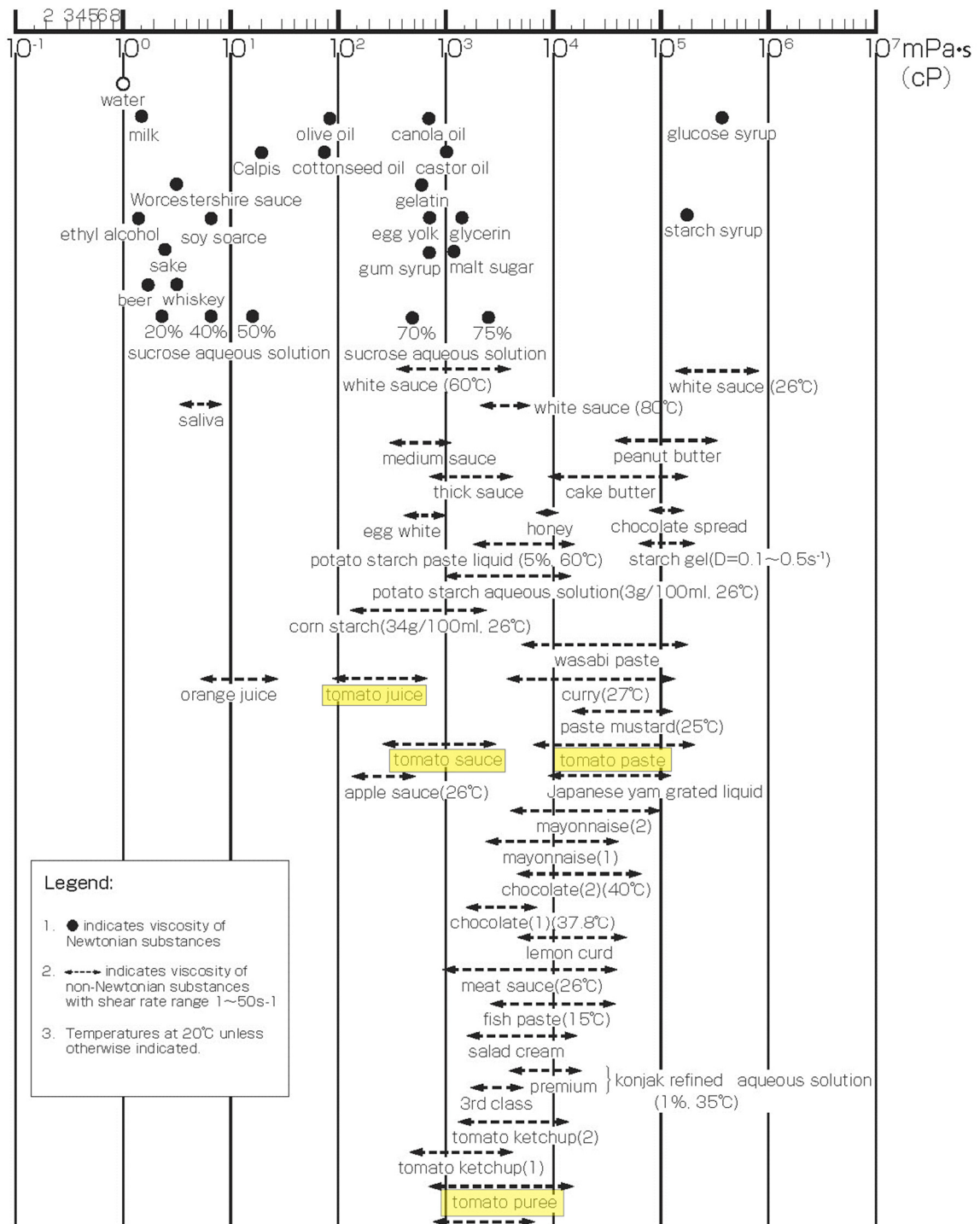
where  $\tau$  is the shear stress,  $\tau_0$  is the shear stress needed to initiate flow,  $dv/dz$  is the velocity gradient of shear rate,  $K$  is called the consistency coefficient, and  $n$  is called the flow behavior index.

When  $\tau_0 = 0$  and  $n = 1$ , the liquid is called Newtonian and  $K$  becomes the viscosity of the liquid. For all other values of  $\tau_0$  and  $n$ , the liquid is described as non-Newtonian.

Tomato products are non-Newtonian liquid foods, and in addition this is a pseudoplastic liquid for which  $\tau_0 = 0$  and  $n < 1$ . These liquids exhibit high apparent viscosity, and pumping pressures required to obtain fully turbulent conditions are not economic for production rates of interest. Likewise, extent of agitation required for containerized non-Newtonian liquid to attain turbulent flow may not always be feasible for practical industrial applications. [5]

All these parameters were crucial for an accurate computational fluid-dynamic study, especially the tomato viscosity range:

**Table 1.2 Food Products Viscosity Data Chart**



Source: DrRheology - on demand technical resources (2012). *Viscosity values*. Retrieved April 2018, from <http://www.drrheology.com/images/foodviscosity.gif>

Table 1.2 shows four different tomato viscosity sections, from 10<sup>2</sup> to 10<sup>5</sup> cP; these data will be discussed later to identify one the scopes of this study.



### **1.2.3 Tomato Juice, Purée And Paste Production Lines**

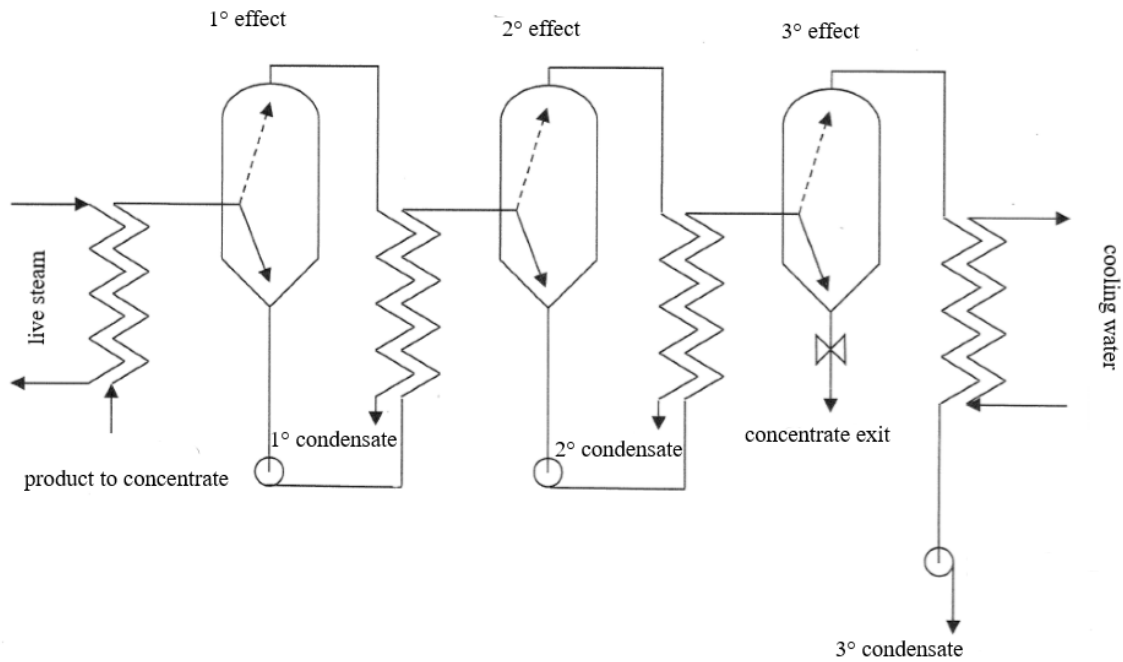
Tomato juice, purée and paste are all prepared on the same production line because they require similar processes. Tomato juice is a pulpy liquid, separated from seeds and skins, obtained with a homogenization treatment that allows to reduce the particles to the micron scale. Instead the purée and the paste are produced by a certain water evaporation extraction.

Tomato purée is intended as a ready to use product for quick contours preparation and reducing drastically cooking times. It's made of tomato juice without high refinement and obtained directly from partially concentrated fresh tomatoes. The purée can be produced only with a direct squeeze, centrifugation, mechanical refinement together with a partial water elimination and a pH lower than 4,5. The common packages used are: glass bottles, composite bricks, or tinplate cans.

Depending on the product's residual humidity it's possible to distinguish:

- Tomato semi-concentrate (12% minimum of dry substances)
- Tomato concentrate (18%)
- Tomato double concentrate (28%)
- Tomato triple concentrate (36%)
- Six times tomato concentrate (55%)

The process is very similar to the tomato purée one, but with the addition of one more step/machine: the concentrator. The juice coming from the refining group is sent in these concentrators where is concentrated with a water evaporation. These implants usually work with a lowered pressure and with multiple effects both for reducing energetic costs and to preserve the juice organoleptic qualities. Then It follows with the pasteurization heat treatment in selected boxes, glasses or aluminum tubes. [4]



**Figure 1.3** Triple effect, no recycle evaporator.

Source: Ingegneria delle macchine e degli impianti dell'industria alimentare (2017). *I processi di trasformazione del pomodoro da industria*. Retrieved December 2018, from [http://elly.dia.unipr.it/2017/pluginfile.php/18230/mod\\_resource/content/1/Pomodoro\\_DEF.pdf](http://elly.dia.unipr.it/2017/pluginfile.php/18230/mod_resource/content/1/Pomodoro_DEF.pdf)

### 1.3 The OpenFOAM Software

OpenFOAM (Open Field Operation and Manipulation) is principally a C++ toolbox for customizing and extending simulations software solutions.

Is a solver based on the theory of continuum mechanic which included the Computational Fluid Dynamic (CFD).

It comes with an extended solvers library, continuously expanded and applicable to general problems.

OpenFOAM is one of the first major scientific software packages written in C++.

It's produced by the British firm OpenCFD Ltd. and released under the GPL license.

Pre and post-processing third parts utilities are the base of user's choice and it comes like:

- A plugin (paraFoam) for final data and mesh visualization with ParaView.

- A broad 3D mesh converters variety allowing to import from a series of important commercial packages.
- An automatic hexahedral mesher to create polygonal grids for engineering configurations.

The Standard Solvers include:

- Basic CFD
- Incompressible fluxes
- Compressible fluxes
- Multiphase fluxes
- DNS e LES
- Particle-tracking fluxes
- Combustion
- Heat Transfer
- Molecular Dynamics
- Monte Carlo direct simulation
- Electromagnetism
- Solid Dynamics
- Finance

In addition to the standard solvers, one of the functionalities that distinguish OpenFOAM is its ease for custom solution solvers creation.

OpenFOAM allows the user to apply the syntax that best resemble to the partial derivative equations during the solution phase. [7]

### 1.3.1 BuoyantBoussinesqPimpleFoam Solver

BuoyantBoussinesqPimpleFoam is a transient solver for buoyant, turbulent flow of incompressible fluids.

The solver couples 3 different equations:

2.2.1 Mass equation:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0 \quad (1.2)$$

2.2.2 Momentum equation:

$$\begin{aligned} \frac{\partial \bar{u}_i}{\partial t} + \frac{\partial}{\partial x_j} (\bar{u}_i \bar{u}_j) - \frac{\partial}{\partial x_j} \left\{ \nu_{eff} \left[ \left( \frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i} \right) - \frac{2}{3} \left( \frac{\partial \bar{u}_k}{\partial x_k} \right) \delta_{ij} \right] \right\} \\ = - \frac{\partial \tilde{p}}{\partial x_i} + g_i [1 - \beta (\bar{T} - T_0)] \end{aligned} \quad (1.3)$$

Where  $\nu_{eff} = \nu_0 + \nu_t$  is the effective kinematic viscosity.

2.2.3 Temperature equation

$$\frac{\partial \bar{T}}{\partial t} + \frac{\partial}{\partial x_j} (\bar{T} \bar{u}_j) - \frac{\partial}{\partial x_k} \left( \kappa_{eff} \frac{\partial \bar{T}}{\partial x_k} \right) = 0 \quad (1.4)$$

Where  $\kappa_{eff} = \frac{\nu_t}{Pr_t} + \frac{\nu_0}{Pr}$ .

In flows where heat transfer is present, the fluid properties are normally functioning of temperature. The variations may be small and yet be the cause of the fluid motion. If the density variation is not large, one may treat the density as constant in the unsteady and convection terms.

This hypothesis is called the Boussinesq approximation. It is common to assume that the density varies linearly with temperature. [8]

We can express the density term as:  $\rho_k = 1 - \beta \cdot (\bar{T} - T_0)$  .

Hereafter, we denote the reference density by  $\rho_0$  at the reference temperature  $T_0$ .

If we replace  $\rho$  by  $\rho_0$  in the mass equation except for the gravitational term, then we get the continuity equation:

$$\nabla \cdot (\rho \mathbf{u}) = 0 \tag{1.5}$$

## **CHAPTER 2**

### **SIMULATION STEPS**

With the advance of new technologies, the food industries are requiring systems that allow to produce the desired products with faster rates and cheaper costs. In this case, the study was initiated with the purpose to better understand what happens inside a package containing tomato puree when this is heated above 343 K in a tunnel pasteurizer. If the fluid must reach the thermal and microbiological condition of “pasteurization”, the system must guarantee that the temperature (around 343° Kelvin) is kept for a certain time allowing to pasteurize even the cooler package’s fluid-particle.

The faster the system can heat the bottle, the higher the productivity could be but, to guarantee the same heat treatment, it may be needed a longer tunnel, raising equipment costs and space allocation.

In addition, with such a broad range of viscosity, when heated, the tomato products may have different behaviors: a convective movement may or may not appear and could be a helping factor for a better temperature distribution.

In this chapter it will be explained the different steps the study had to face to reach the targets mentioned above.

#### **2.1 Initial Modeling**

On the long run the objective was to focus on a thermofluidynamic model considering also the Boussinesq system, but to do that initially, it was necessary to adapt every condition applying simplistic hypothesis.

To begin with, the study converted on a tunnel where inside the cans are transported by a conveyor belt; inside the packages there's a fluid with such a huge value in viscosity that it could be approximated as a solid.

In this situation we could apply a pure heat transfer model using the equation below:

$$\frac{\partial T}{\partial t} + \nabla(\mathbf{U}T) - \nabla^2(D_T T) = 0 \quad (1.5)$$

where  $T$  is the transported scalar,  $\mathbf{U}$  is the fluid velocity, and  $D_T$  is the diffusion coefficient divided by the fluid density, both supposed to be constant.

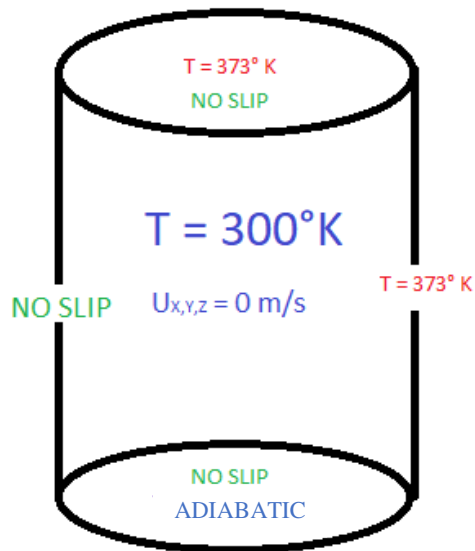
The geometry initially used was a closed square box with Temperature Boundary Conditions (B/C) along the external surfaces; the model is 3D, but because of a very small  $\Delta z$  it was possible to consider a bidimensional behavior.

Next the model started to incorporate the Navier-Stokes equation together with the Boussinesq term; the solver used is called "BuoyantBoussinesqPimpleFoam" as mentioned in paragraph 1.3.1.

The geometry switched to a cylindrical form (radius = 30 mm, height = 150 mm) with a full 3D behavior, while more hypothesis were added:

- No Slip B/C
- No fluid motion initially
- Adiabatic condition for the bottom cylinder (the conveyor belt is considered as an insulator)
- Laminar flux
- Newtonian fluid
- Initial fluid temperature  $T_0 = 300 \text{ }^\circ\text{K}$
- Tomato Purée properties (average cinematic viscosity  $\mu = 5000 \text{ cP}$ , average density  $\rho_0 = 1035 \frac{\text{kg}}{\text{m}^3}$ , thermal expansion coefficient  $\beta = 0.004 \frac{1}{\text{K}}$ )

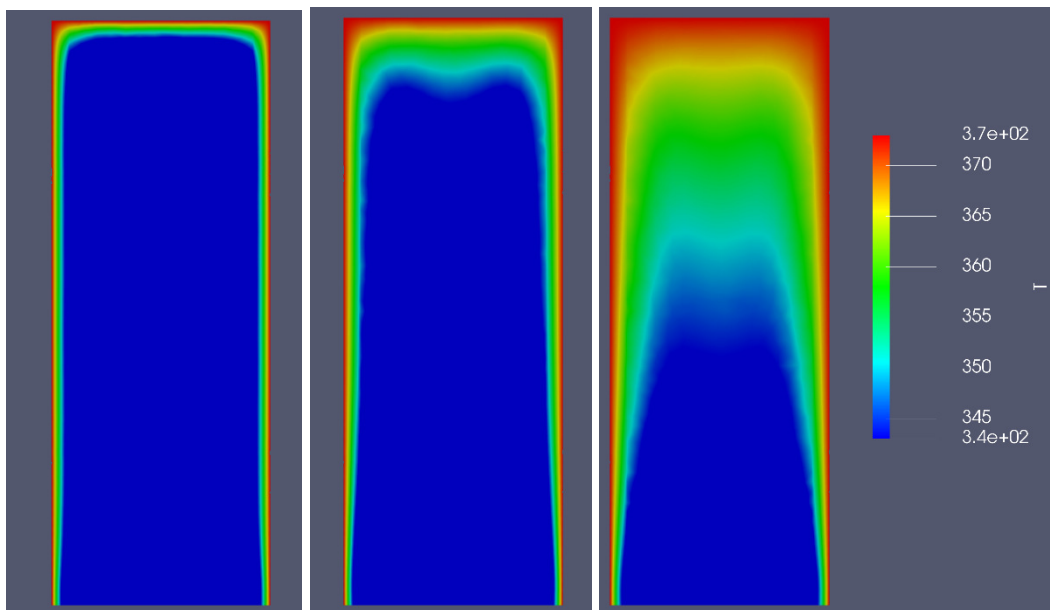
- Headspace and the metal package are not considered as part of the simulation dominium
- Wall Temperature = 373°K due to the contact with vapor sprayed in the tunnel



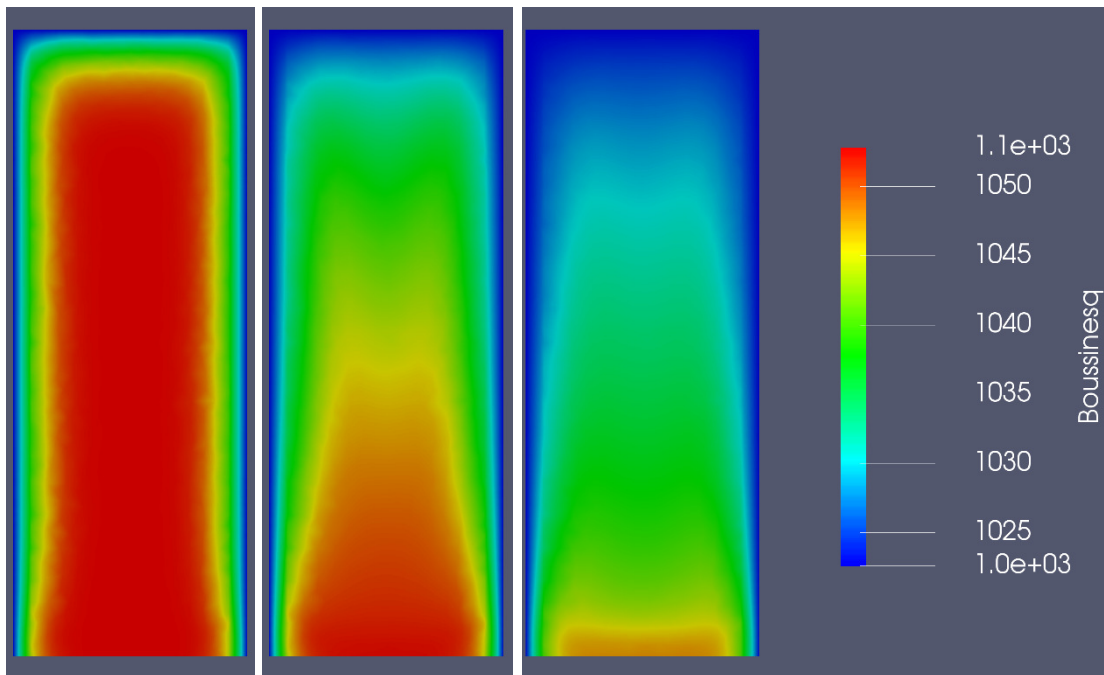
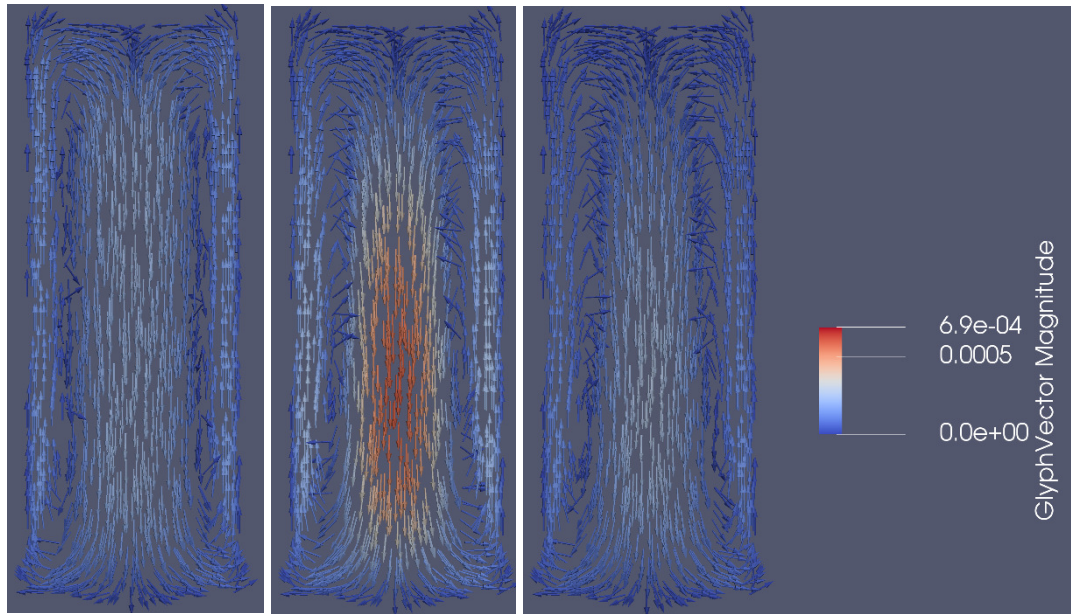
**Figure 2.1** Hypothesis assumed using BuoyantBoussinesqPimpleFoam Solver.

### 2.1.1 Simulation Test

Given these conditions the study could perform the first simulation test:







**Figure 2.2** Simulation test Temperature, Velocity and Density profiles for Newtonian Fluid using BuoyantBoussinesqPimpleFoam Solver.

As the figures 2.1 show, the cylinder is heated at a Temperature of 373° Kelvin around the lateral and top surfaces (except for the bottom).

Because of the geometrical symmetry, looking at the tin can from different angles wouldn't change the heating dynamics, so it was possible to take a slice of it and using it for some observations.

When a fluid is subjected to a rapid temperature increase adjacent to a solid wall, part of the fluid in the wall vicinity expands resulting in an increase in the local pressure with significant effects in heat transfer due to thermal buoyancy effects in a gravitational force field [9]. Similarly, during thermal processing of solid-liquid mixtures in cans, the tomato fluid adjacent to the can walls warms up causing the expansion and getting a lower density while the liquid away from the walls stays at lower temperature. This leads to development of an upward buoyancy force with a motion due to density differences. This movement also carries the colder fluid upward by viscous drag. The fluid flowing upward is deflected by the tin can's top surface modifying the movement to a radial direction (being more dense) and lastly starting to move downwards.

## 2.2 Tomato Purée Simulation

At this point, to obtain a simulation even closer to reality it was necessary to introduce the non-Newtonian conditions (see chapter 1.2.2).

- $\tau_0 = 0$
- $n < 1$

The Power Law fluid relationship was added to the solver, but it only describes approximately the behavior of a real non-Newtonian fluid.

$$\nu = k\dot{\gamma}^{n-1} \quad (1.6)$$

Where  $\nu$  is the kinematic viscosity.

For example, if “n” was less than one, the power law predicts that the effective viscosity would decrease with increasing shear rate indefinitely, requiring a fluid with infinite viscosity at rest and zero viscosity as the shear rate approaches infinity.

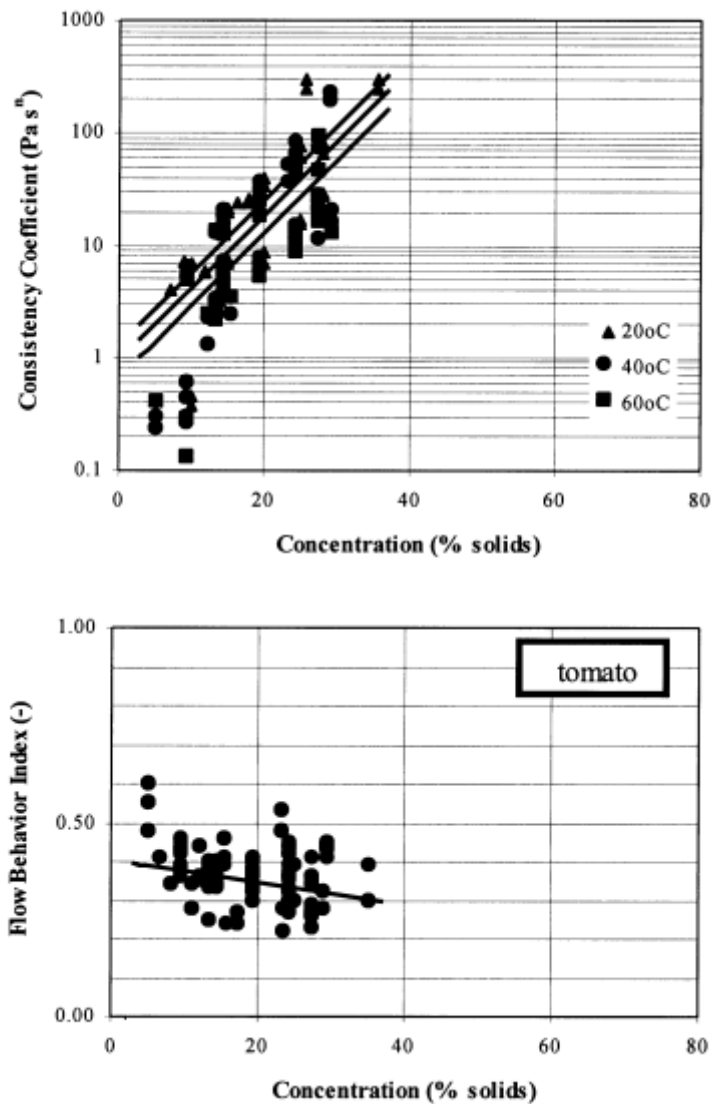
Actually, a real fluid has both a minimum and a maximum effective viscosity that depend on the physical chemistry at the molecular level. Therefore, the power law is only a good description of fluid behavior across the range of shear rates to which the coefficients were fitted. There are several other models that better describe the entire flow behavior of shear-dependent fluids, but they do so at the expense of simplicity; so, the power law is still used to describe it, permit mathematical predictions, and correlate experimental data. [10] To define the apparent viscosity, a shear rate range is required: with a pseudoplastic non – Newtonian fluid, the behavior seems more consistent at higher shear rates (above 300 or 400  $\text{sec}^{-1}$ ) with values of the power-law exponent in the neighborhood of 0,4 over a wide range of concentrations and temperatures.

It was also assumed that K and n don't change their values with the temperature, but only with the range of viscosity. In addition, the fluid was considered with a single-phase model and assuming it as an homogeneous liquid.

The viscosity range decided for the Tomato Purée starts from 1000 cP and reaches up to 10000 cP as the table 1.2 shows.

To select the consistency coefficient “K” [ $\text{Pa}\cdot\text{s}^n$ ] and flow behavior index “n” [-] values, the table 2.1 was used as a guideline.

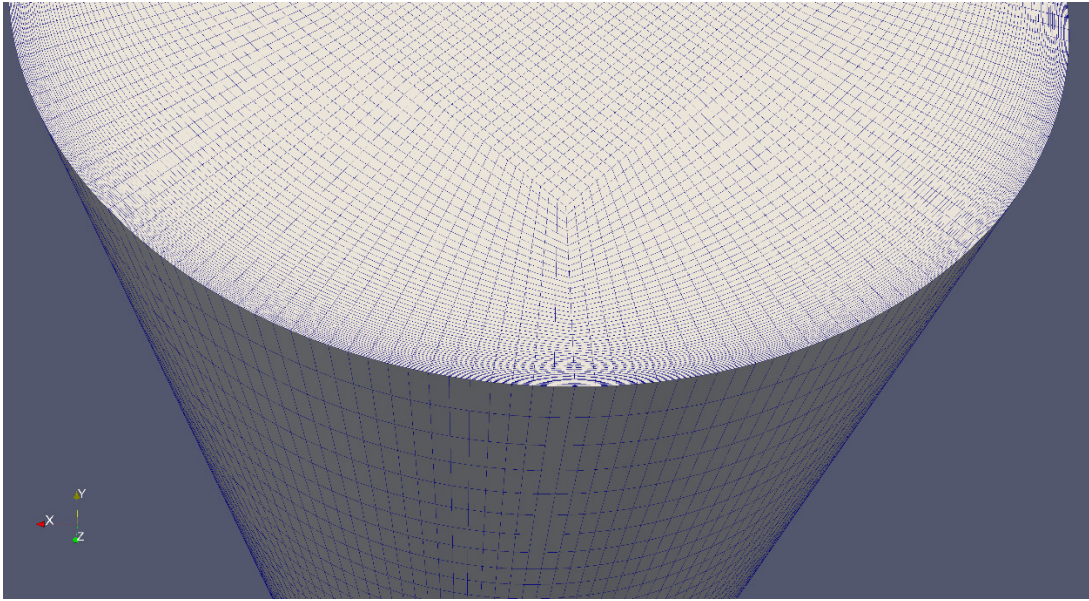
**Table 2.1** Rheological data of tomato juice and concentrates



Source: M. K. Krokida , Z. B. Maroulis & G. D. Saravacos (2001) RHEOLOGICAL PROPERTIES OF FLUID FRUIT AND VEGETABLE PUREE PRODUCTS: COMPILATION OF LITERATURE DATA, International Journal of Food Properties, 4:2, 179-200

Even the geometry had some modifications with the introduction of the viscous layers, and converting the format to a full hexahedral mesh, using a GUI software named Salome.

The new mesh with viscous layer allows to check the existence of any convective moments along the fluid's boundaries and how it affects the temperature distribution when heated.

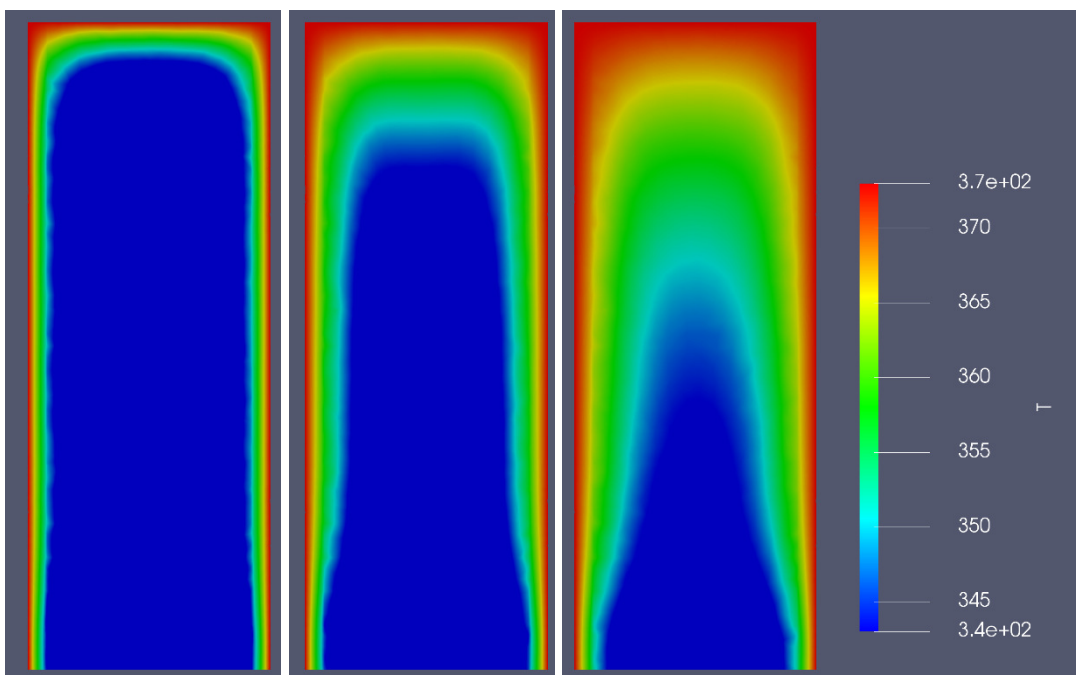


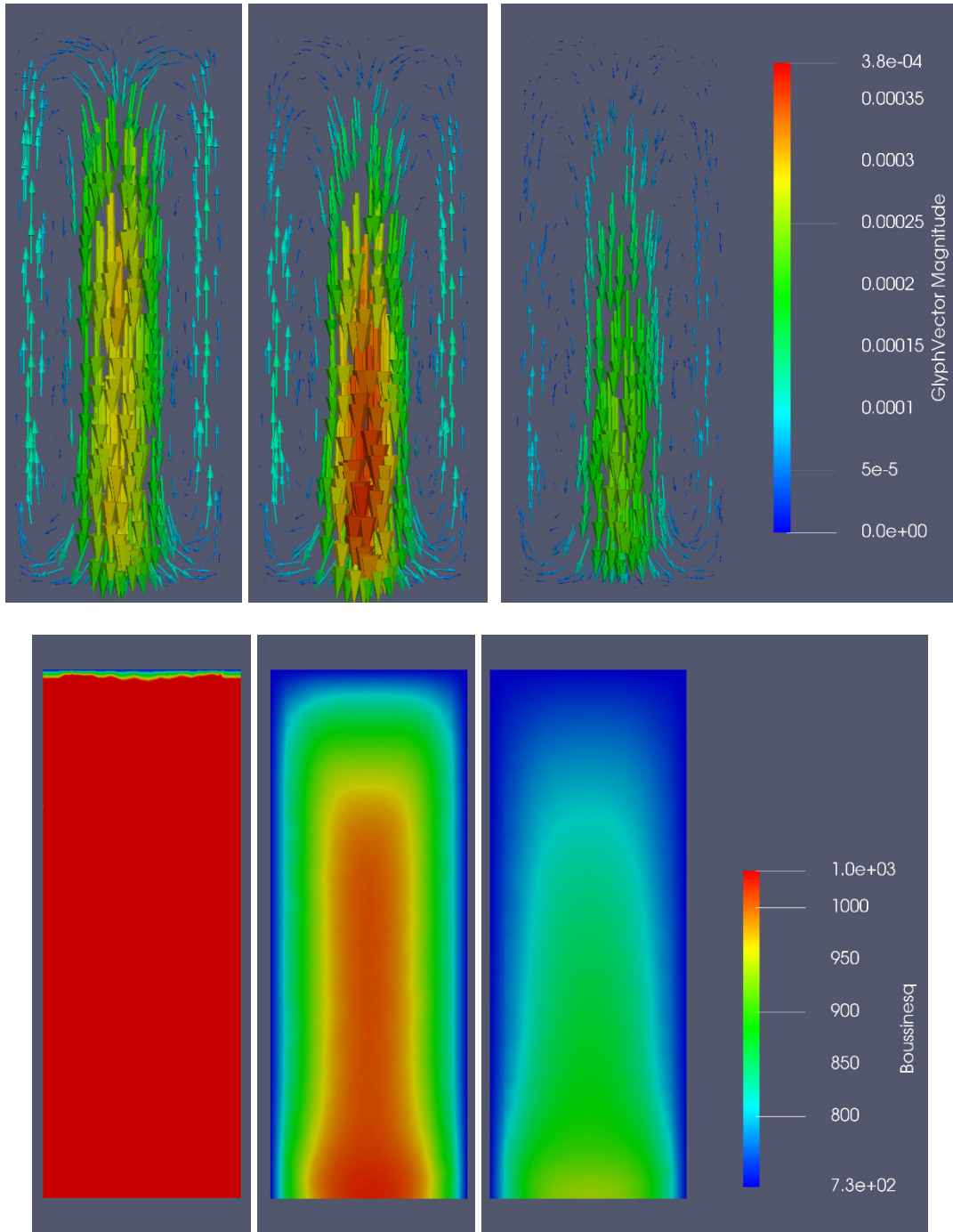
**Figure 2.3** Hexahedral mesh of a tin can obtained with Salome GUI software.

Because the main target is finding the best time-temperature solution for a pasteurized tomato product, the study will look at different simulation situations that may lead to a faster and more uniform heating.

### 2.2.1 Vertical Tin Can

The first simulation starts with a vertical tin can heated all around except for the bottom where we consider having an insulated conveyor belt transporting our product.





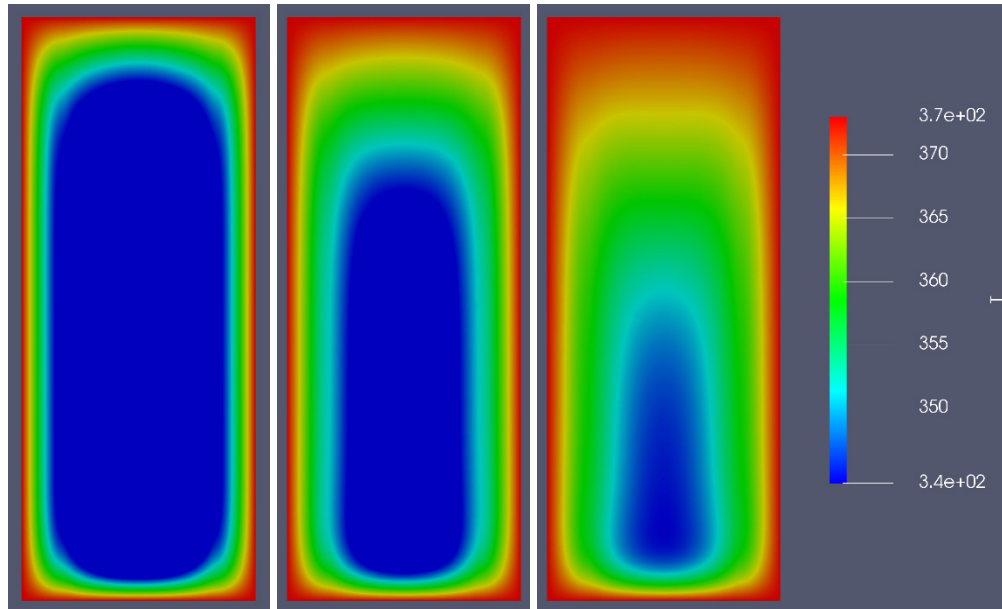
**Figure 2.4** Temperature, Velocity and Density profiles for Tomato Purée product with vertical setup.

Comparing this simulation to the benchmark shows a slight but perceptible difference in the temperature profile.

After 750 seconds the heated fluid hasn't reached the pasteurization condition yet; to improve the performance there's the need to heat even the tin can's bottom.



Industrially speaking this may happen if the tin cans are not being transported by a conveyor belt, but they possibly require an elevation while the heating fluid (steam or hot water) covers the bottom part.



**Figure 2.5** Temperature profile for Tomato Purée product with bottom heating.

In this last situation the fluid reaches the pasteurization condition around 650 seconds; because of very high viscosity, the convective movements are not helping that much the heating performance even when the bottom part is warmed.

Obviously, the pasteurization time has decreased because now we're warming up one more side but accounting industrial costs due to a new set of machines and more heating fluid to produce doesn't seem reasonable with this improvement.

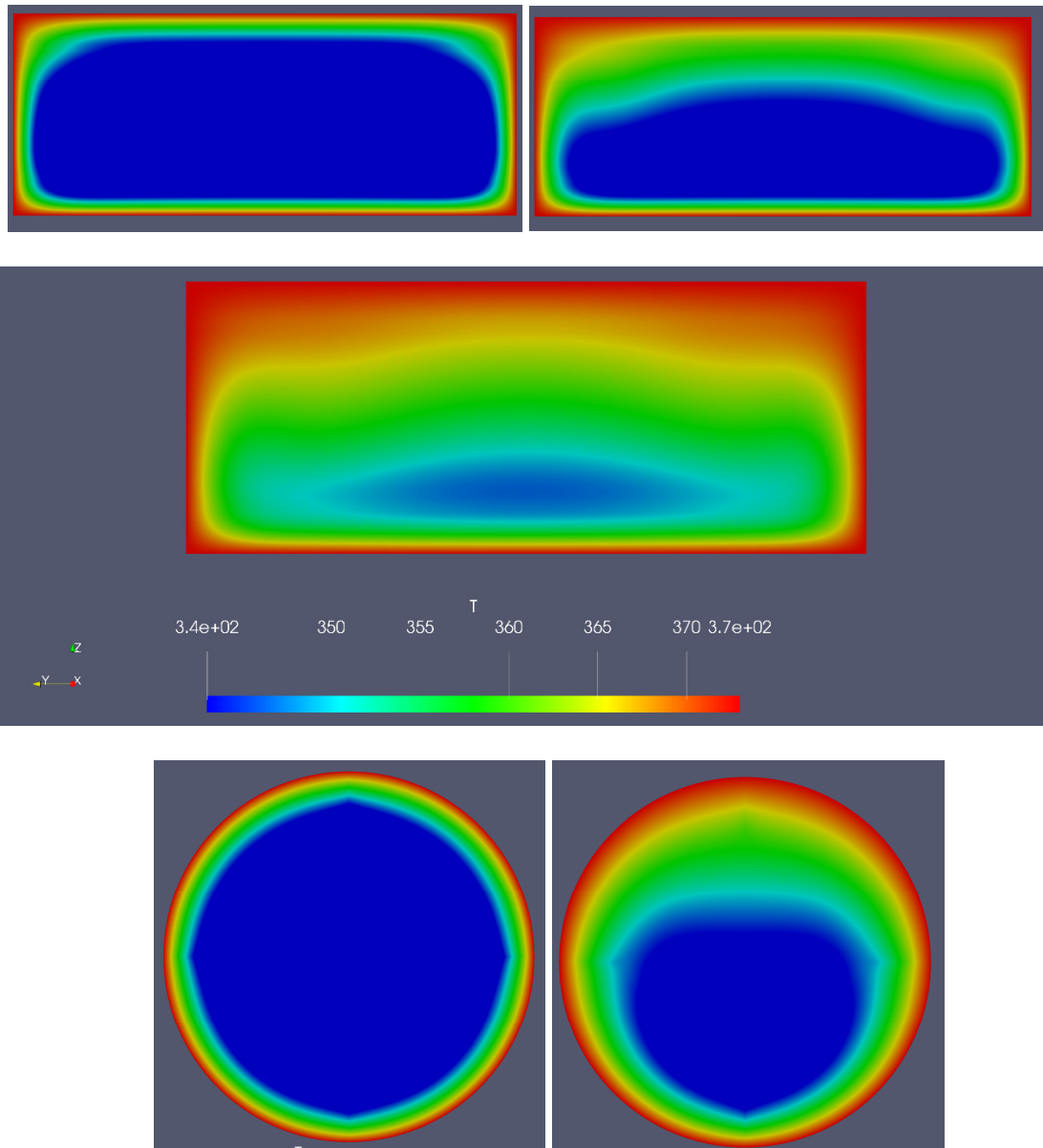
### 2.2.2 Horizontal Tin Can

Setting the can with a horizontal configuration may lead to better performance than a vertical situation.

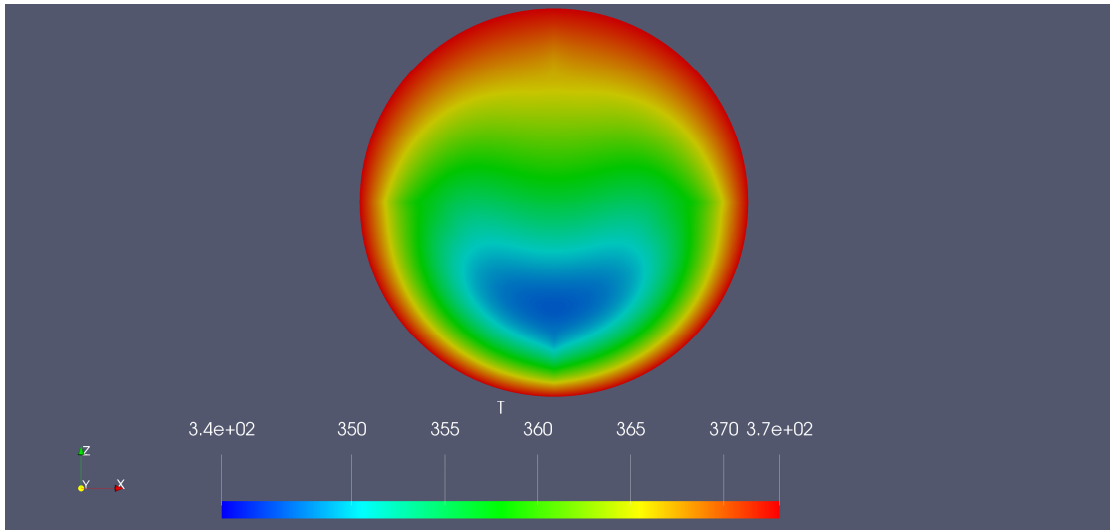
This assumption can be explained thinking about the movement for a tiny little part of the heated fluid:

starting from the tin can bottom, when this part is heated up, its density begins to lower allowing it to float towards the cylinder top face. Once at the top, the fluid will descend gradually exchanging heat with the cooler parts and raising its density value.

Therefore, if the configuration is horizontal, this tiny part would have to complete a much shorter path confronted to a vertical setup and the partial heating/cooling phase would be faster.



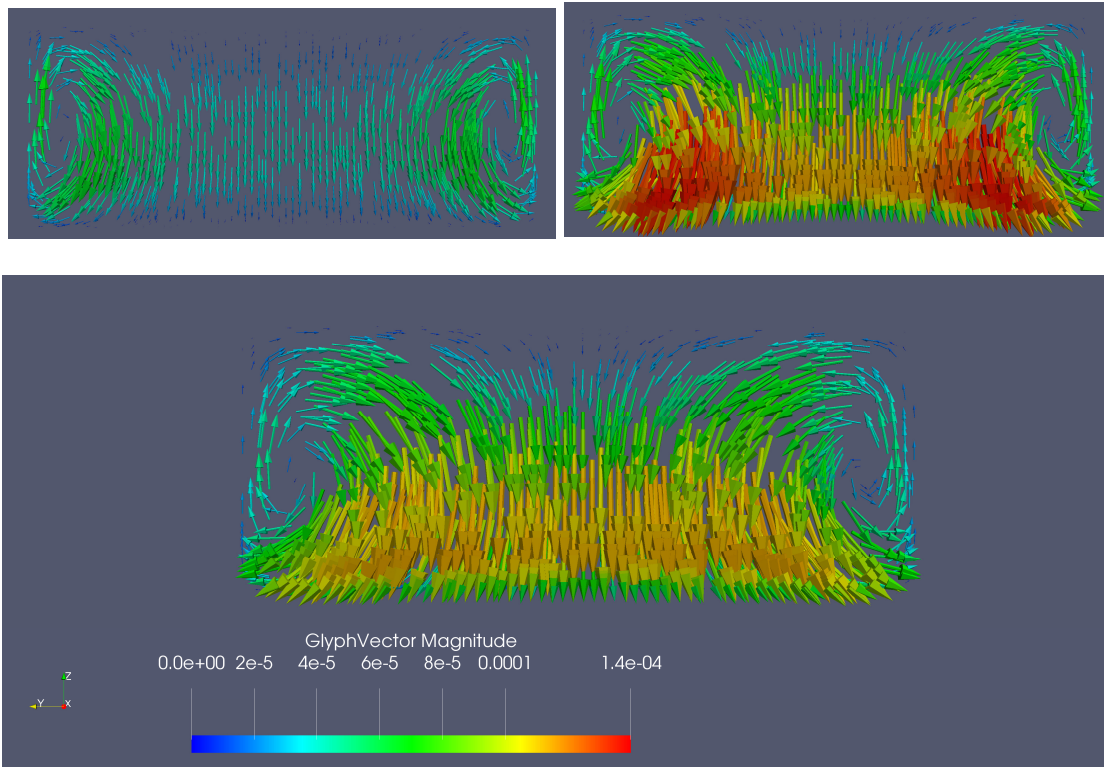




**Figure 2.6** Front and Side Temperature profiles with horizontal setup.

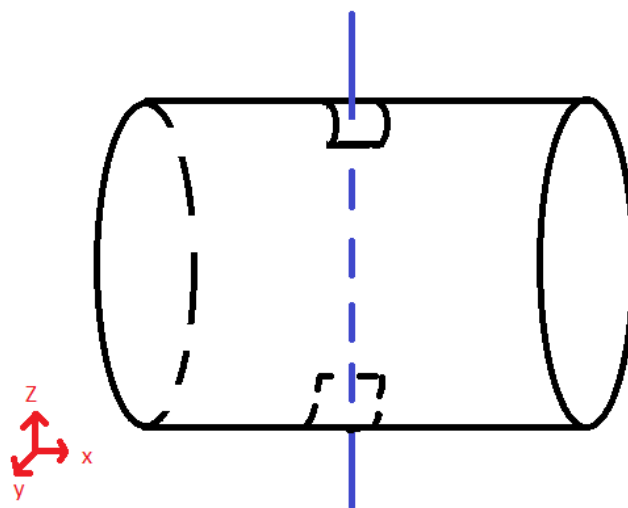
In fact, the simulation results in a faster pasteurization treatment: it takes between 500 – 525 seconds with this configuration to reach, for the coolest particle inside the package, a temperature above 343° K, consisting in a 28% more efficiency compared to the vertical setup.

Looking at the figure 2.6 it shows that roughly most of the fluid is speeding up during the heating; this speed increase allows a faster pasteurization heat treatment and a more uniform temperature distribution.

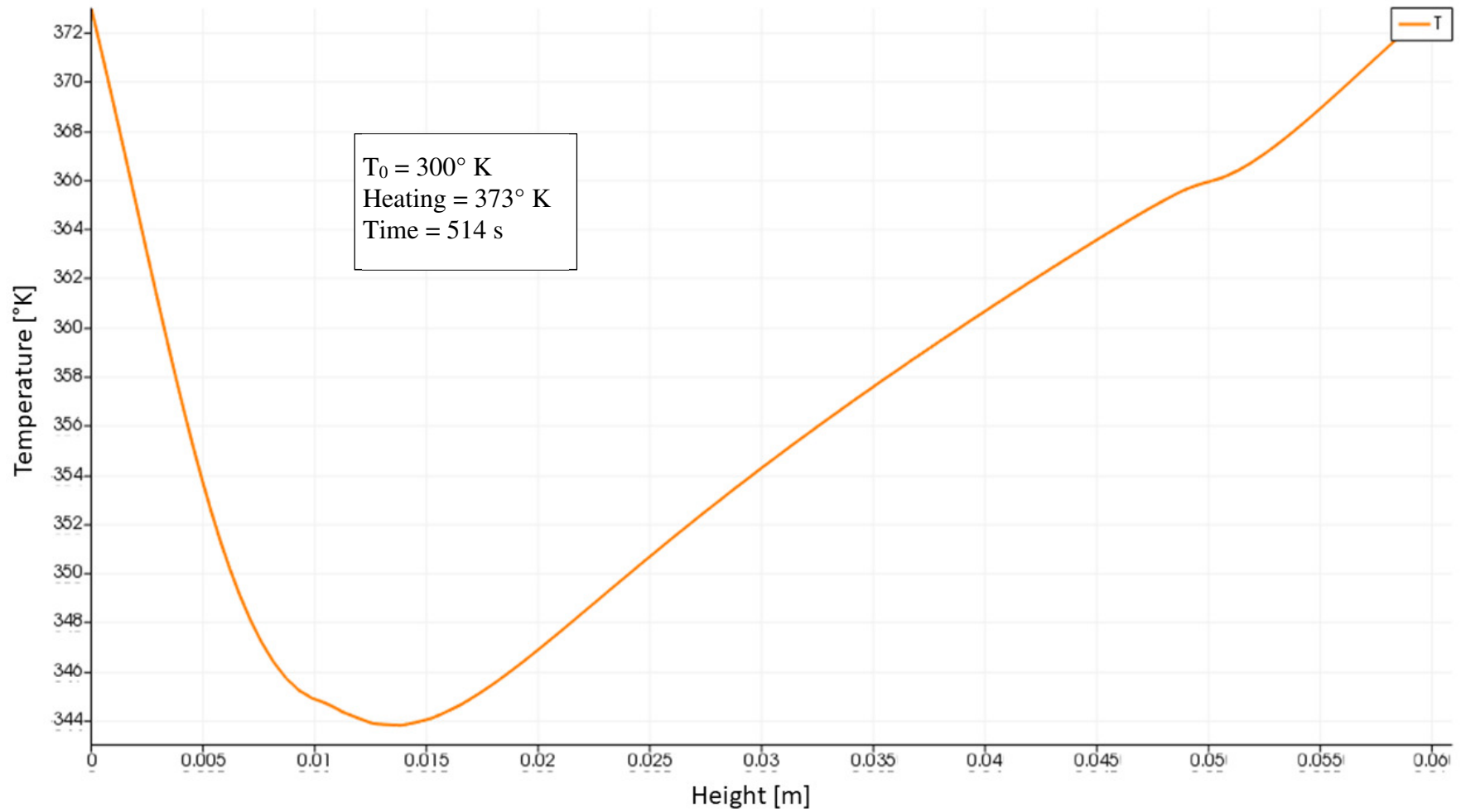


**Figure 2.7** Velocity vector profiles with horizontal setup.

Reaching a uniform temperature with the fastest time is a key factor in the food industry because the product must also meet some organoleptic requirements: if most of the tomato purée fluid particles reach sterilization temperatures (from 373°K and above), the flavor and the nutritional properties would change dramatically.



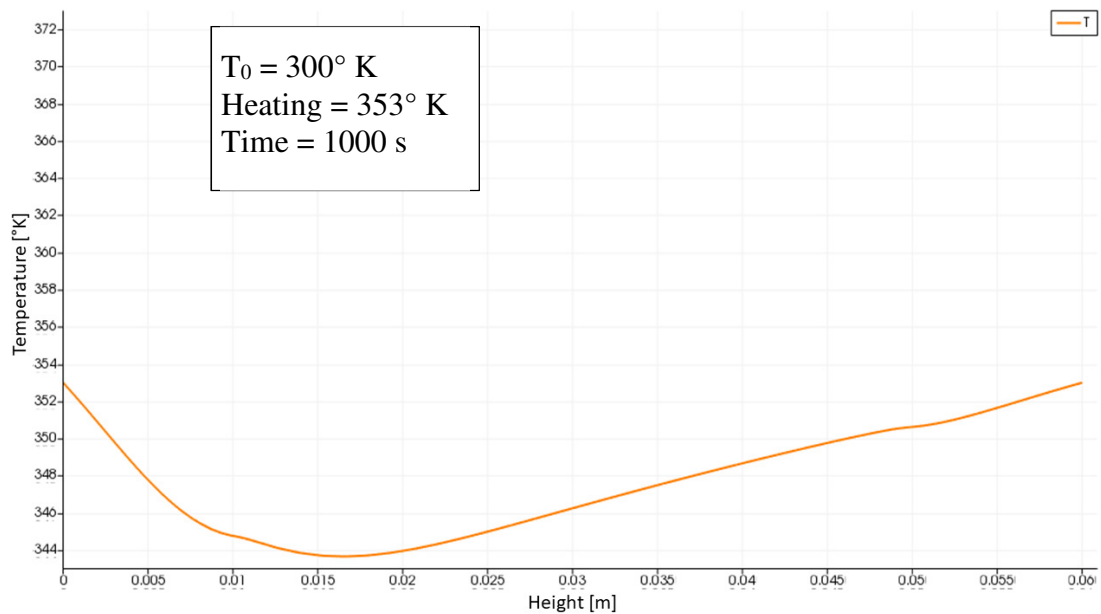
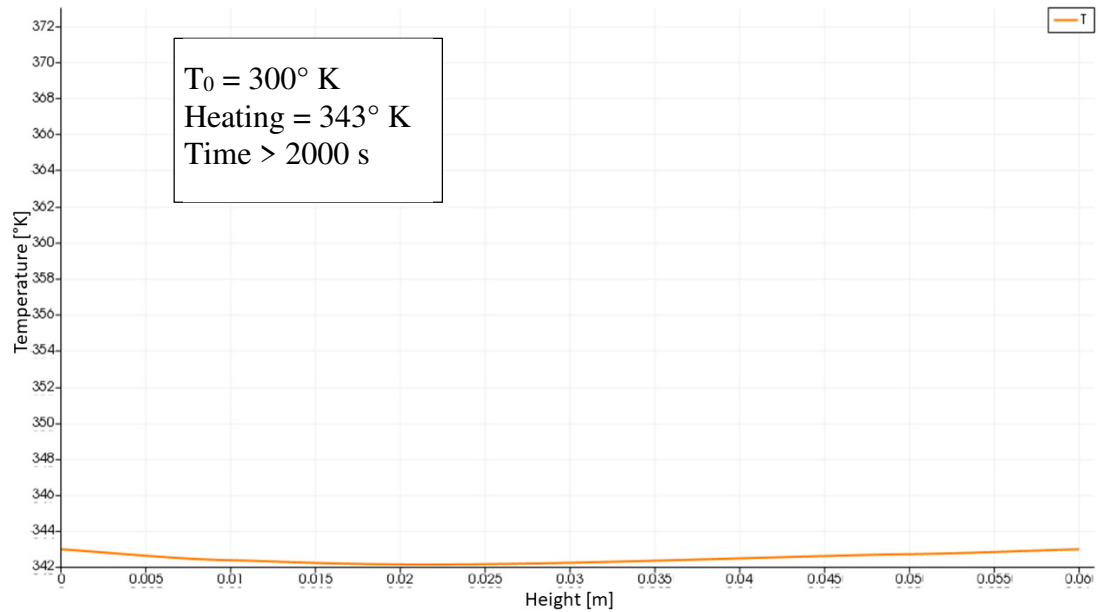
**Figure 2.8** Plot Over Line Configuration

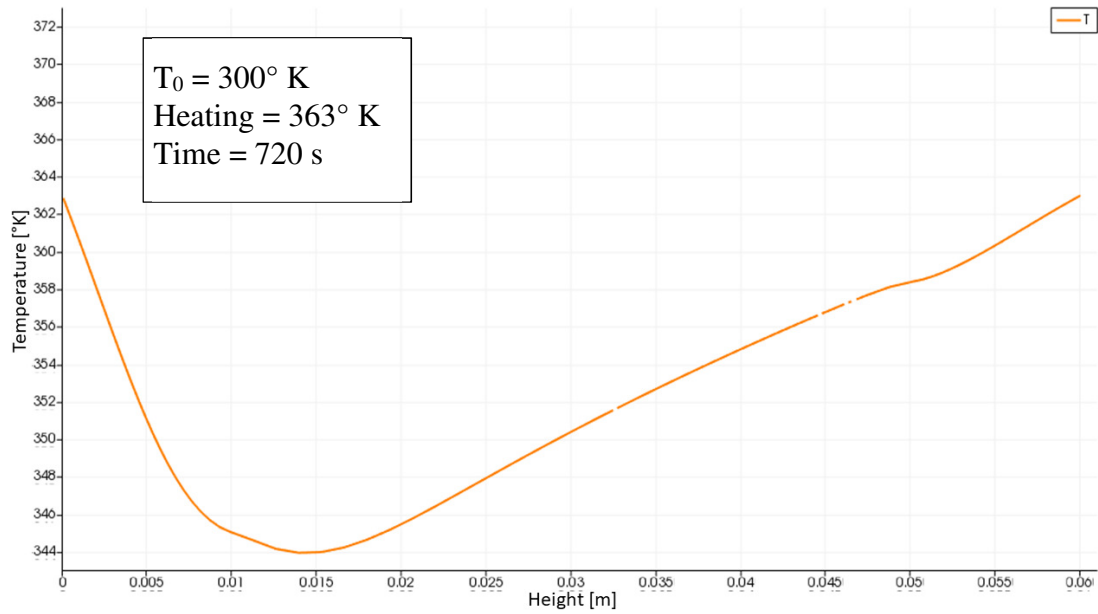


**Figure 2.9** Temperature plot in the z direction at 600 seconds for tomato purée horizontal setup.

During the study then, different heating cases were confronted to understand which one would be more appropriate in an industrial scenario, in particular a pre-heating of 323°K situation was considered.

The figure 2.8 shows the temperatures and the times to reach the pasteurization heat treatment for each one of cases simulated.

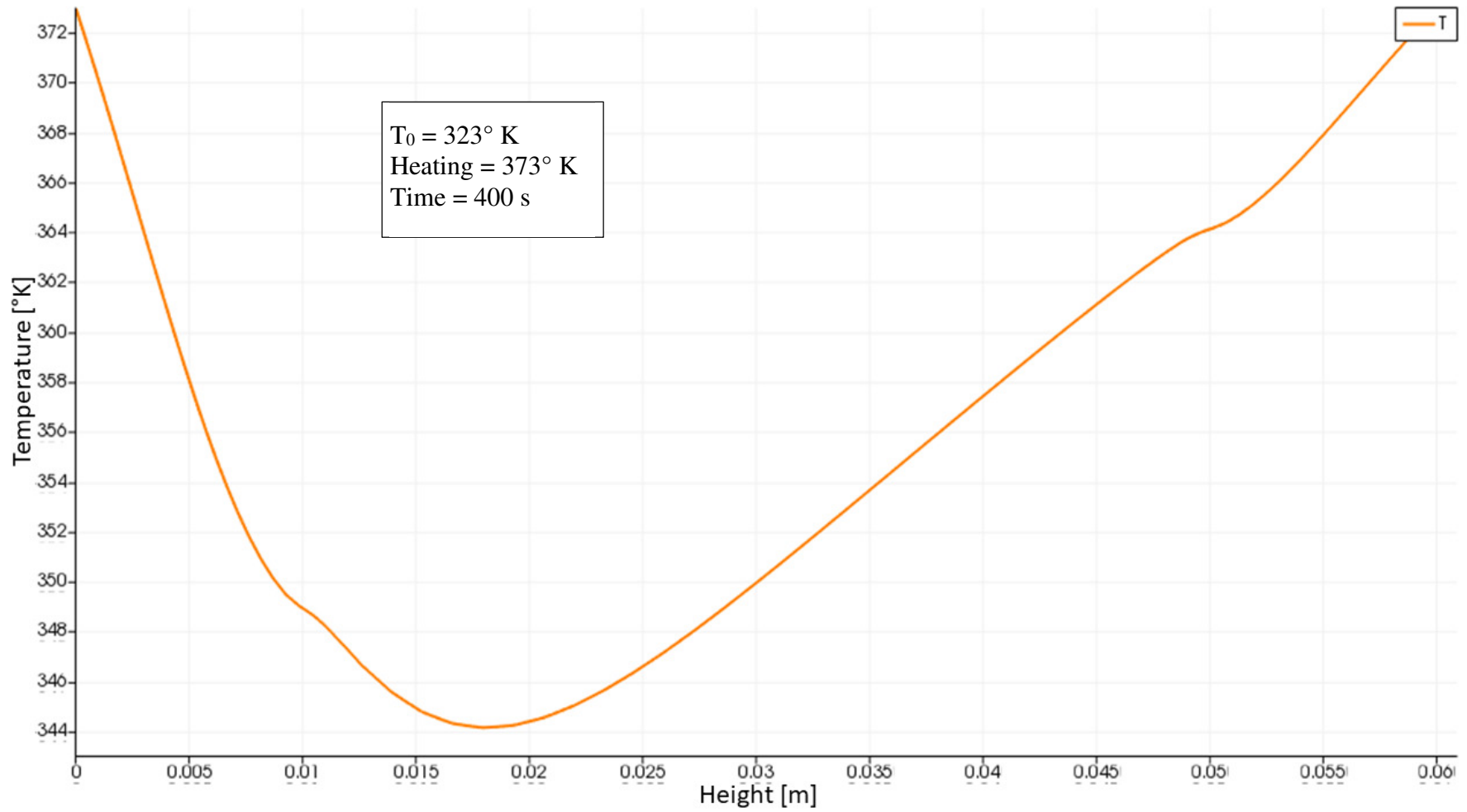




**Figure 2.10** Temperature plot in the z direction for different tomato purée cases.

Comparing the two plots of figure 2.7 and 2.9 gives an idea of how important the pre-heating condition is in order to maintain a product with a good quality overall.

A minor slope in the plot correspond to a smooth temperature distribution, but usually this is also linked to longer heat treatments (see figure 2.8).

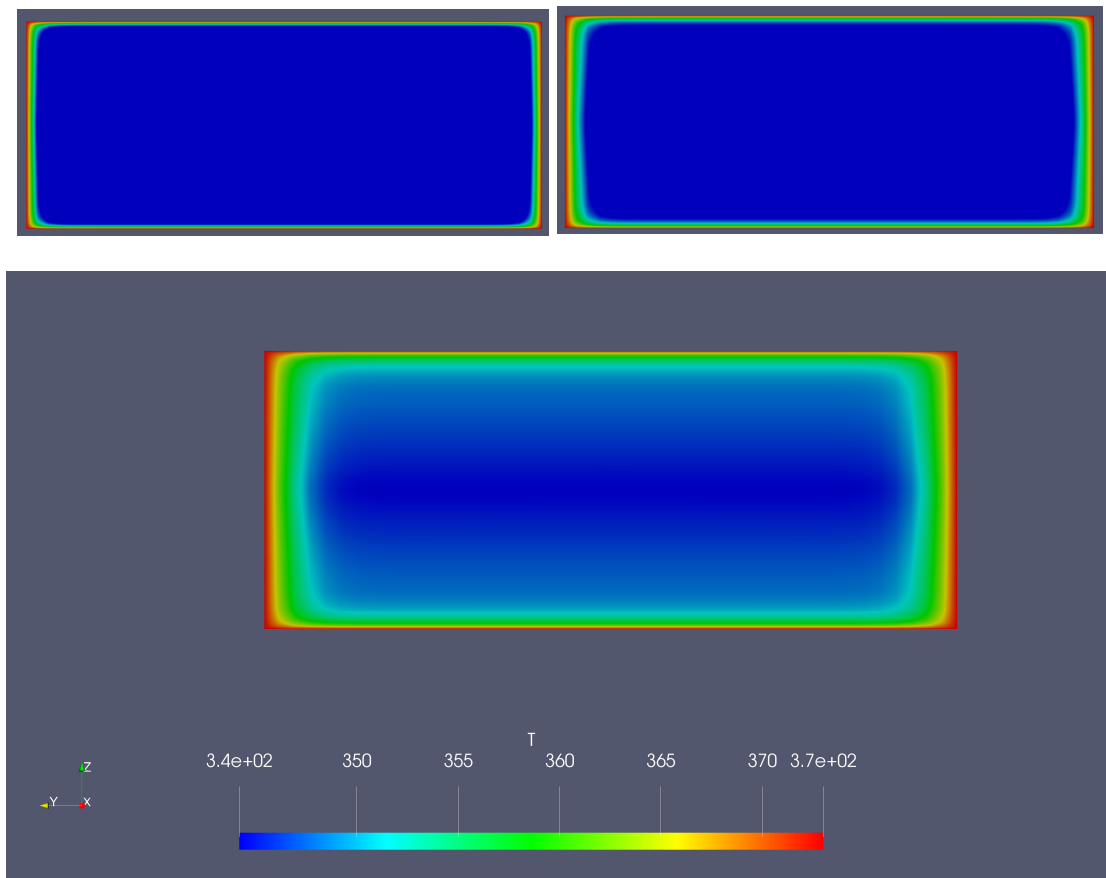


**Figure 2.11** Temperature plot in the z direction with pre-heating condition.

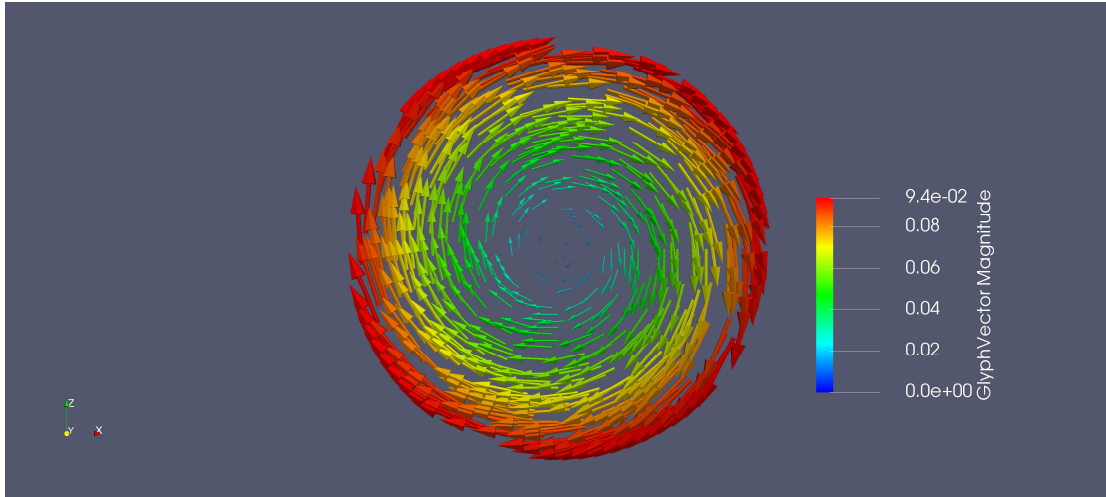
### 2.2.3 Horizontal Tin Can Rotating

To obtain a homogeneous temperature inside the package, one idea could be to “stir” the fluid exactly in the same way the grandmother cooks a tomato purée soup.

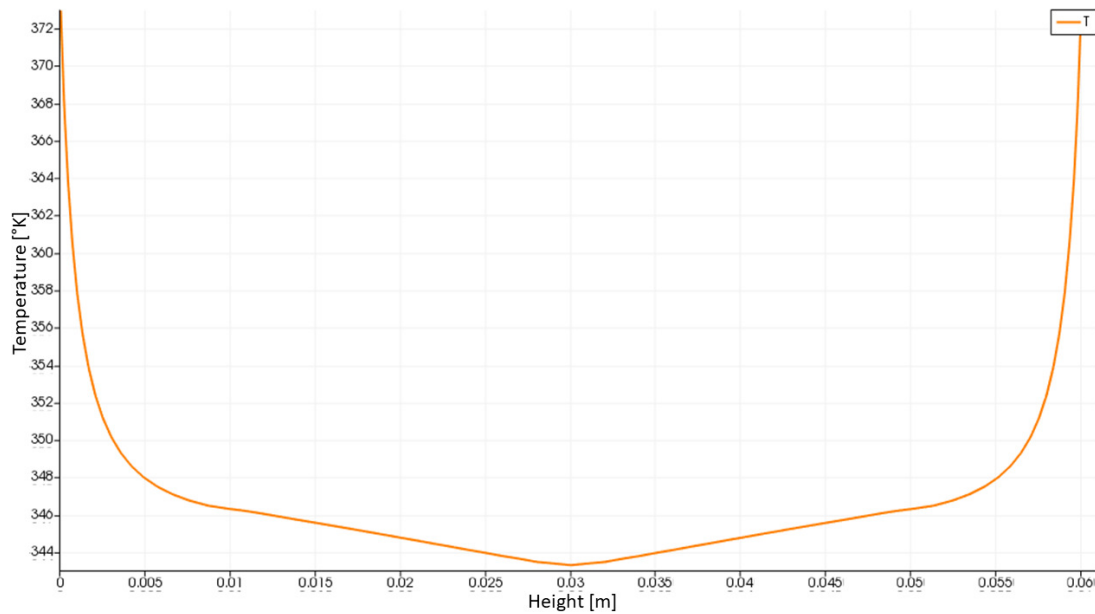
So, it was decided to add to the simulation a rotating function: the motion was considered on the fluid dominium boundaries, referring to the central axis, then the remaining part would start moving due to viscosity effects.



**Figure 2.12** Temperature profiles with both rotating and horizontal setup.



**Figure 2.13** Side velocity profile with both rotating and horizontal setup.



**Figure 2.14** Temperature plot in the z direction at 75 seconds.

With a rotating velocity equivalent to 36 RPM, the simulation results in a 75 seconds pasteurization heat treatment.

In addition, the figure 2.12 shows a more uniform temperature distribution compared to the previous cases: the steepest slopes are represented along the corners of the plot and cover just the 16% of the entire length.

As a result, along the z direction the temperature range sets mostly between 350° and 343° Kelvin.



Of course, if the rotation velocity is increased, the time to reach the pasteurization condition would lower, but higher velocity would also require more quality controls due to the higher risks of bumping packages, and consequently with package ruptures that would lead to more production stops.

### **2.3 Viscosity Range Analysis**

The study has showed, with the change of setup from a vertical position to a horizontal configuration, that in the heat treatment there's a sort of improving.

This gain could be amplified or attenuated by viscosity phenomena depending on its high or low value.

Due to this consideration, a viscosity guideline was made simulating tomato products at different viscosity values.

Looking at table 1.2, four different ranges were evaluated:

- Tomato Juice – Range: 100 – 750 cP
- Tomato Sauce – Range: 500 – 1500 cP
- Tomato Purée – Range: 1000 – 10000 cP
- Tomato Paste – Range: 10000 – 100000 cP

Each one of these ranges was simulated in vertical, horizontal and horizontal-rotating setups, while the solver was maintained the same of the previous cases.

For each one of these ranges, different viscosity values, consistency coefficient and flow behavior index were selected considering an external heating temperature of 373°K.

**Table 2.2** Tomato product ranges and parameters

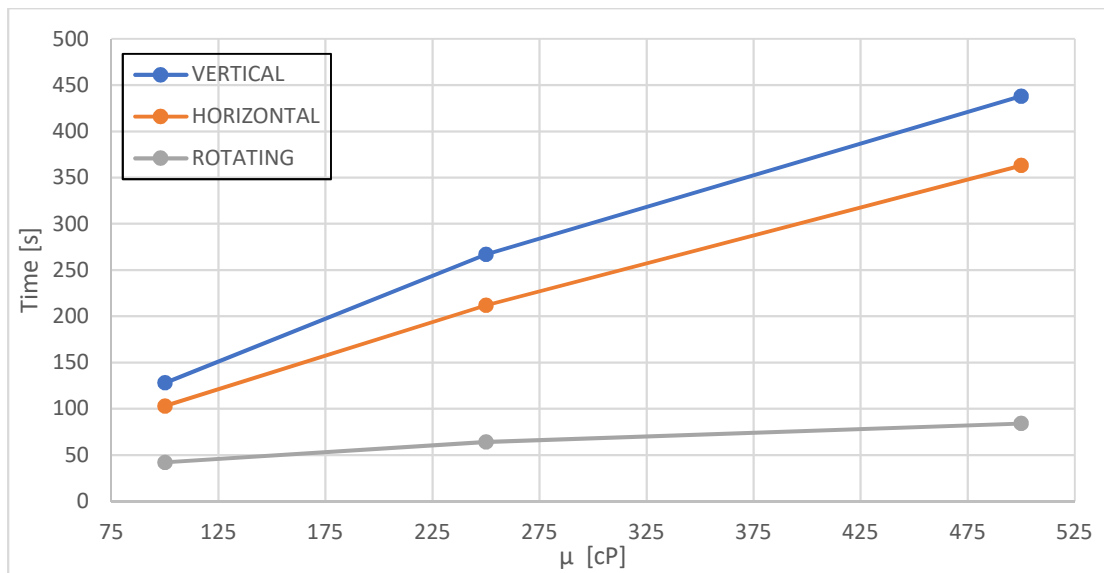
Product	Range [cP]	$\mu$ [cP]	$K$ [Pa*s <sup>n</sup> ] - n [-]
Tomato Juice	100-750	100	K=2,5 n=0,45
		250	
		500	
Tomato Sauce	500-1500	750	K=10 n=0,4
		1000	
		1250	
Tomato Purée	1000-10000	2500	K=40 n=0,35
		5000	
		7500	
		9000	
Tomato Paste	10000-100000	15000	K=100 n=0,3
		30000	
		50000	
		75000	

## CHAPTER 3

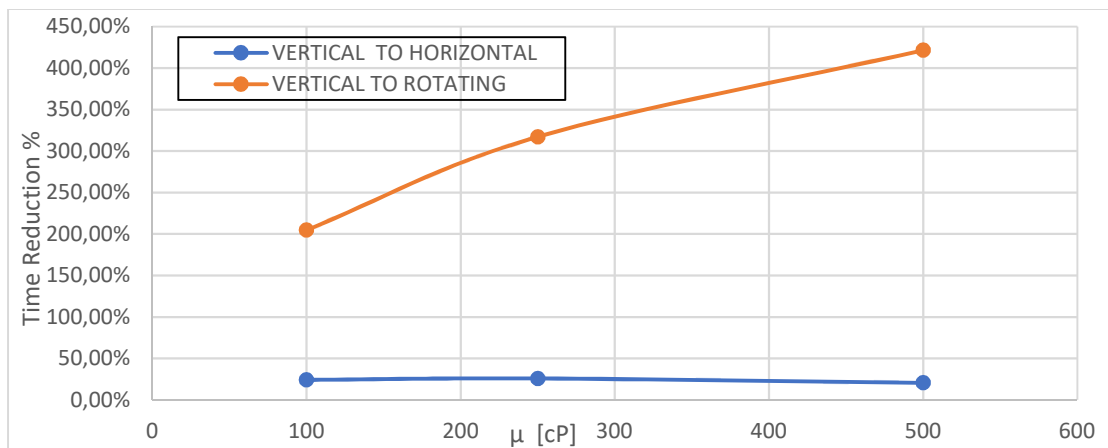
### RESULTS

Below are represented the results obtained for the different viscosity ranges: the first figure shows the amount of time required for the coolest fluid particle to reach the pasteurization temperature (around 343° K) with the three configurations; the second one represents the time percentage drop moving from the vertical configuration to the other ones.

#### 3.1. Tomato Juice

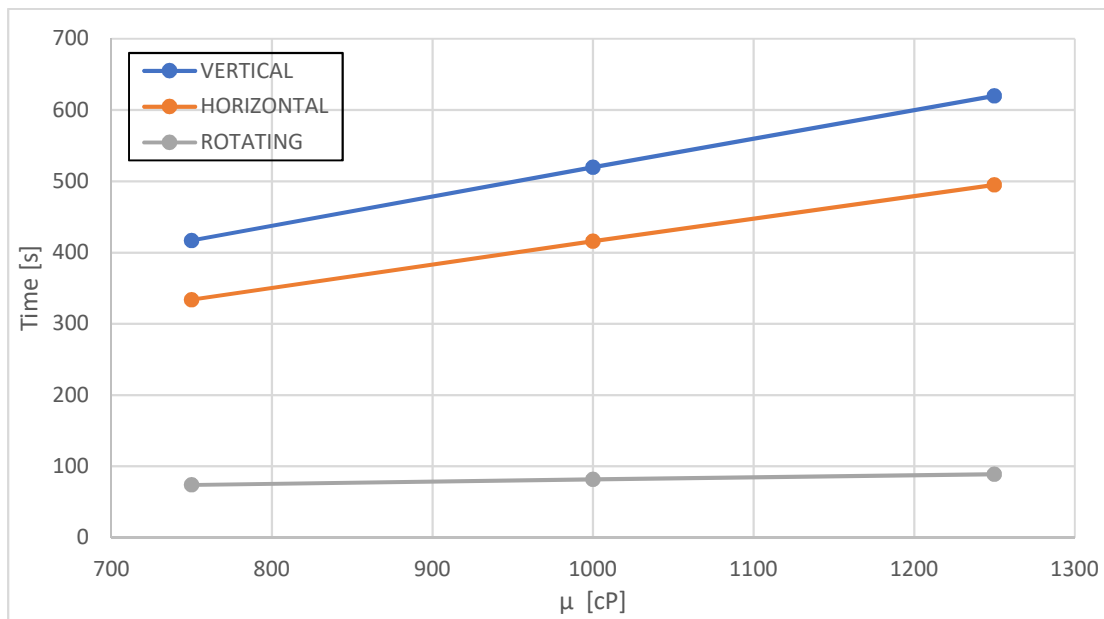


**Figure 3.1** Time - Viscosity - Configuration performance chart Tomato Juice.

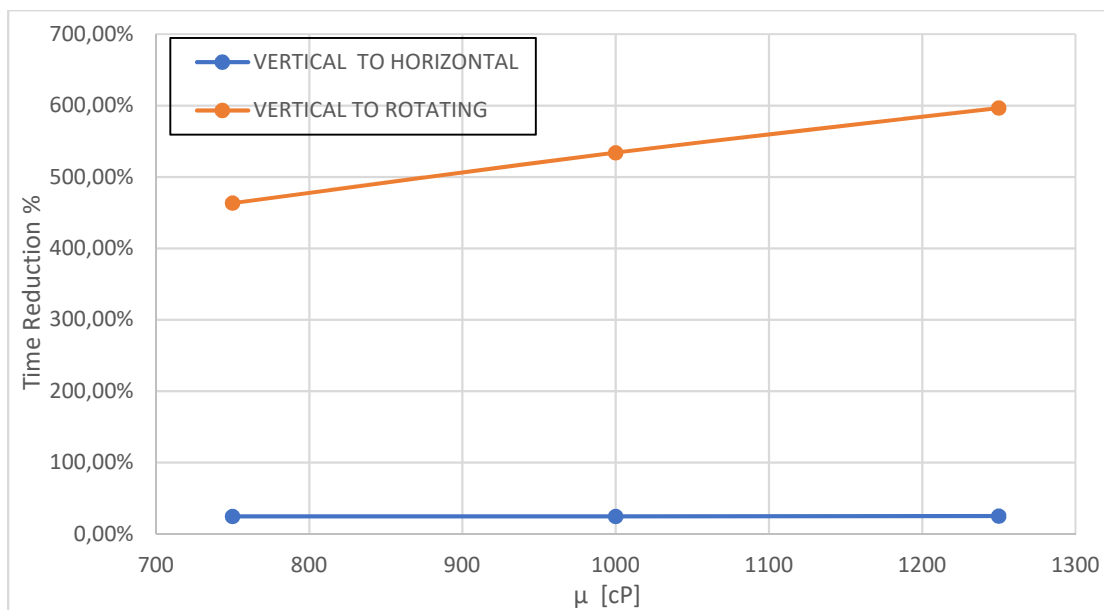


**Figure 3.2** Time Percentage Reduction – Viscosity - Configuration chart Tomato Juice.

### 3.2. Tomato Sauce

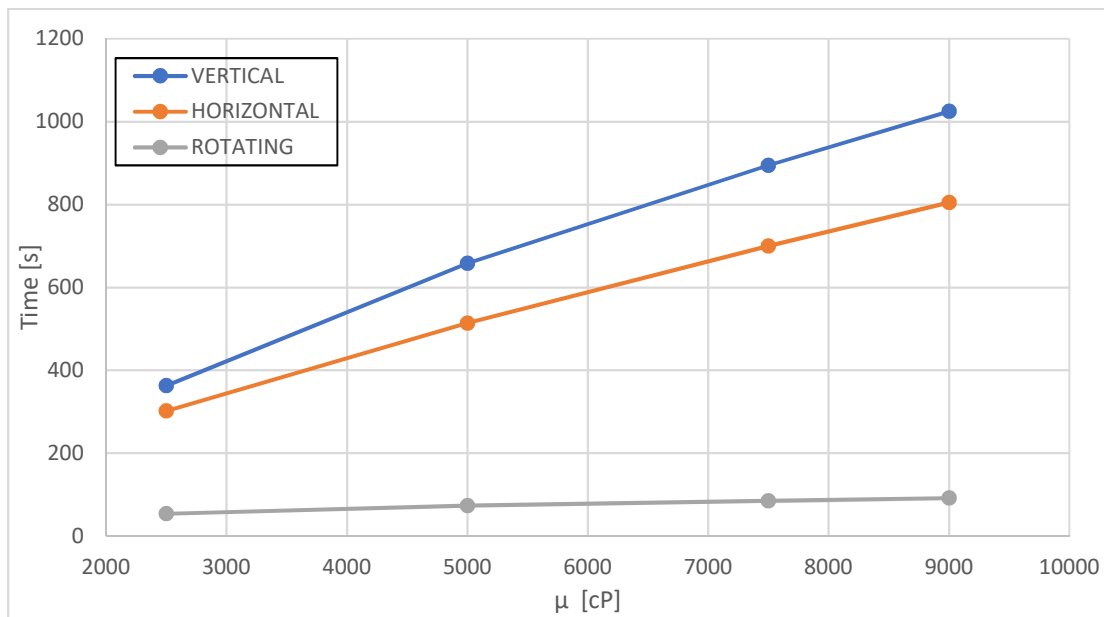


**Figure 3.3** Time - Viscosity - Configuration performance chart Tomato Sauce.

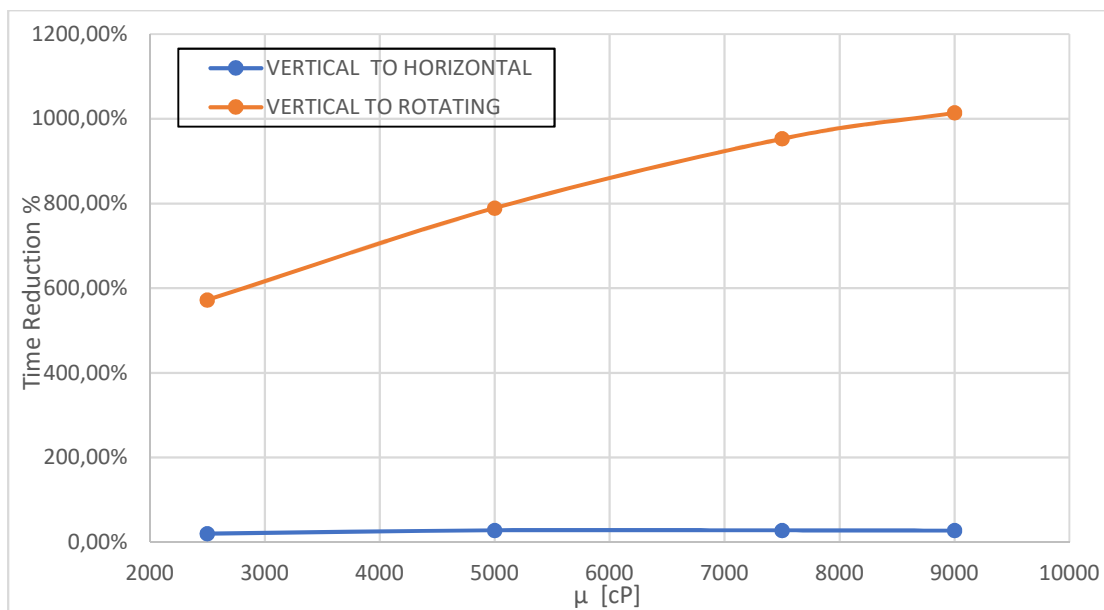


**Figure 3.4** Time Percentage Reduction – Viscosity - Configuration chart Tomato Sauce.

### 3.3. Tomato Purée

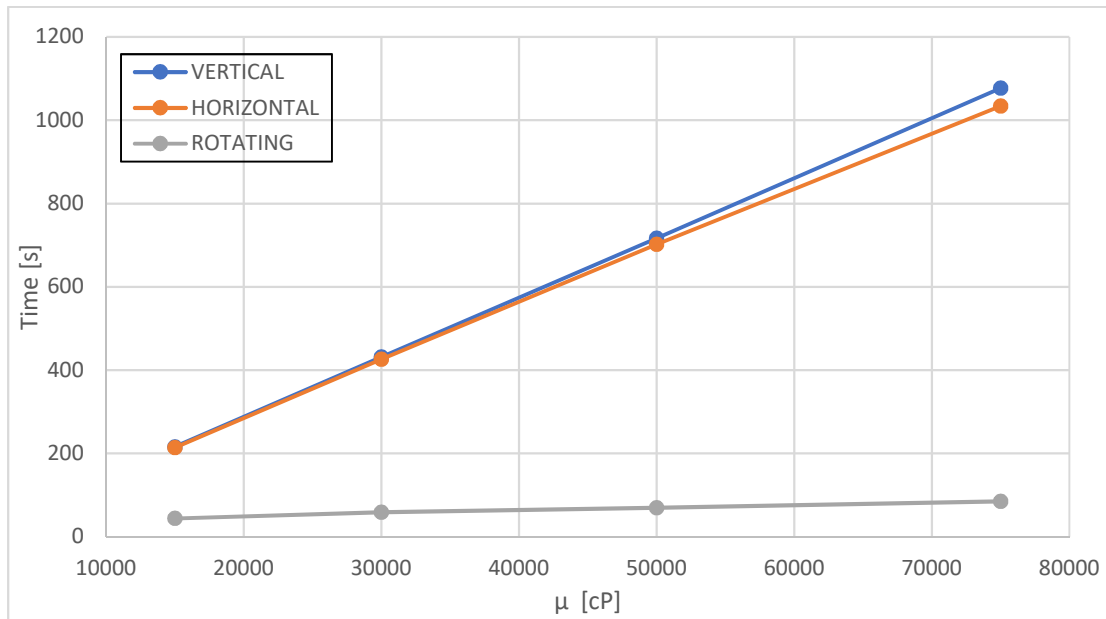


**Figure 3.5** Time - Viscosity - Configuration performance chart Tomato Purée.

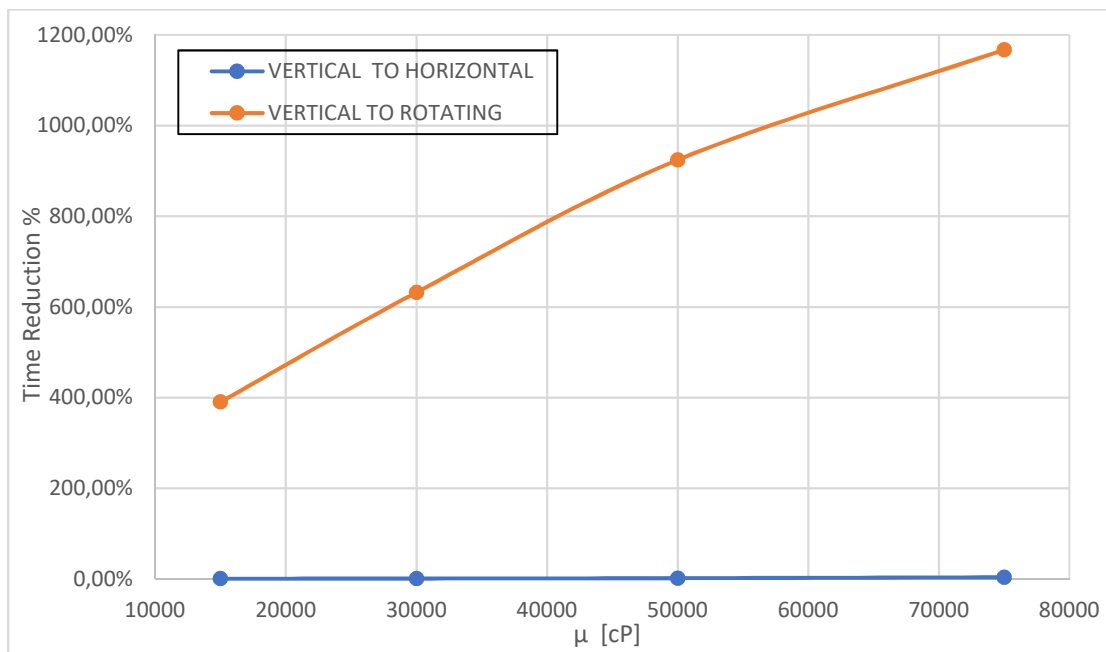


**Figure 3.6** Time Percentage Reduction – Viscosity - Configuration chart Tomato Purée.

### 3.4. Tomato Paste



**Figure 3.7** Time - Viscosity - Configuration performance chart Tomato Paste.



**Figure 3.8** Time Percentage Reduction – Viscosity - Configuration chart Tomato Paste.

### 3.5. Conclusion

The figure 3.1 shows the time results for different viscosity simulation: the blue line represents the vertical configuration while the orange and the grey lines are respectively the horizontal and the horizontal-rotating setups.

Overall it can be stated:

- The rotating configuration allows much faster pasteurization times compared to the other setups and the values don't change much moving from lower to higher viscosity numbers.

For the lowest range (fig. 3.2) the time drop percentage seems smaller, compared to the other ranges, when switching from a horizontal to a rotating configuration; in this case the firm needs to analyze the costs-benefits of this solution, considering the raise of material handling costs too.

Pasteurization Time Average with rotating setup = 74 sec

Std. Deviation = 16,4 sec

- The vertical configuration seems the least appropriate for a tomato product pasteurization heat treatment, but this is not necessarily true for high viscosity values (fig. 3.7). In these situations, there's almost no difference between vertical and horizontal setups, the former might be even better because of less machine costs.

Time Average = 479 sec

Std. Deviation = 293 sec

- The horizontal setup gives his best in the middle viscosity range (Time Percentage Reduction Max Peak = 28,02% at 5000 cP): this happens because for high viscosity values, the conduction prevails on the convection condition and changing the can position wouldn't affect much the heating dynamic and consequently the pasteurization time.

Time Average = 421 sec

Std. Deviation = 258 sec

### **3.5.1 Future Work**

The study could go on adding an experimental analysis, in this way it may be possible to compare real pasteurization times at different viscosity values.

With a field study, many parameters could be considered, and the system would be more complex: in the tunnel pasteurizer there will be more than a single tin can, and depending on their configurations, the packages would have contact points or lay lines that the heating fluid couldn't reach directly. Probably there would be even a different temperature distribution due to the heating exchange between the packages' local contacts, and the heating fluid may or may not always be vapor.

In this study the machine was also considered as ideal, with no heat leakage to the outside and in a steady state condition; normally the efficiency degree stands between 90 – 95%, and when the tunnel is started there's production of condensate due to the initial cold "room".

Applying most of these variables can lead to a better the tunnel pasteurizer's plant design.



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